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Energy levels of light nuclei $A = 5, 6, 7$ [☆]

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Abstract

A review of the evidence on the properties of the nuclei $A = 5$, 6 and 7, with emphasis on material leading to information about the structure of the $A = 5, 6, 7$ systems. (References closed 23 August 2001.) © 2002 Elsevier Science B.V. All rights reserved.

Introduction

In this article, the Triangle Universities Nuclear Laboratory Nuclear Data Evaluation Project continues the series of reviews summarizing experimental information on the properties of the nuclei with mass numbers five through twenty. This $A = 5$–20 series began with a 1966 review of $A = 5$–10 nuclei by T. Lauritsen and Fay Ajzenberg-Selove and was continued by Professor Ajzenberg-Selove with separate reviews for $A = 5$–10, $A = 11$–12, 13–15, 16–17, and 18–20. It comprised a total of 23 "Energy levels of

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Table 1
Energy levels of light nuclei-previous evaluations

Reference	Mass chains covered (A)	Reference
Early evaluations		
[37LI1A]	7−38	M.S. Livingston, H.A. Bethe, Rev. Mod. Phys. 9 (1937) 245
[48HO1A]	7−20	W.F. Hornyak, T. Lauritsen, Rev. Mod. Phys. 20 (1948) 191
[49LA1A]		T. Lauritsen, NRC Preliminary Report No. 5, 1949
[50HO1A]	1−23	W.F. Hornyak, T. Lauritsen, P. Morrison, W.A. Fowler, Rev. Mod. Phys. 22 (1950) 291
[52AJ38]	5−23	F. Ajzenberg, T. Lauritsen, Rev. Mod. Phys. 24 (1952) 321
[55AJ61]	5−23	F. Ajzenberg, T. Lauritsen, Rev. Mod. Phys. 27 (1955) 77
[59AJ76]	5−24	F. Ajzenberg, T. Lauritsen, Nucl. Phys. 11 (1959) 1
The Ajzenberg-Selove $A = 5$–20 series		
[66LA04]	5−10	T. Lauritsen, F. Ajzenberg-Selove, Nucl. Phys. 78 (1966) 1
[74AJ01]	5−10	F. Ajzenberg-Selove, Nucl. Phys. A 227 (1974) 1
[79AJ01]	5−10	F. Ajzenberg-Selove, Nucl. Phys. A 320 (1979) 1
[84AJ01]	5−10	F. Ajzenberg-Selove, Nucl. Phys. A 413 (1984) 1
[88AJ01]	5−10	F. Ajzenberg-Selove, Nucl. Phys. A 490 (1988) 1
[68AJ02]	11−12	F. Ajzenberg-Selove, Nucl. Phys. A 114 (1968) 1
[75AJ02]	11−12	F. Ajzenberg-Selove, Nucl. Phys. A 248 (1975) 1
[80AJ01]	11−12	F. Ajzenberg-Selove, Nucl. Phys. A 336 (1980) 1
[85AJ01]	11−12	F. Ajzenberg-Selove, Nucl. Phys. A 433 (1985) 1
[90AJ01]	11−12	F. Ajzenberg-Selove, Nucl. Phys. A 506 (1990) 1
[70AJ04]	13−15	F. Ajzenberg-Selove, Nucl. Phys. A 152 (1970) 1
[76AJ04]	13−15	F. Ajzenberg-Selove, Nucl. Phys. A 268 (1976) 1
[81AJ01]	13−15	F. Ajzenberg-Selove, Nucl. Phys. A 360 (1981) 1
[86AJ01]	13−15	F. Ajzenberg-Selove, Nucl. Phys. A 449 (1986) 1
[91AJ01]	13−15	F. Ajzenberg-Selove, Nucl. Phys. A 523 (1991) 1
[71AJ02]	16−17	F. Ajzenberg-Selove, Nucl. Phys. A 166 (1971) 1
[77AJ02]	16−17	F. Ajzenberg-Selove, Nucl. Phys. A 281 (1977) 1
[82AJ01]	16−17	F. Ajzenberg-Selove, Nucl. Phys. A 375 (1982) 1
[86AJ04]	16−17	F. Ajzenberg-Selove, Nucl. Phys. A 460 (1986) 1
[72AJ02]	18−20	F. Ajzenberg-Selove, Nucl. Phys. A 190 (1972) 1
[78AJ03]	18−20	F. Ajzenberg-Selove, Nucl. Phys. A 300 (1978) 1
[83AJ01]	18−20	F. Ajzenberg-Selove, Nucl. Phys. A 392 (1983) 1
[87AJ02]	18−20	F. Ajzenberg-Selove, Nucl. Phys. A 475 (1987) 1
TUNL evaluations		
[93TI07]	16−17	D.R. Tilley, H.R. Weller, C.M. Cheves, Nucl. Phys. A 564 (1993) 1
[95TI07]	18−19	D.R. Tilley, H.R. Weller, C.M. Cheves, R.M. Chasteler, Nucl. Phys. A 595 (1995) 1
[98TI06]	20	D.R. Tilley, C.M. Cheves, J.H. Kelley, S. Raman, H.R. Weller, Nucl. Phys. A 636 (1998) 249

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 $A = 16$–17, 18–19 and 20 reviews. In form, arrangement and purpose, this present paper summarizing $A = 5$–7 is similar to the previous reviews dealing with the nuclei $A = 5$–20. In a break with the earlier practice of

Fay Ajzenberg-Selove of grouping $A = 5$–10 for publication, TUNL has chosen to publish the $A = 5$–7 review separately.

Arrangement of 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. Level parameters which are newly adopted in this evaluation or revised from the previous evaluation [88AJ01]) are identified by a footnote. 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, or in some cases, a table listing theoretical references with a one-line description of each.

Since most nuclear reactions provide information on more than one nucleus, each reaction is listed under both the compound and the residual nucleus, with differently oriented discussions and partially overlapping bibliographies. With bombarding energies in the tens of MeV, where direct interactions predominate, it is frequently the target nucleus which is mainly concerned, and here, a third type of listing has been necessary. Generally speaking, in a reaction such as $X(a, b)Y$, information relating to resonances, yields and angular distributions in the resonance region will be found under the listing for the 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 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 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. Previous TUNL evaluations have listed these publications by key number and a one-line description of each under appropriate categorical headings, e.g., shell model, cluster model, astrophysics, etc. Because the lists have become quite lengthy for $A = 5$–7, the authors of the present review have chosen to omit them in the published review and instead will provide them on the TUNL Data Evaluation

Project's website at (*www.tunl.duke.edu/NuclData/General_Tables/General_Tables.shtml*) along with the abridged version of this and other reviews (see *Electronic Data Services* below).

Isobar diagrams and tables

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

Conventions and symbols

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

E: energy in MeV, in lab coordinates unless otherwise specified; subscripts p, d, t, etc., refer to protons, deuterons, tritons, etc.;
E_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}: projectile energy corresponding to a reaction resonance;
Γ: 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;
θ^2: dimensionless reduced width, $\gamma_\lambda^2 2\mu R^2/3\hbar^2$;
ϵ-capture: electron capture;
S(E): astrophysical factor for center-of-mass energy E;
σ(E): reaction cross section for center-of-mass energy E;
${}^AX^*$(E): excited state of the nucleus ${}^AX$, at energy E;
PWBA: plane-wave Born approximation;
DWBA: distorted-wave Born approximation;
FSI: final-state interactions;
RGM: resonating-group method;
TAP: tensor-analyzing power;
VAP: vector-analyzing power.

The reader is reminded of the following abbreviations: 1 μeV = 10^{-6} eV; 1 meV = 10^{-3} eV; 1 ps = 10^{-12} s; 1 fs = 10^{-15} s; 1 Wu = 1 Weisskopf unit.

Other review papers on light nuclei

We wish to remind the readers of the papers on $A = 3$ [87TI07], $A = 4$ [92TI02], $A = 16$–17 [93TI07], $A = 18$–19 [95TI07], $A = 20$ [98TI06] and $A = 21$–44 [90EN08]. Higher mass chains are discussed in *Nuclear Data Sheets*.

Electronic data services

National Nuclear Data Center

Adopted levels, decay data and reaction data for $A = 5$–7 have been entered by the TUNL Nuclear Data Evaluation Group into the Evaluated Nuclear Structure Data Files (ENSDF) maintained by the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory. ENSDF files of adopted levels and decay data for other $A = 2$–20 nuclei as well as higher mass nuclei are also available. Access to these files is available through the World Wide Web (*www.nndc.bnl.gov/*).

Nuclear Physics Electronic

This review paper for $A = 5$–7 in its entirety, as well as the TUNL reviews for $A = 18$–19 and $A = 20$ are available through the Nuclear Physics Electronic (NPE) service by way of the World Wide Web at (*www.elsevier.nl/gej-ng/29/35/show/index.htt*). Also, Elsevier Publishers, in collaboration with TUNL, are providing scanned versions of Fay Ajzenberg-Selove's $A = 5$–20 evaluations (from 1966–1991). Please see the third item below.

TUNL Nuclear Data Evaluation Group WWW server

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

- **Energy level diagrams** in the style of Fay Ajzenberg-Selove for $A = 4$–20 for the most recent FAS (1988, 1990, 1991) and TUNL (1993, 1995, 1998, 2001) evaluations in EPS, GIF and PDF formats, as well as scanned versions of earlier energy level diagrams in GIF, PDF and PS formats to accompany TUNL's PDF and HTML documents: $A = 5$–10 (1984), $A = 11$–12 (1985), $A = 13$–15 (1986) and $A = 16$–17 (1986).

- Abridged versions of **TUNLs published evaluations** for $A = 3$–7, 16–20, and a preliminary version of $A = 9$. The PDF versions include hyperlinks for references, tables and update lists (if applicable). A brief table of contents has been included at the beginning of each PDF document.

- Elsevier Publishers (*Nucl. Phys. A*) recently completed a collaborative effort with TUNL to provide on their website PDF documents (scanned versions only—do not contain hyperlinks) of **all of Fay Ajzenberg-Selove's $A = 5$–20 evaluations from 1966–1991**. These PDF versions can be accessed via our website or directly through Nuclear Physics Electronic at (*www.elsevier.nl/gej-ng/10/33/9/lightnuclei/*).

• **General tables** (please refer to the discussion of general tables stated in the section titled "Arrangement of materials") for the most recent TUNL evaluations of $A = 5$–7, and $A = 9$ preliminary version. Beginning with $A = 5$–7, the general tables will no longer be included in the publications of "Energy levels of light nuclei". The tables can be found online at our website at (*www.tunl.duke.edu/NuclData/General_Tables/General_Tables.shtml*).

• Abridged versions of many of **Fay Ajzenberg-Selove's** $A = 5$–20 compilations (currently for evaluations from the years 1984–1991). These PDF versions are set up in the same manner as mentioned in the second item.

• Our new **HTML project** that will provide HTML documents for individual nuclides found within the Fay Ajzenberg-Selove and TUNL evaluations. The HTML documents will provide a more comprehensive way to obtain information about each nuclide in the $A = 3$–20 energy level series. The HTML documents expand upon the PDF documents by providing: links to the tables that will be in both PDF and PostScript format; links to any reaction and reaction discussion cited within the text that refers to any TUNL or FAS evaluation; links for references cited to either the NSR database or an HTML citation page; links to the energy level diagrams, update lists, and general tables; and links to the PDF documents provided on TUNL and Elsevier websites. HTML documents are now available for 135 nuclides found within the $A = 3$–18 series. Posting of the nuclides will be continuous throughout the year.

• **Update lists** of references for $A = 5$–15 nuclei, which provide brief descriptions of important research bearing on level information published since the last full evaluation. References for the update lists are given for each nuclide with experimental and theoretical subdivisions for each, and include links to the NSR database.

• Link to the **ENSDF** files for the $A = 2$–20 nuclides that have been entered by TUNL that are available through the National Nuclear Data Center (NNDC) site at (*www.nndc.bnl.gov/nndc/ensdf/ensdfindex.html*).

• A new posting of our **Palm Pilot** page that utilizes PalmOS technology and applications of interest to the nuclear physics community ready for easy access and download.

• A short version ($A = 1$–20) of the **Tables of isotopes**, provided by the Berkeley Isotopes Project.

• A webpage providing a **complete list** of links to all of the available TUNL, FAS and preliminary evaluations, general tables, HTML documents, figures, update lists, etc., that are provided by our website.

• **Links** to the National Nuclear Data Center and other useful sites, as well as to the online electronic journals most useful to the nuclear physics community.

- Information about the **status** of the project and our publications.

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We are extremely grateful to our many colleagues who have as usual pointed out many errors in the preliminary versions of $A = 5$, 6 and 7 and provided valuable suggestions. In particular, we acknowledge with special thanks the help of Professor F.C. Barker and Dr. John Millener. We also thank Jim Purcell for his contributions to the update lists. 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. 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.

Definitions of resonance parameters

The subject of resonance parameters is complicated by the fact that several prescriptions have been given for defining them, all of which can give different values for the broad resonances encountered in light nuclei. These prescriptions amount to transforming Wigner's usual R matrix, R_B, from its real, energy-independent boundary conditions B to a more "physical" function $X(E)$ that is energy dependent, and possibly complex. The pole residues of the transformed R matrix, R_X, are given by

$$\gamma_{c\lambda}^{o2} = \frac{\gamma_{c\lambda}^2}{1 + \sum_c \gamma_{c\lambda}^2 \frac{dX_c}{dE}\big|_{E=E_\lambda}}, \tag{1}$$

the denominator of which is the normalization of the energy eigenfunction in all space if it is assumed to vanish asymptotically.

The usual choice for X has been the channel shift function, $S_c(E)$, which gives a real-energy prescription for the resonance parameters. Even at this point, there is confusion arising from the fact that some researchers define so-called *formal* partial widths as

$$\Gamma_{c\lambda} = 2P_c(E_\lambda)\gamma_{c\lambda}^2, \tag{2}$$

neglecting the energy denominator of the residue term, while others include it in defining an *observed* width

$$\Gamma_{\lambda c}^{o} = 2P_c(E_\lambda)\gamma_{c\lambda}^{o2} = \frac{\Gamma_{c\lambda}}{1 + \sum_c \gamma_{c\lambda}^2 \frac{dS_c}{dE}\big|_{E=E_\lambda}}, \tag{3}$$

Table 2
Parameters of the ground state of the light nuclei with $A = 5$–7

	Atomic mass[a] excess (keV)	$\tau_{1/2}$ or Γ_{cm}[b]	Decay[b]	J^π; T[b,c]
^{5}n	see text		n	$T = \frac{5}{2}$
^{5}H	$(32.2 \pm 0.7) \times 10^3$ [b,e]		n, t	$(\frac{1}{2}^+)$; $\frac{3}{2}$
^{5}He	11294[b]	648 keV	n, α	$\frac{3}{2}^-$; $\frac{1}{2}$
^{5}Li	11404[b]	1.23 MeV	p, α	$\frac{3}{2}^-$; $\frac{1}{2}$
^{5}Be	> 33700[h]		p, ^{3}He	$(\frac{1}{2}^+)$; $\frac{3}{2}$
^{6}n	see text		n	(0^+); 3
^{6}H	41860 ± 260[d]	1.6 ± 0.4 MeV	n	(2^-); 2
^{6}He	17594.1 ± 1.0[d]	806.7 ± 1.5 ms	β^-	0^+; 1
^{6}Li[f]	14086.3 ± 0.5[d]	stable		1^+; 0
^{6}Be	18374 ± 5[d]	92 ± 6 keV	p, α	0^+; 1
^{6}B	see text			$T = 2$
^{6}C	see text			(0^+); 3
^{7}H	see text			$T = \frac{5}{2}$
^{7}He	26110 ± 30[d]	150 ± 20 keV	n	$(\frac{3}{2}^-)$; $\frac{3}{2}$
^{7}Li[g]	14907.7 ± 0.5[d]	stable		$\frac{3}{2}^-$; $\frac{1}{2}$
^{7}Be	15769.5 ± 0.5[d]	53.22 ± 0.06[d]	ϵ	$\frac{3}{2}^-$; $\frac{1}{2}$
^{7}B	27870 ± 70[d]	1.4 ± 0.2 MeV	p, α	$(\frac{3}{2}^-)$; $\frac{3}{2}$

[a] The values of the mass excesses shown here were used to calculate Q_{m}. Mass excesses of nuclei not included in this table, but also used in Q_{m} calculations were obtained from [95AU04]. The mass excesses of $\pi^\pm$, π^0 and μ were taken to be 139570.18 ± 0.35, 134976.6 ± 0.6 and 105658.357 ± 0.005 keV [00GR22].
[b] From data reviewed in this article.
[c] J^π values in parentheses are derived from systematics.
[d] [95AU04].
[e] [97KO07]. Uncertainties include combined statistical and systematic errors.
[f] $\mu = +0.8220473$ (6) nm [89RA17], $Q = -0.818$ (17) mb [98CE04].
[g] $\mu = +3.256427$ (2) nm [89RA17], $Q = -40.6$ (8) mb [88DI1B].
[h] [88AJ01].

so-called because it corresponds more closely to the observed FWHM of measured resonant peaks. In the expressions above, $P_c(E)$ is the channel penetrability function. The multilevel version of the single-level real-energy prescription introduced by Lane and Thomas [58LA73] that was used in the $A = 4$ level compilation [92TI02], and for comparison purposes in the present $A = 5$ compilation, corresponds to giving observed widths since the normalization factor in the denominator of the residue is always taken into account. However, this will not be true for all the widths listed in the tables of this article. For example, the widths in Tables 7.3 and 7.4 are *formal*, while those in Table 7.10 are *observed*, making them difficult to compare directly.

In our opinion, the most "physical" choice for $X(E)$ is the Kapur–Peirels boundary value, $L_c(E) = S_c(E) + \mathrm{i}P_c(E)$, which is the logarithmic derivative of the channel

Table 3
Electromagnetic transitions in $A = 5$–7

Nucleus	$E_{\mathrm{xi}} \to E_{\mathrm{xf}}$ (MeV)	$J_i^\pi \to J_f^\pi$ [a]	Γ_γ (eV)	Mult.	S (Wu)[b]
^{5}He	16.84 → 0	$\frac{3}{2}^+ \to \frac{3}{2}^-$	2.1 ± 0.4	E1	$(2.2 \pm 0.4) \times 10^{-3}$
^{5}Li	16.87 → 0	$\frac{3}{2}^+ \to \frac{3}{2}^-$	5 ± 1	E1	$(5 \pm 1) \times 10^{-3}$
^{6}Li[c]	2.19 → 0	$3^+ \to 1^+$	$(4.40 \pm 0.34) \times 10^{-4}$	E2	16.5 ± 1.3
	3.56 → 0	$0^+; 1 \to 1^+; 0$	8.19 ± 0.17	M1	8.62 ± 0.18
	4.31 → 0	$2^+ \to 1^+$	$(5.4 \pm 2.8) \times 10^{-3}$	E2	6.8 ± 3.5
	5.37 → 0	$2^+; 1 \to 1^+; 0$	0.27 ± 0.05	M1	$(8.3 \pm 1.5) \times 10^{-2}$
^{7}Li[d]	0.48 → 0	$\frac{1}{2}^- \to \frac{3}{2}^-$	$(6.30 \pm 0.31) \times 10^{-3}$	M1	2.75 ± 0.14
			$(3.3 \pm 0.2) \times 10^{-7}$	E2	19.7 ± 1.2
	4.65 → 0	$\frac{7}{2}^- \to \frac{3}{2}^-$	6×10^{-3}	E2	4.2
^{7}Be	0.43 → 0	$\frac{1}{2}^- \to \frac{3}{2}^-$	$(3.43 \pm 0.45) \times 10^{-3}$	M1	2.07 ± 0.27

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

[b] The last column gives the γ-ray strengths expressed in Weisskopf units (see D.H. Wilkinson, in: F. Ajzenberg-Selove (Ed.), Nuclear Spectroscopy B, Academic Press, NY, 1960). The Weisskopf estimates (Γ_{W} in eV, E_γ in MeV) are:

$$\Gamma_{\mathrm{W}}(\mathrm{E1}) = 6.8 \times 10^{-2} A^{2/3} E_\gamma^3, \qquad \Gamma_{\mathrm{W}}(\mathrm{E2}) = 4.9 \times 10^{-8} A^{4/3} E_\gamma^5,$$
$$\Gamma_{\mathrm{W}}(\mathrm{E3}) = 2.3 \times 10^{-14} A^2 E_\gamma^7, \qquad \Gamma_{\mathrm{W}}(\mathrm{E4}) = 6.8 \times 10^{-21} A^{8/3} E_\gamma^9,$$
$$\Gamma_{\mathrm{W}}(\mathrm{M1}) = 2.1 \times 10^{-2} E_\gamma^3, \qquad \Gamma_{\mathrm{W}}(\mathrm{M2}) = 1.5 \times 10^{-8} A^{2/3} E_\gamma^5.$$

The values for these γ-ray strengths are occasionally different from those listed in other tables of this paper because different values of r_0 were used. In this table $r_0 = 1.2$ fm is used consistently. The multipolarities in the next to the last column were used to calculate the Γ_{W}. See also [79EN05]. Except for the ^{5}He, ^{5}Li and ^{7}Li transitions, the values in the table were obtained from Table 2 of [88AJ01].

[c] See Table 6.10.

[d] See Table 7.5. See also [84MO1D].

outgoing-wave solution. There are numerical complications associated with this choice resulting from the fact that the boundary conditions are complex functions of *momentum*, rather than energy, but these are outweighed by having a prescription that is based on the complex poles of the S matrix, which have a sound theoretical connection to resonances. This recommended approach, which we refer to in the following as the "extended" R-matrix prescription [87HA20, 97CS01], also results in observed widths.

A = 5

$A = 5$ *resonance parameters*

The resonance parameters tabulated here are based on comprehensive multichannel R-matrix analyzes of reactions in the ^{5}He and ^{5}Li systems (Hale, Dodder and Witte, private communication[1]). These analyzes include data from all possible reactions for the two-body channels d + t (or d + ^{3}He in the case of ^{5}Li) and N + ^{4}He at cm energies corresponding to $E_x < 23$ MeV. In addition, N + ^{4}He* channels are included to approximate the effects of three-body breakup processes. The fits obtained to the measurements for the two-body reactions are generally quite good. In the ^{5}He analysis, for example, the χ^2 per degree of freedom for the fit is 1.6, and it includes more than 2600 data points. Similar results were obtained for the ^{5}Li analysis, which includes even more data.

The level information has been obtained from the $A = 5$ R-matrix parameters using two different prescriptions, given in separate tables. The recommended prescription, called the "extended" R-matrix method [87HA20, 97CS01], comes from the complex poles and residues of the S matrix. This prescription has been found to give resonance parameters that are free, both formally and practically, of all dependence on the "geometric" parameters of R-matrix theory, such as boundary conditions and channel radii. The parameters are listed in Table 5.1 for ^{5}He and in Table 5.3 for ^{5}Li. Positions and widths for the lowest two $A = 5$ states have already been given in [97CS01], and for the second excited state of ^{5}He $(3/2^+)$ in [87HA20], using this prescription.

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

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

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

In some cases, resonances seen using the recommended method are not present in the usual prescription, even though the input R-matrix parameters are identically the same. These differences, which are most evident for light systems having broad resonances, stem from the fact that the resonant K-matrix prescription is based on the *apparent* positions of the S-matrix poles as seen from the real axis of the physical sheet. For broad resonances, as is known from the complex-eigenvalue expansion of the level matrix [58LA73], the

[1] For a discussion of the methods used and earlier results, see G.M. Hale, D.C. Dodder, in: J.L. Fowler, C.H. Johnson, C.D. Bowman (Eds.), Proc. Int. Conf. on Nuclear Cross Sections for Technology, Knoxville, TN, NBS Special Publication, Vol. 594, 1979, p. 650.

apparent pole positions can change rapidly (or even disappear entirely) as the vantage point is varied, causing significant differences with the actual positions (and residues) of the poles in the complex-energy plane.

General

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

^{5}n

(not illustrated)

^{5}n has not been observed. It is suggested that it is unbound by 10 MeV: see [84AJ01]. See also [84DE52].

^{5}H

(not illustrated)

The previous review [88AJ01] noted that the ^{9}Be(^{11}B, ^{15}O) reaction at $E(^{11}\mathrm{B}) =$ 52–76 MeV showed no evidence for the formation of ^{5}H [86BE35, 87BO40]. For the earlier work see [84AJ01]. See also [87KO47, 88SEZJ]. In several experiments on π^- absorption at rest there is some evidence for the formation of a very broad (8 ± 3 MeV) resonance in the ^{5}H system with $E_r = 7.4 \pm 0.7$ MeV in the ^{9}Be(π^-, X) reaction (see [87GO25] and the more recent work of [91GO19, 92AM1H]). Measurements reported in [90AM04, 92AM1H] provide evidence for a state at $E_r = 11.8 \pm 0.7$ MeV, $\Gamma = 5.6 \pm 0.9$ MeV from ^{6}Li(π^-, p) and a state at $E_r = 9.1 \pm 0.7$ MeV, $\Gamma = 7.4 \pm 0.6$ MeV from ^{7}Li(π^-, d). In an experiment on ^{6}Li(π^-, p) at $E_\pi = 125$ MeV [80SE02] a broad ^{5}H state with $E_r = 11.1 \pm 1.5$, $\Gamma \approx 14$ MeV was observed. Evidence for a dineutron-containing breakup channel was reported in [91SE06]. Work on an experiment on ^{7}Li(^{6}Li, ^{8}B)^{5}H described in [95ALZU] reported evidence for an unstable ^{5}H nucleus at 5.2 ± 0.4 MeV above the ^{3}H + 2n dissociation threshold. See also [95AU04]. A recent study of the ^{1}H(^{6}He, 2p)^{5}H reaction [97KO07] reported a ^{5}H resonance with decay energy into ^{3}H + 2n of $1.1 \pm 0.4 \pm 0.3$ MeV (0.3 MeV is the systematic error).

^{5}H is calculated to have $J^\pi = 1/2^+$, to be unstable with respect to two neutron emission and to have excited states at $E_x = 2.44$, 4.29 and 7.39 MeV with $J^\pi = 5/2^+$, $3/2^+$ and $3/2^+$ ($(0 + 1)\hbar\omega$ model space), and at $E_x = 2.85$, 3.46 and 6.02 MeV with $J^\pi = 3/2^+$, $5/2^+$ and $3/2^+$ ($(0 + 2)\hbar\omega$ model space) [85PO10]. A three-body calculation [00SH23] predicts states in the ^{3}H + n + n continuum with $J^\pi = 1/2^+$, $E_x =$ 2.5–3.0 MeV, $\Gamma =$ 3–4 MeV; $J^\pi = 3/2^+$, $E_x =$ 6.4–6.9 MeV, $\Gamma = 8$ MeV; $J^\pi = 5/2^+$, $E_x =$ 4.6–5.0 MeV, $\Gamma = 5$ MeV. A calculation [01DE02] with the generator-coordinate method using ^{3}H + n + n three-cluster state predicts a ^{5}H ground-state energy $E \approx 3$ MeV above the ^{3}H + n + n threshold with $\Gamma_n \approx$ 1–4 MeV and a lifetime longer than the ^{4}H lifetime. See also [82SM09, 83ANZQ, 86BE44, 87PE1C].

^{5}He

(Figs. 1 and 3)

General

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

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

The quasifree neutron knockout reaction was studied with ^{6}He beams produced by 115 MeV ^{15}N primary beams [97KOZV, 97KO07]. ^{5}He was observed in the separation energy spectra. The ^{5}He $\to$ ^{4}He + n decay energy is reported to be consistent with the "known mass of ^{5}He" and is given as 0.97 MeV.

2. ^{3}H(d, γ)^{5}He, $Q_m = 16.792$

At low energies the reaction is dominated by a resonance at $E_d = 107$ keV; the mirror reaction shows resonance at $E_d = 430$ keV. The branching ratio $\Gamma_{\gamma_0}/\Gamma_n$ integrated over the resonance from 0 to 275 keV is $(5.6 \pm 0.6) \times 10^{-5}$ [86MO05], in very good agreement with the earlier value of $(5.4 \pm 1.3) \times 10^{-5}$ for $E_d = 45$ to 146 keV [84CE08]. Assuming Γ_n of ^{5}He*(16.7) is 37 ± 5 keV (see reaction 8), then $\Gamma_{\gamma_0} = 2.1 \pm 0.4$ eV. [86MO05] also report branching ratios up to $E_d = 0.72$ MeV and summarize the earlier work to 5 MeV. More recently, a measurement [93KA01] at $E_d = 100$ keV of the ^{3}H(d, γ)^{5}He/^{3}H(d, α)n ratio gave $(1.2 \pm 0.3) \times 10^{-4}$ which is larger than the results of [86MO05, 84CE08] but includes contribution from decay to both the ground and first excited states.

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

The ^{3}H(d, γ)^{5}He and ^{3}He(d, γ)^{5}Li reactions were used in a measurement [91BA02] of the ground-state widths of ^{5}He and ^{5}Li. The results were $\Gamma_n = 1.36 \pm 0.19$ MeV in ^{5}He and $\Gamma_p = 2.44 \pm 0.21$ MeV for ^{5}Li. These values lead to reduced widths for ^{5}He and ^{5}Li which are equal (within error). This is consistent with charge symmetry expectations. The ground-state widths given by the conventional R-matrix prescription in Tables 5.2 and 5.4 are 0.963 MeV and 2.11 MeV for ^{5}He and ^{5}Li, respectively.

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

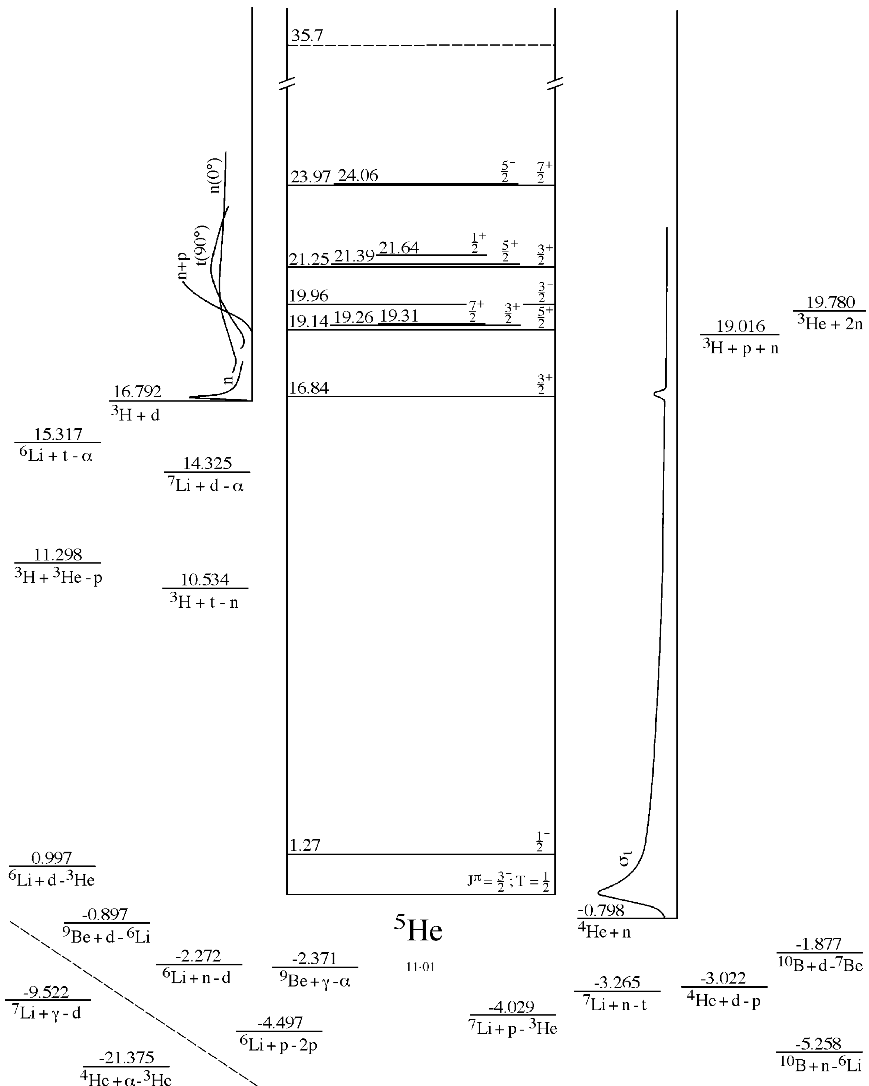

Fig. 1. Energy levels of ^{5}He, extended R-matrix prescription (see Table 5.1). In these diagrams, energy values are plotted vertically in MeV, based on the ground state as zero. For the $A = 5$ diagrams all levels are represented by discrete horizontal lines. Values of total angular momentum J, parity, and isobaric spin T which appear to be reasonably well established are indicated on the levels; less certain assignments are enclosed in parentheses. For reactions in which ^{5}He is the compound nucleus, some typical thin-target excitation functions are shown schematically, with the yield plotted horizontally and the bombarding energy vertically. Bombarding energies are indicated in laboratory coordinates and plotted to scale in cm coordinates. Excited states of the residual nuclei involved in these reactions have generally not been shown. For reactions in which the present nucleus occurs as a residual product, excitation functions have not been shown. Q values and threshold energies are based on atomic masses from [95AU04] except for the ground-state energies of the $A = 5$ nuclei for which the values from Tables 5.1 and 5.3 are used. Further information on the levels illustrated, including a listing of the reactions in which each has been observed, is contained in Table 5.1.

Table 5.1
Energy levels of ^{5}He, extended R-matrix prescription[a]

E_x (MeV)	$J^{\pi}; T$	Γ_{cm} [b] (MeV)	Γ_n (MeV)	Γ_d (MeV)	Γ_{n*} [c] (MeV)	Decay	Reactions (used in analysis)
g.s.[d]	$\frac{3}{2}^-; \frac{1}{2}$	0.648	0.578	8.80[e]	66.0[e]	n, α	5, 8, 13, 23, 24, 25
1.27	$\frac{1}{2}^-; \frac{1}{2}$	5.57	3.18	38.0[e]	1.27[e]	n, α	5, 8, 21, 24, 25
16.84	$\frac{3}{2}^+; \frac{1}{2}$	0.0745	0.040	0.025[f]		γ, n, d, t, α	2, 3, 7, 8, 10, 13, 14, 23, 24, 25
19.14	$\frac{5}{2}^+; \frac{1}{2}$	3.56	0.003	1.62[g]		n, d, t, α	4, 10, 14, 23
19.26	$\frac{3}{2}^+; \frac{1}{2}$	3.96	0.014	1.83[g]		n, d, t, α	4, 10, 14, 23
19.31	$\frac{7}{2}^+; \frac{1}{2}$	3.02	0.045	1.89[g]		n, d, t, α	4, 10, 14
19.96	$\frac{3}{2}^-; \frac{1}{2}$	1.92	0.003	0.325[h]	0.862	n, p, d, t, α	3, 17, 24, 25
21.25	$\frac{3}{2}^+; \frac{1}{2}$	4.61	0.098	2.38[i]		n, d, t, α	21
21.39	$\frac{5}{2}^+; \frac{1}{2}$	3.95	0.091	2.12[l]		n, d, t, α	21
21.64	$\frac{1}{2}^+; \frac{1}{2}$	4.03	0.050	0.878[j]	0.726	n, p, d, t, α	21
23.97	$\frac{7}{2}^+; \frac{1}{2}$	5.44	0.053	2.85[g]		n, d, t, α	
24.06	$\frac{5}{2}^-; \frac{1}{2}$	5.23	0.013	2.18[k]		n, d, t, α	
(35.7 ± 0.4)[l]		≈ 2[l]					21, 25

[a] This prescription, based on the complex poles and residues of the S-matrix, is the recommended one (see the introduction). The channel radii are: $a_n = 3.0$ fm, $a_d = 5.1$ fm. The uncertainties in the widths and positions of the first three levels are less than 1%. Above 19 MeV excitation energy, they increase rapidly, varying from about 5% up to as much as 50% for the broad higher levels. Except where noted, all parameters in the table are newly adopted in this evaluation.

[b] The fact that the sum of the partial widths is unequal to the total width in the extended R-matrix prescription is characteristic of non-Breit–Wigner resonances as was discussed in the appendix of [92TI02].

[c] The n* designation indicates $n + \alpha^*$ where the first excited state of the α particle was included as a way to approximate the effects of three-body breakup on the two-body channels.

[d] Situated 798 keV above the $n + \alpha$ threshold. This value is in excellent agreement with early measurements reported by [63SM03] (790 ± 30 keV) and [60YO06] (800 ± 100 keV).

[e] These large partial widths in closed channels have no meaning as decay widths, but rather as asymptotic normalization constants.

[f] Entirely ^{4}S(d).

[g] Primarily ^{4}D(d).

[h] Primarily ^{2}P(d).

[i] Primarily ^{2}D(d).

[j] Primarily ^{2}S(d).

[k] Primarily ^{4}P(d).

[l] Retained from the previous evaluation [88AJ01].

3. (a) ^{3}H(d, n)^{4}He, $Q_m = 17.58928$, $E_b = 16.79151$
   (b) ^{3}H(d, 2n)^{3}He, $Q_m = -2.98834$
   (c) ^{3}H(d, pn)^{3}H, $Q_m = -2.22457$

The cross section for reaction (a) has been measured in the range $E_t = 12.5$ to 117 keV [84JA08] (0.525(±4.8%) mb to 3.739(±1.4%) b) and in the range $E_d = 79.913$ to

Table 5.2
Energy levels of ^{5}He, R-matrix prescription[a]

E_x (MeV)	$J^\pi; T$	Γ_{cm} (MeV)	Γ_n (MeV)	Γ_d (MeV)	Γ_{n*} (MeV)
g.s.[b]	$\frac{3}{2}^-; \frac{1}{2}$	0.963	0.963	0	0
6.17	$\frac{1}{2}^-; \frac{1}{2}$	20.61	20.61	0	0
16.66	$\frac{3}{2}^+; \frac{1}{2}$	0.889	0.691	0.198[c]	
19.97	$\frac{3}{2}^-; \frac{1}{2}$	3.49	0.127	2.85[d]	0.508
20.32	$\frac{1}{2}^+; \frac{1}{2}$	6.64	0.273	5.08[e]	1.29
20.48	$\frac{7}{2}^+; \frac{1}{2}$	4.43	0.066	4.37[f]	
21.67	$\frac{3}{2}^+; \frac{1}{2}$	6.87	0.156	6.72[f]	
21.77	$\frac{5}{2}^+; \frac{1}{2}$	6.58	0.247	6.33[f]	
23.52	$\frac{5}{2}^+; \frac{1}{2}$	25.21	0.028	25.18[f]	
24.10	$\frac{1}{2}^-; \frac{1}{2}$	57.3	0.177	44.8[d]	12.3
24.58	$\frac{5}{2}^-; \frac{1}{2}$	5.56	0.020	5.54[g]	

[a] See the introduction for a discussion of the two prescriptions. The prescription used here is defined in [92TI02]. The channel radii are: $a_n = 3.0$ fm, $a_d = 5.1$ fm.
[b] Situated 985 keV above the $n + \alpha$ threshold.
[c] Entirely ^{4}S(d).
[d] Primarily ^{2}P(d).
[e] Primarily ^{2}S(d).
[f] Primarily ^{4}D(d).
[g] Primarily ^{4}P(d).

