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Energy Levels of Light Nuclei
$A = 9$

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Abstract: An evaluation of $A = 8$–10 was published in *Nuclear Physics A*745 (2004), p. 155. This version of $A = 9$ differs from the published version in that we have corrected some errors discovered after the article went to press. The introduction and introductory tables have been omitted from this manuscript. Reference key numbers are in the NNDC/TUNL format.

(References closed March 31, 2004)

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Table of Contents for $A = 9$

Below is a list of links for items found within the PDF document or on this website.

A = 9

GENERAL: References to articles on general properties of $A = 9$ nuclei published since the previous review (1988AJ01) are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for $A = 9$ located on our website at (*www.tunl.duke.edu/nucldata/General_Tables/09.shtml*).

^{9}He

(Fig. 10)

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

Mass of ^{9}He: Although the value adopted in the 2003 Atomic Mass Evaluation (2003AU02) for the ^{9}He ground state is 40.939 ± 0.029 MeV based on the results of (1999BO26), an experiment (2001CH31) suggests that the ground-state of ^{9}He has $J^{\pi} = \frac{1}{2}^{+}$ and lies within 0.2 MeV of the ^{8}He + n threshold. In light of this result, the Atomic Mass Evaluation center [private communication from Audi, Wapstra, and Jokinen] has adopted an atomic mass excess of 39.770 ± 0.060 MeV for ^{9}He. See the discussion below.

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

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

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

^{9}Li

(Figs. 6 and 10)

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

Ground state properties:

$\mu = 3.4391 \pm 0.0006\ \mu_{\rm N}$ (1983CO11). See also (1987AR22, 2001STZZ);

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

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

1. ^{9}Li(β^-)^{9}Be $\qquad Q_{\rm m} = 13.6067$

The half-life of ^{9}Li is 178.3 ± 0.4 msec: see (1979AJ01). See also (1986CU01, 1988SA04, 1991RE02). ^{9}Li decays to a number of states in ^{9}Be: see reaction 12 in ^{9}Be and Table 9.8. The nature of the decay to ^{9}Be*(0, 2.43) with $J^\pi = \frac{3}{2}^-, \frac{5}{2}^-$ is evidence for $J^\pi = \frac{3}{2}^-$ for ^{9}Li$_{\rm g.s.}$. The probability for delayed neutron decay, $P_{\rm n}$, is (50.8 ± 0.9)%, obtained by averaging (50.0 ± 1.8)% from (1991RE02) and (51.0 ± 1.0)% from (1992TE03). A recent study has concentrated on the decays to the highest accessible states in ^{9}Be (2003PR11). See also (1990NY01, 1993CH06) and references cited in (1984AJ01, 1988AJ01).

2. ^{1}H(^{8}He, ^{8}He)^{1}H $\qquad E_{\rm b} = 13.933$

Table 9.1: Energy levels of ^{9}Li [a]

E_x (MeV $\pm$ keV)	$J^\pi; T$	$\tau_{1/2}$ or $\Gamma_{c.m.}$ (keV)	Decay	Reactions
g.s.	$\frac{3}{2}^-; \frac{3}{2}$	$\tau_{1/2} = 178.3 \pm 0.4$ msec	β^-	1, 3, 4, 5, 6, 7, 8, 9, 10
2.691 ± 5	$\frac{1}{2}^-$		(γ)	4, 6, 7, 10
4.296 ± 15	$(\frac{5}{2}^-)$	$\Gamma = 100 \pm 30$ [b]		4, 10, 11
5.38 ± 60		600 ± 100		4
6.43 ± 15		40 ± 20		4, 10

[a] The first evidence for $T = \frac{5}{2}$ states of ^{9}Li has been obtained from ^{8}He + p elastic scattering (see reaction 2).
[b] From reaction 4. See also reaction 11.

From an analysis of the excitation function for ^{8}He + p elastic scattering obtained by the thick target inverse kinematics method, three $T = \frac{5}{2}$ states of ^{9}Li were identified at $E_x = 16.0 \pm 0.1$, 17.1 ± 0.2, and 18.9 ± 0.1 MeV. The corresponding widths are < 100, 800 ± 300, and 240 ± 100 keV, respectively. The properties of the three levels are compared with the apparent analog states in ^{9}He (2003RO07).

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

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

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

Protons are observed to excited states at $E_x = 2.691 \pm 0.005$, 4.31 ± 0.02, 5.38 ± 0.06 and 6.430 ± 0.015 MeV. The widths of the three states above the neutron threshold are 100 ± 30, 600 ± 100 and 40 ± 20 keV, respectively. Angular distributions have been studied at $E_t = 11.3$ (1964MI04; p_0), 15 (1971YO04; p_0, p_2, p_4) and 23 MeV (1978AJ02; p_0, p_1, p_2, p_4). It is plausible that the observed levels can be identified with the first five predicted p-shell levels with $J^\pi = \frac{3}{2}^-$, $\frac{1}{2}^-$, $\frac{5}{2}$–, and $\frac{7}{2}^-$ (1971YO04). The largest two-neutron spectroscopic factors are for the ground state $(L = 0)$ and the $\frac{5}{2}^-$ state $(L = 2)$, consistent with the observed angular distributions and the fact that the 4.3 MeV level has the largest cross section. The excited $\frac{3}{2}^-$ state is predicted to decay via n_0, n_1 and the $\frac{7}{2}^-$ state mainly via n_2. See also ^{10}Be (1987AB15, 1990GU36).

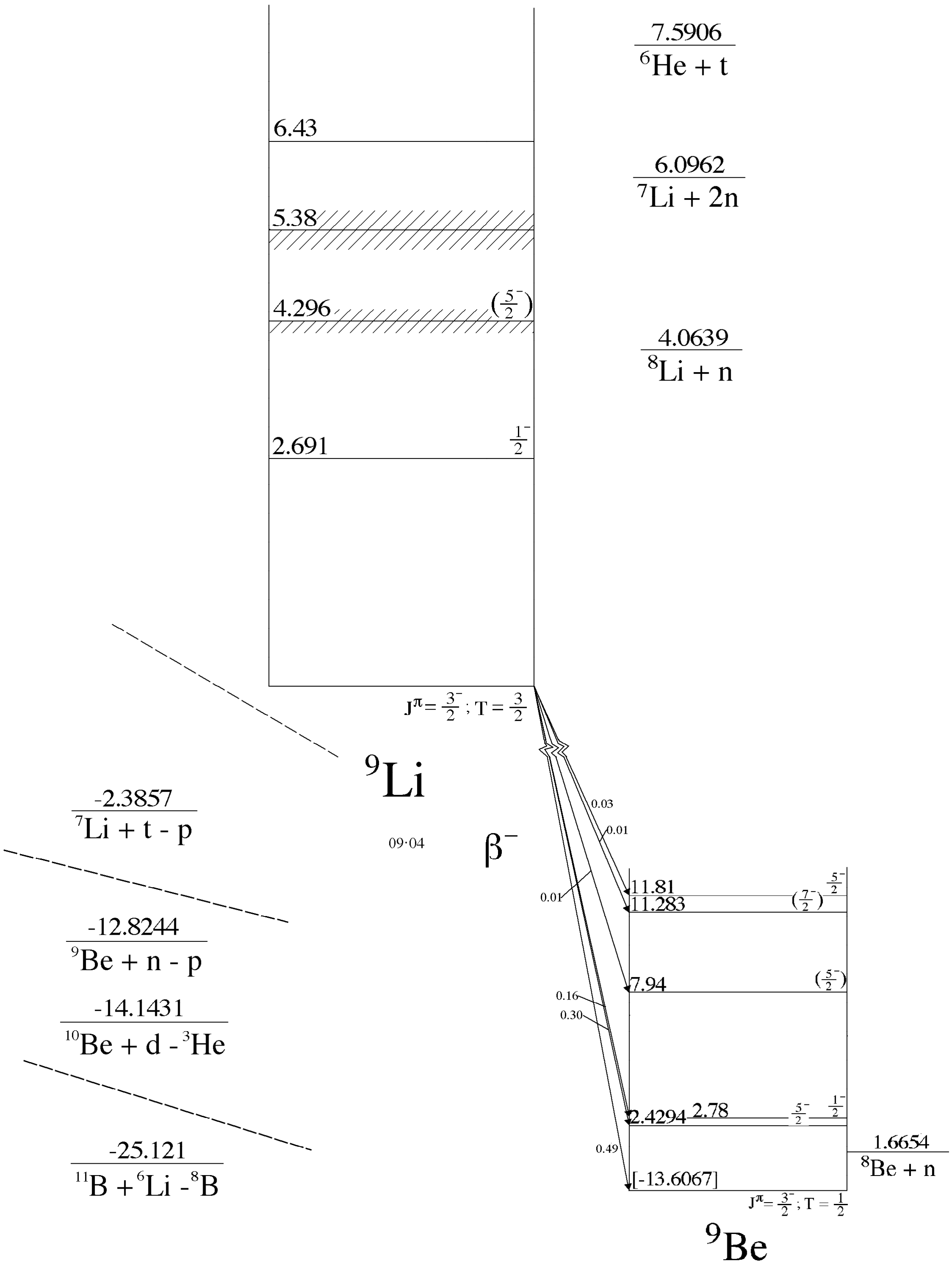

Figure 6: Energy levels of ^{9}Li. For notation see Fig. 7.

5. ^{9}Be(γ, π^{+})^{9}Li $\qquad Q_{\rm m} = -153.1769$

The angular distribution of the π^{+} to ^{9}Li$_{\rm g.s.}$ has been measured at $E_{\rm e} = 200$ MeV (1983SH19). For the earlier work see (1984AJ01).

6. ^{9}Be(π^{-}, γ)^{9}Li $\qquad Q_{\rm m} = 125.9635$

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

7. ^{9}Be(n, p)^{9}Li $\qquad Q_{\rm m} = -12.8244$

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

8. ^{9}Be(t, ^{3}He)^{9}Li $\qquad Q_{\rm m} = -13.5881$

The 0° cross section for $E_{\rm t} = 381$ MeV shows a weak ground-state transition and a strong spin-dipole peak at $E_{x} \approx 6.5$ MeV (1998DA05).

9. ^{9}Be(^{7}Li, ^{7}Be)^{9}Li $\qquad Q_{\rm m} = -14.4689$

See (1984GL06: $E(^{7}{\rm Li}) = 78$ MeV).

10. ^{11}B(^{6}Li, ^{8}B)^{9}Li $\qquad Q_{\rm m} = -25.121$

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

11. $^{\rm nat}$Ag(^{14}N, ^{8}Li + n)X

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

12. $^{\rm nat}$Pb(^{9}Li, ^{8}Li + n)X

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

13. $^{\rm nat}$U(^{9}Li, ^{8}Li + n)X

See reaction 12.

^{9}Be

(Figs. 6, 7 and 10)

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$\mu = -1.1778 \pm 0.0009\ \mu_N$: see (1978LEZA).
$Q = 52.88 \pm 0.38$ mb: see (1967BL09, 1991SU05, 2001STZZ).

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

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

For a discussion of the structure and widths of levels in ^{9}Be and ^{9}B, see the general discussion of ^{9}B.

1. (a) ^{6}Li(t, n)^{8}Be $Q_m = 16.0236$ $E_b = 17.6890$
   (b) ^{6}Li(t, p)^{8}Li $Q_m = 0.80079$
   (c) ^{6}Li(t, n)^{4}He^{4}He $Q_m = 16.115451$

The $0°$ differential cross section for reaction (a) increases monotonically between $E_t = 0.10$ and 2.4 MeV. A resonance has been reported at $E_t = 1.875$ MeV (^{9}Be*(18.94)). The excitation function for ^{8}Li (reaction (b)) increases monotonically for $E_t = 0.275$ to 1.000 MeV. See (1974AJ01) for references. In the range $E_t = 2$ to 10 MeV the total cross section for reaction (b) shows a broad structure [$\Gamma_{cm} = 1.5$ MeV] at $E_t = 4.2$ MeV (^{9}Be*(20.5)) (1986AB04). Yields and angular distributions for reaction (c) have been measured at $E_t = 2$ to 4.5 MeV (1984LIZY). See also (1984AJ01) for other channels and (1984KR1B).

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

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

Table 9.2: Energy levels of ^{9}Be

E_x (MeV ± keV)	$J^\pi; T$	Γ_{cm} (keV)	Decay	Reactions
g.s.	$\frac{3}{2}^-; \frac{1}{2}$		stable	2, 3, 4, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 41, 42, 44, 45, 47, 48, 50, 51, 52, 54
1.684 ± 7	$\frac{1}{2}^+$	217 ± 10	γ, n	4, 9, 10, 13, 16, 18, 19, 21, 23, 24, 33, 39, 42, 44
2.4294 ± 1.3	$\frac{5}{2}^-$	0.78 ± 0.13	γ, n, α	4, 9, 10, 11, 12, 16, 17, 18, 19, 21, 22, 23, 24, 26, 27, 33, 34, 35, 36, 38, 39, 41, 42, 44, 50
2.78 ± 120	$\frac{1}{2}^-$	1080 ± 110	n	4, 9, 12, 19, 42, 50
3.049 ± 9	$\frac{5}{2}^+$	282 ± 11	γ, n	4, 9, 16, 18, 19, 21, 23, 24, 33, 39, 42, 44
4.704 ± 25	$(\frac{3}{2})^+$	743 ± 55	γ, n	4, 9, 16, 19, 21, 23, 24, 42, 50
5.59 ± 100 [a]	$(\frac{3}{2}^-)$	1330 ± 360	γ, n	19, 35
6.38 ± 60 [a,b]	$\frac{7}{2}^-$	1210 ± 230	γ, n	9, 11, 16, 17, 18, 19, 21, 23, 24, 26, 34, 35, 38, 44
6.76 ± 60 [a,b]	$\frac{9}{2}^+$	1330 ± 90	γ, n	16, 19
7.94 ± 80 [c]	$(\frac{5}{2}^-)$	≈ 1000		12, 19, 35
11.283 ± 24	$(\frac{7}{2}^-)$	575 ± 50	n	9, 12, 16, 19, 24, 34, 35, 38, 39
11.81 ± 20	$\frac{5}{2}^-$	400 ± 30	γ, n	9, 12, 13, 41, 50
13.79 ± 30	$\pi = -$	590 ± 60	γ, n	9, 16, 19, 41
14.3922 ± 1.8 [d]	$\frac{3}{2}^-; \frac{3}{2}$	0.381 ± 0.033	γ, n, α	9, 16, 19, 23, 39, 41
14.48 ± 90	$(\frac{5}{2}^-); \frac{1}{2}$	≈ 800		19, 34, 35, 39
15.10 ± 50 [a]		350 ± 180	γ	16, 19, 41
15.97 ± 30	$T = \frac{1}{2}$	≈ 300	γ	16, 19, 41
16.671 ± 8	$(\frac{5}{2}^+); \frac{1}{2}$	41 ± 4	γ	9, 16, 19, 39
16.9752 ± 0.8 [e]	$\frac{1}{2}^-; \frac{3}{2}$	0.389 ± 0.010	γ, n, p, d	4, 5, 6, 15, 16, 19
17.298 ± 7	$(\frac{5}{2})^-$	200	γ, n, p, d, α	5, 6, 7, 13, 16, 19

Table 9.2: Energy levels of ^{9}Be (continued)

E_x (MeV $\pm$ keV)	$J^\pi; T$	Γ_{cm} (keV)	Decay	Reactions
17.493 ± 7	$(\frac{7}{2})^+; \frac{1}{2}$	47	γ, n, p, d, α	5, 6, 7, 16, 19
18.02 ± 50			γ	16
18.58 ± 40			γ, n, p, d, α	6, 16
18.650 ± 50 [a,f]	$(\frac{5}{2}^-; \frac{3}{2})$	300 ± 100	p	19
19.20 ± 50		310 ± 80	n, p, d, t	6, 19
19.420 ± 50 [a]		600 ± 300	γ	13, 16, 19
(19.9 ± 200)			γ, n	13
20.51 ± 30 [a]		600 ± 100	γ, p, d	13, 19
20.75 ± 30 [a]		680 ± 90	γ, n, p, t	13, 16, 19
(21.4 ± 200)			γ, n	13
(22.4 ± 200)		broad	γ, n	13, 19
(23.8 ± 200)			γ, n	13
(27.0 ± 500)		broad	γ, n	13

[a] See reaction 19 and Table 9.11.
[b] (1991DI03). See reaction 19; see also (1991GL02). See, however, reaction 35 and Table 9.12.
[c] See reactions 12 and 35.
[d] See Table 9.4.
[e] See Table 9.5.
[f] Spin assignment from (1985PN01).

