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Energy Levels of Light Nuclei $A = 10$

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Abstract: An evaluation of $A = 8$–10 was published in *Nuclear Physics* A745 (2004), p. 155. This version of $A = 10$ 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 $A = 10$

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

A = 10

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

^{10}n

(Not illustrated)

^{10}n has not been observed: see (1979AJ01). See also (1986AB10; theor.).

^{10}He

(Figs. 11 and 17)

GENERAL: References to articles on general properties of ^{10}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 ^{10}He located on our website at (*www.tunl.duke.edu/nucldata/ General_Tables/10he.shtml*).

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

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

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

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

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

The double charge-exchange reaction ^{10}Be(^{14}C, ^{14}O)^{10}He was studied at $E_{lab} = 334.4$ MeV

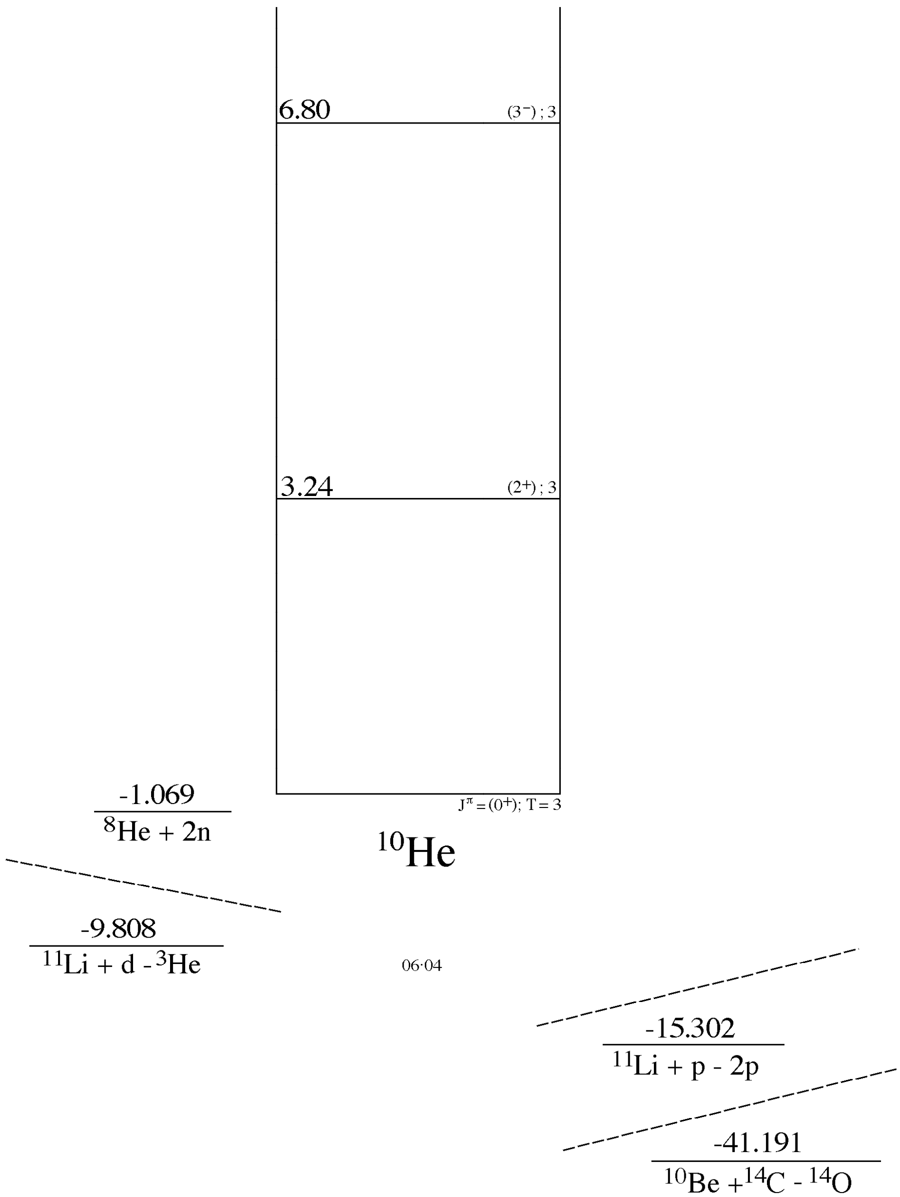


Figure 11: Energy levels of ^{10}He. For notation see Fig. 13.

Table 10.1: Energy levels of ^{10}He [a]

E_x (MeV)	$J^\pi; T$	Γ_{cm} (MeV)	Decay	Reactions
g.s.	$(0^+); 3$	0.3 ± 0.2	n	1, 2, 3
3.24 ± 0.20	$(2^+); 3$	1.0 ± 0.3	n	3
6.80 ± 0.07	$(3^-); 3$	0.6 ± 0.3	n	3

[a] Based on data reviewed in this evaluation.

Table 10.2: ^{10}He level parameters from ^{10}Be(^{14}C, ^{14}O)^{10}He [a]

	$J^\pi; T$		
	$(0^+); 3$	$(2^+); 3$	$(3^-); 3$
E_R (MeV) [b]	1.07 ± 0.07	4.31 ± 0.20	7.87 ± 0.06
E_x (MeV)	0	3.24 ± 0.20	6.80 ± 0.07
Γ (MeV)	0.3 ± 0.2	1.0 ± 0.3	0.6 ± 0.3

[a] From Table I of (1994OS04).
[b] ^{8}He + 2n decay energy.

(1994OS04, 1995BO10, 1999BO26). See also (1995OSZX, 1995VO05, 1996OS1A, 1998BO1M). The measured Q-value for the ^{10}He ground state resonance is -41.19 ± 0.07 MeV which corresponds to a mass excess of 48.81 ± 0.07 MeV. This is also the value adopted in (2003AU03). ^{10}He is then particle unstable against 2n emission by 1.07 ± 0.07 MeV. The measured width of the ground state resonance is $\Gamma = 0.3 \pm 0.2$ MeV. Excited states are reported at $E_x = 3.24 \pm 0.20$ MeV, $\Gamma = 1.0 \pm 0.3$ MeV and $E_x = 6.80 \pm 0.07$ MeV, $\Gamma = 0.6 \pm 0.3$ MeV. Widths of the two excited-state resonances are described using R-matrix calculations by (1994OS04). See Table 10.2.

^{10}Li

(Figs. 12 and 17)

GENERAL: References to articles on general properties of ^{10}Li published since the previous review (1988AJ01) are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for ^{10}Li located on our website at (*www.tunl.duke.edu/nucldata/ General_Tables/10li.shtml*).

^{10}*Li Ground-State Mass:* The mass excess of ^{10}Li adopted by (2003AU03) is 33051 ± 15 keV. This indicates that this nucleus is neutron unbound by 25 ± 15 keV. The width of this state is 230 ± 60 keV (2003AU03). The general consensus for the ^{10}Li ground state configuration is that a broad s-wave neutron resonance couples with the $\frac{3}{2}^-$ ^{9}Li ground state to give either 1^- or 2^- resonance; see reaction 7. This state has been referred to as a virtual resonance in the n + ^{9}Li system with an energy < 50 keV, based on scattering length considerations (2002GA12).

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

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

The separation-energy distribution for 83 MeV/A ^{11}Li incident on a CH_2 target was measured by (1997KO07). Two states in ^{10}Li at $E_{\rm res} = 5.2$ MeV and 0.4 MeV were observed in reactions (a) and (b), respectively. ($E_{\rm res}$ is the resonance energy relative to the ^{9}Li + n threshold). s-wave properties of the ^{9}Li + n potential were studied (2002MA77) by calculation of the break-up reactions of a ^{11}Li beam.

2. ^{2}H(^{9}Li, p)^{10}Li $\qquad Q_{\rm m} = -2.250$

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

3. ^{9}Be(^{9}Be, ^{8}B)^{10}Li $\qquad Q_{\rm m} = -33.277$

In an experiment at $E(^{9}{\rm Be}) = 40.1 \pm 0.1$ MeV/A the measured energy spectrum of ^{8}B particles

Table 10.3: Summary of observed resonances reported for ^{10}Li. Resonances are grouped to reflect different levels in ^{10}Li.

E_{res} [a] (MeV)	Γ_{res} (MeV)	Reaction	Reference	J^π
≤ 0.05		^{nat}C(^{11}Be, ^{9}Li + n)X	(1995ZI03)	
≤ 0.05		^{9}Be(^{18}O, ^{9}Li + n)X	(1999TH01)	
≤ 0.05		^{9}Be(^{11}Be, X)^{10}Li	(2001CH31)	
≤ 0.05		^{9}Be(^{11}Be, X)^{10}Li	(2001CH46)	
< 0.1	< 0.23	^{11}B(^{7}Li, ^{8}B)^{10}Li	(1994YO01)	
0.1 ± 0.1	0.4 ± 0.1	^{11}B(π^-, p)^{10}Li	(1998GO30)	(1^-)
0.15 ± 0.15	< 0.4	^{11}B(π^-, p)^{10}Li	(1990AM05)	
≤ 0.15		^{nat}C(^{18}O, ^{9}Li)X	(1993KR09)	
see [b,c]				
0.24 ± 0.04	0.10 ± 0.07	^{10}Be(^{12}C, ^{12}N)^{10}Li	(1999BO26)	1^+
(0.35 ± 0.11) [d]	< 0.32	^{2}H(^{9}Li, p)^{10}Li	(2003SA07)	
see [e]				
(0.35 ± 0.11) [d]	< 0.32	^{2}H(^{9}Li, p)^{10}Li	(2003SA07)	
0.4		^{1}H(^{11}Li, p + n)^{9}LiX	(1997KO07)	
0.40 ± 0.07	≈ 0.3	^{14}C(π^-, dd)^{10}Li	(1998GO30)	
(0.42 ± 0.05) [f]	0.15 ± 0.07	^{9}Be(^{13}C, ^{12}N)^{10}Li	(1993BO03)	(1^+) [f]
0.50 ± 0.06	0.4 ± 0.06	^{9}Be(^{9}Be, ^{8}B)^{10}Li	(1999CA48)	
0.53 ± 0.06	0.35 ± 0.08	^{9}Be(^{13}C, ^{12}N)^{10}Li	(1999BO26)	(2^+)
		^{9}Be(^{15}N, ^{14}O)^{10}Li	(1998BO38)	
0.538 ± 0.062	0.358 ± 0.023	^{11}B(^{7}Li, ^{8}B)^{10}Li	(1994YO01)	
0.62 ± 0.10	0.6 ± 0.1	^{nat}C(^{11}Li, ^{9}Li + n)X	(1997ZI04)	
0.7 ± 0.2	0.1 ± 0.1	^{11}B(π^-, p)^{10}Li	(1998GO30)	(2^-)
(0.8 ± 0.25) [g]	1.2 ± 0.3	^{9}Be(^{9}Be, ^{8}B)^{10}Li	(1975WI26)	
(0.8 ± 0.06) [f]	0.3 ± 0.1	^{9}Be(^{13}C, ^{12}N)^{10}Li	(1993BO03)	(2^+)
1.40 ± 0.08	0.20 ± 0.07	^{10}Be(^{12}C, ^{12}N)^{10}Li	(1999BO26)	$(2^- + 1^-)$
		^{9}Be(^{13}C, ^{12}N)^{10}Li		
≈ 1.6		^{nat}Pb(^{11}Li, ^{9}Li + n)	(1997ZI04)	
2.35 ± 0.10	1.2 ± 0.4	[h]	(1999BO26)	$(1^+, 3^+)$
2.5		^{nat}C(^{18}O, ^{9}Li)X	(1993KR09)	
2.85 ± 0.07	0.3 ± 0.2	^{9}Be(^{13}C, ^{12}N)^{10}Li	(1999BO26)	$(1^-, 2^+)$
4.19 ± 0.10	0.12 ± 0.08	^{10}Be(^{12}C, ^{12}N)^{10}Li	(1999BO26)	
4.64 ± 0.10	0.2 ± 0.1	^{10}Be(^{12}C, ^{12}N)^{10}Li	(1999BO26)	$(3^-, 2^+)$
		^{9}Be(^{13}C, ^{12}N)^{10}Li		
5.2		^{1}H(^{11}Li, p + n)^{8}LiX	(1997KO07)	
5.2 ± 0.2	≈ 0.4	^{14}C(π^-, d + d)^{10}Li	(1998GO30)	
5.7 ± 0.1	0.2 ± 0.1	^{9}Be(^{13}C, ^{12}N)^{10}Li	(1999BO26)	

[a] Relative to ^{9}Li + n threshold.
[b] An s-wave resonance at $E_{\rm res} = 0.21 \pm 0.05$ MeV, $\Gamma_{\rm lab} = 0.12 \pm 0.1$ MeV is reported in (1997ZI04).
[c] Audi and Wapstra deduce Δm $= 33050 \pm 15$ keV which corresponds to a ^{10}Li$_{\rm g.s.}$ at $E_{\rm res} = 25 \pm 15$ keV [$J^{\pi} = (1^{-}, 2^{-})$] (2003AU03).
[d] It is unclear with which level the observed 0.35 MeV resonance should be grouped.
[e] A weighted average of (1994YO01, 1998GO30, 1999BO26, 1999CA48) yields $E_{\rm res} = 0.50 \pm 0.03$ MeV and $\Gamma_{\rm lab} = 0.36 \pm 0.02$ MeV.
[f] Not reported in the ^{9}Be(^{13}C, ^{12}N)^{10}Li work of (1999BO26).
[g] Not reported in the ^{9}Be(^{9}Be, ^{8}Be)^{10}Li work of (1999CA48).
[h] Not shown in any spectra in (1997BO10) or (1999BO26).

was best fit with a single p-wave resonance at $E_{\rm res} = 0.50 \pm 0.06$ MeV, $\Gamma = 400 \pm 60$ keV (1999CA48) . An excess strength at threshold was observed but that strength could not be definitely attributed to a ^{10}Li level. No higher states were observed. This work reported in (1999CA48) also included a review of previous measurements of ^{10}Li.

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

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

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

5. ^{9}Be(^{13}C, ^{12}N)^{10}Li $\qquad Q_{\rm m} = -35.916$

This reaction at $E_{\rm lab} = 336$ MeV was used in a study of ^{10}Li (1993BO03) in which levels at $E_{\rm res} = 0.4$, 0.8, and 4.5 MeV were reported. Later work by (1998BO38, 1999BO26) did not report these levels. This reaction was also used at $E_{\rm lab} = 336.4$ MeV along with ^{10}Be(^{12}C, ^{12}N)^{10}Li (reaction 8: $E_{\rm lab} = 357.0$ MeV) and ^{9}Be(^{15}N, ^{14}O)^{10}Li (reaction 6: $E_{\rm lab} = 240$ MeV) to study ^{10}Li (1998BO38, 1999BO26). The (^{12}C, ^{12}N) reaction shows a distinct selectivity for unnatural parity states, whereas natural parity states in ^{10}Li are more strongly populated by ^{9}Be(^{13}C, ^{12}N)^{10}Li. A

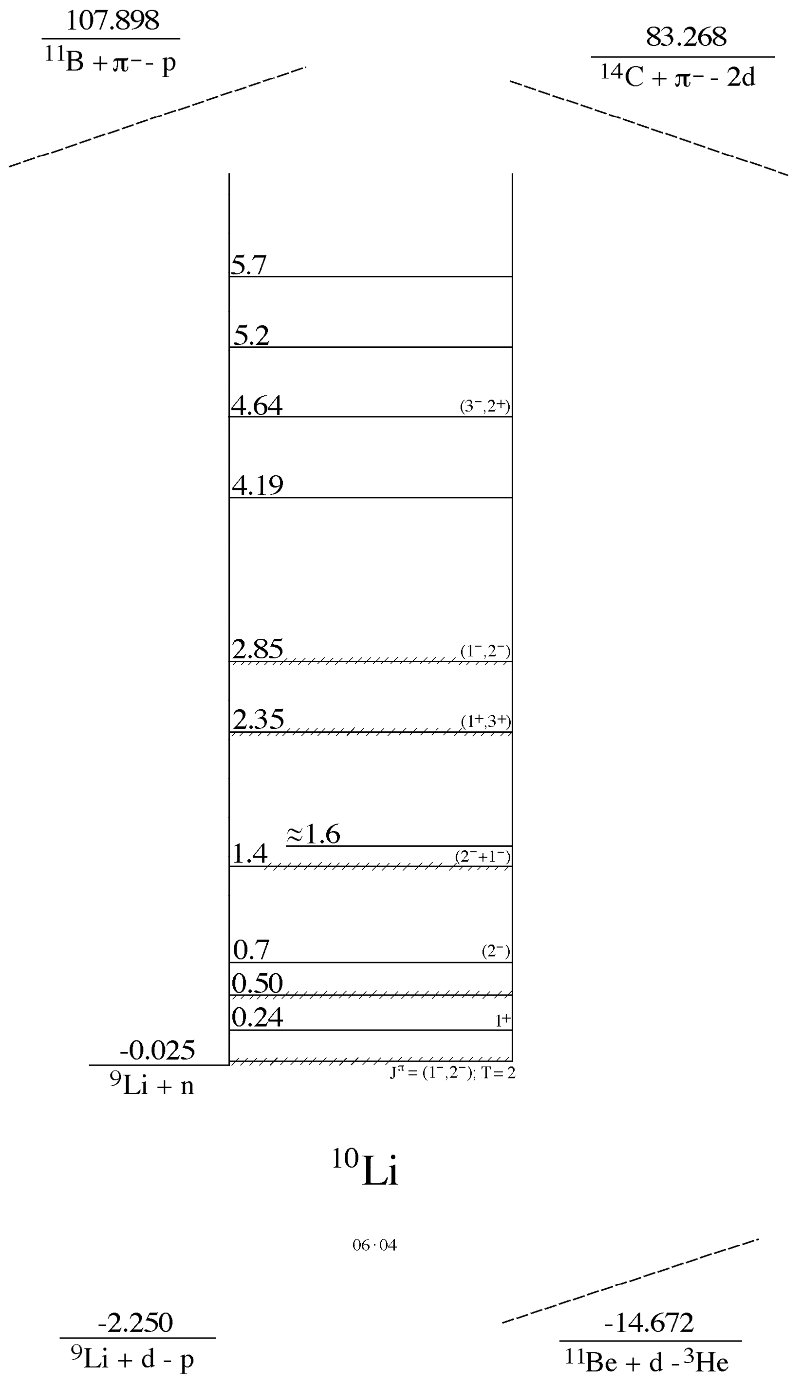


Figure 12: Energy levels of ^{10}Li. For notation see Fig. 13.

Table 10.4: ^{10}Li level parameters from ^{9}Be(^{13}C, ^{12}N)^{10}Li and ^{10}Be(^{12}C, ^{12}N)^{10}Li [a]

E_{res} (MeV) [b]	Γ_{lab} (MeV)	J^{π} [c]
0.24 ± 0.04	0.10 ± 0.07	(1^+)
0.53 ± 0.06	0.35 ± 0.08	(2^+)
1.40 ± 0.08	0.20 ± 0.07	$(2^- + 1^-)$
2.35 ± 0.10	1.2 ± 0.4	$(1^+, 3^+)$
2.85 ± 0.07	0.3 ± 0.2	$(1^-, 2^+)$
4.19 ± 0.10	0.12 ± 0.08	
4.64 ± 0.10	0.2 ± 0.1	$(3^-, 2^+)$
5.7 ± 0.1	0.2 ± 0.1	

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

[b] Resonance energy relative to ^{9}Li + n threshold.

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

summary discussion and analysis of the results of these experiments is given in (1999BO26), and the parameters for eight levels are presented. See Table 10.4 here. See also (1997BO10).

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

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

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

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

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

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

9. ^{11}Be(d, ^{3}He)^{10}Li $\qquad Q_{\rm m} = -14.672$

This reaction was studied in inverse kinematics with ^{11}Be at 35 MeV/A incident on a deuterium target (2000FO17).

10. ^{11}B(π^-, p)^{10}Li $\qquad Q_{\rm m} = 107.898$

Inclusive spectra of protons, deuterons and tritons from the absorption of stopped pions in ^{11}B were measured by (1990AM05). They reported observation of the ^{10}Li ground state at a ^{9}Li + n resonance energy, $E_{\rm res} = 0.15 \pm 0.15$ MeV with a width $\Gamma_{\rm res} < 0.4$ MeV.

In more recent work (1998GO30), stopped pions were used for ^{11}B(π^-, p)^{10}Li along with ^{14}C(π^-, dd) (reaction 15). Missing-mass spectra were measured. An analysis of ^{11}B(π^-, p) in terms of a one-peak description gave a resonance energy and width $E_{\rm res} = 0.48 \pm 0.10$ MeV, $\Gamma_{\rm res} = 0.50 \pm 0.10$ MeV. An appreciably better description in terms of two peaks gave $E_{\rm res} = 0.1 \pm 0.1$ MeV, $\Gamma_{\rm res} = 0.4 \pm 0.1$ MeV and $E_{\rm res} = 0.7 \pm 0.2$ MeV, $\Gamma_{\rm res} = 0.1 \pm 0.1$ MeV. It is suggested that the lower of these two states is the ^{10}Li$_{\rm g.s.}$ with unnatural parity. These results are compared with other available data in ^{10}Li. For results of their analysis of ^{14}C(π^-, dd) see reaction 15.

11. ^{11}B(^{7}Li, ^{8}B)^{10}Li $\qquad Q_{\rm m} = -32.397$

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

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

(b) $^{\rm nat}$C(^{11}Be, ^{9}Li + n)X

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

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

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

14. ^{13}C(^{14}C, ^{17}F)^{10}Li $\qquad Q_{\rm m} = -28.858$

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

15. ^{14}C(π^-, d + d)^{10}Li $\qquad Q_{\rm m} = 83.268$

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

16. $^{\rm nat}$Pb(^{11}Li, ^{9}Li + n)X

See reaction 12 and (1997ZI1F, 1997ZI04).

^{10}Be

(Figs. 13 and 16)

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

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

$$B(\text{E2})\!\uparrow \text{ for } {}^{10}\text{Be*}(3.37) = 52 \pm 6\ e^2 \cdot \text{fm}^4 \text{ (1987RA01)};$$
$$B(\text{E2})\!\downarrow \text{ for } {}^{10}\text{Be*}(3.37) = 10.5 \pm 1.0\ e^2 \cdot \text{fm}^4.$$

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

1. ^{10}Be(β^-)^{10}B $\qquad Q_{\rm m} = 0.5560$

The half-life of ^{10}Be is $(1.51 \pm 0.04) \times 10^6$ years; this is the weighted average of 1.51 ± 0.06 Ma (1987HO1P), $1.53 \pm 5\%$ Ma (1993MI26) and $1.48 \pm 5\%$ Ma (1993MI26). The $\log ft = 13.396 \pm 0.012$. For the earlier work see (1974AJ01). See also (1992WA02, 1990HO28, 1998MA36).

2. ^{4}He(^{6}He, ^{6}He)^{4}He $\qquad E_{\rm b} = 7.4133$

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

3. (a) ^{6}Li(^{6}He, ^{10}Be + d)
   (b) ^{6}Li(^{6}He, ^{6}He + α)^{2}H $\qquad Q_{\rm m} = -1.4738$

Molecular cluster states in ^{10}Be were studied by bombarding ^{6}Li targets with E(^{6}He) $=$ 17 MeV projectiles and detecting the ^{10}Be + d and ^{6}He + ^{4}He reaction products (1999MI39). In reaction (a)

Table 10.5: Energy levels of ^{10}Be [a]

E_x (MeV ± keV) [b]	$J^\pi; T$	τ or Γ_{cm} (keV)	Decay	Reactions
g.s.	$0^+; 1$	$\tau_{1/2} = (1.51 \pm 0.04) \times 10^6$ y	β^-	1, 3, 4, 6, 7, 9, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 41, 42, 43, 44, 46, 47, 50, 52, 53, 55
3.36803 ± 0.03	$2^+; 1$	$\tau_m = 180 \pm 17$ fsec	γ	3, 4, 5, 6, 7, 9, 13, 14, 15, 17, 18, 19, 20, 21, 22, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 41, 42, 43, 44, 46, 47, 50, 51, 52, 55
5.95839 ± 0.05	$2^+; 1$	$\tau_m < 80$ fsec	γ	(3), 6, 9, 14, 15, 17, 18, (21), 22, 25, (26), 27, 28, 30, (31), 34, 42, 44, 46, 47, 50
5.9599 ± 0.6	$1^-; 1$		γ	(3), 6, 14, 15, 17, 18, 19, 21, (26), 27, (30), (31), 34, 42
6.1793 ± 0.7	$0^+; 1$	$\tau_m = 1.1^{+0.4}_{-0.3}$ psec	π, γ	(3), 6, 14, 30
6.2633 ± 5.0	$2^-; 1$		γ	(3), 6, 14, 15, 19, 21
7.371 ± 1	$3^-; 1$	$\Gamma = 15.7 \pm 0.5$ keV	n, γ	(3), 6, 7, 9, 10, 13, 14, 15, 17, 18, 27, 47
7.542 ± 1	$2^+; 1$	6.3 ± 0.8	n, α	(3), 6, 7, 10, 14, 15, 17, 26, 27, 42, 46, (47)
9.27	$(4^-); 1$	150 ± 20	n	6, 7, 10, (13), 14, 15, 18, 21, 27, (47)
see[c]				
9.56 ± 20 [d]	$2^+; 1$	141 ± 10 [e,f]	n, α	6, 7, 10, (13), 14, 15, 17, 18, 26, 27, 28, (30), 34, 42, 44, 46, 47, 54
10.15 ± 20	3^-	296 ± 15 [f]	α	3, 7, 17, 54
10.57 ± 30	$\geq 1; 1$		n, α	6, 7, 10, 14, 47
11.23 ± 50		200 ± 80 [f]	α	(3), 7
11.76 ± 20	(4^+)	121 ± 10 [f]	α	6, 7, 13, 14, 15, 17, 18, 42, 47
(11.93 ± 100)	(5^-) [g]	200 ± 80 [f]	α	7, (21), 45
13.05 ± 100		290 ± 130 [f]	α	7, (45)
13.80 ± 50		330 ± 150 [f]	α	7, 18
14.68 ± 100		310 ± 140 [f]	α	7, 45
15.3 ± 200	(6^-) [g]	800 ± 200 [h]		(18), (21), 47
17.12 ± 200	(2^-)	≈ 150		(4), 6, 45

Table 10.5: Energy levels of ^{10}Be [a] (continued)

E_x (MeV ± keV) [b]	$J^\pi; T$	τ or Γ_{cm} (keV)	Decay	Reactions
17.79		112 ± 35	γ, n, t, α	4, 6, 7, (11)
18.15 ± 50	(0^-)	90 ± 30 [f]	t	7
18.55		310 [f]	n, t	4, 6, 7, 11
(19.8)			p	7
20.8 ± 100			α	7
21.216 ± 23	$(2^-; 2)$	sharp	n, p, t	4, 11
21.8 ± 100		≈ 200 [f]	p, (d)	7
22.4 ± 100		≈ 250 [f]	(n), p, t	7, (11)
23.0 ± 100			p	(4), 7
23.35 ± 50			(n), p, d, (t), α	7, (11)
23.65 ± 50			p, (t), α	7
24.0 ± 100		≈ 150 [f]	d, (t), α	7, 33
24.25 ± 50		≈ 200 [f]	(p), d, t, α	7
24.6 ± 100		≈ 150 [f]	p, d	7
24.8 ± 100		≈ 100 [f]	p, d	7
25.05 ± 100		≈ 150 [f]	d, α	7
25.6 ± 100			(p), d, α	7
25.95 ± 50		≈ 300 [f]	d	7
26.3 ± 100		≈ 100 [f]	d, (t)	7
26.8 ± 100			p, d, α	7
27.2 ± 200			p, d, t, α	7

[a] See also Table 10.12.

[b] See reactions 4, 45 and 47 for evidence of other levels.

[c] A $J^\pi = 3^+$ state is predicted near 9 MeV, however, evidence is ambiguous: see reaction 28.

[d] Previously reported at 9.4 MeV.

[e] 141 ± 10 keV from ^{7}Li(^{7}Li, α); other value 291 ± 20 keV from ^{9}Be(d, p).

[f] Not corrected for experimental system resolution and therefore upper limits.

[g] From systematics in reaction 21.

[h] From (2001BO35): ^{12}C(^{15}N, ^{17}F).

reconstruction of the missing energy indicates that ^{10}Be*(0, 3.37) participate in the reaction as well as unresolved states at 6 MeV and 7.5 MeV. In reaction (b) the 10.2 MeV level is observed, and due to its apparent cluster nature it is suggested that this state could be the 4^+ member in the rotational band (6.18 [0^+], 7.54 [2^+], 10.2 [4^+]) [J^π in brackets]. However, see reaction 7 which indicates $J^\pi = 3^-$ for $E_x = 10.2$ MeV.