115.901 keV ($\pm$0.015 keV) [87BR10] (3.849 to 4.734 b ($\pm$1.6%)). See also [85FI1G]; $E_d = 13.8$ to 114.3 keV. A strong resonance, σ (peak) = 4.88 b, appears at $E_d = 105$ keV: see Table 5.2 in [79AJ01] and [87BR10]. For a discussion of R-matrix analysis and evidence for a "shadow" pole, see [87BR10, 87HA20]. See also [87HA44, 87MO1K]. The related work of [91BO23] uses a resonance coupled-channel model to interpret the ^{5}He $(3/2^+)$ resonance as a coupled-channel pole associated predominantly with the d–t system. A later study by [93CS02] uses a realistic dynamical microscopic reaction approach and reaches the same conclusion. A more recent analysis of cross section data for $E_d = 8$–116 keV is described in [95LA33]. Resonance parameters for the ^{5}He $3/2^+$ second excited state were determined.

From $E_d = 10$ to 500 keV, the cross section is well fitted with the assumption of s-wave formation of a $J^\pi = 3/2^+$ state. (See however the discussion below.) Measurements of cross sections and angular distributions for reaction (a) have been reported to $E_d = 21$ MeV and $E_t = 20.0$ MeV (see [74AJ01, 79AJ01, 84AJ01]) as well as at 1.0, 1.5 and 2.0 MeV [87LI07]. Neutron yields from reaction (a) above have been measured at $E_d = 140$–300 keV [89SH17]. Measurements to determine the intensity of intermediate-energy neutrons are described in [89GA21]. An absolute measurement of the polarization of 50 MeV neutrons at $\theta_{lab} = 29.7°$ was reported in [91SA18].

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

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

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

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

[87BR10] have derived astrophysical S-factors in the range $E_d = 8.3$ to 115.9 keV ($S(0) = 11.71 \pm 0.08$ MeV b), as well as reactivities. See [84AJ01] for the earlier work, and [85CA41, 87VA36]. Angular distributions of α particles were measured for $E_d < 200$ keV [97BE59] and evidence for a D-wave contribution to the cross section in the vicinity of the $3/2^+$ s-wave resonance in ^{5}He was reported. Thermonuclear reaction rates for this reaction calculated from evaluated data are presented in the compilation [99AN35].

Reaction (b) has been studied for $E_d = 10.9$ to 83 MeV. A study of reaction (c) leads to the suggestion of a resonance at $E_{cm} = 2.9 \pm 0.3$ MeV ($E_x = 19.7$ MeV), $\Gamma_{cm} = 1.9 \pm 0.2$ MeV, consistent with $J^\pi = 3/2^-$ (see Table 5.1): see [74AJ01, 79AJ01]. See also the references cited in [88AJ01]. For applications and developments in muon-catalyzed fusion see the references cited in [88AJ01] and the general table for ^{5}He located on our website at (*www.tunl.duke.edu/NuclData/General_Tables/5he.shtml*).

4. ^{3}H(d, d)^{3}H, $E_b = 16.792$

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

5. ^{3}H(t, n)^{5}He, $Q_m = 10.534$

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

6. ^{3}H(α, dα)n, $Q_m = -6.257$

A kinematically complete experiment at $E_\alpha = 67.2$ MeV has been reported by [00GO35]. They report observation of ^{5}He excited states at $E_x = 18.9$, 19.9 and 20.7 MeV with widths of 0.3, 0.25 and 0.25 MeV, respectively.

7. ^{3}He(t, p)^{5}He, $Q_m = 11.298$

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

8. ^{4}He(n, n)^{4}He, $E_b = -0.798$

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

The total cross section has a peak of 7.6 b at $E_n = 1.15 \pm 0.05$ MeV, $E_{cm} = 0.92 \pm 0.04$ MeV, with a width of about 1.2 MeV: see [79AJ01]. A second resonance is observed at $E_n = 22.133 \pm 0.010$ MeV ($\sigma_{peak} = 0.9$ b) with a total width of 76 ± 12 keV and $\Gamma_n = 37 \pm 5$ keV [83HA20]. Attempts to detect additional resonances in the total cross section have been unsuccessful: see [79AJ01]. For curves and tables of neutron cross sections see [88MCZT, 90NAZH, 90SH1C].

The $P_{3/2}$ phase shift shows strong resonance behavior near 1 MeV, while the $P_{1/2}$ phase shift changes more slowly, indicating a broad $P_{1/2}$ level at several MeV excitation. [66HO07] have constructed a set of phase shifts for $E_n = 0$ to 31 MeV, $l = 0, 1, 2, 3,$

using largely p–α phase shifts. At the $3/2^+$ state the best fit to all data is given by $E_{\rm res} = 17.669$ MeV $\pm$ 10 keV, $\gamma_{\rm d}^2 = 2.0$ MeV $\pm$ 25%, $\gamma_{\rm n}^2 = 50$ keV$\pm$20% (see Table 5.2 in [79AJ01]). See also [97BA72] in which properties of the $3/2^+$ levels of ^{5}He and ^{5}Li are discussed in terms of conventional R-matrix parameters.

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

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

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

9. ^{4}He(p, π^+)^{5}He, $Q_{\rm m} = -141.150$

As reported in [88AJ01], differential cross sections were measured at $E_{\rm p} = 201$ MeV [85LE19] and at $E_{\rm p} = 800$ MeV ([84HO01]; also $A_{\rm y}$). See also [87SO1C, 85GE06].

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

10. (a) ^{4}He(d, p)^{5}He, $Q_{\rm m} = -3.022$
(b) ^{4}He(d, pn)^{4}He, $Q_{\rm m} = -2.2246$

A typical proton spectrum (reaction (a)) consists of a peak corresponding to the formation of the ground state of ^{5}He, plus a continuum of protons ascribed to reaction (b). A study of the latter reaction shows evidence for sequential decay via ^{5}He*(0, 16.7 $\pm$ 0.1 ($\Gamma = 80 \pm 30$ keV)) and suggests some fine structure near $E_{\rm x} = 19$ MeV (see also reactions 15 and 23): see [79AJ01]. Differential cross sections and VAP have been measured for the ground-state group at $E_d = 5.4$, 6.0, and 6.8 MeV [85LU08] and at 6 to 11 MeV [85OS02]. Measurements of differential cross sections, analyzing powers, and polarization transfer coefficients at $E_d = 56$ MeV were reported in [90YOZZ]. At $E_\alpha = 28.3$ MeV tensor polarization measurements involving the ground-state transitions to ^{5}He (and ^{5}Li) deviate from theoretical predictions which assume charge symmetry [85WI15]. See also ^{6}Li ([88PUZZ]; $E_d = 2.1$ GeV) and other references cited in [88AJ01].

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

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

11. $^{4}\mathrm{He}(^{4}\mathrm{He}, {}^{3}\mathrm{He})^{5}\mathrm{He}$, $Q_m = -21.375$

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

12. $^{4}\mathrm{He}(^{7}\mathrm{Li}, {}^{6}\mathrm{Li})^{5}\mathrm{He}$, $Q_m = -8.048$

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

13. (a) $^{6}\mathrm{Li}(\gamma, \mathrm{p})^{5}\mathrm{He}$, $Q_m = -4.497$
(b) $^{6}\mathrm{Li}(\mathrm{e}, \mathrm{ep})^{5}\mathrm{He}$, $Q_m = -4.497$
(c) $^{6}\mathrm{Li}(\pi^+, \pi^+\mathrm{p})^{5}\mathrm{He}$, $Q_m = -4.497$
(d) $^{6}\mathrm{Li}(\pi^-, \pi^-\mathrm{p})^{5}\mathrm{He}$, $Q_m = -4.497$

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

14. ^{6}Li(n, d)^{5}He, $Q_m = -2.272$

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

15. ^{6}Li(p, 2p)^{5}He, $Q_m = -4.497$

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

16. ^{6}Li(d, ^{3}He)^{5}He, $Q_m = 0.997$

^{5}He$_{g.s.}$ has been observed at $E_d = 14.5$ MeV: see [79AJ01].

17. ^{6}Li(α, αp)^{5}He, $Q_m = -4.497$

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

18. ^{6}Li(^{6}Li, ^{7}Be)^{5}He, $Q_m = 1.109$

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

19. ^{6}Li(^{12}C, ^{13}N)^{5}He, $Q_m = -2.553$

See reaction 12 and [88WO10].

20. ^{7}Li(γ, d)^{5}He, $Q_m = -9.522$

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

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

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

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

22. $^{7}\mathrm{Li}(\mathrm{n, t})^{5}\mathrm{He}$, $Q_{\mathrm{m}} = -3.265$

The angular distribution of t_0 has been measured at $E_{\mathrm{n}} = 14.4$ MeV: see [79AJ01] and $^{8}\mathrm{Li}$. See also [86BOZG, 89SHZS].

23. (a) $^{7}\mathrm{Li}(\mathrm{p}, ^{3}\mathrm{He})^{5}\mathrm{He}$, $Q_{\mathrm{m}} = -4.029$
    (b) $^{7}\mathrm{Li}(\mathrm{p, pd})^{5}\mathrm{He}$, $Q_{\mathrm{m}} = -9.522$

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

24. (a) $^{7}\mathrm{Li}(\mathrm{d}, \alpha)^{5}\mathrm{He}$, $Q_{\mathrm{m}} = 14.325$
    (b) $^{7}\mathrm{Li}(\mathrm{d, n})^{4}\mathrm{He}^{4}\mathrm{He}$, $Q_{\mathrm{m}} = 15.1223$

At $E_{\mathrm{d}} = 24$ MeV, the α-particle spectrum from reaction (a) shows structures corresponding to the ground and 16.7 MeV states and to states at $E_{\mathrm{x}} \approx 20.2$ and 23.8 MeV with $\Gamma \approx 2$ MeV and ≈ 1 MeV, respectively. Measurements of the α-particle energy spectra at $E_{\mathrm{d}} = 13.6$ MeV were reported in [93PAZP]. An analysis of cross-section data measured at $E_{\mathrm{d}} = 0$–12 MeV is reported in [97HAZX]. Astrophysical S-factors were measured at $E_{\mathrm{cm}} = 57$–141 keV by [97YA08]. Measurements of the reaction rate at low energies for $^{7}\mathrm{Li}$ implanted in Pd foil were reported by [00BAZO]. Reaction (b) proceeds mainly via excited states of $^{8}\mathrm{Be}$ and $^{5}\mathrm{He}_{\mathrm{g.s.}}$ and possibly as well $^{5}\mathrm{He}^{*}(4.)$: see [79AJ01]. Measurements at $E_{\mathrm{d}} = 4.35$ MeV have been reported by [00MIZU]. See also [87WA21] and $^{8}\mathrm{Be}$.

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

25. (a) ^{7}Li(^{3}He, pα)^{5}He, $Q_m = 8.831$
(b) ^{7}Li(^{3}He, ^{3}He d)^{5}He, $Q_m = -9.522$

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

26. ^{8}Li(p, α)^{5}He, $Q_m = 14.516$

Differential cross sections were measured at $E_{cm} = 1.5$ MeV with a ^{8}Li beam, and the data were used to calculate thermonuclear reaction rates for ^{8}Li destruction [92BEZZ, 92BE46].

27. (a) ^{9}Be(p, pα)^{5}He, $Q_m = -2.371$
(b) ^{9}Be(p, d ^{3}He)^{5}He, $Q_m = -20.724$

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

28. ^{9}Be(d, ^{6}Li)^{5}He, $Q_m = -0.897$

The angular distribution to $^5\mathrm{He}_{g.s.}$ has been measured at $E_d = 13.6$ MeV [84SH1F]. See also [89VAZJ].

29. (a) ^{9}Be(^{3}He, ^{7}Be)^{5}He, $Q_m = -0.785$
(b) ^{9}Be(^{3}He, α)^{4}He^{4}He, $Q_m = 19.0041$

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

30. ^{9}Be(α, 2α)^{5}He, $Q_m = -2.371$

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

31. ^{9}Be(^{7}Li, ^{7}Liα)^{5}He, $Q_m = -2.371$

This reaction was studied at $E_{^7\mathrm{Li}} = 52$ MeV [98SO05, 98SO26], and decay from ^{9}Be excited state into the $\alpha + {}^5$He channel was observed.

32. ^{9}Be(^{18}O, ^{22}Ne)^{5}He, $Q_m = 7.296$

Cross sections were measured and the mass excess was extracted by [90BEYY].

33. ^{10}B(n, ^{5}He)^{6}Li, $Q_m = -5.258$

See ^{6}Li in [88AJ01].

34. ^{10}B(d, ^{7}Be)^{5}He, $Q_m = -1.877$

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

35. (a) ^{11}B(^{7}Li, ^{13}C)^{5}He, $Q_m = 9.157$
(b) ^{11}B(^{9}Be, ^{15}N)^{5}He, $Q_m = 8.620$

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

36. ^{12}C(^{6}He, ^{5}He n)^{12}C, $Q_m = -1.771$

Peripheral fragmentation of 240 MeV/A ^{6}He was studied by [97CH24, 97CH1P]. It was found that one-neutron stripping to ^{5}He is the dominant mechanism.

^{5}Li
(Figs. 2 and 3)

General

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

1. ^{1}H(α, γ)^{5}Li $\rightarrow$ ^{1}H + α, $Q_m = -1.69$

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

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

Angular distributions and analyzing powers for polarized ^{3}He on ^{2}H at $E_{^3\mathrm{He}} = 22.5$, 24, 27, 30, 33 MeV were measured and analyzed by [00OK01]. Based on the phase shifts, they report the following resonances identified with ^{5}Li with excitation energies between 15 and 30 MeV:

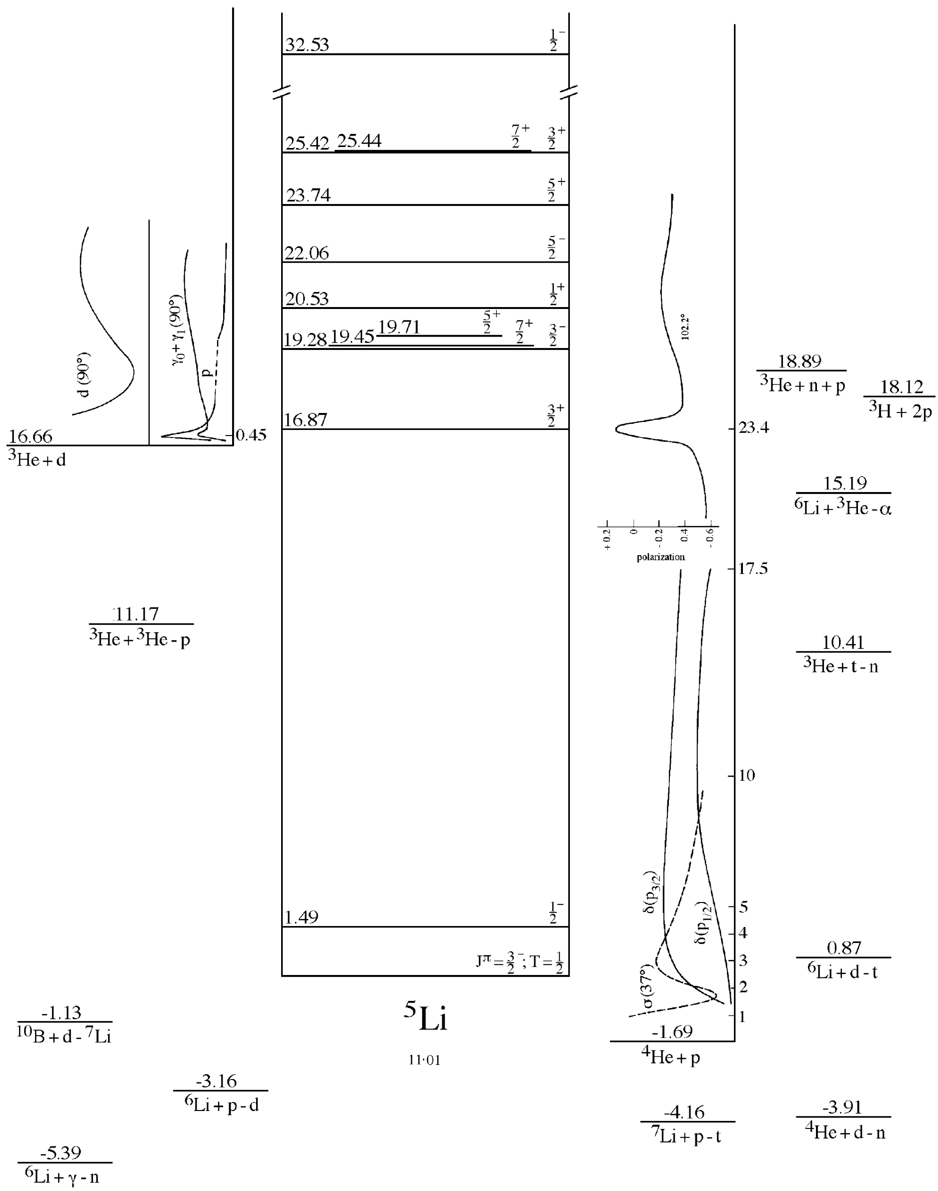

Fig. 2. Energy levels of ^{5}Li, extended R-matrix prescription (see Table 5.3). For notation see Fig. 1.

(i) the well-established [88AJ01] $^{4}S_{3/2}$ state at 16.7 MeV;
(ii) a broad $^{2}S_{1/2}$ state around 19 MeV;
(iii) quartet D states around 20 MeV ($5/2^{+}$ and $3/2^{+}$ assigned before [88AJ01]);
(iv) two doublet P states ($3/2^{-}$, $1/2^{-}$) around 25 MeV; and
(v) at least one negative-parity state around 29 MeV.

Table 5.3
Energy levels of ^{5}Li, extended R-matrix prescription[a]

E_x (MeV)	$J^\pi; T$	Γ_{cm} [b] (MeV)	Γ_p (MeV)	Γ_d (MeV)	Γ_{p*} [c] (MeV)	Decay	Reactions (used in analysis)
g.s.[d]	$\frac{3}{2}^-; \frac{1}{2}$	1.23	1.06	43.1[e]	0.009[e]	p, α	3, 6, 9, 13, 18, 20, 23
1.49	$\frac{1}{2}^-; \frac{1}{2}$	6.60	3.78	16.4[e]		p, α	3, 9, 13, 18, 20
16.87	$\frac{3}{2}^+; \frac{1}{2}$	0.267	0.055	0.134[f]		γ, p, d, ^{3}He, α	3, 4, 5, 18, 20
19.28	$\frac{3}{2}^-; \frac{1}{2}$	0.959	0.001	0.040[g]	0.741	n, p, d, ^{3}He, α	4, 5, 9
19.45	$\frac{7}{2}^+; \frac{1}{2}$	3.28	0.040	1.82[h]		p, d, ^{3}He, α	5
19.71	$\frac{5}{2}^+; \frac{1}{2}$	4.31	0.011	2.03[h]		p, d, ^{3}He, α	3, 5
20.53	$\frac{1}{2}^+; \frac{1}{2}$	5.00	0.026	1.53[i]	0.196	n, p, d, ^{3}He, α	6
22.06	$\frac{5}{2}^-; \frac{1}{2}$	15.5	0.928	2.33[j]		p, d, ^{3}He, α	23, 24
23.74	$\frac{5}{2}^+; \frac{1}{2}$	5.43	0.234	2.49[k]		p, d, ^{3}He, α	
25.42	$\frac{3}{2}^+; \frac{1}{2}$	0.534	0.023	0.467[l]		p, d, ^{3}He, α	
25.44	$\frac{7}{2}^+; \frac{1}{2}$	2.63	0.043	1.94[h]		p, d, ^{3}He, α	23
32.53	$\frac{1}{2}^-; \frac{1}{2}$	35.7	8.75	0.013[m]		p, d, ^{3}He, α	23, 24

[a] This prescription, based on the complex poles and residues of the S-matrix, is the recommended one (see the introduction). The channel radii are $a_p = 2.9$ fm, $a_d = 4.8$ fm. The uncertainties in the widths and positions of the first three levels are less than 1%. Above 19 MeV excitation energy, they increase rapidly, varying from about 5% up to as much as 50% for the broader levels. All parameters in this table are newly adopted in this evaluation.

[b] The fact that the sum of the partial widths is unequal to the total width in the extended R-matrix prescription is characteristic of non-Breit–Wigner resonances as was discussed in the appendix of [92TI02].

[c] The p* designation indicates $p + \alpha^*$ where the first excited state of the α particle was included as a way to approximate the effects of three-body breakup on the two-body channels.

[d] Situated 1.69 MeV above the $p + \alpha$ threshold.

[e] These partial widths in closed channels have no meaning as decay widths, but rather as asymptotic normalization constants.

[f] Primarily ^{4}S(d).

[g] Primarily ^{2}P(d).

[h] Primarily ^{4}D(d).

[i] Primarily ^{2}S(d).

[j] Primarily ^{2}F(d).

[k] Primarily ^{2}D(d).

[l] Mixture of ^{4}S(d) and ^{4}D(d).

[m] Mixture of ^{4}P(d) and ^{2}P(d).

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

3. ^{3}He(d, γ)^{5}Li, $Q_m = 16.66$

The previous review [88AJ01] describes the earlier work as follows:

"The ratio $\Gamma_\gamma/\Gamma_{p\alpha}$ has been determined for $E(^{3}\text{He}) = 63$ to 150 keV ($E_{cm} = 25$ to 60 keV) by [85CE13] by measuring simultaneously the γ-rays and the charged particles. Because of the large widths of the final states, γ_0 and γ_1 could not be resolved but the

Table 5.4
Energy levels of ^{5}Li, conventional R-matrix prescription[a]

E_x (MeV)	$J^\pi; T$	Γ_{cm} (MeV)	Γ_p (MeV)	Γ_d (MeV)	Γ_{p^*} (MeV)
g.s.[b]	$\frac{3}{2}^-; \frac{1}{2}$	2.11	2.11	0	0
6.18	$\frac{1}{2}^-; \frac{1}{2}$	19.8	19.8	0	0
16.63	$\frac{3}{2}^+; \frac{1}{2}$	2.09	0.570	1.52[c]	
19.17	$\frac{3}{2}^-; \frac{1}{2}$	1.50	0.0006	0.136[d]	1.36
20.30	$\frac{1}{2}^+; \frac{1}{2}$	4.64	0.208	3.72[e]	0.709
21.09	$\frac{7}{2}^+; \frac{1}{2}$	7.47	0.115	7.36[f]	
22.60	$\frac{5}{2}^+; \frac{1}{2}$	12.5	0.010	12.5[f]	
24.27	$\frac{5}{2}^+; \frac{1}{2}$	8.15	1.11	7.04[g]	
26.86	$\frac{3}{2}^+; \frac{1}{2}$	24.2	0.009	24.2[f]	

[a] See the introduction for a discussion of the two prescriptions. The channel radii are $a_p = 2.9$ fm, $a_d = 4.8$ fm.
[b] Situated 2.08 MeV above the $p + \alpha$ threshold.
[c] Entirely ^{4}S(d).
[d] Primarily ^{2}P(d).
[e] Primarily ^{2}S(d).
[f] Primarily ^{4}D(d).
[g] Primarily ^{2}D(d).

Table 5.5
Parameters of ^{5}Li resonances deduced from $\alpha + p$ gamma spectra

J^π	Quantity	Experimental result[a]	Conventional[b] R-matrix	Extended[b] R-matrix
$\frac{3}{2}^-$	σ (μb)	8.0 ± 0.7	–	–
	E_x (MeV)[c]	2.9 ± 0.2	2.08	1.69
	Γ (MeV)	1 ± 0.2	2.11	1.23
$\frac{1}{2}^-$	σ (μb)	4.5 ± 0.4	–	–
	E_x (MeV)[c]	9.3 ± 0.4	8.26	3.18
	Γ (MeV)	10 ± 1	19.8	6.60

[a] From Table I of [00HO18]. These results were obtained by fitting the photon spectrum to a background plus two Gaussian peaks representing the two resonances.
[b] See Tables 5.3 and 5.4.
[c] These energies are relative to the $\alpha + p$ threshold.

results are consistent with $E_x = 3.0 \pm 1.0$ MeV for the excited state. $\Gamma_{\gamma_0}/\Gamma_{p\alpha}$ is roughly constant for $E_{cm} = 25$ to 60 keV at $(4.5 \pm 1.2) \times 10^{-5}$ and $\Gamma_{\gamma_1}/\Gamma_{p\alpha} = (8 \pm 3) \times 10^{-5}$ at $E(^3\text{He}) = 150$ keV [85CE13]."

For applications see [85CE13, 85CE16, 88CE04, 92LI32].

"Excitation curves and angular distributions have been measured for $E_d = 0.2$ to 5 MeV and $E(^3\text{He}) = 2$ to 26 MeV. A broad maximum in the cross section is observed at

$E_d = 0.45 \pm 0.04$ MeV (^{5}Li*(16.7)). $\sigma_{\gamma_0} = 21 \pm 4$ μb, $\Gamma_{\gamma_0} = 5 \pm 1$ eV. The radiation at resonance is isotropic, consistent with s-wave capture. Study of γ_0 and γ_1 yields $\Gamma = 2.6 \pm 0.4$ MeV for the ground-state width (but see below), and $E_x = 7.5 \pm 1.0$ MeV, $\Gamma = 6.6 \pm 1.2$ MeV for the $1/2^-$ state: see [79AJ01, 88AJ01]. An excess in the cross section at higher bombarding energies is interpreted as being due to a state at $E_x \approx 18$ MeV: even parity is deduced from the relative intensity of γ_0 and γ_1. A broad peak is also observed at $E_x \approx 20.7$ MeV in the γ_0 cross section. The cross section for γ_1 is ≈ 0. The observations are consistent with $J^\pi = 5/2^+$: angular distributions appear to require at least one other state with significant strength near 19 MeV: see [79AJ01]."

In more recent measurements at $E_d = 8.6$ MeV a ground-state width $\Gamma_p = 2.44 \pm 0.21$ MeV was extracted from the γ_0 spectrum [91BA02]. An analysis of these data with single-level R-matrix fits [96EF03] gave values for the energies and widths of the ground states of ^{5}Li and ^{5}He. Cross-section and analyzing power measurements in the $3/2^+$ fusion resonance region ($E_d = 0.45$ MeV) and $E_d = 8.6$ MeV were reported by [91WE1I, 92BA04, 94BA02, 98WE07], and comparisons with the results of coupled-channel resonating-group model calculations were discussed. See also the shell-model description of the $3/2^+$ resonance discussed in [93KU02]. Potential model descriptions of this reaction are discussed in [90NE14, 92LI32, 92NE03, 95DU13]. Analyzing power formulae derived in a model-independent way are presented in [96TA09].

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

4. (a) ^{3}He(d, p)^{4}He, $Q_m = 18.35304$, $E_b = 16.66292$
   (b) ^{3}He(d, np)^{3}He, $Q_m = -2.22457$
   (c) ^{3}He(d, 2p)^{3}H, $Q_m = -1.46081$
   (d) ^{3}He(d, 2d)^{1}H, $Q_m = -5.49349$
   (e) ^{3}He(d, tp)^{1}H, $Q_m = -1.46081$

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

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

In early work, tensor analyzing power measurements were reported for $E_d = 0.48$ to 6.64 MeV [80DR01]. (See, however, [80GR14] for a discussion of the [80DR01] results and for a summary of $T_{20}(0°)$ for $E_d = 0$ to 40 MeV.) Measurements of angular

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

[99GE19] scheme[a]			Present evaluation[b]		
E_x (MeV)	J^π	Γ_{cm} (MeV)	E_x (MeV)	J^π	Γ_{cm} (MeV)
g.s.	$\frac{3}{2}^-$	1.25	g.s.	$\frac{3}{2}^-$	1.23
1.28	$\frac{1}{2}^-$	6.29	1.49	$\frac{1}{2}^-$	6.60
16.86	$\frac{3}{2}^+$	0.25	16.87	$\frac{3}{2}^+$	0.27
16.88[c]	$\frac{1}{2}^+$	2.26	20.53	$\frac{1}{2}^+$	5.00
17.65[c,d]	$\frac{3}{2}^-$	2.57	19.28	$\frac{3}{2}^-$	0.96
			19.45	$\frac{7}{2}^+$	3.28

[a] See Tables II and III of [99GE19].
[b] See Table 5.3.
[c] Weak resonance.
[d] Above the range of the analysis.

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

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

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

It is suggested that at low energies ($E_d = 2.2$ to 6 MeV) reaction (c) goes primarily via a $J^\pi = 3/2^-$, $T = 1/2$ state of ^{5}Li located 0.8 ± 0.2 MeV above threshold (i.e., $E_x = 18.9 \pm 0.2$ MeV): see [79AJ01]. Other studies of the breakup have been reported at $E_d = 23.08$ MeV ([86BR1J]; reaction (c)) and 60 MeV ([85OK03]; reaction (d)). For the earlier work see [84AJ01]. See also other references cited in [88AJ01]. For a descriptive list of theoretical work on this reaction see the general table for ^{5}Li located on our website at (*www.tunl.duke.edu/NuclData/General_Tables/5li.shtml*).

5. ^{3}He(d, d)^{3}He, $E_b = 16.66292$

In the range $E_d = 380$ to 570 keV, the scattering cross section is consistent with s-wave formation of the $J^\pi = 3/2^+$ state at 16.66 MeV. The excitation curves for $E_d = 1.96$ to

10.99 MeV show a broad resonance ($\Gamma > 1$ MeV) corresponding to $E_x = 20.0 \pm 0.5$ MeV. From the behavior of the angular distributions an assignment of $^2D_{3/2}$ or (^2D, $^4D_{5/2}$ is favored, if only one state is involved: see [79AJ01]. A phase-shift analysis of the angular distribution and VAP data below 5 MeV suggests several MeV broad states ($^2P_{3/2}$, $^4D_{7/2}$, $^4D_{5/2}$, $^4D_{3/2}$ and, possibly, $^4D_{1/2}$): see [84AJ01]. See also [87KR18].

Angular distributions and analyzing powers have been measured at many energies to $E = 44$ MeV: see [79AJ01, 84AJ01] for the earlier work, [82COZO, 83COZR]; $E_d = 10$ MeV and [87YAZJ]; $E_d = 29.5$ MeV on polarized ^{3}He. For d–^{3}He correlations see [87PO03]. See also "Complex reactions" in the ^{5}Li general section of [88AJ01]. The R-matrix formalism was used by [90TR08] to calculate the $S(1/2^+)$-wave cross section for d + ^{3}He, using p + ^{4}He cross section data and d + ^{3}He analyzing power data from the ^{5}Li($3/2^+$) region. See also the work of [97BA72]. A generalized potential model description of ^{3}He + d scattering is discussed in [91NE01]. For earlier theoretical work see references cited in [88AJ01].

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

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

7. ^{3}He(^{3}He, p)^{5}Li, $Q_m = 11.17$

The spectrum of protons at $E(^3\mathrm{He}) = 3$ to 18 MeV shows a pronounced peak corresponding to $^5\mathrm{Li}_{g.s.}$ superposed on a continuum: see [79AJ01]. The angular distribution of p_0 has been measured at $E(^3\mathrm{He}) = 26$ MeV ([83KI10]; polarized target). See also ^{6}Be in [88AJ01] and [86OS1D].

8. ^{3}He(α, d)^{5}Li, $Q_m = -7.18$

The contribution of unbound ^{6}Li nuclear states to deuteron spectra from this reaction was calculated by [93GO16].

9. ^{4}He(p, p)^{4}He, $E_b = -1.69012$

Differential cross sections and polarization measurements have been carried out at many energies: see [66LA04, 79AJ01, 79AJ01, 84AJ01] for the earlier work. More recent measurements were reported [88AJ01] at $E_p = 65$ MeV ([86FU05]; A_y), 100 MeV ([83NAZV, 85GUZX]; $\sigma(\theta)$, A_y) and 495 MeV [88STZZ] and at $E_p = 695$, 793, 890, 991 MeV [85VE13]; $\sigma(\theta)$) and 1 GeV ([85AL09]; $\sigma(\theta)$). Cross sections and A_y at $E_p = 98.7$ and 149.3 MeV for the continuum were reported by [85WE06]. In experimental work reported since the previous review [88AJ01], differential cross sections were measured for $E_p = 695, 793, 890, 991$ MeV by [89GR20] with phase shift analysis and at 607 MeV/c by [91BA1V]. Differential cross sections and analyzing powers at 71.9 MeV were measured [89BU01] and combined with existing data for $E_p = 30$–65 MeV for a phase shift analysis. Measurements of analyzing power at $E_p = 180$ MeV were reported by [90WEZY]. Cross sections for the p + ^{4}He interaction at GeV energies have been measured at 2.7 GeV/c [93AB07], at 8.6 and 13.6 GeV/c [89BR30, 93GL09], and at $\sqrt{s} = 31.5$ GeV [89AK05].

For earlier work at very high energies, see references cited in [88AJ01]. The previous review [88AJ01] summarizes the analyses reported prior to 1988 as follows:

> "Phase shifts below $E_p = 18$ MeV have been determined by [77DO01] based on all the available cross-section and polarization measurements, using an R-matrix analysis program. The $P_{3/2}$ phase shift shows a pronounced resonance corresponding to $^5Li_{g.s.}$ while the $P_{1/2}$ shift changes slowly over a range of several MeV, suggesting that the first excited state is very broad and located 5–10 MeV above the ground state. The reduced widths of the P-wave resonance states are nearly the same. The $D_{5/2}$, $D_{3/2}$, $F_{7/2}$ and $F_{5/2}$ phase shifts become greater than 1° at $E_p \approx 11$, 13, 14 and 16 MeV, respectively [77DO01]. ([86TH1C]; prelim.) have measured A_y for $1.1 \leqslant E_p \leqslant 2.15$ MeV: $A_y = 1$ for $E_p = 1.89$ MeV, $\theta_{cm} = 87.0°$."
>
> "A phase-shift analysis for $E_p = 21.8$ to 55 MeV is presented by [78HO17] (see also analyzing-power contour diagram for $E_p = 20$ to 65 MeV). A striking anomaly is seen in the analyzing power at $E_p = 23$ MeV and the $^2D_{3/2}$ phase shift clearly shows the $3/2^+$ state at $E_x = 16.7$ MeV (see also [79AJ01]). The other phase shifts $^2S_{1/2}$, $^2P_{3/2}$, $^2P_{1/2}$, $^2D_{5/2}$, $^2F_{7/2}$, $^2F_{5/2}$, $^2G_{9/2}$ and $^2G_{7/2}$ are smooth functions of energy. Both the $^2P_{3/2}$ and $^2P_{1/2}$ inelastic parameters show a somewhat anomalous behavior at $E_p \approx 30$ MeV; the absorption first increases then decreases to stay rather constant at $E_p > 40$ MeV. These results are consistent with broad and overlapping states with $J^\pi = 1/2^-$ and $3/2^-$ at $E_x \approx 22$ MeV. There is very little splitting of the real parts of the F-wave phase shifts up to 40 MeV. There is some indication (from the $^2G_{7/2}$ phase shifts) of a $7/2^+$ level around $E_p = 29$ MeV ($E_x \approx 21$ MeV). The G-waves are necessary to fit the detailed shape of the angular distributions for $E_p = 20$ to 55 MeV [78HO17]. For a contour diagram of the analyzing power for $E_p = 130$ to 1800 MeV see [80MO09]. For a measurement of the spin rotation parameter, R, at $E_p = 500$ MeV see [83MO01]. See also ([86SA1J]; prelim.; $E_p = 65$ MeV)."

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

Other theoretical work reported since the previous review [88AJ01] includes calculations for p–α potentials derived from phase shifts for $E_p \leqslant 23$ MeV [91CO05] and at $E_p = 64.9$ MeV [89CO11]. Multichannel resonating-group calculations are presented in [89KA39, 90BL02]. The resonating-group method was applied in the region $E_p =$ 50–120 MeV by [93KA47]. See also the dynamic microscopic model calculation reported by [93CS02]. Glauber theory calculations of cross sections at intermediate energies were reported by [93MA47]. Other theoretical work related to ^{4}He + p scattering is included in the descriptive list in the general table for ^{5}Li located on our website at (*www.tunl.duke.edu/NuclData/General_Tables/5li.shtml*).

In earlier work PNC effects were studied via the elastic scattering of 46 MeV longitudinally polarized protons on ^{4}He: the longitudinal power $A_z = -(3.3 \pm 0.9) \times 10^{-7}$.

This was obtained by measuring σ^+ and σ^- for the positive and negative helicity of the incident protons [85LA01, 86LA29]: the conclusion reached by the authors from this, and all other experiments, is that there does not exist any evidence for a nonzero value of f_π, the weak isovector coupling constant. See also [84AJ01] and [86ADZT, 86HA1Q, 88NA18]. For $\alpha + \mathrm{p}$ correlations see [87PO03].

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

10. (a) $^4\mathrm{He(p, d)}^3\mathrm{He}$, $Q_\mathrm{m} = -18.35304$, $E_\mathrm{b} = -1.69012$
(b) $^4\mathrm{He(p, pn)}^3\mathrm{He}$, $Q_\mathrm{m} = -20.57762$
(c) $^4\mathrm{He(p, 2p)}^3\mathrm{H}$, $Q_\mathrm{m} = -19.81385$
(d) $^4\mathrm{He(p, pd)}^2\mathrm{H}$, $Q_\mathrm{m} = -23.84653$

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

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

11. $^4\mathrm{He}(\bar{\mathrm{p}}, \bar{\mathrm{p}})^4\mathrm{He}$

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

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

12. (a) $^{4}\text{He}(\text{d},\text{n})^{5}\text{Li}$, $Q_\text{m} = -3.91$
    (b) $^{4}\text{He}(\text{d},\text{np})^{4}\text{He}$, $Q_\text{m} = -2.22457$

For reaction (a) see reaction 10 in ^{5}He ([85WI15, 87KAZL]; $E_\text{d} = 15$ MeV; n_0). Early work on reaction (b) reported in [88AJ01] includes measurements at $E_\text{d} = 12$ to 17 MeV and at $E_\alpha = 18.0$ to 140 MeV: see [79AJ01, 84AJ01], ^{6}Li in [88AJ01] and [85DO03, 87KUZI].

More recently, measurements of cross sections and analyzing powers at $E_\text{d} = 7$ MeV were reported by [88GA14]. Comparison of data at $E_\text{d} = 12$ and 17 MeV with predictions of the three-body model are made by [88SU12]. The effects of the internal structure of the α particle in a three-body description of the $\text{d} + \alpha$ reaction are explored by [90KU27]. Multiconfiguration resonating-group calculations are discussed in [91FU01, 92FU10].

13. (a) $^{4}\text{He}(^{3}\text{He},\text{d})^{5}\text{Li}$, $Q_\text{m} = -7.18$
    (b) $^{4}\text{He}(^{3}\text{He},\text{pd})^{4}\text{He}$, $Q_\text{m} = -5.49349$

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

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

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

15. $^{4}\text{He}(^{7}\text{Li},{}^{6}\text{He})^{5}\text{Li}$, $Q_\text{m} = -11.67$

See reaction 12 in ^{5}He and [88WO10].

16. $^{6}\text{Li}(\gamma,\text{n})^{5}\text{Li}$, $Q_\text{m} = -5.39$

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

17. $^{6}\text{Li}(\pi^{+},\text{p})^{5}\text{Li}$, $Q_\text{m} = 134.96$

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

18. (a) $^{6}\text{Li}(\text{p},\text{d})^{5}\text{Li}$, $Q_\text{m} = -3.16$
    (b) $^{6}\text{Li}(\text{p},\text{pd})^{4}\text{He}$, $Q_\text{m} = -1.4743$
    (c) $^{6}\text{Li}(\text{p},\text{pn})^{5}\text{Li}$, $Q_\text{m} = -5.39$

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

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

19. (a) ^{6}Li(d, t)^{5}Li, $Q_m = 0.87$
(b) ^{6}Li(d, pt)^{4}He, $Q_m = 2.5583$

In early work, angular distributions of the t_0 group were measured at $E_d = 15$ and 20 MeV: see [79AJ01]. More recently the production cross section for triton was measured by radiochemical methods [97ABZY]. Calculations of differential cross sections for $E_d <$ 30 MeV are described in [97HAZK, 97HAZY]. Reaction (b) has been studied at $E_d = 0.12$ to 10.5 MeV: see [84AJ01]. See also ^{8}Be.