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

Angular distributions of p_0 have been measured at $E_\alpha = 10.2$ to 14.7 MeV and at 30 MeV: see (1974AJ01). Differential cross sections were measured at $E_\alpha = 26.7$ MeV (1990LI37) in a study of exchange processes. See also (1987BI1C) and (1983BE51).

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

For $E_d = 0.1$ to 1.1 MeV, a resonance in the yield of capture γ-rays is observed at $E_d = 360.8 \pm 0.3$ keV (1987ZI01), 360.7 ± 1.8 keV (1986BE33), corresponding to the excitation of

^{9}Be*(16.97), the second $T = \frac{3}{2}$ state [$J^{\pi} = \frac{1}{2}^{-}$]: see Table 9.5. Another measurement of the total width of this state determined $\Gamma = 389 \pm 10$ eV; see (1992KI05). The reduced width for the isospin "forbidden" deuteron breakup is 3.9×10^{-4} relative to the Wigner limit (1992KI05). See also (1984AJ01). The differential cross section and vector analyzing power were measured by (1993SC19) at $E_{\rm d} = 6$ MeV.

5. (a) ^{7}Li(d, n)^{8}Be	$Q_{\rm m} = 15.0306$	$E_{\rm b} = 16.6959$
(b) ^{7}Li(d, α)^{5}He	$Q_{\rm m} = 14.229$	
(c) ^{7}Li(d, n)^{4}He^{4}He	$Q_{\rm m} = 15.12239$	

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

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

6. ^{7}Li(d, p)^{8}Li	$Q_{\rm m} = -0.19228$	$E_{\rm b} = 16.69594$

Figure 7: Energy levels of ^{9}Be. In these diagrams, energy values are plotted vertically in MeV, based on the ground state as zero. For the $A = 9$ diagrams all levels are represented by discrete horizontal lines. Values of total angular momentum J^{π}, 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 ^{9}Be is the compound nucleus, some typical thin-target excitation functions are shown schematically, with the yield plotted horizontally and the bombarding energy vertically. Bombarding energies are indicated in the lab reference frame, while the excitation function is scaled into the cm reference frame so that resonances are aligned with levels. Excited states of the residual nuclei involved in these reactions have generally not been shown. For reactions in which the present nucleus occurs as a residual product, excitation functions have not been shown. Q values and threshold energies are based on atomic masses from (2003AU03). Further information on the levels illustrated, including a listing of the reactions in which each has been observed, is contained in Table 9.2.

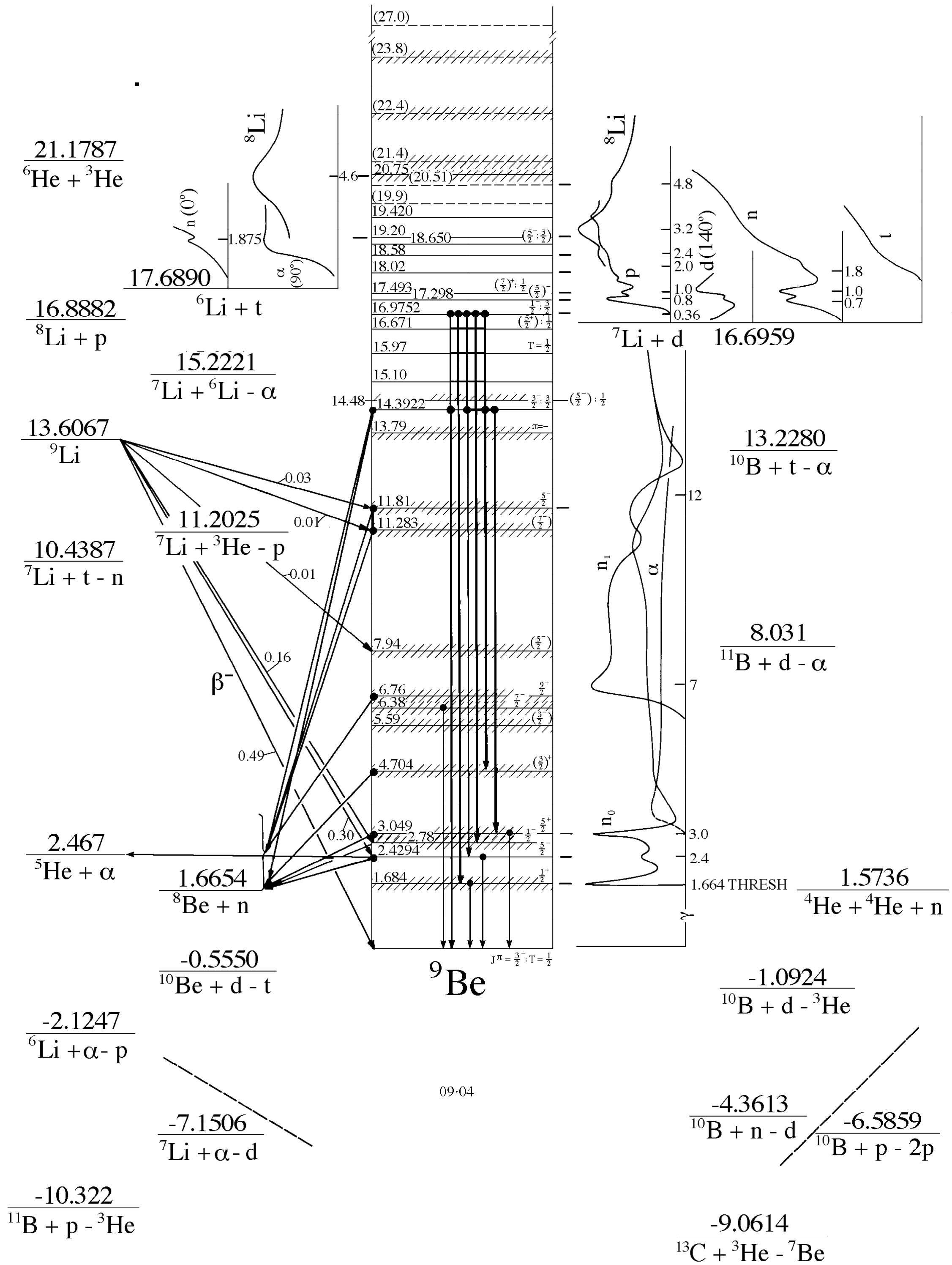
21.1787
^{6}He + ^{3}He
17.6890
^{6}Li + t
16.8882
^{8}Li + p
15.2221
^{7}Li + ^{6}Li - α
13.6067
^{9}Li
11.2025
^{7}Li + ^{3}He - p
10.4387
^{7}Li + t - n
β$^-$
2.467
^{5}He + α
1.6654
^{8}Be + n
-0.5550
^{10}Be + d - t
-2.1247
^{6}Li + α - p
-7.1506
^{7}Li + α - d
-10.322
^{11}B + p - ^{3}He
16.6959
^{7}Li + d
13.2280
^{10}B + t - α
8.031
^{11}B + d - α
1.5736
^{4}He + ^{4}He + n
-1.0924
^{10}B + d - ^{3}He
-4.3613
^{10}B + n - d
-6.5859
^{10}B + p - 2p
-9.0614
^{13}C + ^{3}He - ^{7}Be
^{9}Be
09·04

Table 9.3: Electromagnetic transitions in ^{9}Be

$E_{xi} \to E_{xf}$ (MeV)	$J^\pi_i \to J^\pi_f$ [a]	Γ_γ (eV)	Mult.	Γ_γ/Γ_W
$1.68 \to 0$	$\frac{1}{2}^+ \to \frac{3}{2}^-$	0.30 ± 0.12 [b]	E1	0.22 ± 0.09
$2.43 \to 0$	$\frac{5}{2}^- \to \frac{3}{2}^-$	$(8.9 \pm 1.0) \times 10^{-2}$ [b]	M1	0.30 ± 0.03
		$(1.89 \pm 0.14) \times 10^{-3}$ [b]	E2	24.4 ± 1.8
$3.05 \to 0$	$\frac{5}{2}^+ \to \frac{3}{2}^-$	0.30 ± 0.25 [b]	E1	$(3.6 \pm 3.0) \times 10^{-2}$
$6.38 \to 0$	$\frac{7}{2}^- \to \frac{3}{2}^-$	$(8.2 \pm 3.5) \times 10^{-2}$ [b]	E2	8.5 ± 3.7
$14.39 \to 0$	$\frac{3}{2}^-; \frac{3}{2} \to \frac{3}{2}^-; \frac{1}{2}$	6.60 ± 0.40 [c]	M1	0.106 ± 0.007
$\to 2.43$	$\to \frac{5}{2}^-; \frac{1}{2}$	7.46 ± 0.56 [c]	M1	0.208 ± 0.016
$\to 3.04$	$\to \frac{5}{2}^+; \frac{1}{2}$	1.20 ± 0.28 [c]	E1	$(2.8 \pm 0.7) \times 10^{-3}$
$\to 4.70$	$\to (\frac{3}{2})^+; \frac{1}{2}$	0.84 ± 0.20 [c]	E1	$(3.2 \pm 0.8) \times 10^{-3}$
$16.98 \to 0$	$\frac{1}{2}^-; \frac{3}{2} \to \frac{3}{2}^-; \frac{1}{2}$	16.9 ± 1.0 [d]	M1	0.165 ± 0.010
$\to 1.68$	$\to \frac{1}{2}^+; \frac{1}{2}$	1.99 ± 0.15 [d]	E1	$(1.90 \pm 0.15) \times 10^{-3}$
$\to 2.43$	$\to \frac{5}{2}^-; \frac{1}{2}$	0.56 ± 0.12 [d]	E2	0.94 ± 0.20
$\to 2.78$	$\to \frac{1}{2}^-; \frac{1}{2}$	2.2 ± 0.7 [d]	M1	$(3.7 \pm 1.2) \times 10^{-2}$
$\to 4.70$	$\to (\frac{3}{2})^+; \frac{1}{2}$	2.2 ± 0.3 [d]	E1	$(4.1 \pm 0.6) \times 10^{-3}$

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

[b] See Table 9.8 of (1988AJ01).

[c] See Table 9.4.

[d] See Table 9.5.

Excitation functions and cross sections have been measured for $E_d = 0.29$ to 7 MeV [see (1974AJ01, 1979AJ01, 1984AJ01)] and 0.60 to 0.95 MeV (1983FI13). See also (1983SZZY, 1986AB04). Deuteron energies (in MeV) and widths [Γ_{lab} in brackets in keV] of resonances reported are: $E_d = 0.360 \pm 0.003$ [< 0.5], 0.776 ± 0.007 [250], 1.027 ± 0.007 [60], 2.0 [broad], 2.375 ± 0.050, 3.220 ± 0.050 [400 ± 100] and ≈ 4.8 MeV corresponding to ^{9}Be*(16.975) [see also Table 9.5], 17.298, 17.493, (18.5), 18.54, 19.20, 20.4): for references see Tables 9.3 in (1979AJ01, 1984AJ01). The total cross section at the $E_d = 0.78$ MeV resonance is important because it serves as a normalization for the ^{7}Be(p, γ)^{8}B reaction: the "best" value suggested by (1983FI13) is 157 ± 10 mb. See also (1986BA38) and (1974AJ01, 1984AJ01) for the earlier values. At E (^{7}Li) $= 12.2 \pm 1.3$ MeV [corresponding to $E_d = 3.5$ MeV] the cross section is reported to be 155 ± 20 mb (1985HA40).

At the peak of the $E_d = 0.78$ MeV resonance, $\sigma = 143.6 \pm 8.9$ mb from the proton yield and $\sigma = 151 \pm 20$ mb from the β-delayed α activity of the residual ^{8}Li nucleus (1996ST18).

Table 9.4: Parameters [a] of the first $T = \frac{3}{2}$ states in ^{9}Be and ^{9}B, $J^{\pi} = \frac{3}{2}^{-}$

	^{9}Be		^{9}B
E_x (keV)	14392.2 ± 1.8		14655.0 ± 2.5
Γ_{γ_0} (eV)	6.60 ± 0.40 [b]		(6.97 ± 0.42) [c]
Γ (eV)	365 ± 29		377 ± 38
Γ_{γ_0} (to $\frac{3}{2}^{-}$)/Γ (%)	1.81 ± 0.09		1.85 ± 0.15
Γ_{γ_1} (to $\frac{1}{2}^{+}$)/Γ (%)	< 0.07		< 0.08
Γ_{γ_2} (to $\frac{5}{2}^{-}$)/Γ (%)	2.05 ± 0.11		1.93 ± 0.22
Γ_{γ_3}(to $\frac{1}{2}^{-}$)/Γ (%)	< 0.2		} 0.31 ± 0.18
Γ_{γ_4}(to $\frac{5}{2}^{+}$)/Γ (%)	0.33 ± 0.07		
Γ_{γ_5} (to $\frac{3}{2}^{+}$)/Γ (%)	0.23 ± 0.05		
$\Gamma_{\gamma_2}/\Gamma_{\gamma_0}$	1.13 ± 0.05		1.03 ± 0.11
Γ_{n_0}/Γ	0.028 ± 0.021	Γ_{p_0}/Γ	0.11 ± 0.04
Γ_{n_1}/Γ	0.50 ± 0.11	Γ_{p_1}/Γ	0.33 ± 0.09
$\Gamma_{n_1}/\Gamma_{n_0}$	18 ± 14	$\Gamma_{p_1}/\Gamma_{p_0}$	3.2 ± 1.9
Γ_{γ} (eV)	16.1 ± 1.4		15.4 ± 1.5
Γ_{n_0} (eV)	10 ± 9	Γ_{p_0} (eV)	41 ± 16
Γ_{n_1} (eV)	182 ± 43	Γ_{p_1} (eV)	124 ± 36
Γ_{α} (eV) [d]	156 ± 43 [e]		196 ± 42 [f]

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

[b] Average of 8.1 ± 0.8 eV (1968CL08), 6.2 ± 0.6 eV (1973BE19), 5.9 ± 0.8 eV (1992KI05). Unpublished values of 6.7 ± 1.4 eV and 7.2 ± 0.3 eV are quoted in (1973BE19, 1992KI05).