4. (a) ^{7}Li(t, γ)^{10}Be $Q_{\rm m} = 17.2509$

(b) ^{7}Li(t, n)^{9}Be $Q_{\rm m} = 10.4387$ $E_{\rm b} = 17.2509$

(c) ^{7}Li(t, p)^{9}Li $Q_{\rm m} = -2.3857$

(d) ^{7}Li(t, t)^{7}Li

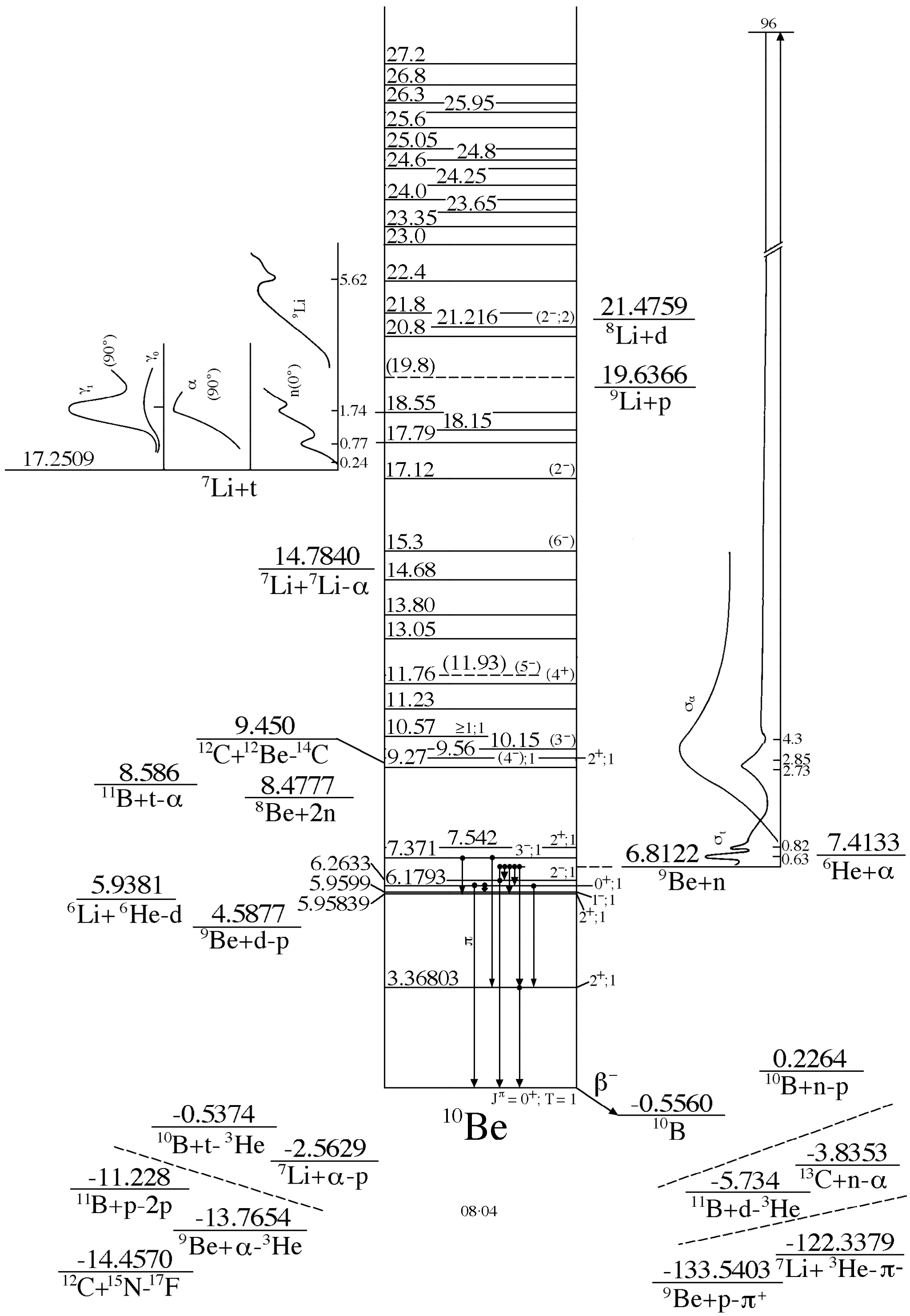
(e) ^{7}Li(t, α)^{6}He $Q_{\rm m} = 9.8376$

The yield of γ_0 and γ_1 has been studied for $E_{\rm t} = 0.4$ to 1.1 MeV [^{10}Be*(17.79) is said to be involved]: see (1984AJ01). The neutron yield exhibits a weak structure at $E_{\rm t} = 0.24$ MeV and broad resonances at $E_{\rm t} \approx 0.77$ MeV [$\Gamma_{\rm lab} = 160 \pm 50$ keV] and 1.74 MeV: see (1966LA04) [^{10}Be*(17.79, 18.47)]. The total cross section for reaction (c), the yield of neutrons (reaction (b) to ^{9}Be*(14.39)), and the yield of γ-rays from ^{7}Li*(0.48) (reaction (d)) all show a sharp anomaly at $E_{\rm t} = 5.685$ MeV: $J^{\pi} = 2^{-}$; $T = 2$ is suggested for a state at $E_{\rm x} = 21.22$ MeV. The total cross section for α_0 (reaction (e)) and the all-neutrons yield do not show this structure: see (1984AJ01, 1988AJ01). An additional anomaly in the proton yield is reported at $E_{\rm t} = 8.5$ MeV [^{10}Be*(23.2)] [see (1987AB15)]. For reaction (c) a reanalysis of the proton yields indicate two states at $E_{\rm x} = 21.216 \pm 0.023$ and 23.138 ± 0.140 MeV with $\Gamma_{\rm cm} = 80 \pm 30$ and 440 ± 178 keV, respectively (1990GU36). For reaction (e) the angular distributions of α_0 and α_1 products were measured at $E_{\rm t} = 151$ and 272 keV, and the analysis suggests possible evidence for a 2^{+} resonance, ^{10}Be*(17.3), at $E_{\rm res} = 117 \pm 3$ keV with $\Gamma_{\rm lab} = 253 \pm 1$ keV (1987AB09). Differential cross sections and S-factors are reported by (1983CE1A) for $E_{\rm t} = 70$ to 110 keV for ^{6}He*(0, 1.80). The zero-energy S-factor for ^{6}He*(1.80) is 14 ± 2.5 MeV $\cdot$ b. The relevance to a Li-seeded tritium plasma is discussed by (1983CE1A). See also (1985CA41; astrophys.).

5. ^{7}Li(^{3}He, π^{+})^{10}Be $Q_{\rm m} = -122.3379$

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

Figure 13: Energy levels of ^{10}Be. In these diagrams, energy values are plotted vertically in MeV, based on the ground state as zero. For the $A = 10$ 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 ^{10}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 10.5.



27.2
26.8
26.3
25.95
25.6
25.05
24.8
24.6
24.25
24.0
23.65
23.35
23.0
22.4
21.8
21.216
(2⁻;2)
20.8
21.4759
⁸Li+d
(19.8)
19.6366
⁹Li+p
18.55
18.15
17.79
17.12
(2⁻)
17.2509
⁷Li+t
5.62
1.74
0.77
0.24
15.3
(6⁻)
14.68
14.7840
⁷Li+⁷Li-α
13.80
13.05
11.76
(11.93)
(5⁻)
(4⁺)
11.23
10.57
≥1;1
10.15
(3⁻)
9.450
¹²C+¹²Be-¹⁴C
9.27
9.56
(4⁻);1
2⁺;1
8.586
¹¹B+t-α
8.4777
⁸Be+2n
7.371
7.542
3⁻;1
2⁺;1
6.8122
⁹Be+n
7.4133
⁶He+α
6.2633
6.1793
5.9599
5.95839
2⁻;1
0⁺;1
1⁻;1
2⁺;1
5.9381
⁶Li+⁶He-d
4.5877
⁹Be+d-p
3.36803
2⁺;1
Jπ = 0⁺; T = 1
¹⁰Be
β⁻
-0.5560
¹⁰B
0.2264
¹⁰B+n-p
-0.5374
¹⁰B+t-³He
-2.5629
⁷Li+α-p
-11.228
¹¹B+p-2p
-13.7654
⁹Be+α-³He
-14.4570
¹²C+¹⁵N-¹⁷F
-3.8353
¹³C+n-α
-5.734
¹¹B+d-³He
-122.3379
⁷Li+³He-π-
-133.5403
⁹Be+p-π⁺
96
4.3
2.85
2.73
0.82
0.63
08·04

Table 10.6: Electromagnetic transition strengths in ^{10}Be [a]

$E_i \to E_f$ (MeV)	$J^\pi_i \to J^\pi_f$	Branch (%)	Γ_γ (eV)	Mult.	Γ_γ/Γ_W
$3.368 \to 0$	$2^+ \to 0^+$	100	$(3.66 \pm 0.35) \times 10^{-3}$	E2	8.00 ± 0.76
$6.179 \to 3.368$	$0^+ \to 2^+$	76 ± 2	$(4.5 \pm 1.7) \times 10^{-4}$ [b]	E2	2.5 ± 0.9
$\to 5.960$	$\to 1^-$	24 ± 2	$(1.44 \pm 0.53) \times 10^{-4}$ [b]	E1	$(4.3 \pm 1.6) \times 10^{-2}$
$7.371 \to 3.368$	$3^- \to 2^+$	85 ± 8	0.62 ± 0.06 [c]	E1	$(3.1 \pm 0.3) \times 10^{-2}$
$\to 5.958$	$3^- \to 2^+$	15 ± 11	0.11 ± 0.08 [c]	E1	$(1.2 \pm 0.9) \times 10^{-1}$

[a] Γ_γ from lifetimes and branching ratios. See also ^{9}Be(d, pγ)^{10}Be [reaction 14] and Table 10.12.

[b] Assumed maximum of asymmetrical uncertainty.

[c] From ^{9}Be(n, γ)^{10}Be (1994KI09).

6. ^{7}Li(α, p)^{10}Be $\qquad Q_m = -2.5629$

Angular distributions were measured at $E_\alpha = 65$ MeV (1994HA16). Observed states are shown in Table 10.8. For ^{10}Be*(11.76) the angular distribution is consistent with $L = 3$ which supports a $J^\pi = 4^+$ assignment. It is suggested that the 11.76 MeV state is the 4^+ member of the ground-state $K^\pi = 0^+$ rotational band (g.s. [0^+], 3.37 [2^+], 11.76 [4^+] [J^π in brackets]).

7. (a) ^{7}Li(^{7}Li, p + ^{9}Li)^{4}He $\qquad Q_m = -4.8526$
   (b) ^{7}Li(^{7}Li, d + ^{8}Li)^{4}He $\qquad Q_m = -6.69185$
   (c) ^{7}Li(^{7}Li, t + ^{7}Li)^{4}He $\qquad Q_m = -2.46691$
   (d) ^{7}Li(^{7}Li, α)^{10}Be $\qquad Q_m = 14.7840$
   (e) ^{7}Li(^{7}Li, α + ^{6}He)^{4}He $\qquad Q_m = 7.3707$
   (f) ^{7}Li(^{7}Li, α + ^{9}Be)n $\qquad Q_m = 7.9718$

Resonant particle decay spectroscopy measurements have been reported for reactions (a), (b), (c), (e), (f): see Table 10.9 for an overview of experimental conditions. These measurements are particularly well-suited for spectroscopic studies of levels that decay to excited states of the component isotopes, i.e. $\alpha_1 + {}^6$He*(1.8). Values of $\Gamma_\alpha/\Gamma = (3.5 \pm 1.2) \times 10^{-3}$ and 0.16 ± 0.04 for ^{10}Be*(7.542, 9.6), respectively, are determined by (2002LI15). See also (2004AR01) for a cluster model analysis.

New evidence suggests that the previously accepted level energy at 9.4 MeV corresponds to the level presently observed at 9.6 MeV (1996SO17, 2001MI39, 2002LI15). (1997CU03, 2001CU06)

Table 10.7: Neutron-capture γ-rays in ^{10}Be [a]

E_γ (keV) [b]	Transition	E_x (keV) [b]
6809.585 ± 0.033	capt. $\to$ g.s.	6812.038 ± 0.029
5955.9 ± 0.5 [a]	5.96 [c] $\to$ g.s.	5958.387 ± 0.051
3443.374 ± 0.030	capt. $\to$ 3.37	
3367.415 ± 0.030	3.37 $\to$ g.s.	3368.029 ± 0.029
2589.999 ± 0.060	5.96 [c] $\to$ 3.37	
853.605 ± 0.060	capt. $\to$ 5.96 [c]	

[a] See also Table 10.2 in (1974AJ01, 1979AJ01).

[b] (1983KE11). 12 eV has been added in quadrature to the uncertainties. See (1988AJ01). Some of the work displayed in Table 10.2 of (1984AJ01) is not shown here because it has not been published. However, those particular transitions are shown in Fig. 13 here since it is clear that they have been observed although the lack of published uncertainties make their inclusion in this table inadvisable.

[c] This is the 2^+ member of the doublet at $E_x = 5.96$ MeV.

measured $E_x = 9.56 \pm 0.02$ MeV and determined $\Gamma_{cm} = 141 \pm 10$ keV and $J^\pi = 2^+$. Assuming that the ^{10}Be*(9.56) state is 2^+ suggests that it is probably a member of the $K^\pi = 1^+$ band and the 3^- 10.15 MeV level is probably in the $K^\pi = (1^-, 2^-)$ band (2001CU06, 2002LI15). See also (2004MI07) and Fig. 8 in (2002LI15).

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

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

For reaction (d), angular distributions of α_1 and $\alpha_{2+3+4+5}$ were reported in (1969CA1A). Groups corresponding to ^{10}Be*(0, 3.4, 6.0, 7.4, 9.4, 10.7, 11.9, 17.9) and possibly ^{10}Be*(18.8) were reported in (1971GL07). See (1974AJ01).

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

Table 10.8: Levels of ^{10}Be from ^{7}Li(α, p)^{10}Be [a]

E_x (MeV)	J^π	Γ_{cm} (keV)	L [c]	S_{rel}
0	0^+		1	1.00
3.37	2^+		3	0.067
5.96	$2^+, 1^-$		doublet	
6.18	0^+		1	0.86
6.26	2^-		2	0.53
7.37	3^-		2	0.67
7.54	2^+		3	0.10
9.27	(4^-)		2	0.84
9.64 ± 0.10	(2^+)		3	0.13
10.57	≥ 1		0, 1	0.08, 0.035
11.76	(4^+)		3	0.049
17.12 ± 0.20	(2^-)	≈ 150	0	0.3
17.79	(2^-) [b]	170	2	1.0
18.55	(2^-) [b]	380	2	1.0

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

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

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

The thermal capture cross section is 8.49 ± 0.34 mb (1986CO14). Reported γ-ray transitions are displayed in Table 10.7 (1983KE11). Partial cross sections involving ^{10}Be*(0, 3.37, 5.96) are listed in (1987LY01). See also the references cited in (1988AJ01).

Retardation of E1 strength was found in a measurement of the capture γ-rays from ^{9}Be+n using $E_n = 622$ keV neutrons to populate the $J^\pi = 3^-$ D-wave resonance at ^{10}Be*(7.372) (1994KI09); $\Gamma_n = 17.5$ keV. Capture to the $J^\pi = 2^+$ states at ^{10}Be*(3.368, 5.958) was observed, and $\Gamma_\gamma = 0.62 \pm 0.06$ and 0.11 ± 0.08 eV were deduced, respectively. Simple capture models indicate that

Table 10.9: ^{10}Be levels observed in ^{7}Li + ^{7}Li

$E(^7$Li) (MeV)	Observed levels in ^{10}Be* (MeV)	Reactions	Refs.
8	9.27, 9.64, 10.2, 10.57	(^{7}Li, $\alpha + {}^6$He), (^{7}Li, $\alpha + {}^9$Be)	(1996SO17)
34, 50.9	9.56, 10.15, 10.6, 11.23, 11.8, (13.1), (13.9), (14.7), 17.8	(^{7}Li, $\alpha + {}^6$He)	(1997CU03, 2001CU06)
34	7.542, ≈ 9, 17.76, 18.15, 18.5	(^{7}Li, $\alpha + {}^6$He), (^{7}Li, t + ^{7}Li)	(2002LI15)
8, 30, 52	7.5, 9.6, 10.2, 10.6, 11.8	(^{7}Li, α), (^{7}Li, 2α), (^{7}Li, $\alpha + {}^6$He)	(2001MI39)
34, 50.9	see Table 10.10	(^{7}Li, $\alpha + {}^6$He), (^{7}Li, t + ^{7}Li), (^{7}Li, p + ^{9}Li), (^{7}Li, d + ^{8}Li)	(2003FL02)

capture to the 3368 keV state is appreciably hindered, which is explained by assuming a strong coupling between the d-state single particle neutron motion and the E1 giant resonance.

10. (a) ^{9}Be(n, n)^{9}Be $\qquad E_b = 6.8122$
(b) ^{9}Be(n, 2n)^{8}Be $\qquad Q_m = -1.6654$

The scattering amplitude (bound) $a = 7.778 \pm 0.003$ fm, $\sigma_{\text{free}} = 6.151 \pm 0.005$ b (1981MUZQ). The difference in the spin-dependent scattering lengths, $b^+ - b^-$ is $+0.24 \pm 0.07$ (1987GL06). See also (1987LY01). Total cross section measurements have been reported for $E_n = 0.002$ eV to 2.6 GeV/c [see (1979AJ01, 1984AJ01)] and at 24 keV (1983AI01), 7 to 15 MeV (1983DA22; also reaction cross sections) and 10.96, 13.89 and 16.89 MeV (1985TE01; for n_0 and n_2).

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

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

11. (a) ^{9}Be(n, p)^{9}Li $Q_m = -12.8244$ $E_b = 6.8122$

(b) ^{9}Be(n, d)^{8}Li $Q_m = -14.6636$

(c) ^{9}Be(n, t)^{7}Li $Q_m = -10.4387$

Cross sections have been measured at $E_n = 14.1$–14.9 MeV for reaction (a), and at 16.3–18.8 MeV for reaction (b): see (1979AJ01). For reaction (c), measurements have been reported at $E_n = 13.3$–15.0 (t_1), at 22.5 MeV (see (1979AJ01)), and at 14.6 MeV (1987ZA01). A measurement of the ^{9}Be(n, tγ_1)^{7}Li inclusive cross sections that encompassed $E_n = 12$–200 MeV observed peaks corresponding to ^{10}Be*((17.79), 18.55, 21.22, 22.26, (24.0)) (2002NE02). For the 18.55 and 24.0 MeV states, the peaks were observed at 18.76 and 23.4 MeV, respectively.

12. ^{9}Be(n, α)^{6}He $Q_m = -0.6011$ $E_b = 6.8122$

The cross section for production of ^{6}He shows a smooth rise to a broad maximum of 104 ± 7 mb at 3.0 MeV, followed by a gradual decrease to 70 mb at 4.4 MeV. From $E_n = 3.9$ to 8.6 MeV, the cross section decreases smoothly from 100 mb to 32 mb. Excitation functions have been measured for α_0 and α_1 for $E_n = 12.2$ to 18.0 MeV: see (1979AJ01) for references.

13. (a) ^{9}Be(p, π^+)^{10}Be $Q_m = -133.5403$

(b) ^{9}Be(p, K^+)

Angular distributions for reaction (a) have been studied at $E_p = 185$ to 800 MeV [see (1984AJ01)] and at $E_{\vec{p}} = 650$ MeV (1986HO23; to ^{10}Be*(0, 3.37)). States at $E_x = 6.07 \pm 0.13$, 7.39 ± 0.13, 9.31 ± 0.24, 11.76 MeV have also been populated. A_y measurements involving ^{10}Be*(0, 3.37) are reported at $E_{\vec{p}} = 200$ to 250 MeV [see (1984AJ01)] and at 650 MeV (1986HO23).

For reaction (b), the K^+ production cross sections were measured for $E_p = 835$–990 MeV (1988KO36). Calculations for one- and two-step K^+ production for $E_p = 0.8$–3 GeV are given in (2000PA15).

14. ^{9}Be(d, p)^{10}Be $Q_m = 4.5877$

Angular distributions of proton groups have been studied at many energies in the range $E_d = 0.06$ to 17.3 MeV and at 698 MeV [see (1979AJ01, 1984AJ01, 1988AJ01) and (1997YA02)], as well as at $E_{\vec{d}} = 2.0$ to 2.8 MeV (1984AN16, 1984DE46; p_0, p_1; also VAP) and $E_d = 12.5$ MeV (1987VA13; p_0, p_1). The angular distributions show $l_n = 1$ transfer for ^{10}Be*(0, 3.37, 5.958, 7.54), $l_n = 0$ transfer for ^{10}Be*(5.960, 6.26), $l_n = 2$ transfer for ^{10}Be*(7.37). ^{10}Be*(6.18, 9.27,

Table 10.10: Levels of ^{10}Be from ^{7}Li(^{7}Li, p + ^{9}Li), (^{7}Li, t + ^{7}Li) and (^{7}Li, α + ^{6}He) at $E(^{7}\text{Li}) = 34$ and 51 MeV [a]

E_x (MeV)	Γ_{cm} (keV)	Decay	E_x (MeV)	Γ_{cm} (keV)	Decay
7.542 [b]		α	21.8 ± 0.1	≈ 200 [f]	p, (d)
9.56 ± 0.02 [c]	141 ± 10	α	22.4 ± 0.1	≈ 250 [f]	p, t, (t_1)
10.15 ± 0.02 [d]	296 ± 15	α	23.0 ± 0.1		p
10.57		α	23.35 ± 0.05		p, d, (t), α_1
11.23 ± 0.05	200 ± 80 [f]	α	23.65 ± 0.05		p_1, (t), α, α_1
11.76		α	24.0 ± 0.1	≈ 150 [f]	d, (t), α_1
(11.93 ± 0.1)	200 ± 80 [f]	α	24.25 ± 0.05	≈ 200 [f]	(p), d, (d_1), t, α, α_1
13.05 ± 0.1	290 ± 130 [f]	α	24.6 ± 0.1	≈ 150 [f]	p_1, d
13.85 ± 0.1	330 ± 150 [f]	α	24.8 ± 0.1	≈ 100 [f]	p, d, d_1
14.68 ± 0.1	310 ± 140 [f]	α	25.05 ± 0.1	≈ 150 [f]	d, d_1, α_1
17.79	≈ 130	t, α	25.6 ± 0.1		(p), d_1, α_1
18.15 ± 0.05 [e]	$\approx 90 \pm 30$	t_1	25.95 ± 0.05	≈ 300 [f]	d, d_1
18.55	≈ 310	t_1	26.3 ± 0.1	≈ 100 [f]	d, d_1, (t_1), (t_2)
(19.8)		p	26.8 ± 0.1		p, d, d_1, d_2, α_1
20.8 ± 0.1		α	27.2 ± 0.2		p, d, d_1, d_2, t, t_1, α, α_1

[a] (2001CU06, 2002LI15, 2003FL02).

[b] $\Gamma_\alpha = 22 \pm 8$ eV (2002LI15).

[c] $J^\pi = 2^+$, $\Gamma_\alpha = 23 \pm 6$ keV (2002LI15).

[d] $J^\pi = 3^-$ (2001CU06).

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

[f] Not corrected for experimental system resolution and therefore upper limits (2003FL02).

Table 10.11: Resonances in ^{9}Be(n, n)^{9}Be [a]

$E_{\rm res}$ (MeV $\pm$ keV)	^{10}Be* (MeV)	$\Gamma_{\rm cm}$ (keV)	J^{π}	l	θ^2 [b]
0.6220 ± 0.8	7.371	15.7 ± 0.5	3^-	2	0.075
0.8118 ± 0.7	7.542	6.3 ± 0.8	2^+	1	0.0028
2.73	9.27	≈ 100	(4^-)	(2)	
(2.85)	9.4	≈ 400	(2^+)	(1)	
4.3	10.7		≥ 1		

[a] For references see Table 10.3 in (1979AJ01).
[b] $R = 5.6$ fm.

9.6) are also populated, as are two states at $E_{\rm x} = 10.57 \pm 0.03$ and 11.76 ± 0.02 MeV. The state reported by (1974AN27) at 9.4 MeV is most likely the 9.6 MeV 2^+ state based on its separation from the 9.27 MeV state (2001CU06). ^{10}Be*(9.27, 9.6, 11.76) have $\Gamma_{\rm c.m.} = 150 \pm 20$, 291 ± 20 and 121 ± 10 keV, respectively. See (1979AJ01) for references. See also (1989SZ02, 1995LY03, 1998LE27, 2000GE16).

Angular distributions and excitation functions for ^{9}Be(d, p$_0$) and (d, p$_1$) were measured for the energy range $E_{\rm cm} = 57$–139 keV (1997YA02, 1997YA08). Astrophysical $S(E)$-factors were deduced and the spectroscopic factor $S = 0.92$ was deduced for ^{9}Be(d, p$_0$). (2000GE16) analyzed $\sigma(E)$ and $S(E)$ for $E = 0.085$–11 MeV and evaluated the impact of this reaction for forming heavier B, C and N nuclei in nucleosynthesis.

At $E_{\rm d} = 1.0$ MeV, p + γ coincidences were measured. In this experiment $E_{\rm x} = 3368.34 \pm 0.43$ keV was measured, which confirms $E_{\rm x} = 3368.03 \pm 0.03$ keV [Table 10.5] for ^{10}Be*(3.3) (1999BU26): see reaction 55.

At $E_{\rm d} = 15.3$ MeV the p$_0$ and p$_1$ + γ_1 double-differential cross sections were measured and evaluated with coupled-channel calculations which suggest that multistep processes are important in the reaction mechanism (2001ZE09).

Attempts to understand the γ-decay of ^{10}Be*(5.96) and its population in ^{9}Be(n, γ)^{10}Be led to the discovery that it consisted of two states separated by 1.6 ± 0.5 keV. The lower of the two has $J^{\pi} = 2^+$ and decays primarily by a cascade transition via ^{10}Be*(3.37) [it is the state fed directly in the ^{9}Be(n, γ) decay]; the higher state has $J^{\pi} = 1^-$ and decays mainly to the ^{10}Be$_{\rm g.s.}$. Angular distributions measured with the γ-ray detector located normal to the reaction plane lead to $l_{\rm n}$ values consistent with the assignments of 2^+ and 1^- for ^{10}Be*(5.9584, 5.9599) obtained from the character of the γ-decay. ^{10}Be*(6.18) decays primarily to ^{10}Be*(3.37): $E_{\gamma} = 219.4 \pm 0.3$ keV for the $6.18 \rightarrow 5.96$ transition. See Table 10.12 for a listing of the information on radiative transitions obtained in this reaction and lifetime measurements. For (p, γ) correlations through ^{10}Be*(3.37) see (1987VA13) and references in (1974AJ01). For polarization measurements see ^{11}B in (1990AJ01).

15. ^{9}Be(α, ^{3}He)^{10}Be $\qquad Q_{\rm m} = -13.7654$

Angular distributions have been studied at $E_\alpha = 65$ MeV to ^{10}Be*(0, 3.37, 5.96, 6.26, 7.37, 7.54, 9.33 [u], 11.88). DWBA analyses of these lead to spectroscopic factors (1980HA33) which are in poor agreement with those reported in other reactions: see (1984AJ01).

Cluster model analyses of the reaction (1996VO03, 1997VO06, 1997VO17) explain the levels between 5.95 and 6.26 MeV as 2α–2n-cluster states, by analogy with cluster states in ^{9}Be. The analysis further suggests that states at 5.960, 6.263, 7.371, 9.27 and 11.76 MeV (with $J^\pi = 1^-$, 2^-, 3^-, 4^- and 5^-, respectively) comprise the $K^\pi = 1^-$ rotational band.

16. ^{9}Be(^{6}He, ^{5}He)^{10}Be $\qquad Q_{\rm m} = 4.946$

At $E(^{6}\text{He}) = 25$ MeV/A, 1- and 2-neutron transfer cross sections were measured in a study of n-n correlations for neutrons in ^{6}He (2003GE05). The reaction was dominated by 1-neutron transfer.

17. (a) ^{9}Be(^{7}Li, ^{6}Li)^{10}Be $\qquad Q_{\rm m} = -0.4381$
(b) ^{9}Be(^{7}Li, $\alpha + {}^{6}$He)^{6}Li $\qquad Q_{\rm m} = -7.8514$
(c) ^{9}Be(^{8}Li, ^{7}Li)^{10}Be $\qquad Q_{\rm m} = 4.7799$

Angular distributions have been measured at $E(^{7}\text{Li}) = 34$ MeV (reactions (a) and (b)) to $^{10}\text{Be}_{\text{g.s.}}$, $S = 2.07$, and ^{10}Be*(3.4), $S = 0.42$ ($\text{p}_{1/2}$), 0.38 ($\text{p}_{3/2}$): see (1979AJ01). At $E(^{7}\text{Li}) = 52$ MeV, states are reported at ^{10}Be*(0, 3.37, ≈ 6 (multiplet), 7.5 (doublet), 9.6, 10.2 11.8) (2001MI39). At $E(^{8}\text{Li}) = 11$ MeV (1989KO17) and 14.3 MeV (1989BE28, 1993BE22) angular distributions for ^{10}Be*(0, 3.37) have been measured. A DWBA analysis of the $E(^{8}\text{Li}) = 14.3$ MeV data yields spectroscopic factors of $S_{\text{g.s.}} = 4.0$ and $S_{3.37} = 0.2$ ($\text{p}_{1/2}$). At $E(^{9}\text{Be}) = 20$ MeV an angular distribution involving $^{8}\text{Be}_{\text{g.s.}} + {}^{10}\text{Be}_{\text{g.s.}}$ has been measured: transitions to excited states of ^{10}Be are very weak (1985JA09).