20. (a) ^{6}Li(^{3}He, α)^{5}Li, $Q_m = 15.19$
(b) ^{6}Li(^{3}He, pα)^{4}He, $Q_m = 16.8787$

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

In reaction (b) an analysis [89AR20] of data at E(^{3}He) = 2.5 MeV gave $\Gamma = 1.55 \pm 0.2$ MeV for ^{5}Li$_{g.s.}$. Measurements at E(^{3}He) = 1.6, 3.5, 7.0 and 9.0 [92AR20] found the ^{5}Li$_{g.s.}$ width consistent with [88AJ01] and independent of ^{3}He incident energy. Work reported for E(^{3}He) = 1.6 MeV [91AR25] and E(^{3}He) = 7 and 9 MeV [93AR12] determined that the ground-state width is independent of detector angle. In early work reviewed in [88AJ01] the parameters of the first excited state are deduced to be $E_x = 5.0 \pm 0.7$ MeV, $\Gamma_{cm} = 5.7 \pm 0.7$ MeV ([84AR17]; E(^{3}He) = 1.7 and 2.3 MeV), $E_x = 5.8 \pm 0.5$ MeV, $\Gamma_{cm} = 5.2 \pm 0.5$ MeV ([87FA1I]; E(^{3}He) = 1.65 MeV). More recently, an experiment at E(^{3}He) = 2.0 and 2.2 MeV [92DA1K] found values in line with those measured at E(^{3}He) = 1.65 and 1.7 MeV. Measurements at E(^{3}He) = 11, 13 and 14 MeV reported by [89AR08] determined parameters for $E_x \approx 18$ MeV and found a level at $E_x = 17.9 \pm 0.4$ MeV, $\Gamma = 3.5 \pm 0.8$ MeV. Angular distributions of protons from the decay of ^{5}Li$_{g.s.}$ are reported by ([88BU04]; E(^{3}He) = 1.5 MeV). See also references cited in [88AJ01].

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

21. $^{6}\mathrm{Li}(^{6}\mathrm{Li}, ^{7}\mathrm{Li})^{5}\mathrm{Li}$, $Q_{\mathrm{m}} = 1.86$

Angular distributions have been measured at $E(^{6}\mathrm{Li}) = 156$ MeV to $^{5}\mathrm{Li}_{\mathrm{g.s.}}$. Unresolved states at $E_{\mathrm{x}} = 16$–20 MeV are also populated [87MI34].

22. $^{6}\mathrm{Li}(^{13}\mathrm{C}, ^{14}\mathrm{C})^{5}\mathrm{Li}$, $Q_{\mathrm{m}} = 2.79$

See reaction 12 in ^{5}He and [88WO10].

23. (a) $^{7}\mathrm{Li}(\mathrm{p, t})^{5}\mathrm{Li}$, $Q_{\mathrm{m}} = -4.16$
(b) $^{7}\mathrm{Li}(\mathrm{p, nd})^{5}\mathrm{Li}$, $Q_{\mathrm{m}} = -10.41$

At $E_{\mathrm{p}} = 43.7$ MeV, a triton group is observed to $^{5}\mathrm{Li}_{\mathrm{g.s.}}$ ($\Gamma = 1.55 \pm 0.15$ MeV): the angular distribution is consistent with a substantial mixing of $L = 0$ and 2 transfer. There is some evidence also for a very broad excited state between $E_{\mathrm{x}} = 2$ and 5 MeV. $^{5}\mathrm{Li}^{*}(16.7, 20.0)$ were not observed. The formation of $^{5}\mathrm{Li}^{*}(16.7)(^{4}\mathrm{S}_{3/2})$ would be S-forbidden: the absence of $^{5}\mathrm{Li}^{*}(20.0)$ would indicate that this state(s) is also of quartet character (see reaction 23 in ^{5}He). Weak, broad states at $E_{\mathrm{x}} = 22.0 \pm 0.5$ MeV and 25.0 ± 0.5 MeV and possibly 34 MeV are reported in a coincidence experiment in which three- and four-particle breakup was analyzed: see [79AJ01]. Measurements of angular distributions and differential cross sections at $E_{\mathrm{p}} = 29.1$ and 35 MeV are reported in [89BA88]. See also [88BAZH]. For reaction (b) at $E_{\mathrm{p}} = 670$ MeV see [84AJ01]. See also [85NEZW].

24. $^{7}\mathrm{Li}(^{3}\mathrm{He, dt})^{5}\mathrm{Li}$, $Q_{\mathrm{m}} = -9.65$

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

25. $^{7}\mathrm{Li}(^{6}\mathrm{Li}, ^{8}\mathrm{Li})^{5}\mathrm{Li}$, $Q_{\mathrm{m}} = -3.36$

See [84KO25].

26. $^{9}\mathrm{Be}(\alpha, ^{8}\mathrm{Li})^{5}\mathrm{Li}$, $Q_{\mathrm{m}} = -18.58$

At $E_{\alpha} = 90$ MeV differential cross sections have been measured for the transitions to $^{5}\mathrm{Li}_{\mathrm{g.s.}} + ^{8}\mathrm{Li}_{\mathrm{g.s.}}$: see [84AJ01].

27. $^{10}\mathrm{B}(\mathrm{d}, ^{7}\mathrm{Li})^{5}\mathrm{Li}$, $Q_{\mathrm{m}} = -1.13$

An angular distribution is reported at $E_{\mathrm{d}} = 13.6$ MeV [83DO10]. See also [84SH1E].

28. $^{10}\mathrm{B}(^{3}\mathrm{He}, 2\alpha)^{5}\mathrm{Li}$, $Q_{\mathrm{m}} = 10.73$

At $E(^{3}\mathrm{He}) = 2.3$ and 5.0 MeV the reaction is reported to proceed via $^{9}\mathrm{B}^{*}(4.9)$ to $^{5}\mathrm{Li}_{\mathrm{g.s.}}$ [86AR14]. See also [88AR05] and ^{9}B in [88AJ01].

Table 5.7
Mirror states in $A = 5$ nuclei[a]

^{5}He		^{5}Li		ΔE_x (MeV)[b]
E_x (MeV)	J^π	E_x (MeV)	J^π	
0	$\frac{3}{2}^-$	0	$\frac{3}{2}^-$	–
1.27	$\frac{1}{2}^-$	1.49	$\frac{1}{2}^-$	+0.22
16.84	$\frac{3}{2}^+$	16.87	$\frac{3}{2}^+$	+0.03
19.14	$\frac{5}{2}^+$	19.71	$\frac{5}{2}^+$	+0.57
19.26	$\frac{3}{2}^+$	25.42	$\frac{3}{2}^+$	+6.16
19.31	$\frac{7}{2}^+$	19.45	$\frac{7}{2}^+$	+0.14
19.96	$\frac{3}{2}^-$	19.28	$\frac{3}{2}^-$	−0.68

[a] As taken from Table 5.1 and 5.3.
[b] Defined as $E_x(^5\text{Li}) - E_x(^5\text{He})$.

^{5}Be
(Fig. 3)

The absence of any group structure in the neutron spectrum in the ^{3}He(^{3}He, n)^{5}Be reaction at $E(^3\text{He}) = 18.0$ to 26.0 MeV indicates that $^5\text{Be}_{\text{g.s.}}$ is at least 4.2 MeV unstable with respect to $^3\text{He} + 2\text{p}$ ($M - A > 33.7$ MeV). With Coulomb corrections adjusted to match the 16.7 MeV states of ^{5}He–^{5}Li, this observation places the first $T = 3/2$ level in these nuclei above $E_x = 21.4$ MeV: see [79AJ01].

$A = 6$

General

References to articles on general properties of $A = 6$ nuclei published since the previous review [88AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the general tables for $A = 6$ located on our website at (*www.tunl.duke.edu/NuclData/General_Tables/06.shtml*).

^{6}n
(not illustrated)

^{6}n has not been observed. See [79AJ01, 88AJ01] and references cited there. More recently [90AL40] reports a search for ^{6}n in a ^{14}C(^{7}Li, ^{6}n) activation experiment at $E(^7\text{Li}) = 82$ MeV. No evidence for ^{6}n was obtained.

The method of angular potential functions was used by [89GO18] in a calculation of the properties of multineutron systems which indicated that these systems have no bound

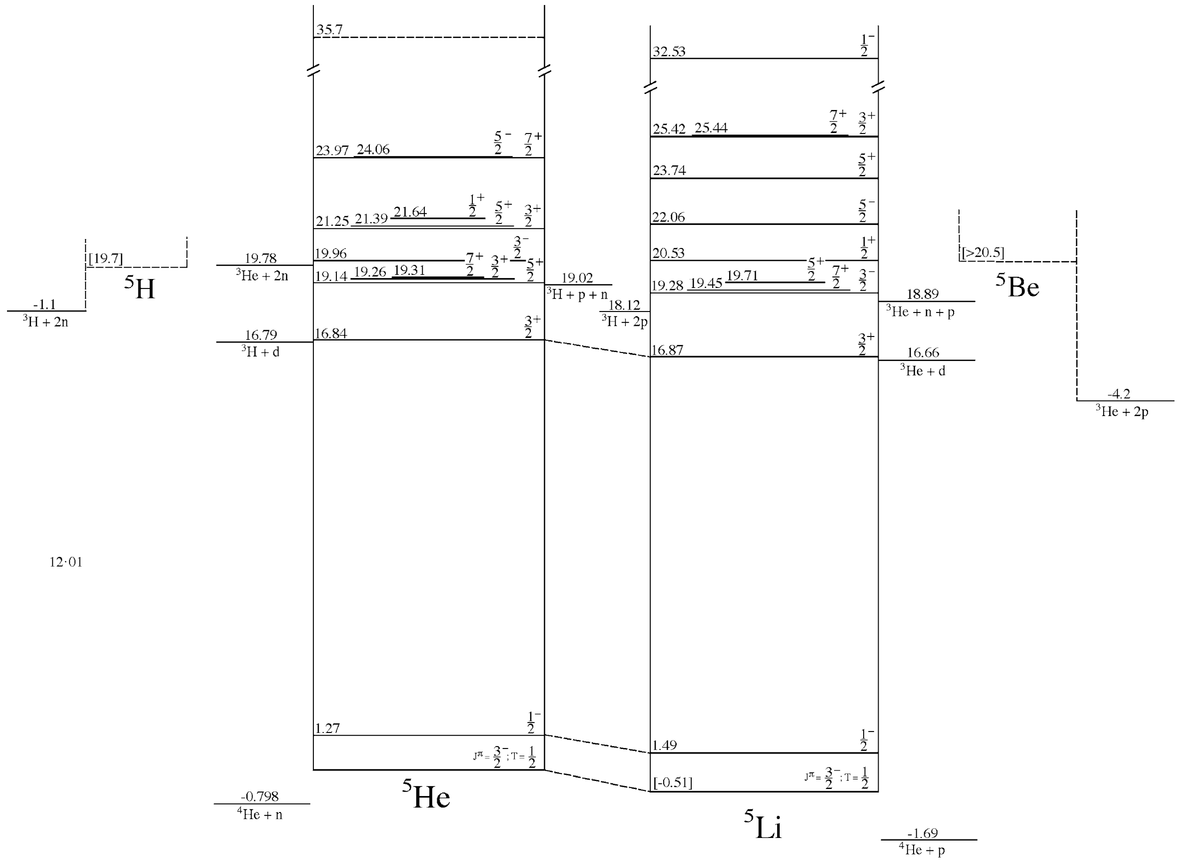

Fig. 3. Isobar diagram, $A = 5$. The diagrams for individual isobars have been shifted vertically to eliminate the neutron–proton mass difference and the Coulomb energy, taken as $E_C = 0.60Z(Z-1)/A^{1/3}$. Energies in square brackets represent the (approximate) nuclear energy, $E_N = M(Z,A) - ZM(\mathrm{H})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

states. The ground-state energy of a six-neutron drop has been computed with variational and Green's function Monte Carlo methods [97SM07].

^{6}H
(Fig. 7)

^{6}H was reported in the ^{7}Li(^{7}Li, ^{8}B)^{6}H reaction at $E(^7\text{Li}) = 82$ MeV [84AL08, 85AL1G] ($\sigma(\theta) \approx 60$ nb/sr at $\theta = 10°$) and in the ^{9}Be(^{11}B, ^{14}O)^{6}H reaction at $E(^{11}\text{B}) = 88$ MeV [86BE35]) ($\sigma(\theta) \approx 16$ nb/sr at $\theta \approx 8°$). ^{6}H is unstable with respect to breakup into ^{3}H + 3n by 2.7 ± 0.4 MeV, $\Gamma = 1.8 \pm 0.5$ MeV [84AL08], 2.6 ± 0.5 MeV, $\Gamma = 1.3 \pm 0.5$ MeV [86BE35]. The value adopted in the previous review [88AJ01] is 2.7 ± 0.3 MeV, $\Gamma = 1.6 \pm 0.4$ MeV. See also [87BO40]. The atomic mass excess of ^{6}H using the [95AU04] masses for ^{3}H and n, is then 41.9 ± 0.3 MeV. There is no evidence for the formation of ^{6}H in the ^{6}Li(π^-, π^+) reaction at $E_{\pi^-} = 220$ MeV as reported in [90PA25]. [91SE06] shows that the continuum missing mass spectra can be explained in terms of the presence of dineutrons in the breakup products. An analysis of the proton spectra for the ^{7}Li(π^-, p) reaction [90AM04] showed no evidence for ^{6}H.

The ground-state of ^{6}H is calculated to have $J^\pi = 2^-$. Excited states are predicted at 1.78, 2.80 and 4.79 MeV with $J^\pi = 1^-$, 0^- and 1^+ ($(0+1)\,\hbar\omega$ model space) [85PO10] (see also for $(0+2)\,\hbar\omega$ calculations). See also the additional references cited in [88AJ01].

^{6}He
(Figs. 4 and 7)

General

References to articles on general properties of ^{6}He published since the previous review [88AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the general tables for ^{6}He located on our website at (*www.tunl.duke.edu/NuclData/General_Tables/6he.shtml*).

Ground-state properties. The interaction radius of ^{6}He, obtained from measurements of the total interaction cross section, is 2.18 ± 0.02 fm [85TA13, 85TA18]. These authors have also derived nuclear matter, charge and neutron r.m.s. radii.

^{6}He is considered to be a neutron-halo nucleus because its interaction radius, which is deduced from the total interaction cross section in [85TA13, 85TA18], is appreciably larger than that of ^{6}Li. A Glauber calculation using proton and neutron densities from an alpha-core valence-neutron model leads to the conclusion that the matter radius is much larger than the charge radius, as predicted by theoretical models of the ^{6}He ground-state wave function. These theoretical models include three-body models [93ZH1J, 95HI15], cluster-orbital shell models [91SU03, 94FU04], no-core microscopic shell models [96NA24], and microscopic cluster models for various effective nucleon–nucleon interactions [93CS04, 97WU01]. See also [92TA18]. The point-proton and point-

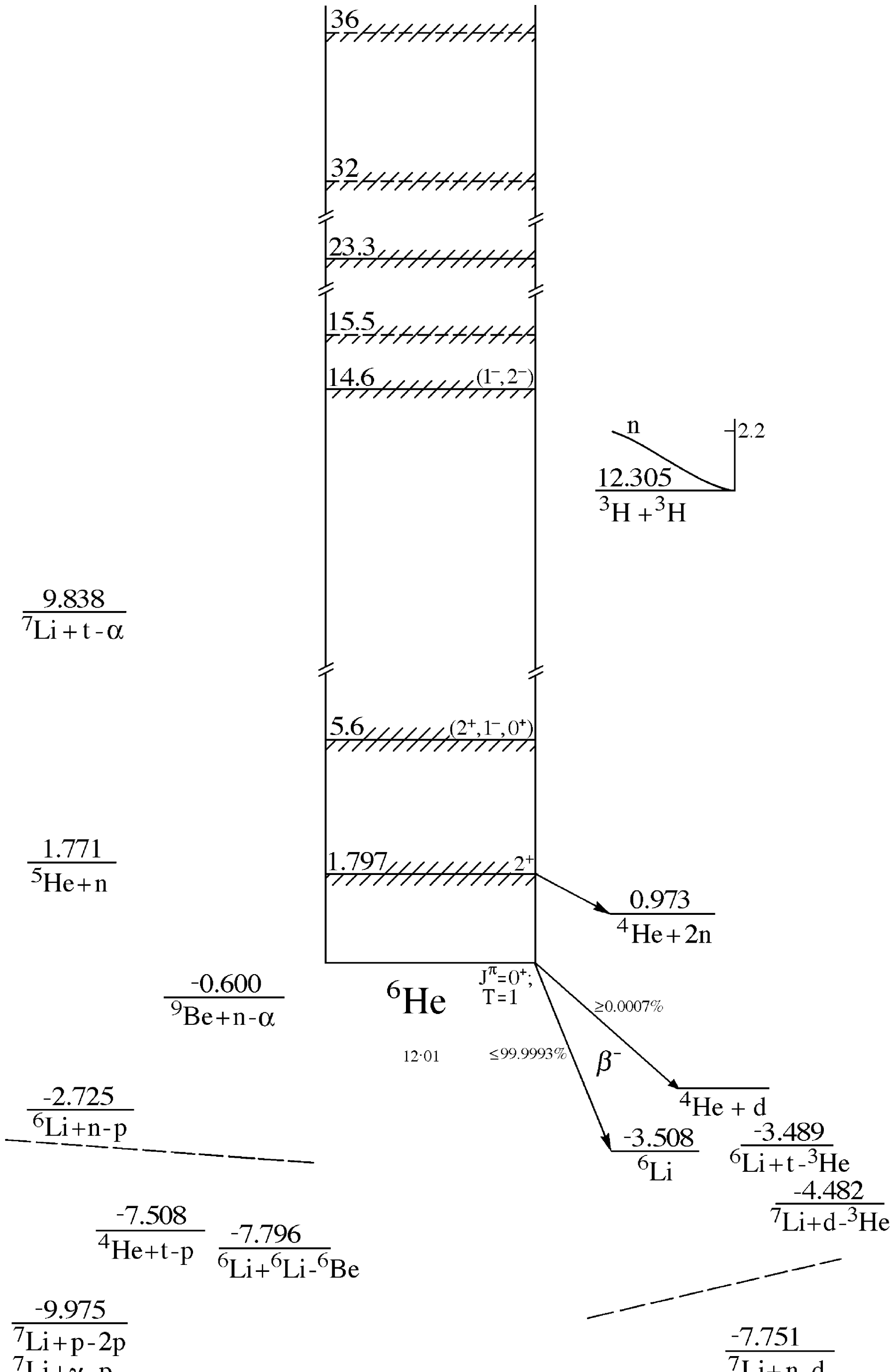

Fig. 4. Energy levels of ^{6}He. For notation see Fig. 5.

Table 6.1
Energy levels of ^{6}He

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

[a] Newly adopted in this evaluation or revised from the previous evaluation [88AJ01].

neutron radii are often compared in order to enhance the effect, and are found to differ by 0.4–0.8 fm. For other typical properties of halo nuclei see [95HA56].

1. ^{6}He(β^-)^{6}Li, $Q_m = 3.508$

The half-life is 806.7 ± 1.5 ms [84AJ01]. The decay to the ground state of ^{6}Li ($J^\pi = 1^+$) is via a superallowed Gamow–Teller transition; $\log ft = 2.910 \pm 0.002$ [84AJ01, 88AJ01]. A second beta-decay branch leading to an unbound final state consisting of a deuteron and an α particle was reported [90RI01] based on the observation of beta-delayed deuterons. The branching ratio for $E_d > 350$ keV was measured [93BO24, 93RIZY] to be $(7.6 \pm 0.6) \times 10^{-6}$. Calculations are presented which consider alternative decay routes. (One considers a decay to an unbound state of ^{6}Li which then decays into $\alpha + d$. In the other route ^{6}He breaks up into an alpha particle plus a dineutron which β decays to a deuteron.) The calculation of [94BA11] successfully reproduces the deuteron spectrum shape and branching ratios. References to theoretical work on the ^{6}He(β^-)^{6}Li decay are presented in Table 6.2.

2. ^{1}H(^{6}He, ^{6}He)^{1}H, $E_b = 9.975$

Angular distributions for elastic scattering and for 1n and 2n transfer were measured at 25 MeV/A, and spectroscopic amplitudes were extracted by [99WO13]. An analysis of elastic scattering data at 700 MeV/A is described in [98AL05]. See also the analysis [00DE43] of data at $E = 25$, 40 MeV and that of [00GU19] at $E = 25$–70 MeV. The reaction cross section was measured for 36 MeV/A ^{6}He on hydrogen, and a value of $\sigma_R = 409 \pm 22$ mb was obtained [01DE19]. Analysis within a microscopic model allowed the ^{6}He density distribution to be explored.

The use of elastic and inelastic scattering with secondary beams to probe ground-state transition densities of halo nuclei has been explored in a theoretical study [95BE26]. Cross sections for $E = 151$ MeV were calculated by [00AV02], and density-distribution features were deduced. See also the discussion of [99EG02].

Table 6.2
$^{6}He(\beta^{-})^{6}Li$—theoretical work

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

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

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

4. $^{4}He(2n,\gamma)^{6}He$, $Q_m = 0.973$

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

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

Angular distributions of the protons to $^{6}He^{*}(0, 1.80)$ have been measured at $E_t = 22$ and 23 MeV. (No L-values were assigned.) No other states are observed with $E_x \leqslant 4.2$ MeV: see [79AJ01]. Cross sections and angular distributions for the reaction products of the $^{3}H(\alpha,p)^{6}He$ reaction were measured at $E_\alpha = 27.2$ MeV [92GO21]. A potential description of $^{3}H + ^{4}He$ elastic scattering is discussed in [93DU09].

6. $^{4}\mathrm{He}(\alpha, 2\mathrm{p})^{6}\mathrm{He}, \quad Q_{\mathrm{m}} = -27.322$

Total cross sections for the production of ^{6}He have been measured [01AU06] at $E_{\alpha} = 159$, 280 and 620 MeV in a study of cosmic ray nucleosynthesis. The resulting cross sections decrease rapidly with energy.

7. $^{4}\mathrm{He}(^{6}\mathrm{He}, ^{6}\mathrm{He})^{4}\mathrm{He}, \quad E_{\mathrm{b}} = 7.412$

Differential cross sections were measured at $E(^{6}\mathrm{He}) = 151$ MeV. DWBA analysis suggests a spectroscopic factor of ≈ 1 for the dineutron cluster [98TE1D, 98TE03]. Measurements at $E_{\mathrm{cm}} = 11.6$ and 15.9 MeV [99RA15] also show evidence for the 2n transfer process in the elastic scattering. However, a couple-discretized-continuum channel analysis discussed in [00RU03] suggests a smaller 2n transfer process than commonly assumed [01TE03]. See also the analyzes and calculations of [98GO1J, 99OG06, 99OG09]. A microscopic multicluster model description of the elastic scattering process is discussed in [99FU03].

8. $^{6}\mathrm{He}(\mathrm{p}, \mathrm{p})^{6}\mathrm{He}, \quad E_{\mathrm{b}} = 9.975$

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

Calculations of the elastic scattering of protons from ^{6}He at $E_{\mathrm{p}} \geqslant 100$ MeV are described in [92GA27]. A folding model with target densities which reproduce the r.m.s. radii and a range of electroweak data was used.

A calculation of the expansion of the Glauber amplitude described in [99AB37] found that a ^{6}He matter radius consistent with the analysis is 2.51 fm. Finite-range coupled-channel calculations have been performed below the ^{6}He three-body breakup threshold [00TI02]. A theoretical study [00WE03] with four differential nuclear structure models concluded that elastic scattering at <100 MeV$/A$ does not provide good constraints on the structure of the ^{6}He ground state. First-order optical potentials were studied for 20–40 MeV scattering by [00DE43]. A microscopic multicluster calculation of $\sigma(\theta)$ and σ(E) for $E_{\mathrm{cm}} = 0$–5 MeV is reported in [01AR05].

9. $^{6}\mathrm{Li}(\mathrm{e}, \pi^{+})^{6}\mathrm{He}, \quad Q_{\mathrm{m}} = -143.078$

[86SH14] report breaks in (e, π^{+}) spectra at $E_{\mathrm{e}} = 202$ MeV corresponding to $E_{\mathrm{x}} = 7$, 9, 12, 13.6, 17.7 and 24.0 MeV. Using the shape of the virtual photon spectrum results in groups with angular distributions that suggest that the states at 13.6, 17.7 and 24.0 MeV are spin-dipole isovector states ($J^{\pi} = 1^{-}, 2^{-}$). See also [90SH1I]. For the earlier work see [84AJ01]. (Note: the states reported here at 7, 9 and 12 MeV are inconsistent with the work reported in reactions 12, 13, 22 and 23, and with the work on the analog region in ^{6}Be.)

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

The excitation of $^{6}\mathrm{He}^{*}(0, 1.8)$ and possibly of (broad) states at $E_{\mathrm{x}} = 15.6 \pm 0.5$, 23.2 ± 0.7 and 29.7 ± 1.3 MeV has been reported: see [79AJ01]. A study of capture branching ratios to $^{6}\mathrm{He}^{*}(0, 1.8)$ was reported in [86PE05]. For reaction (b) see [84AJ01].

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

Angular distributions of the ground-state proton group, p_0, have been reported at $E_n = 4.7$ to 6.8 MeV, at 14 MeV and at 59.6 MeV (see [79AJ01, 84AJ01]) and at 118 MeV [87PO18, 88HA2C, 88WA24]. At $E_n = 59.6$ MeV, broad structures in the spectra are ascribed to states at $E_x = 15.5 \pm 0.5$ and 25 ± 1 MeV with $\Gamma = 4 \pm 1.5$ and 8 ± 2 MeV [83BR32, 84BR03] (see for discussions of the GDR strength). The ground-state reaction has also been studied at $E_n = 198$ MeV [88JA01]. Proton spectra were measured at $E_n = 118$ MeV by [98HA24].

An angular distribution of the proton group corresponding to population of the $E_x = 1.8$ MeV $J^\pi = 2^+$ state in ^{6}He was also reported [88WA24]. See also [89WA1F]. Angular distributions were measured for p_0 at $E_n = 280$ MeV in tests of isospin symmetry in (n, p), (p, p′) and (p, n) reactions populating the $T = 1$ isospin triads in $A = 6$ nuclei [90MI10]. Cross sections for $\theta_{lab} = 1°–10°$ for $E_n = 60–260$ MeV were measured to obtain the energy dependence of the Gamow–Teller strength [91SOZZ, 92SO02].

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

12. ^{6}Li(d, 2p)^{6}He, $Q_m = -4.950$

The previous review [88AJ01] notes that at $E_d = 55$ MeV, ^{6}He*(0, 1.8) (the latter weak) are populated: no other states are observed with $E_x \leqslant 25$ MeV (see [84AJ01]). More recently cross sections at 0° were measured at $E_d = 260$ MeV [93OH01] and at $E_d = 125.2$ MeV [95XU02]. In both studies the cross section for (d, ^{2}He) showed a linear relationship with Gamow–Teller strength from β decay or (p, n) reactions.

13. ^{6}Li(t, ^{3}He)^{6}He, $Q_m = -3.489$

The ground-state angular distribution has been studied at $E_t = 17$ MeV. At $E_t = 22$ MeV only ^{6}He*(0, 1.8) are populated for $E_x \leqslant 8.5$ MeV: see [79AJ01]. Differential cross sections for the transition to ^{6}He*(1.8) are reported at $E(^{6}\text{Li}) = 65$ MeV [87AL23]. In a more recent experiment at $E_t = 336$ MeV reported in [00NA35], the ^{6}He ground and 1.8 MeV states were populated. In addition, a broad asymmetric structure around $E_x \approx 5$ MeV was observed with an angular distribution which exhibited $\Delta L = 1$ dominance. Another structure at $E_x \approx 14.6$ MeV was observed with the angular distribution indicating $\Delta L = 1$.

14. ^{6}Li(^{6}Li, ^{6}Be)^{6}He, $Q_m = -7.796$

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

15. ^{6}Li(^{7}Li, ^{7}Be)^{6}He, $Q_m = -4.370$

Measurements of differential cross sections at $E(^7\text{Li}) = 82$ MeV are reported in [92GLZX, 93GLZZ, 94SAZZ] and at $E(^7\text{Li}) = 78$ MeV in [93SA35, 94RUZZ]. The ^{6}He levels at $E_x = 0$, $J^\pi = 0^+$ and $E_x = 1.80$, $J^\pi = 2^+$ were identified. A maximum at $E_x \approx 6$ MeV is interpreted as consistent with a soft-dipole response expected in neutron-halo nuclei. A study [96JA11, 99AN13] at $E(^7\text{Li}) = 350$ MeV utilized magnetic analysis to observe transitions to the $J^\pi = 0^+$ ground state, and the $J^\pi = 2^+$ state at $E_x = 1.8$ MeV, as well as pronounced resonances at ≈ 5.6 MeV, ≈ 14.6 MeV and ≈ 23.3 MeV [96JA11]. See Table 6.3. In experiments at $E = 65$ MeV$/A$ with this reaction, isovector spin-flip and spin non-flip resonances were deduced [98NAZP, 98NAZR]. See also the more recent measurements described in [00NA22, 01NA18].

A theoretical study of ^{6}He structure with an extended microscopic three-cluster model is described in [99AR08].

16. (a) ^{7}Li(γ, p)^{6}He, $Q_m = -9.975$
(b) ^{7}Li(e, ep)^{6}He, $Q_m = -9.975$

At $E_\gamma = 60$ MeV, the proton spectrum shows two prominent peaks attributed to ^{6}He*$(0 + 1.8, 18 \pm 3)$: see [79AJ01]. Reactions (a) and (b) have been studied by [85SE17]. See also ^{7}Li, [84AJ01, 86BA2G]. An analysis of the available experimental data on ^{7}Li photodisintegration at energies up to $E_\gamma = 50$ MeV is presented in [90VAZM, 90VA16]. See also the discussion of reactions involving scattering of polarized electrons from polarized targets [93CA11]. In more recent work a broad excited state was observed [01BO38] in ^{6}He with energy $E_x = 5 \pm 1$ MeV and width $\Gamma = 3 \pm 1$ MeV. In experiments with reaction (b) momentum distributions from transitions to the ^{6}He ground and first excited states were measured by [99LA13, 00LA17]. The deduced spectroscopic factor for both reactions is 0.58 ± 0.05 in agreement with variational Monte Carlo calculations.

17. ^{7}Li(π^-, ^{6}He)n, $Q_m = 128.812$

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

Table 6.3
Levels in ^{6}He from ^{6}Li(^{7}Li, ^{7}Be)^{6}He [a]

E_x (MeV)	J^π	Γ (MeV)	$d\sigma/d\Omega$ [b] (mb/sr)	G [c]
g.s.	0^+		0.72 ± 0.08	0.46 ± 0.05
1.92 ± 0.17	2^+		0.25 ± 0.04	0.40 ± 0.10
5.6 ± 0.3	$(2^+, 1^-, 0^+)$ [d]	12.1 ± 1.1	4.56 ± 0.48	0.39 ± 0.04
14.6 ± 0.7	$(1, 2)^-$	7.4 ± 1.0	2.11 ± 0.23	0.43 ± 0.06
23.3 ± 1.0		14.8 ± 2.3	1.75 ± 0.19	0.47 ± 0.07

[a] [96JA11]. $E(^7\text{Li}) = 350$ MeV.
[b] $\theta_{cm} = 4.5°$.
[c] Averaged spin-flip signatures $G = Y_{coinc}/Y_{singles}$.
[d] [99AN13] and J. Jänecke, private communication.

18. ^{7}Li(π^-, π^-p)^{6}He, $Q_m = -9.975$

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

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

At $E_n = 60$ MeV, the deuteron spectrum shows two prominent peaks attributed to states centered at $E_x = 13.6$, 15.4 and 17.7 MeV (± 0.5 MeV) and a possible state or states (populated with an l_p transfer $\geqslant 2$) at $E_x = 23.7$ MeV. DWBA analyzes of the d_0 and d_1 groups are consistent with $l_p = 1$ and $S(1p_{3/2}) = 0.62$ for ^{6}He$_{g.s.}$ and to $S(1p_{1/2}) = 0.35$ for ^{6}He*(1.8): see [79AJ01]. Measurements of the cross section as a function of energy for $E_x = 10$–30 MeV were reported in [89CO22]. See also the measurements at $E_n = 14.1$ MeV [89SHZS].

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

From measurements at $E_p = 1$ GeV [85BE30, 85DO16], the separation energy between 6–7 MeV broad $1p_{3/2}$ and $1s_{1/2}$ peaks is reported to be 14.1 ± 0.7 MeV. See also [83GO06, 79AJ01]. Differential cross section measurements at $E_p = 70$ MeV are reported in [88PA26, 98SH33, 01SH03]. Contributions from 1p and 1s nucleons in ^{7}Li were distinguished. Proton spectra measurements for $E_p = 1$ GeV were reported by [00MI17, 01MI07]. Effective proton polarizations were deduced. See also the review of experimental and theoretical nucleon and cluster knockout reactions in light nuclei presented in [87VD1A].

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

As summarized in the previous review [88AJ01], angular distributions of the ^{3}He ions to ^{6}He*(0, 1.8) have been measured at $E_d = 14.4$ and 22 MeV: they have an $l_p = 1$ character and therefore these two states have $J^\pi = (0\text{–}3)^+$. There is no evidence for any other states of ^{6}He with $E_x < 10.7$ MeV: see [79AJ01]. In [87BO39] ($E_d = 30.7$ MeV) it is deduced that the branching ratio of ^{6}He*(1.8) into a dineutron (n^2: $T = 1$, $S = 0$) and an α particle is 0.75 ± 0.10. See also [85BO55, 87DA31]. More recently, the energy spectrum of neutrons from the ^{6}He excited state at $E_x = 1.8$ MeV populated in this reaction was measured at $E_d = 23$ MeV [94BO46].

22. ^{7}Li(t, α)^{6}He, $Q_m = 9.838$

As summarized in [88AJ01], the energy of the first-excited state is 1.797 ± 0.025 MeV, $\Gamma = 113 \pm 20$ keV. ^{6}He*(1.80) decays into ^{4}He + 2n. The branching ratio $\Gamma_\gamma/\Gamma_\alpha \leqslant 2 \times 10^{-6}$: for $\Gamma_{cm} = 113 \pm 20$ keV, $\Gamma_\gamma \leqslant 0.23$ eV. Angular distributions of the α_0 and α_1 groups have been measured at $E_t = 13$ and 22 MeV. No other α groups are reported corresponding to ^{6}He states with $E_x < 24$ MeV (region between $E_x \approx 13$ and 16 MeV was obscured by the presence of breakup α particles): see [79AJ01]. Angular distributions were reported at $E_t = 0.151$ and 0.272 MeV ([87AB09]; α_0, α_1) and at $E(^7\text{Li}) = 31$ MeV ([87AL23]; to ^{6}He*(0, 1.8, 13.6)).

In more recent work, differential cross sections were measured at $E_t = 38$ MeV [92CL04]. DWBA calculations are presented and spectroscopic factors are deduced.

The resonance theory of threshold phenomena was used to analyze differential cross sections for ^{7}Li(t, α)^{6}He*(1.8) for $\theta < 90°$ at $E_t = 80$–500 keV in a study of ^{10}Be levels [91LA1D].

23. ^{7}Li(^{3}He, p^{3}He)^{6}He, $Q_m = -9.975$

At $E(^3\text{He}) = 120$ MeV the missing mass spectra show ^{6}He*(0, 1.8) and a strong, broad peak corresponding to ^{6}He*(16) (possibly due to unresolved states). There is no indication of a state near 23.7 MeV but there is some evidence of structures at $E_x = 32.0$ and 35.7 MeV, with $\Gamma \leqslant 2$ MeV [85FR01].

24. (a) ^{7}Li(^{6}Li, ^{7}Be)^{6}He, $Q_m = -4.370$
(b) ^{7}Li(^{7}Li, ^{8}Be)^{6}He, $Q_m = 7.280$

In reaction (a) at $E(^6\text{Li}) = 93$ MeV a broad peak ($\Gamma = 5.5$ MeV) was reported at $E_x = 14$ MeV. A second structure may also be present at 15.5 MeV [87GLZW, 88BUZH]. ^{6}He*(0, 1.8) are also populated [88BUZH]. For reaction (b) see ^{8}Be. See also ^{7}Be, [84AJ01, 88BU1Q, 84BA53], and see [96SO17] which involves ^{10}Be excited states. Measurements of differential cross sections at $E(^7\text{Li}) = 22$ MeV were reported in [88BO18].

25. ^{9}Be(γ, ^{3}He)^{6}He, $Q_m = -21.178$

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

26. ^{9}Be(n, α)^{6}He, $Q_m = -0.600$

Angular distributions have been reported for $E_n = 12.2$ to 18.0 MeV (α_0, α_1). No other states are observed with $E_x \leqslant 7$ MeV: see [79AJ01]. For a study of possible dineutron breakup of ^{6}He*(1.8) see [83OT02]. An analysis of the alpha and neutron spectra observed in this reaction for $E_n \approx 14$ MeV is presented in [88FE06]. See also ^{10}Be and [83SH1J].

27. ^{9}Be(^{6}He, ^{6}He)^{9}Be, $E_b = 19.069$

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

28. ^{9}Be(^{6}Li, ^{9}B)^{6}He, $Q_m = -4.576$

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

29. $^9Be(^7Li, ^6He)^{10}B$, $Q_m = -3.390$

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

30. $^9Be(^9Be, ^6He)^{12}C$, $Q_m = 5.101$

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

31. $^{11}B(^7Li, ^{12}C)^6He$, $Q_m = 5.982$

At $E(^{11}B) = 88$ MeV, the population of the ground state and the first-excited state at $E_x = 1.8 \pm 0.3$ MeV ($\Gamma \leqslant 0.2$ MeV) is reported [87BEYI]. See also [88BEYJ].

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

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

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

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

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

Measurements at 240 MeV/A are described in [98AL10, 98AN02, 99AU01, 00AL04]. Fragmentation cross sections of ^{6}He were analyzed in the Glauber theory to investigate the importance of neutron correlation [94SU02]. Fragmentation reaction data and beta-delayed particle emission data are reproduced successfully. Detailed structure is described with a multicluster model and halo-like structure is discussed in [95SU13]. See also [98BE09, 98GA37].

35. $^{12}C(^6He, ^6He)^{12}C$, $E_b = 18.376$

Elastic and quasielastic scattering of ^{6}He on ^{12}C was studied at $E(^6He) = 10.2$ MeV [95WA01]. See also [95PE1D]. Measurements of cross sections were made at 41.6 MeV/A [96AL11]. The results were successfully analyzed within a 4-body ($\alpha + n + n + {}^{12}C$) eikonal scattering model.

Potential parameters were deduced and differential cross sections were calculated for ^{6}He scattering at 50 and 100 MeV/A [93GO06]. The possibility of studying the structure of the neutron halo in ^{6}He elastic rainbow scattering is discussed. See also [89SI02, 92CL04, 93FE02, 95GA24]. Calculations of cross sections at $E = 20$–60 MeV/A were reported in [00BO45]. Proton, neutron and matter r.m.s. distributions were also calculated.