[c] Assuming the same reduced transition strength as for ^{9}Be.

[d] By subtraction.

[e] $\Gamma_{\alpha_0}/\Gamma_{\gamma_0} = 31.2 \pm 9.8$ (1972AD04) gives $\Gamma_{\alpha_0} = 206 \pm 65$ eV.

[f] $\Gamma_{\alpha_0}/\Gamma_{p_1} \approx 1.4$ (2001BE51) gives $\Gamma_{\alpha_0} \approx 174$ eV.

In (1998WE05), a value $\sigma = 155 \pm 8$ mb was obtained, backscattering effects were examined, and the consequences for the ^{7}Be(p, γ) cross sections were discussed. The ^{7}Li(d, p) yield for $E_{\rm d} = 0.4$–1.8 MeV was measured by (1998ST20) to deduce corrections due to recoil loss. See also the compilation and analysis of astrophysical S-factor data and calculations in (1998AD12).

7. ^{7}Li(d, d)^{7}Li $\qquad E_{\rm b} = 16.69594$

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

8. ^{7}Li(d, t)^{6}Li $\qquad Q_{\rm m} = -0.99306 \qquad E_{\rm b} = 16.69594$

The cross section rises steeply from threshold to 95 mb at $E_{\rm d} = 2.4$ MeV and then more slowly to ≈ 165 mb at $E_{\rm d} = 4.1$ MeV. The t_0 yield curve ($\theta_{\rm lab} = 155°$) decreases monotonically for $E_{\rm d} = 10.0$ to 12.0 MeV: see (1974AJ01). Differential cross sections measured at $E_{\rm d} = 30.7$ MeV were reported in (1987BO39). An analysis of data from this reaction at $E_{\rm d} = 8$–50 MeV is discussed in (1995GU22).

9. ^{7}Li(^{3}He, p)^{9}Be $\qquad Q_{\rm m} = 11.2025$

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

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

10. ^{7}Li(α, d)^{9}Be $\qquad Q_{\rm m} = -7.1506$

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

Table 9.5: Parameters [a] of the second $T = \frac{3}{2}$ state in ^{9}Be, $J^\pi = \frac{1}{2}^-$

E_x (keV)	16975.2 ± 0.8
$\Gamma_{c.m.}$ (eV)	389 ± 10
Γ_γ (eV)	23.8 ± 1.6
Γ_{γ_0} (eV)	16.9 ± 1.0 [c]
Γ_{γ_1} (eV)	1.99 ± 0.15
Γ_{γ_2} (eV)	0.56 ± 0.12
Γ_{γ_3} (eV)	2.2 ± 0.7
Γ_{γ_4} (eV) [b]	< 0.8
Γ_{γ_5} (eV) [b]	2.2 ± 0.3
Γ_n (eV)	< 290 [d]
Γ_{n_0} (eV)	36^{+36}_{-18}
Γ_p (eV)	12^{+12}_{-6}
Γ_d (eV)	62 ± 10
Γ_{α_0} (eV)	< 290

[a] (1992KI05). These are revised values of the partial widths given in Table 9.4 of (1988AJ01). They are based on the resonant absorption measurements of (1992KI05).
[b] See Table 9.4 of (1988AJ01).
[c] See also Table 9.8 of (1988AJ01).
[d] $\Gamma_\alpha + \Gamma_n = 290 \pm 20$ eV.

11. ^{7}Li(^{6}Li, α)^{9}Be $\qquad Q_m = 15.2221$

Angular distributions of the α-groups to ^{9}Be*(0, 2.43, 6.76) have been measured at $E(^7\text{Li}) = 78$ MeV (1989GL03). For the excitation of ^{4}He* see (1987GLZX, 1987GLZY; $E(^6\text{Li}) = 93$ MeV). For the earlier work see (1974AJ01).

12. ^{9}Li(β^-)^{9}Be $\qquad Q_m = 13.6067$

^{9}Li decays by β^- emission with $\tau_{1/2} = 178.3 \pm 0.4$ msec and $P_n = 50.8 \pm 0.9$% to several ^{9}Be states: see reaction 1 in ^{9}Li and Table 9.8. A series of studies at ISOLDE (1981LA11, 1990NY01, 2003PR11) have measured β-α coincidences and established the existence of transitions with large

Table 9.6: Excited states of ^{9}Be from ^{7}Li(^{3}He, p)^{9}Be [a]

E_x (MeV $\pm$ keV)	$\Gamma_{c.m.}$ (keV)
1.64	
2.4292 ± 1.7	< 8
2.9 ± 250	1000 ± 250
3.076 ± 15	289 ± 22
4.704 ± 25	743 ± 55
6.7 ± 100	2000 ± 200
11.29 ± 30	620 ± 70
11.81 ± 20	400 ± 30
13.78 ± 30	590 ± 60
14.396 ± 5 [b]	0.38 ± 0.03
16.671 ± 8	41 ± 4

[a] See also Tables 9.4 in (1974AJ01, 1979AJ01) for references.
[b] See also Table 9.4.

B(GT) values to ^{9}Be*(11.28) and/or ^{9}Be*(11.81). The information in Table 9.8 is based largely on the results of (1990NY01) and an analysis by (1993CH06). The most recent study (2003PR11) finds that the low-energy decays are mostly to ^{9}Be*(11.81) with a B(GT) value of 8.5 ± 1.5, that a spin assignment of $\frac{5}{2}^-$ is favored, and note that the B(GT) value is a factor of 4.4 ± 1.0 larger than that of the mirror transition in ^{9}C (see reaction 10 in ^{9}B). Such a large asymmetry for a strong transition and the magnitude of the B(GT) value for ^{9}Li decay are difficult to understand theoretically. The latter difficulty is highlighted by the fact that, in the limit of good supermultiplet symmetry only $\frac{1}{3}$ of the GT sum-rule strength $9(g_A/g_V)^2_{\rm eff}$ [see footnote [c] in Table 9.8] goes to $\frac{5}{2}^-$ states.

13. (a) ^{9}Be(γ, n)^{8}Be $Q_m = -1.6654$
    (b) ^{9}Be(γ, α)^{5}He $Q_m = -2.467$
    (c) ^{9}Be(γ, n)^{4}He^{4}He $Q_m = -1.5736$

As noted in the previous review (1988AJ01), "the photoneutron cross section has been measured from threshold to 320 MeV: see Table 9.6 in (1966LA04), (1979AJ01) and (1988DI02). A pronounced peak occurs $\approx$ 29 keV above threshold with $\sigma_{max} = 1.33 \pm 0.24$ mb. The shape of the resonance has been measured very accurately for $E_\gamma = 1675$ to 2168 keV. The FWHM of the peak is estimated to be 100 keV (1982FU11). See also (1983BA52) and (1987KU05). The cross

Table 9.7: Neutron decay of ^{9}Be states [a]

^{9}Be state (MeV)	Γ_{cm} [b] (keV)	l_n [c]	Decay (in %) to		S [d]
			^{8}Be$_{g.s.}$	^{8}Be*(3.0)	
2.43	0.77	3	7.0 ± 1.0		0.047
2.78	1080	1	mainly		0.67
3.05	282	2	87 ± 13		1.24
4.70	743	2	13 ± 4		0.080
6.67 [e]	1210	3	≤ 2		< 0.044
		1		55 ± 14	0.47
11.28	575	3	≤ 2		< 0.003
		1		14 ± 4	0.014
11.81	400	3	≤ 3		< 0.003
		1		12 ± 4	0.008

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

[b] See Table 9.2.

[c] The l_n values for the 11.28 and 11.81 MeV levels reflect the probable assignments of $\frac{7}{2}^-$ and $\frac{5}{2}^-$, respectively.

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

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

section then decreases slowly to 1.2 mb at 40 keV above threshold. From bremsstrahlung studies, peaks in the (γ, n) cross section are observed corresponding to $E_x = 1.80$ and 3.03 MeV".

Subsequently (1992GO27) measured the photoneutron yield and mean energies of photoneutron spectra from bremsstrahlung photons. The reaction cross section for energies from threshold to 20 MeV was extracted. Resonances were observed corresponding to $E_x = 1.68$ MeV ($\frac{1}{2}^+$), 2.43 MeV ($\frac{5}{2}^-$), and 3.05 MeV ($\frac{5}{2}^+$) in ^{9}Be. See Table 1 in (1992GO27) for resonance parameters. In other work (2001UT01, 2002SU19), laser-induced Compton backscattering photons with $E_\gamma = 1.78$–6.11 MeV were used to measure the photoneutron cross section resonance parameters for the ^{9}Be $\frac{1}{2}^+$, $\frac{5}{2}^-$ and $\frac{5}{2}^+$ states; see Table 9.9. The radiative widths in Table 9.9 are not in good agreement with those from low-energy electron scattering listed in Table 9.3. Also, the width given for the $\frac{5}{2}^+$ state is roughly twice the accepted width of 282 ± 11 keV in Table 9.2; using the accepted width while maintaining a fit to the peak (γ, n) cross section would reduce Γ_γ by almost a factor of two and into the range of the values from (e, e′) listed in Table 9.3. Shell-model calculations give a stable B(M1)$\downarrow \approx 1$ W.u. ($\Gamma_\gamma \approx 0.45$ eV) for the broad $\frac{1}{2}^-$ state at 2.78 MeV implying significant (γ, n) cross section underlying the energy region of interest. A one-level R-matrix analysis of the $E_\gamma = 1.6$–2.2 MeV cross section is described in (2000BA21). The energy at which the cross section due to the $\frac{1}{2}^+$ state peaks and the FWHM of the peak vary somewhat for different fits to a number of data sets but are relatively stable. However, the extracted B(E1)$\downarrow$ values vary considerably and generally correspond to larger Γ_γ's than those listed in Table 9.3 and Table 9.9. For theoretical calculations of the low-energy (γ, n) cross section see (1998EF05, 1999EF01, 2002IT07). See also the calculation of ^{9}Be Coulomb dissociation (1994KA25) and polarized neutron production by magnetic Bremsstrahlung gamma rays (1997ER03).

(1988AJ01) notes that "at higher energies, using monoenergetic photons, the (γ, n) cross section is found to be relatively smooth from $E_\gamma = 17$ to 37 MeV with weak structures which correspond to $E_x = 17.1$, 18.8, 19.9, 21.4, 22.4, 23.8 [± 0.2] MeV and 27 ± 0.5 MeV (broad). In the range $E_\gamma = 18$ to 26 MeV the integrated (γ, n_0) cross section is < 0.1 MeV · mb, that for (γ, n_1) $= 2.4 \pm 0.4$ MeV · mb and the combined integrated cross section for (γ, n) to ^{8}Be*(16.6) and (γ, α_0) to ^{5}He$_{\rm g.s.}$ is 13.1 ± 2 MeV · mb".

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

14. (a) ^{9}Be(γ, p)^{8}Li $Q_m = -16.8882$
(b) ^{9}Be(γ, n + p)^{7}Li $Q_m = -18.9205$
(c) ^{9}Be(γ, d)^{7}Li $Q_m = -16.6959$

Table 9.8: Branching ratios in ^{9}Li(β^-) decay from measurements of β-delayed particle decay [a]

E_x in ^{9}B (MeV)	J^π	Branching ratio (%) [b]	B(GT) [c]
0	$\frac{3}{2}^-$	49.2 ± 0.9 [d]	0.0292 ± 0.0009
2.43	$\frac{5}{2}^-$	29.7 ± 3.0 [e]	0.046 ± 0.005
2.78	$\frac{1}{2}^-$	15.8 ± 3.0 [e]	0.011 ± 0.005 [g]
7.94	$(\frac{5}{2}^-)$ [b]	1.5 ± 0.5 [f]	0.048 ± 0.018 [g]
11.28	[h]	1.1 ± 0.2 [e]	1.4 ± 0.5 [g]
11.81	$\frac{5}{2}^-$ [i]	2.7 ± 0.2 [e]	8.9 ± 1.9 [g]

[a] See also Table 9.7 of (1988AJ01).

[b] Based on Tables II and III of (1993CH06) taking into account the different value for P_n.

[c] B(GT) includes the factor $(g_A/g_V)^2$. The empirical quenching found by (1993CH06) gives $(g_A/g_V)^2_{\rm eff} = 1.14$ and permits a comparison with p-shell calculations.

[d] Obtained using $P_n = 50.8 \pm 0.9$%, which is the average of 50.0 ± 1.8% (1991RE02) and 51.0 ± 1.0% (1992TE03).

[e] (1990NY01).

[f] (1981LA11). (1990NY01) give a branch of < 2%.

[g] For decay to an unbound level B(GT) is not well defined. (1990NY01) deduce B(GT) taking into account the variation of the statistical factor over the width of the final states and the considerable error in this procedure is reflected in the errors tabulated.

[h] A $\frac{7}{2}^-$ level is known at this energy. A strong β transition implies $J^\pi = \frac{1}{2}^-, \frac{3}{2}^-$, or $\frac{5}{2}^-$, with $\frac{5}{2}^-$ unlikely on theoretical grounds given that the 11.8 MeV state has been assigned $\frac{5}{2}^-$.

[i] (2003PR11) find that the decay mainly populates the 11.8 MeV state, determine a spin of $\frac{5}{2}^-$, and extract a B(GT) value of 8.5 ± 1.5.

Table 9.9: Resonance parameters for ^{9}Be(γ, n)^{8}Be [a]

J^π	Mult.	$E_{\rm R}$ (MeV)	Γ_γ (eV)	$\Gamma \approx \Gamma_{\rm n}$ (keV)
$\frac{1}{2}^+$	E1	1.735 ± 0.003	0.568 ± 0.011	225 ± 12
$\frac{5}{2}^-$	M1	2.43	0.049 ± 0.012	
$\frac{5}{2}^+$	E1	3.077 ± 0.009	1.24 ± 0.02	549 ± 12

[a] From Table 1 of (2002SU19); see also Table I of (2001UT01), and reaction 13 here.