18. ^{9}Be(^{9}Be, ^{8}Be)^{10}Be $\qquad Q_{\rm m} = 5.1468$

At $E(^{9}\text{Be}) = 20$ MeV an angular distribution involving $^{8}\text{Be}_{\text{g.s.}}$ and $^{10}\text{Be}_{\text{g.s.}}$ was measured: transitions to excited states are weak (1985JA09). At $E(^{9}\text{Be}) = 48$ MeV, excited states of ^{10}Be were populated (2003AS04): see Table 10.13. The excitation energy of ^{10}Be states was deduced from the measured energy of the ^{8}Be recoil, which was detected as two α particles. The α-particle energy spectra were analyzed in a CCBA model analysis to justify their interpretation of spin values.

Table 10.12: Radiative transitions in ^{9}Be(d, p)^{10}Be [a]

E_x (keV)	Transition	ΔJ^π	Mult.	Branch (%)	τ_m (psec)	Γ_γ (meV)
3368.34 ± 0.43 [b]	$3.37 \to$ g.s.	$2^+ \to 0^+$	E2	100	0.189 ± 0.020	3.48 ± 0.37
					0.160 ± 0.030	4.11 ± 0.78
5958.3 ± 0.3	$5.96 \to 3.37$	$2^+ \to 2^+$	M1	> 90	< 0.08	
	$5.96 \to$ g.s.	$2^+ \to 0^+$	E2	< 10		
5959.9 ± 0.6	$5.96 \to$ g.s.	$1^- \to 0^+$	E1	83^{+10}_{-6}		
	$5.96 \to 3.37$	$1^- \to 2^+$	E1	17^{+6}_{-10}		
6179.3 ± 0.7	$6.18 \to 5.96$	$0^+ \to 1^-$	E1	24 ± 2	$1.1^{+0.4}_{-0.3}$	0.14 ± 0.05
	$6.18 \to 3.37$	$0^+ \to 2^+$	E2	76 ± 2		0.46 ± 0.28
	$6.18 \to$ g.s.	$0^+ \to 0^+$	E0			
6263.3 ± 5	$6.26 \to 5.96$	$2^- \to 1^-$	M1	≤ 1		
		$\to 2^+$	E1	≤ 1		
	$6.26 \to 3.37$	$2^- \to 2^+$	E1	99^{+1}_{-2}		
	$6.26 \to$ g.s.	$2^- \to 0^+$	M2	1 ± 1		

[a] See Table 10.4 in (1979AJ01) for references. However, note that there are several typographical errors in the ^{10}Be*(6.18) decay.
[b] From (1999BU26). (Corrected on 10/05/2006.)

Table 10.13: ^{10}Be states populated in ^{9}Be(^{9}Be, ^{8}Be)^{10}Be (2003AS04)

E_x (MeV)	J^π
0.00 ± 0.06	0^+
3.31 ± 0.06	2^+
5.91 ± 0.06	$2^+, 1^-$
7.31 ± 0.07	3^-
9.20 ± 0.06	4^- [a]
9.58 ± 0.06	
11.79 ± 0.06	
13.78 ± 0.06	
(15.25 ± 0.06)	

[a] W.N. Catford, private communication.

19. ^{9}Be(^{11}Be, ^{10}Be)^{10}Be $\qquad Q_{\rm m} = 6.308$

The ^{10}Be core excitations in the ^{11}Be ground state were determined by measuring ^{10}Be fragments in coincidence with γ-rays in ^{9}Be(^{11}Be, ^{10}Be$+\gamma$)X at 60 MeV/A. The γ-rays corresponding to ^{10}Be*(3.37, 5.96, 6.26) were observed in 6.1%, 6.6% and 9.1% of the events, respectively. This indicates a small $0d$ admixture to the ^{11}Be ground state which is dominated by a $1s$ single-particle component (2000AU02). In a different experiment at $E(^{11}\text{Be}) = 46$ MeV/A, γ-ray plus ^{10}Be coincidences were observed. The γ-rays corresponding to transitions between $6.263 \rightarrow 3.368$ MeV, $5.96 \rightarrow 0$ MeV and $3.368 \rightarrow 0$ MeV were observed (2001CH46), though in this case excitation energies were not resolved in the charged particle spectra. See (1992WA22, 2000PA53) for calculations of spectroscopic factors. Also see (1995KE02, 1996ES01, 1999TO07).

20. ^{9}Be(^{11}B, ^{10}B)^{10}Be $\qquad Q_{\rm m} = -4.642$

Differential cross sections for ^{9}Be(^{11}B, ^{10}B)^{10}Be were measured at $E(^{11}\text{B}) = 45$ MeV for the angular range $\theta_{\rm lab} = 10$–165° (2003KY01). The quasi-symmetric distributions involving ^{10}Be*(0, 3.368) and ^{10}B*(0.0.78, 1.74, 2.154, 3.587) were analyzed in a coupled-reaction-channels method. Spectroscopic amplitudes are discussed for all possible 1- and 2-step processes. Analysis indicates that the reaction proceeds primarily by one-step proton- or neutron transfer.

21. ^{9}Be(^{14}N, ^{13}N)^{10}Be $\qquad Q_{\rm m} = -3.7412$

At $E(^{14}\text{N}) = 217.9$ MeV, ^{10}Be*(0, 3.37, 5.960, 6.25, 7.37, 9.27, 11.8, 15.34) states are reported with $J^{\pi} = 0^{+}$, 2^{+}, $1^{-}(+2^{+})$, 2^{-}, 3^{-}, 4^{-}, (5^{-}), (6^{-}), respectively (2003BO24, 2003BO38). The data are interpreted by assuming that the levels are α-cluster molecular states with the binding energy provided by the excess neutrons. In this analysis, the members of the $K^{\pi} = 1^{-}$ rotational band are described by the formula, $E_{\rm x} \approx 0.25\,[J(J+1) - 1 \times 2] + 5.96$ MeV. See also (2003HO30).

22. (a) ^{10}Be(p, p$'$)^{10}Be
(b) ^{10}Be(d, d)^{10}Be

Angular distributions of the p_0 and p_1 groups have been measured at $E_{\rm p} = 12.0$ to 16.0 MeV. The reaction was measured in inverse kinematics by scattering 59.2 MeV ^{10}Be projectiles from protons (2000IW02) and measuring the ^{10}Be recoils and associated de-excitation γ-rays. Scattering reactions involving ^{10}Be*(0, 3.77, 5.96) were observed. For the first excited state, a deformation length of $\delta = 1.80 \pm 0.25$ fm, $\beta^2 = 0.635 \pm 0.042$ and $(M_{\rm n}/M_{\rm p})/(N/Z) = 0.51 \pm 0.12$ are deduced. For the 5.96 MeV level, the branching ratio for decay via the 3.368 MeV state is 14 ± 6%

of the branch for decay directly to the ground state. For reaction (b), elastically scattered deuterons have been studied at $E_{\rm d} = 12.0$ and 15.0 MeV: see (1974AJ01).

23. ^{10}Be(^{11}Be, ^{11}Be)^{10}Be

Theoretical analysis of elastic and inelastic ^{11}Be scattering suggest enhancement of the fusion process due to strong multi-step processes in the inelastic and transfer transitions of the active neutron. In some cases, a neck formation is suggested that is analogous to a "covalent bond" for ^{10}Be–n–^{10}Be (1995IM01).

24. (a) ^{10}B(γ, π^+)^{10}Be $\qquad Q_{\rm m} = -140.1262$

(b) ^{10}B(e, e$'\pi^+$)^{10}Be $\qquad Q_{\rm m} = -140.1262$

Differential cross sections have been measured to ^{10}Be*(0, 3.37) at $E_\gamma = 230$ to 340 MeV [see (1984AJ01)] and at $E_{\rm e} = 185$ MeV (1986YA07) and 200 MeV (1984BLZY). A theoretical study of $\gamma + {\rm N} \rightarrow \pi + {\rm N}$ dynamics, for $E_\gamma = 183$ and 320 MeV (1994SA02), indicates that core polarization non-local effects due to off-shell dynamics must be accounted for rigorously to obtain agreement with data. See also (1990BE49) for calculations at $E_\gamma \approx 200$ MeV and (1990ER03) for $E_\gamma = 180$–320 MeV.

25. ^{10}B(μ^-, ν)^{10}Be $\qquad Q_{\rm m} = 105.1024$

Partial capture rates leading to the 2^+ states ^{10}Be*(3.37, 5.96) have been reported: see (1984AJ01). A review of muon capture rates (1998MU17), discusses a renormalization of the nuclear vector and axial vector strengths.

26. ^{10}B(π^-, γ)^{10}Be $\qquad Q_{\rm m} = 139.0142$

The photon spectrum from stopped pions is dominated by peaks corresponding to ^{10}Be*(0, 3.4, 6.0, 7.5, 9.4). Branching ratios have been obtained: those to ^{10}Be*(0, 3.4) are (2.02 ± 0.17)% and (4.65 ± 0.30)%, respectively [absolute branching ratio per stopped pion] (1986PE05). See (1979AJ01) for the earlier work. Also see (1998NA01).

27. (a)^{10}B(n, p)^{10}Be $\qquad Q_{\rm m} = 0.2264$

(b) ^{10}B(d, 2p)^{10}Be $\qquad Q_{\rm m} = -1.9982$

The cross section for reaction (a) at thermal neutron energies is $\sigma = 6.4 \pm 0.5$ mb, which is one order of magnitude lower than that of the (n, t) channel (1987LA16). At $E_n = 96$ MeV, the ^{10}Be excitation spectra was evaluated by carrying out a multipole decomposition up to $E_x = 35$ MeV (2001RI02) to deduce the Gamow-Teller strength distribution; while low-lying states were unresolved, the high excitation spectra was dominated by a broad $L = 1$ peak that was centered at $E_x = 22$ MeV. Also see (1974AJ01) and ^{11}B in (1990AJ01). For reaction (b) at $E_d = 55$ MeV, states are reported at ^{10}Be*(0, 3.37, 5.96, 7.37, 7.54, 9.27 [u], 9.4 [u]) [u = unresolved] (1979ST15), and angular distributions are given for the $J^\pi = 0^+$ ^{10}Be$_{\rm g.s.}$ and the $J^\pi = 2^+$ states at 3.37, 5.96 and 9.4 MeV.

28. ^{10}B(t, ^{3}He)^{10}Be $\qquad Q_m = -0.5374$

At $E_t = 381$ MeV, states were observed at 0, 3.37, 5.96 and 9.4 MeV with some strength at 12–13.25 MeV (1997DA28, 1998DA05). A proportionality between the 0-degree (t, ^{3}He) cross section and the Gamow-Teller strength deduced from β-decay measurements is discussed. The 3.37, 5.96 and 9.4 MeV states are identified as spin-flip Gamow-Teller excitations ($\Delta S = 1$, $\Delta T = 1$). $J^\pi = 3^+$ is suggested for the 9.4 MeV state, though 2^+ or 4^+ cannot be ruled out. Shell model predictions indicate $J^\pi = 3^+$ Isobaric Analog States (IAS) in ^{10}Be, ^{10}B and ^{10}C at approximately 9, 11 and 8 MeV, respectively (1993WA06, 2001MI29). However, the uncertainty in J^π and lack of observation of these states in ^{10}B and ^{10}C prevents an acceptance of this suggested $J^\pi = 3^+$ state as a new level at the present time; we associate this level with the 9.56 MeV, $J^\pi = 2^+$ level in Table 10.5. The 2^+ states at 3.37 and 5.96 MeV are Gamow-Teller excitations and the IAS of the 3.35 and 5.3 MeV states in ^{10}C. The values $B(\text{GT}_-) = 0.68 \pm 0.02$ from ^{10}B(p, n)^{10}C*(5.38) and $B(\text{GT}_+) = 0.95 \pm 0.13$ from ^{10}B(t, ^{3}He)^{10}Be*(5.96) may indicate that the nuclear structure of ^{10}Be and ^{10}C differs because of the presence of the Coulomb force, giving rise to isospin symmetry violation.

29. ^{10}B(^{7}Li, ^{7}Be)^{10}Be $\qquad Q_m = -1.4182$

At $E(^7\text{Li}) = 39$ MeV, ^{10}Be*(0, 3.37, 5.96) states were observed (1988ET02). At this energy sequential processes are blocked, due to isospin mixing, and the one-step mechanism is most important. Also see (1989ET03).

30. ^{11}Li(β^-)^{11}Be $\rightarrow$ ^{10}Be + n $\qquad Q_m = 20.1190$

New constraints on the ^{11}Li β-decay branch that feeds the ^{11}Be ground state indicate that the ^{11}Li β-delayed single neutron emission probability is $P_{1n} = 87.6 \pm 0.8\%$ (1997BO01).

The β-delayed neutrons following ^{11}Li decay were measured by (1997MO35); results of their observations are presented in Table 10.14. A different technique, utilizing a β-neutron-γ-ray triple coincidence was employed by (1997AO01, 1997AO04): see Table 10.15. While the overall shape of the neutron energy spectra measured by (1997MO35) and (1997AO01, 1997AO04) are in excellent agreement, the analysis of their data leads to different interpretations and conflicting results. The measurements of (1997AO01, 1997AO04) reported involvement of a new ^{11}Be state at $E_x = 8.03$ MeV; this new state is implied by both an ≈ 1.5 MeV neutron in coincidence with the 2590 keV ^{10}Be*($5.96 \rightarrow 3.36$) γ-ray, and an ≈ 3.6 MeV neutron in coincidence with the 3368 keV ^{10}Be*($3.36 \rightarrow 0$) γ-ray. However, the interpretation of β-n coincidences by (1997MO35) included low-energy neutrons from the unobserved ^{11}Be*(3.87, 3.96) $\rightarrow$ ^{10}Be*(3.36) $+$ n and ^{11}Be*(6.51, 6.70, 7.03) $\rightarrow$ ^{10}Be*(≈ 6) $+$ n decay branches into the analysis, and with their inferred branching ratios it was not necessary to introduce a new state at 8.03 MeV.

To address the question of a possible level in ^{11}Be at $E_x = 8.03$ MeV, (2003FY01) developed a procedure to evaluate Doppler broadening in isotropic γ-ray decay that occurs, for example, following β-delayed neutron decay. A model was developed that indicates a well-defined γ-ray spectrum shape that depends on recoil velocity after decay, the level lifetime, and recoil energy-losses/stopping powers in the target. The 2590 keV γ-ray from ^{10}Be*(5.958) decay was evaluated, and the observed Doppler broadening was consistent with population of this level via neutron-decay from a ^{11}Be level around $E_x = 8.6$–9.1 MeV. This interpretation favors the analysis of (1997AO01, 1997AO04).

For earlier work see (1984AJ01, 1988AJ01) where population of complex decay branches are reported.

31. ^{11}Be(p, d)^{10}Be $\qquad Q_m = 1.7206$

Angular distributions were measured for $E(^{11}\text{Be}) = 35$ MeV/A (2000FO17, 2001WI05). The ^{10}Be$_{\text{g.s.}}$, 3.4 MeV and unresolved states near 6 MeV were observed. The spectroscopic factors for the ^{10}Be*(3.37) state inferred from standard DWBA and coupled-channels analysis differ by roughly a factor of 1.7. A "best estimate" for describing the ^{11}Be ground-state wave function includes a 16% core excitation of the ^{10}Be*(3.34) state [$2^+ \otimes$ d]. Also see (1999TI04, 2000YI02). For calculations at $E(^{11}\text{Be}) = 800$ MeV see (1998CA18).

32. ^{11}B(γ, p)^{10}Be $\qquad Q_m = -11.228$

See (1984AL22) and ^{11}B in (1990AJ01). See also (1979AJ01).

33. ^{11}B(p, 2p)^{10}Be $\qquad Q_m = -11.228$

Structure is observed in the summed proton spectrum corresponding to $Q = -10.9 \pm 0.35$,

Table 10.14: ^{10}Be levels observed following ^{11}Li β-delayed neutron decay in a β-n coincidence measurement (1997MO35)

Decay to ^{11}Be* (MeV)	Branching ratio (%) [a]	B(GT)	^{11}Be n-decay to ^{10}Be* (MeV)	Branching ratio (%)
0	0.5 ± 6.0			
0.32	7.8 ± 0.8	0.0084 ± 0.0009		
2.643	33.3 ± 2.0	0.064 ± 0.004	0	33.3
3.866	$(16.4 + x) \pm 1.0$ [b]	0.045 ± 0.003	0 3.368	16.4 [b]
3.955	$\approx 6.4 + y$ [b]	0.021 ± 0.03	0 3.368	≈ 6.4 [b]
5.15	4.9 ± 0.5	0.020 ± 0.002	3.368	4.9
5.849	10 ± 1	0.050 ± 0.005	3.368	10
6.51–7.03	≈ 9 [c]	0.060 ± 0.007	5.958, 6.179	≈ 9
8.816	≈ 4	0.058 ± 0.007	2n-decay to ^{9}Be [d]	
≈ 10.6	6.3 ± 0.7	0.199 ± 0.022	3.368 6.179 9.403	2.8 1.0 2.5
18.1	≈ 0.3	≥ 1.6	3n decay to ^{8}Be [e]	

[a] Branching ratios relative to 100 ^{11}Li decays.

[b] ^{11}Li decays following the branches ^{11}Li $\rightarrow$ ^{11}Be*(3.866, 3.955) $\rightarrow$ ^{10}Be*(3.386) produce very low energy neutrons and lead to an additional $\approx$ 7.5% $(= x + y)$ of unobserved strength that should be shared by decays to ^{11}Be*(3.866, 3.955).

[c] ^{11}Li decays following the branches ^{11}Li $\rightarrow$ ^{11}Be*(6.51–7.03) $\rightarrow$ ^{10}Be*(5.958, 6.179) produce very low energy neutrons and lead to $\approx$ 9% of unobserved strength that should be shared by decays to ^{11}Be*(6.51–7.03).

[d] $P_{2n} = 4.2 \pm 0.4$% (1997BO01).

[e] $P_{3n} = 1.9 \pm 0.2$% (1997BO01).

Table 10.15: ^{10}Be levels observed following ^{11}Li β-delayed neutron decay in a triple coincidence (β-n-γ) measurement (1997AO01, 1997AO04)

Decay to ^{11}Be* (MeV)	J^π	Branching ratio (%) [a]	$\log ft$	^{11}Be* n-decay to ^{10}Be*		Branching ratio (%) [a]
				E_x (MeV)	J^π	
0.32	$\frac{1}{2}^-$	7.6 ± 0.8	5.67 ± 0.04			
2.69	$\frac{3}{2}^-$	26 ± 5	4.87 ± 0.08	0	0^+	26
3.96	$\frac{3}{2}^-$ [b]	21 ± 4	4.81 ± 0.08	0	0^+	11
				3.368	2^+	10
5.24	$\frac{5}{2}^-$	8.1 ± 1.6	5.05 ± 0.08	3.368	2^+	8.1
8.03 ± 0.05	$(\frac{1}{2}, \frac{3}{2})^-$	13 ± 3	4.43 ± 0.08	0	0^+	0.8
				3.368	2^+	2.8
				5.958	2^+	8.0
				6.179	0^+	1.5

[a] Branching ratios relative to 100 ^{11}Li decays.
[b] One co-author (D.J.M.) suggests $J^\pi = \frac{5}{2}^-$.

-14.7 ± 0.4, -21.1 ± 0.4, -35 ± 1 MeV: see (1974AJ01). See also (1994SH21) for a quasi-quantum multi-step reaction model.

34. ^{11}B(d, ^{3}He)^{10}Be $\qquad Q_m = -5.734$

Angular distributions have been measured at $E_d = 11.8$ and 22 MeV to ^{10}Be$_{g.s.}$ [see (1974AJ01)] and at 52 MeV to ^{10}Be*(0, 3.37, 5.96, 9.6): $S = 0.65$, 2.03, 0.13, 1.19 (normalized to the theoretical value for the ground state); $\pi = +$ for ^{10}Be*(9.6): see (1979AJ01).

35. ^{11}B(^{7}Li, ^{10}Be + γ)X

Fusion evaporation products from ^{11}B + ^{7}Li were measured at $E(^7\mathrm{Li}) = 5.5$–19 MeV by detecting the reaction products and corresponding γ-rays (2000VL04). Reactions were observed indicating ^{10}Be$_{g.s.}$ and ^{10}Be* $+ \gamma(3368)$. Results were used to evaluate the ^{7}Li $+$ ^{11}B fusion barrier and the angular momentum achieved in the compound nucleus.

36. ^{11}B(^{11}B, ^{12}C)^{10}Be $\qquad Q_m = 4.729$

Table 10.16: Summary of two-proton photo- and electro-breakup measurements on ^{12}C

E_γ (MeV)	Refs.	E_e (MeV)	Refs.
80–157	(1995MC02)	100-400	(1996RY04)
114–600	(1996LA15)	475	(1992KE02, 1995KE06)
120–400	(1996MA02)	510	(1995ZO01)
150–400	(1996HA17)	705	(1998BL06, 2000RO17)
150–700	(2000WA20)	950	(1998RY05)
160–350	(2001PO19)	14.5 GeV	(1994DE17)
200–500	(1995CR04)		
250–600	(1998HA01)		
300	(1987KA13)		

See (1985PO02).

37. ^{12}C(γ, 2p)^{10}Be $\qquad Q_m = -27.1846$

Photo-breakup reactions on ^{12}C have been reported for $E_\gamma = 80$–700 MeV (see Table 10.16). Two-nucleon photoemission shows promise as a means to study short-range nucleon-nucleon correlations, however it is necessary to understand the reaction mechanism and final state interactions. Between the Giant Dipole Resonance and the Δ-resonance, γ-ray absorption is primarily on clusters or pairs of nucleons which are emitted after photon absorption. Above the Δ resonance ($E_x \approx 300$ MeV) γ-rays may interact with a single nucleon to form a Δ, which then either decays into a nucleon plus pion, or the Δ may interact with another nucleon leading to emission of a pair of nucleons. The missing-mass spectra show strong peaks corresponding to (1p)^2 and (1p1s) proton pair removal, while the (1s)^2 peak is weak and broad which makes that contribution difficult to identify. Ejectile energy correlations appear to indicate that final state interactions play a role at low missing mass, however at high missing mass the energy appears to be divided between the two protons and hence final state interactions are not relevant. Polarization observables were measured by (2001PO19) and asymmetries were observed to be smaller than expected. See also (1994RY02, 1996RY04, 1998RY01, 1999IR01).

38. ^{12}C(e, e′2p)^{10}Be $\qquad Q_m = -27.1846$

Electro-production of proton pairs on ^{12}C targets has been reported for electron energies ranging from $E = 0.1$–14.5 GeV: see Table 10.16. The ^{10}Be$_{\rm g.s.}$ is observed, but low-lying resonances are not resolved. Above $E_x = 25$ MeV, peaks corresponding to $(1p)^2$, (1p1s) and $(1s)^2$ proton pair removal are observed. As in (γ, 2p) reactions [see reaction 37], two-nucleon emission induced by virtual photons also shows promise as a means to study short-range nucleon-nucleon correlations; however the reaction mechanism and final state interactions must be understood. See also (1996RY04, 1997RY01, 2003AN15).

39. ^{12}C(π^-, n + p)^{10}Be $\qquad Q_m = 111.6032$

The reaction mechanism for the absorption of stopped pions on α, np and pp clusters in ^{12}C is discussed in (1987GA11).

40. ^{12}C(n, ^{3}He)^{10}Be $\qquad Q_m = -19.4666$

At $E_n = 40$–56 MeV, the pulse shape response for discriminating various final-state channels resulting from n + ^{12}C interactions in NE213 and BC401a liquid scintillator was measured by (1994MO41). See also (1989BR05) for calculated cross sections at $E_n = 15$–60 MeV.

41. ^{12}C(^{6}He, ^{10}Be + 2α)

At $E(^6\text{He}) = 18$ MeV, this reaction was studied by detecting the triple coincidence (^{10}Be + 2α) (2004MI05). The kinematical reconstruction indicates that ^{10}Be*(0, 3.37) and the multiplet near $E_x \approx 6$ MeV participate in this reaction.

42. ^{12}C(^{6}Li, ^{8}B)^{10}Be $\qquad Q_m = -21.4414$

At $E(^6\text{Li}) = 80$ MeV, ^{10}Be*(0, 3.37, 5.96, 7.54, (9.4; J^π probably 2^+), 11.8) are populated and the angular distribution to $^{10}\text{Be}_{\text{g.s.}}$ has been measured: see (1976WE09, 1977WE03).

43. ^{12}C(^{9}Be, ^{11}C)^{10}Be $\qquad Q_m = -11.9094$

The ^{10}Be*(0, 3.368) states, and higher lying unresolved states were observed at $E(^9\text{Be}) = 40.1$ MeV (1999CA48).

44. ^{12}C(^{11}B, ^{13}N)^{10}Be $\qquad Q_m = -9.284$

At $E(^{11}\mathrm{B}) = 190$ MeV, the $J^{\pi} = 0^{+}$ $^{10}\mathrm{Be}_{\mathrm{g.s.}}$ and $J^{\pi} = 2^{+}$ excited states at ^{10}Be*(3.36, 5.95, 9.4) excited states are observed (1998BE63).

45. ^{12}C(^{12}Be, $\alpha + {}^{6}$He)^{14}C $\qquad Q_{\mathrm{m}} = 2.037$

Excited states in ^{10}Be were reconstructed from the $\alpha+{}^{6}$He relative energy spectra at $E(^{12}\mathrm{Be}) = 378$ MeV (2001FR02). Tentative evidence was found for states at $E_{\mathrm{x}} = 13.2$, 14.8 and 16.1 MeV, while other known levels were observed at 11.9 and 17.2 MeV.

46. ^{12}C(^{12}C, ^{14}O)^{10}Be $\qquad Q_{\mathrm{m}} = -20.6141$

At $E(^{12}\mathrm{C}) = 357$ MeV, the ^{10}Be*(0, 3.37, 5.96, 7.54, 9.4) levels were populated (1996ST29). The $J^{\pi} = 0^{+}$ ^{10}Be ground state is strongly populated and appears to result from a two-proton transfer which tends to leave the neutron configuration undisturbed.

47. ^{12}C(^{15}N, ^{17}F)^{10}Be $\qquad Q_{\mathrm{m}} = -14.4567$

At $E(^{15}\mathrm{N}) = 318.5$ MeV, known ^{10}Be levels at 0, 3.37, 5.96, 7.37 and 9.5 MeV were observed (2001BO35). Additional measurements by (2001BO35) at $E(^{15}\mathrm{N}) = 240$ MeV observed known levels at 3.37, 5.96, 7.37 [u] $+ 7.54$ [u], 9.27 [u] $+ 9.55$, 10.5, 11.8 MeV [u $=$ unresolved] and new levels at 13.6 ± 0.1, 15.3 ± 0.2, 16.9 ± 0.2 MeV with $\Gamma = 200 \pm 50$ keV, 0.8 ± 0.2 MeV and 1.4 ± 0.3 MeV, respectively.

48. ^{13}C(π^{+}, 3p)^{10}Be $\qquad Q_{\mathrm{m}} = 108.2216$

The mechanism for π^{+} absorption on 2 and 3 nucleon clusters in targets ranging from Li to C was studied using pions at $E_{\pi^{+}} = 50$, 100, 140 and 180 MeV (1992RA11).

49. ^{13}C(p, d $+$ 2p)^{10}Be $\qquad Q_{\mathrm{m}} = -29.9064$

See ^{12}C in (1990AJ01).

50. ^{13}C(t, ^{6}Li)^{10}Be $\qquad Q_{\mathrm{m}} = -8.6187$

Table 10.17: ^{10}Be levels from ^{13}C(t, ^{6}Li)^{10}Be (1989SI02)

E_x (MeV)	J^π	L	S
0	0^+	1	0.16
3.36	2^+	3 [a]	3.1
5.96	4^+ [b]	3 [a]	4.1

[a] (1975KU01) suggest $L = 1$ should be dominant.

[b] Levels at $E_x = 5.96$ MeV are known to have $J^\pi = 2^+$ and 1^-. See Table 10.5.

Angular distributions were measured at $E(^3\mathrm{H}) = 38$ MeV (1989SI02). ^{10}Be*(0, 3.36, 5.96) levels were observed and a DWBA analysis was used to extract spectroscopic factors shown in Table 10.17. The results indicate that more strength goes to the ^{10}Be excited states than shell model calculations predict.

51. ^{14}C(^{14}C, ^{18}O)^{10}Be $\qquad Q_m = -5.79$

See (1985KO04).

52. ^{14}C(^{18}O, ^{22}Ne)^{10}Be $\qquad Q_m = -2.34$

At $E(^{18}\mathrm{O}) = 102$ MeV, a study of α-unbound states in ^{22}Ne indicated that ^{10}Be*(0, 3.37) participate in the reaction (2002CU04).

53. (a) ^{12}C, N, O, Mg, Al, Si, Mn, Fe, Ni, Au(p, ^{10}Be)X
(b) C, ^{14}N, ^{16}O(n, ^{10}Be)X

Astrophysical production of ^{10}Be has been evaluated by measuring formation cross sections for protons incident on ^{16}O and ^{28}Si at $E_p = 30$–500 MeV (1997SI29), on ^{12}C at $E_p = 40$–500 MeV (2002KI19) and on O, Mg, Al, Si, Mn, Fe and Ni targets at $E_p = 100$ MeV–2.6 GeV (1990DI13, 1990DI06, 1993BO41). The results of (1997SI29) suggest “a soft solar proton spectrum with relatively few high energy protons over the last few million years”, when compared with ^{10}Be concentrations found in lunar rocks. See (1997BA2M, 1997GR1H, 1997MU1D, 1997ZO1C) for surveys of terrestrial ^{10}Be concentrations, and see (2000NA34) for a model estimating ^{14}N,

^{16}O(p, ^{10}Be) and (n, ^{10}Be) cross sections for $E_{\rm p} = 10$ MeV–10 GeV and for discussion of various atmospheric transport models for distributing ^{10}Be.