36. ^{208}Pb(^{6}He, 2nα)X

Measurements and analyzes of a three-body breakup experiment at 240 MeV/A are described in [99AU01, 00AL04]. Two-neutron interferometry measurements at 50 MeV/A are discussed in [00MA12].

^{6}Li

(Figs. 5 and 7)

General

References to articles on general properties of ^{6}Li published since the previous review [88AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the general tables for ^{6}Li located on our website at (*www.tunl.duke.edu/NuclData/General_Tables/6li.shtml*).

Ground-state properties. $\mu = +0.8220473(6)$ nm, $+0.8220567(3)$ nm: see [89RA17], $Q = -0.818(17)$ mb [98CE04].

The interaction nuclear radius of ^{6}Li is 2.09 ± 0.02 fm [85TA18]. These authors have also derived nuclear matter, charge and neutron r.m.s. radii.

Quadrupole moment. The tiny quadrupole moment of ^{6}Li poses a difficult task for theoretical calculations. Except for a phenomenological [85ME02], a microscopic cluster [86ME13], and a Green's-function Monte-Carlo [97PU03] calculation, the models fail even to predict the sign. See the discussion of three-body models in [93SC30]. In [91UN02], this failure of the three-body models is blamed on the missing antisymmetrization of the valence nucleons with the nucleons in the alpha core. Another microscopic cluster calculation [92CS04] considers the findings of [86ME13] to be due to a fortuitous choice of the model space.

Asymptotic D/S ratio.[1] The ratio of the D- and S-state asymptotic normalization constants, referred to in the literature as η, has been used widely to quantify the properties of the D-state wave function. There is general agreement in the $A = 2$–4 systems between theoretical calculations and empirical determinations of the normalization constants. See [88WE20, 90EI01, 90LE24]. The S-state $\alpha + \mathrm{d}$ normalization constant for ^{6}Li appears to be well determined [93BL09, 99GE02], but both the magnitude and sign of η are uncertain.

In a two-body $\alpha + \mathrm{d}$ model it was found [84NI01] that in order to reproduce the experimental quadrupole moment Q, the wave functions must have $\eta < 0$. However, three-body ($\alpha + \mathrm{n} + \mathrm{p}$) models consistently result in predictions of $\eta > 0$ [90LE24, 95KU08]. Recent microscopic six-body calculations using realistic NN potentials predict $\eta = -0.07$ [96FO04].

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

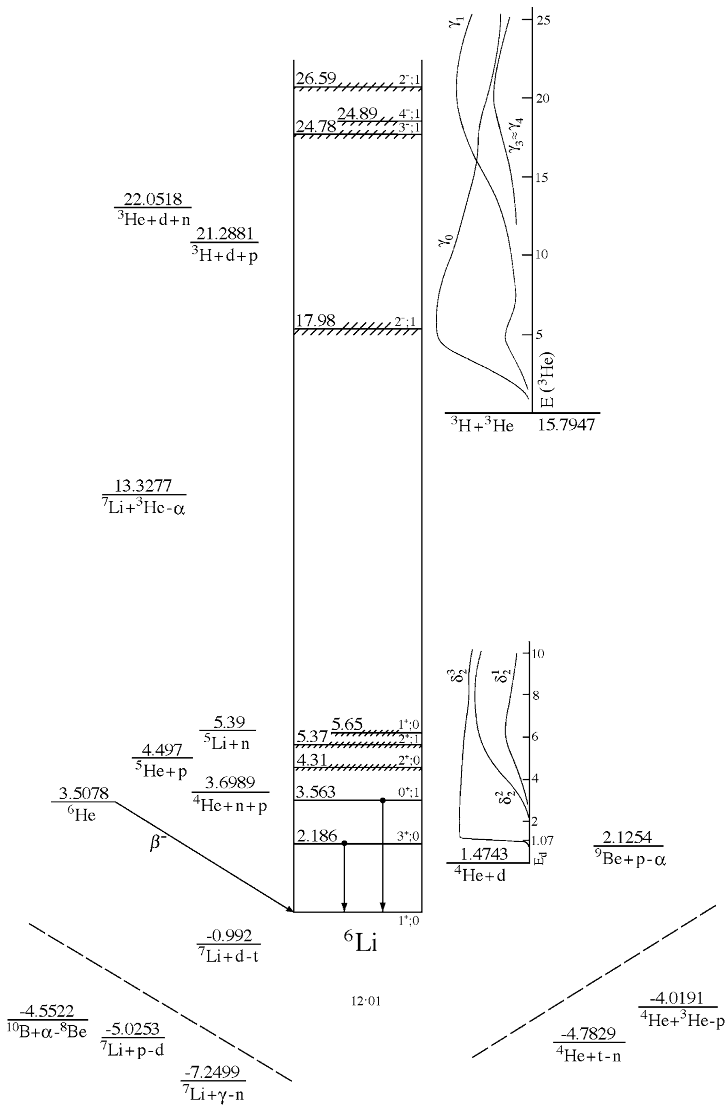

Fig. 5. Energy levels of ^{6}Li. In these diagrams, energy values are plotted vertically in MeV, based on the ground state as zero. Uncertain levels or transitions are indicated by dashed lines; levels which are known to be particularly broad are cross-hatched. Values of total angular momentum J, parity,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

Table 6.4
Energy levels of ^{6}Li

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

[a] See also Table 6.12.
[b] Newly adopted in this evaluation or revised from the previous evaluation [88AJ01].
[c] See remarks under reaction 3, and see Table 6.5.
[d] For possible states at high E_x, see reactions 8, 37, 39 and 45 and Table 6.9.

The asymptotic D/S ratio has been probed empirically by studying scattering processes, transfer reactions, and ^{6}Li breakup. These determinations usually rely on an underlying assumption as to the scattering or reaction mechanism. The S- and D-state asymptotic normalization constants were determined in a study of d–α scattering [78BO43] from which η was found to be $+0.005 \pm 0.014$. Several $^{6}\vec{\mathrm{Li}} + {}^{58}$Ni elastic scattering studies [84NI01, 95DE06, 95RU14] have described polarization observables with $\eta \approx -0.01$, while an investigation of the breakup of $^{6}\vec{\mathrm{Li}}$ on ^{1}H suggests $\eta > 0$ [92PU03]. A study of the ^{6}Li(d, α)^{4}He reaction [90SA47] found that η should lie in the range -0.010 to -0.015. Recently, a phase-shift analysis of $^{6}\vec{\mathrm{Li}} + {}^{4}$He scattering determined $\eta = -0.025 \pm 0.006 \pm 0.010$ [99GE02] while an analysis of ($^{6}\vec{\mathrm{Li}}$, d) transfer reactions resulted in a near zero value of $\eta = +0.0003 \pm 0.0009$ [98VE03].

Based on these theoretical and empirical results, we conclude that both the magnitude and sign of η for the $^{6}\mathrm{Li} \to \alpha + \mathrm{d}$ wave function are not well determined. See also [98VE03, 99GE02].

Isotopic abundance. (7.5 ± 0.2)% [84DE1A]. See also [87LA1J, 88LA1C].

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

1. ^{1}H(^{6}Li, ^{6}Li)^{1}H

Differential cross sections were measured at $E = 0.7$ GeV/A by [00DOZY, 01EG02]. Matter distribution radii and halo features of ^{6}Li*(3.56) were deduced.

2. ^{2}H(α, π^{0})^{6}Li, $Q_{\mathrm{m}} = -133.503$

Measurements of cross sections at $E_{\alpha} = 418$, 420 MeV are reported by [00AN15, 00AN31]. Halo features of ^{6}Li* were deduced.

3. (a) ^{3}He(^{3}H, γ)^{6}Li, $Q_{\mathrm{m}} = 15.7947$
(b) ^{3}He(^{3}H, n)^{5}Li, $Q_{\mathrm{m}} = 10.41$, $E_{\mathrm{b}} = 15.80$
(c) ^{3}He(^{3}H, d)^{4}He, $Q_{\mathrm{m}} = 14.32037$
(d) ^{3}He(^{3}H, ^{3}H)^{3}He

In the previous review [88AJ01], information on radiative capture of ^{3}H on ^{3}He was summarized as follows:

> "Capture γ-rays (reaction (a)) to the first three states of ^{6}Li (γ_0, γ_1, γ_2) have been observed for $E(^{3}\mathrm{He}) = 0.5$ to 25.8 MeV, while the yields of γ_3 and γ_4 have been measured for $E(^{3}\mathrm{He}) = 12.6$ to 25.8 MeV. The γ_2 excitation function does not show resonance structure. However, the γ_0, γ_1, γ_3 and γ_4 yields do show broad maxima at $E(^{3}\mathrm{He}) = 5.0 \pm 0.4$ (γ_0, γ_1), 20.6 ± 0.4 (γ_1), ≈ 21 (γ_3) and 21.8 ± 0.8 (γ_4) MeV. The magnitude of the ground-state-capture cross section is well accounted for by a direct-capture model; that for the γ_1 capture indicates a nondirect contribution above $E(^{3}\mathrm{He}) = 10$ MeV, interpreted as a resonance due to a state with $E_{\mathrm{x}} = 25 \pm 1$ MeV, $\Gamma_{\mathrm{cm}} = 4$ MeV, $T = 1$ (because the transition is E1, to a $T = 0$ final state) (the E1 radiative width $|M|^2 \geqslant 5.2/(2J + 1)$ W.u.), $J^{\pi} = (2, 3, 4)^{-}$, $\alpha + \mathrm{p} + \mathrm{n}$ parentage. The γ_4 resonance is interpreted as being due to a broad state at $E_{\mathrm{x}} = 26.6$ MeV with $T = 0$. $J^{\pi} = 3^{-}$ is consistent with the measured angular distribution. The ground and first excited state reduced widths for $^{3}\mathrm{He} + \mathrm{t}$ parentage, $\theta_0^2 = 0.8 \pm 0.2$ and $\theta_1^2 = 0.6 \pm 0.3$: see [74AJ01]. See also [85MOZZ, 86MOZQ, 87MO1I]."

Since the previous review [88AJ01], a new resonance analysis [88MO1I, 90HE20, 90MO10, 92HE1E] has been applied to the $^{3}\mathrm{He} + {}^{3}\mathrm{H}$ elastic scattering in odd-parity states and to the ^{3}He(^{3}H, γ) data. This analysis explains the shape of the capture cross sections and angular distributions in terms of very wide overlapping resonances. See Table 6.5. These correspond to ^{6}Li states at $E_{\mathrm{x}} = 17.985 \pm 0.025$ MeV, $\Gamma_{\mathrm{cm}} = 3.012 \pm 0.007$ MeV, $J^{\pi} = 2^{-}$; $E_{\mathrm{x}} = 24.779 \pm 0.054$ MeV, $\Gamma_{\mathrm{cm}} = 6.754 \pm 0.110$ MeV, $J^{\pi} = 3^{-}$; $E_{\mathrm{x}} = 24.890 \pm 0.055$ MeV, $\Gamma_{\mathrm{cm}} = 5.316 \pm 0.112$ MeV, $J^{\pi} = 4^{-}$; $E_{\mathrm{x}} = 26.590 \pm 0.065$ MeV, $\Gamma_{\mathrm{cm}} = 8.684 \pm 0.125$ MeV, $J^{\pi} = 2^{-}$ (all with $S = 1$, $T = 1$). The analysis is compatible with an almost pure ^{3}He–^{3}H cluster structure of the negative-parity unbound ^{6}Li states with $S = 1$, $T = 1$. These results are supported by calculations described in [95OH03] which utilize a complex-scaled $^{3}\mathrm{He} + \mathrm{t}$ resonating-group method to calculate the energies and widths of the ^{6}Li $^{3}\mathrm{He} + \mathrm{t}$ states. Note, however, that the calculated scattering phase shifts rise only gradually with energy and stay well below 90°. Consequently, the stated precision on the extracted level parameters is a point of controversy between the authors of [90MO10, 90HE20] and one of the authors (H.M.H.) of this review. The radiative capture reaction as a source of ^{6}Li production in Big Bang nucleosynthesis is discussed in [90FU1H, 90MA1O, 97NO04]. See also [95DU12].

The angular distribution and polarization of the neutrons in reaction (b) have been measured at $E(^{3}\mathrm{He}) = 2.70$ and 3.55 MeV. The excitation function for $E(^{3}\mathrm{He}) = 0.7$ to 3.8 MeV decreases monotonically with energy. The excitation function for n_0 has been measured for $E(^{3}\mathrm{He}) = 2$ to 6 MeV and for $E(^{3}\mathrm{He}) = 14$ to 26 MeV; evidence for a broad structure at $E(^{3}\mathrm{He}) = 20.5 \pm 0.8$ MeV is reported (^{6}Li*(26.1)): see [79AJ01].

Angular distributions of deuterons (reaction (c)) have been measured for $E_t = 1.04$ to 3.27 MeV and at $E(^{3}\mathrm{He}) = 0.29$ to 32 MeV. Polarization measurements are reported for $E_t = 9.02$ to 17.27 MeV (see [79AJ01]), as well as at $E(^{3}\vec{\mathrm{He}}) = 18.0$ and 33.0 MeV [86RA1C]. See also [86KO1K, 85CA41]. A microscopic calculation for reaction (c) and its inverse with special emphasis on isospin breaking in the analyzing power is described in [90BR09]. See also the calculations of [90BLZW, 93DU02, 93FI06].

Elastic scattering (reaction (d)) angular distributions were measured at $E(^{3}\mathrm{He}) = 5.00$ to 32.3 MeV and excitation functions were reported for $E(^{3}\mathrm{He}) = 4.3$ to 33.4 MeV see [79AJ01]). At the lower energies the elastic yield is structureless and decreases monotonically with energy. Polarization measurements were reported for $E_t = 9.02$ to 33.3 MeV. A strong change occurs in the analyzing power angular distributions at $E_t = 15$ MeV. See [88AJ01] for a description of earlier analyses of these data. More recently a new resonance analysis [90HE20, 90MO10] of these same data along with $^{3}\mathrm{He}(^{3}\mathrm{H},\gamma)$ data led to the ^{6}Li $S = 1$, $T = 1$ states discussed above under reaction 3(a). See Table 6.5. A coupled-channel variational-model calculation of the ^{3}He(total) cross section for $E_t = 9$ MeV has been reported by [01TH12].

For other channels see [84AJ01]. See also [84KR1B]. For thermonuclear reaction rates see [88CA26].

4. (a) $^{3}\mathrm{H}(\alpha,n)^{6}\mathrm{Li}$, $Q_m = -4.7829$
(b) $^{3}\mathrm{H}(\alpha,\alpha d)n$, $Q_m = -6.25725$
(c) $^{3}\mathrm{H}(\alpha,t^{3}\mathrm{He})n$, $Q_m = -20.57762$

^{6}Li*(0, 2.19) have been populated with reaction (a): see [74AJ01]. See also ^{7}Li [83CO1E] and [83FU11]. Cross sections for $E_\alpha < 20$ MeV were calculated with a resonating-group method by [91FU02]. A kinematically complete experiment on

Table 6.5
Levels of ^{6}Li from $^{3}\mathrm{He}(^{3}\mathrm{H},{}^{3}\mathrm{H})^{3}\mathrm{He}$ and $^{3}\mathrm{He}(^{3}\mathrm{H},\gamma_1)^{6}\mathrm{Li}^*(2.18)$[a]

State	$J^\pi;T$	$E_{^3\mathrm{He}}$ (MeV)	E_x (MeV)	Γ_{cm} (MeV)
$^{33}P_2$	$2^-;1$	2.190 ± 0.025	17.985 ± 0.025	3.012 ± 0.007
$^{33}F_3$	$3^-;1$	8.984 ± 0.054	24.779 ± 0.054	6.754 ± 0.110
$^{33}F_4$	$4^-;1$	9.095 ± 0.055	24.890 ± 0.055	5.316 ± 0.112
$^{33}F_2$	$2^-;1$	10.795 ± 0.065	26.590 ± 0.065	8.684 ± 0.125

[a] From the analysis [90HE20, 90MO10] of data from [68BL10, 73VE09, 77VL01].

reaction (b) at $E_\alpha = 67.2$ MeV is described in [00GO35]. ^{6}Li excited states at $E_x = 14.5$ and 16.0 MeV with widths ≈ 1 MeV are reported. In a similar experiment [99GO36] at $E_\alpha = 67.2$ MeV on reaction (c) a ^{6}Li level at $E_x \approx 20$–21 MeV was reported based on the energy of the final state between ^{3}H and ^{3}He.

5. ^{3}He(^{3}He, π^+)^{6}Li, $Q_m = -123.7941$

Differential cross sections were measured for the transitions to ^{6}Li*(0, 2.19) for $E(^{3}\mathrm{He}) = 350$, 420, 500 and 600 MeV [83LE26]. See also [84AJ01, 83BR1B, 83JA13, 84GE05]. Analyses of data for $E(^{3}\mathrm{He}) = 295$–810 MeV and microscopic reaction model calculations are reported by [91HA22]. See also the calculations of [99VO01].

6. ^{4}He(d, γ)^{6}Li, $Q_m = 1.4743$

The previous review [88AJ01] summarized the information on this reaction as follows:

> "No resonance has been observed corresponding to formation of ^{6}Li*(3.56) (0^+; $T = 1$): the parity-forbidden $\Gamma_\alpha \leqslant 6 \times 10^{-7}$ eV [84RO04]."

See also [84BU01, 86BU07].

> "The cross section for the capture cross section has been measured for $E_\alpha = 3$ to 25 MeV by detecting the recoiling ^{6}Li ions: the direct capture is overwhelmingly E2 with a small E1 contribution. The spectroscopic overlap between the $^{6}\mathrm{Li}_{\mathrm{g.s.}}$ and $\alpha + \mathrm{d}$ is 0.85 ± 0.04: see [84AJ01]. See also [82KI1A, 85CA41, 86LA22, 86LA27] and theoretical work presented in [84AK01, 85AK1B, 86AK1C, 86BA1R]."

Since the previous review [88AJ01], measurements of the cross section at energies $E_\alpha \approx 2$ MeV corresponding to the 3^+ resonance at $E_x = 2.186$ MeV in ^{6}Li have been reported [94MO17]. Values extracted for the total width Γ and the radiative width Γ_γ confirm the adopted value [88AJ01]. An experimental search for the reaction at $E_{\mathrm{cm}} \approx 53$ keV [96CE02] gave an upper limit for the S-factor of 2×20^{-7} MeV b at the 90% confidence level. Implications for Big Bang nucleosynthesis of ^{6}Li are discussed. Thermonuclear reaction rates for this reaction calculated from evaluated data are presented in the compilation [99AN35].

A considerable amount of theoretical work has been devoted to this reaction—much of it related to its importance in astrophysics. A list of references with brief descriptions is provided in Table 6.6.

7. (a) ^{4}He(d, np)^{4}He, $Q_m = -2.224$, $E_b = 1.475$
   (b) ^{4}He(d, t)^{3}He, $Q_m = -14.320$

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

Table 6.6
$^{4}He(d,\gamma)^{6}Li$—theoretical work

Reference	Description
[89CR01]	D-state effects in the $^{4}He(d,\gamma)^{6}Li$ reaction
[89SC25]	The reaction rate at $T = 300$ K for $^{2}H(\alpha,\gamma)^{6}Li$ and other reactions
[90CR04]	Tensor interaction effects in $^{4}He(d,\gamma)^{6}Li$
[90KRZX]	Polarization observables for $^{4}He(d,\gamma)^{6}Li$ and the D state of ^{6}Li
[90SC22]	The extended elastic model II applied to $^{2}H(\alpha,\gamma)^{6}Li$
[91SC23]	A simple expression for the cross-section factor in nuclear fusion
[91TY02]	Low-energy $^{2}H(\alpha,\gamma)^{6}Li$ and $^{208}Pb(^{6}Li,d\alpha)^{208}Pb$ cross sections
[93JA02]	Polarizability and E1 radiation in $^{4}He(d,\gamma)^{6}Li$
[93MU12]	Calculation of the $^{6}Li \to \alpha + d$ vertex constant
[94MO17]	Direct capture in the 3^{+} resonance of $^{2}H(\alpha,\gamma)^{6}Li$
[95DU12]	Cluster model descriptions of ^{6}Li photodisintegration
[95IG06]	Analysis of the nuclear astrophysical reaction $^{4}He(d,\gamma)^{6}Li$
[95MU21]	Astrophysical factor for $^{4}He(d,\gamma)^{6}Li$
[95MU1J]	Peripheral astrophysical radiative capture processes, a survey
[95RY01]	$^{4}He(d,\gamma)^{6}Li$ capture and the isoscalar E1 multipole
[97NO04]	Nuclear reaction rates and primordial ^{6}Li
[98KH06]	Microscopic study of $^{2}H(\alpha,\gamma)^{6}Li$ in a multicluster model
[00IG03]	Coulomb breakup and astrophysical. S-factor of $^{2}H(\alpha,\alpha)$ at extremely low energies
[01NO01]	Six-body calculation of the $^{2}H(\alpha,\gamma)^{6}Li$ cross section

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

For reaction (b), measurements of vector and tensor analyzing power at $E_{d} = 35$, 45 MeV have been reported [86BR1N, 86VA23, 86VUZZ, 87VU1A]. Cross sections and polarization observables were measured at $E_{d} = 32.1$, 35.15, 39.6, 49.7 MeV to investigate ^{3}H and ^{3}He asymptotic normalization constants [87VU1B] and charge symmetry breaking [88VU01]. Cross sections and polarization observables measured at $E_{cm} = 14$–33 MeV [89BR23] were compared with microscopic-model predictions in a study of isospin violation. See also [90BR09]. The role of tensor force was explored in [88BR18].

For earlier work and other breakup channels, see [88AJ01].

8. $^{4}He(d,d)^{4}He$, $E_{b} = 1.4743$

Elastic differential cross-section and polarization measurements have been carried out up to $E_{\alpha} = 166$ MeV and $E_{d} = 45$ MeV: see [74AJ01, 79AJ01, 84AJ01]. Measurements were also reported at $E_{d} = 0.87$ to 1.43 MeV [84BA19, 85BAYZ], at $E_{d} = 11.9$ MeV [88EL01], 21 MeV [86MI1E], 24.0 and 38.2 MeV [86GR1D], 31.8 to 39.0 MeV

Table 6.7
Levels of ^{6}Li from ^{4}He(d, d)^{4}He[a]

E_d (MeV)	$J^\pi; T$	E_x (MeV)	Γ_{cm} (MeV)	Γ_d/Γ[b]	γ_d^2[c]
1.070 ± 0.003	$3^+; 0$	2.187			0.27
4.34 ± 0.04	$2^+; 0$	4.36	1.32 ± 0.04	0.967	0.511
5.7 ± 0.1[d]	$1^+; 0$	5.3	1.9 ± 0.1	0.74	0.34
(19.3 ± 1.3)	$3^+; 0$	(14.3)	26.7 ± 1.0	0.34	1.69
(21.6 ± 1.1)	$3^+; 0$	(15.8)	17.8 ± 0.8	0.76	0.77
33 ± 2	4^+	23	12 ± 2	0.15	0.14
34 ± 5	3^-	24	16 ± 3	0.30	0.24
39^{+3}_{-9}	2^-	27	22 ± 7	0.43	0.42

[a] The data in this table are mostly from the S-matrix analysis of [83JE03]. The results are unique up to $E_d = 15$ MeV. See also Table 6.4 in [74AJ01], and Tables 6.3 in [79AJ01] and [84AJ01].
[b] The errors in Γ_d/Γ are typically 0.03.
[c] In units of the Wigner limit $\gamma_W^2 = 2.93$ MeV for a radius of 4.0 fm. See [88AJ01].
[d] 6.26 MeV (R-matrix analysis): $E_x = 5.65$ MeV.

[86KO1M], 40 MeV [89DE1A], 56 MeV [85NI01] and at $E_\alpha = 7.0$ GeV/c [84SA39]. A compilation of data for energies $E_d = 1$–56 MeV is presented in [87GR08]. For a study of the inclusive inelastic scattering at $E_\alpha = 7.0$ GeV/c see [87BA13].

Phase-shift analyses, particularly that by [83JE03] which uses all available differential cross section, vector and tensor analyzing power measurements and $L \leqslant 5$, in the range $E_d = 3$ to 43 MeV lead to the results displayed in Table 6.7. It is found that the d-wave shifts are split and exhibit resonances at $E_x = 2.19$ ($^3D_3$), 4.7 ($^3D_2$) and 5.65 MeV ($^3D_1$). [83JE03] suggest very broad G_3 and G_4 resonances at $E_d = (19.3)$ and 33 MeV, a D_3 resonance at 22 MeV and F_3 and F_2 resonances at ≈ 34 and ≈ 39 MeV, corresponding to states which are primarily of $(d + \alpha)$ parentage.

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

For additional references to early work see references cited in [88AJ01].

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

9. (a) ^{4}He(^{3}He, p)^{6}Li, $Q_m = -4.0192$
   (b) ^{4}He(^{3}He, pd)^{4}He, $Q_m = -5.49349$

Angular distributions have been measured at $E(^3\mathrm{He}) = 8$ to 18 MeV and $E_\alpha = 42$, 71.7 and 81.4 MeV: see [74AJ01]. More recently, proton polarization was measured as a function of angle at $E_{cm} = 12.6$ MeV [89GR02]. At $E_\alpha = 28$, 63.7, 71.7 and 81.4 MeV the α-spectra show that the sequential decay (reaction (b)) involves ^{6}Li*(2.19)

Table 6.8
^{4}He(d, d)^{4}He—theoretical work

Reference	Description
[88BE58]	Polarization phenomena in ^{4}He(d, d) at intermediate energies
[88KA25]	Convergence features in the pseudostate theory of the d + α system
[88WE20]	Manifestations of the D state in light nuclei
[89ET05]	Description of diffraction scattering on nuclei
[89FI1E]	Microscopic theory of collective resonances of light nuclei
[89KR08]	Pade approximation technique for processing scattering data
[90BL13]	Analysis of higher partial waves in ^{4}He(d, d) in three-body framework
[90DA1H]	Two body phase space in α–d breakup at 40 MeV
[90GU23]	D-wave effect in α–d elastic scattering at intermediate energies
[90HO1R]	Microscopic study of clustering phenomena
[90HU09]	A geometric model for nucleus–nucleus scattering at high energies
[90KU06]	Reconstruction of interaction potential from scattering data
[90KU16]	Padé-approximation techniques for processing scattering data
[90LI11]	Further study of α elastic scattering on light nuclei
[91BL04]	Manifestation of Pauli-forbidden states in ^{4}He(d, d) at low energies
[91KR02]	Energy-dependent phase-shift analysis of ^{4}He(d, d) at low energies
[91KU09]	d–α scattering in a three-body model
[91KU27]	Recovering α + d potential from Faddeev and measured phase shifts
[92ES04]	α–d resonances and the low-lying states of ^{6}Li
[92FU10]	Reaction mechanisms in $A = 6$ with the multiconfiguration RGM
[92KU16]	Supersymmetric potentials and the Pauli Principle in ^{4}He(d, d)
[92KU1G]	Deuteron size effects in d–α scattering
[93BL09]	Determination of ^{6}Li $\to$ α + d vertex constant for d–α phase-shifts
[93FI06]	Study of continuous spectrum of ^{6}Li in RGM
[94CS01]	Microscopic description of beta-delayed deuteron emission in ^{6}He
[95DU12]	Cluster model description of photonuclear processes in ^{6}Li
[97DU15]	Electromagnetic effects in light nuclei and the cluster potential
[97KU14]	Reconstruction of analytic S matrix from experimental d–α data
[98DU03]	Potential cluster model description of the d–α interaction
[99CO11]	An S-matrix inversion technique applied to α–d scattering

and possibly ^{5}Li: see [79AJ01]. See also the recent theoretical work of [93GO16] and the multiconfiguration RGM calculations of [95FU16].

10. (a) ^{4}He(α, d)^{6}Li, $Q_{\rm m} = -22.3722$
    (b) ^{4}He(α, pn)^{6}Li, $Q_{\rm m} = -24.5968$
    (c) ^{4}He(α, αd)^{2}H, $Q_{\rm m} = -23.84653$

Reactions (a) and (b) have been studied to $E_\alpha = 158.2$ MeV (see [79AJ01, 84AJ01]) and at 198.4 MeV [85WO11]. The dependence of the cross section on energy shows that the $\alpha + \alpha$ process does not contribute significantly to ^{6}Li (and ^{7}Li) synthesis above $E_\alpha = 250$ MeV [85WO11] (and see for additional comments on astrophysical problems). A more recent measurement of the cross section for reaction (b) [01AU06, 01ME13] at

$E_\alpha = 159.3$, 279.6 and 619.8 MeV found cross sections which differ significantly from tabulated values commonly used in cosmic-ray production calculations and lead to lower predicted production of ^{6}Li. For reaction (c) (and excited states of ^{4}He) see [84AJ01]: ^{6}Li*(2.19) is involved in the process.

11. $^6\mathrm{He}(\beta^-)^6\mathrm{Li}$, $Q_\mathrm{m} = 3.508$

See ^{6}He, reaction 1.

12. (a) $^6\mathrm{He(p, n)}^6\mathrm{Li}$, $Q_\mathrm{m} = 2.7254$
(b) $^6\mathrm{He(p, p)}^6\mathrm{He}$

The (p, n) reaction has been studied in inverse kinematics by $^1\mathrm{H}(^6\mathrm{He}, ^6\mathrm{Li})\mathrm{n}$ experiments with secondary ^{6}He beams. An experiment utilizing a secondary ^{6}He beam with $E(^6\mathrm{He}) = 42$ MeV/A was reported by [95CO05, 98CO1M, 98CO19, 98CO28]. The ^{6}Li ground state and $E_\mathrm{x} = 3.56$ MeV state were observed. Angular distributions were reported and the ratio of the cross section for the Gamow–Teller transition to the ground state and the Fermi transition to the isobaric analog state was measured. The reaction was also studied at $E/A = 93$ MeV [96BR30]. The 0° ground-state cross section was measured to be $\mathrm{d}\sigma/\mathrm{d}\Omega = 43 \pm 16$ mb/sr. The ratio of Gamow–Teller to Fermi strength was found to be (87 ± 6)% of that expected from p, n systematics and beta decay. Differential cross sections at $E/A = 41.6$–68 MeV were measured by [97CO04] to study the effects of halo structure. Measurements on reactions (a) and (b) utilizing a secondary ^{6}He beam at 36 MeV/A are reported by [01DE19].

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

13. $^6\mathrm{Li}^*(0^+; 1) \to \alpha + \mathrm{d}$, $Q_\mathrm{m} = 2.0886$

A theoretical study in a microscopic three-cluster model of the parity-violating $\alpha + \mathrm{d}$ decay of the lowest 0^+ state in ^{6}Li ($E_\mathrm{x} = 3.5629$ MeV) is described in [96CS03]. A phase-shift analysis of $^4\mathrm{He} + \mathrm{d}$ was used in a determination of the vertex constant for the $^6\mathrm{Li}(1^+; 0)_{\mathrm{g.s.}} \to \alpha + \mathrm{d}$ virtual decay by [92BLZX, 93BL09, 97KU14]. See also [90RY07, 91KR02, 93BO38].

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

The previous review [88AJ01] summarizes the information on these reactions as follows:

"The (γ, n) and $(\gamma, X\mathrm{n})$ cross sections increase from threshold to a maximum at $E_\gamma \approx 12$ MeV then decrease to $E_\gamma = 32$ MeV: see [84AJ01, 88DI02]. [84DY01] also report a broad peak at 16 MeV. The cross section for photoproton production (reaction (b)) is generally flat up to 90 MeV. (The previously reported hump at $E_\gamma \approx 16$ MeV is almost certainly due to oxygen contamination: see [84AJ01].) See also [88CA11] and ^{5}He. The cross section for reaction (c) is $\leqslant 5$ μb in the range $E_\gamma = 2.6$ to 17 MeV consistent with the expected inhibition of dipole absorption by isospin selection rules: see [66LA04]. The onset of quasideuteron photodisintegration between 25 and 65 MeV is suggested by the study of ([84WA18]; E_γ(bremsstrahlung) $= 67$ MeV). The 90° differential cross section for reaction (e) decreases monotonically for $E_\gamma = 18$ to 70 MeV: reaction (e) contributes $\approx 1/3$ of the total cross section for $^{6}\mathrm{Li} + \gamma$, consistent with a $^{3}\mathrm{H} + {}^{3}\mathrm{He}$ cluster description of $^{6}\mathrm{Li}_{\mathrm{g.s.}}$ with $\theta^2 \approx 0.68$. The agreement with the inverse reaction, $^{3}\mathrm{H}(^{3}\mathrm{He}, \gamma)$ (see reaction 3) is good: see [84AJ01]. See also [86LI1F]."

"The absorption cross section has been studied in the range $E_\gamma \approx 100$ to 340 MeV; it shows a broad bump centered at ≈ 125 MeV and a fairly smooth increase to a maximum at ≈ 320 MeV: see [84AJ01]. For spallation studies see [74AJ01, 84AJ01]. For pion production see [86GL07, 87GL01, 84AJ01]."

Since the previous review [88AJ01] tagged photons were used to study $^{6}\mathrm{Li}(\gamma, \mathrm{p})$ at $\theta_\mathrm{p} = 0°$ for $E_\gamma \approx 59$ and 75 MeV. Strong evidence for the photo–deuteron mechanism was found. Measurements made for angles between 30° and 150° [95DI01] showed most of the strength occurring in three-body breakup channels. Studies at these same energies of the (γ, d) and (γ, t) reaction were reported in [97DI01]. See also [94RY01]. Measurements of $^{6}\mathrm{Li}(\gamma, \mathrm{d})$ at $E_\gamma \approx 60$ MeV indicated strict nonviolation of the isospin selection rule for E1 absorption.

The (γ, pn) reaction was also studied at $E_\gamma = 55$–100 MeV with bremsstrahlung photons and with linearly polarized tagged photons for $E_\gamma = 0.3$–0.9 GeV. See also [90RIZX].

Linearly polarized photons were used to measure the cross section asymmetry in $^{6}\mathrm{Li}(\gamma, \mathrm{t})^{3}\mathrm{He}$ up to $E_\gamma \approx 70$ MeV [89BU10] and differential cross sections up to $E_\gamma \approx 90$ MeV [93DE07, 95BU08]. Results of a measurement of the absolute total photoabsorption cross section for $E_\gamma = 300$–1200 MeV are presented in [94BI06].

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

Table 6.9
$^{6}\mathrm{Li}(\gamma, X)$—theoretical work

Reference	Description
[88DU04]	Calculation of the $^{6}\mathrm{Li}(\gamma, \mathrm{d}\gamma')$ cross section at $E_\gamma = 2.23$ MeV
[89AR02]	Quark degrees of freedom and nuclear photoabsorption
[90BU29]	Possibility (?) of observing an isoscalar E1 multipole in $^{6}\mathrm{Li}(\gamma, \mathrm{d})$
[90VA16]	Cluster effects in ^{6}Li photodisintegration
[90ZH19]	Manifestations of cluster structure in $^{6}\mathrm{Li}(\gamma, \mathrm{d})$
[91BE05]	$^{6}\mathrm{Li} \to \alpha + \mathrm{d}$ break-up—astrophysical significance
[95DU12]	Description of photonuclear processes in ^{6}Li

15. ^{6}Li(γ,γ)^{6}Li

The width, Γ_γ, of ^{6}Li*(3.56) = 8.1 ± 0.5 eV: see [74AJ01] and Table 6.4 in [79AJ01]; $E_x = 3562.88 \pm 0.10$ keV: see [84AJ01]. See also [87PI06]. The results of an absolute measurement of the total photoabsorption cross section are described in [94BI06]. Photon absorption and photon scattering for light elements is discussed in terms of a collective resonance phenomenon in [90ZI03].

16. (a) ^{6}Li(γ,π^0)^{6}Li, $Q_m = -134.97660$
(b) ^{6}Li(γ,π^+)^{6}He, $Q_m = -143.0780$
(c) ^{6}Li(γ,π^-)^{6}Be, $Q_m = -143.8579$

Measurements of neutral-pion photoproduction yield (reaction (a)) for $E < 10$ MeV above threshold were reported in [89NA23]. The total cross section was measured in the energy region from the reaction threshold to $E_\gamma \approx 146.5$ MeV [89GL07] and analyzed in the impulse approximation. The cross section increases monotonically to $\sigma = 6.50 \pm 0.96$ μb at $E_\gamma = 146.5$ MeV. See also [86GL07, 87GL01, 84AJ01]. An analysis [91TR1C] of early measurements suggests that anomalously large measured values of the cross section are due to target impurities. The differential cross section at small angles at energies $E \approx 300$–450 MeV has been measured by [91BE16]. Total and differential cross sections were measured within 23 MeV of threshold with tagged photons by [99BE14]. Differential cross sections for reaction (b) leading to the ^{6}He ground state have been measured at $E_\gamma = 200$ MeV [91SH02] and analyzed by DWBA. See also the measurements of [91GA26]. The energy distributions of electroproduced π^+ at $E_e \approx 200$ MeV were measured and (γ,π^+) cross sections were deduced [94SH38]. For reaction (c) see [88KA41, 91GA26].

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

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

The previous review [88AJ01] summarized the information then available on electron scattering as follows:

> "The elastic scattering has been studied for $E_e = 85$ to 600 MeV: see [74AJ01, 79AJ01, 84AJ01]. The results appear to require that the ground state be viewed as an α–d cluster in which the deuteron cluster is deformed and aligned. The ground-state M1 current density has also been calculated [82BE11]. A model-independent

Table 6.10
Levels of ^{6}Li from ^{6}Li(e, e′) and ^{6}Li(γ, γ′)[a]

E_x (MeV)	$J^\pi; T$	Γ_{γ_0} (eV)	Multipolarity
2.183 ± 0.009	$3^+; 0$	$(4.40 \pm 0.34) \times 10^{-4}$ [b]	E2
3.56288 ± 0.00010 [c]	$0^+; 1$	8.19 ± 0.17 [d]	M1
4.27 ± 0.04	$2^+; 0$	$(5.4 \pm 2.8) \times 10^{-3}$	E2
5.379 ± 17 [d,e]	$2^+; 1$	0.27 ± 0.05	M1

[a] See Tables 6.4 in [79AJ01, 84AJ01] for references and for the earlier work.
[b] [69EI06], $B(\mathrm{E2})\!\uparrow = 25.6 \pm 2.0\, e^2\ \mathrm{fm}^4$. The value given in [88AJ01] was incorrect. We are grateful to Dr. John Millener for pointing out this error.
[c] [81RO02].
[d] Weighted mean of values shown in Table 6.4 in [79AJ01].
[e] $\Gamma = 540 \pm 20$ keV.

analysis of the elastic scattering yields $r_{\mathrm{r.m.s.}} = 2.51 \pm 0.10$ fm. See also the discussion in [84DO1A]."

"Table 6.10 summarizes the results obtained in the inelastic scattering of electrons. Form factors have been measured for ^{6}Li*(2.19, 3.56, 5.37) as well as for the t + ^{3}He continuum up to 4 MeV above threshold (no narrow structures corresponding to ^{6}Li states are observed): see [84AJ01]."

In more recent work, nucleon spin structure functions were extracted from measurements of deep inelastic scattering on polarized targets by [99RO13].