(d) ^{9}Be(γ, t)^{6}Li $\qquad$ $Q_{\rm m} = -17.6890$

The yield shows structure in the energy region corresponding to the ^{9}Be levels at 17–19 MeV followed by the giant resonance at $E_\gamma \approx 23$ MeV ($\sigma = 2.64 \pm 0.30$ mb). Structure attributed to eleven states of ^{9}Be with $18.2 < E_{\rm x} < 32.2$ MeV has also been reported. Integrated cross sections have been obtained for each of these resonances, and over different energy intervals for protons leading to ^{8}Li*($0 + 0.98$, $2.26 + 3.21$, 9.0, 17.0). Angular and energy distributions of phototoprotons in various energy intervals have been studied by many groups: see (1974AJ01) for early references. For momentum spectra of protons using tagged photons with $E_\gamma = 360$–600 MeV, see (1984BA09). See also (1984AJ01) and (1984HO24), and see the analysis for $E_\gamma = 200$–420 MeV by (1988TE04).

The integrated cross sections are reported to be 1.0 ± 0.5 MeV $\cdot$ mb ($E_\gamma = 21$–33 MeV) for reaction (c) to ^{7}Li*($0 + 0.4$), and 0.6 ± 0.3 MeV $\cdot$ mb ($E_\gamma = 25$–33 MeV) for reaction (d) to ^{6}Li$_{\rm g.s.}$. The total integrated cross section for [(γ, p)+(γ, pn)+(γ, d)+(γ, t)] is 33±3 MeV·mb. Calculations for reaction (b) at $E_\gamma = 247$ MeV are presented in (1993BO35). Resonances in the (γ, d) and (γ, t) cross sections corresponding to ^{9}Be*(26.0 ± 0.2) and ^{9}Be*(32.2 ± 0.3), respectively, have been reported: see (1974AJ01). A recent measurement and cluster-model analyses for reactions (a), (c), (d) for $E_\gamma = 21$–39 MeV are described in (1999SH05). For momentum spectra of deuterons and tritons at $E_\gamma = 360$–600 MeV see (1986BA07). Cross sections have been measured in the region of the $\Delta(1232)$ resonance by (1984HO09) [(γ, pn), (γ, 2p)], (1987KA13) [(γ, p), (γ, pn), (γ, 2p)] and (1986AR06) [(γ, π^0)]. For a high energy study of hadron production see (1983AR24). See also (1986MC1G), (1985HO27, 1985MA1G) and the calculations of (1983TR04, 1986HO11, 1987LU1B, 1988DU04).

15. ^{9}Be(γ, γ)^{9}Be

The ground state radiative widths of the $E_{\rm x} = 14.393$ and 16.975 MeV $T = \frac{3}{2}$ levels of ^{9}Be have been measured in a resonant absorption experiment (1992KI05) that updates the results of (1986ZI01, 1987ZI01). The results are $\Gamma_{\gamma_0} = 5.9 \pm 0.8$ eV and $\Gamma_{\gamma_0} = 16.9 \pm 1.0$ eV for

$E_x = 14.393$ and 16.975 MeV, respectively. See Tables 9.4 and 9.5. With $E_{\rm brem} = 31$ MeV eight resonances in (γ, γ') were reported for $17.4 < E_x < 29.4$ MeV (1984AL22).

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

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

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

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

$$\langle r^2\rangle^{1/2} = 2.519 \pm 0.012 \text{ fm (1973BE19, 1979AJ01)}, Q = 5.86 \pm 0.06 \text{ fm}^2 \text{ (1991GL02)},$$

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

$\langle r^2\rangle^{1/2}_{\rm M} = 3.2 \pm 0.3$ fm; $\Omega = 6 \pm 2\ \mu_{\rm N} \cdot {\rm fm}^2$ [this value of the magnetic octupole moment implies a deformation of the average nuclear potential] (1975LA23, 1979AJ01).

The previous review (1988AJ01) observed that: "The elastic scattering of electrons has been studied for E_e up to 700 MeV. Magnetic elastic scattering gives indications of both M1 and M3 contributions. Inelastic scattering populates a number of levels: see Table 9.8 in (1988AJ01). At $E_e = 45$ and 49 MeV ^{9}Be*(1.68) has a strongly asymmetric line shape, as expected from its closeness to the ^{8}Be + n threshold. The form factor is dominated by a 0p$_{3/2}$ →1s$_{1/2}$ particle-hole transition. ^{9}Be*(2.43) is strongly excited (1987KU05). Form factors have also been measured for ^{9}Be*(0, 14.39, 16.67, 16.98, 17.49) by (1983LO11; $E_e = 100.0$ to 270.2 MeV). See also (1985HY1A, 1986MA48, 1987HY01). (1984WO09) suggests that the $T = \frac{1}{2}$ states [^{9}Be*(16.67, 17.49)] have $J^\pi = \frac{5}{2}^+$ and $\frac{7}{2}^+$, respectively, and that they have large parentage amplitudes with ^{8}Be*$(16.6 + 16.9)$ [$J^\pi = 2^+$], rather than with ^{8}Be$_{\rm g.s.}$. See (1974AJ01, 1979AJ01, 1984AJ01)".

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

A previously unknown state at 6.38 MeV was isolated from the known 6.76 MeV state in both the (e, e′) data of (1991GL02) and the (p, p′) data (1991DI03) using the dependence of the peak position upon momentum transfer. On the basis of the form factor the 6.38 MeV state replaces the 6.76 MeV state as the $\frac{7}{2}^-$ member of the ground state rotational band, and the 6.76 MeV state is identified with the lowest $\frac{9}{2}^+$ state predicted by the shell model. Results of these measurements are tabulated and compared with the shell model prediction in Table V in (1991GL02) and in Table 9.10 here.

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

For early work in the quasifree and Δ-resonance regions see references cited in (1988AJ01).

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

Table 9.10: Electromagnetic matrix elements for ^{9}Be(e, e′) [a]

$E_{\text{expt.}}$ (MeV)	$E_{\text{theor.}}$ [b] (MeV)	J^π	Matrix element [c]	(e, e′) [d]	Other	Theory [e]
0	0	$\frac{3}{2}^-$	Q(fm^2)	5.86 ± 0.06	5.3 ± 0.3 [f]	4.35
			μ (μ_{N})	-1.16 ± 0.02	-1.1778 ± 0.0009 [f]	-1.27
			B(M3)	4.4 ± 0.3		9.72
			B(C2)	17.1 ± 0.3		9.43
1.68	1.68	$\frac{1}{2}^+$	B(C1)	0.034 ± 0.003	0.027 ± 0.002 [g]	0.0045
			B(M2)	0.023 ± 0.008	0.097 ± 0.017 [g]	0.022
2.43	2.64	$\frac{5}{2}^-$	B(C2)	46.0 ± 0.5	41.6 ± 2.9 [h]	32.2
			B(M1)	0.0090 ± 0.0003	0.0089 ± 0.0010 [h]	0.0068
			B(M3)	0.5 ± 0.3		2.22
3.05	2.87	$\frac{5}{2}^+$	B(C1)	0.029 ± 0.005	0.015 ± 0.013 [h]	0.0039
			B(M2)	0.16 ± 0.02		0.018
			B(C3)	0.9 ± 0.6		12.5
			B(M4)	58 ± 3		127.6
6.38	6.19	$\frac{7}{2}^-$	B(C2)	33 ± 1	25.6 ± 1.4 [i]	12.7
6.76	6.39	$(\frac{9}{2}^+)$ [j]	B(C3)	216 ± 5		17.6
			B(M4)	174 ± 16		223.8
	7.52	$\frac{5}{2}^+$	B(C3)			25.7
	8.17	$\frac{3}{2}^+$	B(C3)			19.3
11.28	8.46	$(\frac{7}{2}^+)$ [j]	B(C3)	57 ± 6		26.5
			B(M4)			35.9

[a] Adapted from Table V of (1991GL02).

[b] Normalized to the ground-state for negative-parity levels and to the $\frac{1}{2}^+$ state for positive-parity levels.

[c] The units of B(CJ) and B(MJ) are both e^2 fm^{2J}.

[d] Polynomial-Gaussian expansion (PGE) fits (1991GL02). The error is from the statistical error on the leading polynomial coefficient and is dependent on the number of terms in the polynomial.

[e] Harmonic oscillator (HO) wave functions with $b = 1.765$ fm, $e_{\text{p}} + \delta\ e_{\text{p}} + \delta\ e_{\text{n}} = 1.6e$, $e_{\text{p}} + \delta\ e_{\text{p}} - \delta\ e_{\text{n}} = 0.7e$, and bare nucleon g factors (1991GL02).

[f] From (1988AJ01).

[g] Low q (e, e′) from (1987KU05).

[h] Low q (e, e′) from (1968CL08). Data from (1968CL08) is included in the fits of (1991GL02).

[i] Low q (e, e′) from (1963NG01).

[j] Suggested identifications (1991GL02).

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

18. (a) ^{9}Be(n, n)^{9}Be
(b) ^{9}Be(n, 2n)^{8}Be $\qquad Q_{\rm m} = -1.6654$

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

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

For reaction (b) the n-n scattering length was measured at $E_{\rm n} = 10.3$ MeV (1990BO43). A thick target neutron spectrum was used in a measurement of the reaction cross section by (1994ME08). See also the analysis and model calculations for ^{9}Be(n, 2n) at $E_{\rm n} = 5.9$ MeV (1988BE04).

19. (a) ^{9}Be(p, p)^{9}Be
(b) ^{9}Be(p, p$'$)^{9}Be*

The previous review (1988AJ01) summarized the information available from the reaction as follows: "Elastic and inelastic angular distributions have been studied at many energies in the range $E_{\rm p} = 2.3$ to 1000 MeV [see (1974AJ01, 1979AJ01, 1984AJ01)], at $E_{\rm p} = 2.31$ to 2.73 MeV (1983AL10; p_0), 11 to 17 MeV (1988AJ01; p_0) and 1 GeV (1985AL16; p_0) as well as at $E_{\vec{\rm p}} = 200$ MeV (1985GLZZ; p_0) and 220 MeV (1985RO15; p_0, p_2). The elastic distributions show pronounced diffraction maxima. A quadrupole-deformed optical-model potential is necessary to obtain a good fit to the p_0 and p_2 angular distributions: see (1974AJ01). The spin-flip probability at $E_{\vec{\rm p}} = 31$ MeV is ≈ 0 for the p_2 group, which is expected in view of the collective nature of the transition (1981CO08)."

"The structure corresponding to ^{9}Be*(1.7) is asymmetric, as expected: see reaction 16 and Table 9.8 in (1988AJ01) for its parameters. [At $E_{\rm p} = 13$ MeV the spectra are dominated by

Table 9.11: Energy levels (E_x) and widths (Γ) for ^{9}Be states observed in ^{9}Be(p, p′) [a]

E_x (MeV)	Γ (MeV)	$J^\pi; T$	Comments
0		$\frac{3}{2}^-; \frac{1}{2}$	
1.680 ± 0.015	0.217 ± 0.010	$\frac{1}{2}^+; \frac{1}{2}$	
2.4294 ± 0.0013		$\frac{5}{2}^-; \frac{1}{2}$	
2.78 ± 0.12	1.08 ± 0.11	$\frac{1}{2}^-; \frac{1}{2}$	
3.049 ± 0.009	0.282 ± 0.011	$\frac{5}{2}^+; \frac{1}{2}$	
4.704 ± 0.025	0.743 ± 0.055	$\frac{3}{2}^+; \frac{1}{2}$	
5.59 ± 0.10*	1.33 ± 0.36*	$(\frac{3}{2}^-; \frac{1}{2})$	
6.38 ± 0.06*	1.21 ± 0.23*	$(\frac{7}{2}^-; \frac{1}{2})$	clearly member of $K = \frac{3}{2}^-$ band
6.76 ± 0.06	1.33 ± 0.09*	$(\frac{9}{2}^+; \frac{1}{2})$	assignment based on C3 angular distribution
11.28 ± 0.05*	1.10 ± 0.23*	$(\frac{7}{2}^+; \frac{1}{2})$	weak assignment based on C3 shape
13.79 ± 0.03	0.59 ± 0.06	$(\frac{5}{2}^-; \frac{1}{2})$	also consistent with $J^\pi; T = \frac{7}{2}^-; \frac{1}{2}$
14.3926 ± 0.0018		$\frac{3}{2}^-; \frac{3}{2}$	
14.4 ± 0.3	≈ 0.8		
15.10 ± 0.05	0.35 ± 0.18*		
15.97 ± 0.05	≈ 0.310	$(\frac{5}{2}^-; \frac{1}{2})$	also consistent with $J^\pi; T = \frac{7}{2}^-; \frac{1}{2}$
16.671 ± 0.008	0.041 ± 0.004	$\frac{5}{2}^+; \frac{1}{2}$	
16.976 ± 0.002		$\frac{1}{2}^-; \frac{3}{2}$	
17.297 ± 0.010	≈ 0.2	$(\frac{5}{2}^-; \frac{3}{2})$	
17.490 ± 0.009	0.047	$\frac{7}{2}^+; \frac{1}{2}$	
18.65 ± 0.05*	0.3 ± 0.1*	$(\frac{3}{2}^+; \frac{3}{2})$	assignment based on M2 shape
19.20 ± 0.05	0.31 ± 0.08		
19.42 ± 0.05*	0.6 ± 0.3*	$(\frac{9}{2}^+, \frac{3}{2})$	assignment based on M4 shape
20.53 ± 0.03*	0.6 ± 0.1*		
20.8 ± 0.1*	0.68 ± 0.09*		

[a] As presented in Table I of (1991DI03). New values for positions or widths are marked with asterisks (*). Widths smaller than 40 keV were neglected. Proposed assignments are given within parentheses. Unmarked parameters are taken from (1988AJ01).

^{9}Be*(2.43) (1987KU05)]. The weighted mean of the values of E_x for ^{9}Be*(2.4) listed in (1974AJ01) is 2432 ± 3 keV. ^{9}Be*(3.1) has $E_x = 3.03 \pm 0.03$ MeV, $\Gamma = 250 \pm 50$ keV, $J^\pi = (\frac{3}{2}^+, \frac{5}{2}^+)$. Higher states are observed at (E_x and Γ in MeV) $E_x = 4.8 \pm 0.2$, 6.76 ± 0.06 [$J^\pi = (\frac{1}{2}^+, \frac{5}{2}^+, \frac{7}{2}^+)$ (but see below), $\Gamma = 1.2 \pm 0.2$], 7.94 ± 0.08 ($\Gamma \approx 1$), 11.3 ± 0.2 ($\Gamma \approx 1$), 14.4 ± 0.3 ($\Gamma \approx 1$), 16.7 ± 0.3, 17.4 ± 0.3, 19.0 ± 0.4, 21.1 ± 0.5 and 22.4 ± 0.7 [the five highest states are all broad]. The strong population of ^{9}Be*(2.4, 6.8) is consistent with the assumption that they have $J^\pi = \frac{5}{2}^-$ and $\frac{7}{2}^-$, respectively, and are members of the ground state $K = \frac{3}{2}^-$ band. See (1966LA04, 1974AJ01) for references."