Spallation cross sections for $E_{\rm p} = 50$–250 MeV protons on ^{16}O were measured and were compared with Monte Carlo predictions from MCNPX (1999CH50); these data are relevant, for example, for estimating secondary radiation induced in proton therapy treatments. The target mass dependence of the cross sections for formation of ^{10}Be from $E_{\rm p} = 12$ GeV proton induced spallation reactions on Al through Au targets was measured by (1993SH27). Overall, ^{10}Be production cross sections are found to increase with increasing target mass.

For reaction (b), the ^{10}Be production cross sections for neutron induced reactions on C, N and O targets were measured at $E_{\rm n} = 14.6$ MeV by (2000SU23). See also (2000NA34).

54. (a) ^{12}C(^{10}Be, X)

(b) ^{28}Si(^{10}Be, X)

At E(^{10}Be) $\approx$ 30 MeV/A, the ^{10}Be + ^{12}C reaction was observed to populate various exit channels (2004AH02, 2004AS02). States at $E_{\rm x} = 9.6 \pm 0.1$ and 10.2 ± 0.1 MeV were observed in the ^{6}He + α breakup channel. Cross sections were given for breakup channels populating ^{8}Be*(0, 3.0) and ^{9}Be*(2.43), and other cross section were given for the (n, p) charge exchange reaction and proton pickup reaction that populate ^{10}B and ^{11}B, respectively.

For reaction (b), fragmentation of ^{10}Be was measured on Si targets for E(^{10}Be) $= 20$–60 MeV/A (1996WA27) and E(^{10}Be) $= 30$–60 MeV/A (2001WA40). The total reaction cross section was found to be near 1.55 b in this energy region, and $R^{\rm total}_{\rm rms}$ (^{10}Be) ≈ 2.38 fm is deduced from the cross section data.

55. ^{252}Cf ternary cold fission

The de-excitation of ^{10}Be* nuclei formed in the ternary cold fission of ^{252}Cf $\rightarrow$ ^{146}Ba + ^{96}Sr + ^{10}Be*(3.37) yields γ-rays that are roughly 6 keV lower in energy (1998RA16) than expected from the accepted excitation energy of $E_{\rm x} = 3368.03 \pm 0.03$ keV. The absence of Doppler broadening suggests that the ^{10}Be is formed and decays while in the potential well of the heavier Ba and Sr nuclei (1998RA16). A theoretical analysis of the reaction explains the observation as an anharmonic perturbation, which shifts the excitation energy lower (2000MI07).

^{10}B

(Figs. 14, 15 and 17)

GENERAL: References to articles on general properties of ^{10}B published since the previous review (1988AJ01) are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for ^{10}B located on our website at: (*www.tunl.duke.edu/nucldata/ General_Tables/10b.shtml*).

$$\mu = +1.80064475 \pm 0.00000057\ \mu_{\rm N}\text{: see (1989RA17)}$$
$$Q = +84.72 \pm 0.56\ \text{mb: see (1978LEZA, 1989RA17).}$$

Mass of ^{10}B: The mass excess adopted by (2003AU03) is 12050.7 ± 0.4 keV.

Isotopic abundance: (19.9 ± 0.2)% (1984DE53).

$$^{10}\text{B*(0.72)}: \mu = +0.63 \pm 0.12\ \mu_{\rm N}\text{: see (1978LEZA, 1989RA17).}$$
$$B(\text{E2})\!\downarrow \text{for } ^{10}\text{B*(0.72)} = 4.18 \pm 0.02\ e^2 \cdot \text{fm}^4\ \text{(1983VE03).}$$

Electromagnetic transitions:

Detailed information on electromagnetic transition strengths in ^{10}B is displayed in Tables 10.19 and 10.20. Table 10.19 relates to levels below the proton threshold and draws on Table 10.21 for the lifetimes of bound levels and on Table 10.22 for radiative widths from the ^{6}Li(α, γ)^{10}B reaction. With the exception of the 5.11 MeV 2^- level with one nucleon in the sd shell and the 5.18 MeV 1^+ level with two nucleons in the sd shell, the remaining levels in Table 10.19 have been established as being dominantly p-shell in character. Furthermore, analysis of the empirical p-shell wave functions which best fit the electromagnetic data shows that the p-shell states all have mainly [42] spatial symmetry and that L and $K_{\rm L}$ (to distinguish the two D states) are rather good quantum numbers (1979KU05). Table 10.20 relates to levels above the proton threshold studied mainly via the ^{9}Be(p, γ)^{10}B reaction. The region contains a number of overlapping resonances including a number of isospin-mixed s-wave resonances involving the analogs of the 5.96 MeV 1^- and 6.26 MeV 2^- levels of ^{10}Be. The lowest negative-parity states also have mainly [42] spatial symmetry and in addition (51) SU3 symmetry. Thus, the 1^- and 2^- $T = 1$ states above are mainly ^{1}P and ^{1}D in character while for the $T = 0$ states the dominant components are as follows: ^{3}P for the 5.11 MeV 2^- state, ^{3}D for the 6.13 MeV 3^- state, ^{3}F for the 6.56 MeV 4^- state, and ^{3}P for the 6.88 MeV 1^- state.

1. ^{6}Li(α, γ)^{10}B $\qquad Q_{\rm m} = 4.4610$

Observed resonances are displayed in Table 10.22. For a discussion of isovector parity-mixing

Table 10.18: Energy levels of ^{10}B [a]

E_x (MeV ± keV)	$J^\pi; T$	τ_m or Γ_{cm} (keV)	Decay	Reactions
g.s.	$3^+; 0$	stable [b]		1, 4, 5, 10, 12, 17, 18, 19, 20, 21, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 44, 45, 46, 47, 51, 52, 53, 54, 55, 56, 58, 59
0.71835 ± 0.04	$1^+; 0$	$\tau_m = 1.020 \pm 0.005$ nsec [c]	γ	1, 4, 5, 10, 12, 17, 18, 19, 20, 22, 24, 25, 26, 27, 28, 30, 31, 36, 42, 44, 45, 46, 47, 50, 51, 52, 53, 55, 58
1.74015 ± 0.17	$0^+; 1$	7 ± 3 fsec	γ	1, 4, 10, 12, 17, 18, 19, 20, 24, 25, 26, 27, 30, 42, 43, 44, 45, 46, 47, 51, 52, 56
2.1543 ± 0.5	$1^+; 0$	2.13 ± 0.20 psec	γ	1, 4, 12, 17, 18, 19, 20, 24, 25, 26, 27, 28, 30, 31, 36, 44, 45, 46, 47, 50, 51, 52, 53, 54, 55
3.5871 ± 0.5	$2^+; 0$	153 ± 12 fsec	γ	1, 4, 5, 12, 17, 18, 19, 24, 25, 26, 27, 28, 30, 31, 43, 44, 46, 51, 52, 53, 55, 58
4.7740 ± 0.5	$3^+; 0$	$\Gamma = 7.8 \pm 1.2$ eV [d]	γ, α	1, 4, 5, 11, 17, 18, 19, 24, 25, 26, 27, 28, 31, 46, 51, 52, 53, 58, 60
5.1103 ± 0.6	$2^-; 0$	0.98 ± 0.07 keV	γ, α	1, 11, 12, 17, 18, 24, 25, 27, 31, 46, 52
5.1639 ± 0.6	$2^+; 1$	1.8 ± 0.4 eV [d]	γ, α	1, 12, 17, 18, 24, 25, 27, 28, 43, 46, 51
5.180 ± 10	$1^+; 0$	110 ± 10 keV	γ, α	1, 3, 11, 12, 17, 18, 28, 31, 46
5.9195 ± 0.6	$2^+; 0$	5.82 ± 0.06 [e]	γ, α	1, 3, 11, 12, 17, 18, 19, 24, 27, 28, 30, 31, 46, 51, 52, 53
6.0250 ± 0.6	$4^+; 0$	0.052 ± 0.019 [e]	γ, α	1, 3, 11, 17, 18, 19, 24, 25, 26, 27, 28, 30, 31, 44, 46, 52, 53, 56, 58
6.1272 ± 0.7	$3^-; 0$	1.52 ± 0.08 [e]	α	3, 11, 17, 18, 19, 24, 25, 27, 28, 30, 44, 46, 52
6.560 ± 1.9 [f]	$(4)^-; 0$	25.1 ± 1.1	α	3, 11, 17, 18, 19, 24, 25, 27, 28, 30, 31, 44, 46, 51, 52, 60
6.873 ± 5	$1^-; 0 + 1$	120 ± 5	γ, p, d, α	1, 11, 12, 14, 16, 17
7.002 ± 6	$3^+; 0$ [g]	100 ± 10	p, d, α	3, 11, 16, 17, 19, 25, 27, 28, 30, 46, 52, 58
7.430 ± 10	$1^-; 1 + 0$ [h]	100 ± 10	γ, p, d, α	1, 12, 14, 16

Table 10.18: Energy levels of ^{10}B [a] (continued)

E_x (MeV ± keV)	$J^\pi; T$	τ_m or Γ_{cm} (keV)	Decay	Reactions
7.469 ± 6 [h,i]	$2^+; 1$ [i]	65 ± 10 [i]	γ, p	12, 14, 17, 19, 24, 46, 51, 56
7.480 ± 4 [h,i]	$2^-; 0 + 1$ [i]	80 ± 8 [i]	γ, p, d, α	12, 14, 16, 19, 28
7.5599 ± 0.6	$0^+; 1$	2.65 ± 0.18	γ, p	12, 14, 17, 46
(7.67 ± 30)	$(1^+; 0)$	250 ± 20	p, (d), α	14, 16, 25
7.75 ± 30 [h]	$2^-; 0 + 1$ [i]	210 ± 60 [h]	γ, p, d, α	12, 14, 16, 17, 19, 25, 46
7.96 ± 70 [j]	$T = 0$	285 ± 91	α, ^{6}Li(3^+)	11
8.07	2^+; (0)	800 ± 200	p, d, α	14, 16, 17, 24, 25
8.68 [k]	$(1^+, 2^+)$; 0 [k]		p	16, 58
8.889 ± 6	$3^-; 1$	84 ± 7	n, p, α	13, 14, 16, 17, 19, 24, 25, 51
8.894 ± 2	$2^+; 1$	40 ± 1	p, α	14, 16, 19, 24, 25, 51
9.58 ± 60 [j]	$T = 0$	257 ± 64	α, ^{6}Li(3^+)	11
10.84 ± 10	$(2^+, 3^+, 4^+)$	300 ± 100	γ, n, p	12, 13, 14, 16, 24, 25, 46
11.52 ± 35		500 ± 100	(γ), α	16, 24, 25, 44, 46
12.56 ± 30	$(0^+, 1^+, 2^+)$	100 ± 30	γ, p	12, 24, 46
13.49 ± 5	$(0^+, 1^+, 2^+)$	300 ± 50	γ, p	12, 24, 46
14.4 ± 100		800 ± 200	γ, p, α	3, 12, 44, 46
(18.2 ± 200)		(1500 ± 300)		46
18.43	$2^-; 1$	340	γ, ^{3}He	5, 7
18.80	2^+	< 600	γ, ^{3}He, α	5, 9
19.29	$2^-; 1$	190 ± 20	γ, n, p, ^{3}He, α	5, 6, 7, 9
20.1 ± 100	$1^-; 1$	broad	γ, n, p, t, ^{3}He, α	5, 6, 7, 8, 9, 23
(21.1)			γ, ^{3}He	5
23.1 ± 100		broad	γ, n	23

[a] See footnotes on level parameters changed since (1988AJ01). See also Tables 10.19, 10.20, 10.21 and 10.24.

[b] $\mu = 1.80064475 \pm 0.00000057\ \mu_N$, $Q = 84.72 \pm 0.56$ mb.

[c] $\mu = +0.63 \pm 0.12\ \mu_N$.

[d] See Table 10.22.

[e] See Table 10.23.

[f] See (1971YO05).

[g] See (1971YO05, 1979OE01).

[h] See Table 10.24 and reaction 12.

[i] From (1969MO29); see reaction 14 and Table 10.25.

[j] New levels since (1988AJ01).

[k] Energy and tentative spin assignment from (1979OE01). If this is the same level as seen in reaction 16, the width is $\approx$ 220 keV (see Table 10.26) and decay modes of p, d, α are likely.

between the 5.11 MeV and 5.16 MeV levels of ^{10}B see (1984NA07) in which thick-target yields were measured with a ^{6}Li polarized target to obtain a parity-mixing parameter. In later work (1989BA24) strengths and mixing ratios of γ-transitions from these two levels were measured. However, it is clear that for the transitions to the 1.740 MeV level contributions from the double-escape peaks of stronger transitions to the 0.718 MeV level were not properly accounted for. For the 2^+; $1 \rightarrow 0^+$; 1 transition, the published 4% branch disagrees with the limit of $< 0.5\%$ in Table 10.19 and would correspond to a B(E2) of 140 W.u. Similarly, the branch of 10.9% for the 2^-; $0 \rightarrow 0^+$; 1 transition corresponds to a B(M2) of 130 W.u. The mixing ratios from 3-point angular distributions also appear unreliable. Total transition strengths of $\omega\gamma_{\rm cm} = 0.046 \pm 0.004$ eV and 0.385 ± 0.020 eV were determined for the 2^- and 2^+ resonances, respectively, which are in good agreement with the values in Table 10.22. For a preliminary report involving a target of laser-polarized ^{6}Li atoms see (1987MU13). See also the astrophysics-related work in (1996RE16, 1997NO04).

2. (a) ^{6}Li(α, n)^{9}B	$Q_{\rm m} = -3.9753$	$E_{\rm b} = 4.4610$
(b) ^{6}Li(α, p)^{9}Be	$Q_{\rm m} = -2.1249$	
(c) ^{6}Li(α, d)^{8}Be	$Q_{\rm m} = -1.5657$	

The excitation functions for neutrons [from threshold to $E_\alpha = 15.5$ MeV] and for deuterons [$E_\alpha = 9.5$ to 25 MeV; d_0, d_1 over most of range] do not show resonance structure: see (1974AJ01, 1979AJ01). Reaction-mechanism studies of (α, p) and (α, d) at $E_\alpha = 26.7$ MeV are reported in (1990LI37) and (1989LI24), respectively. A calculation of the (α, d) cross section at $E_\alpha \leq 24$ MeV is described in (1994FU17).

3. (a) ^{6}Li(α, α)^{6}Li		$E_{\rm b} = 4.461008$
(b) ^{6}Li(α, 2α)^{2}H	$Q_{\rm m} = -1.473844$	

Excitation functions of α_0 and α_1 have been reported for $E_\alpha \leq 18.0$ MeV and 9.5 to 12.5 MeV, respectively: see (1974AJ01). Reported anomalies are displayed in Table 10.23. Elastic scattering and VAP measurements are reported for $E(^{6}\vec{\rm Li}) = 15.1$ to 22.7 MeV [see (1984AJ01)] and at $E(^{6}\vec{\rm Li}) = 19.8$ MeV (1986CAZT; also TAP). Differential cross section measurements at $E_\alpha = 50$ MeV are reported by (1992SA01, 1996BU06). Theoretical work reported since the previous review include: studies of target-clustering influence on exchange effects (1988LE06); knock-out exchange contributions in RGM (1989LE07); a description of a double-folding model potential (1993SI09); calculations with a multi-configuration RGM (1995FU11); a study of continuum-continuum coupling for $^{6}{\rm Li} \rightarrow \alpha + {\rm d}$ breakup data (1995KA07); a folding-potential analysis for $E_\alpha = 3$–50.5 MeV (1995SA12); and a study of coupling effects of resonant and continuum states for ^{6}Li(α, α) at $E_\alpha = 40$ MeV (1996SI13). Small anomalies have been reported in reaction (b) corresponding to ^{10}B*(8.67, 9.65, 10.32, 11.65): see (1984AJ01). See, however, Table 10.18. See also ^{6}Li in (1988AJ01, 2002TI10), (1987BU27), (1986ST1E; applications) and (1986YA15, 1988LE06; theor.).

4. ^{6}Li(^{6}Li, d)^{10}B $\quad Q_{\rm m} = 2.9872$

Angular distributions of deuteron groups have been determined at $E(^{6}\text{Li}) = 2.4$ to 9.0 MeV (d_0, d_1, d_3) and 7.35 and 9.0 MeV (d_4, d_5). The d_2 groups corresponding to the isospin-forbidden reaction ^{6}Li(^{6}Li, d_2)^{10}B (0^+; 1) were observed weakly in early work (see (1974AJ01)) and ^{12}C in (1980AJ01). More recent angular distribution measurements (1993WI13) at $E(^{6}\text{Li}) = 3$–8 MeV deduced the isospin-breaking matrix element.

A reaction-mechanism study of ^{6}Li(^{6}Li, d)^{10}B for $E_{\rm cm} = 7.2$–13.3 MeV is described in (1987AR13).

5. ^{7}Li(^{3}He, γ)^{10}B $\quad Q_{\rm m} = 17.7883$

Capture γ-rays have been observed for $E(^{3}\text{He}) = 0.8$ to 6.0 MeV. The γ_0 and γ_5 yields [to ^{10}B*(0, 4.77)] show resonances at $E(^{3}\text{He}) = 1.1$ and 2.2 MeV [$E_{\rm res} = 0.92$ and 2.1 MeV], the γ_1 and γ_4 yields [to ^{10}B*(0.72, 3.59)] at 1.4 MeV and the γ_4 yield at 3.4 MeV: see Table 10.10 in (1979AJ01). Both the 1.1 and 2.2 MeV resonances [^{10}B*(18.4, 19.3)] appear to result from s-wave capture; the subsequent decay is to two 3^+ states [^{10}B*(0, 4.77)]. Therefore the most likely assignment is $J^\pi = 2^-$; $T = 1$ for both [there appears to be no decay of these states via α_2 to ^{6}Li*(3.56) which has $J^\pi = 0^+$; $T = 1$: see reaction 9]. The assignment for ^{10}B*(18.8) [1.4 MeV resonance] is 1^+ or 2^+ but there appears to be α_2 decay and therefore $J^\pi = 2^+$. ^{10}B*(20.1) [3.4 MeV resonance] has an isotropic angular distribution of γ_4 and therefore $J^\pi = 1^-, 2^-$. The γ_2 group resonates at this energy which eliminates 2^-. See (1974AJ01) for references.

6. ^{7}Li(^{3}He, n)^{9}B $\quad Q_{\rm m} = 9.3520 \quad E_{\rm b} = 17.7883$

The excitation curve is smooth up to $E(^{3}\text{He}) = 1.8$ MeV and the n_0 yield shows resonance behavior at $E(^{3}\text{He}) = 2.2$ and 3.25 MeV, $\Gamma_{\rm lab} = 270 \pm 30$ and 500 ± 100 keV. No other resonances are observed up to $E(^{3}\text{He}) = 5.5$ MeV. See Table 10.10 in (1979AJ01), (1986AB10; theor.) and (1974AJ01).

7. ^{7}Li(^{3}He, p)^{9}Be $\quad Q_{\rm m} = 11.2025 \quad E_{\rm b} = 17.7883$

Table 10.19: Electromagnetic transition strengths for levels below the proton threshold in ^{10}B

$E_{\rm i} \rightarrow E_{\rm f}$ (MeV)	$J^{\pi}_{\rm i}; T_{\rm i} \rightarrow J^{\pi}_{\rm f}; T_{\rm f}$	Branch (%)	Mixing ratio (δ) (E2/M1)	Γ_γ (eV)	Mult.	$\Gamma_\gamma/\Gamma_{\rm W}$
$0.718 \rightarrow 0$ [a]	$1^+; 0 \rightarrow 3^+; 0$	100		$(6.453 \pm 0.032) \times 10^{-7}$	E2	3.240 ± 0.016
$1.740 \rightarrow 0.718$ [a]	$0^+; 1 \rightarrow 1^+; 0$	100		0.094 ± 0.040	M1	4.2 ± 1.8
$2.154 \rightarrow 0$ [a,b,c]	$1^+; 0 \rightarrow 3^+; 0$	21.1 ± 1.6		$(6.52 \pm 0.79) \times 10^{-5}$	E2	1.33 ± 0.16
$\rightarrow 0.718$	$\rightarrow 1^+; 0$	27.3 ± 0.9	$-(3.75 \pm 0.55)^{\pm 1}$	$(5.6 \pm 1.6) \times 10^{-6}$	M1	$(9.1 \pm 2.7) \times 10^{-5}$
				$(7.9 \pm 0.8) \times 10^{-5}$	E2	12.2 ± 1.3
$\rightarrow 1.740$	$\rightarrow 0^+; 1$	51.6 ± 1.6		$(1.59 \pm 0.16) \times 10^{-4}$	M1	0.107 ± 0.011
$3.587 \rightarrow 0$ [a,b,c,d]	$2^+; 0 \rightarrow 3^+; 0$	19 ± 3	1.5 ± 0.6	$(2.5 \pm 1.5) \times 10^{-4}$	M1	$(2.6 \pm 1.5) \times 10^{-4}$
				$(5.7 \pm 1.7) \times 10^{-4}$	E2	0.90 ± 0.28
$\rightarrow 0.718$	$\rightarrow 1^+; 0$	67 ± 3	$(0.11 \pm 0.10)^{-1}$	$< 2.5 \times 10^{-4}$	M1	$< 5 \times 10^{-4}$
				$(2.85 \pm 0.27) \times 10^{-3}$	E2	13.9 ± 1.4
$\rightarrow 2.154$	$\rightarrow 1^+; 0$	14 ± 2	$-(0.38 \pm 0.09)$	$(5.3 \pm 0.9) \times 10^{-4}$	M1	$(8.5 \pm 1.5) \times 10^{-3}$
				$(7.6 \pm 3.4) \times 10^{-5}$	E2	11.9 ± 5.4
$4.774 \rightarrow 0$ [e,f,j]	$3^+; 0 \rightarrow 3^+; 0$	0.5 ± 0.1		$(9.0 \pm 2.0) \times 10^{-5}$	M1	$< 4.8 \times 10^{-5}$
					E2	$< 4.2 \times 10^{-2}$
$\rightarrow 0.718$	$\rightarrow 1^+; 0$	99.5 ± 0.1		$(1.79 \pm 0.15) \times 10^{-2}$	E2	15.4 ± 1.3
$5.110 \rightarrow 0$ [e,g,h]	$2^-; 0 \rightarrow 3^+; 0$	64 ± 7		$(2.1 \pm 0.4) \times 10^{-2}$	E1	$(5.0 \pm 1.0) \times 10^{-4}$
$\rightarrow 0.718$	$\rightarrow 1^+; 0$	31 ± 7		$(1.0 \pm 0.3) \times 10^{-2}$	E1	$(3.7 \pm 1.1) \times 10^{-4}$
$\rightarrow 1.740$	$\rightarrow 0^+; 1$	5 ± 5		$(1.8 \pm 1.8) \times 10^{-3}$	M2	< 120
$5.164 \rightarrow 0$ [e,i]	$2^+; 1 \rightarrow 3^+; 0$	4.4 ± 0.4	0.12 ± 0.05	$(6.6 \pm 1.8) \times 10^{-2}$	M1	$(2.3 \pm 0.6) \times 10^{-2}$
				$(9.4 \pm 8.2) \times 10^{-4}$	E2	< 0.7
$\rightarrow 0.718$	$\rightarrow 1^+; 0$	22.6 ± 0.6	0.03 ± 0.03	0.34 ± 0.09	M1	0.18 ± 0.05

Table 10.19: Electromagnetic transition strengths for levels below the proton threshold in ^{10}B (continued)

$E_{\rm i} \rightarrow E_{\rm f}$ (MeV)	$J^\pi_{\rm i}; T_{\rm i} \rightarrow J^\pi_{\rm f}; T_{\rm f}$	Branch (%)	Mixing ratio (δ) (E2/M1)	Γ_γ (eV)	Mult.	$\Gamma_\gamma/\Gamma_{\rm W}$
$\rightarrow 1.740$	$\rightarrow 0^+; 1$	< 0.5		$< 7.5 \times 10^{-3}$	E2	< 15
$\rightarrow 2.154$	$\rightarrow 1^+; 0$	65.3 ± 0.9	0.02 ± 0.03	0.98 ± 0.26	M1	1.71 ± 0.46
$\rightarrow 3.587$	$\rightarrow 2^+; 0$	7.8 ± 0.3	0.00 ± 0.02	0.12 ± 0.03	M1	1.41 ± 0.38
$5.180 \rightarrow 1.740$ [e]	$1^+; 0 \rightarrow 0^+; 1$	≈ 100		0.06 ± 0.02	M1	$(7.0 \pm 3.5) \times 10^{-2}$
$5.920 \rightarrow 0$ [e,g]	$2^+; 0 \rightarrow 3^+; 0$	82 ± 5		0.112 ± 0.022	M1	$(2.6 \pm 0.5) \times 10^{-2}$
$\rightarrow 0.718$	$\rightarrow 1^+; 0$	18 ± 5		0.025 ± 0.007	M1	$(8.6 \pm 2.4) \times 10^{-3}$
$6.025 \rightarrow 0$ [c,e]	$4^+; 0 \rightarrow 3^+; 0$	100	$-(3.16 \pm 0.12)$	$(1.04 \pm 0.16) \times 10^{-2}$	M1	$(2.3 \pm 0.4) \times 10^{-3}$
				0.104 ± 0.015	E2	12.4 ± 1.8

[a] Γ_γ from lifetime in Table 10.21.

[b] Branches are averages from (1969YO01).

[c] Mixing ratios from (1968WA15). Note that the inverse of δ was determined for the $3.587 \rightarrow 0.718$ transition and that there is an ambiguity for the $2.154 \rightarrow 0.718$ transition. The solution with the larger E2 value is more consistent with the value from the perturbed Cohen and Kurath wave functions (1968WA15) and is used here to obtain the M1 and E2 strengths.

[d] Branches from (1969YO01) and (1969GA06) are in agreement.

[e] Γ_γ from Table 10.22.

[f] Branches from (1966AL06).

[g] Branches from (1966FO05).

[h] M2 < 120 W.u. for all branches.

[i] Branches and mixing ratios from (1979KE08). Limit on branch to 1.74 MeV level from (1967PA01, 1968WA15, 1982RI04).

Γ_γ is a sensitive function of Γ_α/Γ (see footnote [e] of Table 10.22).

[j] Without a mixing ratio, only upper limits can be given on the M1 and E2 strengths for the ground-state transition.

Table 10.20: Electromagnetic transition strengths for levels above the proton threshold in ^{10}B [a]

$E_i \rightarrow E_f$ (MeV)	$J^\pi_i; T_i \rightarrow J^\pi_f; T_f$	Branch (%)	$\omega\gamma_{cm}$ (eV)	Γ_γ (eV)	Mult.	Γ_γ/Γ_W
$6.87^{b} \rightarrow 0$	$1^-; 0$ [c] $\rightarrow 3^+; 0$	< 4.6		< 0.09	M2	< 84
$\rightarrow 0.718$	$\rightarrow 1^+; 0$	20 ± 2		0.31 ± 0.08	E1	$(4.2 \pm 1.1) \times 10^{-3}$
$\rightarrow 1.740$	$\rightarrow 0^+; 1$	53 ± 2		0.82 ± 0.20	E1	$(1.9 \pm 0.5) \times 10^{-2}$
$\rightarrow 2.154$	$\rightarrow 1^+; 0$	13 ± 1		0.20 ± 0.5	E1	$(6.0 \pm 1.5) \times 10^{-3}$
$\rightarrow 5.110$	$\rightarrow 2^-; 0$	4 ± 1		0.062 ± 0.022	M1	0.54 ± 0.19
$\rightarrow 5.164$	$\rightarrow 2^+; 1$	3 ± 1		0.046 ± 0.019	E1	$(2.9 \pm 1.2) \times 10^{-2}$
$\rightarrow 5.920$	$\rightarrow 2^+; 0$	3.5 ± 1.0		0.054 ± 0.021	E1	0.20 ± 0.08
7.43 [d] $\rightarrow 0.718$	$1^-; 1$ [c] $\rightarrow 1^+; 0$	46	0.58 ± 0.13	2.21 ± 0.50	E1	$(2.3 \pm 0.5) \times 10^{-2}$
$\rightarrow 1.740$	$\rightarrow 0^+; 1$	< 5	< 0.06	< 0.23	E1	$< 4.0 \times 10^{-3}$
$\rightarrow 2.154$	$\rightarrow 1^+; 0$	22	0.27 ± 0.08	1.03 ± 0.30	E1	$(2.2 \pm 0.7) \times 10^{-2}$
$\rightarrow 5.110$	$\rightarrow 2^-; 0$	32	0.4 ± 0.1 [e]	1.52 ± 0.38	M1	5.8 ± 1.5
7.47 [f] $\rightarrow 0$	$2^+; 1 \rightarrow 3^+; 0$	[f]	7.3 ± 0.5	11.7 ± 0.7	M1	1.34 ± 0.08
7.48 [f] $\rightarrow 0$	$2^-; 1$ [i] $\rightarrow 3^+; 0$	[f]	2.8 ± 1.4	5.0 ± 2.5	E1	$(3.8 \pm 1.9) \times 10^{-2}$
$\rightarrow 2.154$	$\rightarrow 1^+; 0$	1.9	0.20 ± 0.07	0.32 ± 0.11	M1	0.10 ± 0.03
7.56 [g] $\rightarrow 0.718$	$0^+; 1 \rightarrow 1^+; 0$	77 ± 5		4.8 ± 0.6	M1	0.72 ± 0.09
$\rightarrow 2.154$	$\rightarrow 1^+; 0$	9 ± 2		0.57 ± 0.14	M1	0.17 ± 0.05
$\rightarrow 5.180$	$\rightarrow 1^+; 0$	14 ± 2		0.87 ± 0.15	M1	3.1 ± 0.6
7.75 [h] $\rightarrow 0$	$2^-; 1$ [i] $\rightarrow 3^+; 0$	77	2.7 ± 0.7	4.32 ± 1.12	E1	$(2.9 \pm 0.8) \times 10^{-2}$
$\rightarrow 0.718$	$\rightarrow 1^+; 0$	11	0.40 ± 0.18	0.64 ± 0.29	E1	$(5.8 \pm 2.6) \times 10^{-3}$
$\rightarrow 2.154$	$\rightarrow 1^+; 0$	3.7	0.13 ± 0.07	0.21 ± 0.11	E1	$(3.8 \pm 2.0) \times 10^{-3}$
$\rightarrow 3.587$	$\rightarrow 2^+; 0$	3.4	0.12 ± 0.07	0.19 ± 0.11	E1	$(8.3 \pm 4.8) \times 10^{-3}$

Table 10.20: Electromagnetic transition strengths for levels above the proton threshold in ^{10}B [a] (continued)

$E_i \rightarrow E_f$ (MeV)	$J^\pi_i; T_i \rightarrow J^\pi_f; T_f$	Branch (%)	$\omega\gamma_{cm}$ (eV)	Γ_γ (eV)	Mult.	Γ_γ/Γ_W
$\rightarrow 5.110$	$\rightarrow 2^-; 0$	4.8	0.17 ± 0.09	0.27 ± 0.14	M1	0.70 ± 0.35

[a] The $\omega\gamma_{cm}$ values for individual transitions are for the ^{9}Be(p, γ)^{10}B reaction (1964HO02) and the corresponding γ-ray branches are given without errors. Otherwise the total $\omega\gamma_{cm}$ or Γ_γ value is given in a footnote and the branches are given with errors.