For reaction (b) see ^{5}He and [87VA08, 87VA1N]. Angular distributions for the d_0 group in the (e, d_0) reaction have been measured for $E_x = 10$ to 28 MeV. The deduced E1 and E2 components of the (γ, d_0) cross section show no structure. The E1 strength implies nonnegligible isospin mixing in this energy region [86TA06]. Triple differential cross sections were measured for $E_x = 27$–49 MeV in a search for GDR evidence [99HO02]. At $E_e = 480$ MeV (reaction (c)) the α–d momentum distribution in the ground state of ^{6}Li has been studied. The results are well accounted for by an αNN model. The α–d probability in the ground state of ^{6}Li is 0.73 (estimated ±0.1). The data are consistent with the expected $2S$ character of the α–d relative wave function [86EN05]. See also [86EV1A]. π^0 production involving ^{6}Li*(2.19, 3.56, 5.37) is reported at $E_e = 500$ MeV [87NA1I].

For the earlier work see [79AJ01, 84AJ01] and the references cited in [88AJ01].

Since the previous review [88AJ01], experimental results on quasielastic response have been reviewed [88LO1E]. Measurements of the quasielastic scattering cross section for electrons on ^{6}Li are reported at momentum transfer 0.85–2.3 fm^{-1} [88BU25]. See also the measurements at $E_e = 80$–680 MeV by [89LI09]. Cross sections for ^{6}Li(e, ep) were measured in the missing energy region $0 \leqslant E_m \leqslant 30$ MeV and in the range $-100 \leqslant p_m \leqslant 200$ MeV/c of missing momentum [89LA22]. The $^6\mathrm{Li} \to \mathrm{p} + (\mathrm{n}\alpha)$ spectral function was measured [89LA13]. The ratio of transverse and longitudinal response function was investigated in [90LA06]. See also the review [90DE16] of proton spectral functions and momentum distributions in (e, e′p) experiments and see the report [90GH1E] on nuclear density dependence of electron proton coupling in ^{6}Li(e, e′p).

Reaction (c) was used [90JO1D] in a study of correlation functions in ^{6}Li. A measurement in parallel kinematics to study the mechanism of the ^{6}Li(e, e$'\alpha$)^{2}H reaction is reported in [91MI19, 94EN04]. Cross sections for ^{6}Li(e, e$'$t)^{3}He (reaction (d)) at $E_e = 523$ MeV and the momentum-transfer dependence of the ^{3}H and ^{3}He knockout reaction was measured by [98CO06].

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

18.	(a)	^{6}Li($\pi^{\pm}, \pi^{\pm}$)^{6}Li	
	(b)	^{6}Li(π^{+}, π^{-})	
	(c)	^{6}Li(π^{-}, π^{+})^{6}H,	$Q_m = -27.77$
	(d)	^{6}Li(π^{+}, π^{+}p)^{5}He,	$Q_m = -4.497$
	(e)	^{6}Li(π^{+}, p)^{5}Li,	$Q_m = 134.96$
	(f)	^{6}Li(π^{-}, p)^{5}H,	$Q_m = 114.2$
	(g)	^{6}Li(π^{+}, 2p)^{4}He,	$Q_m = 136.6536$
	(h)	^{6}Li(π^{-}, 2p)4n,	$Q_m = 106.7933$
	(i)	^{6}Li(π^{+}, π^{+}d)^{4}He,	$Q_m = -1.4743$
	(j)	^{6}Li(π^{+}, pd)^{3}He,	$Q_m = 118.3006$
	(k)	^{6}Li(π^{+}, ^{3}He)^{3}He,	$Q_m = 123.7941$
	(l)	^{6}Li(π^{-}, ^{3}He)3n,	$Q_m = 114.5113$

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

A number of experimental studies with polarized targets have been reported for elastic and inelastic (E_x(^{6}Li) = 2.19 MeV, $J^{\pi} = 3^{+}$) scattering. Measurements of polarization observables are reported at $E_{\pi^+} = 134$, 164 MeV [89TA21, 90TA1L, 91BO1R], $E_{\pi^+} =$ 160–219 MeV [91RI01, 94RI06]. Comparison of these data with a coupled-channel model is discussed in [95BO1H]. See also the Δ–hole model analysis of [92JU1B] and the multicluster dynamic model analysis by [95RY1C]. Calculations of cross sections and polarization observables at $E_{\pi^+} = 80$–260 MeV are presented in [88ER06, 88NA06]. A theoretical study in terms of a strong absorption model is described in [98AH06]. Quantum Monte-Carlo calculations of cross sections for $E_{\pi} = 100$–240 MeV are reported in [01LE01]. Transition densities and B(E2) transition strengths were also calculated.

Measurements of pion double-charge exchange cross section (reactions (b) and (c)) at incident pion energies $E_{\pi} = 180$, 240 MeV are reported in [89GR06, 95FO1J]. In [91SE06] it is shown that continuum missing-mass spectra from reaction (c) can be explained in terms of the presence of dineutrons in the products of the breakup.

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

Table 6.11
^{6}Li(e, e)^{6}Li—theoretical work

Reference	Description
[87KR07]	EM properties of ^{6}Li in cluster model
[87LE1N]	Coincidence reactions and the three-body structure of ^{6}Li
[88AL1J]	Second Born approximation correction to ^{6}Li electron scattering
[88ES01]	Elastic electromagnetic form factors of ^{6}Li from three-body models
[89ER07]	Exchange and correlation effects in EM structure of ^{6}Li
[89ES05]	Inelastic $(1^+ \to 0^+)$ EM form factor of ^{6}Li with three-body models
[89KU21]	Correlation and exchange effects in EM form factors
[90BE54]	Analysis of ^{6}Li(e, e′)^{6}Li transitions to the low-lying ^{6}Li levels
[90DE1V]	NN correlations, evidence from ^{6}Li(e, e′p)^{5}He
[90KU12]	Detailed study of EM structure of ^{6}Li from three-body model
[90LO14]	Cluster-model interpretation of ^{6}Li(e, e′p)^{5}He
[90LU06]	Calculation of the magnetic form factor of ^{6}Li
[90RE1I]	Parity-invariance violation in ^{6}Li(e, e′d)^{4}He
[90WA1J]	Occupation probabilities of shell-model orbitals
[91LU07]	Magnetic form factor of ^{6}Li
[91UN02]	^{6}Li elastic form factors and antisymmetrization
[92JO02]	Two-body correlations in ^{6}Li through the (e, e′d) reaction
[92LO09]	Multiquark configuration effect on nuclear charge form factor
[92LOZX]	Short-range correlation in the six-body ^{6}Li wave function
[92RYZY]	EM properties of ^{6}Li in multicluster dynamic model
[92ZH18]	Calculation of ^{6}Li(e, ed) cross section in α2N model
[93KU27]	Prohibition and suppression of multicluster states by Pauli principle
[93RY01]	^{6}Li properties—multicluster dynamic model
[93SC30]	Nucleon polarization in three-body models of polarized Li
[94BO04]	Shell-model calculation of magnetic electron scattering
[94WE10]	^{6}Li inelastic form factors in a cluster model
[95AR10]	Halo structure in ^{6}Li $E_x = 3.563$ 0^+ state
[95DO23]	Phenomenological transition amplitudes in selected p-shell nuclei
[95KU08]	Cluster structure of ^{6}Li low-lying states
[95MA59]	Finite-size effects in quasielastic scattering—Fermi gas model
[98WI10]	Quantum Monte Carlo calculations for light nuclei
[98WI28]	Microscopic calculation of ^{6}Li elastic and transition form factors
[99GN01]	Multicluster calculation of ^{6}Li(e, e′) asymmetric and polarization ratios

Pion absorption followed by nucleon emission (reactions (e)–(l)) has been studied in a number of experiments. For reaction (k) see [83BA26, 83LO10, 85MC05, 86MC11]. Measurements have been reported for cross sections for reaction (g) at $E_{\pi^+} = 30, 50, 80, 115$ MeV [89ROZY]; reactions (g) and (h) angular distributions at $E_\pi = 70, 130, 165$ MeV [89YO05]; reactions (g) and (h) angular correlations at $E_\pi = 165$ MeV [89YO07]; cross sections for reaction (g) at $E_{\pi^+} = 115, 140, 165, 190, 220$ MeV [89ZHZZ]; angular distributions for reaction (h) at $E_\pi = 70, 130, 165$ MeV [89YO03]; two-particle coincidences for reactions (g) and (h) at low energies [91YO1C]; cross sections at $E_\pi = 50, 100, 150, 200$ MeV [90RA05, 90RA20, 92RA01, 92RA11]; differential and total cross sections for reaction (g) at $E_{\pi^+} = 100$, 165 MeV [95PA22, 96LO04]; inclusive spectra of ^{3}He produced in reaction (l) [92AM1H, 93AM09]; total reaction cross sections for (π^+, X), (π^-, X) at $E_\pi = 42$–65 MeV [96SA08]. See also the earlier work on reaction (g) at $E_{\pi^+} = 59.4$ MeV [86RI01], and see the compilation and review of [92BA57, 93IN01].

Analysis of particle emission following π^+ absorption on ^{6}Li [90RA20] has produced evidence for a three-nucleon absorption model. Distorted-wave impulse approximation calculations of cross sections and analyzing powers have been made [92KH04] for two-nucleon pion absorption on polarized ^{6}Li targets. A model based solely on isospin was used [93MA14] in a calculation of ratios of pion absorption on three nucleons and agreement with experiment suggest a one-step process.

19. (a) ^{6}Li(n, n)^{6}Li
 (b) ^{6}Li(n, nd)^{4}He, $Q_m = -1.4743$
 (c) ^{6}Li(n, p)^{6}He, $Q_m = -2.7254$
 (d) ^{6}Li(n, d)^{5}He, $Q_m = -2.272$
 (e) ^{6}Li(n, t)^{4}He, $Q_m = 4.7829$
 (f) ^{6}Li(n, α)^{3}H, $Q_m = 4.7829$

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

An analysis [88HA25] of (n, n) and (n, n′) data at $E_n = 24$ MeV indicated that neutron and proton transition densities were approximately equal ($\rho_n \approx \rho_p$) in ^{6}Li. Cross sections and analyzing powers for $E_n = 8$–40 MeV were analyzed [89HAZV] with microscopic optical model potentials. Secondary neutron spectra induced by 14.2 MeV neutrons on ^{6}Li were measured by [93XI04].

An analysis of (n, n′) data at $E_n = 7.45$–14 MeV is discussed in [90BE54]. See also the calculation for elastic coherent and incoherent scattering of thermal neutrons on ^{6}Li [90GO26] and the multicluster dynamic model calculation for ^{6}Li(n, n) at $E_n = 12$ MeV [92KA06].

Theoretical studies of ^{6}Li(n, n) include multiconfiguration resonating-group calculations [88FU09, 91FU02], folding model descriptions for $E_n = 25$–50 MeV [93PE13], study of antisymmetry in NN potentials [95CO18], study of optical model potentials for intermediate energies [96CH33].

For reaction (b) see [84AJ01, 85CH37, 93XI04, 94EL08].

A number of experiments on the (n, p) charge exchange (reaction (c)) have been reported. They include: measurements of $\sigma(E_p)$ and $\sigma(\theta)$ at $E_n \approx 198$ MeV [87HE22]; $\sigma(\theta, E_p)$ at $E_n \approx 118$ MeV [87PO18, 88HA12, 98HA24]; $\sigma(\theta)$ at $E_n = 198$ MeV [88JA01]; $\sigma(\theta)$ to explore the Gamow–Teller sum rule [88WA24]; $\sigma(\theta)$, $\sigma(E_p)$ at $E_n = 280$ MeV for an isospin symmetry test [90MI10]; $\sigma(\theta, E)$ at $E_n = 60$–260 MeV [92SO02]; and polarization observables at $E_n = 0.88$ GeV [96BB23].

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

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

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

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

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

Reaction (b) was studied at 70 MeV [83GO06], at 50–100 MeV [84PA1B, 85PA1B] and 1 GeV [85BE30, 88BE2B, 00MI17]: see ^{5}He and [84AJ01] for the earlier work. Reaction (c) has been studied at $E_p = 9$ MeV to 1 GeV (see [74AJ01, 79AJ01, 84AJ01]) and at 20 and 42 MeV [83CA13] (report involvement of ^{6}Li*(4.31, 5.65)), at 70 MeV [83GO06, 85PA1C, 85PA04] and at 119.6 and 200.2 MeV [84WA09, 85WA25]. In the latter experiments, the spectroscopic factors for $^{6}\text{Li}_{\text{g.s.}}$ are deduced to be 0.76 (at 119.6 MeV) and 0.84 (at 200.2 MeV) using DWIA and a bound-state Woods–Saxon 2S wave function [84WA09, 85WA25].

Work on reaction (d) has suggested that the ^{3}He + t parentage of ^{6}Li is comparable with the α + d parentage: see [84AJ01]. See also [85PA1C]. Reaction (e) was studied at $E_p = 70$ MeV [88PA27]. See also ^{5}Li, ^{6}Be and [85BE30, 93ST06]. The (p, 3p) reaction has been studied by [84NA17]. The spectral function for pn pairs in ^{6}Li was obtained in a study of the ^{6}Li(p, pα)pn reaction at $E_p = 200$ MeV [90WA17]. A measurement of tensor analyzing powers in ^{1}H(^{6}Li, d or α or t)X with 4.5 GeV polarized ^{6}Li deuterons

Table 6.12
Parameters of levels of ^{6}Li[a]

E_x (MeV ± keV)	Γ_{cm} (keV)	Reactions
2.185 ± 3	20.0 ± 2.8	^{4}He(d, d)^{4}He
2.187 ± 3		^{4}He(d, d)^{4}He
2.188 ± 6	24 ± 2[b]	^{6}Li(p, p′), (d, d′), ^{7}Li(d, t)^{6}Li
2.203 ± 6		^{9}Be(p, α)^{6}Li
2.186 ± 2	**24 ± 2**	**“best” value**
3.56288 ± 0.10[c]	$(8.2 \pm 0.2) \times 10^{-3}$[c]	^{6}Li(γ, γ′)^{6}Li
4.36 ± 40	1320 ± 40	^{4}He(d, d)^{4}He
4.27 ± 40		^{6}Li(e, e′)^{6}Li
	1044 ± 58[d]	^{6}Li(e, e′)^{6}Li
4.40 ± 120	1490 ± 150	^{6}Li(p, p′)^{6}Li
4.32 ± 40	1820 ± 110	^{6}Li(d, d′)^{6}Li
4.3 ± 100	600 ± 100	^{7}Li(^{3}He, α)^{6}Li
4.3 ± 200	1600 ± 300	^{7}Li(^{3}He, αd)^{4}He
4.3	1600 ± 120[e]	^{7}Li(^{3}He, αd)^{4}He
4.30 ± 10	850 ± 50, 480 ± 80	^{9}Be(p, α)^{6}Li
4.312 ± 22	**1300 ± 100**[f]	**“best” value**
5.379 ± 17[g]	540 ± 20[g]	^{6}Li(e, e′)^{6}Li
	546 ± 36[d]	^{6}Li(e, e′)^{6}Li
5.33 ± 80	560^{+340}_{-100}	^{6}Li(p, p′)^{6}Li
5.34 ± 20	560 ± 40[b]	^{7}Li(^{3}He, α)^{6}Li
5.325 ± 5	270 ± 12	^{9}Be(p, α)^{6}Li
5.366 ± 15	**541 ± 20**[h]	**“best” value**
5.65 ± 50[i]	1900 ± 100	^{4}He(d, d)^{4}He
5.7	1000^{+600}_{-400}[j]	^{6}Li(p, p′)^{6}Li
5.65 ± 200	1650 ± 300	^{7}Li(^{3}He, αd)^{4}He
5.65 ± 40	900 ± 60, 1260 ± 120	^{9}Be(p, α)^{6}Li
5.65 ± 50	**1500 ± 200**	**“best” value**

[a] For references and other values see Tables 6.5 in [79AJ01, 84AJ01, 88AJ01].
[b] See [88AJ01].
[c] [81RO02].
[d] [79BE38].
[e] Average of measurements for $E(^3\mathrm{He}) = 4, 5, 6$ MeV [95AR14].
[f] Weighted average of “best” values from [88AJ01] and values of 1320 ± 40 keV (Table 6.7), 1044 ± 58 keV [79BE38], and 1600 ± 120 keV from [95AR14].
[g] See Table 6.4 in [79AJ01].
[h] Weighted average of “best” values from [88AJ01] and 546 ± 36 keV from [79BE38].
[i] See Table 6.3 in [79AJ01].
[j] See references (c) and (d) in Table 6.5 in [79AJ01].

provided information on the ^{6}Li D state [92PU03]. Systematic studies of electron screening effects on low-energy reactions including $^6\mathrm{Li} + \mathrm{p}$ are reported in [92EN01, 92EN04, 95RO37]. For antiproton studies see [87AS06]. See also [84AJ01, 88AJ01] for the earlier work.

Theoretical work on these reactions reported since the previous review [88AJ01] is listed in Table 6.13 along with brief descriptions.

Table 6.13
^{6}Li(p, p)^{6}Li—theoretical work

Reference	Description
[88HA25]	^{6}Li proton and neutron transition densities from elastic scattering
[90ZH1R]	Quasiresonating-group method analysis of ^{6}Li(p, p)^{6}Li
[92GA27]	Folding-model study of elastic scattering in halo nuclei
[93DU09]	Potential description of N + ^{6}Li elastic scattering
[93KO44]	Description of ^{6}Li(p, p)^{6}Li with microscopic effective interaction
[93PE13]	Folding model description of ^{6}Li(p, p)^{6}Li at 25–50 MeV
[93SA10]	DWBA analysis of ^{6}Li(p, p)^{6}Li near the α–d breakup threshold
[94ZH28]	Elastic and inelastic proton scattering on ^{6}Li nucleus at intermediate energies
[94ZH34]	Glauber–Sitenko diffraction theory calculation of ^{6}Li(p, p)^{6}Li
[95GA24]	Analysis of properties of exotic nuclei in elastic scattering
[95KA03]	Folding-model analysis of ^{6}Li(p, p$'$)^{6}Li at $E_p = 10$–136 MeV
[95KA07]	Continuum–continuum coupling in ^{6}Li(p, p)^{6}Li at $E_p = 65$ MeV
[95KA43]	Folding-model analysis of ^{6}Li(p, p$'$)^{6}Li at $E_p = 10$–136 MeV
[97DO01]	Fully microscopic model analyses of ^{6}Li(p, p$'$)^{6}Li at $E_p = 200$ MeV
[97KA24]	Shell-model structures of ^{6}Li states excited in ^{6}Li(p, p$'$)^{6}Li
[98DO16]	Microscopic analysis of ^{6}Li(p, p) at $E_p = 65$ MeV
[98FUZP]	Microscopic optical-model calculation for $E_p = 60$–70 MeV
[00TI02]	Finite-range coupled-channel calculation for ^{6}He + p r × n
[00DE61]	Microscopic model analysis of ^{6}Li(p, p)^{6}Li for $E_p = 25, 30, 40$ MeV
[00LA40]	Resonance optical model analysis for ^{6}Li(p, p)^{6}Li for $E_p = 1$–10 MeV
[00ZH40]	Glauber–Sitenko diffraction theory calculation for $E_p = 0.16$–1.04 GeV
[01AR05]	Microscopic multicluster calculation for ^{6}He + p at $E_{cm} = 0$–5 MeV

21. (a) ^{6}Li(d, d)^{6}Li
(b) ^{6}Li(d, pn)^{6}Li, $Q_m = -2.2246$
(c) ^{6}Li(d, 2d)^{4}He, $Q_m = -1.4743$
(d) ^{6}Li(d, αp)^{3}H, $Q_m = 2.5583$
(e) ^{6}Li(d, αn)^{3}He, $Q_m = 1.7946$

Angular distributions of deuterons have been measured at $E_d = 4.5$ to 19.6 MeV (see [79AJ01]) and at 50 MeV [88KO1C, 96RU10]. The 0^+, $T = 1$ state, ^{6}Li*(3.56) is not appreciably populated. For a summary of the results on excited states, see Table 6.12. Gaussian potentials were derived for the description of ^{6}Li + d elastic scattering by [92DU07].

At $E_d = 21$ MeV reaction (b) shows spectral peaking (characteristic of $^{1}S_0$ for the pn system ($T = 1$)) when ^{6}Li*(3.56) is formed, in contrast with the much broader shape (characteristic of $^{3}S_1$) seen when ^{6}Li*(0, 2.19) are populated. A study of reaction (c) at $E_d = 52$ MeV shows that the α-clustering probability, $N_{eff} = 0.12^{+0.12}_{-0.06}$ if a Hankel function is used. The α-particle and the deuteron clusters in ^{6}Li have essentially a relative orbital momentum of $l = 0$. The D-state probability of the ground state of ^{6}Li is $\approx 5\%$ of the S-state. Quasifree scattering is an important process even for $E_d = 6$ to 11 MeV. Interference effects are evident in reaction (c) proceeding through ^{6}Li*(2.19, 4.31): this is due to the experiment being unable to determine whether the detected particle was emitted first or second in the sequential decay. Reactions (c) and (d) studied at $E_d = 7.5$ to

10.5 MeV indicate that the three-body breakup of ^{6}Li at these low energies is dominated by sequential decay processes [79AJ01, 90YA11]. Differential cross sections for cluster pickup by 20 MeV/A deuterons on ^{6}Li were measured by [95MA57].

Calculation of maxwellian rate parameters for reaction (d) and (e) are described in [00VO08]. See also ^{8}Be and references cited in [88AJ01].

22. ^{6}Li(t, t)^{6}Li

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

23. (a) ^{6}Li(^{3}He, ^{3}He)^{6}Li
(b) ^{6}Li(^{3}He, pα)^{4}He, $Q_m = 16.878$

Angular distributions have been measured at $E(^{3}\text{He}) = 8$ to 217 MeV (see [79AJ01, 84AJ01]) and at 34, 50, 60 and 72 MeV ([86BR31]; elastic).

More recently, differential cross sections were measured for elastic scattering at $E(^{3}\text{He}) = 93$ MeV [94DO32], and at $E(^{3}\text{He}) = 60$ MeV [95MA57], and for inelastic scattering to ^{6}Li* ($E_x = 2.185$ MeV, $J^{\pi} = 3^{+}$) at $E(^{3}\text{He}) = 50$, 60, 72 MeV [95BU20]. A microscopic-potential analysis of data at $E(^{3}\text{He}) = 34$, 50, 60, 72 MeV is described in [93SI06]. Differential cross section and energy spectra were compiled and analyzed by [95MI16]. For reaction (b), cross sections have been measured at $E(^{3}\text{He}) = 11$, 13, 14 MeV [89ARZR, 89AR08]; $E(^{3}\text{He}) = 2.5$ MeV [89AR20]; $E(^{3}\text{He}) = 1.6$ MeV [91AR25]; $E(^{3}\text{He}) = 1.6$–9 MeV [92AR20]; $E(^{3}\text{He}) = 8$–14 MeV [95KO51]; $E(^{3}\text{He}) =$ 2.0, 22 MeV [92DA1K]; $E(^{3}\text{He}) = 7$, 9 MeV [93AR12]. A calculation of near-threshold two-fragment resonance amplitudes and widths for this reaction at $E(^{3}\text{He}) = 8$–14 MeV was reported in [95KO51]. See also ^{5}Li [84AR17, 87ZA07] and see ^{9}B.

24. (a) ^{6}Li(α, α)^{6}Li
(b) ^{6}Li(α, 2α)^{2}H, $Q_m = -1.4743$

Angular distributions (reaction (a)) have been measured at $E_{\alpha} = 1.39$ to 166 MeV (see [74AJ01, 79AJ01, 84AJ01]) and at $E_{\alpha} = 36.6$ and 50.5 MeV [86BR31]. See also [86ROZK, 87BU27]. See also ^{10}B.

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

Studies of continuum coupling effects in inelastic scattering are described in [95KA1Y, 95KA43, 97RU06, 98RU1C, 00RU03]. Folding-model potential analyses of elastic scattering are reported in [93SI09, 95SA12]. Multiconfiguration resonating-group methods applied to the $^{6}\text{Li} + \alpha$ system are discussed in [94FU17, 95FU11]. Other recent theoretical studies include: a potential model description [99MA02]; analysis of density distribution influence [98GO1J]; a phase-shift-analysis determination of the asymptotic D- to S-state ratio [99GE02]; a calculation for $E_\alpha = 16.3$ and 48 MeV with a modified Volkov potential [00KO52]; and a calculation of the nuclear potential and polarization tensor for $E_\alpha = 27.2$ MeV [00KO67]. See also [88KO32, 89LE07, 99OG09].

Reaction (b) has been studied at $E_\alpha = 6.6$ to 700 MeV: see [74AJ01, 79AJ01, 84AJ01]. At the latter energy and using a width parameter of 60.6 MeV/c the effective number of $\alpha + \mathrm{d}$ clusters for $^{6}\mathrm{Li}_{\mathrm{g.s.}}$, $n_{\mathrm{eff}} = 0.98 \pm 0.05$. The results are very model dependent: see [84AJ01]. At $E_\alpha = 27.2$ MeV ^{6}Li*(2.19) is very strongly populated [85KO29]. See also references cited in [88AJ01].

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

25. (a) $^{6}\mathrm{Li}(^{6}\mathrm{Li}, ^{6}\mathrm{Li})^{6}\mathrm{Li}$
(b) $^{6}\mathrm{Li}(^{6}\mathrm{Li}, 2\mathrm{d})^{4}\mathrm{He}^{4}\mathrm{He}$, $Q_{\mathrm{m}} = -2.9487$
(c) $^{6}\mathrm{Li}(^{6}\mathrm{Li}, \alpha)^{4}\mathrm{He}^{4}\mathrm{He}$, $Q_{\mathrm{m}} = 20.8979$

Angular distributions of ^{6}Li ions have been studied for $E(^{6}\mathrm{Li}) = 3.2$ to 36 MeV (see [74AJ01, 79AJ01, 84AJ01]) and at $E(^{6}\mathrm{Li}) = 2.0$ to 5.5 MeV [83NO08] and 156 MeV [85SA36] (^{6}Li*(0, 2.19)), [85MI05] (elastic; ^{6}Li*(2.19, 3.56) are also populated), [87EY01] (several states in ^{12}C). Reaction (b) has been studied for $E(^{6}\mathrm{Li}) = 36$ to 47 MeV: enhancements in yield, due to double spectator poles, have been observed in d–d and α–α but not in α–d double coincidence spectra. The widths of the peaks are smaller than those predicted from the momentum distribution of $\alpha + \mathrm{d}$ clusters in ^{6}Li. ^{6}Li*(2.19) was also populated. See references in [84AJ01]. Other work on reaction (b) is reported in [84LA19] (2.4 and 4.2 MeV) and [85NO1A].

For reaction (c), the energy dependence of quasifree effects were investigated in the range $E(^{6}\mathrm{Li}) = 2.4$–6.7 MeV [87LA25, 88LA11]. An analysis [96CH1C] used quasifree data from reaction (c) to extract the $^{6}\mathrm{Li}(\mathrm{d}, \alpha)^{4}\mathrm{He}$ excitation function at astrophysical energies. See also ^{12}C in [85AJ01] and references cited in [88AJ01].

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

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

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

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

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

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

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

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

The elastic and inelastic scattering (reaction (a)) has been studied at $E(^{6}\text{Li}) = 4.5$ to 156 MeV (see [84AJ01]) and at $E(^{6}\text{Li}) = 19.2$ MeV [83RU09], 36 and 45 MeV (and $E(^{12}\text{C}) = 72$ and 90 MeV) ([84VI02, 85VI03]; also to $^{6}\text{Li}^{*}(2.19, 4.31)$ and to various states of ^{12}C), at $E(^{12}\text{C}) = 58.4$ MeV [87PA12], 90 MeV ([87DE02]; also to various states of ^{12}C), 123.5 and 168.6 MeV ([88KA09]; and to various states of ^{12}C), 150 MeV [87TA21, 88TA08], 156 MeV ([87EY01]; and to various states in ^{12}C) and at 210 MeV [88NA02]. See also [86SHZP, 87PA12]. More recently, measurements of cross sections and/or analyzing power observables have been reported at $E(^{6}\text{Li}) = 93$ MeV [89DE34]; at $E_{\text{cm}} = 13.3$ MeV ([89HN1A, 95CA26] and to $^{6}\text{Li}^{*}(3^{+}, 2.186)$ and $^{12}\text{C}^{*}(2^{+}, 4.44)$); at $E(^{6}\text{Li}) = 210$ MeV ([89NA11], to $^{12}\text{C}^{*}(2^{+}, 4.44)$); at $E(^{6}\text{Li}) = 30$ MeV ([89VA04], to $^{12}\text{C}^{*}(2^{+}, 4.44)$); at 50 MeV ([90TR02], to $^{12}\text{C}^{*}(2^{+}, 4.44;\ 0^{+}, 7.65;\ 3^{-}, 9.64)$); at $E(^{6}\text{Li}) = 30$ MeV [94RE01]; at $E(^{6}\text{Li}) = 30$, 60 MeV ([96KE09], to $^{12}\text{C}^{*}(2^{+}, 4.44;\ 0^{+}, 7.65;\ 3^{-}, 9.64)$); at $E_{\text{cm}} = 20$ MeV ([96GA29], to $^{6}\text{Li}^{*}(3^{+}, 2.18)$ and $^{12}\text{C}^{*}(2^{+}, 4.44)$); at $E(^{6}\text{Li}) = 318$ MeV [93NA01]; at $E(^{6}\text{Li}) = 30$ MeV ([94RE15], to $^{12}\text{C}^{*}(2^{+}, 4.44;\ 3^{-}, 9.64)$); and at $E(^{6}\text{Li}) = 50$ MeV [95KE10]. At $E(^{6}\text{Li}) = 34$ MeV the d–α angular correlations involve $^{6}\text{Li}^{*}(0, 2.19)$ [85CU04]. See also [88SE07], and see ^{12}C in [85AJ01, 90AJ01]. An experimental study of the $\alpha + \text{d}$ breakup in $^{6}\text{Li} + {}^{12}\text{C}$ collision at $E(^{6}\text{Li}) = 156$ MeV is reported in [89JE01]. For pion production see [84CH16]. For the interaction cross section at $E(^{6}\text{Li}) = 790$ MeV/A, see [85TA18]. For VAP measurements at $E(^{6}\text{Li})= 30$ MeV see [88VAZY]. Fusion cross sections for $E(^{6}\text{Li}) = 3.11$–12.07 MeV are reported by [98MU12].

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

Several theoretical studies relating to $^{6}\text{Li} + {}^{12}\text{C}$ have been reported. The role of the Pauli principle in heavy-ion scattering has been studied [88GR32]. The dispersive contribution to the $^{6}\text{Li} + {}^{12}\text{C}$ real potential was estimated [90KA14]. Elastic cross sections for $E(^{6}\text{Li}) =$

30 MeV were analyzed [90SA05]. A semimicroscopic analysis of inelastic scattering at $E(^6\text{Li}) = 156$ MeV is described in [92GA17]. Folding-model analysis of $^6\text{Li} + {}^{12}\text{C}$ scattering is discussed in [94NA03, 94SA10, 95KH03]. Differential cross sections were analyzed with an S-matrix approach by [98PI02].

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

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

Elastic angular distributions have been reported at $E(^6\text{Li}) = 4.5$ to 50.6 MeV (see [84AJ01]), at $E(^6\text{Li}) = 35.3$ and $E(^{16}\text{O}) = 94.2$ MeV [84VI02] and at 50 MeV ([88TRZY]; also inelastic). At $E(^6\text{Li}) = 25.7$ and $E(^{16}\text{O}) = 68.6$ MeV [84VI01, 85VI03] report some $\sigma(\theta)$ to $^6\text{Li}^*(2.19)$ (and to $^{16}\text{O}^*(6.13)$). See also [87PA12]. See [85VI03, 86SC28] for studies of the breakup. Polarization observables have has been measured at $E(^6\text{Li}) = 25.7$ MeV, and also using ^{16}O ions [87VAZY, 89VA04]. Measurements of $E(^6\text{Li}) = 50$ MeV for elastic scattering and inelastic scattering to $^{16}\text{O}^*$ $(2^+, 6.05;\ 3^-, 6.13;\ 2^+, 6.92;\ 1^-, 7.12)$ were reported [90TR02]. For fusion cross sections see [86MA19]. See also ^{16}O in [86AJ04], [86MO1E, 87PA12] and references cited in [88AJ01]. Theoretical work on this scattering reaction includes: $E(^6\text{Li}) = 29.8$ MeV, optical model description [90SA05]; $E(^6\text{Li}) = 29.8$–30.6 MeV, Pauli-principle rule [88GR32]; $E(^6\text{Li}) = 30.6$, optical-model analysis [90SA05]; projectile effects [91BO48]; $E(^6\text{Li}) = 154$ MeV, three-body cluster model [91HI07]; $E(^6\text{Li}) = 22.8$ MeV, nonresonant breakup states [91HI11]; and $E(^6\text{Li}) = 30$ MeV, double-folding model, role of Pauli principle [91SA26].

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

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

Theoretical studies for these reactions include: analyzed non-Rutherford cross-sections [91BO48]; effects of nonresonant breakup states [91HI11]; strong absorption model analysis [94SA33]; cluster folding interaction [91HI07]; coupled-channel study [92HI02]; and cluster-folding analysis [94RU11].

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

The elastic scattering has been studied at $E(^6\text{Li}) = 13$ to 154 MeV (see [84AJ01]), at 27 and 34 MeV [83VI03] and at 210 MeV [88NAZX]. For a study of the decay see [87NI04]. See also references cited in [88AJ01].

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

For reaction (b) see [87AR13].

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

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

For theoretical studies related to these reactions see: energy and target dependence of projectile breakup [87SA21]; sequential breakup cross sections [87VA31]; role of Pauli principle [88GR32]; exchange effects [88KH08, 90DA23]; imaginary part of channel-coupling potentials [90TA1I]; $E(^6\mathrm{Li}) = 30$ MeV, deduced optical-model parameters [90SA05]; cluster-folding interactions [91HI07]; strong absorption model [94SA33]; S-matrix approach [95BE60, 98PI02]; and microscopic potentials [96KN02]. For earlier work see references cited in [88AJ01].

34. (a) $^7\mathrm{Li}(\gamma, \mathrm{n})^6\mathrm{Li}$, $Q_\mathrm{m} = -7.249$
(b) $^7\mathrm{Li}(\gamma, \mathrm{p}\pi^-)^6\mathrm{Li}$, $Q_\mathrm{m} = -146.038$

Transitions to $^6\mathrm{Li}^*(0, 2.19, 3.56)$ have been observed in reaction (a): see [79AJ01, 84AJ01]. Differential cross sections are reported for $E_\mathrm{brem} = 60$ to 120 MeV for the $\mathrm{n}_0 + \mathrm{n}_2$ groups [85SE17]. Bremsstrahlung yield for (γ, n_0) was measured for $E_\gamma = 7$–9 MeV [89KA30]. Reaction (b) at 0.9 GeV involves ^{6}Li*(2.19) [85RE1A]. See also the measurements of $E_\gamma = 350$ MeV reported by [91GA26], and see ^{7}Li, [85ST1A, 86BA2G, 86GO1M].

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

35. ^{7}Li$(\pi^-, \pi^- p)^{6}$He, $Q_m = -9.9754$

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

36. ^{7}Li$(\pi^+, p)^{6}$Li, $Q_m = 133.1026$

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

37. (a) ^{7}Li(p, d)^{6}Li, $Q_m = -5.0254$
(b) ^{7}Li(p, pn)^{6}Li, $Q_m = -7.2499$

Angular distributions of deuterons (reaction (a)) have been studied for $E_p = 167$ to 800 MeV (see [79AJ01, 84AJ01]) and at 18.6 MeV ([86GO23, 87GO27]; d_0, d_1, d_2; see for spectroscopic factors), 200 and 400 MeV ([85KR13]; d_0, d_1; d_2 is weakly populated at 200 MeV) and at 800 MeV ([84SM04]; d_0, d_1). The ratio of the intensities of the groups to ^{6}Li*(2.19) and ^{6}Li$_{g.s.}$ increases with energy. It is suggested that this can be understood in terms of a small admixture of 1f orbital in these states [85KR13]. A DWBA analysis of $E_p = 185$ MeV data leads to $C^2S = 0.87, 0.67, 0.24, (0.05), 0.14$, respectively for ^{6}Li*(0, 2.19, 3.56, 4.31, 5.37). No other states were seen below $E_x \approx 20$ MeV: see [79AJ01]. The tensor analyzing power T_{20} was measured for the ^{1}H(^{7}Li, d)^{6}Li reaction at $E(^{7}\text{Li}) = 70$ MeV to ^{6}Li*(0, 2.186) [91DA07]. Data at $E_p = 33.6$ MeV were analyzed by [91AB04] in a test for Cohen–Kurath wave functions. See also the analysis of data at $E_p = 698$ MeV in [93AL05], η production. In reaction (b) at $E_p = 1$ GeV the separation energy between ≈ 6.5 MeV broad $1p_{3/2}$ and $1s_{1/2}$ groups is reported to be 18.0 ± 0.8 MeV [85BE30, 85DO16]. See also [83LY04, 88BE1I, 88GUZW]. Differential cross sections were measured at $E_p = 70$ MeV [88PA26] and at $E_p = 2.7$–3.8 MeV ([88BO37], application). See also the measurements for nuclear microprobe utilization [95RI14].

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

A study at $E_d = 23.6$ MeV of the relative cross sections of the analog reactions ^{7}Li(d, t)^{6}Li (to the first two $T = 1$ states at 3.56 and 5.37 MeV) and ^{7}Li(d, ^{3}He)^{6}He (to the ground and 1.80 MeV excited states) shows that ^{6}Li*(3.56, 5.37) have high isospin purity ($\alpha^2 < 0.008$): this is explained in terms of antisymmetrization effects which prevent mixing with nearby $T = 0$ states: see [79AJ01]. [87BO39] ($E_d = 30.7$ MeV) deduce that the branching ratio of ^{6}Li*(4.31) (2^+) into a dinucleon ($T = 1$, $S = 0$) is (85 ± 10)%: see also reactions 21 in ^{6}He and 4 in ^{6}Be. See also [87GUZZ] ($E_d = 18$ MeV, angular distributions to ^{6}Li*(0, 2.19, 3.56)) and [84BL21, 86AV01, 88GUZW]. See also the analysis method discussed in [95GU22] (DWBA and dispersive theory).

39. (a) ^{7}Li(^{3}He, α)^{6}Li, $Q_m = 13.3277$
    (b) ^{7}Li(^{3}He, dα)^{4}He, $Q_m = 11.8534$

Angular distributions have been reported at $E(^3\text{He}) = 5.1$ to 33.3 MeV (see [74AJ01, 84AJ01]: the lower-energy work has not been published) and more recently at $E(^3\text{He}) =$ 60 MeV [94BUZX]. Excited states observed in this reaction are displayed in Table 6.12. See also [68CO07] which reported observation of ^{6}Li states at 0.0, 2.17 ± 0.02, 3.55 ± 0.02 and 5.34 ± 0.02 MeV. [86AN04] have analyzed unpublished data which suggest the involvement of several broad highly excited states of ^{6}Li. See also [87AL23].