In an experimental and theoretical study of ^{9}Be structure (1991DI03), cross section and analyzing power measurements made with 180 MeV protons provided data for 24 states below $E_x = 21$ MeV. Detailed line shape analysis was used to isolate several broad states. In particular the strong resonance at 6.76 MeV (1988AJ01) was separated into two levels identified as the $\frac{7}{2}^-$ member of the ground state rotational band at 6.38 MeV and the $\frac{9}{2}^+$ weak-coupling state at 6.76 MeV. Level energies, suggested assignments and widths are summarized in Table 9.11. Transition densities were fitted to (p, p′) data and compared with results from (e, e′) data (1991GL02). Shell model calculations in $0\hbar\omega$ and $1\hbar\omega$ model space were performed and used in making suggested assignments (1991DI03).

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

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

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

The reactions (p, 2p)X and (p, pd)X have been studied at $E_p = 300$ MeV (1983GR21, 1984HE03). For reactions (a) and (c) see also ^{8}Li, ^{8}Be (1985BE30 , 1985DO16; 1 GeV) and (1984AJ01). Reaction (c) at $E_p = 10$–24 MeV involves ^{9}Be*(3.0, 4.7): see (1984AJ01). See also (1984WA21). For reactions (b) and (d) at $E_p = 58$ MeV see ^{7}Li and ^{6}Li in (2002TI10), and (1984DE1F, 1985DE17). For reactions (e) and (f) see (1985PAZL; $E_{\vec{p}} = 70$ MeV). The (p, pα) process (reaction (f)) has been studied at $E_p = 150.5$ MeV (1985WA13), at 200 MeV (1989NA10), and at 296 MeV (1998YO09). Alpha cluster knockout spectroscopic factors were deduced. For inclusive proton spectra yields see (1985SE15). Inclusive differential cross sections for ^{4,6,8}He and ^{6,7,8}Li formation by 1 GeV protons on ^{9}Be were measured by (1994AM09). Cross section and proton and neutron spectra for reactions (a) and (c) at $E_p = 70$ MeV were studied by (2000SH01). See also the earlier work cited in (1988AJ01).

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

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

Inelastic groups have been reported to ^{9}Be*(1.7, 4.7, 6.8) and to states with $E_x = 2431.9 \pm 7.0$ keV and 3040 ± 15 keV ($\Gamma = 294 \pm 20$ keV): see (1974AJ01). Measurements at $E_d = 6.7$–7.5 MeV of differential cross sections for inelastic groups to ^{9}Be*(2.43) and DWBA analysis were reported by (1989SZ02). An analysis by (1989VA17) of (d, d$'$) data at $E_d = 13.6$ MeV found evidence for kinematic focusing of the products of 3-particle decay of ^{9}Be*(2.43). An optical-model description for $E_d = 4$–11 MeV is discussed in (1993AB10).

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

(b) ^{9}Be(t, n + t)^{8}Be $\qquad Q_m = -1.6654$

Angular distributions of elastically scattered tritons have been measured at $E_t = 2.10$ MeV and at $E_{\vec{t}} = 15$ and 17 MeV: see (1974AJ01, 1984AJ01). A more recent analysis by a strong absorption model of cross sections measured at $E_t = 17$ MeV is reported in (1994SO26). Reaction (b) at 4.2 and 4.6 MeV proceeds via ^{9}Be*(2.4): see (1974AJ01).

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

(b) ^{9}Be(^{3}He, 2α)^{4}He $\qquad Q_m = 19.0041$

Angular distributions have been studied for $E(^3\text{He}) = 1.6$ to 46.1 MeV and at 217 MeV [see (1974AJ01, 1979AJ01, 1984AJ01)]. At $E(^3\text{He}) = 39.8$ MeV, ^{9}Be*(1.7, 2.4, 3.1, 4.7, 6.8, 14.4) are populated. Data for $E(^3\text{He}) = 50$, 60 MeV were analyzed by (1992AD06), and rainbow effects were observed. Differential cross sections for $E(^3\text{He}) = 60$ MeV were measured by

(1993MA48, 1996RU13). Measurements and analysis of the α-particle spectra from the decay of ^{9}Be*(2.43) populated in the inelastic scattering reaction with $E(^3\text{He}) = 40.5$ MeV are reported in (1990BO51). An optical model description of the elastic scattering is discussed in (1987TR01).

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

24. (a) ^{9}Be(α, α)^{9}Be

(b) ^{9}Be(α, 2α)^{5}He $\qquad Q_\text{m} = -2.467$

Angular distributions have been studied at many energies in the range $E_\alpha = 5.0$ to 104 MeV [see (1974AJ01, 1984AJ01)] and $E_\alpha = 23.1$ MeV (1984HU1D, 1985HU1B; α_0, α_2). At $E_\alpha = 35.5$ MeV, states belonging to the $K = \frac{3}{2}^-$ ground-state band are strongly excited [^{9}Be*(0, 2.43, 6.76, 11.28); it is suggested that the latter has $J^\pi = (\frac{9}{2}^-)$; see, however, reaction 12]. The first three states belonging to the $K = \frac{1}{2}^+$ band are also excited [^{9}Be*(1.68, 3.05, 4.70)] (1982PE03; coupled channels analysis). A coupled channel folding model analysis for data at $E_\alpha = 65$ MeV is described in (1995RO21). See also (2000ZH38).

See also the multicluster model calculation of (1993KU21) and the calculations of levels and rotational bands using (α, α') data reported in (1997VO06). In application-related work backscattering cross sections were measured for $E_\alpha = 6.00$–6.52 MeV (1996QI03), 0–5.3 MeV (1994LE18), 0.15–3.0 MeV (1994LI51). Related data were compiled and reviewed in (1991LE33, 1996ZH36). For reaction (b) see (1983ZH09; 18 MeV); $S_\alpha = 0.96$ [see (1984AJ01)] and (1987WA25; $E(^3\text{He}) = 12$ to 24 MeV). A measurement of energy-sharing distributions at $E_\alpha = 197$ MeV was reported in (1994CO16). Cluster knockout at $E_\alpha = 580$ MeV was studied by (1999NA05). See also ^{8}Be, (1987BU27, 1987KO1K) and (1984LI28, 1985SR01).

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

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

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

(b) ^{9}Be(^{7}Li, ^{7}Li)^{9}Be

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

For reaction (b), cross section measurements at $E(^{7}\text{Li}) = 63$, 130 MeV and optical-model analyses are reported in (2000TR01). The α-^{5}He decay of ^{9}Be excited states populated by $E(^{7}\text{Li}) = 52$ MeV was studied by (1998SO05).

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

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

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

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

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

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

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

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

Elastic angular distributions have been measured at $E(^{14}\text{N}) = 25$ and 27.3 MeV: see (1974AJ01). For a fusion study see (1984MA28).

31. (a) ^{9}Be(^{16}O, ^{16}O)^{9}Be
(b) ^{9}Be(^{18}O, ^{18}O)^{9}Be

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

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

Elastic angular distributions have been measured for many of these reactions: see (1979AJ01, 1984AJ01). They have been studied on ^{26}Mg and ^{40}Ca at $E(^{9}\text{Be}) = 43$ and 45 MeV, respectively (1985WI18) and on ^{26}Mg, ^{27}Al and ^{40}Ca at $E(^{9}\text{Be}) = 158.1$–158.3 MeV (1984FU10). For pion production in reaction (a) see (1985FR13). The interaction cross section for 790 MeV/A ^{9}Be on

^{27}Al has been measured by (1985TA18). Breakup measurements involving ^{40}Ca are reported by (1984GR20). See also the other references cited in (1988AJ01).

33. ^{10}Be(d, t)^{9}Be $\quad Q_{\rm m} = -0.5550$

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

34. ^{10}B(γ, p)^{9}Be $\quad Q_{\rm m} = -6.5859$

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

35. ^{10}B(e, e′p)^{9}Be $\quad Q_{\rm m} = -6.5859$

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

36. ^{10}B(n, d)^{9}Be $\quad Q_{\rm m} = -4.3613$

See (1974AJ01).

37. ^{10}B(p, 2p)^{9}Be $\quad Q_{\rm m} = -6.5859$

Table 9.12: Levels of ^{9}Be from ^{10}B(e, e′p)^{9}Be

E_x (MeV) [a]	$C^2S_{\text{expt.}}$ [a,b]	$C^2S_{\text{theor.}}$ [b,c]	J^π [d]
0.00 ± 0.02	1.000 ± 0.025	1.000	$\frac{3}{2}^-$
2.41 ± 0.02	0.958 ± 0.025	0.964	$\frac{5}{2}^-$
6.67 ± 0.14	0.668 ± 0.028	0.994	$\frac{7}{2}^-$
11.17 ± 0.03	1.299 ± 0.036	1.352	$(\frac{7}{2})^-$
14.48 ± 0.09	0.260 ± 0.025	0.412	$(\frac{5}{2})^-$

[a] (1993DE02). There is evidence for $l = 1$ strength at ≈ 17.5 MeV, for a state at 7.81 ± 0.18 MeV (identified with, and suggesting a $\frac{5}{2}^-$ assignment for the 7.94 MeV level in Table 9.2), and for weakly populated states at 5.72 ± 0.26 MeV (identified with the 5.59 MeV level in Table 9.2) and 10.56 ± 0.23 MeV (existence uncertain).

[b] Normalized to unity for the ground-state transition.

[c] (6–16)2BME interaction of (1965CO25). The relative spectroscopic factors for the $\frac{7}{2}^-$ levels are sensitive to the details of the effective interaction. For calculations of spectroscopic factors using the (8–16)POT interaction, see (1967CO32).

[d] J suggested by comparison with theory.

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

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

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

39. ^{10}B(t, α)^{9}Be $\qquad Q_m = 13.2280$

At $E_t = 12.9$ MeV α-groups are observed to the ground state of ^{9}Be and to excited states at $E_x = 1.75 \pm 0.03$, 2.43, 3.02 ± 0.04 ($\Gamma = 320 \pm 60$ keV), 11.27 ± 0.04 ($\Gamma = 530 \pm 70$ keV), (14.4)

[$\Gamma \approx 800$ keV], 14.39 and 16.67 MeV. The $T = \frac{3}{2}$ state ^{9}Be*(14.39) is very weakly populated [≈ 5% of intensity of α_2]. The angular distribution of the α_2 group shows sharp forward and backward peaking. The α_0 group is not peaked in the backward direction: see (1979AJ01). See also (1984AJ01) and (1982CI1A).

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

This reaction was studied with an 84 MeV ^{7}Be radioactive beam (1999AZ02, 2001GA19, 2001TR04). The measured cross section determined the asymptotic normalization coefficients for the virtual transition ^{8}B $\rightarrow$ ^{7}Be + p which may be used to calculate the astrophysical S factor for ^{7}Be(p, γ)^{8}B at solar energies. See also the calculations and analysis of (1995GA20).

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

At $E_p = 45$ MeV angular distributions are reported for the ^{3}He ions corresponding to ^{9}Be*(0, 2.4, 11.8, 13.8, 14.39 [$T = \frac{3}{2}$], 15.96 ± 0.04 [$T = \frac{1}{2}$]). In addition one or more states may be located at ^{9}Be*(15.13). It is suggested that ^{9}Be*(11.8, 13.8, 15.96) are the $J^\pi = \frac{3}{2}^-$; $T = \frac{1}{2}$ analogs to ^{9}B*(12.06, 14.01, 16.02). Angular distributions are also reported at $E_p = 40$ MeV. The intensity of the group to ^{9}Be*(3.1) is ≈ 1% of the ground-state group at that energy: see (1974AJ01). The excitation energy of the first $T = \frac{3}{2}$ state is $E_x = 14392.2 \pm 1.8$ keV (1974KA15), using Q_m. Cross sections for this reaction at $E_p = 4$–11 MeV were calculated by (1994SH21) with Feshbach-Kerman-Koonin quantum multi-step direct reaction theory.

42. (a) ^{11}B(d, α)^{9}Be $\qquad Q_m = 8.031$

(b) ^{11}B(d, nα)^{4}He^{4}He $\qquad Q_m = 6.458$

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

Angular distributions for α_0 and α_2 are reported at $E_d = 0.39$ to 3.9 MeV and at 12 MeV [see (1974AJ01, 1979AJ01)]. Recent measurements for $E_{cm} = 57$–141 keV were reported by (1997YA02, 1997YA08). Astrophysical S-factors were deduced. Reaction (b), at $E_d = 10.4$ and 12.0 MeV, proceeds via ^{9}Be*(2.4) and to some extent via ^{9}Be*(3.1, 4.7) and possibly some higher excited states. The dominant decay of ^{9}Be*(2.4) state is to ^{5}He$_{g.s.}$ + α while ^{9}Be*(3.1, 4.7) states decay to $^8Be_{g.s.} + n$. It should be noted, however, that the peaks corresponding to ^{9}Be*(3.0) have a FWHM of ≈ 1 MeV, which may imply that ^{9}Be*(2.8) is involved.

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

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

44. (a) $^{12}C(n, \alpha)^9Be$ $Q_m = -5.7012$

(b) $^{12}C(n, n\alpha)^4He^4He$ $Q_m = -7.274747$

Angular distributions of the α_0 group have been measured at $E_n = 13.9$ to 18.8 MeV [see (1974AJ01)] and at 14.1 MeV (1984HA48). ^{9}Be*(1.7, 2.4, 3.1, 6.8) are also populated. Cross sections and particle-spectra related to neutron detector development have been measured at $E_n = 4$–11 MeV (1991BR09), 14.1 MeV (2000SA06), 14.6 MeV (1994KO53) and 40, 56 MeV (1994MO41). See also the calculated cross sections of (1989BR05). Reaction (b) at $E_n = 13$ to 18 MeV involves ^{9}Be*(2.4). See (1984HA48) for differential cross sections at 14.1 MeV and for partial and total cross sections.

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

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

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

Differential cross sections were measured at $E_t = 33$ MeV to $^9Be_{g.s.}$ (1989SI02). Spectroscopic factors for ^{3}He-cluster pickup were deduced.

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

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

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

For reaction (a) see ^{10}B. Differential cross sections for reaction (b) were measured at $E(^{12}\text{C}) = 480$ MeV (1988KR11). For reaction (c) see (1988KR11) and (1985OS06). For reaction (d) see (1986GO1B; $E(^{14}\text{N}) = 150$ MeV).

49. ^{13}C(t, ^{7}Li)^{9}Be $Q_{\rm m} = -8.1806$

Differential cross sections were measured at $E_{\rm t} = 33$ MeV to ^{9}Be*(0, 2.43) (1989SI02). Spectroscopic factors for α-cluster pickup were deduced.

50. ^{13}C(^{3}He, ^{7}Be)^{9}Be $Q_{\rm m} = -9.0614$

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

51. ^{13}C(α, ^{8}Be)^{9}Be $Q_{\rm m} = -10.7393$

See ^{8}Be here and ^{9}Be in (1979AJ01).

52. ^{14}N(^{7}Li, ^{12}C)^{9}Be $Q_{\rm m} = 6.4236$

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

53. ^{16}O(α, ^{11}C)^{9}Be $Q_{\rm m} = -24.3100$

See (1987KW02, 1987KW01).

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

See ^{20}Ne in (1987AJ02). See also (1985KA1J).