[b] $\Gamma_{cm} = 120 \pm 5$ keV, $\Gamma_p\Gamma_\gamma/\Gamma = 0.38 \pm 0.10$ eV, $\Gamma_\alpha\Gamma_\gamma/\Gamma = 0.48 \pm 0.11$ eV from (1975AU02). $\Gamma_p/\Gamma = 0.23 \pm 0.04$, $\Gamma_\alpha/\Gamma = 0.33 \pm 0.02$ from (1997ZA06). $\Gamma_\gamma = 1.54 \pm 0.40$ eV is an equally weighted average from (p, γ) and (α, γ). The three major branches and the non-observation of a ground-state branch are in agreement with earlier work (1979AJ01).

[c] $\approx$ 20% isospin mixed (1956WI16). See discussion of reaction 12.

[d] $\Gamma_{cm} = 140 \pm 30$ keV, $\Gamma_p/\Gamma = 0.7$ (1964HO02). Note, however, $\Gamma_p/\Gamma = 0.38 \pm 0.06$ in Table 10.25.

[e] Some of this strength could be due to the 7.48 MeV doublet (1964HO02).

[f] The doublet analyzed as a single state gives $\Gamma_{cm} = 72 \pm 4$ keV and a ground-state branch of 96.8% with $\omega\gamma_{cm} = 10.1 \pm 1.3$ eV (1964HO02). Small branches with $\omega\gamma_{cm} = 0.13 \pm 0.04$ eV and $\omega\gamma_{cm} = 0.20 \pm 0.07$ eV to the 0.718 and 2.154 MeV 1^+ states could be due to either or both members of the doublet. Analysis of elastic proton scattering shows a doublet of 2^+ ($E_x = 7.469$ MeV, $\Gamma_{cm} = 65 \pm 10$ keV, $\Gamma_p/\Gamma = 1$) and 2^- ($E_x = 7.480$ MeV, $\Gamma_{cm} = 80 \pm 8$ keV, $\Gamma_p/\Gamma = 0.90 \pm 0.05$) levels (1969MO29). $\Gamma_{\gamma_0} = 11.7 \pm 0.7$ eV for M1 excitation in (e, e$'$) and $\Gamma_p/\Gamma = 1$ gives $\omega\gamma_{cm} = 7.3 \pm 0.5$ eV for the 2^+; 1 level.

[g] Branches are averages of (1961SP04, 1964HO02). $\Gamma_{cm} = 2.65 \pm 0.18$ keV (1972HA63). Using σ(p, γ) $= 920 \pm 84$ μb (1964HO02) gives $\omega\gamma_{cm} = 0.82 \pm 0.10$ eV. This is averaged with $\omega\gamma_{cm} = 0.73 \pm 0.11$ eV (1995ZA04) to give $\omega\gamma_{cm} = 0.78 \pm 0.08$ eV.

[h] $\Gamma_{cm} = 210 \pm 60$ keV (1964HO02). The transition strengths are for $\Gamma_p/\Gamma = 1.0$ instead of $\Gamma_p/\Gamma = 0.7$ (1964HO02). Analysis of elastic proton scattering gives $E_x = 7.79$ MeV, $\Gamma_{cm} = 265 \pm 30$ keV, $\Gamma_p/\Gamma = 0.90 \pm 0.05$ (1969MO29).

[i] The 7.48 MeV and 7.75 MeV 2^- levels may form an isospin mixed pair because both possess strong ground-state E1 transitions and only one 2^-; $T = 1$ level, corresponding to the analog of the 6.26 MeV level of ^{10}Be, is expected.

The yield of protons has been measured for $E(^3\text{He}) = 0.60$ to 4.8 MeV: there is some indication of weak maxima at 1.1, 2.3 and 3.3 MeV. Measurements of A_y for the ground-state group at $E(^3\vec{\text{He}}) = 14$ MeV (1983LE17, 1983RO22) and 33 MeV (1983LE17) have been reported. Measurements of differential cross sections and analyzing powers were reported at $E(^3\text{He}) = 4.6$ MeV (1995BA24). The polarization at $E(^3\text{He}) = 14$ MeV was measured by (1984ME11, 1984TR03). $P = A$ in this and in the inverse reaction [see reaction 4 in ^{12}C in (1985AJ01) for some additional comments]. Proton yields as a function of angle were measured for $E(^3\text{He}) = 93$ MeV by (1994DO32). Astrophysics-related measurements at $E_\text{cm} = 0.5$–2 MeV (1990RA16) and $E(^3\text{He}) = 160$, 170 keV (2002YA06) have been reported. Astrophysical S-factors were deduced. A theoretical study of the reaction mechanism and astrophysical implications are described in (1993YA01). Calculations for the reaction and the inverse reaction to deduce time-reversal-invariance violation amplitude features were reported in (1988KH11). For earlier references see (1984AJ01). See also (1986AB10; theor.).

8. (a) ^{7}Li(^{3}He, d)^{8}Be $\quad Q_\text{m} = 11.2025 \quad E_\text{b} = 17.7883$

(b) ^{7}Li(^{3}He, t)^{7}Be $\quad Q_\text{m} = -0.88081$

(c) ^{7}Li(^{3}He, ^{3}He)^{7}Li

Yields of deuterons have been measured for $E(^3\text{He}) = 1.0$ to 2.5 MeV (d_0) and yields of tritons are reported for 2.0 to 4.2 MeV (t_0): a broad peak is reported at $E(^3\text{He}) \approx 3.5$ MeV in the t_0 yield. See (1979AJ01) for references. Polarization measurements are reported at $E(^3\vec{\text{He}}) = 33.3$ MeV for the deuteron groups to ^{8}Be*(16.63, 17.64, 18.15) and for the triton and ^{3}He groups to ^{7}Be*(0, 0.43) and ^{7}Li*(0, 0.48, 4.63): see (1984AJ01). Measurements of the yields for deuterons, alphas, tritons and ^{3}He as a function of angle at $E(^3\text{He}) = 93$ MeV are described in (1994DO32). A compilation and analysis of cross section data for studying evidence for clusters in ^{7}Li is presented in (1995MI16).

9. ^{7}Li(^{3}He, α)^{6}Li $\quad Q_\text{m} = 13.32732 \quad E_\text{b} = 17.78833$

Excitation functions have been measured for $E(^3\text{He}) = 1.3$ to 18.0 MeV: see (1974AJ01). The α_0 group (at $8°$) shows a broad maximum at ≈ 2 MeV, a minimum at 3 MeV, followed by a steep rise which flattens off between $E(^3\text{He}) = 4.5$ and 5.5 MeV. Integrated α_0 and α_1 yields rise monotonically to 4 MeV and then tend to decrease. Angular distributions give evidence of the resonances at $E(^3\text{He}) = 1.4$ and 2.1 MeV seen in ^{7}Li(^{3}He, γ)^{10}B: $J^\pi = 2^+$ or 1^-; $T = (1)$ for both [see, however, reaction 5]: Γ_α is small. The α_2 yield [to ^{6}Li*(3.56), $J^\pi = 0^+$; $T = 1$] shows some structure at $E(^3\text{He}) = 1.4$ MeV and a broad maximum at ≈ 3.3 MeV: see Table 10.10 in (1979AJ01). Polarization measurements are reported at $E(^3\vec{\text{He}}) = 33.3$ MeV to ^{6}Li*(0, 2.19, 3.56): see (1984AJ01). See also (1983AN1D, 1984PA1E, 1994DO32).

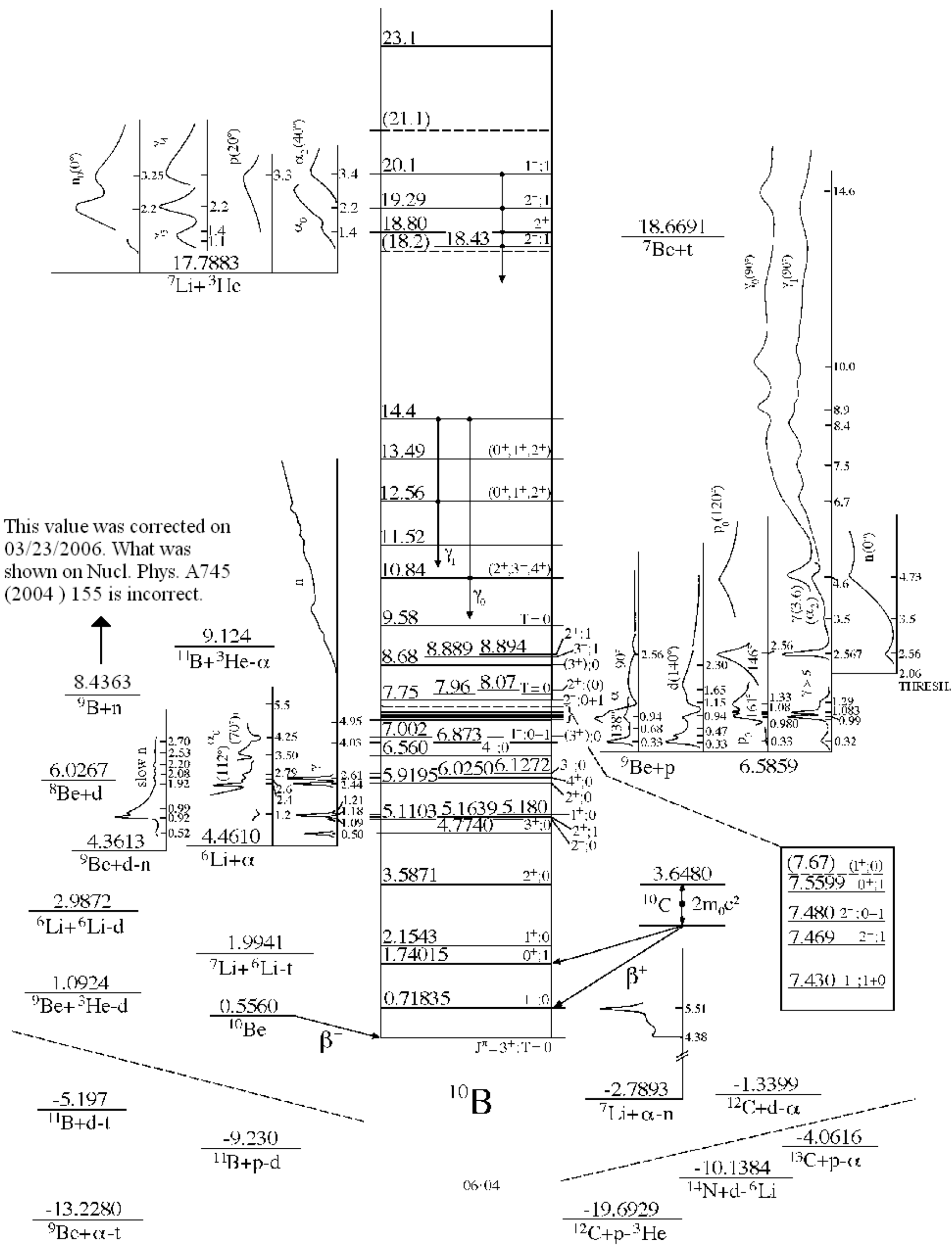


Figure 14: Energy levels of ^{10}B. For γ transitions see Fig. 15, and Tables 10.19 and 10.20. For notation see Fig. 13.

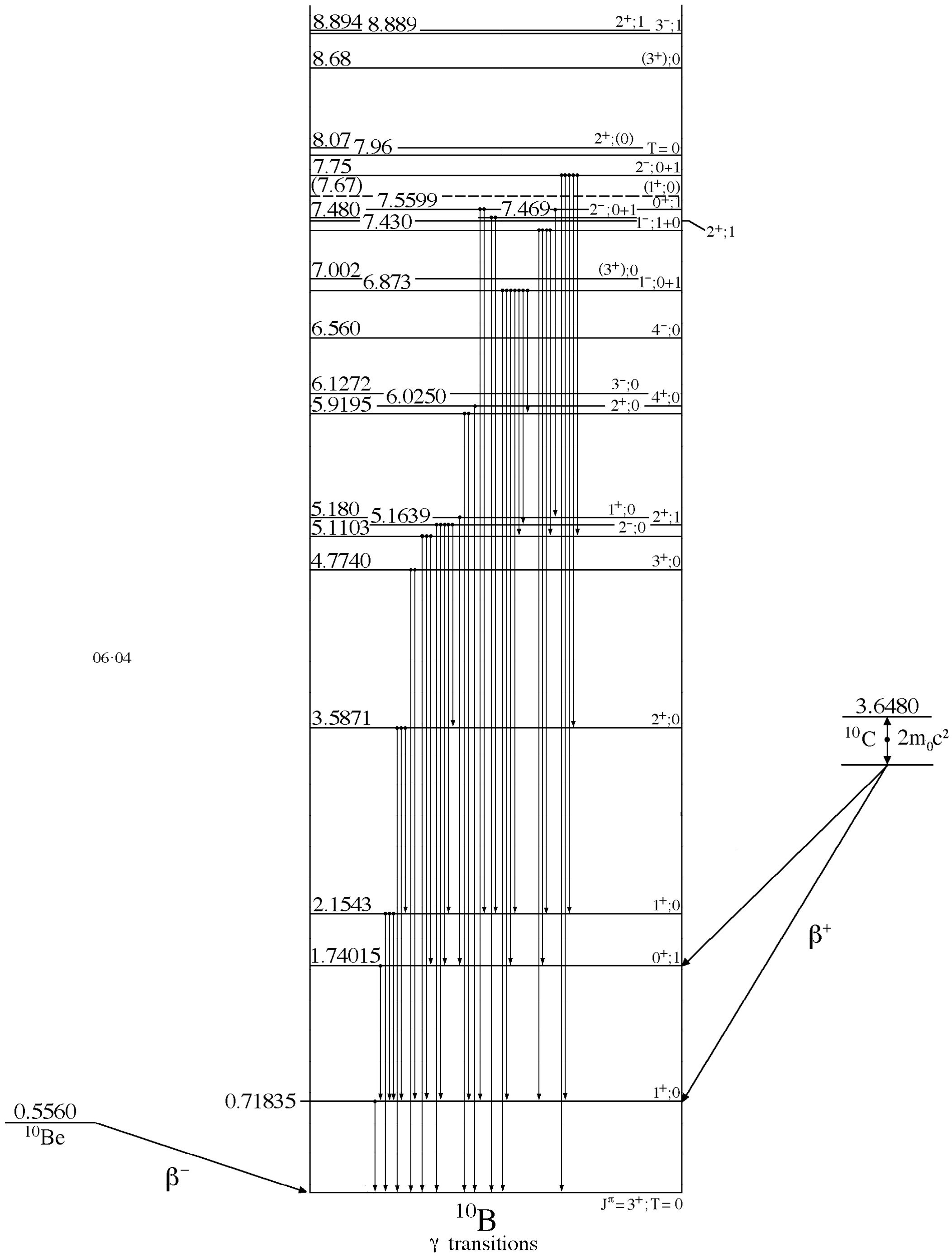


Figure 15: γ transitions for ^{10}B. See Tables 10.19 and 10.20. For notation see Fig. 13.

Table 10.21: Lifetimes of bound states of ^{10}B

^{10}B* (MeV)	τ_m	Reactions	Refs.
0.72	1.020 ± 0.005 nsec	^{10}B(p, p′)	(1983VE03) [a]
1.74	7 ± 3 fsec	^{6}Li(α, γ)	(1979KE08)
2.15	2.30 ± 0.26 psec	mean	(1979AJ01) [b]
	1.9 ± 0.3 psec	^{6}Li(α, γ)	(1979KE08)
	2.13 ± 0.20 psec	mean	all values
3.59	153 ± 13 fsec	mean	(1979AJ01)
	150 ± 30 fsec	^{6}Li(α, γ)	(1979KE08)
	153 ± 12 fsec	mean	all values

[a] See also Table 10.20 of (1966LA04).
[b] Table 10.9 in (1979AJ01).

10. ^{7}Li(α, n)^{10}B $\qquad Q_m = -2.7893$

Angular distributions are reported at $E_\alpha = 28$ and 32 MeV for the n_0, n_1 and n_2 groups (1985GUZQ). See (1979AJ01, 1984AJ01) for the earlier work. Neutron spectra and photon yields from ^{7}Li(α, n) neutron sources for $E_\alpha = 5.5$–5.8 MeV were measured by (1993VL02).

11. (a) ^{7}Li(^{12}C, $\alpha + {}^{6}$Li)^{9}Be $\qquad Q_m = -12.9515$
(b) ^{7}Li(^{12}C, d $+ {}^{8}$Be)^{9}Be $\qquad Q_m = -14.5172$
(c) ^{7}Li(^{12}C, p $+ {}^{9}$Be)^{9}Be $\qquad Q_m = -15.0764$

The breakup of ^{10}B was studied (2001LE05) in an experiment with 76 MeV ^{12}C incident on Li_2O. Breakup of ^{10}B into $\alpha + {}^{6}$Li, $\alpha + {}^{6}$Li*(3^+), ^{8}Be + d and ^{9}Be + p was observed. Evidence was obtained for two new ^{10}B states at $E_x = 7.96 \pm 0.07$ MeV, $\Gamma = 285 \pm 91$ keV and $E_x = 9.58 \pm 60$ MeV, $\Gamma = 257 \pm 64$ keV. The energy spectrum is dominated by $T = 0$ states that decay into $^{6}\mathrm{Li}_{\mathrm{g.s.}} + \alpha$.

12. ^{9}Be(p, γ)^{10}B $\qquad Q_m = 6.5859$

Parameters of the observed resonances are listed in Table 10.24. An angle-integrated excitation function has been measured over the energy range $E_p = 75$ to 1800 keV (1995ZA04). This establishes the absolute (p, γ) cross sections for this region with considerably more certainty than existed

Table 10.22: Levels of ^{10}B from ^{6}Li(α, γ)^{10}B [a]

E_x (MeV)	$J^\pi; T$	Γ_{cm}	$\omega\gamma_{cm}$ (eV) [b]	Γ_γ (eV) [b]
4.774 [c]	$3^+; 0$	7.8 ± 1.2 eV	$(4.20 \pm 0.36) \times 10^{-2}$	$(1.80 \pm 0.15) \times 10^{-2}$
5.112 [d]	$2^-; 0$	0.98 ± 0.07 keV	0.055 ± 0.010	0.033 ± 0.006
5.164 [e]	$2^+; 1$	1.8 ± 0.4 eV	0.40 ± 0.04	1.50 ± 0.40
5.180 [f]	$1^+; 0$	200 ± 30 keV	0.06 ± 0.03	0.06 ± 0.03
5.920 [g]	$2^+; 0$	6 ± 1 keV	0.228 ± 0.038	0.135 ± 0.023
6.024 [h]	$4^+; 0$		0.342 ± 0.048	0.114 ± 0.016
6.873 [i]	$1^-; 0+1$	120 ± 5 keV	0.48 ± 0.11	1.44 ± 0.34
7.440 [j]	$2^-; 0$	90 ± 10 keV	0.29 ± 0.13	

[a] E_x from adopted level energies: see Table 10.8 in (1988AJ01) for resonance energies and measured branching ratios. The measured branching ratios also appear in Table 10.19. Values of $\omega\gamma$ from (1966AL06, 1966FO05) have been multiplied by 0.6 to convert them to the cm system (1979SP01).

[b] $\omega\gamma_{cm}$ and Γ_γ represent the sum for all transitions from a given level.

[c] Average of $\omega\gamma_{cm} = 0.041 \pm 0.004$ (1985NE05) and $\omega\gamma_{cm} = 0.046 \pm 0.008$ (1966AL06); $\Gamma_{cm} = \Gamma_\alpha = 7.8 \pm 1.2$ eV (1981HE05). $\Gamma_\gamma/\Gamma = (2.3 \pm 0.3) \times 10^{-3}$ (1966AL06).

[d] $\Gamma_\alpha = \Gamma_{cm} = 0.98 \pm 0.07$ keV (1984NA07); $\omega\gamma_{cm}$ (1966FO05).

[e] $\omega\gamma_{cm}$ (1979SP01) and $\Gamma_\alpha/\Gamma = 0.16 \pm 0.04$ from averaging $\Gamma_\alpha/\Gamma = 0.13 \pm 0.04$ (1966AL06) and $\Gamma_\alpha/\Gamma = 0.27 \pm 0.15$ (1966SE03). Then $\Gamma_\alpha = 0.29 \pm 0.03$ eV, $\Gamma_\gamma = 1.50 \pm 0.40$ eV and $\Gamma_{cm} = 1.79 \pm 0.40$ eV. Using just the more precise value $\Gamma_\alpha/\Gamma = 0.13 \pm 0.04$, itself an average of two measurements, gives $\Gamma_\alpha = 0.28 \pm 0.03$ eV, $\Gamma_\gamma = 1.85 \pm 0.60$ eV and $\Gamma_{cm} = 2.13 \pm 0.60$ eV. This would raise the transition strengths in Table 10.19 by 23%.

[f] (1961SP02). The accepted width is $\Gamma_{cm} = 110 \pm 10$ keV: see Table 10.18.

[g] (1966FO05). $\Gamma_\alpha = 5.82 \pm 0.06$ keV: see Table 10.23.

[h] (1966FO05). $\Gamma_\alpha = 0.054 \pm 0.024$ keV: see Table 10.23.

[i] (1975AU02). $\omega\gamma_{cm}$ from $\sigma(\alpha, \gamma) = 1.8 \pm 0.4$ μb and Γ_{cm}. Relative intensities at 0° are $13 \pm 3\%$ ($\rightarrow 0.72$), $66 \pm 4\%$ ($\rightarrow 1.74$), and $8 \pm 3\%$ ($\rightarrow 2.15$). $\Gamma_\alpha/\Gamma = 0.33 \pm 0.02$ (1997ZA06) is used to get Γ_γ.

[j] (1975AU02). $E_x = 7.440 \pm 0.020$ MeV. Relative intensities at 0° are $50 \pm 12\%$ ($\rightarrow 0$), and $50 \pm 12\%$ ($\rightarrow 0.72$). $\omega\gamma_{cm}$ from $\sigma(\alpha, \gamma) = 0.07 \pm 0.03$ μb/sr at 0°, angular correlations for $J^\pi = 2^-$ (assumed), and Γ_{cm}. This level may not exist because the cross section to the first excited state can be accounted for by the decay of the 7.43 MeV 1^- level and that to the ground state by the tail of the 7.48 MeV 2^- level: see Tables 10.20 and 10.24.

Table 10.23: ^{10}B levels from ^{6}Li(α, α)^{6}Li [a]

E_α (MeV ± keV)	E_x (MeV)	Γ_{cm} (keV)	$J^\pi; T$
1.210 ± 30	5.19	105	$1^+; 0$
2.440 [b]	5.920	5.82 ± 0.06	$2^+; 0$
2.6060 ± 1.5	6.024	0.054 ± 0.024	$4^+; 0$
2.7855 ± 1.5 [c]	6.132	1.52 ± 0.08	$3^-; 0$
3.4985 ± 1.6	6.560	25.1 ± 1.1	$(4^-, 2)^-; 0$
4.250 ± 15	7.011	110 ± 15	$(2)^+; 0$

[a] For references see Table 10.8 in (1979AJ01) and Table 10.8 in (1974AJ01).
[b] (1981HE05).
[c] (1981HE05): $\Gamma_\alpha = 1.47 \pm 0.07$ keV, $\Gamma_d = 0.048 \pm 0.030$.

Table 10.24: Resonances in ^{9}Be(p, γ)^{10}B [a]

E_p (MeV ± keV)	E_x (MeV ± keV)	Γ_{cm} (keV)	$J^\pi; T$	$\omega\gamma_{cm}$ (eV)
0.319 [b]	6.873 ± 5	120 ± 5	$1^-; 0 + 1$	0.14 ± 0.04
0.938 ± 10 [c]	7.430	140 ± 30	$1^-; 1 + 0$	1.25 ± 0.18
0.992 ± 2 [c]	7.478	82 ± 4	{ $2^+; 1$ / $2^-; 1$ }	10.4 ± 1.3
1.0832 ± 0.4 [d]	7.5599	2.65 ± 0.18 [e]	$0^+; 1$	0.78 ± 0.08 [e]
1.290 ± 30 [c]	7.75	210 ± 60	$2^-; 1 + 0$	3.52 ± 0.74

[a] See Table 10.20 for decay schemes.
[b] (1975AU02).
[c] (1964HO02).
[d] (1964BO13).
[e] See Table 10.20.

at the time of the previous review (1988AJ01). Table 10.24 lists six resonances in this energy region with 5 rather broad resonances and a narrow $J^{\pi} = 0^{+}$; $T = 1$ resonance ($\Gamma_{\rm cm} = 2.65$ keV) at $E_{\rm p} = 1038$ keV. The excitation function is dominated by three broad unresolved resonances at $E_{\rm p} = 938$, 980, and 992 keV. The existence of the 938 keV resonance has been established from analyses of the excitation functions for γ-ray transitions to specific final states. However, the 2^{+} and 2^{-} levels near 990 keV have similar widths and dominant ground-state radiative transitions and thus cannot be distinguished from consideration of the (p, γ) data alone. The γ transitions from this reaction are given in Table 10.20 and the information obtained is summarized in the following discussion.

The $E_{\rm p} = 330$ keV resonance ($E_{\rm x} = 6.87$ MeV) is ascribed to s-wave protons because of its comparatively large proton width [see ^{9}Be(p, p)] and because of the isotropy of the γ radiation. The strong E1 transitions to both $T = 0$ and $T = 1$ final states in Table 10.20 indicate considerable isospin mixing (1956WI16) because only $T = 0 \leftrightarrow T = 1$ isovector E1 transitions are possible in ^{10}B. The transition to the 1.74 MeV level implies $J^{\pi} = 1^{-}$ and its relative strength, together with the existence of substantial deuteron and alpha widths, indicates a dominance of $T = 0$ for the 6.87 MeV state.

Most of the data in Table 10.20 comes from an analysis of the excitation functions for γ-ray transitions to specific final states (1964HO02). The $E_{\rm p} = 938$ keV resonance was originally given a tentative $J^{\pi} = 2^{-}$; $T = 0$ assignment. The 1^{-} assignment was made for a resonance in elastic proton scattering at $E_{\rm p} = 945 \pm 10$ keV with a width $\Gamma_{\rm cm} = 130 \pm 10$ keV and the suggestion was made that this level is the missing isospin-mixed partner of the 6.87 MeV level (1969MO29). An estimate of the isospin mixing was made in (1969RO12). See also the appendix in (2001BA47). The relative E1 strengths for the transitions to the 1^{+}; 0 levels at 0.72 and 2.15 MeV imply $T = 1$ isospin admixtures of 15% and 21%, respectively, and the strength of the $7.43 \rightarrow 1.74$ E1 transition expected for this level of admixture is just below the observed upper limit. The strong M1 transition to the 2^{-}; 0 level at 5.11 MeV, expected to be mainly $^{1}P \rightarrow ^{3}P$, implies an isospin admixture of ≈ 8.5% but this should be treated as a lower limit because some of the $7.43 \rightarrow 5.11$ strength may be due to one or both of the two levels near 7.48 MeV (1964HO02). However, it does appear from Fig. 6 of (1975AU02) that the transition is mainly from the 7.43 MeV level. The $T = 1$ component of the 1^{-} doublet corresponds to the 5.96 MeV level of ^{10}Be shifted downwards by ≈ 400 keV with respect to p-shell levels on account of the smaller Coulomb energy shift for (sd) orbits. The 0.93 MeV resonance is also observed in the ^{9}Be(p, d) and ^{9}Be(p, α) reactions via the $T = 0$ component in the wave function (1956WE37). The α width which results from the isospin mixing is sufficient to account for the strength of the $7.43 \rightarrow 0.72$ transition observed via the ^{6}Li(α, γ) reaction and calls into question the existence of a 2^{-}; 0 level at 7.43 MeV proposed by (1975AU02).