Several attempts have been made to observe the isospin-forbidden decay of ^{6}Li*(5.37) (2^+; 1) via ^{7}Li(^{3}He, α)^{6}Li* $\rightarrow$ d + α: the branching is < 1%. $\Gamma_p/\Gamma = 0.35 \pm 0.10$ and $\Gamma_{p+n}/\Gamma = 0.65 \pm 0.10$ for ^{6}Li*(5.37): see [79AJ01]. ^{4}He + d spectra suggest the excitation of ^{6}Li*(4.3) ($E_x = 4.3 \pm 0.2$ MeV, $\Gamma = 1.6 \pm 0.3$ MeV) and ^{6}Li*(5.7) ($E_x =$ 5.65 ± 0.2 MeV, $\Gamma = 1.65 \pm 0.3$ MeV): see [84AJ01]. See also [85DA29, 88BO1Y]. A more recent measurement at $E(^3\text{He}) = 4, 5, 6$ MeV [95AR14] gave values for the width of ^{6}Li*(4.31) in agreement with the adopted value $\Gamma = 1700 \pm 200$ keV and found no dependence on incident energy. Measurements of d–α coincidence spectra at $E(^3\text{He}) = 11.5$ MeV [88AR20] and 5.0 MeV [91AR19] gave spectroscopic parameters for ^{6}Li*(5.65) in agreement with adopted values [88AJ01]. At $E(^3\text{He}) = 120$ MeV the missing mass spectra for (^{3}He, 2d) and (^{3}He, pt) reflect the population of ^{6}Li*(0, 2.19) and suggest broad structures at $E_x = 28.5$ and 32.9 MeV [85FR01]. See also ^{10}B and [83KU17, 88BO1J].

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

At $E(^6\text{Li}) = 93$ MeV, a broad group ($\Gamma \approx 11$ MeV) centered at $E_x = 20$ MeV is reported in addition to other peaks at $E_x = 17.1 \pm 0.3$, 18.9 ± 0.3 and 21.2 ± 0.3 MeV [87GLZW]. See [84KO25] for reaction (b).

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

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

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

Angular distributions of α particles (reaction (a)) have been measured at $E_p = 0.11$ to 45 MeV (see [74AJ01, 79AJ01]) and at $E_p = 22.5$, 31 and 41 MeV ([86HA27]; α_0, α_1, α_2; see for spectroscopic factors). See also Table 6.12 and [84AJ01]. Recent measurements of angular distributions and analyzing power at $E_p = 77$–321 keV are reported in [98BR10]. Measurements at $E_x = 1$ GeV are reported in [00ANZX]. Calculations of the cross section and polarization observables for $E_p = 40$ MeV are reported in [00GA49, 00GA59]. A study of possible reasons for nonobservation of certain ^{6}Li excited states in the reaction is discussed in [99TI07]. ^{6}Li*(3.56) decays by γ-emission consistent with M1; $\Gamma_\alpha/\Gamma < 0.025$ (forbidden by spin and parity conservation): see [84AJ01]. An analysis of the ^{9}Be(p, α) cross section at $E_p = 16$–700 keV is described in [01BA47]. Astrophysical S-factor, analyzing powers and R-matrix parameters were deduced. At $E_p = 9$ MeV, the yield of reaction (b) is dominated by FSI through ^{8}Be*(0, 2.9) and ^{6}Li*(2.19) with little or no yield from direct three-body decay: see [79AJ01]. More recent measurements of cross sections and/or polarization observables have been reported at $E_p = 50$ MeV [89GU05], $E_p = 25$, 30 MeV ([92PE12]; determined spectroscopic strengths), $E_p = 40$ MeV [97FA17] (see also [89FA1B]), $E_p = 2$–5 MeV [88ABZW], $E_p = 16$–390 keV (deduced $S(E)$) [97ZA06], $E_p = 77$–321 keV (deduced stellar reaction rates) [98BR10], $E_p = 30$–300 keV [00ISZZ]. See also application-related experiments [90RE09, 95RI14]. Analyses of data for this reaction have been reported for $E_p = 45$–50 MeV (DWBA) [96YA09, 97YAZV] and $E_p < 2$ MeV (analyzed reaction rates, primordial ^{6}Li) [97NO04]. Reactions (b) and (c) at $E_p = 58$ MeV involve ^{6}Li*(0, 2.19) [85DE17]. See also ^{10}B and [85MA1F, 86AN26, 86KA26].

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

See ^{5}He.

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

Angular distributions of ^{6}He$_{g.s.}$ + ^{6}Li$_{g.s.}$ and ^{6}He$_{g.s.}$ + ^{6}Li*(3.56) (both ions listed were detected) have been measured at $E_t = 21.5$ and 23.5 MeV. In the latter case the final state is composed of two isobaric analog states: angular distributions are symmetric about 90° cm, within the overall experimental errors. In the reaction leading to the ground states of ^{6}He and ^{6}Li differences from symmetry of as much as 40% are observed at forward angles. Angular distributions involving ^{6}He$_{g.s.}$ + ^{6}Li*(2.19) and ^{6}Li$_{g.s.}$ + ^{6}He*(1.8) have also been measured. This reaction appears to proceed predominantly by means of the direct pickup of a triton or ^{3}He from ^{9}Be. Differential cross sections are also reported at $E_t = 17$ MeV: see [84AJ01] for references.

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

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

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

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

47. ^{10}B(d, ^{6}Li)^{6}Li, $Q_m = -2.9861$

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

48. ^{10}B(^{3}He, ^{7}Be)^{6}Li, $Q_m = -2.8738$

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

49. ^{10}B(α, ^{8}Be)^{6}Li, $Q_m = -4.5522$

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

50. ^{11}B(d, ^{7}Li)^{6}Li, $Q_m = -7.1903$

See [84AJ01].

51. ^{11}B(^{3}He, ^{8}Be)^{6}Li, $Q_m = 4.5712$

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

52. ^{12}C(p, ^{7}Be)^{6}Li, $Q_m = -22.5668$

Angular distributions involving ^{7}Be*(0, 0.43) have been measured at $E_p = 40.3$ MeV [85DE05]. For the earlier work at $E_p = 30.6$ to 56.8 MeV see [74AJ01, 79AJ01]. See also references cited in [88AJ01].

53. ^{12}C(d, ^{8}Be)^{6}Li, $Q_m = -5.8922$

Angular distributions involving states in ^{8}Be have been studied at $E_d = 19.5$ and 51.8 MeV (see [74AJ01]) and at 50 MeV [85GO1G, 89GO07, 89GO26], 54.2 MeV [84UM04] and 78 MeV [86JA14], as well as at $E_d = 18$ and 22 MeV [87TA07] and 51.7 MeV [86YA12]. See also [84NE1A, 87GO1S] and the DWBA calculations at $E_d =$ 50 MeV [88KA46] and $E_d = 15$ MeV [88RA27].

54. ^{12}C(^{3}He, ^{9}B)^{6}Li, $Q_m = -11.5708$

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

55. (a) $^{12}C(\alpha, {}^{10}B)^{6}Li$, $Q_m = -23.7122$
    (b) $^{12}C(\alpha, d\alpha)^{10}B$, $Q_m = -25.1865$

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

56. (a) $^{12}C(^{6}Li, \alpha)^{14}N$, $Q_m = 8.7980$
    (b) $^{12}C(^{6}Li, \alpha d)^{12}C$, $Q_m = -1.4743$

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

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

57. $^{12}C(^{10}B, {}^{16}O)^{6}Li$, $Q_m = 2.7015$

See ^{16}O in [86AJ04].

58. $^{12}C(^{11}B, {}^{6}Li)^{17}O$, $Q_m = -4.609$

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

59. $^{12}C(^{12}C, {}^{12}C)^{6}Li^{6}Li$, $Q_m = -28.1726$

The fragmentation of ^{12}C into two ^{6}Li ions has been observed at $E(^{12}C) = 2.1$ GeV/A [86LIZP].

60. $^{12}C(^{14}N, {}^{20}Ne)^{6}Li$, $Q_m = -4.1810$

Angular distributions of reaction products were measured for $E(^{14}N) = 50$ MeV, and multinucleon transfer mechanisms were studied [92ARZX]. See also the analysis for $E(^{14}N) = 54$ MeV [87GO12], and see ^{20}Ne in [87AJ02, 98TI06].

61. $^{13}C(p, {}^{8}Be)^{6}Li$, $Q_m = -8.6140$

See [74AJ01].

62. $^{13}C(t, {}^{6}Li)^{10}Be$, $Q_m = -8.6181$

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

63. $^{13}C(^{3}He, {}^{6}Li)^{10}B$, $Q_m = -8.0809$

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

64. $^{16}O(d,{}^{12}C)^{6}Li$, $Q_m = -5.6876$

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

65. $^{16}O(^{3}He,{}^{6}Li)^{13}N$, $Q_m = -9.2376$

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

66. $^{19}F(d,{}^{6}Li)^{15}N$, $Q_m = -2.5394$

Differential cross sections at $E_d = 50$ MeV were reported [90GO14].

67. $^{19}F(^{3}He,{}^{16}O)^{6}Li$, $Q_m = 4.0945$

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

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

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

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

Angular distributions measured for $E(^{6}Li) = 21$–32 MeV are reported in [99MA16].

70. (a) $^{208}Pb(^{6}Li,{}^{6}Li)^{208}Pb$
(b) $^{208}Pb(^{6}Li, \alpha d)^{208}Pb$, $Q_m = -1.4743$

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

For reaction (b), measurements of triple differential cross sections for elastic breakup of 156 MeV ^{6}Li were reported in [89HE28, 89HE17, 89RE1G]. Data were analyzed on the basis of a diffractive disintegration approach. Breakup measurements at $E(^{6}Li) = 60$ MeV were reported in [88HE16]. See also reaction 56, and see the theoretical study of angular correlation of breakup fragments in [89BA25].

^{6}Be

(Figs. 6 and 7)

General

References to articles on general properties of ^{6}Be published since the previous review [88AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the general tables for ^{6}Be located on our website at (*www.tunl.duke.edu/NuclData/General_Tables/6be.shtml*).

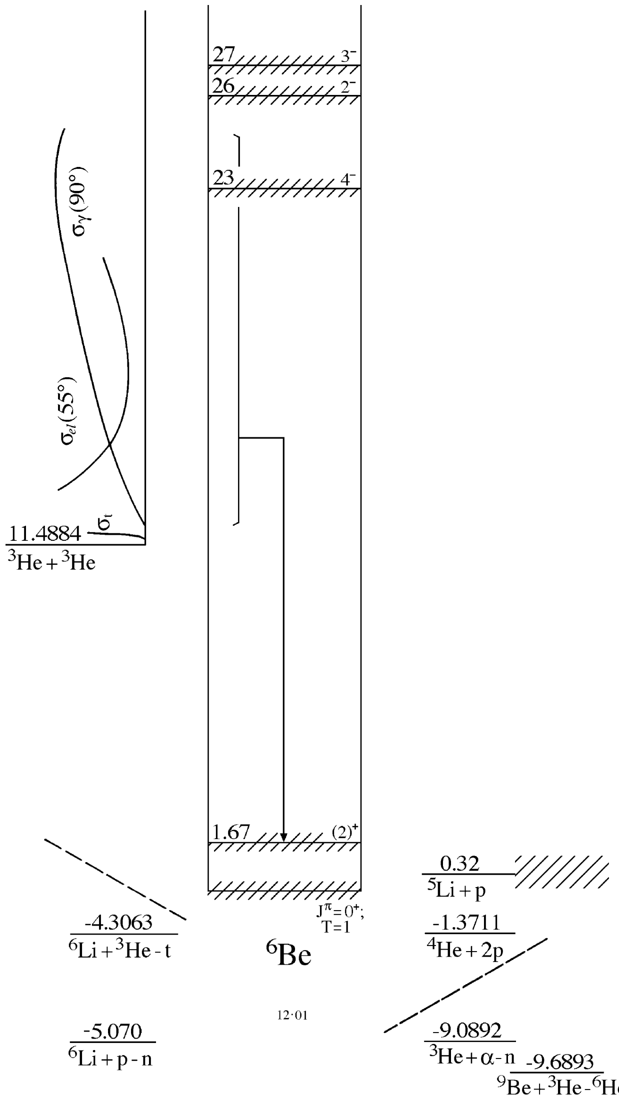

Fig. 6. Energy levels of ^{6}Be. For notation see Fig. 5.

1. (a) $^{3}\mathrm{He}(^{3}\mathrm{He},\gamma)^{6}\mathrm{Be}$, $Q_{\mathrm{m}} = 11.4884$
   (b) $^{3}\mathrm{He}(^{3}\mathrm{He},\mathrm{p})^{5}\mathrm{Li}$, $Q_{\mathrm{m}} = 11.17$, $E_{\mathrm{b}} = 11.49$
   (c) $^{3}\mathrm{He}(^{3}\mathrm{He},2\mathrm{p})^{4}\mathrm{He}$, $Q_{\mathrm{m}} = 12.8596$
   (d) $^{3}\mathrm{He}(^{3}\mathrm{He},{}^{3}\mathrm{He})^{3}\mathrm{He}$
   (e) $^{3}\mathrm{He}(^{3}\mathrm{He},\mathrm{pd})^{3}\mathrm{He}$, $Q_{\mathrm{m}} = -5.4935$

The yield of γ-rays to $^{6}\mathrm{Be}^{*}(1.7)$ (reaction (a)) increases smoothly from 0.4 to 9.3 μb (assuming isotropy) for $0.86 < E(^{3}\mathrm{He}) < 11.8$ MeV (90°). No transitions are observed

Table 6.14
Energy levels of ^{6}Be

E_x (MeV $\pm$ keV)	$J^\pi; T$	Γ_{cm}	Decay	Reactions
g.s.	$0^+; 1$	92 ± 6 keV	p, α	2, 3, 4
1.67 ± 50[a]	$(2)^+; 1$	1.16 ± 0.06 MeV	p, α	1, 2, 3, 4
23	4^-	broad	γ, ^{3}He	1, 3
26	2^-	broad	^{3}He	1, 3
27	3^-	broad	^{3}He	1

[a] See Table 6.8 in [74AJ01].

to ^{6}Be$_{g.s.}$ ($\sigma < 0.01$ μb at $E(^3\text{He}) = 1.4$ MeV). This is understood in terms of a direct capture of ^{3}He by ^{3}He in the singlet-spin state and with zero angular momentum: the $0^+ \to 0^+$ γ-transition is forbidden. Reaction (a) is thus of negligible astrophysical importance compared to reaction (c): see [79AJ01]. The capture cross section from $E(^3\text{He}) = 12$ MeV to 27 MeV continues to increase smoothly with energy at first and then shows a broad structure centered at $E(^3\text{He}) = 23 \pm 1$ MeV ($E_x = 23.0 \pm 0.5$ MeV), $\Gamma_{cm} \approx 5$ MeV. This appears to be a ^{33}F cluster resonance which decays by an E1 transition to ^{6}Be*(1.7). The γ-ray angular distributions are consistent with $J^\pi = 3^-$: see [79AJ01]. See also [89IS1B]. Thermonuclear reaction rates for this reaction calculated from evaluated data are presented in the compilation [99AN35].

A_y has been measured for $E(^3\text{He}) = 14$ to 30 MeV (reaction (b)) by [83KI10] using a polarized target. See also ^{5}Li.

Measurements of the total cross section for reaction (c) have been carried out for $E(^3\text{He}) = 60$ keV to 2.2 MeV (see [79AJ01]) and for 36 to 685 keV [87KR09]. The measurements are consistent with a nonresonant reaction mechanism, at least down to $E_{cm} = 24.5$ keV. Upper limits for $\omega\gamma$ for a resonance below that energy (and with E_R (cm) as low as 16.2 keV) (which might help explain the low observed flux of solar neutrinos), are given in [87KR09]. (It should be noted that a corresponding mirror state in ^{6}He has not been observed.) The best fit to the data is given by $S(0) = 5.57 \pm 0.31$ MeV b [87KR09]. See [79AJ01] for the earlier work. See also [66LA04, 74AJ01]. For work on astrophysical considerations see references cited in [88AJ01], and see also the following work: thermonuclear reaction rates calculated from evaluated data [88CA26, 99AN35]; dynamic screening [88CA1J]; neutrino astrophysics [89BA2P]; reaction rates [89SC25]; plasma fusion [88PO1J]; S-factors, RGM [89VA20]; cross sections, extended elastic model [90SC15]; cross sections, microscopic study [91TY01]; phase shifts, generator coordinate method [90KR12]; astrophysical S-factor, potential model [92WI09]; cross sections, microscopic analysis [94DE27]; S-factor, electron screening effects [89BE08]; and nucleosynthesis around black holes [89JI1A]. [85SI12] report α–d correlation measurements at $E(^3\text{He}) = 13.6$ MeV, which suggest the breakup of the diproton (^{2}He) into $^2\text{H} + e^+ + \nu$.

The elastic scattering (reaction (d)) has been studied for $E(^3\text{He}) = 3$ to 32 MeV and at 120 MeV. The excitation function shows a smooth monotonic behavior except for an anomaly at $E(^3\text{He}) = 25$ MeV in the $L = 3$ partial wave corresponding to a broad state in ^{6}Be at $E_x \approx 24$ MeV. Polarization measurements have been carried out at $E(^3\vec{\text{He}}) = 17.9$ to 32.9 MeV. A two-level R-matrix analysis of the phase shifts ($L \leqslant 5$) suggests three broad

F-wave states at $E_x \approx 23.4$ (4^-), 26.2 (2^-) and 26.7 MeV (3^-), in disagreement with the capture γ-ray results described above: see [79AJ01]. Calculations using the generator coordinate method have been reported for phase shifts ($E(^3\mathrm{He}) < 5$ MeV) [90KR12], and for differential cross sections and astrophysical S-factors ($E(^3\mathrm{He}) = 2$–6 MeV) [94DE27]. See also [84AJ01] and [86FO04].

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

The total reaction cross sections $\sigma_R = 156.7 \pm 3.8$, 250 ± 14 and 296 ± 12 mb at $E(^3\mathrm{He}) = 17.9$, 21.7 and 24.0 MeV [87BR02] (see also for partial cross sections for the breakup reactions and for unpublished results for σ_R for $E(^3\mathrm{He}) = 3.0$ to 17.9 MeV). See also [84AJ01] and references cited in [88AJ01].

2. $^4\mathrm{He}(^3\mathrm{He}, \mathrm{n})^6\mathrm{Be}$, $Q_m = -9.0892$

Neutron groups to $^6\mathrm{Be}^*(0, 1.7)$ have been observed at $E(^3\mathrm{He}) = 19.4$ to 38.61 MeV: see Table 6.8 in [74AJ01] for the parameters of the first excited state. There is no evidence for other states of ^{6}Be with $E_x \leqslant 5$ MeV, nor for a state near the ^{3}He threshold at 11.5 MeV: see [79AJ01].

3. (a) $^6\mathrm{Li}(\mathrm{p}, \mathrm{n})^6\mathrm{Be}$, $Q_m = -5.070$
(b) $^6\mathrm{Li}(\mathrm{p}, \mathrm{pn})^5\mathrm{Li}$, $Q_m = -5.39$

Neutron groups have been observed to $^6\mathrm{Be}^*(0, 1.7)$ as has the ground-state threshold. The width of the ground state is 95 ± 28 keV. The parameters of $^6\mathrm{Be}^*(1.7)$ are displayed in Table 6.8 of [74AJ01]. Angular distributions have been reported at $E_p = 8.3$ to 144 MeV (see [79AJ01, 84AJ01]) and at 800 MeV [86KI12]. The transverse spin transfer coefficient, D_{NN} (0°), at $E_p = 160$ MeV for the ground-state transition is -0.37 ± 0.04 in agreement with results in other light nuclei [84TA07]. See also ^{7}Be and references cited in [88AJ01].

In more recent work, evidence for a proportionality between $\sigma_{pn}(0°)$ and Gamow–Teller transition strengths were examined [87TA13]. See also [89RA1G]. Measurements are reported at: $E_p = 60$–200 MeV ($\mathrm{D_{NN}}(0°)$ [90RA08]); $E_p = 256$, 800 MeV (double differential cross sections [93ST06]); $E_p = 186$ MeV (polarization observables [93WAZX, 93YAZZ, 94RA23], quasifree excitations [94WA22, 99WAZV], dipole excitations [95YA12]); $E_p = 392$ MeV ($\sigma(\theta)$, $A_y(\theta)$ [94TO08]); $E_p = 300$, 400 MeV (quasifree excitations, D_{NN} (0°) [94SA43]); $E_p = 295$ MeV (spin-flip strength, D_{NN} (0°) [95WA16]); $E_p = 200$ MeV ($A_y(\theta)$ [95WAZW]); $E_p = 35$ MeV ($\sigma(\theta)$ [96ORZZ, 98OR1B]); and $E_p = 280$ MeV ($\sigma(\theta)$, isospin-symmetry test [90MI10]). For recent applications, see [98HA24, 98WA12]. Calculations with a dynamical multicluster model are discussed in [91DA08, 93SH1G]. See also the review of two-particle neutron halo nuclei in [96DA31].

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

4. $^{6}\mathrm{Li}(^{3}\mathrm{He}, t)^{6}\mathrm{Be}$, $Q_{\mathrm{m}} = -4.3063$

Triton groups have been observed to $^{6}\mathrm{Be}^{*}(0, 1.7)$. The width of the ground state is 89 ± 6 keV. The parameters of the excited state are displayed in Table 6.8 of [74AJ01]. No other excited states have been seen with $E_{\mathrm{x}} < 13$ MeV. There is no evidence for a state near 11.5 MeV: see [79AJ01]. [87BO39] have studied the decay of $^{6}\mathrm{Be}^{*}(1.7)$ at $E(^{3}\mathrm{He}) = 38.7$ MeV: they report that the branching ratio for decay via the emission of $^{2}\mathrm{He}$ ($T = 1$, $S = 0$) is 0.60 ± 0.15: see also reactions 21 in ^{6}He and 38 in ^{6}Li and [84BO49, 85BO56, 88BO1J]. See also [84AJ01, 87DA31] (theory) and ^{9}B.

In more recent work, kinematically complete experiments for $^{6}\mathrm{Li}(^{3}\mathrm{He}, t)^{6}\mathrm{Be}^{*}(0, 1.7) \rightarrow \alpha + p + p$ were reported in [88BO38, 89BO1N, 89BO25, 89BO42] and in [92BO25, 93BO38] (studied decay mechanism). Measurements of differential cross sections at $E(^{3}\mathrm{He}) = 93$ MeV are described in [94DOZW].

^{6}B, ^{6}C

(not illustrated)

Not observed: see [79AJ01, 84AJ01, 89GR06] for ($^{6}\mathrm{Li}(\pi^{+}, \pi^{-})$ at $E_{\pi^{+}} = 180$, 240 MeV, [93PO11] (properties of exotic light nuclei) and [98SU18].

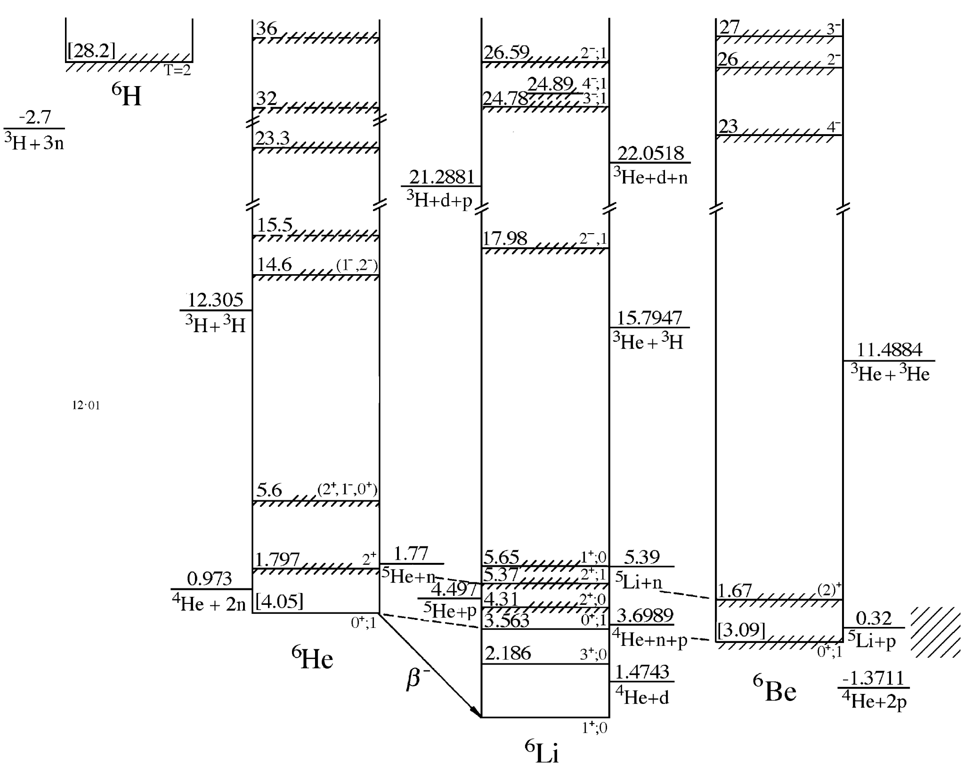

Fig. 7. Isobar diagram, $A = 6$. For notation see Fig. 3.

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

^{6}He		^{6}Li		ΔE_x[b] (MeV)	^{6}Be		ΔE_x[c] (MeV)
E_x (MeV)	J^π	E_x (MeV)	J^π; T		E_x (MeV)	J^π	
0	0^+	3.56	0^+; 1		0	0^+	
1.80	2^+	5.37	2^+; 1	+0.01	1.67	(2^+)	−0.13
5.6	$(2^+, 1^-, 0^+)$						
14.6	$(1^-, 2^-)$	17.99	2^-; 1	−0.17	26	2^-	11.4
		24.78	3^-; 1		27	3^-	
		24.89	4^-; 1		23	4^-	
		26.59	2^-; 1				

[a] As taken from Tables 6.1, 6.4 and 6.14.
[b] Defined as $E_x(^{7}\mathrm{Li}) - E_x(^{6}\mathrm{He}) - 3.56$ MeV.
[c] Defined as $E_x(^{6}\mathrm{Be}) - E_x(^{6}\mathrm{He})$.

A = 7

General

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

^{7}H
(not illustrated)

^{7}H has not been observed. Attempts have been made to detect it in the spontaneous fission of ^{252}Cf [82AL33] and in the $^{7}\mathrm{Li}(\pi^-, \pi^+)$ reaction (see [84AJ01]). A study of $^{9}\mathrm{Be}(\pi^-, 2\mathrm{p})$ [87GO25] found no evidence for ^{7}H. See also the review of [89OG1B] and the $^{7}\mathrm{Li}(\pi^-, \pi^+)$ investigation reported in [89GR06]. The ground state is calculated to have $J^\pi = 1/2^+$ and to be unstable with respect to 1n, 2n, 3n and 4n emission. Excited states are predicted at 4.84, 5.00 and 6.96 MeV, with $J^\pi = 3/2^+$, $5/2^+$, and $5/2^-$ ($(0+1)\,\hbar\omega$ model space) and at 3.88, 3.94 and 5.99 MeV with $J^\pi = 3/2^+$, $5/2^+$ and $1/2^+$ ($(0+2)\,\hbar\omega$ model space) [85PO10]. See also references cited in [88AJ01].

^{7}He
(Figs. 8 and 11)

General

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

Mass of ^{7}He. The atomic mass excess of ^{7}He is 26.11 ± 0.03 MeV: ^{7}He is then unbound with respect to decay into $^{6}\mathrm{He} + \mathrm{n}$ by 0.44 MeV: see [84AJ01]. The ground state is

Table 7.1
Energy levels of ^{7}He

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

[a] Newly adopted in this evaluation or revised from the previous evaluation [88AJ01].

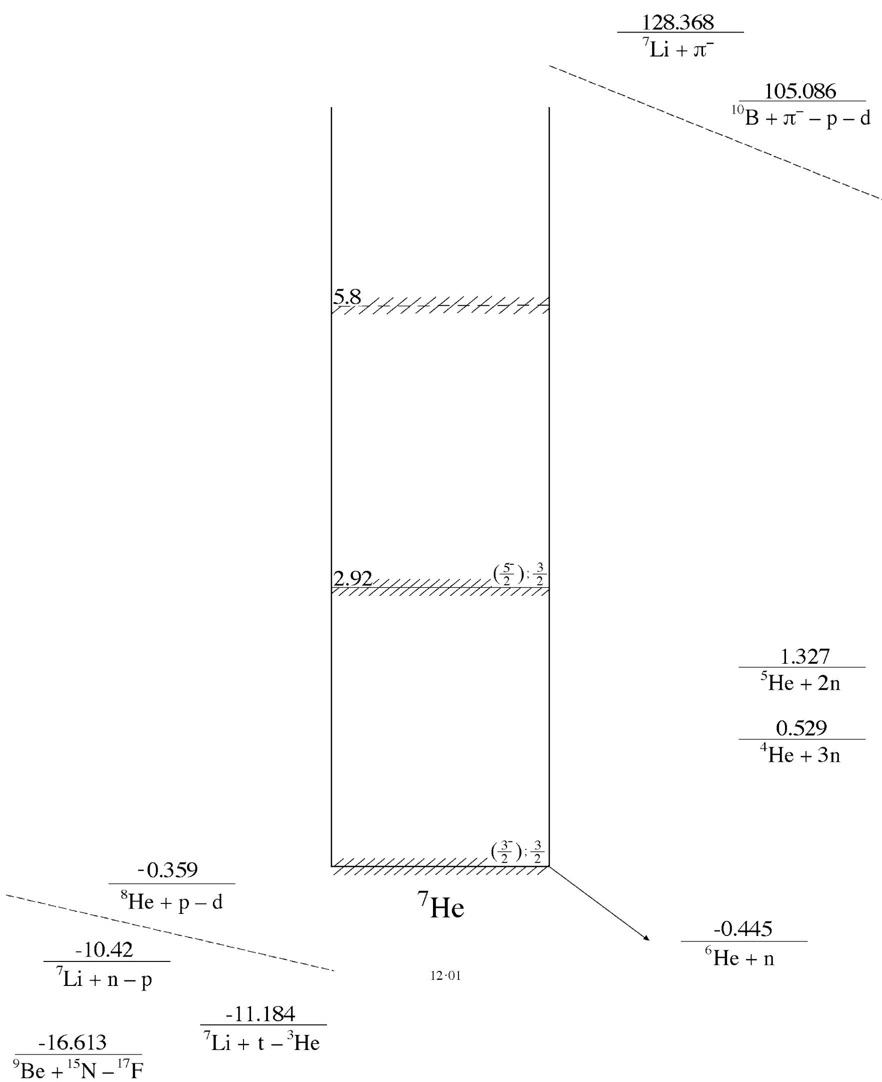

Fig. 8. Energy levels of ^{7}He. For notation see Fig. 5.

calculated to have $J^\pi = 3/2^-$ and to be unstable with respect to decay into ^{6}He + n by about 1 MeV [85PO10]. See [88AJ01].

^{7}He excited-state calculations. In addition to the $(0+1)\,\hbar\omega$ and $(0+2)\,\hbar\omega$ model-space calculation of [85PO10] cited in [88AJ01], a number of calculations have been reported since the previous evaluation. They include calculations: in a $(0+2)\,\hbar\omega$ model space [90WO10]; in a two-frequency shell model [01CO21]; in a large-basis shell model [98NA17]; with Green's function Monte-Carlo methods [97PU03, 00WI09, 01PI07]; and in a refined resonating-group model [97WU01].

1. ^{1}H(^{8}He, d)^{7}He, $Q_m = -0.36$

This reaction was studied at $E(^8\mathrm{He}) = 50$ MeV$/A$ [99KO14, 00KO46]. Deuterons, neutrons, ^{4}He and ^{6}He were detected. Spectra indicate a level in ^{7}He at $E_x = 2.9 \pm 0.3$ MeV, $\Gamma = 2.2 \pm 0.3$ MeV which decays mainly into 3n + ^{4}He, $\Gamma_{\alpha+3n}/\Gamma_{tot} = 0.7 \pm 0.2$. Arguments are given for a tentative assignment $J^\pi = (5/2^-)$.

2. ^{7}Li(π^-, γ)^{7}He, $Q_m = 128.37$

Capture γ-rays from the transition to ^{7}He$_{g.s.}$ are reported by [86PE05].

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

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

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

The ^{3}He particles leading to the ground state of ^{7}He have been observed at $E_t = 22$ MeV. The width of the ground state given in [88AJ01] is 160 ± 30 keV; for a radius of 2.2 fm and $l_n = 1$, this width is 0.22 of the Wigner limit. The angular distribution is peaked in the forward direction. No other states of ^{7}He were observed for $E_x < 2.4$ MeV: see [79AJ01].

5. (a) ^{6}Li(^{14}C, ^{13}N)^{7}He, $Q_m = -14.36$
(b) ^{7}Li(^{7}Li, ^{7}Be)^{7}He, $Q_m = -12.06$
(c) ^{7}Li(^{11}B, ^{11}C)^{7}He, $Q_m = -13.19$
(d) ^{9}Be(^{6}Li, ^{8}B)^{7}He, $Q_m = -23.60$
(e) ^{9}Be(^{9}Be, ^{11}C)^{7}He, $Q_m = -14.07$
(f) ^{9}Be(^{11}B, ^{13}N)^{7}He, $Q_m = -11.44$
(g) ^{9}Be(^{14}C, ^{16}O)^{7}He, $Q_m = -7.01$
(h) ^{9}Be(^{15}N, ^{17}F)^{7}He, $Q_m = -16.61$

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

A more recent experiment with incident energies $E_{\mathrm{lab}} = 240$ MeV and 318.5 MeV is described in [01BO35]. The width of the ^{7}He ground-state resonance was measured to be 0.14 ± 0.02 MeV. An excited state with $E_x = 2.95 \pm 0.10$ MeV, corresponding to a resonance energy $E_R = 3.39 \pm 0.10$ and width $\Gamma_R = 1.9 \pm 0.2$ MeV, was observed. There was no indication of a state at $E_x = 0.8$ MeV reported by [01MA05] (see reaction 7). Evidence for a broad excited state at $E_x = 5.8 \pm 0.3$ MeV with $\Gamma = 4 \pm 1$ MeV was also obtained.

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

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

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

The relative energy spectra of fragments from 227 MeV$/A$ ^{8}He on a carbon target were measured [01MA05]. The $^{6}\mathrm{He} + \mathrm{n}$ spectra show a structure which is interpreted as being due to a $J^{\pi} = 3/2^{-}$ resonance (the ^{7}He ground state) with $E_R = 0.44$ MeV, $\Gamma = 0.16$ MeV with about equal contribution from a $J^{\pi} = 1/2^{-}$ resonance with $E_R = 1.2 \pm 0.2$ MeV, $\Gamma = 1.0 \pm 0.2$ MeV ($E_x = 0.8 \pm 0.2$ MeV).

^{7}Li

(Figs. 9 and 11)

General

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

$\mu = +3.256427(2)$ nm: see [89RA17].

$Q = -40.6 \pm 0.8$ mb [88DI1B]. See [88DI1B] for a review of earlier determinations, particularly those of [84SU09, 84VE03, 84VE08, 85WE08]. See also [89RA17].

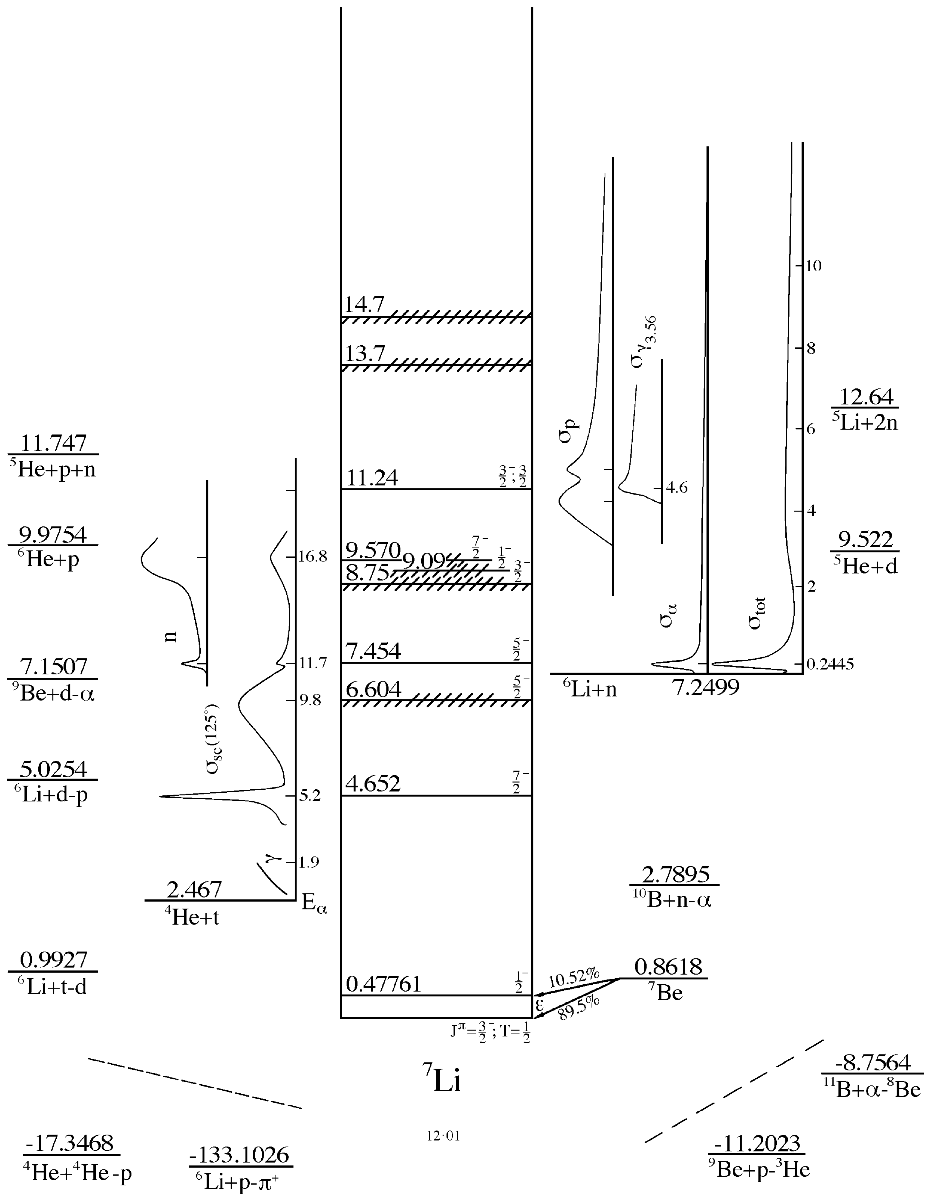

Fig. 9. Energy levels of ^{7}Li. For notation see Fig. 5.

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

Isotopic abundance. $92.5 \pm 0.2\%$ [84DE1A]. See also [87LA1J, 88LA1C].

Table 7.2
Energy levels of ^{7}Li

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

[a] See Table 7.2 in [79AJ01], Table 7.5 here and reaction 40.
[b] Newly adopted in this evaluation. These level parameters were obtained with the extended R-matrix prescription (see the introduction) from an analysis of ^{6}Li(n, n), ^{6}Li(n, t), ^{4}He(t, n), and ^{4}He(t, t) data, and are somewhat different from the corresponding parameters of [88AJ01]. The uncertainties in the widths and positions of the second through fourth excited states above the ground state are less than 5%. Uncertainties for the higher-lying states range from 10–30%.
[c] See also reactions 8, 10, 15, 22 and 38 for possible additional states.

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

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

Gamma spectra were measured for 40 MeV/A ^{6}He incident on a solid hydrogen target [01SA37]. The ^{7}Li ground state and the 0.48 MeV first excited states were not resolved. Measurements of momentum spectra of fragments as well as gamma-ray intensity distributions are described in [01SA37]. See also [01SAZS].