^{9}B
(Figs. 8 and 10)

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

The low-lying levels of ^{9}B have mainly [441] spatial symmetry and thus large amplitudes for breakup into $\alpha+\alpha+$p. With increasing excitation energy, these states develop large widths making it difficult to identify specific states and the analyses of often rather featureless spectra depend very much on which "known" levels are included in the fit. The relatively narrow states starting, as far as is known, with the $\frac{7}{2}^{-}$ level at 11.65 MeV, and including the $T = \frac{3}{2}$ states, have mainly [432] spatial symmetry with the $T = \frac{1}{2}$ states acquiring their widths through small admixtures of [441] symmetry. States with [432] symmetry and $L = 1$, e.g. the 12.19 MeV level, can have large Gamow-Teller matrix elements for ^{9}C(β^{+}) decay. The analogs of two very narrow positive-parity states of ^{9}Be appear to have been identified near 16.7 and 17.5 MeV in ^{9}B. See reaction 7(a).

1. (a) ^{6}Li(^{3}He, γ)^{9}B	$Q_{\rm m} = 16.6023$	
(b) ^{6}Li(^{3}He, n)^{8}B	$Q_{\rm m} = -1.9748$	$E_{\rm b} = 16.6023$
(c) ^{6}Li(^{3}He, p)^{8}Be	$Q_{\rm m} = 16.7874$	
(d) ^{6}Li(^{3}He, d)^{7}Be	$Q_{\rm m} = 0.11226$	
(e) ^{6}Li(^{3}He, t)^{6}Be	$Q_{\rm m} = -4.307$	
(f) ^{6}Li(^{3}He, ^{3}He)^{6}Li		
(g) ^{6}Li(^{3}He, α)^{5}Li	$Q_{\rm m} = 14.913$	

The 90° yields of γ_0 and of γ to ^{9}B*(2.36) (reaction (a)) have been measured for $E(^{3}\text{He}) = 0.6$ to 1.2 MeV [as have the 2α-particles from the decay of ^{8}Be*(16.6) (reaction (c))]: they are reported to show a resonance at $E(^{3}\text{He}) = 765 \pm 5$ keV [^{9}B*(17.111)], attributed to ^{9}B*(17.076) $[T = \frac{3}{2}]$. The total cross section for reaction (b) increases monotonically from threshold to ≈ 7 mb at 3.8 MeV. It then decreases monotonically from $E(^{3}\text{He}) = 5.5$ to 7.6 MeV and also from 8.9 to 26.5 MeV: see (1979AJ01, 1984AJ01), and ^{8}B.

Absolute cross sections for protons (reaction (c)) to ^{8}Be*(0, 2.9, 16.6, 16.9) as well as for the continuum protons have been measured for $E(^{3}\text{He}) = 0.5$ to 1.85 MeV. Reaction rate parameters, $\langle\sigma v\rangle$, have been calculated for $kT = 0.01$ to 10.0 MeV. Excitation functions for p_0 and p_1 have been measured for $E(^{3}\text{He}) = 0.9$ to 17 MeV, and polarization measurements are reported at $E(^{3}\text{He}) = 14$ MeV. Resonances are observed at $E(^{3}\text{He}) = 1.6$ and 3.0 MeV [$\Gamma = 0.25$ and 1.5 MeV]: see (1974AJ01, 1979AJ01), and ^{8}Be. Polarization measurements are also reported at $E(^{6}\vec{\text{Li}}) = 21$ MeV, and vector analyzing powers for the transition to the ground state of ^{8}Be were measured (1983KO04). Differential cross sections and analyzing powers were measured for $E(^3\mathrm{He}) = 4.6$ MeV (1995BA24). In the range $E(^3\mathrm{He}) = 0.7$ to 2.0 MeV, a resonance in the excitation function for deuterons (reaction (d)) is reported corresponding to ^{9}B*(17.6). Polarization measurements at $E(^3\vec{\mathrm{He}}) = 33.3$ MeV for the d_0 and d_1 groups are reported. Excitation functions for t_0 (reaction (e)) have been measured for $E(^3\mathrm{He}) = 10$ to 16, and 23.3 to 25.4 MeV: see (1974AJ01). Polarization measurements are reported at $E(^3\vec{\mathrm{He}}) = 33.3$ MeV for the t_0 group as well as for the ^{3}He ions to ^{6}Li*(0, 2.19) (reaction (f)). The decay of ^{6}Be levels populated by reaction (e) for $E(^3\mathrm{He}) = 30.7$–40 MeV was studied in experiments reported in (1987BO39, 1988BO38, 1989BO42, 1992BO25). The elastic scattering (reaction (f)) has also been studied for $E(^3\mathrm{He}) = 0.7$ to 2.0 MeV [see references cited in (1974AJ01, 1979AJ01, 1984AJ01)]. Differential cross section measurements have been reported at $E(^3\mathrm{He}) = 93$ MeV (1994DO32), and 50–72 MeV (1995BU20). See also the calculations in (1992KA06, 1993SI06) and the analyses in (1995MA57, 1995MI16). The α-α coincidences ($^5\mathrm{Li}_{\mathrm{g.s.}}$ decay) (reaction (g)) have been measured for $E(^3\mathrm{He}) = 1.4$ to 1.8 MeV: a resonance is observed at 1.57 ± 0.02 MeV [^{9}B*(17.63)], $\Gamma = 70 \pm 20$ keV. Polarization measurements of the α-particles to ^{5}Li*(0, 16.7) are reported at $E(^3\vec{\mathrm{He}}) = 33.3$ MeV. See also the measurements at $E(^3\mathrm{He}) = 1.5$–3.5 MeV (1988BU04) and at $E(^3\mathrm{He}) = 8$–14 MeV (1990AR17). Reaction amplitudes for resonance scattering were calculated for $E(^3\mathrm{He}) = 8$–14 MeV by (1996FA05). For a study of the (^{3}He, pα)^{4}He reaction at 3.5, 4.4 and 5.5 MeV see (1987ZA07). See (1979AJ01, 1984AJ01) for references.

2. ^{6}Li(α, n)^{9}B $\qquad Q_{\mathrm{m}} = -3.9753$

See (1974AJ01).

3. ^{6}Li(^{6}Li, t)^{9}B $\qquad Q_{\mathrm{m}} = 0.8081$

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

4. ^{7}Li(^{3}He, n)^{9}B $\qquad Q_{\mathrm{m}} = 9.3520$

Table 9.13: Energy levels of ^{9}B

E_x [a] (MeV ± keV)	$J^\pi; T$	$\Gamma_{c.m.}$ (keV)	Decay	Reactions
g.s.	$\frac{3}{2}^-; \frac{1}{2}$	0.54 ± 0.21	p	1, 2, 3, 4, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17
≈ 1.6 [b]			p, (α)	3, 4, 8, 13
2.361 ± 5	$\frac{5}{2}^-; \frac{1}{2}$	81 ± 5	p, α	1, 2, 4, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17
2.75 ± 300 [c]	$\frac{1}{2}^-; \frac{1}{2}$	3130 ± 200	p	3, 7, 10
2.788 ± 30	$\frac{5}{2}^+; \frac{1}{2}$	550 ± 40	p, α	4, 7, 10, 11, 13, 15, 16
4.3 ± 200 [d]		1600 ± 200		7
6.97 ± 60	$\frac{7}{2}^-; \frac{1}{2}$	2000 ± 200	p	4, 7, 11, 14, 15, 16
11.65 ± 60 [e]	$(\frac{7}{2})^-; \frac{1}{2}$	800 ± 50	p	11, 13, 15, 16
12.19 ± 40 [f]	$\frac{5}{2}^-; \frac{1}{2}$	450 ± 20	p, α	4, 7, 10, 14
14.01 ± 70	$\pi = -; \frac{1}{2}$	390 ± 110	p, α	4, 7, 10, 14
14.6550 ± 2.5	$\frac{3}{2}^-; \frac{3}{2}$	0.395 ± 0.042	γ, p	4, 7, 8, 10, 14
14.7 ± 200 [g]	$(\frac{5}{2})^-; \frac{1}{2}$	1350 ± 200		11
15.29 ± 40	$T = \frac{1}{2}$			14
15.58 ± 40	$T = \frac{1}{2}$			14
16.024 ± 25	$T = (\frac{1}{2})$	180 ± 16		4, 14
16.71 ± 100 [h]	$(\frac{5}{2}^+); (\frac{1}{2})$			7
17.076 ± 4	$\frac{1}{2}^-; \frac{3}{2}$	22 ± 5	(γ, ^{3}He)	1, 14
17.190 ± 25		120 ± 40	p, d, ^{3}He	4, 5, 14
17.54 ± 100 [h,i]	$(\frac{7}{2}^+); (\frac{1}{2})$			7
17.637 ± 10 [i]		71 ± 8	p, d, ^{3}He, α	1, 4, 5, 14

[a] See reactions 7 and 8 for additional states and other values.

[b] A wide range of excitation energies and widths have been given from searches for the analog of the 1.68 MeV $\frac{1}{2}^+$ state of ^{9}Be. See (1987BA54, 1992CA31, 1995TI06, 1996BA22, 1999EF01).

[c] Analog to ^{9}Be*(2.78). See (1985PU1A, 1995TI06, 2000GE09).

[d] See (1985PU1A). A level listed at $E_x = 4.8$ MeV in (1988AJ01) was based on (1986AR14, 1987KA36).

[e] See (1974AJ01, 1985PU1A). Width from (1968KU04).

[f] See (1985PU1A, 2000GE09, 2001BE51).

[g] From (1968KU04).

[h] From (1985PU1A). See (1991DI03).

[i] These two levels may not be distinct.

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

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

The cross section for reaction (a) for $E(^7\text{Be}) = 16.9$ MeV is 58 ± 11 mb (1983HA17, 1985HA40). The differential cross section was measured at $E_{cm} = 5.8$ MeV (1997LI05) in order to obtain the $^8\text{B} \rightarrow {}^7\text{Be} + \text{p}$ asymptotic normalization coefficient (ANC), from which the astrophysical S factor for the ^{7}Be(p, γ)^{8}B reaction was deduced. The reaction cross section was calculated for $E_{cm} = 5.8$, 15.6, 38.9 MeV (1999FE04). For $E_d = 0.75$ to 1.70 MeV, resonances in the yields of protons are observed at $E_d = 0.900 \pm 0.025$ MeV (p_0, p_1) and 1.475 ± 0.010 MeV (p_1 only) with $\Gamma_{cm} = 120 \pm 40$ and 71 ± 8 keV, respectively [$^9\text{B}^* = 17.19$ and 17.64 MeV]: see (1974AJ01). See also (1985CA41; astrophys.).

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

Experiments on isospin splitting in analog giant resonances excited by single pion charge exchange reactions are reviewed in (1994HA41).

7. (a) ^{9}Be(p, n)^{9}B $\quad Q_m = -1.8504$
(b) ^{9}Be(p, p + n)^{8}Be $\quad Q_m = -1.6654$

For reaction (a), angular distributions have been reported at many energies in the range $E_p = 3.5$ to 49.3 MeV [see (1979AJ01, 1984AJ01)] and at 16.44 and 17.57 MeV (1986MU07; n_0). The width of the ground state is 0.54 ± 0.21 keV: see (1974AJ01).

At $E_p = 135$ MeV, excitation energies, widths, and angular distributions have been measured for states up to $E_x = 17.54$ MeV (1985PU1A). Below $E_x = 5$ MeV, the dominant excitations are to the ground state and a broad $\frac{1}{2}^-$ state at $E_x = 2.75 \pm 0.30$ MeV [$\Gamma = 3.13 \pm 0.20$ MeV]. The 2.36 MeV $\frac{5}{2}^-$ state, the 2.788 MeV $\frac{5}{2}^+$ state, taken at 2.71 ± 0.1 MeV [$\Gamma = 0.7 \pm 0.1$ MeV], and a new level at 4.3 ± 0.2 MeV [$\Gamma = 1.6 \pm 0.2$ MeV] are also populated. The 0° cross sections for the 0 and 2.75 MeV states are comparable and the extracted B(GT) values for these states and the $\frac{5}{2}^-$ level agree well with p-shell predictions (1987RA32, 1988MI03). States at $E_x = 7.0 \pm 0.1$ MeV [$\Gamma = 2.0$ MeV] and 11.63 ± 0.2 MeV [not broad] are not seen at $0°$ and have angular distributions consistent with the $\frac{7}{2}^-$ assignments from single-neutron pickup reaction on ^{10}B. The angular distributions for states at $E_x = 12.23 \pm 0.1$ MeV [$\Gamma = 0.5 \pm 0.1$ MeV], 13.96 ± 0.1 MeV [not broad] and 14.60 ± 0.1 MeV [narrow state plus a broad component with $\Gamma = 0.6 \pm 0.1$ MeV] are forward peaked with modest B(GT) values. Cross sections for the 0, 2.36, 12.2, 14.0, 14.6 MeV states and two narrow states at $E_x = 16.71 \pm 0.1$ and 17.54 ± 0.1 MeV are compared with shell-model predictions in (1991DI03). The 16.7 and 17.5 MeV states appear to be the analogs of the 16.67 MeV ($\frac{5}{2}^+$) and 17.49 MeV ($\frac{7}{2}^+$) states of ^{9}Be. There is also evidence at some angles for narrow states at 15.15 ± 0.1 MeV, 15.44 ± 0.1 MeV, and 15.86 ± 0.1 MeV (1985PU1A).

Measurements of neutron polarization for $E_p = 54$ MeV were reported in (1988HE08). See also the cross section measurements at $E_p = 35$ MeV of (1987OR02). For earlier work see (1974AJ01, 1984AJ01). Quasi-elastic scattering at $E_p = 300$–400 MeV was studied by (1994SA43), and differential cross sections for isobaric analog $\Delta\ J^\pi = 0^+$ (Fermi-type) transitions were measured at $E_p = 35$ MeV (2000JO17). See also the analysis and calculations of (1994GA49) for $E_p = 1$ GeV, and (1998IO03) for pion production at $E_p = 800$ MeV. A summary of monoenergetic neutron sources for $E_n > 14$ MeV is presented in (1990BR24). Application-related measurements are discussed in (1987RA23, 1996SH29).

Reaction (b) does not seem to involve states of ^{9}B. See also (1982GU13, 1983BY02, 1984BA1R, 1987RA32, 1988BO47, 1988HE08) and the application-related work of (1984ALYS, 1987VO1F). For yield and polarization measurements see ^{10}B.