The prominent $E_{\rm p} = 992$ keV resonance was originally assigned as 2^{-}; 1 largely on account of the apparent s-wave formation and the strength of the ground-state transition (1964HO02). However, earlier elastic proton scattering data had indicated the existence of a p-wave 2^{+} state near 980 keV and an s-wave 2^{-} state near 998 keV (1956MO90). See also (1969MO29). Then, low-energy electron scattering [see ^{10}B(e, e′)] revealed a very strong M1 transition to a state at this energy (1965SP04) which can account for over 70% of the (p, γ) cross section. This state was identified with the second 2^{+}; 1 level predicted by shell model calculations with similar spatial structure to the ^{10}B ground state. The analog in ^{10}Be is at 5.96 MeV and is populated as a strong Gamow-Teller transition in charge-exchange reactions on ^{10}B [see reaction 28 in ^{10}Be].

Subtraction of the M1 strength associated with the 2^+; 1 level leaves substantial ground-state transition strength for the 2^- level, indicating a $T = 1$ component. The s-wave resonance at $E_\mathrm{p} = 1290 \pm 30$ keV also has a strong ground-state transition and was assigned as 2^-; 1 (1964HO02). Thus, there appears to be a doublet of isospin-mixed 2^- levels with the $T = 1$ component corresponding to the 6.26 MeV level of ^{10}Be.

The narrow $E_\mathrm{p} = 1083$ keV level is formed by p-wave protons and has $J^\pi = 0^+$ (see reaction 14 [^{9}Be(p, p)] and reaction 16 [^{9}Be(p, α)]). The isotropy of the γ rays supports this assignment. The strong M1 transitions to the $J^\pi = 1^+$; $T = 0$ levels at 0.72, 2.15, and 5.18 MeV [Table 10.22] indicate $T = 1$. The analog is at 6.18 MeV in ^{10}Be. The width of the 5.18 MeV level of ^{10}B observed in the decay is 100 ± 10 keV (1975AU02). The 7.56 MeV 0^+; 1 and 5.18 MeV 1^+; 0 levels are the lowest (sd)^2, or $2\hbar\omega$, levels in ^{10}B. The strong M1 transition between them is consistent with these assignments.

Since the previous review (1988AJ01) several measurements and analyses have been done for low proton energies. Branching ratios and angular distributions for capture to ^{10}B states at $E_\mathrm{x} = 0$, 0.718, 1.740 and 2.154 MeV were measured for proton energies $E_\mathrm{p} = 40$–180 keV (1992CE02). Astrophysical S-factors were deduced. Measurements of an angle integrated S-factor for $E_\mathrm{p} = 75$–1800 keV were reported by (1995ZA04). The spectrum is dominated by three broad peaks and the analysis included interference effects with the direct-capture process. The best fit was obtained for J^π values of 1^-, 2^-, and 2^- and the resulting resonance energies were E_p(lab) $= 380 \pm 30$, 989 ± 2 and 1405 ± 20 keV. The widths were $\Gamma_\mathrm{lab} = 330 \pm 30$, 90 ± 3 and 430 ± 30 keV, respectively. The low-energy S-factor is about one third of that obtained by (1992CE02). A measurement by (1998WU05) with 100 keV polarized protons on a thick ^{9}Be target determined analyzing powers for capture to the ^{10}B ground state and the first three excited states. Astrophysical S-factors were deduced using a direct-capture-plus-resonance model. These data were used in an evaluation of thermonuclear proton-capture rates by (2000NE09). Polarized protons at $E_\mathrm{p} = 280$–0 keV were used (1999GA21) to measure the analyzing power for the ground state transition. Comparison of the results to calculations showed that the analyzing power could be reproduced only by the interference of direct capture with the tail of a 2^+ resonance that was taken to be at 7.478 MeV (the 7.469 MeV state in Table 10.18). Although these results indicate that the resonance strength in the (p, γ) channel near 7.48 MeV is predominantly 2^+, the data do not rule out a small contribution from an additional state.

Existing data on ^{9}Be(p, γ)^{10}B were reanalyzed within the framework of an R-matrix method by (1999SA39). Parameters of resonances at E_p(cm) $= 296$, 890, 972 and 1196 keV were determined and compared (see Table II of (1999SA39)) with parameters given in (1988AJ01, 1995ZA04, 1998WU05). Data for proton energies up to $E_\mathrm{p} = 1800$ keV and γ-transitions to the four lowest ^{10}B states were fitted using R-matrix formulae by (2002BA09). A good fit was obtained with two 1^- levels, two 2^- levels, one 0^+ level and one 2^+ level. Level parameters derived from these fits using different combinations of input data are presented in Tables 5, 6, and 8 of (2002BA09). In related work since (1988AJ01), asymptotic normalization coefficients obtained from peripheral transfer reactions such as ^{10}B(^{7}Be, ^{8}B)^{9}Be at low energies have been used to determine ^{9}Be(p, γ)^{10}B S-factors (1999SA39). Extracted asymptotic normalization coefficients used for determining stellar reaction rates for ^{9}Be(p, γ)^{10}B are discussed in (2003KR14). See also the astrophysics-related work (1996RE16, 1997NO04, 2000IC01).

For further information concerning ^{9}Be(p, γ)^{10}B experiments for $E_{\rm p} > 1330$ keV, refer to (1988AJ01).

13. ^{9}Be(p, n)^{9}B $\qquad Q_{\rm m} = -1.8504 \qquad E_{\rm b} = 6.5859$

As noted in (1988AJ01), "Resonances in the neutron yield occur at $E_{\rm p} = 2562 \pm 6$, 4720 ± 10 and, possibly, at 3500 keV with $\Gamma_{\rm cm} = 84 \pm 7$, ≈500 and ≈700 keV. These three resonances correspond to ^{10}B*(8.890, 10.83, 9.7): see Table 10.13 in (1974AJ01). Cross section measurements for the (p, n) and (p, n_0) reactions have been obtained by (1983BY01; $E_{\rm p} = 8.15$ to 15.68 MeV) [see also for a review of earlier work]. They indicate possible structure in ^{10}B near 13–14 MeV (1983BY01)."

"The $E_{\rm p} = 2.56$ MeV resonance is considerably broader than that observed at the same energy in ^{9}Be(p, α) and ^{9}Be(p, γ) and the two resonances are believed to be distinct. The shape of the resonance and the magnitude of the cross section can be accounted for with $J^{\pi} = 3^{-}$ or 3^{+}; the former assignment is in better accord with ^{10}Be*(7.37). For $J^{\pi} = 3^{-}$, $\theta^2_{\rm n} = 0.135$, $\theta^2_{\rm p} = 0.115$ ($R = 4.47$ fm): see (1974AJ01)."

"The analyzing power for n_0 has been measured for $E_{\rm p} = 2.7$ to 17 MeV (1980MA33, 1983BY02, 1986MU07) as has the polarization in the range $E_{\rm p} = 2.7$ to 10 MeV (1983BY02). See (1983BY02, 1986MU07) for discussions of the $\sigma(\theta)$, $A_{\rm y}(\theta)$ and $P(\theta)$ measurements. Polarization measurements have also been reported at $E_{\vec{\rm p}} = 3.9$ to 15.1 MeV and 800 MeV: [see (1984AJ01)] and at 53.5, 53.9 and 71.0 MeV (1988HE08) [$K_{\rm y}^{\rm y'}$, $K_{\rm z}^{\rm z'}$]."

A summary of monoenergetic neutron beam sources for $E_{\rm n} > 14$ MeV is presented in (1990BR24). See also the measurements at $E_{\rm p} = 300$, 400 MeV reported in (1994SA43). Neutron spectra were measured for $E_{\rm p} = 20$–40 MeV (1996SH29) and for $E_{\rm p} = 3$–5 MeV (2001HO13). See also the measurements of $\sigma(E_{\rm n})$ for $E_{\rm p} = 35$ MeV (1987OR02) and the thick-target yield measurements of (1987RA23). This reaction was used by (1987RA32) at $E_{\rm p} = 135$ MeV to deduce Gamow-Teller transitions B(GT) and the quenching factor. Measurements of $\sigma(\theta)$ at $E_{\rm p} = 35$ MeV were used to study the isovector part of optical potentials through analog transitions. Calculations of $\sigma(\theta, E_{\rm n})$ for $E_{\rm p} = 1$ GeV are described in (1994GA49). See also the analysis for $E_{\rm p} = 800$ MeV to study pion-production medium effects (1998IO03). See also ^{9}B and references cited in (1988AJ01).

14. (a) ^{9}Be(p, p)^{9}Be $\qquad E_{\rm b} = 6.5859$

(b) ^{9}Be(p, p + n)^{8}Be $\qquad Q_{\rm m} = -1.6654$

(c) ^{9}Be(p, p + α)^{5}He $\qquad Q_{\rm m} = -2.467$

The elastic scattering resonances up to $E_{\rm x} = 8$ MeV shown in Table 10.25 come from (1956MO90,

Table 10.25: Resonances in ^{9}Be(p, p)^{9}Be

E_p (keV)	E_x (MeV)	Γ_{cm} (keV)	J^π	Γ_p/Γ
330 [a]	6.88		1^-	0.30
945 ± 10 [b]	7.437	130 ± 10	1^-	0.38 ± 0.06
980 ± 6 [b]	7.469	65 ± 10	2^+	1.0
992 ± 4 [b]	7.480	80 ± 8	2^-	0.90 ± 0.05
1084 ± 2 [b]	7.564	3.3	0^+	1.0
(1200 ± 30) [b]	(7.67)	250 ± 20	(1^+)	0.30 ± 0.10
1340 ± 30 [b]	7.795	265 ± 30	2^-	0.90 ± 0.05
1650 ± 200 [b]	8.07	≈ 800	2^+	0.06–0.2
2550 ± 5 [c]	8.880	105 ± 5	3^-	0.85
2563 ± 5 [c]	8.892	36 ± 4	2^+	0.35
4720 ± 100 [d]	10.83	400 ± 100	2^+	0.4

[a] From (1956MO90) where it is noted that Γ_{cm} cannot be determined accurately from the ^{9}Be(p, p) data alone and that Γ_p/Γ is accurate only to within a factor of two. In (1969MO29), the following values for widths are taken from other reactions: $\Gamma_{cm} = 145$ keV, $\Gamma_p = 40$ keV, $\Gamma_d = 50$ keV, and $\Gamma_\alpha = 55$ keV.

[b] (1969MO29).

[c] (1983AL10). See also (1956MA55, 1977KI04).

[d] (1983AL10). See (1974YA1C).

1969MO29). Below $E_p = 0.7$ MeV only s-waves are present exhibiting a resonance at $E_p = 330$ keV with $J^\pi = 1^-$. Apart from the tentative 1^+ assignment at $E_p = 1200$ keV, which was introduced to satisfy a need for resonant p-wave formation (1969MO29), there is good agreement between the results of (1956MO90) and (1969MO29). The analysis requires a large d-wave admixture with the s-wave protons forming the $E_p = 1340$ keV resonance (1969MO29).

Between $E_p = 0.8$ and 1.6 MeV polarization and cross section measurements are well fitted by a phase-shift analysis using only $^3S_1$, $^5S_2$, $^5P_1$, and $^5P_2$ phases (1973RO24). However, the spin assignments of 1^+ for a state at $E_x = 7.48$ MeV and 1^- for a state at $E_x = 7.82$ MeV to fit this data are in disagreement with the assignments in Table 10.25 and with other data. In particular, these assignments leave no state near 7.48 MeV to explain the strong M1 transition observed in electron scattering and no state near 7.8 MeV to explain the strong radiative transition to the ground state (2001BA47).

The 2^+ state at 8.07 MeV has been observed via inelastic electron scattering and given the same spin-parity assignment. It has also been observed via inelastic pion scattering.

The next prominent elastic scattering resonance occurs at $E_p = 2.56$ MeV ($E_x = 8.89$ MeV) and has a width of ≈ 100 keV. The analogs of the 7.37 MeV 3^- and 7.54 MeV 2^+ levels of ^{10}Be are known to be nearly degenerate at 8.89 MeV in ^{10}B. The 3^- level ($\Gamma \approx 85$ keV) dominates in the ^{9}Be(p, p) and ^{9}Be(p, n) reactions while the 2^+ level ($\Gamma \approx 40$ keV) dominates the ^{9}Be(p, $\alpha_2\gamma$)^{6}Li cross section (1977KI04). In fits to elastic scattering in this region (1983AL10), including polarization data (1976MA58), a number of other relatively narrow states have been introduced between 8.4 and 9.1 MeV. The data of (1983AL10) extends to $E_p = 5$ MeV and three more levels have been proposed. The highest at $E_p = 4.72$ MeV ($E_x = 10.83$ MeV) occurs at an energy where resonances have been observed in a number of other reaction channels. The assignment of $J^\pi = 2^+$; $T = 1$ is consistent with that obtained for a resonance observed in the ^{9}Be(p, p$_0$), ^{9}Be(p, p$_2$), and ^{9}Be(p, α_2) reactions (1974YA1C).

15. (a) ^{9}Be(p, t)^{7}Be	$Q_m = -12.0833$	$E_b = 6.5859$
(b) ^{9}Be(p, ^{3}He)^{7}Li	$Q_m = -11.2025$	

Polarization measurements (reaction (b)) are reported at $E_{\vec{p}} = 23.06$ MeV: see (1984AJ01). For a study at $E_p = 190$ and 300 MeV see (1987GR11). See also (1985SE15).

16. (a) ^{9}Be(p, d)^{8}Be	$Q_m = 0.5592$	$E_b = 6.5859$
(b) ^{9}Be(p, α)^{6}Li	$Q_m = 2.1249$	

Proton-induced reactions on ^{9}Be are of considerable interest in regard to primordial and stellar nucleosynthesis. Subsequent to the previous compilation (1988AJ01), there have been two studies of the reactions (a) and (b) at low proton energies (1997ZA06, 1998BR10). Excitation functions and angular distributions for $E_p = 16$ to 390 keV have been measured by (1997ZA06). Both polarized and unpolarized protons have been used by (1998BR10) to measure angular distributions and analyzing powers for $E_p = 77$ to 321 keV. Earlier measurements (1973SI27) provided excitation functions for $E_p = 30$ to 700 keV and angular distributions for $E_p = 110$ to 600 keV. The prominent feature in the excitation functions for both reactions, expressed as values of the astrophysical S factors, is a peak at $E_p \approx 310$ keV attributed to the 6.87 MeV 1^- level of ^{10}B. The analyses of both (1997ZA06) and (1998BR10) indicate substantial direct reaction contributions to the ^{9}Be(p, d)^{8}Be cross section at energies below the $E_p \approx 310$ keV resonance.

The low-energy data and attempts to fit it are summarized by (2001BA47) where an R-matrix fit of almost all the data is performed for $E_p \leq 700$ keV. The discussion in (2001BA47) includes arguments questioning some of the ^{10}B J^π assignments of (1988AJ01). In particular, it is argued in Appendix A of (2001BA47) that the dominantly $T = 1$ isospin-mixed partner of the 6.87 MeV 1^-; $0 + 1$ level exists near $E_x = 7.44$ MeV (see reaction 12 and Table 10.20) where a resonance is seen in reactions (a) and (b) (1956WE37).

Table 10.26 shows resonances observed in early measurements of excitation functions for deuterons and α-particles. Up to $E_{\rm p} = 2.3$ MeV, the information is taken from a multi-level R-matrix analysis of the p, d_0, α_0, α_1, and γ channels by (1969CO1J) [see also (1964HO02, 1969MO29)] omitting only the nearly pure $T = 1$ states at 7.47 MeV (2^+) and 7.56 MeV (0^+). (1969CO1J) give reduced widths and radiative widths for all these states. The separation of the $3^-/2^+$; $T = 1$ doublet at $E_{\rm p} = 2.56$ MeV comes from an R-matrix analysis of the $(\alpha_2\gamma)$ and p_0 yields by (1977KI04). The higher resonances appear on a background of direct reaction contributions and, given the assignment of both α_2 and α_0 or α_1 decays in the same or different experiments (1959MA20, 1974YA1C), it is not clear whether the resonances are due to isospin-mixed or unresolved states.

The existence of a 3.5 MeV resonance ($E_{\rm x} = 9.7$ MeV) included in the previous compilation (1988AJ01) and assigned $T = 1$ was based on a small bump in the ^{9}Be(p, $\alpha\gamma$)^{6}Li cross section between the 2.56 MeV and 4.5 MeV resonances (1959MA20). However, there is no known analog state in ^{10}Be and no resonance structure is observed in the ^{9}Be(n, α)^{6}He spectrum (1957ST95).

Other measurements at higher energies include those at $E_{\rm p} = 50$ MeV (1989GU08), $E_{\rm p} = 25$, 30 MeV (1992PE12), $E_{\rm p} = 2.475$ MeV (1994LE08; applications), $E_{\rm p} = 40$ MeV (1997FA17), and $E_{\rm p} = 60$ MeV (1987KA25). For earlier measurements see (1988AJ01). Polarization measurements have been made in the range $E_{\rm p} = 0.30$ to 15 MeV and at 185 MeV [see (1974AJ01, 1979AJ01)] and at $E_{\vec{\rm p}} = 60$ MeV (1987KA25; $A_{\rm y}$; inclusive deuteron spectra).

Theoretical work and other analyses of these reactions are discussed in (1987GO27, 1991AB04, 1992KO26, 1992KW01, 1996YA09, 1997NO04, 1999TI07, 2000GA49, 2000GA59).

17. ^{9}Be(d, n)^{10}B $\qquad$ $Q_{\rm m} = 4.3613$

Neutron groups are observed corresponding to the ^{10}B states listed in Table 10.27. Angular distributions have been measured for $E_{\rm d} = 0.5$ to 16 MeV [see (1974AJ01, 1979AJ01)], at 8 MeV (1986BA40; $n_0 \rightarrow n_5$, n_{6+7+8}; also at 4 MeV to the latter) and at 18 MeV (1987KAZL; n_0, n_1) and at 0.5, 1.0, 1.5 and 2.0 MeV (1995VU01; n_0, n_6). At 25 MeV differential cross sections were measured and analyzed for levels below 6.57 MeV (1992MI03). Spectroscopic factors were deduced and compared with previous data and with coupled-reaction-channel calculations. See Tables 2 and 3 of (1992MI03). Observed γ-transitions are listed in Table 10.16 of (1979AJ01). See Tables 10.19, 10.20 and 10.21 here for the parameters of radiative transitions and for $\tau_{\rm m}$. Measurements of neutron angular distributions for $E_{\rm d} = 15$, 18 MeV were analyzed (1988KA30) in the framework of the peripheral model of direct reactions. Neutron yields and differential cross sections at $E_{\rm d} = 40$ MeV were measured by (1987SC11). See also the neutron measurements at $E_{\rm d} = 2.6$–7 MeV (1993ME10), $E_{\rm d} = 21$ MeV (1994CO26), $E_{\rm d} = 20.2$ MeV (1998BE31), $E_{\rm d} = 5$–10 MeV (1998OL04), $E_{\rm d} = 0.5$–1.54 MeV (1999AB38), and $E_{\rm d} = 9.8$ MeV (1999JO03). Application-related yields and spectra were measured at $E_{\rm d} = 1.5$, 1.95, 2.5 and 5 MeV by (2002COZZ). At low energies ($E_{\rm d} =$ 24-111 keV), cross sections were measured and astrophysical S factors were deduced by (2001HO23). An analysis of differential cross sections for $E_{\rm d} = 7$–15 MeV was used to deduce optical model parameters and asymptotic normalization coefficients (2000FE08). ^{10}B

Table 10.26: Resonances in ^{9}Be(p, d)^{8}Be and ^{9}Be(p, α)^{6}Li [a]

E_p (MeV)	E_x (MeV)	Γ_{cm} (keV)	$J^\pi; T$	Decay channels	Γ_p/Γ
0.330	6.880	135	$1^-; 0+1$	d_0, α_0	0.27
0.375 [b]	6.924	110	$1^+; 0$	d_0, α_0	≈ 0.015
0.450 [c]	6.992	90	$3^+; 0$	d_0, α_0	≈ 0.017
0.650	7.171	430	$2^-; 0$	d_0, α_0	≈ 0.10
0.955	7.447	130	$1^-; 1+0$	d_0, α_0	0.38
0.992	7.480	80	$2^-; 0+1$	d_0, α_0	0.90
1.20	7.66	250	$1^+; 0$	(d_1), α_0	0.30
1.30	7.76	245	$2^-; 0$	d_0, α_0	0.90
1.65–1.80	8.07–8.21	≈ 1000	$2^+; 0$	d_0, α_0, α_1	
2.30 [d]	8.66	≈ 300	$(2^-, 3^-)$		small
2.561 [e]	8.89	100 ± 20	$3^-; 1$	α_2	0.06–0.3
2.566 [e]	8.89	40 ± 1	$2^+; 1$	α_2	
4.5 [f,g]	10.6	200 [g]		α_0 [g], α_2 [f]	
4.7 [g]	10.8	300	$2^+; 1$	p_2, α_2, (α_1)	
5.5 [g]	11.5	500		α_1, α_2	

[a] For references and for a listing of other reported resonances and additional information see Table 10.14 in (1979AJ01). The information up to $E_p = 2.3$ MeV is taken from a multi-level R-matrix analysis of the p, d_0, α_0, α_1, and γ channels by (1969CO1J). See also (1964HO02, 1969MO29).

[b] Level appears only in the analysis of (1969CO1J).

[c] Other analyses have given 1^+, 2^+, or 3^+ (1979AJ01). See also (2001BA47).

[d] See also (1956WE37) for (p, d) and (1965MO27) for (p, α).

[e] From an R-matrix analysis of the ($\alpha_2\gamma$) and p_0 yields (1977KI04).

[f] (1969MO29).

[g] (1974YA1C).

level information resulting from ^{9}Be(d, n) experiments prior to (1988AJ01) was summarized in (1988AJ01).

See also ^{11}B in (1985AJ01) and references cited in (1988AJ01). Angular distributions of neutrons from ^{9}Be(d, n) at $E(^9\text{Be}) = 3–7$ MeV were measured by (2002MA20).

18. ^{9}Be(^{3}He, d)^{10}B $\qquad Q_\text{m} = 1.0924$

Deuteron groups have been observed to a number of states of ^{10}B: see Table 10.27. Prior to the previous review (1988AJ01) angular distributions had been reported at $E(^3\text{He}) = 10$–33.3 MeV [see (1974AJ01, 1979AJ01, 1984AJ01)]. More recently, differential cross sections were measured and analyzed at $E(^3\text{He}) = 32.5$ MeV (1993AR14), 22.3–34 MeV (1996AR07), and 42 MeV (1998AR15). Nuclear vertex constants and spectroscopic factors were deduced for the population of ^{10}B levels at $E_\text{x} = 0.0$, 0.72, 1.74, 2.15 MeV. As noted in (1988AJ01), spectroscopic factors obtained in the (d, n) and (^{3}He, d) reactions are not in good agreement: see the discussions in (1974KE06, 1980BL02, 1992MI03). See also the theoretical discussions in (1986AV01, 1989BO26, 1990KA17, 1997VO06).

19. ^{9}Be(α, t)^{10}B $\qquad Q_\text{m} = -13.2280$

Angular distributions have been studied at $E_\alpha = 27$, 28.3 and 43 MeV [see (1979AJ01)], at 30.2 MeV (1984VA07; t_0, t_1, t_3, t_4) and at 65 MeV (1980HA33). In the latter experiment DWBA analyses have been made of the angular distributions to ^{10}B*(0, 0.72, 1.74, 2.15, 3.59, 5.2, 5.92, 6.13, 6.56, 7.00, 7.5, 7.82, 8.9) and spectroscopic factors were derived. The angular distributions to ^{10}B*(4.77, 6.03) could not be fitted by either DWBA or coupled channel analyses. In general coupled-channels calculations give a better fit to the 65 MeV data than does DWBA (1980HA33). Comparisons with other one-proton stripping reactions [(d, n) and (^{3}He, d)] are discussed in (1980HA33) as well as in (1997VO06).

20. (a) ^{9}Be(^{7}Li, ^{6}He)^{10}B $\qquad Q_\text{m} = -3.3904$
(b) ^{9}Be(^{10}B, ^{10}B)^{9}Be
(c) ^{9}Be(^{11}B, ^{10}B)^{10}Be $\qquad Q_\text{m} = -4.642$
(d) ^{9}Be(^{12}C, ^{11}B)^{10}B $\qquad Q_\text{m} = -9.371$

At $E(^7\text{Li}) = 34$ MeV angular distributions have been obtained for the ^{6}He ions to the first four states of ^{10}B. Absolute values of the spectroscopic factors are $S = 0.88$, 1.38 ($p_{1/2}$ or $p_{3/2}$), 1.40, and 0.46 ($p_{1/2}$), 0.54 ($p_{3/2}$) for ^{10}B*(0, 0.74, 1.74, 2.15) (FRDWBA analysis): see (1979AJ01).

Table 10.27: Levels of ^{10}B from ^{9}Be(d, n) and ^{9}Be(^{3}He, d) [a]

E_x (MeV ± keV) [a]	^{9}Be(d, n) [b]		^{9}Be(^{3}He, d) [c]		$J^\pi; T$ [a]
	l_p	S_{rel}	l_p	$(2J+1)C^2S$	
0	1	1.0	1	3.30	$3^+; 0$
0.72	1	1.97	1	2.76	$1^+; 0$
1.74	1	1.36	1	1.20	$0^+; 1$
2.15	1	0.41	1	0.82	$1^+; 0$
3.59	1	0.10	1	0.29	$2^+; 0$
4.77	(≥ 2)		$1 + (3)$ [d]	0.10	$3^+; 0$
				≤ 0.82	
5.11	0	0.14	$0 + 2$	0.34, 0.14	$2^-; 0$
5.16 }	1	0.43	1	0.86	$2^+; 1$
5.18 }					$1^+; 0$
5.92	1	0.49	1	2.05	$2^+; 0$
6.03			(3) [d]	≤ 0.20	4^+
6.13	(2)		(2) [e]	3.04	3^-
6.56	(3)		(2) [e]	2.01	$(4)^-$
6.89 ± 15	(1)				$1^-; 0 + 1$
7.00 ± 15	(1)				$(1, 2)^+; (0)$
7.48 ± 15	[f]				[g]
7.56 ± 25	[f]				$0^+; 1$
(7.85 ± 50)	[f]				1^-
(8.07 ± 50)	[f]				$(2^-; 0)$
(8.12 ± 50)	[f]				

[a] Values without uncertainties are from Table 10.18; others are from Table 10.15 in (1979AJ01). See that table for additional information and for references. See also (1984AJ01), and see the discussions under ^{9}Be(d, n) and ^{9}Be(^{3}He, d) in this review.

[b] S_{rel} from experiment at $E_d = 12.0 - 16.0$ MeV.

[c] $E(^3\text{He}) = 18$ MeV; DWBA analysis; values shown are those obtained with one of the two optical-model potentials used in the analysis. For earlier (^{3}He, d) results see Table 10.17 in (1979AJ01).

[d] Angular distribution poorly fitted by DWBA.

[e] See (1980BL02) for a discussion of these two states, including a comparison with the (d, n) data: $l_p = 2$ is slightly preferred to $l_p = 1$ on the basis of the observed strengths. Neither $l_p = 2$ nor 1 gives a good DWBA fit.

[f] State observed in (d, n) reaction; l_p not determined.

[g] Group shown corresponds to unresolved states in ^{10}B.

See also (1988AL1G). At $E(^{7}\text{Li}) = 14.13$ MeV a measurement of secondary beam production yields was reported by (1991BE49).

Cross sections have been measured for reaction (b) at $E(^{10}\text{B}) = 100$ MeV to obtain asymptotic normalization coefficients (ANC's) (1997MU19, 1998MU09, 2001KR12). Astrophysical S-factors for ^{9}Be(p, γ)^{10}B were deduced. In work described in (2000FE08) ANC's were deduced from a set of proton transfer reactions at different energies to study the uniqueness of the ANC method.

For reaction (c), angular distributions were measured at $E_{\text{lab}}(^{11}\text{B}) = 45$ MeV (2003KY01) optical parameters for the $^{10}\text{B} + {}^{10}\text{Be}$ interaction.

For reaction (d) angular distributions were measured at $E(^{12}\text{C}) = 65$ MeV for transitions to ^{10}B levels at 0.0, 0.72, 1.74 and 2.15 MeV (2000RU05). Data were analyzed within the coupled reaction channel (CRC) method. It was found that two-step processes are important for all transitions.

21. ^{10}Be(β^-)^{10}B $\qquad Q_{\text{m}} = 0.5560$

See ^{10}Be.