2. ^{3}H(α, γ)^{7}Li, $Q_m = 2.4670$

Excitation functions and angular distributions have been studied for $E_\alpha = 0.5$ to 2.0 MeV. The cross section rises smoothly as expected for a direct capture process: see [66LA04] and [87BU18] (γ_0, γ_1). Measurements of the astrophysical S-factor, $S(E)$, and the branching ratio R for direct capture to the 478 keV state compared to direct capture to the ground state were reported in [87SC18]. They deduce $S(0) = 0.14 \pm 0.02$ keV b, $R = 0.32 \pm 0.01$. More recently, available data on ^{3}H $+ \alpha$ scattering were analyzed [93MO11] in the optical-model framework to predict $S(0) = 0.10$ keV b and branching ratio $R = 0.43$. Measurements of the cross sections and angular distributions in the energy range $50 \leqslant E \leqslant 1200$ keV were reported in [94BR25]. They determined $R \approx 0.45$ at low energies in disagreement with [87SC18]. An extended two-cluster model study for $E_{\text{c.m.}} < 5$ MeV is described in [00CS06]. Effects of inclusion of the ^{6}Li + n channel on the zero-energy cross section and astrophysical S-factor as well as the quadrupole moment are explored. A recent analysis in [99BU10] estimated the uncertainties in Big Bang nucleosynthesis ^{7}Li yields. For astrophysical calculations related to ^{3}H(α, γ) see the general table for ^{7}Li located on our website at (*www.tunl.duke.edu/NuclData/General_Tables/7li.shtml*). See also references cited in [88AJ01].

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

3. ^{3}H$(\alpha, \text{n})^6$Li, $Q_\text{m} = -4.7829$, $E_\text{b} = 2.4670$

The cross section for this reaction has been measured for $E_\alpha = 11$ to 18 MeV: the data show the effect of ^{7}Li*(7.46) and indicate a broad resonance near $E_\alpha = 16.8$ MeV (^{7}Li*(9.6)). The level parameters derived from this reaction and from reaction 4 are displayed in Table 7.3. The yield of ^{6}Li ions at 0° (lab) has also been measured for $E_\alpha = 11.310$ to 11.930 MeV with 2–3% accuracy: the data were then reduced to obtain the cm differential cross sections at 0° and 180° for the inverse reaction in the energy region corresponding to formation of ^{7}Li*(7.46): see [79AJ01]. See also the compilation of [85CA41]. A resonating-group calculation of $\sigma(E)$ from threshold to 20 MeV is reported in [91FU02].

4. ^{3}H$(\alpha, \alpha)^3$H, $E_\text{b} = 2.4670$

The excitation curves for the elastic scattering show the effects of ^{7}Li*(4.63, 6.68, 7.46, 9.67). The derived level parameters are displayed in Table 7.3. Angular distributions have

Table 7.3
^{7}Li levels from ^{3}H + ^{4}He[a]

E_x (MeV ± keV)	J^π	l_α	LS term	R (fm)	θ^2_α [b]	$\theta^2_{\text{n}_0}$ [c]
4.65 ± 20	$\frac{7}{2}^-$	3	$^2\text{F}_{7/2}$	4.0	0.57 ± 0.04	
6.64 ± 100	$\frac{5}{2}^-$	3	$^2\text{F}_{5/2}$	4.0	1.36 ± 0.13	0.000 ± 0.002
6.79 ± 90	$\frac{5}{2}^-$	3	$^2\text{F}_{5/2}$	4.4	0.52	
7.47 ± 30	$\frac{5}{2}^-$	3	$^4\text{P}_{5/2}$	4.0	0.011 ± 0.001	0.26 ± 0.02
9.67 ± 100	$\frac{7}{2}^-$	3	$^4\text{D}_{7/2}$	4.0	0.53 ± 0.22	2.3 ± 0.7[d]

[a] For references see Table 7.3 in [79AJ01].
[b] $\gamma^2_\lambda 2\mu R^2/3\hbar^2$.
[c] See reaction 3: ^{3}H$(\alpha, \text{n})^6$Li.
[d] $\theta^2_{\text{n}_1}$ to ^{6}Li*(2.19).

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

For muon catalysis see references cited in [88AJ01].

5. ^{4}He(^{3}He, π^+)^{7}Li, $Q_m = -137.1217$

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

6. ^{4}He(α, p)^{7}Li, $Q_m = -17.3469$

Angular distributions have been reported at $E_\alpha = 39.9$ to 140 MeV (see [79AJ01, 84AJ01]) and at 61.5 to 158.2 MeV [82GL01] and 198.4 MeV [85WO11] for the transitions to ^{7}Li*(0, 0.48). Cross sections for $E_\alpha = 159.3$, 279.6 and 619.8 MeV were measured by [01ME13] to enable calculation of the amount of ^{7}Li produced in early-galaxy cosmic rays. See also [01AU06]. See [82GL01, 85WO11] for a discussion of ^{7}Li production in the Big Bang. See also ^{8}Be and [86KA26].

7. ^{6}Li(n, γ)^{7}Li, $Q_m = 7.2499$
$Q_0 = 7251.02 \pm 0.09$ keV [85KO47]

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

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

8. ^{6}Li(n, n)^{6}Li, $E_b = 7.2499$

The real coherent scattering length is 2.0 ± 0.1 fm; the complex scattering lengths are $b_+ = (0.67 \pm 0.14) - i(0.08 \pm 0.01)$ fm, $b_- = (4.67 \pm 0.17) - i(0.62 \pm 0.02)$ fm; $\sigma_{\text{free}} = 0.70 \pm 0.01$ b [83KO17]. See also [79GL12]. [83AL1E] report σ_s (below 10 keV) $= 0.72 \pm 0.02$ b. See also [81MUZQ]. The total cross section has been measured from

Table 7.4
Resonance parameters for 7.5–7.2 MeV levels in ^{7}Li and ^{7}Be[a]

Reaction	^{6}Li + n	^{6}Li + p
E_r (keV, lab)	262[b]	1840[c]
$\Gamma(E_r)$ (keV, cm)	154	836
E_λ (keV above g.s.)	7700	7580
$\Gamma_{n,p}(E_r)$ (keV, cm)	118	798
radius (n, p) in fm	3.94	4.08
$\gamma^2_{n,p}$ (MeV fm)[d]	4.85	5.02
$\theta^2_{n,p}$	0.26	0.28
$\Gamma_\alpha(E_r)$ (keV, cm)	36	38
radius (α) in fm	4.39	4.39
γ^2_α (MeV fm)[d]	0.101	0.101
θ^2_α	0.012	0.012

[a] These states are believed to have a ^{4}P$_{5/2}$ character, consistent with their large θ^2_n and θ^2_p. See Table 7.4 in [79AJ01]. These parameters are from Table I of [63MC09]. See also [59GA08].

[b] 244.5 ± 1.0 keV [82SM02].

[c] See also the measurements and analysis of [95SK01].

[d] The authors of [59GA08, 63MC09] use a definition of $\gamma^2_{n,p}$ and γ^2_α for which the units are MeV fm.

$E_n = 4$ eV to 49.6 MeV (see [76GAYV, 84AJ01]), at 0.6 to 80 keV [82AL35] and at 0.08 to 3.0 MeV [83KN1D].

A pronounced resonance occurs at $E_n = 244.5 \pm 1.0$ keV ($E_x = 7459.5 \pm 1.0$ keV) with a peak cross section of 11.2 ± 0.2 b [82SM02]: see Table 7.4. No other clearly defined resonance is observed to $E_n = 49.6$ MeV although the total cross section exhibits a broad maximum at $E_n \approx 4.5$ MeV: see [84AJ01]. The analyzing power has been measured for $E_n = 1.48$ to 5 MeV (see [84AJ01]) and 5 to 17 MeV [86PF1A]. Multilevel, multichannel R-matrix analyses [87KN04, 83KN06] for $E_n \leqslant 8$ MeV (using also data from other channels) include 13 normal and 14 nonnormal-parity states with $E_x \leqslant 17$ MeV. (Only ten states have been seen directly in reaction or compound nucleus cross-section work.) Two positive-parity states provide an explanation for the anisotropy of the ^{6}Li(n, α) work at low energies [83KN06]. For the results of an earlier R-matrix analysis see [84AJ01].

The excitation function for 3.56 MeV γ-rays exhibits an anomaly, also seen in the (n, p) reaction (reaction 9). The data are well fitted assuming $E_{res} = 3.50$ and 4.60 MeV ($E_x = 10.25 \pm 0.10$ and 11.19 ± 0.05 MeV), $T = 1/2$ and 3/2, $\Gamma_{cm} = 1.40 \pm 0.10$ and 0.27 ± 0.05 MeV, respectively; both $J^\pi = 3/2^-$. However, [79AJ01] notes that an R-matrix study of ^{4}He(t, t), ^{6}Li(n, n), and ^{6}Li(n, α) data leads to the identification of a $3/2^-$ state at $E_x = 9.85$ MeV, $\Gamma = 1.2$ MeV. See [79AJ01] for a discussion of these and other unpublished data.

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

See also earlier references cited in [88AJ01].

9. (a) ^{6}Li(n, 2n)^{5}Li, $Q_m = -5.39$, $E_b = 7.25$
(b) ^{6}Li(n, p)^{6}He, $Q_m = -2.7254$
(c) ^{6}Li(n, d)^{5}He, $Q_m = -2.272$

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

10. ^{6}Li(n, α)^{3}H, $Q_m = 4.7829$, $E_b = 7.2499$

The thermal cross section is 940 ± 4 b: see [81MUZQ]. See also [85SW01]. A resonance occurs at $E_n = 241 \pm 3$ keV with $\sigma_{max} = 3.3$ b: see [84AJ01, 86CA28]. The resonance is formed by p-waves, $J^{\pi} = 5/2^{-}$, and has a large neutron width and a small α-width: see Table 7.4. Above the resonance the cross section decreases monotonically to $E_n = 18.2$ MeV, except for a small bump near $E_n \approx 1.8$ MeV and an inflection near $E_n = 3.5$ MeV. For a description of R-matrix analyses which suggest the location of higher states of ^{7}Li, see reaction 8 and [84AJ01], as well as [87KN04].

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

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

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

See also the references cited in [88AJ01].

11. ^{6}Li(p, π^{+})^{7}Li, $Q_{\rm m} = -133.1026$

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

12. ^{6}Li(d, p)^{7}Li, $Q_{\rm m} = 5.0254$

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

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

13. ^{6}Li(^{6}Li, ^{5}Li)^{7}Li, $Q_{\rm m} = 1.86$

See [87MI34] and ^{5}Li.

14. ^{6}Li(^{7}Li, ^{7}Be)^{6}He, $Q_{\rm m} = -4.3696$

The reaction was studied by [99NA36] for $E(^{7}\mathrm{Li}) = 65$ MeV/A to compare the Gamow–Teller transition strengths to those deduced from β decay.

15. (a) ^{7}Li(γ, n)^{6}Li, $Q_{\mathrm{m}} = -7.2499$
(b) ^{7}Li(γ, 2n)^{5}Li, $Q_{\mathrm{m}} = -12.64$
(c) ^{7}Li(γ, p)^{6}He, $Q_{\mathrm{m}} = -9.9753$
(d) ^{7}Li(γ, pn)^{5}He, $Q_{\mathrm{m}} = -11.747$
(e) ^{7}Li(γ, d)^{5}He, $Q_{\mathrm{m}} = -9.522$
(f) ^{7}Li(γ, t)^{4}He, $Q_{\mathrm{m}} = -2.4670$

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

The total absorption cross section for $^{\mathrm{nat}}$Li in the range 10 to 340 MeV shows a broad peak at ≈ 30 MeV ($\sigma_{\max} \approx 3$ mb), a minimum centered at ≈ 150 MeV at ≈ 0.3 mb and a fairly smooth increase in cross section to ≈ 3 mb at ≈ 320 MeV: see [84AJ01].

The cross section for the (γ, p) reaction (reaction (c)) shows a maximum at ≈ 15.6 MeV with a width of ≈ 4 MeV. It then decreases fairly smoothly to 27 MeV. The integrated cross section for $11 \to 28$ MeV is 13.2 ± 2.0 MeV mb: see [74AJ01, 79AJ01, 84AJ01]. Differential cross sections for the (γ, $\mathrm{n}_0 + \mathrm{n}_2$) and ($\gamma$, p_0) processes are reported in [83SE07, 85SE17], $E_{\gamma} = 48$ to 141 MeV. Photodisintegration cross sections in the giant resonant range were analyzed in [87VA05]. Analyses of photodisintegration data for reactions (a)–(d) at $E_{\gamma} < 50$ MeV [90VA16] were used to deduce the role of cluster configuration. Reaction (e) has been studied in the giant resonance region with bremsstrahlung photons, $E_{\mathrm{brem}} \leqslant 30$ MeV. Deuteron groups to $^{5}\mathrm{He}_{\mathrm{g.s.}}$ and possibly to the first excited state are reported. States of ^{7}Li with $E_{\mathrm{x}} = 25$–30 MeV may be involved when $E_{\mathrm{brem}} = 37$ to 50 MeV is used: see [79AJ01]. At $E_{\gamma} = 0.9$ GeV, [85RE1A] have studied π^{-} emission with the population of ^{6}Li*(2.19).

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

16. ^{7}Li(γ,γ)^{7}Li

See Table 7.4 in [66LA04] (summary of early measurements) for τ_m of ^{7}Li*(0.48) $= 107 \pm 5$ fs. See also [84AJ01, 87BE1K, 86DU03].

17. (a) ^{7}Li(e, e)^{7}Li
(b) ^{7}Li(e, e$'\pi^+$)X
(c) ^{7}Li(e, ep)^{6}He, $Q_m = -9.9754$
(d) ^{7}Li(e, en)^{6}Li, $Q_m = -7.2499$

The electric form factor measurements for $E_e = 100$ to 600 MeV are well accounted for by a simple harmonic-oscillator shell model with a quadrupole contribution described by an undeformed p-shell: $r_{\text{r.m.s.}} = 2.39 \pm 0.03$ fm, $|Q| = 42 \pm 2.5$ mb. From results obtained for $E_e = 24.14$ to 97.19 MeV, $r_{\text{r.m.s.}} = 2.35 \pm 0.10$ fm (model independent), 2.29 ± 0.04 fm (shell model). A study of the ratio of the electric-charge scattering from ^{6}Li and from ^{7}Li as a function of (momentum transfer)^2 yields $\langle r^2\rangle_6^{1/2}/\langle r^2\rangle_7^{1/2} = 1.001 \pm 0.008$. The r.m.s. radius of the ground-state magnetization density distribution, $\langle r^2\rangle_M^{1/2} = 2.98 \pm 0.05$ fm. See [79AJ01] for references. More recent theoretical studies include: a study by [91BE40] which obtained vertex constants from an analysis of form factors; a shell-model calculation of large-basis space and mesonic effects [92BO30]; a calculation of form factors including meson-exchange contributions [92WA37]; and a study of shell-model structures of low-lying states [97KA24].

Inelastic scattering studies show peaks corresponding to ^{7}Li*(0.48, 4.63, 6.68, 7.46): see [74AJ01] and Table 7.5. Form factors for ^{7}Li*(0, 0.48) have recently been studied at $E_e = 80$ to 680 MeV [89LI09, 90LI21]. Theoretical work includes: a calculation by [89TA31] of cross section and reduced transition matrix elements for oriented nuclei; a calculation for polarized electron and polarized targets [90LE14]; a shell-model calculation in a $(0+2)\,\hbar\omega$ space [90WO10]; a study of spin modes [91AR22]; a microscopic cluster calculation

Table 7.5
Levels of ^{7}Li from ^{7}Li(e, e$'$)[a]

E_x (MeV)	$J^\pi; T$	Γ_{γ_0} (eV)	Type
0.48	$\frac{1}{2}^-; \frac{1}{2}$	$(2.8 \pm 1.6) \times 10^{-7}$	C2
		$(6.30 \pm 0.31) \times 10^{-3}$	M1
4.63 ± 0.05[b]	$\frac{7}{2}^-; \frac{1}{2}$		C2[c]
6.6 ± 0.1[d]	$\frac{5}{2}^-; \frac{1}{2}$		C2
7.5 ± 0.08	$\frac{5}{2}^-; \frac{1}{2}$	0.6 ± 0.3	C2
		0.9 ± 0.4[e]	

[a] For a summary of B(E2↑) measurements, see Table 7.6 in [66LA04] and the general tables for ^{7}Li located on our website at (*www.tunl.duke.edu/NuclData/General_Tables/7he.shtml*). For references see [79AJ01, 84AJ01].

[b] B(E2↑) $[3/2^- \to 7/2^-] = 17.5\ e^2\,\text{fm}^4$.

[c] Purely longitudinal.

[d] $\Gamma_{\text{cm}} = 875^{+200}_{-100}$ keV.

[e] From ^{7}Li(γ, n). See also fit by [80BA34].

[91UN01]; calculation of form factors including meson-exchange contribution [92BO30, 92WA37]; and a shell-model study of low-lying states [97KA24]. For reaction (b), energy and angular distributions were measured at $E_e = 203$ MeV [99SH25] to study spin–isospin flip giant resonances.

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

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

^{7}Li*(0, 0.48, 4.63, 6.68, 7.46, 9.67) have been populated in this reaction. Angular distributions have been measured at $E_{\pi^+} = 49.7$ MeV and $E_{\pi^\pm} = 143$ and 164.4 MeV: see [84AJ01]. Total and partial cross sections have been obtained for $E_{\pi^\pm}$ in the range $85 \to 315$ MeV (see [84AJ01]) and at $E_{\pi^+} = 50$ MeV [83NA18]. A measurement of inclusive analyzing power at $E_\pi = 134$, 164, 194 MeV was reported by [94ME01]. A cluster-model calculation of quadrupole effects is described in [94NO06]. Calculations of pion scattering for $E_\pi = 100$–240 MeV are described in [01LE01]. Nuclear transition densities predicted by quantum Monte-Carlo calculations were used. The $^7\mathrm{Li}(\pi^-,\pi^-\mathrm{p})$ reaction was studied at 0.7 GeV/c in [00AB25]. For $^7\mathrm{Li}(\pi^+,\pi^-\mathrm{p})$, see [98PA31]. For the $(\pi^+, 2\mathrm{p})$ reaction see ^{5}He [86RI01]. For studies of (π^+, pd) and $(\pi^\pm, \mathrm{pn})$ see [86WH01] and [86YO06], respectively. For π^+ induced fission of ^{7}Li see [83BA26]. See also references in the general table for ^{7}Li located on our website at (*www.tunl.duke.edu/NuclData/General_Tables/7li.shtml*).

19. (a) $^7\mathrm{Li}(\mathrm{n},\mathrm{n})^7\mathrm{Li}$
(b) $^7\mathrm{Li}(\mathrm{n},\mathrm{nt})^4\mathrm{He}$, $Q_m = -2.4673$

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

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

Angular distributions of protons have been measured for $E_{\mathrm{p}} = 1.0$ to 185 MeV (see [74AJ01, 84AJ01]) and at $E_{\mathrm{p}} = 1.89$ to 2.59 MeV ([86SA1P]; p_0). Inelastic proton groups have been observed to $^{7}\mathrm{Li}^{*}(0.48, 4.63, 6.68, 7.46, 9.6)$: see [52AJ38, 74AJ01]. Double differential cross sections for the continuum are reported at $E_{\mathrm{p}} = 65$ MeV and 85 MeV [87TO06, 89TO04]. Measurements of differential cross sections and analyzing powers for $\mathrm{p}_0, \mathrm{p}_1$ and p_2 for $E_{\mathrm{p}} = 200$ MeV were used to deduce radial transition density differences [91GL01]. Cross sections for inelastic scattering to the ^{7}Li $E_{\mathrm{x}} = 0.478$ MeV level have been measured in application-related experiments for $E_{\mathrm{p}} = 2.2$–3.8 MeV [88BO37], 3.2–3.6 MeV [90BO15], 2.5–3.5 MeV [94MI21], 1.03 MeV [94WI15], 0.7–3.2 MeV [95RI14]. See also [99SA16].

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

See also ^{8}Be, and references to earlier work cited in [88AJ01]. For early theoretical work on these reactions, see references cited in [88AJ01]. More recent calculations include: threshold effects in elastic scattering for $E_{\mathrm{p}} = 1.35$–3 MeV [90GU22]; differential cross section calculated at high energies with a geometric model [90HU09]; a potential description of $^{7}\mathrm{Li(p,p)}$ with $E_{\mathrm{p}} < 7$ MeV [92DU07]; calculation with a microscopic effective interaction [93KO44]; a folding model description for $E_{\mathrm{p}} = 25$–50 MeV [93PE13]; a microscopic three-cluster model calculation for $E_{\mathrm{cm}} = 0.5$–25 MeV, $\sigma(E)$, S-factors [94DE09]; a fully microscopic analysis for $E_{\mathrm{p}} = 200$ MeV [97DO01]; an analysis of $E_{\mathrm{p}} = 200$ MeV data studying shell-model structures of low-lying ^{7}Li levels [97KA24]; a microscopic analysis of elastic scattering at $E_{\mathrm{p}} = 25$, 30 and 40 MeV [00DE61], $E_{\mathrm{p}} = 65$ MeV [98DO16], and at 60–70 MeV [98FUZP]; a resonance optical-model calculation for $E_{\mathrm{p}} = 1$–10 MeV [00LA40]; and a Glauber–Sitenko diffraction theory calculation for $E_{\mathrm{p}} = 0.16$–1.04 GeV [00ZH50]. See also [00ZH53]. Reaction rate uncertainties for reaction (g) were analyzed by [98FI02].

21. ^{7}Li(d, d)^{7}Li

Angular distributions have been reported for $E_d = 1.0$ to 28 MeV (see [74AJ01, 79AJ01]) and at 50 MeV [88KO1C]. See also ^{9}Be and [87GOZF] for a breakup study.

22. (a) ^{7}Li(^{3}He, ^{3}He)^{7}Li
    (b) ^{7}Li(^{3}He, pd)^{7}Li, $Q_m = -5.4935$

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

23. (a) ^{7}Li(α, α)^{7}Li
    (b) ^{7}Li($\alpha, 2\alpha$)^{3}H, $Q_m = -2.4673$

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

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

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

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

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

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

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

For reaction (a) see ^{10}B in [88AJ01]. Angular distributions have been studied for reaction (b) to $^{7}\mathrm{Li}^{*}(0, 0.48)$ at $E(^{7}\mathrm{Li}) = 34$ MeV [87CO07, 87CO02]. See also [87HN1A].

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

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

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

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

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

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

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

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

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

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

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

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

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

33. $^7Be(\epsilon)^7Li$, $Q_m = 0.8618$

The decay proceeds to the ground and 0.48 MeV states. The branching ratio to $^7Li^*(0.48)$ is $10.44 \pm 0.04\%$, and the adopted half-life is 53.22 ± 0.06 d. Both transitions are superallowed: log $ft = 3.32$ and 3.55 for the decays to $^7Li^*(0, 0.48)$. See also [79AJ01]. The first excited state has E_x (from E_γ) $= 477.612 \pm 0.002$ keV: see [84AJ01]. A recent investigation of the decay utilized a high efficiency BeO calorimeter developed for use in a ^7Li solar neutrino experiment [98GA08]. The decay rate of $BeOH_2$ was studied under pressures up to 441 kbar [00LI21] and showed systematic dependences at the 1% level. A large change in the decay rate for ^7Be implanted in Au and Al_2O_3 was observed in [99RA12] indicating that the chemical environment affects the ^7Be lifetime. A further decay study using ^7Be in BeO, $BeOH_2$ and $Be^{2+}(OH_2)_4$ molecular forms [99HU20] found considerable variation ($\approx 1.5\%$) in the lifetime. Less significant effects of the chemical environment on the measured half-life have been measured in [49SE20, 53KR16, 56BO36, 70JO21, 73HE27]. The authors of [00HU20] deduced a half-life value of 53.42 ± 0.01 d for ^7Be in $BeOH_2$. A systematic discussion of ^7Be half-lives is included in the evaluation of R. Helmer (see Table 7.6). Helmer's evaluation produced a general-use value of the half-life, 53.22 ± 0.06 d, which is intended to be valid for Be and BeO samples and adequate for various chemical forms. In spite of more precise measurements of the ^7Be lifetime that show these environmental effects, we presently adopt this value.

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

Table 7.6
^{7}Be(ϵ)^{7}Li decay[a]

Branching ratio to ^{7}Li*(0.48)		^{7}Be Half-life	
Branching ratio (%)	References	Half-life (days)	References
10^{+20}_{-7}	[38RU01]	53 ± 2	[40HI01]
10.7 ± 2.0	[49WI13]	52.93 ± 0.22	[49SE20]
11.8 ± 1.2	[49TU06]	53.61 ± 0.17	[53KR16]
12.3 ± 0.6	[51DI12]	53.0 ± 0.4	[56BO36]
10.35 ± 0.08	[69TAZX]	53.5 ± 0.2	[57WR37]
10.47 ± 0.20	[70MUZU]	53.1 ± 0.3	[65EN01]
10.42 ± 0.18	[73PO10]	53.52 ± 0.10	[70JO21]
10.35 ± 0.08	[74GO26]	53.0 ± 0.3	[74CR05]
10.10 ± 0.45	[83BA15]	53.17 ± 0.02	[75LA16]
10.61 ± 0.23	[83DA14]	53.16 ± 0.01	[82CHZF]
10.6 ± 0.5	[83DO07]	53.284 ± 0.004	[82RUZV]
10.9 ± 1.1	[83KU10]	53.12 ± 0.07	[96JA10]
10.7 ± 0.2	[83MA34]		
9.8 ± 0.5	[83NO03]		
11.4 ± 0.7	[84EV01]		
10.61 ± 0.17	[84FI10]		
10.49 ± 0.07	[84SK01]		
10.44 ± 0.04	weighted average	53.22 ± 0.06[b]	adopted

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

[b] Adopted by the evaluator from Limitation of Relative Statistical Weight (LRSW) [85ZIZY, 92RA09] analysis.

34. ^{7}Be(n, p)^{7}Li, $Q_{\mathrm{m}} = 1.6441$

Total cross sections have been measured at $E_{\mathrm{n}} = 0.025$–13.5 keV [88KO03]. The cross sections obtained for the ^{7}Li ground and first excited states ($E_{\mathrm{x}} = 0.477$ MeV) were 38400 ± 800 b and 420 ± 120 b, respectively. The astrophysical reaction rate $N_{\mathrm{A}}\langle\sigma v\rangle$ was calculated. Uncertainties in elemental abundances from primordial nucleosynthesis were deduced in [98FI02].

35. ^{8}Li(α, αn)^{7}Li, $Q_{\mathrm{m}} = -2.0328$

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

36. ^{9}Be(γ, d)^{7}Li, $Q_{\mathrm{m}} = -16.6958$

Differential cross sections for $E_{\alpha} = 21$–39 MeV were measured by [99SH05]. See [99ZHZN] for a compilation and evaluation of cross section data.

37. ^{9}Be(π^{-}, 2n)^{7}Li, $Q_{\mathrm{m}} = 119.8674$

The capture of stopped pions has been studied in a kinematically complete experiment: ^{7}Li*(0, 0.48) are weakly populated. Two large peaks are attributed to the excitation of

^{7}Li*(7.46, 10.25). The recoil momentum distributions corresponding to these peaks are rather similar and both indicate a strong $L = 0$ component: see [79AJ01].

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

An angular distribution is reported at $E_n = 14.6$ MeV ([87ZA01]; t_{0+1}). See also [79AJ01] and ^{10}Be in [88AJ01]. Cross section measurements have also been reported for $E_n = 12.9$–19.6 MeV [88LI05] and for $E_n = 16$–19.6 MeV with Hauser–Feshbach calculations [90WO07].

39. (a) ^{9}Be(p, ^{3}He)^{7}Li, $Q_m = -11.2021$
(b) ^{9}Be(p, pd)^{7}Li, $Q_m = -16.6961$

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

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

Angular distributions have been measured for $E_d = 0.4$ to 27.5 MeV (see [66LA04, 74AJ01, 79AJ01]) and at $E_d = 2.0$ to 2.8 MeV ([84AN16]; α_0, α_1). A study at 11 MeV finds $\Gamma_{cm} = 93 \pm 25$ and 80 ± 20 keV, respectively for ^{7}Li*(4.63, 7.46). No evidence is found for the $T = 3/2$ state ^{7}Li*(11.25). Differential cross sections measured at $E_d =$ 67–75 MeV for excitation of ^{7}Li*(0, 0.48, 4.63, 7.46) were used to deduce spectroscopic amplitudes [89SZ02]. Measurements of vector analyzing powers for ^{7}Li*(0, 0.48) were reported by [94LY02] for $E_d = 1.3$–3.1 MeV. Measurements at $E_{cm} = 57$–139 keV [97YA02] and $E_{cm} = 30$–130 keV [97YA08] were used to deduce astrophysical S-factors. Differential cross sections for $E_d = 90$–290 keV are reported in [01OCZZ]. Astrophysical S-factors were deduced. See also [99OCZZ]. The previous review [88AJ01] notes that in a kinematically complete study of reaction (b) at $E_d = 26.3$ MeV, ^{7}Li*(4.6, 6.5 + 7.5, 9.4) are strongly excited. No sharp α-decaying states of ^{7}Li are observed with $10 < E_x < 25$ MeV. Parameters for ^{7}Li*(9.7) are $E_x = 9.36 \pm 0.05$ MeV, $\Gamma = 0.8 \pm 0.2$ MeV: see [79AJ01]. ($E_x = 6.75 \pm 0.20$ MeV, $\Gamma = 0.87 \pm 0.20$ MeV [86PA1E].) A study of inclusive α-spectra at $E_d = 50$ MeV has been reported by [87KA17] who suggest the involvement of a ^{7}Li state at $E_x = 18 \pm 1$ MeV, $\Gamma = 5 \pm 1$ MeV. For reaction (b) see also [87VA29]. See also ^{11}B in [90AJ01, 88NE1A]. In more recent studies of reaction (b), differential cross sections have been measured at $E_d = 18$ MeV [88GO02, 88GU20] and $E_d = 7$ MeV [88SZ02]. See also the measurements of $\sigma(E)$ for $E_d = 0.9$–11.2 MeV [94AB25], $A_y(\theta)$ for $E_d = 1.3$–3.1 MeV [94LY02], $\sigma(\theta)$ at $E_d = 3$–11 MeV [95AB41] and $E_d =$ 8–50 MeV [95GU22]. Astrophysical S-factors were determined in measurements at $E_{cm} =$ 57–139 keV [97YA02, 97YA08].

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

Angular distributions involving ^{7}Li*(0, 0.48) have been reported at $E(^{6}\mathrm{Li}) = 32$ MeV [85CO09] and $E(^{9}\mathrm{Be}) = 14$ MeV [85JA09]. Reaction cross sections have been calculated in [01BH02] for $E(^{6}\mathrm{Li}) = 790$ MeV/A.

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

Angular distributions of α_0, α_1 and of α_2 at the higher energies have been measured from $E_n = 2$ keV to 14.4 MeV: see [79AJ01, 84AJ01]. $\tau_m(0.48) = 102 \pm 5$ fs [85KO47]. More recently measurements of the ground to excited-state transition ratio $\sigma(\mathrm{n}, \alpha_0)/\sigma(\mathrm{n}, \alpha\gamma)$ for $E_n = 0.2$–1.0 MeV were reported by [91WE11]. A relative measurement of the ^{10}B(n, $\alpha\gamma$)^{7}Li cross section has been made [93SC20] for $E_n =$ 0.2–4.0 MeV. A study of P-odd effects (in the mixing of opposite-parity levels) in this reaction determined forward–backward asymmetries for the α_0 and α_1 groups $(3.4 \pm 6.7) \times 10^{-7}$ and $(-2.5 \pm 1.6) \times 10^{-7}$, respectively [96VE02]. Earlier work was reported in [86ER05, 94GL07]. Measurement and analysis of the Doppler-broadened gamma line shapes produced in the (n, α, γ) reaction for the purpose of boron concentration determination are described in [94SA72, 98MA61]. See also [97SA70]. For early polarization studies (involving both n and ^{10}B) see [86KO19] and ^{11}B in [90AJ01]. See also [86CO1M], applications. See also the more recent measurements and calculations of [99VE03] and the measurement at thermal energies of [00GO03]. A calculation of α–γ correlation parameters and study of time-reversal invariance related features are described in [00GA43].

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

See ^{5}Li.

44. ^{10}B(α, ^{7}Be)^{7}Li, $Q_m = -16.2015$

Angular distributions involving $^{7}\mathrm{Li}_{\mathrm{g.s.}}$ $^{7}\mathrm{Be}_{\mathrm{g.s.}}$ and ^{7}Li*(0.48) + ^{7}Be*(0.43) have been studied at $E_\alpha = 91.8$ MeV [85JA12, 86JA03]. See also [88SH1E], theory.

45. ^{11}Be(β^-)^{11}B* $\rightarrow$ ^{7}Li + α, $Q_m = 1.211$

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

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

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

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

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

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

Cross sections were measured at $E_\gamma = 27$–47 MeV with bremsstrahlung photons in [98KO77].

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

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

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

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

Angular distributions have been studied at $E_t = 38$ MeV to $^8Be_{g.s.}$ and $^7Li^*(0, 0.48)$ [86SIZS].

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

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

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

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

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

The reaction was studied [99NA36] at $E(^7Li) = 65$ MeV$/A$, and Gamow–Teller transition strengths were compared to those deduced from β decay.

54. $^{13}C(d, {}^8Be)^7Li$, $Q_m = -3.5887$

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

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

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

56. ^{14}O(n, γ ^{7}Li)X

Gamma-ray intensities and photo-production cross sections were measured for $E_{\mathrm{n}} =$ 4–200 MeV in [01NE09].

57. (a) ^{17}O(d, ^{12}C)^{7}Li, $Q_{\mathrm{m}} = -2.5807$
(b) ^{18}O(d, ^{13}C)^{7}Li, $Q_{\mathrm{m}} = -5.6791$
(c) ^{19}F(d, ^{14}N)^{7}Li, $Q_{\mathrm{m}} = -6.1228$

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

58. ^{27}Al(^{7}Li, tα)X

A Coulomb breakup experiment reported in [01TO07] used a 42 MeV ^{7}Li beam incident on targets of ^{27}Al, ^{58}Ni, ^{64}Zn, ^{90}Zr, ^{120}Sn, ^{144}Sm, ^{169}Tm, ^{197}Au and ^{208}Pb. The spectra of breakup particles were studied and the astrophysical S-factors, $S(E)$ for ^{3}H(α, γ)^{7}Li, were deduced.

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

Measurements of charged-particle multipolarity, angular distributions and rapidity distributions were reported in [01AB25]. ^{7}Li cluster structure was deduced.

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

Elastic and inelastic cross sections and analyzing powers were measured at $E(^{7}\mathrm{Li}) =$ 27 MeV to study the effect of electric dipole polarizability of ^{7}Li [98MA65].

^{7}Be

(Figs. 10 and 11)

General

References to articles on general properties of ^{7}Be published since the previous review [88AJ01] are grouped into categories and listed, along with brief descriptions of each item, in the general tables for ^{7}Be located on our website at (*www.tunl.duke.edu/NuclData/General_Tables/7be.shtml*).

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

1. ^{7}Be(ϵ)^{7}Li, $Q_{\mathrm{m}} = 0.8618$

The ϵ-capture decay is complex: see reaction 33 in ^{7}Li.

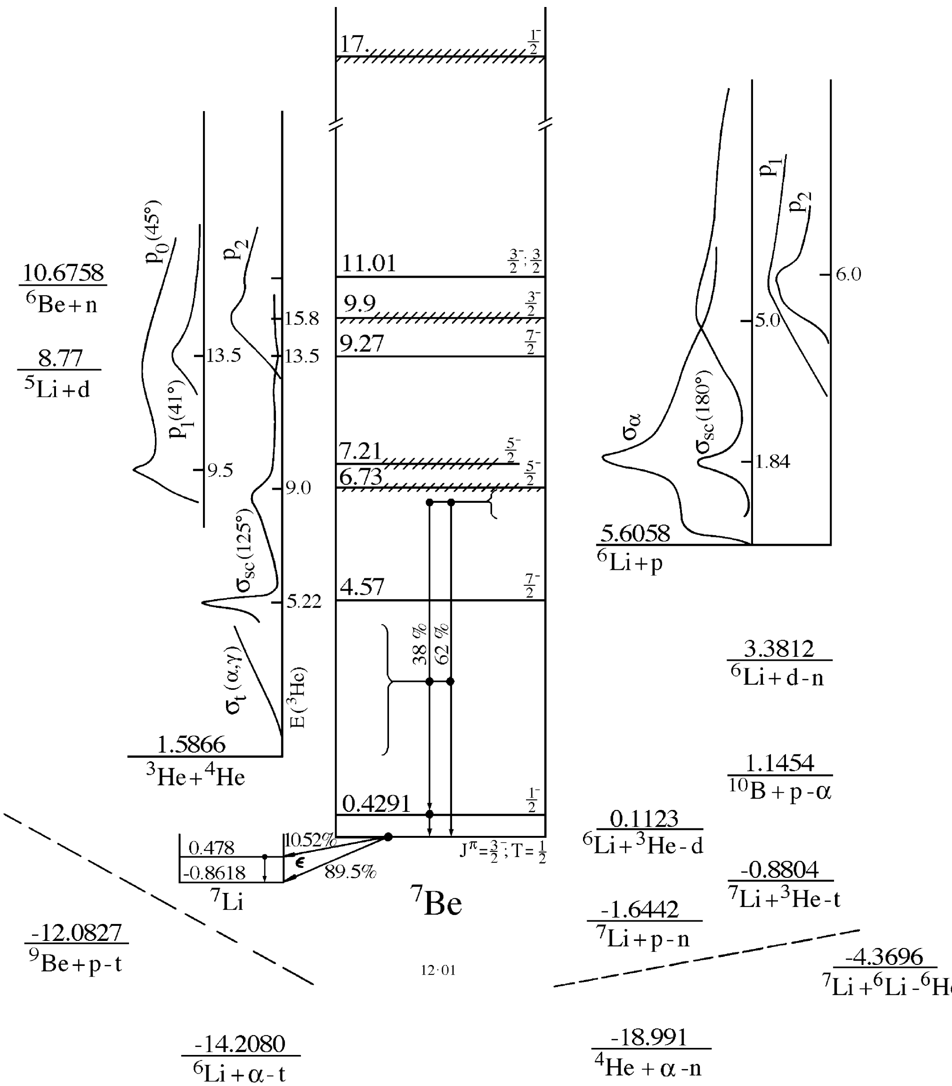

Fig. 10. Energy levels of ^{7}Be. For notation see Fig. 5.