8. ^{9}Be(^{3}He, t)^{9}B $\qquad Q_m = -1.0867$

Angular distributions have been measured for $E(^3\text{He}) = 3.0$ to 25 MeV and at 217 MeV: see (1974AJ01, 1979AJ01). At $E(^3\text{He}) = 39.8$ MeV, $^9\text{B}_{\text{g.s.}}$ is strongly populated and ^{9}B*(2.33, 2.83, 11.62, 12.06, 14.67, (17.19), 17.63) are also observed (1969BA06). At $E(^3\text{He}) = 90$ MeV triton groups are reported to states at $E_x = 1.16 \pm 0.05$ MeV [$\Gamma = 1.3 \pm 0.05$ MeV], 2.32 ± 0.03, 2.72 ± 0.04 and 4.8 ± 0.03 MeV [1.5 ± 0.3 MeV], 16.7 ± 0.1 MeV [< 0.1 MeV], 18.6 ± 0.3 and 20.7 ± 0.5 MeV [1.6 ± 0.3 MeV] [Γ in brackets], in addition to known and possibly unresolved ^{9}B*(7.0, 11.7, 12.1, 14.7, 17.64) states (1987KA36). See also (1983DJZV). (2001AK09) have fitted $0°$, $2°$, and $3.5°$ spectra at $E(^3\text{He}) = 450$ MeV with levels fixed at excitation energies of 0, 2.361, 2.788, 4.8, and 6.97 MeV together with two levels at $1.80^{+0.22}_{-0.16}$ and $3.82^{+0.23}_{-0.22}$ MeV with widths of 600^{+300}_{-270} and 1330^{+620}_{-360} keV; see also (1994AK02) for the excitation of states above $E_x = 10$ MeV at $0°$. Neither (1987KA36) nor (2001AK09) include in their fits the broad $\frac{1}{2}^-$ level that is strongly excited in the ^{9}Be(p, n)^{9}B reaction.

The ^{9}Be(^{3}He, tα)^{9}B reaction with $E(^3\text{He}) = 40.5$ MeV has been used to obtain α-decay spectra from the $\frac{5}{2}^-$ level at 2.36 MeV (1990BO51). The data were analyzed in terms of series expansions of the decay amplitudes in hyperspherical harmonics.

9. (a) ^{9}Be(^{6}Li, ^{6}He)^{9}B $\qquad Q_{\rm m} = -4.5764$

(b) ^{9}Be(^{7}Li, ^{7}Be)^{9}B $\qquad Q_{\rm m} = -1.9303$

At $E(^6\text{Li}) = 32$ MeV angular distributions are reported to ^{9}B*(0, 2.36) (1985CO09). Measurements with $E(^6\text{Li}) = 32$ MeV are also reported by (1988BU18). In addition to ^{9}B*(0, 2.36) they report weak levels at $E_{\rm x} = 1.32 \pm 0.08$ MeV, $\Gamma = 0.86 \pm 0.26$ MeV and $E_{\rm x} = 4.60 \pm 0.16$ MeV, $\Gamma = 0.68 \pm 0.43$ MeV. See also (1984GL06; $E(^6\text{Li}) = 93$ MeV, $E(^7\text{Li}) = 78$ MeV).

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

10. ^{9}C(β^+)^{9}B $\qquad Q_{\rm m} = 16.4948$

The previous review (1988AJ01) notes that ^{9}C β^+ decay was observed by (1988MI03) to ^{9}B*(0, 2.36, 2.8) [$J^\pi = \frac{3}{2}^-, \frac{5}{2}^-, \frac{1}{2}^-$] with branching ratios of (60 ± 10), (17 ± 6) and (11 ± 5)%, respectively. A state at $E_{\rm x} = 12.1 \pm 0.6$ MeV, $\Gamma = 0.4 \pm 0.1$ MeV was also observed with the remaining strength going to it. In (2000GE09, 2001BE51), the β-delayed particle decay of ^{9}C has been studied and secondary decays into $^8\text{B} + \text{p}$ and $^5\text{Li} + \alpha$ have been observed. In (2001BE51), a value of 54.1 ± 1.5% is reported for the ground-state branch and no asymmetry is found with the corresponding transition in ^{9}Li(β^-)^{9}Be. They determine $J^\pi = \frac{5}{2}^-$ for the 12.2 MeV level from a study of angular correlations and measure a large B(GT) value for the transition to the 12.2 MeV level. They observe a transition to the isobaric analog state and obtain new information on the decay of this state. In (2000GE09) a number of ^{9}B level energies, branching ratios, and Gamow-Teller strengths were deduced using an R-matrix analysis with simplified one-level expressions. Level energies, branching ratios, B(GT) values, and other decay information obtained by combining the results of (2000GE09) and (2001BE51) are presented in Table 9.14 and its footnotes. The data of (2000GE09) have also been analyzed using a multichannel, multilevel R-matrix approach and the results are described in (2001BU05). See reaction 12 in ^{9}Be and Table 9.8 for the mirror decay ^{9}Li(β^-)^{9}Be; note the large asymmetry for the decays to the 11.81 MeV level of ^{9}Be and 12.16 MeV level of ^{9}B.

11. (a) ^{10}B(p, d)^{9}B $\qquad Q_{\rm m} = -6.2118$

(b) ^{10}B(p, p + n)^{9}B $\qquad Q_{\rm m} = -8.4363$

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

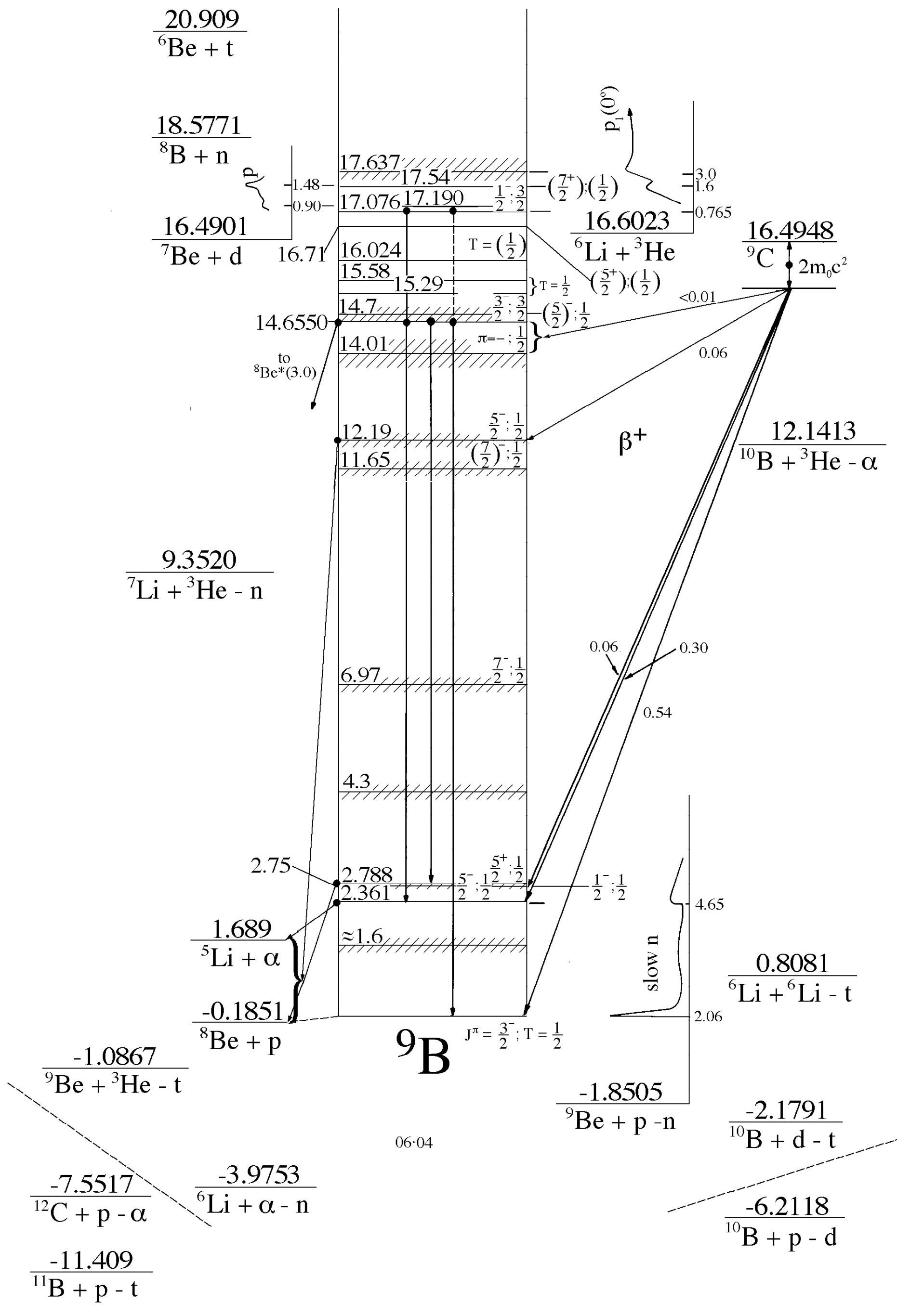

Figure 8: Transitions accounting for 96% of the ^{9}C(β)^{9}B decay are shown. The remaining 4% is spread over several uncertain levels (see Table 9.14). For notation see Fig. 7.

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

12. ^{10}B(d, t)^{9}B $\qquad Q_{\rm m} = -2.1791$

Angular distributions have been measured at $E_{\rm d} = 11.8$ to 28 MeV [see (1974AJ01, 1979AJ01)] and 18 MeV (1988GO02, 1988GU20; to ^{9}B*(0, 2.36)). See also the analysis of cross section data for $E_{\rm d} = 8$–50 MeV (1995GU22).

13. (a) ^{10}B(^{3}He, α)^{9}B $\qquad Q_{\rm m} = 12.1413$

(b) ^{10}B(^{3}He, αp)^{8}Be $\qquad Q_{\rm m} = 12.3264$

(c) ^{10}B(^{3}He, 2α)^{5}Li $\qquad Q_{\rm m} = 10.452$

Alpha-particle spectra show the excitation of ^{9}B*(0, 2.4, 2.8, 11.8): see (1966LA04). Measurements by (1968KR02) determine $E_{\rm x} = 2.361 \pm 0.005$ and 2.788 ± 0.030 MeV [$\Gamma = 81 \pm 5$ and 548 ± 40 keV, respectively]: see Table 9.11 in (1966LA04) for other values. There is some evidence for a state with $E_{\rm x} \approx 1.6$ MeV, $\Gamma \approx 0.7$ MeV, but it is not conclusive. No evidence is found for any narrow levels in ^{9}B with $\Gamma \leq 100$ keV and $4 < E_{\rm x} < 7$ MeV: the upper limit to the intensity of the corresponding α-group is 1% of the intensity of the group to ^{9}B*(2.4). Angular distributions have been determined at $E(^{3}{\rm He}) = 5.5$ and 33.7 MeV [see (1974AJ01)].

In reaction (b), a study of the decays of ^{9}B*(2.4, 2.8) shows that ^{9}B*(2.4) decays < 0.5% by proton emission to $^{8}{\rm Be}_{\rm g.s.}$ [it decays to $^{5}{\rm Li}_{\rm g.s.}$ by α-emission] while the second state, $E_{\rm x} = 2.71 \pm 0.03$ MeV [$\Gamma = 0.71 \pm 0.06$ MeV], decays almost 100% by that channel (1966WI08). No evidence is found for excited states of ^{9}B with $3.5 < E_{\rm x} < 9.5$ MeV which decay by proton emission to $^{8}{\rm Be}_{\rm g.s.}$ (1968KR02). In a kinematically complete experiment (reaction (c)) at $E(^{3}{\rm He}) = 2.3$ and 5.0 MeV, a state is reported at 4.9 ± 0.2 MeV with a width of 1.5 ± 0.3 MeV (1986AR14). Likewise, from reactions (b) and (c) a state is reported at 1.8 ± 0.2 MeV with a width of 0.9 ± 0.3 MeV (1988AR05).

14. ^{11}B(p, t)^{9}B $\qquad Q_{\rm m} = -11.409$

At $E_{\rm p} = 45$ MeV angular distributions have been obtained for the triton groups to ^{9}B*(0, 2.36, 12.06, 14.01, 14.66, 16.02). In addition the spectra show some indication of the groups corresponding to ^{9}B*(7.0, 17.19, 17.64). $T = \frac{1}{2}$ states are reported at $E_{\rm x} = 15.29 \pm 0.04$ and 15.58 ± 0.04 MeV (1971HA10). The first two $T = \frac{3}{2}$ states have been observed at $E_{\rm x} = 14.6550 \pm 0.0025$ (1974KA15) and 17.076 ± 0.004 MeV [$\Gamma = 22 \pm 5$ keV] (1974BE66).

Table 9.14: Branching ratios in ^{9}C(β^{+}) decay from measurements of β-delayed particle decay [a]

$E_{\rm x}$ in ^{9}B (MeV)	J^{π}	Branching ratio (%)	B(GT)
0	$\frac{3}{2}^{-}$	54.1 ± 1.5 [b]	0.0295 ± 0.0008
2.34 ± 0.03	$\frac{5}{2}^{-}$	30.4 ± 5.8 [c]	0.053 ± 0.012
2.8 ± 0.2	$\frac{1}{2}^{-}$	5.8 ± 0.6 [d]	0.013 ± 0.002
12.16 ± 0.10	$\frac{5}{2}^{-}$ [e]	5.9 ± 0.6 [f]	2.16 ± 0.22
14.0 ± 0.2		0.16 ± 0.02 [g]	0.36 ± 0.05
14.663 [h]	$\frac{3}{2}^{-}$	0.010	3.1 [h]

[a] Except for the transition to the isobaric analog state at 14.66 MeV, the energies and branching ratios are taken from Table VII of (2000GE09) after normalization ($\times 0.864$) to the ground-state branch from (2001BE51). (2000GE09) also list a very weak branch to a narrow, and previously unknown, state at 13.3 MeV and a $\approx$ 4% background contribution attributed to the tails of higher states. See also (2001BU05).

[b] From (2001BE51).

[c] From (2000GE09). The p_0 decay branch is 0.5% from this state.

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

[e] (2001BE51). $J^{\pi} = \frac{5}{2}^{-}$ from the α-p angular distribution for the α_0 branch; $E_{\rm x} = 12.19 \pm 0.04$ MeV, $\Gamma = 450 \pm 20$ keV; p_0 9.0 ± 1.0 %, p_1 25 ± 7 %, α_0 60 ± 7 %, α_1 6 ± 4 %; B(GT) $= 1.92 \pm 0.24$.

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

[g] From (2000GE09). Only p_0 observed.

[h] From (2001BE51). The summed energy for the decay is measured to be 14940 keV. α_0 $(4.8 \pm 0.7) \times 10^{-3}$%; $\Gamma_{\alpha_0}/\Gamma = 0.46$; B(F) + B(GT) is listed where B(F) $= 3.0$.

Table 9.15: Levels of ^{9}B from ^{10}B(p, d)^{9}B

E_x [a] (MeV)	E_x [b] (MeV)	Γ_{cm} [b] (MeV)	$C^2S_{expt.}$ [a]	$C^2S_{theor.}$ [c]	J^{π} [d]
0	0		0.44	0.59	$\frac{3}{2}^-$
2.4 ± 0.1	2.35 ± 0.02		0.60	0.58	$\frac{5}{2}^-$
7.1 ± 0.2	7.1 ± 0.2	2.15 ± 0.15	0.52	0.56	$\frac{7}{2}^-$
11.5 ± 0.2	11.75 ± 0.1	0.80 ± 0.05	1.12	0.78	$(\frac{7}{2})^-$
14.9 ± 0.3	14.6 ± 0.2	1.35 ± 0.2	0.32	0.24	$(\frac{5}{2})^-$

[a] (1969BA05): $E_p = 155.6$ MeV.
[b] (1968KU04): $E_p = 33.6$ MeV.
[c] (6–16)2BME interaction of (1965CO25). The relative spectroscopic factors for the $\frac{7}{2}^-$ levels are sensitive to the details of the effective interaction [co-author D.J.M.]. For the (8–16)POT interaction, see (1967CO32). (1968KU04) make a graphical comparison of relative experimental and theoretical spectroscopic factors; see also (1991AB04).
[d] J suggested by comparison with theory.