22. ^{10}Be(p, n)^{10}B $\qquad Q_{\text{m}} = -0.2264$

The yield of the n_1 group has been studied for $E_{\text{p}} = 0.9$ to 2.0 MeV: see ^{11}B in (1990AJ01) and (1986TE1A). An analysis of data for $E = 0.95$–1.9 MeV and application of dispersion theory of reaction excitation functions at two-particle channel thresholds was reported in (1988DU06).

23. (a) ^{10}B(γ, n)^{9}B $\qquad Q_{\text{m}} = -8.4363$

(b) ^{10}B(γ, p)^{9}Be $\qquad Q_{\text{m}} = -6.5859$

(c) ^{10}B(γ, p + n)^{8}Be $\qquad Q_{\text{m}} = -8.2513$

(d) ^{10}B(γ, π^+)^{10}Be $\qquad Q_{\text{m}} = -140.1262$

Absolute measurements have been made of the ^{10}B(γ, n) cross section from threshold to 35 MeV with quasimonoenergetic photons; the integrated cross section is 0.54 in units of the classical dipole sum ($60NZ/A$ MeV·mb). The (γ, 2n)+(γ, 2np) cross section is zero, within statistics, for $E_\gamma = 16$ to 35 MeV: see (1979AJ01) and (1988DI02). The giant resonance is broad with the major structure contained in two peaks at $E_{\text{x}} = 20.1 \pm 0.1$ and 23.1 ± 0.1 MeV ($\sigma_{\text{max}} \approx 5.5$ mb for each of the two maxima): see (1979AJ01). (1987AH02) [and H. H. Thies, private communication] [using bs] report two broad [$\Gamma \approx 2$ MeV] maxima at 20.2 and 23.0 MeV [± 0.05 MeV] ($\sigma = 5.0$

and 6.0 mb, respectively; $\pm 10\%$) and a minor structure at $E_x = 17.0$ MeV. For reaction (b), differential cross section measurements were reported at $E_\gamma = 66$–103 MeV (1988SU14) and at 57.6 and 72.9 MeV (1998DE13). See also the knock-out mechanism analysis described in (1997JO07).

For reaction (c) see (1988SU14). For a DWIA study of reaction (d) for $E_\gamma = 164$ MeV, see the analysis reported in (1994SA44). See also ^{9}Be, and the earlier references cited in (1988AJ01).

24. (a) ^{10}B(e, e)^{10}B

(b) ^{10}B(e, eπ^+)^{10}Be $\qquad Q_m = -140.1262$

(c) ^{10}B(e, en)^{9}B $\qquad Q_m = -8.4363$

(d) ^{10}B(e, ep)^{9}Be $\qquad Q_m = -6.5859$

Inelastic electron groups for which extensive form-factor measurements are available are displayed in Table 10.28. Transverse form factors in the momentum-transfer range $q = 2.0$–3.8 fm^{-1} were measured for ^{10}B*(0, 1.74, 5.16) by (1988HI02). Measurements spanning the range $q = 0.48$–2.58 fm^{-1} were made by (1995CI02) to determine longitudinal and transverse form factors for ^{10}B levels up to $E_x = 6.7$ MeV with the exception of the broad $E_x = 5.18$ MeV level. The experimental form factors are compared with the results of extensive shell-model calculations (1995CI02). Similar shell-model calculations of transverse scattering form factors for the 0, 1.74, and 5.16 MeV levels are reported in (1994BO04).

In (1995CI02), analyses that determined the r.m.s. radius of the ground-state charge distribution to be $2.58 \pm 0.05 \pm 0.05$ fm are described. This value is consistent with the tabulated value of 2.45 ± 0.12 fm (1987DE43). In an appendix, B(E2) values derived from the longitudinal form factors (1995CI02, 1966SP02, 1976FA13, 1979AN08) are given for the 0.72, 2.15, 3.59, 5.92, and 6.03 MeV levels. The B(E2) value for the 4.77 MeV level is known to be very small and the longitudinal form factor appears to be dominated by the C0 multipole. The results of an analysis by the same method [by co-author D.J.M.; see (2004MIZX)] are listed in Table 10.28, together with similar analyses for other states for which the form factors appear to be dominated by a single multipole. The effects of including electron distortion, not taken into account in the transition strengths reported in the previous tabulation (1988AJ01), are significant.

The previous tabulation also included information on states at 8.07 and 8.9 MeV from (1979AN08) and at 10.79 and 11.56 MeV from (1976FA13). The C2 strength reported for the 8.07 MeV level, analyzed as a 2^+ level, was such that the level should have been very strongly populated by inelastic pion scattering and this is not the case (1988ZE01). For the 8.9 MeV excitation, the contributions from the 2^+; 1 and 3^-; 1 members of the doublet near this energy cannot be separated. In the 11 MeV region, there is evidence for considerable M1 strength (1976FA13).

For reaction (b) see ^{10}Be. For reactions (c) and (d) see (1984AJ01) and (1997JO07). See also the earlier references cited in (1988AJ01).

25. ^{10}B(π, π')^{10}B

Table 10.28: Transition strengths and radiative widths from ^{10}B(e, e′) [a]

E_x (MeV)	$J^\pi; T$	Mult.	$B(\lambda)\uparrow$ e^2 fm$^{2\lambda}$	$B(\lambda)\downarrow$ (W.u.)	Γ_{γ_0} (eV)
0.72	$1^+; 0$	C2	1.71 ± 0.14	3.12 ± 0.26	$(6.1 \pm 0.5) \times 10^{-7}$
1.74	$0^+; 1$	M3	7.00 ± 0.20 [b]	125 ± 4	$(8.90 \pm 0.26) \times 10^{-10}$
2.15	$1^+; 0$	C2	0.41 ± 0.05	0.75 ± 0.08	$(3.6 \pm 0.4) \times 10^{-5}$
3.59	$2^+; 0$	C2	0.62 ± 0.05	0.67 ± 0.05	$(4.1 \pm 0.3) \times 10^{-4}$
5.16 [c]	$2^+; 1$	M3	19.4 ± 1.3	69.2 ± 4.6	$(1.00 \pm 0.07) \times 10^{-6}$
5.92	$2^+; 0$	C2	0.15 ± 0.05	0.16 ± 0.06	$(1.2 \pm 0.4) \times 10^{-3}$
6.03	$4^+; 0$	C2	18.7 ± 0.7	11.4 ± 0.4	$(9.3 \pm 0.4) \times 10^{-2}$
6.13	$3^-; 0$	C3 [d]	33.0 ± 3.8	5.6 ± 0.7	$(4.0 \pm 0.5) \times 10^{-6}$
6.56	$4^-; 0$	C3 [e]	21.7 ± 3.1	2.8 ± 0.4	$(3.3 \pm 0.5) \times 10^{-6}$
7.48 [f]	$2^+; 1$	M1	0.018 ± 0.002	1.27 ± 0.14	11.0 ± 1.2

[a] From (2004MIZX, analysis using polynomial times Gaussian fits to data from (1966SP02, 1976FA13, 1979AN08, 1995CI02). Distortion effects are taken into account by using $q_{\rm eff} = q(1 + 2.75/E_0)$ where E_0 is the incident electron energy in MeV (1995CI02).

[b] From a full DWBA analysis (R.S. Hicks, private communication).

[c] Assumed to correspond to 2^+ state at 5.164 MeV. F_T^2 at $q_{\rm eff} = 1.32$ fm^{-1} for the transition to the 2^- state at 5.110 MeV is an order of magnitude smaller than F_T^2 for the 5.164 MeV level (1995CI02). A small M1 contribution at low q has been subtracted.

[d] Shell-model calculations predict a dominant C3 contribution and a smaller C1 contribution (1995CI02).

[e] Shell-model calculations predict a dominant C3 contribution (1995CI02).

[f] Using the low-q data from (1966SP02, 1976FA13). In this evaluation, we have adopted a 2^- assignment for the 7.48 MeV state. However, see Tables 10.18 and 10.20 for a nearby 2^+ level.

The inelastic scattering of 162 MeV pions has been studied (1988ZE01) over the angular range $35°$ to $100°$ in the laboratory system and the data were analyzed with a model that incorporates shell-model wave functions into a distorted-wave impulse approximation formalism. Reduced transition probabilities were obtained for low-lying states. Higher states, or groups of unresolved states, at 7.0, 7.8, 8.07, 8.9, 9.7, 10.7, 11.5, and 12.8 MeV were studied.

26. ^{10}B(n, n)^{10}B

Angular distributions have been studied for $E_{\rm n} = 1.5$ to 14.1 MeV [see (1974AJ01, 1979AJ01)] and at 3.02 to 12.01 MeV (1986SAZR, 1987SAZX; $n_1 \rightarrow n_5$), 8 to 14 MeV (1983DA22; n_0) and 9.96 to 16.94 MeV (1986MU08; n_0). Measurements were made by (1990SA24) for $E_{\rm n}$ from 3.02 MeV up to 12.01 MeV. See also the experimental study of (1988RE09) and the optical model analysis of (1996CH33). See also ^{11}B in (1985AJ01, 1990AJ01) and (1984TO02).

27. (a) ^{10}B(p, p)^{10}B
(b) ^{10}B(p, 2p)^{9}Be $\qquad Q_{\rm m} = -6.5859$

Angular distributions have been measured for a number of energies between $E_{\rm p} = 3.0$ and 800 MeV [see (1974AJ01, 1979AJ01, 1984AJ01)] and at 10 to 17 MeV (1986MU08; p_0). Differential cross sections have been measured (2001CH78) from $E_{\rm p} = 0.5$–3.3 MeV in $5°$ steps from $100° - 170°$. Cross sections and polarization observables for 200 MeV polarized protons were measured by (1992BA76; p_0, p_1). See also the $E_{\rm p} = 200$ MeV measurements and analyses reported in (1991LE22). Microscopic model analyses are reported for $E_{\rm p} = 25$, 30, 40 MeV by (2000DE61) and for $E_{\rm p} = 200$ MeV by (1997DO01). Table 10.29 displays the states observed in this reaction. Inelastic scattering data were used to deduce the deformation parameters, $\beta_{\rm L}$. The γ-ray results are shown in Tables 10.19 and 10.20. See also (1979AJ01). For $\tau_{\rm m}$ see Table 10.21 (1983VE03).

Axions may cause e^+e^- pairs in competition with γ-ray emission in an isoscalar M1 transition: a search for axions was undertaken in the case of the $3.59 \rightarrow$ g.s. $[2^+ \rightarrow 3^+]$ transition. It was negative (1986DE25). A beam dump experiment and other attempts to observe axions are discussed in (1987HA1O). For reaction (b) at $E_{\rm p} = 1$ GeV see (1985BE30, 1985DO16) and (1974AJ01). See also (1988KRZY), (1985KI1B, 1988KOZL; applied) and ^{11}C in (1985AJ01, 1990AJ01).

28. ^{10}B(d, d)^{10}B

Angular distributions have been reported at $E_{\rm d} = 4$ to 28 MeV: see (1974AJ01, 1979AJ01). Observed deuteron groups are displayed in Table 10.29. The very low intensity of the group to

Table 10.29: ^{10}B levels from ^{10}B(p, p), ^{10}B(d, d) and ^{10}B(^{3}He, ^{3}He) [a]

E_x (MeV ± keV) [b]	Γ_{cm} (keV)	L	β_L [b,c]
0 [d]			
0.7183 ± 0.4 [d,e,f]		2	0.67 ± 0.05
1.7402 [f,g]		(3)	
2.1541 ± 0.5 [d]		2	0.49 ± 0.04
3.5870 ± 0.5 [d]		2	0.45 ± 0.04
4.7740 ± 0.5 [h]			
5.1103 ± 0.6		3	0.45 ± 0.04
5.1639 ± 0.6			
5.18 ± 10 [h,i]	110 ± 10		
5.9195 ± 0.6 [d]	< 5		0.28 ± 0.03
6.0250 ± 0.6 [d]	< 5	2	0.95 ± 0.04
6.1272 ± 0.7 [d]	< 5	3	0.58 ± 0.03
6.55 ± 10 [d]	25 ± 5	3	0.46 ± 0.04 [j]
7.00 ± 10 [d]	95 ± 10		
7.48 ± 10	90 ± 15		

[a] For references and a more complete presentation see Table 10.19 in (1979AJ01).
[b] From (p, p) and (p, p′).
[c] See results obtained from (^{3}He, ^{3}He′) in Table 10.19 of (1979AJ01).
[d] Also observed in (d, d) and (^{3}He, ^{3}He).
[e] $E_x = 718.35 \pm 0.04$ (from E_γ).
[f] $E_x = 718.5 \pm 0.2$ and 1740.0 ± 0.6 keV (from E_γ).
[g] Also observed in (^{3}He, ^{3}He).
[h] Also observed in (d, d).
[i] Not reported in (p, p) at $E_p = 10$ MeV.
[j] Assumes $J^\pi = 4^-$; $\beta_L = 0.59 \pm 0.03$ if $J^\pi = 2^-$.

^{10}B*(1.74) and the absence of the group to ^{10}B*(5.16) is good evidence of their $T = 1$ character: see (1974AJ01). See also the cross section measurements at $E_d = 13.6$ MeV reported in (1991BE42).

29. ^{10}B(t, t)^{10}B

Angular distributions of elastically scattered tritons have been measured at $E_t = 1.5$ to 3.3 MeV: see (1974AJ01).

30. ^{10}B(^{3}He, ^{3}He)^{10}B

Angular distributions have been measured at $E(^3\text{He}) = 4$ to 46.1 MeV [see (1974AJ01, 1979AJ01, 1984AJ01)] and at 2.10 and 2.98 MeV (1987BA34; elastic). $L = 2$ gives a good fit of the distributions of ^{3}He ions to ^{10}B*(0.72, 2.15, 3.59, 6.03): derived β_L are shown in Table 10.19 of (1979AJ01). See also Table 10.29 here, ^{13}N in (1986AJ01) and see the Strong-Absorption Model analysis for $E(^3\text{He}) = 41$ MeV reported in (1987RA36).

31. (a) ^{10}B(α, α)^{10}B
(b) ^{10}B(α, 2α)^{6}Li $\qquad Q_m = -4.4610$

Angular distributions have been measured for $E_\alpha = 5$ to 56 MeV [see (1974AJ01, 1979AJ01, 1984AJ01)] and at 91.8 MeV (1985JA12; α_0). Measurements of cross sections relative to Rutherford scattering at large angles for $E_\alpha = 1$–3.3 MeV were reported by (1992MC03). Data for $E_\alpha = 1.5$–10 MeV were compiled and reviewed for depth-profiling applications in (1991LE33). Reaction (b) has been studied at $E_\alpha = 24$ and 700 MeV: see (1979AJ01, 1984AJ01). See also (1983GO27, 1985SH1D; theor.).

32. (a) ^{10}B(^{6}Li, ^{6}Li)^{10}B
(b) ^{10}B(^{7}Li, ^{7}Li)^{10}B

Elastic-scattering angular distributions have been studied at $E(^6\text{Li}) = 5.8$ and 30 MeV: see (1979AJ01). A model for calculating departures from Rutherford backscattering for Lithium targets is described in (1991BO48). For reaction (b), elastic scattering angular distributions were studied at $E(^7\text{Li}) = 24$ MeV: see (1979AJ01). Differential cross section measurements at $E(^7\text{Li}) = 39$ MeV were reported in (1988ET02).

33. (a) ^{10}B(^{7}Be, ^{7}Be)^{10}B
(b) ^{10}B(^{9}Be, ^{9}Be)^{10}B

Elastic scattering differential cross section measurements at $E(^{7}\text{Be}) = 84$ MeV have been reported (1999AZ02, 2001AZ01, 2001GA19, 2001TR04). The results were used along with ^{10}B(^{7}Be, ^{8}B) data to deduce asymptotic normalization coefficients for the virtual transitions $^{8}\text{B} \rightarrow {}^{7}\text{Be} + \text{p}$ and to calculate the astrophysical S factor and direct-capture rates for ^{7}Be(p, γ)^{8}B. See also the analysis in (2002GA11).

For reaction (b), the elastic angular distributions have been measured at $E(^{10}\text{B}) = 20.1$ and 30.0 MeV (1983SR01). For yield and cross section measurements see (1983SR01, 1986CU02). See also the calculations of (1984IN03, 1986RO12).

34. (a) ^{10}B(^{10}B, ^{10}B)^{10}B
(b) ^{10}B(^{11}B, ^{11}B)^{10}B

Elastic angular distributions (reaction (a)) have been studied at $E(^{10}\text{B}) = 8$, 13 and 21 MeV (see the references cited in (1979AJ01)) and at $E(^{10}\text{B}) = 4$–15 MeV (1975DI08). These data were used by (2000RU05) to study the energy dependence of optical model parameters. For reaction (b) see the references cited in (1988AJ01). See also (2000RU05).

35. (a) ^{10}B(^{12}C, ^{12}C)^{10}B
(b) ^{10}B(^{13}C, ^{13}C)^{10}B

Elastic angular distributions have been measured at $E(^{10}\text{B}) = 18$ and 100 MeV for reaction (a) [see (1979AJ01)] and at 18–46 MeV [see (1984AJ01)] and 42.5, 62.3 and 80.9 MeV for reaction (b) (1985MA10). For yield, cross section and fusion experiments see (1983DA20, 1983MA53, 1985MA10, 1988MA07) and (1984AJ01). For other references on these reactions, see (1988AJ01).

36. ^{10}B(^{14}N, ^{14}N)^{10}B

Angular distributions have been reported at $E(^{10}\text{B}) = 100$ MeV and $E(^{14}\text{N}) = 73.9$ and 93.6 MeV (1979AJ01, 1984AJ01), and at 38.1, 42.0 and 50 MeV (1988TA13). For fusion cross section studies see (1983DE26, 2001DI12) and the references cited in (1979AJ01, 1984AJ01, 1988AJ01).

37. (a) $^{10}B(^{16}O, ^{16}O)^{10}B$
(b) $^{10}B(^{17}O, ^{17}O)^{10}B$
(c) $^{10}B(^{18}O, ^{18}O)^{10}B$

Elastic angular distributions (for reaction (a)) have been studied at $E(^{10}B) = 33.7$ to 100 MeV and at $E(^{16}O) = 15$–32.5 MeV (1979AJ01, 1984AJ01), at $E_{cm} = 14.77$, 16.15 and 18.65 MeV (1988KO10), and for reactions (a), (b) and (c) at $E(^{16}O) = 16$–64 MeV (1994AN05). For elastic cross sections for reaction (c) at $E(^{18}O) = 20$, 24 and 30.5 MeV, see (1974AJ01). For a study of the time scales for binary processes for the $^{16}O + ^{10}B$ system at $E_{cm} = 17$–25 MeV see (2002SU17). See also (2001DE50). For yield and fusion cross section measurements see (1993AN08, 1993AN15, 1994AN05) and earlier references cited in (1988AJ01).

38. (a) $^{10}B(^{19}F, ^{19}F)^{10}B$
(b) $^{10}B(^{20}Ne, ^{20}Ne)^{10}B$

The elastic scattering has been investigated for $E(^{19}F) = 20$ and 24 MeV for reaction (a) and $E(^{10}B) = 65.9$ MeV for reaction (b): see (1974AJ01, 1984AJ01).

39. (a) $^{10}B(^{24}Mg, ^{24}Mg)^{10}B$
(b) $^{10}B(^{25}Mg, ^{25}Mg)^{10}B$

The elastic scattering for both reactions has been studied at $E(^{10}B) = 87.4$ MeV: see (1984AJ01). The elastic scattering for reaction (b) has been measured at $E(^{10}B) = 34$ MeV by (1985WI18).

40. (a) $^{10}B(^{27}Al, ^{27}Al)^{10}B$
(b) $^{10}B(^{28}Si, ^{28}Si)^{10}B$
(c) $^{10}B(^{30}Si, ^{30}Si)^{10}B$

The elastic scattering for all three reactions has been studied at $E(^{10}B) = 41.6$ and ≈ 50 MeV [and also at 33.7 MeV for reaction (b)]: see (1984AJ01). See also (1984TE1A).

41. (a) $^{10}B(^{39}K, ^{39}K)^{10}B$
(b) $^{10}B(^{40}Ca, ^{40}Ca)^{10}B$

The elastic scattering has been studied at $E(^{10}\text{B}) = 44$ MeV for reaction (a) (1985WI18) and at 46.6 MeV for reaction (b): see (1984AJ01).

42. $^{10}\text{C}(\beta^+)^{10}\text{B}$ $\qquad Q_\text{m} = 3.6480$

The half-life of ^{10}C is 19.290 ± 0.012 sec (1990BA02): the decay is to ^{10}B*(0.72, 1.74) with branching ratios of (98.53 ± 0.02)% (1979AJ01) and (1.4645 ± 0.0019)% [world average (1999FU04)], see (1991KR19, 1991NA01, 1995SA16, 1999FU04) for measurements since (1988AJ01): an upper limit for decay to ^{10}B*(2.15), $\leq 8 \times 10^{-4}$%, is given in (1979AJ01). The excitation energies of ^{10}B*(0.72, 1.74) are 718.380 ± 0.011 keV and 1740.05 ± 0.04 keV, respectively, which were determined from de-excitation γ-rays with $E_\gamma = 718.353 \pm 0.010$ keV and 1021.646 ± 0.014 keV (1988BA55, 1989BA28). See (2003SU04) for discussion of B(GT) values.

The $0^+ \rightarrow 0^+$ super-allowed β-decay branch for ^{10}C decay to ^{10}B*(1.74) is important for determining the V_ud matrix element and for testing the unitarity of the Cabibbo-Kobayashi-Maskawa matrix. The V_ud matrix element is determined by ft-values; for ^{10}C, this depends on the ^{10}C*(0, $[0^+]$) $\rightarrow$ ^{10}B*(1.74, $[0^+]$) branching ratio, 1.4645 ± 0.0019 [J^π in brackets], the ^{10}C half-life (1990BA02), and the decay energy to the ^{10}B*(1.74) state, 1907.86 ± 0.12 keV (1998BA83). The experimental ft value is 3037 ± 8, which yields $\log ft = 3.4825 \pm 0.0014$. Various corrections to the ft-values, to account for nuclear structure and isospin effects, are discussed in (1991RA09, 1992BA22, 1993CH06, 1994BA65, 1996SA09, 1998TOZQ, 2000BA52, 2000HAZU). After correction, the ft value is $\approx 3068.9 \pm 8.5$ (99FU04), which by itself satisfies the unitarity test of the CKM matrix. However, higher precision measurements are desirable since the satisfaction of CKM unitarity, based on all $0^+ \rightarrow 0^+$ decays, continues to be debated in the literature (2002HA47, 2002TO19, 2002WI09, 2003WI01).

43. $^{11}\text{B}(\gamma, \text{n})^{10}\text{B}$ $\qquad Q_\text{m} = -11.454$

The intensities of the transitions to ^{10}B*(3.59, 5.16) [$T = 0$ and 1, respectively] depend on the region of the giant dipole resonance in ^{11}B from which the decay takes place: it is suggested that the lower-energy region consists mainly of $T = \frac{1}{2}$ states and the higher-energy region of $T = \frac{3}{2}$ states: see ^{11}B in (1980AJ01). See also ^{11}B in (1985AJ01, 1990AJ01) and (1984AL22).

44. (a) $^{11}\text{B}(\text{p, d})^{10}\text{B}$ $\qquad Q_\text{m} = -9.230$

(b) $^{11}\text{B}(\text{p, p + n})^{10}\text{B}$ $\qquad Q_\text{m} = -11.454$

Angular distributions of deuteron groups have been measured at several energies in the range $E_\text{p} = 17.7$ to 154.8 MeV [see (1979AJ01)] and at 18.6 MeV (1985BE13; d_0, d_1). The population of the first five states of ^{10}B and of ^{10}B*(5.2, 6.0, 6.56, 7.5, 11.4 ± 0.2, 14.1 ± 0.2) is reported. Data at $E_{\rm p} = 33$ MeV was used (1991AB04) in a test of Cohen-Kurath wave functions and intermediate coupling. For reaction (b) see (1985BE30, 1985BO05; 1 GeV). Cross sections $\sigma(E)$ for both reactions (a) and (b) are calculated in a "quasiquantum multistep direct reaction" theory described in (1994SH21). See also references cited in (1988AJ01).

45. ^{11}B(d, t)^{10}B $\qquad Q_{\rm m} = -5.197$

Angular distributions have been measured at $E_{\rm d} = 11.8$ MeV ($t_0 \rightarrow t_3$; $l = 1$) [see (1974AJ01)] and at 18 MeV (1987GUZZ, 1988GUZW). A combined DWBA and dispersion-theory analysis of cross section data is described in (1995GU22). Vertex constants and spectroscopic factors were deduced.

46. (a) ^{11}B(^{3}He, α)^{10}B $\qquad Q_{\rm m} = 9.124$
(b) ^{11}B(^{3}He, 2α)^{6}Li $\qquad Q_{\rm m} = 4.663$

Reported levels are displayed in Table 10.30. Angular distributions have been measured at a number of energies between $E(^3{\rm He}) = 1.0$ and 33 MeV [see (1974AJ01)] and at 23.4 MeV (1987VA1I; α_0, α_1). For the decay of observed states see Tables 10.19 and 10.20.

The α-α angular correlations (reaction (b)) have been measured for the transitions via ^{10}B*(5.92, 6.03, 6.13, 6.56, 7.00). The results are consistent with $J^\pi = 2^+$ and 4^+ for ^{10}B*(5.92, 6.03) and require $J^\pi = 3^-$ for ^{10}B*(6.13). There is substantial interference between levels of opposite parity for the α-particles due to ^{10}B*(6.56, 7.00): the data are fitted by $J^\pi = 3^+$ for ^{10}B*(7.00) and (3, 4)$^-$ for ^{10}B*(6.56) [the ^{6}Li(α, α) results then require $J^\pi = 4^-$]. See, however, reaction 16, and see (1974AJ01) for the references. See also (1988GOZB; theor.).

47. ^{11}B(^{7}Li, ^{8}Li)^{10}B $\qquad Q_{\rm m} = -9.422$

Angular distributions have been measured at $E(^7{\rm Li}) = 34$ MeV involving ^{10}B*(0, 0.72, 1.74, 2.15) and ^{8}Li$_{\rm g.s.}$ (as well as ^{8}Li*(0.98) in the case of the ^{10}B$_{\rm g.s.}$ transition) (1987CO16).

48. (a) ^{12}C(γ, d)^{10}B $\qquad Q_{\rm m} = -25.1864$
(b) ^{12}C(γ, p + n)^{10}B $\qquad Q_{\rm m} = -27.4110$

For reaction (a) see (1986SH1M) and ^{12}C in (1990AJ01). Reaction (b) was studied at $E_\gamma = 189$–427 MeV (1987KA13), 83–133 MeV (1988DA16), 80–159 MeV (1993HA12), 300 MeV

Table 10.30: ^{10}B levels from ^{11}B(^{3}He, α)^{10}B [a]

E_x (MeV ± keV)	Γ_{cm} (keV)	l	S_{rel}
0		1	1.0
0.718 ± 7		1	0.22
1.744 ± 7		1	0.73
2.157 ± 6		1	0.44
3.587 ± 6		1	0.09
4.777 ± 5		1	0.09
5.114 ± 5			
5.166 ± 5		1	1.81
5.923 ± 5			
6.028 ± 5			
6.131 ± 5			
6.570 ± 7	30 ± 10		
7.002 ± 10	95 ± 10		
7.475 ± 10			
7.567 ± 10			
7.87 ± 40	240 ± 50		
10.85 ± 100	300 ± 100		
11.52 ± 35	500 ± 100		
12.56 ± 30	100 ± 30		
13.49 ± 50	300 ± 50		
14.4 ± 100	800 ± 200		
(18.2 ± 200)	(1500 ± 300)		

[a] See Table 10.21 in (1979AJ01) for references.

(1995CR04), 80–157 MeV (1995MC02), 150–400 MeV (1996HA16), 114–600 MeV (1996LA15), 250–600 MeV (1998HA01), 120–400 MeV (1998MA02), 120–150 MeV (1998YA05), 150 MeV (1999KH06) and 150–700 MeV (2000WA20). Measurements with polarized photons at energies $E_\gamma = 160$–350 MeV were reported by (1999FR12, 2001PO19). Analyses of data and theoretical calculations are described in (1989VO01, 1994RY02, 1998RY01, 1999IR01, 2002GR05). For earlier work see the references cited in (1988AJ01).

49. ^{12}C(n, t)^{10}B $\qquad Q_m = -18.9292$

Cross section measurements at $E_{\rm n} = 40$–56 keV for determining efficiency of neutron detectors were reported in (1994MO41). Calculated cross sections are tabulated in (1989BR05). See also (1985FR07, 1987FR16; $E_{\rm n} = 319$ to 545 MeV) and (1986DO12).

50. ^{12}C($\pi^{\pm}$, $\pi^{\pm}$d)^{10}B $\qquad Q_{\rm m} = -25.1864$

At $E_{\pi^+} = 180$ MeV and $E_{\pi^-} = 220$ MeV, ^{10}B*(0.72, 2.15) are populated: see (1984AJ01). At $E_{\pi^+} = 150$ MeV momentum distributions of pions to unresolved states of ^{10}B are reported by (1987HU13).