2. $^4He(^3He, \gamma)^7Be$, $\quad Q_m = 1.5866$

The capture cross sections have been measured for $E_\alpha = 0.250$ to 5.80 MeV and at $E(^3He) = 19$ to 26 MeV (see [74AJ01, 84AJ01]), at $E_{cm} = 195$ to 686 keV [88HI06], and at $E_\alpha = 385$ to 2728 keV [84OS03] and 1225 keV [84AL24]. One of the main reasons for doing these measurements is to determine the astrophysical $S(0)$-factor. The values of $S(0)$ appear, on the average, to be higher if the experiment involves measurement of the 0.48 MeV γ following ϵ-capture rather than if it involves a direct measurement of the capture γ-rays. It is not entirely clear why this should be so. Contaminant pro-

Table 7.7
Energy levels of ^{7}Be

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

[a] Newly adopted in this evaluation or revised from the previous evaluation [88AJ01].
[b] For possible states at higher E_x see reactions 3 and 6.

duction of ^{7}Be may be involved: see [88HI06] and, e.g., [84AL24, 85FI1D, 86LA22]. Earlier measurements, sometimes recalculated, are discussed in [86LA22, 87KA1R, 88HI06]. The latter adopt best values of $S(0) = 0.51 \pm 0.02$ keV b (prompt γ-rays) and 0.58 ± 0.02 keV b (^{7}Be activity) [88HI06]. See also [84AL24, 85FI1D, 87KA1R, 88BA1H]. More recently, [93MO11] measured differential cross sections for ^{3}He–α scattering for $E_{lab}(^{3}\mathrm{He}) < 3$ MeV and obtained optical potentials which were used to calculate $S(0)$ for the capture reaction. They obtained $S(0) = 0.516$ keV b in agreement with [88HI06]. They also calculated the branching ratio for transition to the first excited state and ground state to be $R = 0.43$. Theoretical calculations are in general agreement with the experimental values. See [88AJ01] for examples from some of the early work. Calculations of astrophysical S-factors for the capture reaction are included in [88BU17, 88KA07, 89CH37, 89CH48, 89KA18, 95DU09, 95LI07, 97DU15, 01NO04]. Phase shifts and cross sections ($E_{cm} < 5$ MeV) were calculated in an extended two-cluster model in [00CS06]. Astrophysical S-factors were deduced. See also the S-factor calculation of [01CS03]. The reaction rate at $T = 300$ K was calculated in [89SC25]. See also the related work of [90SC16, 90SC26]. The reaction rate and the effects of electron screening on the solar-neutrino flux has been calculated in [00LI13]. The reaction rate and a correction to the Gamow penetration factor were calculated in [94KA02]. See also the calculations described in [98FI02, 99BU10, 99SH13, 00BA09]. As noted in [88AJ01], the solar model calculations of [82BA80] used $S_{34}[S(0)] = 0.52 \pm 0.02$ keV b. It appears clear that the uncertainty in S_{34} is not of severe consequence to the solar neutrino problem (see, e.g., [85FI1D]). For other early astrophysical-related work see [84AJ01, 88AJ01]. See also [86LI04].

3. (a) $^4He(^3He, ^3He)^4He$, $E_b = 1.5866$
(b) $^4He(^3He, p)^6Li$, $Q_m = -4.0193$

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

For $l \leqslant 4$, only f-wave phase shifts show resonance structure for $E(^3He) < 18$ MeV, corresponding to $^7Be^*(4.57, 6.73, 9.27)$: see Table 7.8. No structure corresponding to $^7Be^*(7.21)$ ($J^\pi = 5/2^-$) is seen in the elastic data. The s-wave phase shift is somewhat greater than hard-sphere. The decay of $^7Be^*(9.27)$ ($J^\pi = 7/2^-$) to $^6Li_{g.s.}$ requires f-shell configuration admixture. An estimate of the yield of ground-state protons relative to those corresponding to $^6Li^*(2.19)$ yields $\gamma^2(p_0)/\gamma^2(p_1) = (16^{+5}_{-10})\%$ [67SP10]. A phase-shift analysis (single-level R-matrix) has been carried out for $E(^3He) = 18$ to 32 MeV: the p-wave phase shifts indicate a $1/2^-$ state at $E_x \approx 16.7$ MeV ($E_r = 26.4$ MeV), with $\Gamma = 6.5$ MeV [78LU05]. An R-matrix and S-matrix analysis [92ZU03] of elastic

Table 7.8
^{7}Be level parameters[a] from $^3He + ^4He$

E_x (MeV $\pm$ keV)	J^π	l_α	LS term	θ_α^2 [b]	θ_p^2
4.57 ± 50	$\frac{7}{2}^-$	3	$^2F_{7/2}$	0.70 ± 0.04	
6.73 ± 100	$\frac{5}{2}^-$	3	$^2F_{5/2}$	1.36 ± 0.13	0.000 ± 0.002
7.21 ± 60	$\frac{5}{2}^-$	3	$^4P_{5/2}$	0.010 ± 0.001	0.26 ± 0.02
9.27 ± 100	$\frac{7}{2}^-$	3	$^4D_{7/2}$	0.70 ± 0.26	$0.29^{+0.09}_{-0.18}$ [c]
10.0[d]	$\frac{3}{2}^-$	1	$(^4P_{3/2})$		
≈ 10.0[e]	$\frac{1}{2}^-$		$(^4P_{1/2})$		
11.00 ± 50[f]	$\frac{3}{2}^-$	1	$(^2P_{3/2}, ^2D_{3/2})$		0.13 ± 0.02[g]

[a] See also Table 7.10 [66LA04]. For references see Table 7.7 in [79AJ01].
[b] $\gamma_\lambda^2 2\mu R^2/3\hbar^2$. $R = 4.0$ fm.
[c] $\theta_{p1}^2 = 1.8 \pm 0.5$.
[d] $\Gamma = 1.8$ MeV.
[e] Broad.
[f] $\Gamma = 0.4 \pm 0.05$ MeV; $T = 3/2$.
[g] $\theta_{p_2}^2$.

Table 7.9
^{7}Be levels from $^3He(\alpha, \alpha)$[a] for $l \geqslant 4$

E_{res} (MeV)[b]	Γ (MeV)	E_x	J^π
29.5 ± 1.0	8.5 ± 2.5	31.1 ± 1.0	$\frac{9}{2}^+$
32.5 ± 1.5	10.5 ± 3.0	34.1 ± 1.5	$\frac{11}{2}^-$

[a] From R-matrix analysis [92ZU03]. See also the analysis of [89OS06].
[b] Center-of-mass energies.

scattering at $E_{\alpha}(\text{cm}) = 11$–$41$ MeV on a polarized ^{3}He target gave evidence of broad $9/2^{+}$ and $11/2^{-}$ resonances. The R-matrix center-of-mass resonance energies and widths for the $9/2^{+}$ and $11/2^{-}$ resonances are $E_{\text{res}} = 29.5 \pm 1.0$ MeV, $\Gamma = 8.5 \pm 2.5$ MeV and $E_{\text{res}} = 32.5 \pm 1.5$ MeV, $\Gamma = 10.5 \pm 3.0$ MeV, respectively (see Table 7.9). See also the earlier analysis reported in [89OS06]. Differential cross sections were measured for $E(^{3}\text{He}) = 1$–3 MeV in [93MO11]. The data together with other available data were analyzed, and the optical potentials obtained were used to calculate astrophysical S-factors for the radiative capture reaction (see reaction 1).

The differential cross section for reaction (b) has been determined for $E(^{3}\text{He}) = 8$ to 28 MeV (see [79AJ01]) and at $E_{\alpha} = 22.2$ to 26.5 MeV. Resonances are observed corresponding to $^{7}\text{Be}^{*}(7.21, 9.27)$ in the p_0 yield, to $^{7}\text{Be}^{*}(9.27)$ in the p_1 yield and to states at $E_{\text{x}} \approx 10$ MeV ($T = 1/2$) and 11.0 MeV ($T = 3/2$) in the yield of 3.56 MeV γ-rays. The evidence for the latter derives mainly from interference arguments. There is also some evidence for an extremely broad $J^{\pi} = 1/2^{-}$ structure at $E_{\text{x}} \geqslant 10$ MeV (see also $^{6}\text{Li(p, p)}$: reaction 6): see Table 7.8 and [74AJ01, 84AJ01]. For $\alpha + {}^{3}\text{He}$ correlations see [87PO03]. See also the general table for ^{7}Be located on our website at (*www.tunl.duke.edu/NuclData/General_Tables/7be.shtml*). For elastic and inelastic inclusive scattering cross sections at $p_{\alpha} = 7.0$ GeV/c see [84SA39, 87BA13]. See also [84IW01], astrophysics.

References to early theoretical work on $^{3}\text{He} + {}^{4}\text{He}$ reactions are given in [88AJ01]. More recent theoretical studies include: an RGM study of the $\text{d} + {}^{5}\text{He}$ cluster configuration [91FU02]; a potential description of cluster channels [93DU02]; inversion of phase shifts and ^{7}Be bound-state energies to obtain potentials [94CO08]; a calculation of ^{7}Be charge form factors [87RO24]; microscopic cluster theory [87TA06]; Glauber amplitude expansion calculation of $\sigma(\theta)$ [88CH16, 90LI11]; a calculation of scattering lengths and astrophysical S-factors [88CH47, 89CH34]; a study of potentials deduced from phase shifts [95MA37]; and a multiconfiguration RGM calculation of reaction cross sections [95FU16].

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

Angular distributions have been reported at $E_{\alpha} = 61.5$ to 158.2 MeV [82GL01] and 198.4 MeV [85WO11] for the transitions to $^{7}\text{Be}^{*}(0 + 0.43)$. Cross section measurements at $E_{\alpha} = 160, 280, 620$ MeV are reported in [01ME13]. See also [01AU06]. Thermonuclear reaction rates for this reaction calculated from evaluated data are presented in the compilation [99AN35].

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

At low energies ($E_{\text{p}} = 0.2$ to 1.2 MeV), gamma transitions to the ground (γ_0) and to the 0.43 MeV (γ_1) states have been observed. The yield shows no resonance and the branching ratio remains approximately constant at $61 \pm 5\%$ to the ground state and $39 \pm 2\%$ to $^{7}\text{Be}^{*}(0.43)$: see [74AJ01, 84AJ01]. Angular distributions of γ_0 and γ_1 have been studied at $E_{\text{p}} = 0.50$, 0.80 and 1.00 MeV [87TI05]. At $E_{\text{p}} = 44.4$ MeV, $^{7}\text{Li}^{*}(4.57)$ is strongly populated [85HA05]. See also [83OS04] ([83HA1B, 84BO1C, 85CA41]; astrophysics) and [85BL1B].

In other work, γ angular distributions and γ-to-charged-particle ratios were measured for $E_p = 40$–180 keV and used to deduce astrophysical S-factors [92CE02]. See also the measurements at $E_p = 30$–180 keV of [93BRZQ]. Measurements of thick-target yields and analyzing power versus θ were made with 80 keV polarized beams and used to deduce relative s–p wave contributions and astrophysical S-factors [96LA10]. The slope of the astrophysical S-factor was deduced from measurements at $E_p =$ 80, 95 and 110 keV [99KEZY]. See also the cross section measurements at $E_p =$ 0.8 MeV of [00SK02]. A compilation and review of Coulomb dissociation experiments of astrophysical significance is presented in [96RE16]. Reaction rates for $E_p < 2$ MeV were analyzed in [97NO04]. The primordial ^{6}Li component was deduced. A compilation of charged-particle-induced thermonuclear reaction rates is presented in [99AN35]. Cross-section measurements at $E_p = 0.8$ MeV are reported in [00SK02].

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

The previous review [88AJ01] notes that measurements of elastic angular distributions have been reported for $E_p = 0.5$ to 600 MeV: see [66LA04, 74AJ01] and ^{6}Li. Two resonances are reported at $E_p = 1.84$ and 5 MeV in the elastic yield ($^{7}\mathrm{Be}^*(7.21, 9.9)$). The parameters of the lower resonance are shown in Table 7.4. The 5-MeV resonance has $\Gamma \approx 1.8$ MeV and appears to also be formed by p-waves: γ_p^2 is then 3 ± 2 MeV fm. A weak rise near $E_p = 8$ to 9 MeV may indicate a further level, $^{7}\mathrm{Be}^* \approx 13$ MeV. A broad resonance at $E_p = 14$ MeV has also been suggested. Polarization measurements have been carried out for $E_p = 1.2$ to 800 MeV (see [74AJ01, 79AJ01, 84AJ01]) and at $E_p = 4$ to 10 MeV ([86BE1H]; p_0) and 25 and 35 MeV ([82ROZT, 83PO1B, 83POZX]; p_0, p_1). A phase-shift analysis for $E_p = 0.5$ to 5.6 MeV shows that only ^{2}S, ^{4}S and ^{4}P are involved. The $^{4}\mathrm{P}_{5/2}$ amplitude resonates at $E_p = 1.8$ MeV, and the broad resonance at 5 MeV can be reproduced equally well by either $^{4}\mathrm{P}_{3/2}$ or $^{4}\mathrm{P}_{1/2}$: tensor polarization measurements are necessary to distinguish between the two: see [74AJ01].

In more recent work, cross sections and analyzing powers were measured at $E_p =$ 1.6–10 MeV [89HA17], at $E_p = 200$ MeV [90GL04] and at $E_p = 0.4$–2.2 MeV [95SK01]. Parameters for the $E_p(\mathrm{lab}) = 1.8$ MeV resonance were measured by [95SK01] (see Table 7.10). The depolarization parameter was measured at $E_p = 72$ MeV [94HE11].

The reaction cross section for formation of $^{6}\mathrm{Li}^*(2.19)$ has been measured for $E_p = 3.6$ to 9.40 MeV: a broad resonance indicates the presence of a state with $E_x \approx 10$ MeV, $\Gamma = 1.8$ MeV, $J^\pi = (3/2, 5/2)^-$, $T = 1/2$. The cross-section and angular distributions of p_2 ($^{6}\mathrm{Li}^*(3.56)$) for $E_p = 4.26$ to 9.40 MeV are analyzed in terms of two $J^\pi = 3/2^-$ states at $E_x \approx 10$ and 11 MeV: see reaction 3. The total cross section for formation of $^{6}\mathrm{Li}^*(3.56)$ decreases slowly with energy for $E_p = 24.3$ to 46.4 MeV. The total reaction cross section has been measured for $E_p = 25.0$ to 48 MeV [85CA36]. K_y^y spectra at $E_p = 50$, 65 and 80 MeV, $\theta = 3°$–$20°$, are reported in [87SA46]. For the inclusive cross section at $E_p = 200$ MeV (back angles) see [84AV07]. See also the measurement of cross sections and analyzing powers for excitation of $^{6}\mathrm{Li}^*(2.18, 3.56)$ at $E_p = 200$ MeV [90GL04]. Theoretical work on this reaction published since the previous

Table 7.10
^{7}Be level parameters from ^{6}Li + p phase shift analysis[a,b]

Phase shift	$E_{\rm res}$[c] (MeV)	$E_{\rm x}$ (MeV)	$\Gamma_{\rm p}$ (MeV)	Γ (MeV)
$^{4}P_{5/2}$[a]	1.56 ± 0.1	7.2 ± 0.1	0.19 ± 0.05	0.40 ± 0.05
$^{2}P_{1/2}$[b]	3.68 ± 0.31	9.29 ± 0.31	0.47 ± 0.33	1.93 ± 0.96
$^{4}P_{1/2}$[b]	4.20 ± 0.12	9.81 ± 0.12	1.65 ± 0.25	2.21 ± 0.29
$^{4}P_{5/2}$[b]	4.39 ± 0.17	10.00 ± 0.17	0.42 ± 0.14	1.68 ± 0.58
$^{4}P_{3/2}$[b]	6.76 ± 1.27	12.37 ± 1.27	1.81 ± 1.03	4.95 ± 3.23

[a] From Table 1 of [95SK01].
[b] From Table 2 of [89HA18].
[c] Center of mass energies.

review [88AJ01] includes: a folding-model calculation to deduce halo effects [92GA27]; self-consistent calculation with matter-cluster dynamic model [92KA06]; a potential description study with a supermultiplet symmetry approximation [93DU09]; a description with a microscopic effective interaction [93KO44]; a consistent folding-model description [93PE13]; a calculation for (p, p) and (p, p′) with Glauber–Sitenko diffraction theory [94ZH28, 94ZH34]; an analysis with phenomenological microscopic optical potentials [95GA24]; a consistent analysis of the analyzing power puzzle [95KA03]; a continuum-continuum coupling analysis [95KA07]; a fully-microscopic analysis at $E_{\rm p} = 200$ MeV [97DO01]; an RGM study of a $5/2^{-}$ resonance [97IG04]; a study of shell-model structures observed in proton and electron scattering [97KA24]; and a microscopic-model analysis for $E_{\rm p} = 65$ MeV [98DO16].

For reaction (b) see ^{5}He and ^{6}Li. For reaction (c) see ^{6}Li, and references cited in [88AJ01].

7. ^{6}Li(p, n)^{6}Be, $Q_{\rm m} = -5.0700$, $E_{\rm b} = 5.6058$

The yield of neutrons increases approximately monotonically from threshold to $E_{\rm p} = 14.3$ MeV: see [74AJ01]. The transverse polarization transfer, $D_{\rm NN}$ (0°), for the g.s. transition has been measured for $E_{\rm p} = 30$ to 160 MeV: see [84TA07, 86TA1E] and ^{6}Be. Analyzing-power measurements are reported at $E_{\rm p} = 50$ and 80 MeV [87SA46] and at 52.8 MeV [88HE08] ($K_{\rm y}^{\rm y'}$ (0°) $= -0.33 \pm 0.04$; also $K_{\rm z}^{\rm z'}$). See also [86MC09] ($E_{\rm p} = 800$ MeV) and [84BA1U, 86RA21, 86SA1Q]. For more recent work see the discussion on this reaction under ^{6}Be.

8. ^{6}Li(p, α)^{3}He, $Q_{\rm m} = 4.0193$, $E_{\rm b} = 5.6058$

Thermonuclear reaction rates and the astrophysical S-factor have been derived from the low-energy ($E_{\rm p} < 0.7$ MeV) cross-section measurements: $S(0) \approx 3.1$ MeV b: see [74AJ01, 79AJ01, 84AJ01]. At higher energies the cross section exhibits a broad, low maximum near $E_{\rm p} = 1$ MeV and a pronounced resonance at $E_{\rm p} = 1.85$ MeV ($\Gamma < 0.5$ MeV). No other structure is reported up to $E_{\rm p} = 5.6$ MeV. Measurements between $E_{\rm p} = 0.4$ and 3.4 MeV show that the polarizations are generally large and positive: see [74AJ01].

Angular distributions have been reported for $E_p = 0.15$ to 45 MeV (see [74AJ01, 79AJ01, 84AJ01]) and at 47.8, 53.5, 58.5 and 62.5 MeV [84NE05]. For other early work, see references cited in [88AJ01]. More recently, measurements of analyzing power versus E_p for $E_p = 180$–280 keV were reported in [91BU14]. Tests of isotopic dependence of electron-screening effects on the astrophysical S-factor were reported for $E_{cm} = 10$–1004 keV [92EN01, 92EN04]. See also: an analysis of S-factor data for $E_{cm} = 10$–1000 keV [92SO25]; a study of atomic screening and other small effects in reaction rates [97BA95]; a study of screening effects for solid targets [97BO12]; an optical-model formulation and S-factor calculation for $E = 10$–100 keV [97KI02]; a study of reaction rates and the primordial ^{6}Li component [97NO04]; and a study of R-matrix parameterization for $E_{cm} < 1$ MeV [98AN18]. Thermonuclear reaction rates for this reaction calculated from evaluated data are presented in the compilation [99AN35].

9. ^{6}Li(d, n)^{7}Be, $Q_m = 3.3812$

Angular distributions of the n_0 and n_1 groups have been measured at $E_d = 0.20$ to 15.25 MeV: see [74AJ01, 79AJ01]. The n_1–γ correlations are isotropic, indicating $J^\pi = 1/2^-$ for ^{7}Be*(0.43). Broad maxima are observed in the ratio of low-energy to high-energy neutrons at $E_d = 4.2$ and 5.1 MeV (^{7}Be*(6.5, 7.2), $\Gamma_{cm} = 1.2$ and 0.5 MeV, respectively): see [66LA04]. See also ^{8}Be and [88KO1C].

Measurements at $E < 1$ MeV and determination of the astrophysical S-factor as well as studies of the (d, n)/(d, p) ratio are described in [93CZ01, 97CZ04]. Cross-section measurements and S-factor determinations at $E_d = 24$–111 keV are reported in [01HO23]. A calculation of the (d, n)/(d, p) branching ratio and discussions of the rate of Coulomb-induced predissociation is presented in [90KO26]. Cross sections for $E < 1$ MeV were calculated and reaction rates were deduced in [01VO02]. Calculations of radiated power vs. plasma temperature in controlled fusion are described in [99HA50]. See also [96BO27, 97NO04].

10. ^{6}Li(^{3}He, d)^{7}Be, $Q_m = 0.1123$

Angular distributions of the d_0 and d_1 groups to ^{7}Be*(0, 0.43) have been measured at $E(^3\text{He}) = 8$, 10, 14 and 18 MeV and at $E(^3\text{He}) = 33.3$ MeV (^{7}Be*(4.57) is also populated): see [74AJ01, 84AJ01].

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

See [87MI34] and ^{5}He.

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

The reaction was used by [98NA14] to separate $\Delta S = 0$ and $\Delta S = 1$ transitions through coincidence measurements of γ-rays from the ^{7}Be 0.43 MeV state.

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

Forward-angle differential cross sections have been measured at $E_{\pi^+} = 20$ MeV ([87IR01]; also at 155° and 166°), at 33.5, 41.1, 48.7 and 58.8 MeV [85IR01, 85IR02], 70 to 180 MeV (see [84AJ01]) and from 300 to 550 MeV [88RO03].

A Glauber-model analysis of $\sigma(\theta)$ for $E = 250$–650 MeV is described in [90OS01]. Model calculations of cross sections and polarization observables are presented in [99NO02].

14. $^{7}\mathrm{Li}(\mathrm{p},\mathrm{n})^{7}\mathrm{Be}$, $Q_{\mathrm{m}} = -1.6442$,
$E_{\mathrm{thresh.}} = 1880.443 \pm 0.020$ keV [85WH1A]

The excitation energy of $^{7}\mathrm{Be}^{*}(0.43)$ is 429.20 ± 0.10 keV, $\tau_{\mathrm{m}} = 192 \pm 25$ fs: see [79AJ01]. Angular distributions of n_0 and n_1 have been reported at $E_{\mathrm{p}} = 1.9$ to 119.8 MeV (see [74AJ01, 79AJ01, 84AJ01]) and at 200, 300 and 400 MeV ([87WAZT]; n_{0+1}). $^{7}\mathrm{Be}^{*}(4.55, 6.51, 7.19, 10.79)$ have also been populated: see [74AJ01, 79AJ01]. The ratios of σ_1/σ_0 ($^{7}\mathrm{Be}^{*}(0.43)/^{7}\mathrm{Be}_{\mathrm{g.s.}}$) have been measured at 24.8, 35 and 45 MeV and yield the ratio of spin–flip to non-spin–flip strength $|V_{0\tau}/V_{\tau}|^2$ [80AU02].

Cross-section measurements related to neutron-production targets and detector efficiency calibration include [87TE04, 88HE08, 89AM03, 89BY02, 89GU13, 90BR24, 90DR10, 90TA11, 92AM03, 92DA20, 97TA03, 98KA20, 98MA49, 99BA73, 99NA02, 99NA15]. Measurements or analyses of Gamow–Teller transition strength are reported in [87TA13, 89RA09, 90RA08, 94SA43]. See also [87HE22, 87OR02]. An analysis of neutron spectra for $E_{\mathrm{p}} = 120$, 160 MeV and deduction of Gamow–Teller matrix elements are described in [01GO25]. A compilation of analyzing-power data is presented in [87TA22]. For studies of quadrupole excitation see [94RA23, 94WA22, 95YA12]. Application-related measurements are described in [87RA23, 88BO33, 89CR05, 95RI14, 96BB13, 96SH29, 96TA23, 97DE54, 97UW01, 97ZH35, 99LE16, 99NA02, 99SA16, 99SH16]. See also the astrophysical-related analysis in [89BU10]. See also the analysis [98IO03] of 647 and 800 MeV data, and the study of the isovector part of optical potentials for 35 MeV (p, n) data [98JOZW, 00JO17]. For earlier work see [88AJ01].

15. (a) $^{7}\mathrm{Li}(\mathrm{d},2\mathrm{n})^{7}\mathrm{Be}$, $Q_{\mathrm{m}} = -3.8687$
(b) $^{7}\mathrm{Li}(\mathrm{t},3\mathrm{n})^{7}\mathrm{Be}$, $Q_{\mathrm{m}} = -10.1260$

See [87AL10], $E(^{7}\mathrm{Li}) = 65$ MeV.

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

Angular distributions of t_0 and t_1 have been measured at $E(^{3}\mathrm{He}) = 3.0$ to 4.0 MeV and at $E(^{3}\mathrm{He}) = 33.3$ MeV: see [74AJ01, 84AJ01]. The width of $^{7}\mathrm{Be}^{*}(4.57)$, $\Gamma_{\mathrm{cm}} = 175 \pm 7$ keV: see [74AJ01]. See also ^{10}B in [88AJ01].

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

This reaction has been studied at $E(^{6}\mathrm{Li}) = 14$, 25 and 35 MeV/A. $^{7}\mathrm{Be}^{*}(0, 0.43)$ are strongly populated and $^{7}\mathrm{Be}^{*}(4.57, 7.21)$ are also evident. At the highest energy, the reaction mechanism is predominantly one-step [86AN29, 87WI09]. See also ^{6}He and references cited in [88AJ01]. See also reaction 12.

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

See [98NA14].

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

Neutron yields have been measured with backscattered laser photons [99TOZZ].

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

Cross sections were measured at $E_\mathrm{n} = 28$–68 MeV [98DU06].

21. $^{9}\mathrm{Be}(\mathrm{p},\mathrm{t})^{7}\mathrm{Be}, \quad Q_\mathrm{m} = -12.0827$

Angular distributions of tritons have been measured at $E_\mathrm{p} = 43.7$ and 46 MeV (see [79AJ01]) and at 50 and 72 MeV ([84ZA07]; t_{0+1}, t_2). The 11-MeV state has $E_\mathrm{x} = 11.01 \pm 0.04$ MeV, $\Gamma = 298 \pm 25$ keV, $J^\pi = 3/2^-$; $T = 3/2$ (the J^π; T assignments are based on the similarity of the angular distribution to that in the (p, ^{3}He) reaction to ^{7}Li*(11.13)): see [79AJ01].

22. $^{10}\mathrm{B}(\mathrm{p},\alpha)^{7}\mathrm{Be}, \quad Q_\mathrm{m} = 1.1454$

Angular distributions have been studied for $E_\mathrm{p} = 2.8$ to 7.0 MeV (see [74AJ01]) and for 18 to 45 MeV ([86HA27]; α_0, α_1, α_2; see for spectroscopic factors). E_x of ^{7}Be*(0.43) = 428.89 ± 0.13 keV [79RI12]. See also ^{11}C in [85AJ01], [83DO07] and [88KOZL] (applications).

More recently several studies at astrophysical energies have been reported. They include measurements of $\sigma(\theta)$ and $\sigma(E)$ at $E_\mathrm{p} = 120$–480 keV [91YO04] and at $E_\mathrm{p} = 37$–120 keV [93KNZZ]; measurements of electron screening corrections at $E_\mathrm{cm} = 17$–134 keV and determination of $S(E)$ [93AN06]; direct-model calculations of astrophysical reaction rates [96RA14]; and a calculation of small-effect corrections in fusion reactions [97BA95]. A calculation of ^{7}Be level population intensities at $E_\mathrm{p} = 45$ MeV is described in [92KW01]. For application-related measurements see [90BO15, 95RI14, 95SJ01, 99SA16].

23. $^{10}\mathrm{B}(\mathrm{d},{}^{5}\mathrm{He})^{7}\mathrm{Be}, \quad Q_\mathrm{m} = -1.8770$

See ^{5}He.

24. $^{10}\mathrm{B}(\alpha,{}^{7}\mathrm{Li})^{7}\mathrm{Be}, \quad Q_\mathrm{m} = -16.2015$

See ^{7}Li.

25. $^{11}\mathrm{B}({}^{3}\mathrm{He},{}^{7}\mathrm{Li})^{7}\mathrm{Be}, \quad Q_\mathrm{m} = -7.0780$

Spectroscopic amplitudes calculated with an intermediate-coupling model are reported in [87KW03]. See also the discussion under ^{7}Li.

26. $^{12}\mathrm{C}(\mathrm{p},{}^{6}\mathrm{Li})^{7}\mathrm{Be}, \quad Q_\mathrm{m} = -22.5668$

Yields of fragments, observed in protons at $E_\mathrm{p} = 1$ GeV incident on ^{12}C, were measured in [00ANZX]. A calculation of spectroscopic amplitudes in an intermediate coupling model analysis is reported in [87KW03]. See also the discussion under ^{6}Li.

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

Differential cross sections were measured at $E_d = 78$ MeV in a study of five-nucleon simultaneous transfer [96JA12]. Spectroscopic amplitudes were calculated in an intermediate-coupling model in [87KW03]. See [95CH69] for a measurement of ^{12}C(d, ^{7}Be)^{7}Li, and see ^{7}Li in this review.

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

Angular distributions involving ^{7}Be*(0, 0.43) have been reported at $E(^{3}\mathrm{He}) = 25.5$ to 70 MeV (see [79AJ01, 84AJ01]) and at $E(^{3}\mathrm{He}) = 33.4$ MeV ([86CL1B]; also A_y). See also [86RA15] and see discussions of ^{12}C(^{3}He, ^{7}Be)^{8}Be under ^{8}Be.

29. ^{12}C(α, ^{9}Be)^{7}Be, $Q_m = -24.6922$

At $E_\alpha = 42$ MeV, angular distributions have been measured involving ^{7}Be*(0, 0.43) and ^{9}Be$_{\mathrm{g.s.}}$: see [74AJ01]. Angular distributions have also been measured at $E_\alpha = 49.0$ and 80.1 MeV [84GO03]. An angular distribution and DWBA analysis for ^{12}C(α, ^{7}Be)^{9}Be is reported in [91GL03].

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

See [84BA53, 98NA14, 98NA16].

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

Cross sections for ^{7}Be produced by protons and neutrons at $E = 10$–10 000 MeV were analyzed [00NA34] and atmospheric production rates were deduced.

32. ^{16}O(γ, ^{7}Be)X

^{7}Be yields were measured with 250–1050 MeV bremsstrahlung photons on the O, Al, Cr, Cl, CO targets [98SH18].

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

Angular distributions have been reported at $E(^{3}\mathrm{He}) = 25.5$ to 70 MeV to ^{7}Be*(0, 0.43) and to various states of ^{12}C: see ^{12}C in [85AJ01]. See also [86BA1F]. A measurement of $\sigma(\theta)$ for ^{16}O(^{3}He, ^{7}Be)^{12}C at $E(^{3}\mathrm{He}) = 41$ MeV is reported in [87RA37]. See also the calculation for $E(^{3}\mathrm{He}) = 60$ MeV in [95MA57].

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

Angular distributions have been studied at $E(^{7}\mathrm{Li}) = 50$ MeV involving ^{7}Be*(0, 0.43) and various states of ^{16}N [84CO20, 86CL03]. See also ^{16}N in [86AJ04] and [84BA53]. A compilation and analysis of data for $E(^{7}\mathrm{Li}) = 78$ MeV is presented in [89GA26].

35. ^{27}Al(γ, ^{7}Be)X

Target dependence of ^{7}Be production by bremsstrahlung photons ($E_\gamma < 1200$ MeV) incident on ^{27}Al and several other targets were studied by [00MA75]. See also [98SH18].

36. ${}^{24}\mathrm{Mg}({}^3\mathrm{He}, {}^{20}\mathrm{Ne}){}^7\mathrm{Be}, \quad Q_\mathrm{m} = -7.7297$

See the calculations reported in [86RA15]. Measurements of $\sigma(\theta)$ for ${}^{24}\mathrm{Mg}({}^3\mathrm{He}, {}^7\mathrm{Be})$ at $E({}^3\mathrm{He}) = 41$ MeV are reported in [87RA37]. Spectroscopic factors were deduced [88RA20].

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

Cross sections have been calculated for $E({}^8\mathrm{B}) = 25.8$, 415 MeV [99SH20].

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

Production cross sections for ^{7}Be for protons with $E_\mathrm{p} = 0.66$, 1.0 and 8.1 GeV incident on separated tin isotopes ^{112}Sn, ^{118}Sn, ^{120}Sn and ^{124}Sn were measured by an activation technique [98DAZI].

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

Production cross sections were measured for $E_\mathrm{p} = 65$–2600 MeV [01GL05].

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

Dissociation of ^{8}B in the Coulomb field of ^{208}Pb was measured at $E({}^8\mathrm{B}) = 51.9$ MeV$/A$. Cross sections for ${}^7\mathrm{Be}(\mathrm{p}, \gamma){}^8\mathrm{B}$ were extracted [98KI19].

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

Yields of ^{7}Be from photon-induced ^{232}Th fission were measured by [98KAZL].

^{7}B

(Fig. 11)

The mass excess of ^{7}B adopted by [97AU04] is 27.870 ± 0.070 MeV. It was obtained by averaging the values of 27.94 ± 0.10 MeV from the ${}^{10}\mathrm{B}({}^3\mathrm{He}, {}^6\mathrm{He}){}^7\mathrm{B}$ reaction [67MC14, 88AJ01] and the value 27.800 ± 0.10 MeV obtained in the ${}^7\mathrm{Li}(\pi^+, \pi^-){}^7\mathrm{B}$ reaction [81SE1B]. The width of the ground state is $\Gamma = 1.4 \pm 0.2$ MeV: see [67MC14, 88AJ01]. ^{7}B is unbound with respect to ${}^6\mathrm{Be} + \mathrm{p}$, ${}^5\mathrm{Li} + 2\mathrm{p}$ and ${}^4\mathrm{He} + 3\mathrm{p}$ by 2.21, 1.61 and 3.38 MeV, respectively.

The predicted mass excess for ^{7}B based on the isobaric multiplet mass equation using the $T = 3/2$ level energies in ^{7}He, ^{7}Li and ^{7}Be is 27.76 ± 0.17 MeV [67MC14]. See also the early references cited in [88AJ01, 84AJ01, 79AJ01, 74AJ01]. Recent cross section measurements for ${}^7\mathrm{Li}(\pi^+, \pi^-){}^7\mathrm{B}$ ([98PA40] were used to deduce information on ^{7}B proton halo features. Measurements at $E_\pi = 30$–90 MeV reported in [00DR19] were used to deduce energy-dependent features. Theoretical studies relevant to ^{7}B include work on the spherical properties of nuclei [95JA06, 97AB27]; Skyrme Hartree–Fock model calculations [97BA54]; Coulomb-energy studies [97PO12]; and large-basis shell-model calculations of level energies and other properties [98NA17].

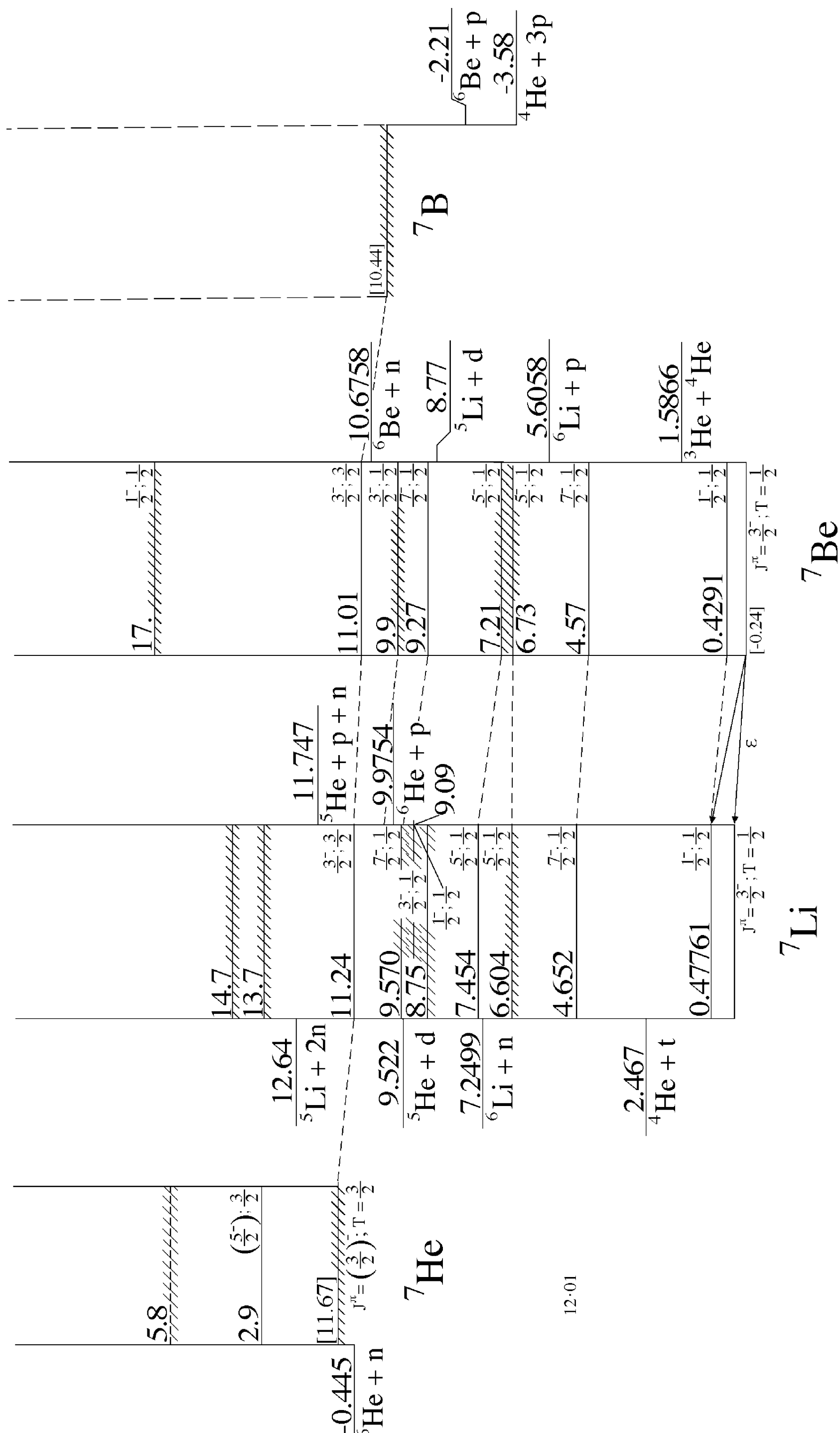

Fig. 11. Isobar diagram, $A = 7$. For notation see Fig. 3.

Table 7.11
Mirror states in $A = 7$ nuclei[a]

^{7}Li		^{7}Be		ΔE_x (MeV)[b]
E_x (MeV)	J^π	E_x (MeV)	J^π	
0	$\frac{3}{2}^-$	0	$\frac{3}{2}^-$	–
0.478	$\frac{1}{2}^-$	0.429	$\frac{1}{2}^-$	-0.049
4.65	$\frac{7}{2}^-$	4.57	$\frac{7}{2}^-$	-0.08
6.60	$\frac{5}{2}^-$	6.73	$\frac{5}{2}^-$	$+0.13$
7.45	$\frac{5}{2}^-$	7.21	$\frac{5}{2}^-$	-0.24
8.75	$\frac{3}{2}^-$	9.9	$\frac{3}{2}^-$	$+1.15$[c]
9.09	$\frac{1}{2}^-$			
9.57	$\frac{7}{2}^-$	9.27	$\frac{7}{2}^-$	-0.3

[a] As taken from Tables 7.2 and 7.7.
[b] Defined as $E_x(^7\text{Be}) - E_x(^7\text{Li})$.
[c] This difference may be unphysical since the ^{7}Li level parameters were obtained from the "extended R-matrix prescription" (see the introduction in this publication). The equivalent information for ^{7}Be levels is not available.

Table 7.12
Isospin quadruplet components ($T = \frac{3}{2}$) in $A = 7$[a]

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

[a] As taken from Tables 7.1, 7.2 and 7.7.

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[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 † please refer to the Reference key for a complete citation of the conference proceeding.

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