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

Angular distributions have been measured at $E_p = 14.0$ to 54.1 MeV [see (1974AJ01)]. At $E_p = 54.1$ MeV peaks are observed at 0, 2.32 ± 0.04, 6.97 ± 0.06, and 11.46 ± 0.25 MeV (1971MA2C). The angular distribution for the 6.97 MeV state is similar to other $J = \frac{7}{2}$ transitions (1972MA21). At $E_p = 42.8$ MeV angular distributions for ^{9}B*(0, 2.36, 6.98) involve $l = 1$, 3 and 3, respectively (1983PE07). A broad state at 2.9 ± 0.2 MeV has also been reported: see (1974AJ01). Angular distributions involving the α_0 and α* groups [to ^{4}He*(20.1), 0^+] to ^{9}B$_{g.s.}$ have been studied at $E_p = 42$ MeV: see (1984AJ01). For reaction (c) see (1985DE17; $E_p = 58$ MeV). See also (1984AJ01, 1988AJ01).

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

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

17. ^{12}C(α, ^{7}Li)^{9}B $\qquad Q_{\rm m} = -24.8986$

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

^{9}C

(Figs. 9 and 10)

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

Ground state properties:

$$\mu = -1.3914 \pm 0.0005\ \mu_N \text{ (1996MA38). See also (1998HU08).}$$

The sum of the magnetic moments of ^{9}Li and ^{9}C leads to $\langle\sigma\rangle = 1.44$, an anomalously high value that remains unexplained (1996MA38, 1998HU08).

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

1. ^{9}C(β^{+})^{9}B $\qquad Q_m = 16.4948$

The half-life of ^{9}C is 126.5 ± 0.9 msec: see (1974AJ01). New information on the decay scheme is given in (2000GE09, 2001BE51) and the data of (2000GE09) has been the subject of a separate R-matrix fit (2001BU05). The decay is complex; see reaction 10 in ^{9}B.

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

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

3. ^{8}B(p, γ)^{9}C $\qquad Q_m = 1.3000$

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

Table 9.16: Energy levels of ^{9}C [a]

E_x (MeV $\pm$ keV)	$J^\pi; T$	$\tau_{1/2}$ or Γ	Decay	Reactions
g.s.	$\frac{3}{2}^-; \frac{3}{2}$	$\tau_{1/2} = 126.5 \pm 0.9$ msec	β^+	1, 4, 6 [a]
2.218 ± 11	$\frac{1}{2}^-$	$\Gamma = 100 \pm 20$ keV		6

[a] See also (1974AJ01, 1979AJ01).

[b] Evidence for additional levels in ^{9}C is presented in reaction 6.

4. ^{9}Be(π^+, π^-)^{9}C $\qquad Q_m = -17.5629$

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

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

The ground state of ^{9}C has been observed in the angular range $0°$ to $12°$ at $E(^{7}\text{Li}) = 350$ MeV (2001CA37).

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

At $E(^{3}\text{He}) = 74.1$ MeV ^{6}He groups are observed to the ground state and to a state at $E_x = 2218 \pm 11$ keV, $\Gamma = 100 \pm 20$ keV: see (1984AJ01).

At $E(^{3}\text{He}) = 76.6$ MeV a new ^{9}C level at $E_x = 3.3 \pm 0.05$ MeV is claimed in addition to ^{9}C*(0, 2.2). There is evidence for a broad level at $E_x \approx 4.3$ MeV that could be the analog of the 4.3 MeV level of ^{9}Li and is expected to have a width of ≈ 2.6 MeV: see (1991GO13).

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

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

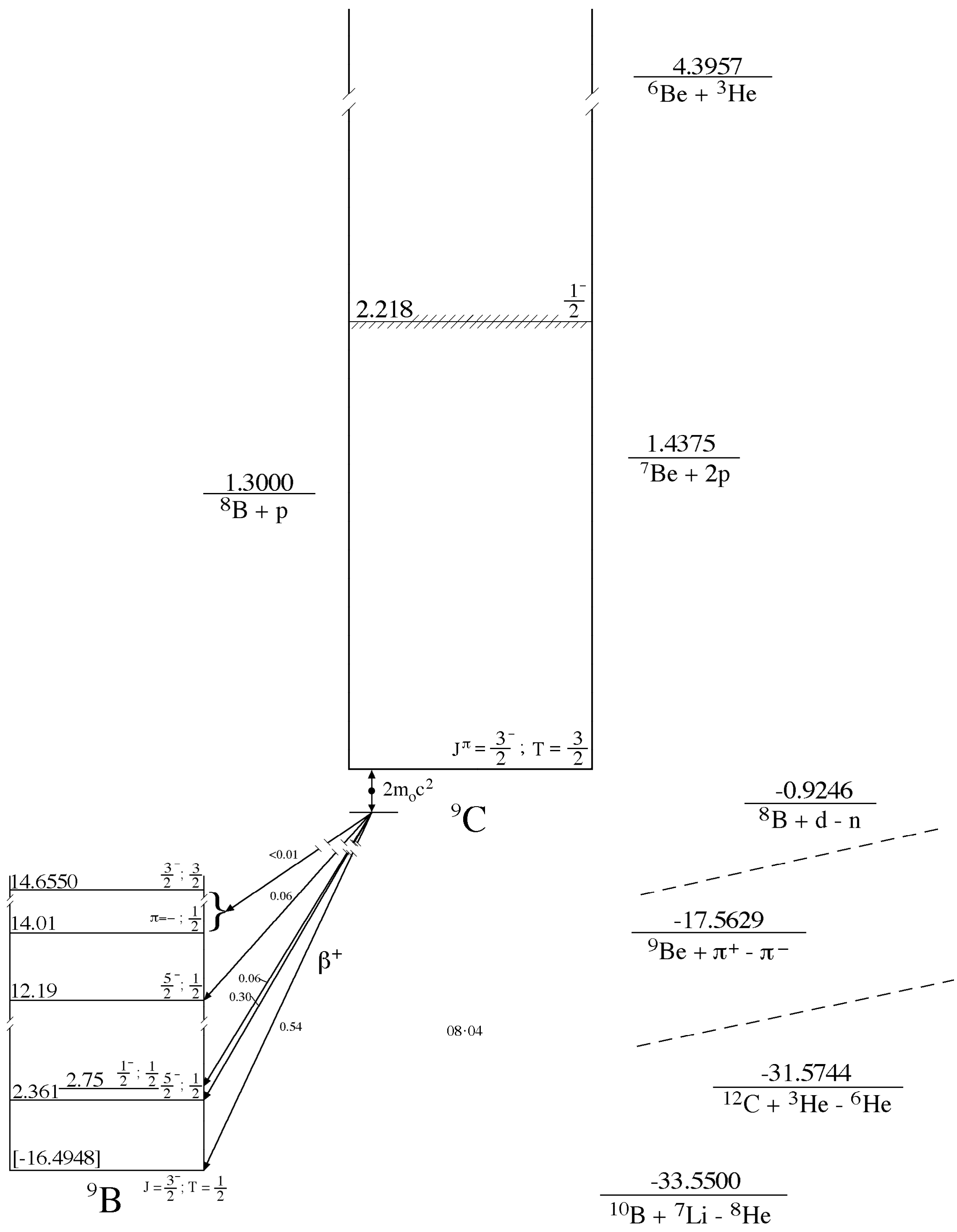

Figure 9: Energy levels of ^{9}C. For notation see Fig. 7.

Table 9.17: Mirror states $(T = \frac{1}{2})$ in $A = 9$ nuclei [a]

^{9}Be		^{9}B		
E_x (MeV)	J^π	E_x (MeV)	J^π	ΔE_x (MeV) [b]
0	$\frac{3}{2}^-$	0	$\frac{3}{2}^-$	
1.684	$\frac{1}{2}^+$	[c]		
2.429	$\frac{5}{2}^-$	2.361	$\frac{5}{2}^-$	-0.068
2.78	$\frac{1}{2}^-$	2.75	$\frac{1}{2}^-$	-0.03
3.049	$\frac{5}{2}^+$	2.788	$\frac{5}{2}^+$	-0.261
4.704	$(\frac{3}{2})^+$	4.3		-0.4
5.59	$(\frac{3}{2}^-)$			
6.38 [d]	$\frac{7}{2}^-$	6.97	$\frac{7}{2}^-$	$+0.59$
6.76	$\frac{9}{2}^+$			
7.94	$(\frac{5}{2}^-)$			
11.283	$(\frac{7}{2}^-)$	11.65	$(\frac{7}{2}^-)$	$+0.37$
11.81	$\frac{5}{2}^-$	12.19	$\frac{5}{2}^-$	$+0.25$
13.79	$\pi = -$	14.01	$\pi = -$	$+0.22$
15.97		16.02		$+0.05$
16.671	$(\frac{5}{2}^+)$	16.71	$(\frac{5}{2}^+)$	$+0.04$
17.493	$(\frac{7}{2}^+)$	17.54	$(\frac{7}{2}^+)$	$+0.05$

[a] As taken from Tables 9.2 and 9.13.

[b] Defined as $E_x(^9\text{B}) - E_x(^9\text{Be})$.

[c] See footnote b to Table 9.13.

[d] See footnote b to Table 9.2.

^{9}N
(Not illustrated)

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

Table 9.18: Isospin quadruplet states $(T = \frac{3}{2})$ in $A = 9$ nuclei [a]

^{9}Li		^{9}Be		^{9}B		^{9}C	
E_x (MeV)	J^π	E_x (MeV)	J^π	E_x (MeV)	J^π	E_x (MeV)	J^π
0	$\frac{3}{2}^-$	14.392	$\frac{3}{2}^-$	14.655	$\frac{3}{2}^-$	0	$\frac{3}{2}^-$
2.691	$\frac{1}{2}^-$	16.975	$\frac{1}{2}^-$	17.076	$\frac{1}{2}^-$	2.218	$\frac{1}{2}^-$
4.296	$(\frac{5}{2}^-)$	18.65	$(\frac{5}{2}^-)$				
5.38							
6.43							

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

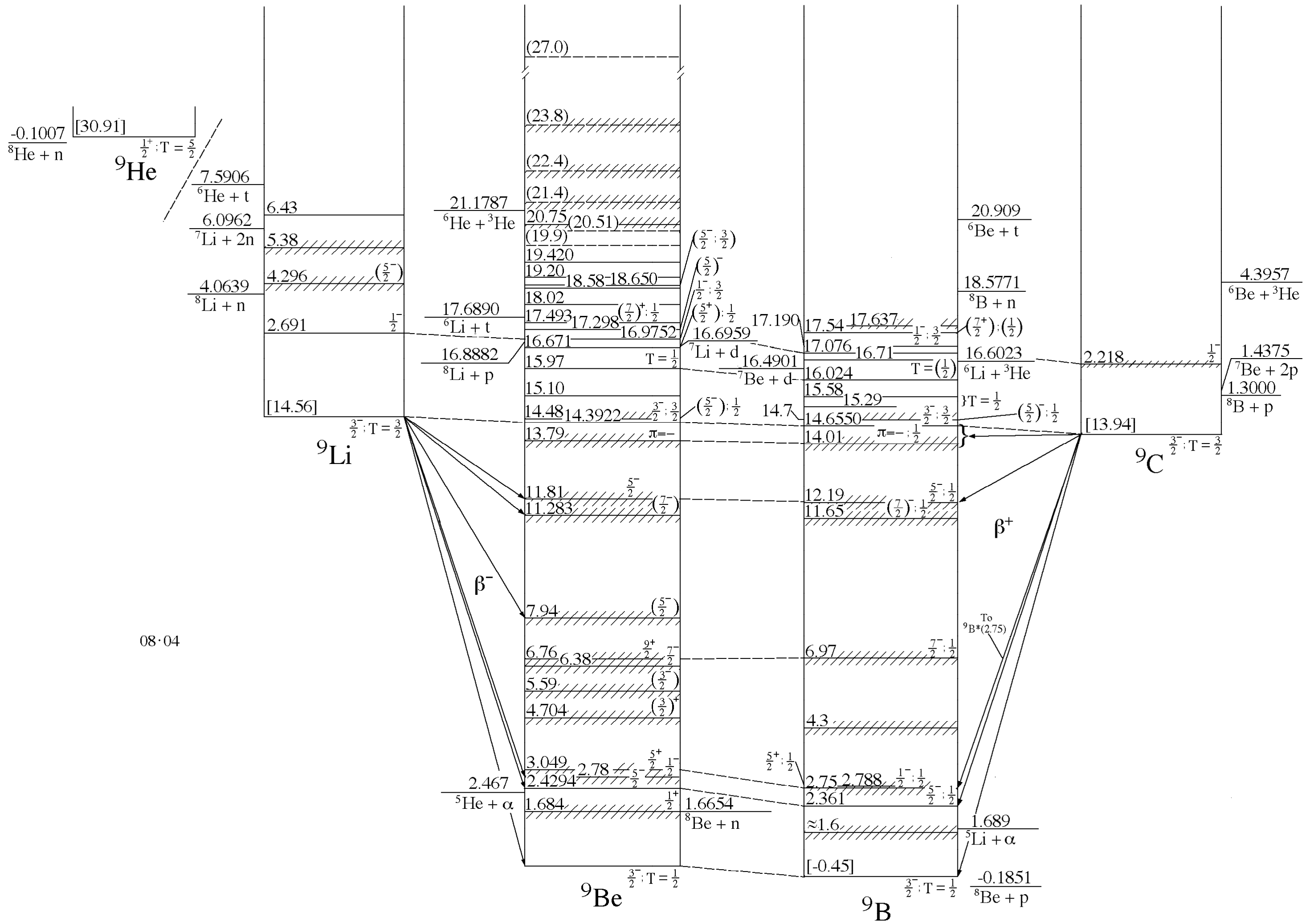

Figure 10: Isobar diagram, $A = 9$. The diagrams for individual isobars have been shifted vertically to eliminate the neutron-proton mass difference and the Coulomb energy, taken as $E_{\mathrm{C}} = 0.60Z(Z-1)/A^{1/3}$. Energies in square brackets represent the (approximate) nuclear energy, $E_{\mathrm{N}} = M(Z, A) - ZM(\mathrm{H}) - NM(\mathrm{n}) - E_{\mathrm{C}}$, minus the corresponding quantity for ^{9}Be: here M represents the atomic mass excess in MeV. Levels which are presumed to be isospin multiplets are connected by dashed lines.

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(Closed 31 March 2004)

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