51. (a) ^{12}C(p, ^{3}He)^{10}B $\qquad Q_{\rm m} = -19.6929$

(b) ^{12}C(p, p + d)^{10}B $\qquad Q_{\rm m} = -25.1864$

Angular distributions of ^{3}He ions have been measured for $E_{\rm p} = 39.8$, 51.9 and 185 MeV: see (1979AJ01). ^{10}B*(0, 0.72, 1.74, 2.15, 3.59, 4.77, 5.16, 5.92, 6.56, 7.50, 8.90) are populated. A calculation of ^{3}He and α-particle multiplicities is described in (1987GA08). For reaction (b) see (1985DE17); $E_{\rm p} = 58$ MeV; ^{10}B*(0.72, 1.74)) and (1984AJ01). Calculations of cross sections for $E_{\rm p} = 58$ MeV and 0.7 GeV are described in (1990LO18) and (1987ZH10), respectively. See also the references cited in (1988AJ01).

52. ^{12}C(d, α)^{10}B $\qquad Q_{\rm m} = -1.3400$

Alpha groups have been observed to most of the known states of ^{10}B below $E_{\rm x} = 7.1$ MeV: see Table 10.23 in (1974AJ01). Angular distributions have been measured for $E_{\rm d} = 5.0$ to 40 MeV: see (1979AJ01). Single-particle S-values are 1.5, 0.5, 0.1, 0.1 and 0.3, respectively, for ^{10}B*(0, 0.72, 2.15, 3.59, 4.77). A study of the $m_{\rm s} = 0$ yield at $E_{\rm d} = 14.5$ MeV ($\theta = 0°$) leads to assignments of 3^+, 2^- and (3^+, 4^-) for ^{10}B*(4.77, 5.11, 6.56). The population of the isospin-forbidden group to ^{10}B*(1.74) [α_2] has been studied with $E_{\rm d}$ up to 30 MeV: see ^{14}N in (1986AJ01). See also (1984LOZZ).

53. ^{12}C(α, ^{6}Li)^{10}B $\qquad Q_{\rm m} = -23.7126$

Angular distributions have been reported at $E_\alpha = 42$ and 46 MeV: see (1979AJ01). At $E_\alpha = 65$ MeV, an investigation of the ^{6}Li breakup shows that ^{10}B*(0, 0.72, 2.16, 3.57, 4.77, 5.2, 5.9, 6.0) are involved: see (1984AJ01). See also the cross section measurements at $E_\alpha = 33.8$ MeV (1987GA20) and at $E_\alpha = 90$ MeV (1991GL03).

54. ^{12}C(^{7}Li, ^{9}Be)^{10}B $Q_{\mathrm{m}} = -8.4905$

At $E(^{7}\mathrm{Li}) = 78$ MeV angular distributions have been measured to ^{10}B*(0, 2.15) (1986GLZV).

55. (a) ^{12}C(^{12}C, ^{14}N)^{10}B $Q_{\mathrm{m}} = -14.9141$
(b) ^{12}C(^{14}N, ^{16}O)^{10}B $Q_{\mathrm{m}} = -4.4503$

Angular distributions (reaction (a)) involving ^{10}B*(0, 0.7) have been studied at $E(^{12}\mathrm{C}) = 49.0$ to 75.5 and 93.8 MeV. Angular distributions (reaction (b)) involving ^{10}B*(0, 0.72, 2.15, 3.59) have been measured at $E(^{14}\mathrm{N}) = 53$ MeV and 78.8 MeV (not to ^{10}B*(3.59)): see (1979AJ01, 1984AJ01) for references. See also (1986AR04, 1986CR1A, 1986MOZV).

56. ^{13}C(p, α)^{10}B $Q_{\mathrm{m}} = -4.0616$

Differential cross sections were measured (1988AB11) at $E_{\mathrm{p}} = 18$–45 MeV. Measurements at $E_{\mathrm{p}} = 30.95$ MeV were reported by (1988BA30). Known p-shell levels at 0, 0.72, 1.74, 2.15, 3.59, 4.77, 5.16, 5.92, 6.03 and 7.47 MeV were excited (1988AB11, 1988BA30). Analyses in both these studies used DWBA direct pickup calculations using a triton cluster form factor and the shell model calculations of (1975KU01). Spectroscopic factors were deduced. For earlier work at $E_{\mathrm{p}} = 5.8$–18 MeV and 43.7 and 50.5 MeV see (1979AJ01). See also references cited in (1988AJ01).

57. ^{14}N(p, p + α)^{10}B $Q_{\mathrm{m}} = -11.6122$

See (1986VDZY; $E_{\mathrm{p}} = 50$ MeV). See also (1986GO28; theor.).

58. ^{14}N(d, ^{6}Li)^{10}B $Q_{\mathrm{m}} = -10.1384$

At $E_{\mathrm{d}} = 80$ MeV angular distributions are reported to ^{10}B*(0, 0.72, 2.15, 3.59, 4.8, 6.04, 7.05, 8.68): see (1979OE01).

59. ^{16}O(^{9}Be, ^{15}N)^{10}B $Q_{\mathrm{m}} = -5.5415$

See (1985WI18).

60. (a) $^{\rm nat}$Ag(^{14}N, $\alpha + {}^6$Li)X

(b) $^{\rm nat}$Ag(^{14}N, p + ^{9}Be)X

The breakup of ^{10}B was studied (1989NA03, 1992NA01) in an experiment with an $E/A = 35$ MeV ^{14}N beam incident on $^{\rm nat}$Ag. In the breakup of ^{10}B into $\alpha + {}^6$Li the 4.77 MeV 3^+ and 6.56 MeV 4^- states were observed together with unresolved groups of states near 5.1, 6.0, and 7.0 MeV. In the ^{9}Be + p channel peaks centered near 6.9, 7.5, and 8.9 MeV were observed. Similar results have been obtained for an ^{36}Ar beam incident on ^{197}Au (1992ZH08).

^{10}C

(Figs. 16 and 17)

GENERAL: References to articles on general properties of ^{10}C published since the previous review (1988AJ01) are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for ^{10}C located on our website at: (*www.tunl.duke.edu/nucldata/ General_Tables/10c.shtml*).

Mass of ^{10}C: The threshold energy for the ^{10}B(p, n)^{10}C reaction is 4877.03 ± 0.13 keV: then $Q_0 = -4430.30 \pm 0.12$ keV (1998BA83). Using the (2003AU03) masses for ^{10}B, p and n, the atomic mass excess is then 15698.8 ± 0.4 keV. However, we adopt the (2003AU03) value: 15698.6 ± 0.4 keV. See also unpublished work on ^{12}C(p, t)^{10}C that is quoted in (1984AJ01).

$$B(\text{E2})\!\uparrow \text{ for } ^{10}\text{C*}(3.35) = 62 \pm 10\ e^2 \cdot \text{fm}^4;$$

$$B(\text{E2})\!\downarrow \text{ for } ^{10}\text{C*}(3.35) = 12.4 \pm 2.0\ e^2 \cdot \text{fm}^4 \text{ (1968FI09)}.$$

1. ^{10}C(β^+)^{10}B $\qquad Q_m = 3.6480$

The half-life of ^{10}C is 19.290 ± 0.012 sec (1990BA02), which is the average of 19280 ± 20 msec (1974AZ01) (Corrected on 04/11/2007), 19270 ± 80 msec (1963BA52), 19300 ± 41 msec (1990BA02) and 19294 ± 16 msec (1990BA02). The nucleus ^{10}C decays to ^{10}B*(0.7, 1.7): the branching ratios are (98.53 ± 0.02)% (1979AJ01) and (1.4645 ± 0.0019)% (1999FU04), respectively. See also the discussion of reaction 42 in ^{10}B.

By measuring the relative polarization of positrons emitted from ^{10}C β-decay (pure G-T) and ^{14}O (pure Fermi), ratio $= 0.9996 \pm 0.0036$ (1988GI02, 1990CA41, 1991CA12), constraints on the scalar and tensor admixtures to the dominant vector and axial vector currents were determined as, $|\frac{C_S}{C_V} - \frac{C_T}{C_A}| = 0.001 \pm 0.009$.

2. ^{1}H(^{10}C, ^{10}C + p)

Elastic and inelastic scattering cross sections for ^{10}C*(0, 3.35) were measured at $E(^{10}\text{C}) = 45.3$ MeV/A (2003JO09). The data is best fit with $|M_n|/|M_p| = 0.71$ which gives $|M_n| = 5.51 \pm 1.07$ fm^2 when compared with the known value $|M_p| = 7.87 \pm 0.64$ fm^2, which is derived from $B(\text{E2}) = 62 \pm 10\ e^2 \cdot \text{fm}^4$.

3. ^{6}Li(α, π^-)^{10}C $\qquad Q_m = -138.7572$

Table 10.31: Energy levels of ^{10}C

E_x (MeV $\pm$ keV)	$J^\pi; T$	τ or Γ_{cm} (keV)	Decay	Reactions
g.s.	$0^+; 1$	$\tau_{1/2} = 19.290 \pm 0.012$ sec	β^+	1, 2, 3, 6, 8, 9, 11, 12
3.3536 ± 0.7	2^+	$\tau_m = 155 \pm 25$ fsec	γ	2, 4, 6, 8, 9, 11, 12
5.22 ± 40	[a]	$\Gamma = 225 \pm 45$ keV		6, 8, 9, 11
5.38 ± 70	[a]	300 ± 60		6, 8, 9, 11
6.580 ± 20	(2^+)	190 ± 35		6, 8, 9, 11
≈ 9				8
≈ 10				8
≈ 16.5	(2^+) [b]			8
[c]				

[a] One of these two states is presumably a 2^+ state.
[b] Presumed analog of ^{10}B*(18.80) (1993WA06).
[c] See reaction 8 for possible evidence of other states.

Table 10.32: Electromagnetic transition strengths in ^{10}C [a]

$E_i \to E_f$ (MeV)	$J_i^\pi \to J_f^\pi$	Branch (%)	Γ_γ (eV) [a]	Mult.	Γ_γ/Γ_W
$3.354 \to 0$	$2^+ \to 0^+$	100	$(4.25 \pm 0.69) \times 10^{-3}$	E2	9.5 ± 1.5

[a] Γ_γ from lifetime.

The π^- production rates for various projectile and target combinations, including ^{6}Li + ^{4}He, were measured at 4.5 GeV/c per nucleon in (1993CH35). In general the observed π^- production cross section falls off exponentially with increasing π^- energy. In some cases the angular distributions show a slight dependence on target and projectile mass.

4. ^{7}Li(^{3}He, π^-)^{10}C $\qquad Q_m = -125.4299$

At $E(^3\text{He}) = 235$ MeV ^{10}C*(3.35) is populated (1984BI08). π^- production in this reaction has also been studied by (1984BR22) at $E(^3\text{He}) = 910$ MeV.

5. ^{7}Li(^{7}Li, 4n)^{10}C $\qquad Q_m = -18.1683$

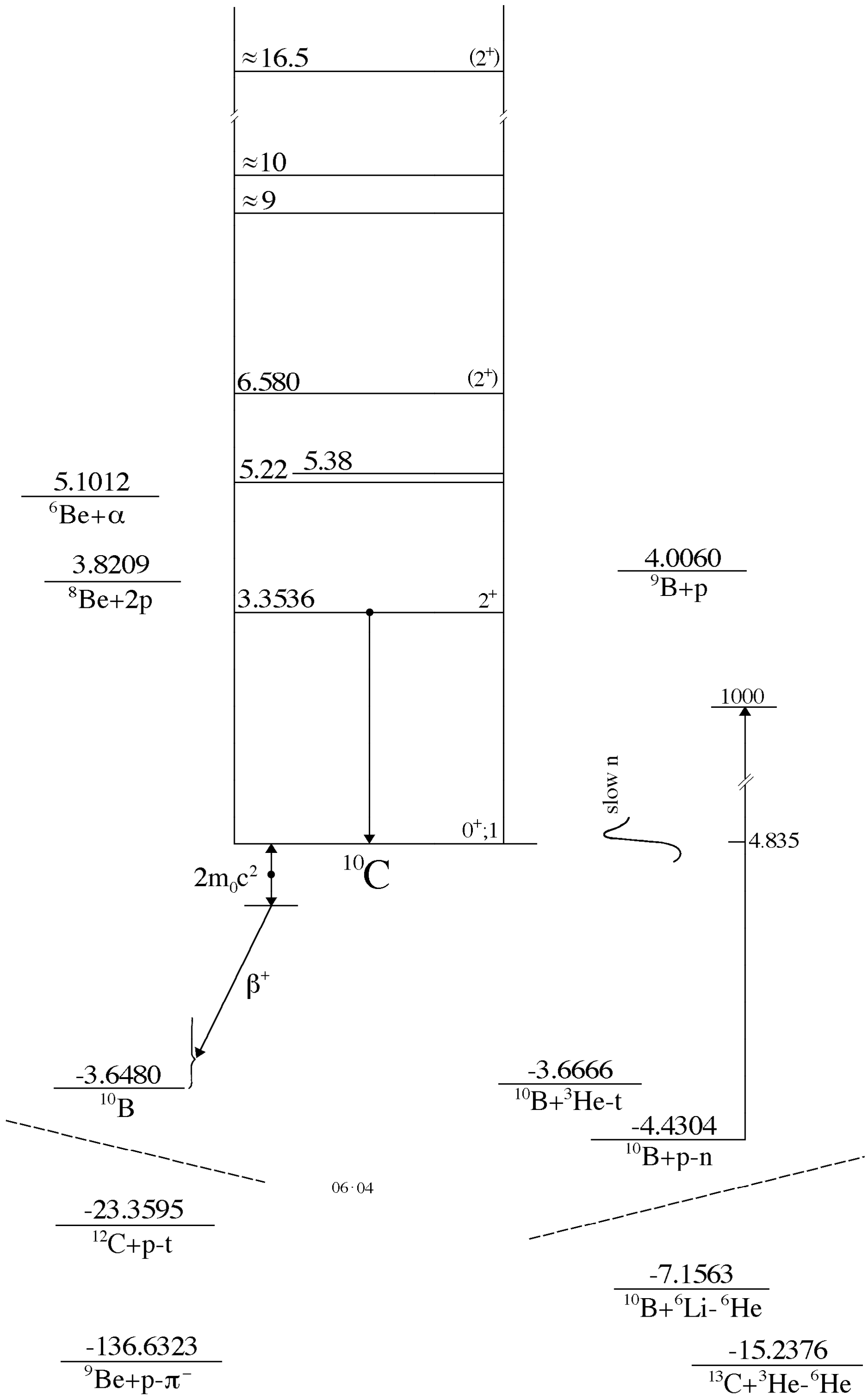


Figure 16: Energy levels of ^{10}C. For notation see Fig. 13.

Tetraneutron (n^4) production has been studied in this and in other reactions involving ^{10}C at $E(^7\text{Li}) = 82$ MeV (1987ALZG): it was not observed. However, evidence that is consistent with the existence of n^4 is observed in the breakup of ^{14}Be (2002MA21).

6. ^{9}Be(p, π^-)^{10}C $\qquad Q_\text{m} = -136.6323$

Angular distributions of π^- groups have been measured at $E_\text{p} = 185$ MeV (to ^{10}C*(0, 3.35, 5.28, 6.63)), at 200 MeV (g.s.), at 800 MeV (to ^{10}C*(0, 3.35, 5.3, 6.6)) [see (1984AJ01)] and at $E_{\vec{\text{p}}} = 650$ MeV (1986HO23; ^{10}C*(0, 3.35); also A_y). A_y measurements have also been reported at $E_{\vec{\text{p}}} = 200$ to 250 MeV: see (1984AJ01). At $E_\text{p} = 800$ MeV, the angular distributions of produced pions were measured for Be and C targets (1988BA58); they observed $\sigma(0°)/\sigma(20°) \approx 6$.

7. (a) ^{10}B(π^+, π^0)^{10}C $\qquad Q_\text{m} = 0.9456$

(b) ^{10}B(π^+, η)^{10}C $\qquad Q_\text{m} = -411.3778$

In (1987SI18), calculations of polarization observables for ^{10}B(π^+, π^0) at 70 MeV and ^{10}B(π^+, η) at 460 MeV suggest that new measurements could provide insight into the single-charge-exchange reaction mechanism.

8. ^{10}B(p, n)^{10}C $\qquad Q_\text{m} = -4.4304$

$Q_0 = -4430.30 \pm 0.12$ keV (1998BA83).

Level parameters for ^{10}C*(3.35) are $E_\text{x} = 3352.7 \pm 1.5$ keV, $\tau_\text{m} = 155 \pm 25$ fsec, $\Gamma_\gamma = 4.25 \pm 0.69$ meV. [See (1969PA09) and other references cited in (1974AJ01).] Angular distributions have been measured for the n_0 and n_1 groups and for the neutrons to ^{10}C*(5.2 ± 0.3) at $E_\text{p} = 30$ and 50 MeV [see (1974AJ01, 1979AJ01)] and for the n_0 and n_1 groups at $E_\text{p} = 14.0$, 14.3 and 14.6 MeV (1985SC08) and 15.8 and 18.6 MeV (1985GU1C).

At $E_{\vec{\text{p}}} = 186$ MeV, angular distributions of neutrons were measured for $\theta = 0°$–$50°$ (1993WA06). Levels were observed at 0 [0^+], 3.35 [2^+], 5.3 [2^+], 6.6, ≈ 9, ≈ 10, and 16.5 MeV [(2^+)] [J^π in brackets]. For $E_\text{x} = 3.35$ MeV, B(GT) $= 0.03$ and for 5.3 MeV, B(GT) $= 0.68 \pm 0.02$. A multipole decomposition analysis suggests additional states at 17.2 and 20.2 with $J^\pi = 2^-$ or 1^-, respectively. Higher-lying resonances that were excited with $E_\text{p} = 186$ MeV protons, the Giant-Dipole Resonance ($\Delta L = 1$, $\Delta S = 0$) and the Giant Spin Dipole Resonance ($\Delta L = 1$, $\Delta S = 1$), are discussed in (1994RA23, 1994WA22, 1995YA12). In their analysis a broad peak from quasi-free scattering, was estimated phenomenologically and subtracted from the excitation spectrum; a multipole decomposition analysis of the remaining structure indicated a prominent $\Delta L = 1$ resonance around $E_\text{x} = 17$–20 MeV with a possible mixture of 2^-, 1^- and 2^+ states (analogous to

^{10}B*(18.43, 18.8, 19.3, 20.1) and a small peak at $E_x = 24$ MeV (possible analog of the ^{10}B GDR). Data from $E_p = 1$ GeV were analyzed to develop a formalism for charge-exchange processes involving pion and Δ-isobar excitations (1994GA49).

The threshold value for ^{10}B(p, n) was measured by (1989BA28); a subsequent analysis of that data, by (1998BA83), rigorously evaluated the proton beam energy spread (740 eV), non-uniform energy losses for all protons, and energy losses induced by ionizing target atoms prior to capture. The threshold value was determined to be $E_{\text{thresh.}} = 4877.30 \pm 0.13$ keV, which yields $Q_0 = 4430.30 \pm 0.12$ keV for ^{10}B(p, n).

At $E_p = 7$ and 9 MeV, thick target neutron and γ-ray yields and relative ratios are measured for a compilation of proton-induced radiations that provide elemental analysis (1987RA23). Neutron production rates were measured for $E_{\text{cm}} = 5.9$ MeV (1988CHZN). The ^{10}B(p, n) cross section was measured at $E_p = 4.8$–30 MeV to evaluate the feasibility of producing isotopically enriched $^{10}CO_2$ for use in PET imaging (2000AL06).

9. ^{10}B(^{3}He, t)^{10}C $\qquad Q_m = -3.6666$

Angular distributions have been measured at $E(^3\text{He}) = 14$ MeV and 217 MeV: see (1979AJ01). The latter [to ^{10}C*(0, 3.35, 5.6)] have been compared with microscopic calculations using a central + tensor interaction [$J^\pi = 0^+, 2^+, 2^+$, respectively]. Structures have been reported at $E_x = 5.22 \pm 0.04$ [$\Gamma = 225 \pm 45$ keV], 5.38 ± 0.07 [300 ± 60 keV] and 6.580 ± 0.020 MeV [190 ± 35 keV].

10. ^{12}C(μ^+, X)^{10}C

The production of radioactive isotopes from 100 and 190 GeV muons incident on a ^{12}C target was measured by (2000HA33) to estimate the μ-induced backgrounds in large volume scintillator detector experiments.

11. ^{12}C(p, t)^{10}C $\qquad Q_m = -23.3595$

Angular distributions have been reported at $E_p = 30.0$ to 54.1 MeV and at 80 MeV [see (1974AJ01, 1979AJ01, 1984AJ01)]. $L = 0$, 2 and 2 to ^{10}C*(0, 3.35, 5.28) thus leading to 0^+, 2^+ and 2^+, respectively, for these states [but note that the "5.28 MeV" state is certainly unresolved]: see reaction 9 and Table 10.31. ^{10}C*(6.6) is also populated. Two measurements of the excitation energy of ^{10}C*(3.4) are 3353.5 ± 1.0 keV and 3354.3 ± 1.1 keV: see (1984AJ01) [based on Q_m]. See also (1987KW01; theor.).

12. ^{13}C(^{3}He, ^{6}He)^{10}C $\qquad Q_{\rm m} = -15.2376$

At $E(^{3}\text{He}) = 70.3$ MeV the angular distributions of the ^{6}He ions corresponding to the population of ^{10}C*(0, 3.35) have been measured. The group to ^{10}C*(3.35) is much more intense than the ground-state group: see (1979AJ01).

13. ^{16}O(p, X)^{10}C

Spallation reaction rates for incident protons on ^{16}O and ^{12}C targets with $E_{\rm p} \approx 50$–250 MeV were calculated by (1999CH50) using the GNASH code. These reaction rates are important for estimating the secondary radiation induced in medical proton therapy treatment.

14. ^{9}Be, $^{\rm nat}$C, ^{27}Al(^{10}C, X)

Total interaction cross sections of $E(^{10}\text{C}) = 730$ MeV/A projectiles were measured on ^{9}Be, $^{\rm nat}$C and ^{27}Al targets (1996OZ01). The deduced cross sections, $\sigma = 752 \pm 13$, 795 ± 12 and 1171 ± 20 mb, respectively, indicate $R_{\rm rms}(^{10}\text{C}) = 2.27 \pm 0.03$ fm.

^{10}N

(Not illustrated)

GENERAL: References to articles on general properties of ^{10}N published since the previous review (1988AJ01) are grouped into categories and listed, along with brief descriptions of each item, in the General Tables for ^{10}N located on our website at: (*www.tunl.duke.edu/nucldata/ General_Tables/10n.shtml*).

The first evidence for a state in ^{10}N has been observed in the ^{10}B(^{14}N, ^{14}B)^{10}N reaction at $E(^{14}\text{N}) = 30$ MeV/A (2002LE16). The resonance is 2.6 ± 0.4 MeV above the ^{9}C + p threshold and the width is $\Gamma = 2.3 \pm 1.6$ MeV. Large $L = 2$ two-nucleon transfer amplitudes calculated for $^{10}\text{B} + 2\text{p} \rightarrow {}^{12}\text{N}_{\rm g.s.}$ and $^{12}\text{N}_{\rm g.s.} \rightarrow {}^{10}\text{N}(1^{+})$ suggest that the observed state is the analog of the 0.24 MeV 1^{+} state of ^{10}Li. Furthermore, the energy of the observed state is consistent with a p-shell Coulomb energy shift. The virtual s-wave state near threshold in $^{9}\text{Li} + \text{n}$ (see ^{10}Li) implies a broad s-wave state about 1.8 MeV above the $^{9}\text{C} + \text{p}$ threshold in ^{10}N (see the discussion of ^{9}N).

^{10}O, ^{10}F, ^{10}Ne

(Not illustrated)

Not observed: see (1979AJ01). See also (1988AJ01).

Table 10.33: Isospin triplet components $(T = 1)$ in $A = 10$ nuclei [a]

^{10}Be		^{10}B			^{10}C		
E_x (MeV)	$J^\pi; T = 1$	E_x (MeV)	$J^\pi; T$	ΔE_x (MeV) [b]	E_x (MeV)	$J^\pi; T = 1$	ΔE_x (MeV) [c]
0	0^+	1.74015	$0^+; 1$	0	0	0^+	
3.36803	2^+	5.1639	$2^+; 1$	0.05572	3.3536	2^+	-0.01443
5.9599 [d]	1^-	6.873	$1^-; 0+1$	-0.82705			
5.9599 [d]	1^-	7.430	$1^-; 1+0$	-0.27005			
5.95839	2^+	7.469	$2^+; 1$	-0.22954	{ 5.22 5.38	(2^+) [e] (2^+) [e]	-0.73839 -0.57839
6.2633 [d]	2^-	7.480	$2^-; 0+1$	-0.52345			
6.1793	0^+	7.5599	$0^+; 1$	-0.35955			
6.2633 [d]	2^-	7.75	$2^-; 0+1$	-0.25345			
7.371	3^-	8.889	$3^-; 1$	-0.22215			
7.542	2^+	8.894	$2^+; 1$	-0.38815	6.58	(2^+)	-0.962

[a] As taken from Tables 10.5, 10.18 and 10.31.
[b] Defined as $E_x(^{10}$B)–$E_x(^{10}$Be) $- 1.74015$.
[c] Defined as $E_x(^{10}$C)–$E_x(^{10}$Be).
[d] Two entries for the same ^{10}Be level.
[e] See footnote [a] in Table 10.31 and (1997DA28).

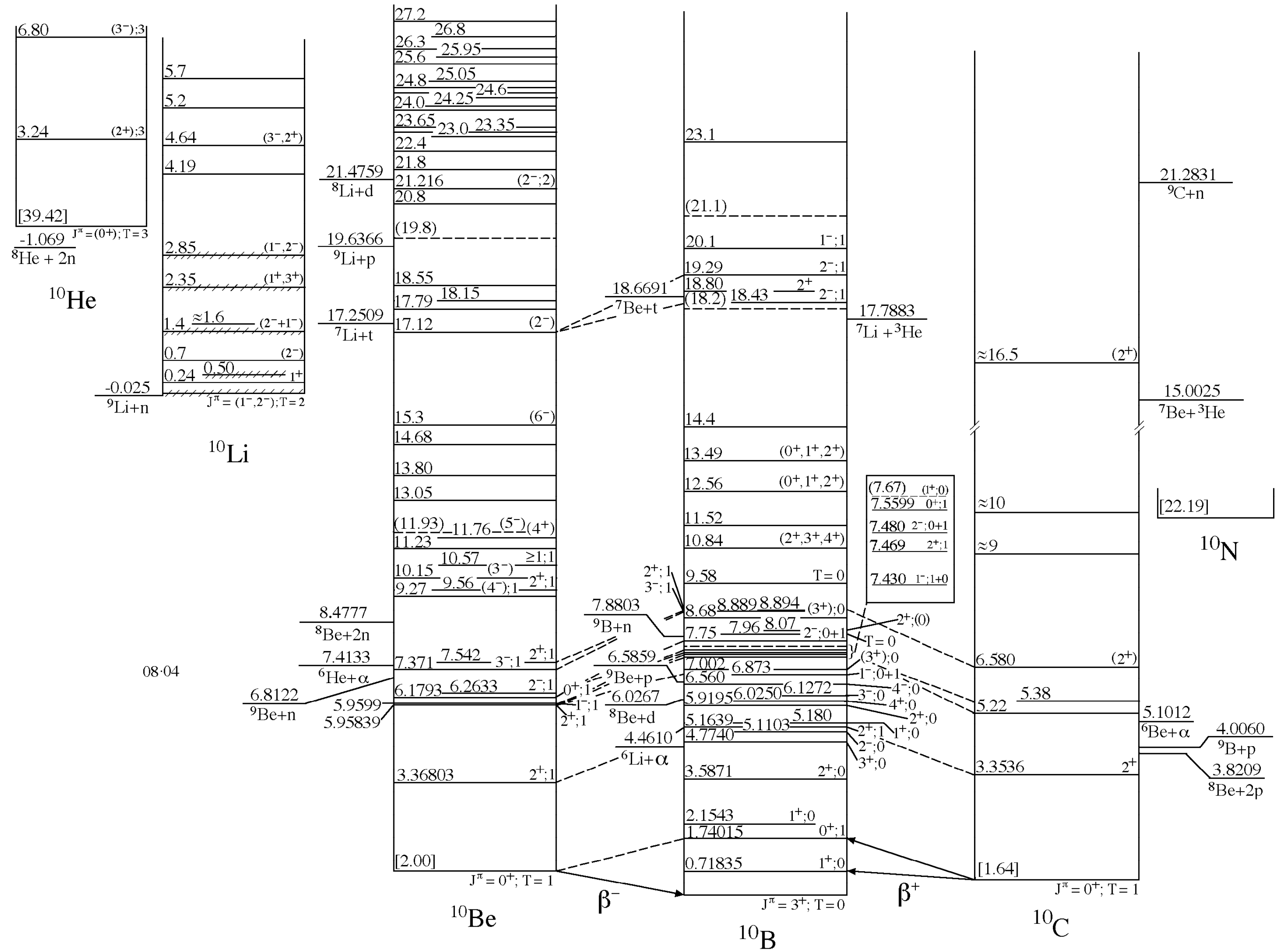


Figure 17: Isobar diagram, $A = 10$. The diagrams for individual isobars have been shifted vertically to eliminate the neutron-proton mass difference and the Coulomb energy, taken as $E_C = 0.60Z(Z-1)/A^{1/3}$. Energies in square brackets represent the (approximate) nuclear energy, $E_N = M(Z, A) - ZM(\mathrm{H}) - NM(\mathrm{n}) - E_C$, minus the corresponding quantity for ^{10}B: 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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