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Energy Levels of Light Nuclei $A = 11$

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Abstract: An evaluation of $A = 11$ was published in *Nuclear Physics A*880 (2012), p. 88. This version of $A = 11$ differs from the published version in that we have corrected some errors discovered after the article went to press. The introduction has been omitted from this manuscript. Reference key numbers are in the NNDC/TUNL format.

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CONVENTIONS AND SYMBOLS

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

E:	energy in MeV, in lab coordinates unless otherwise specified; subscripts p, d, t, etc. refer to protons, deuterons, tritons, etc.;
$E_{\rm b}$:	the separation energy, in MeV;
$E_{\rm x}$:	excitation energy, in MeV, referred to the ground state;
$E_{\rm cm}$:	energy in the center-of-mass system;
$E_{\rm brem}$:	energy of bremsstrahlung photons;
$E_{\rm res}$:	reaction resonance energy in the center-of-mass system;
Γ:	full width at half maximum intensity of a resonance excitation function or of a level; subscripts when shown indicate partial widths for decay via channel shown by the subscript;
C^2S:	the isospin Clebsch-Gordan coefficient (squared) times the spectroscopic factor (S);
$S(E)$:	astrophysical S-factor for center-of-mass energy E;
$\sigma(E)$:	reaction cross section for center-of-mass energy E;
${}^AX^*(E)$:	excited state of the nucleus ${}^AX$, at energy E;
ΔM:	mass excess (see a list of $A = 11$ mass excesses in Table 1);
DWBA:	Distorted-Wave Born Approximation;
DWIA:	Distorted-Wave Impulse Approximation;
FRDWBA:	Finite Range Distorted-Wave Born Approximation;
QRPA:	Quasi-particle Random Phase Approximation;
CDCC:	Continuum Discretized Coupled Channels;
AMD:	Antisymmetrized Molecular Dynamics;
DSAM:	Doppler Shift Attenuation Method;
DBLA:	Doppler Broadened Line Shape Analysis;
PET:	Positron Emission Tomography;

PIGE: Particle Induced Gamma-ray Emission;

GDR: Giant Dipole Resonance;

GQR: Giant Quadrupole Resonance;

IAS: Isobaric Analog State;

VAP: Vector Analyzing Power;

ANC: Asymptotic Normalization Constant.

Table 1: Parameters of the ground states of the light nuclei with $A = 11$

	Atomic mass excess [a] (keV)	$T_{1/2}$ or Γ_{cm} [b]	Decay [b]	$J^\pi; T$ [c]
^{11}Li [d]	40728.415 ± 1.118 [c]	$T_{1/2} = 8.75 \pm 0.14$ ms	β^-	$\frac{3}{2}^-; \frac{5}{2}$
^{11}Be [e]	20177.165 ± 0.238 [c]	$T_{1/2} = 13.76 \pm 0.07$ s	β^-	$\frac{1}{2}^+; \frac{3}{2}$
^{11}B [f]	8667.929 ± 0.418 [c]	stable		$\frac{3}{2}^-; \frac{1}{2}$
^{11}C [g]	10650.341 ± 0.950 [c]	$T_{1/2} = 20.364 \pm 0.014$ min	β^+	$\frac{3}{2}^-; \frac{1}{2}$
^{11}N	see text	$\Gamma = 830 \pm 30$ keV	p	$\frac{1}{2}^+; \frac{3}{2}$

[a] The values of the mass excesses shown here were used to calculate Q_m. Mass excesses of nuclei not included in this table, but also used in Q_m calculations were obtained from (2011AUZZ). The masses of $\pi^\pm$, π^0 and $\mu^\pm$ were taken to be 139570.18 ± 0.35, 134976.6 ± 0.6 and 105658.367 ± 0.005 keV (2000GR22).
[b] From data reviewed in this article.
[c] (2011AUZZ).
[d] $\mu = +3.6712 \pm 0.0003\ \mu_N$ (2008NE11), $Q = -33.3 \pm 0.5$ mb (2008NE11).
[e] $\mu = -1.6814 \pm 0.0004\ \mu_N$ from weighted average of $\mu = -1.6813 \pm 0.0005\ \mu_N$ (2009NO02) and $\mu = -1.6816 \pm 0.0008\ \mu_N$ (1999GE18, 2000NE11).
[f] $\mu = +2.6886489\ (10)$ nm (1989RA17), $Q = 40.65 \pm 0.26$ mb (1970NE05).
[g] $\mu = -0.964 \pm 0.001$ nm (1969WO03), $Q = 34.26$ mb (1969SC34: calculated).

Table 2: Some electromagnetic transitions in $A = 11$

Nucleus	$E_{\rm xi} \to E_{\rm xf}$ (MeV)	$J^\pi_{\rm i} \to J^\pi_{\rm f}$	Γ_γ (eV)	Mult.	$\Gamma_\gamma/\Gamma_{\rm W}$ (W.u.)
^{11}Be	$0.32 \to 0$	$\frac{1}{2}^- \to \frac{1}{2}^+$	$(3.97 \pm 0.35) \times 10^{-3}$	E1	0.360 ± 0.031
^{11}B	$2.125 \to 0$	$\frac{1}{2}^- \to \frac{3}{2}^-$	0.117 ± 0.004	M1	0.58 ± 0.02
	$4.445 \to 0$	$\frac{5}{2}^- \to \frac{3}{2}^-$	0.54 ± 0.05	M1	0.29 ± 0.03
		a	$(1.27 \pm 0.46) \times 10^{-2}$	E2	6.1 ± 2.2
	$5.020 \to 0$	$\frac{3}{2}^- \to \frac{3}{2}^-$	1.68 ± 0.06	M1	0.63 ± 0.02
		b	$(2.2^{+1.8}_{-1.4}) \times 10^{-3}$	E2	$0.57^{+0.49}_{-0.35}$
	$\to 2.125$	$\to \frac{1}{2}^-$	0.27 ± 0.02	M1	0.54 ± 0.03
		c	$(9.6^{+20}_{-7}) \times 10^{-3}$	E2	40^{+80}_{-9}
	$6.742 \to 0$	$\frac{7}{2}^- \to \frac{3}{2}^-$	$(2.1 \pm 0.5) \times 10^{-2}$	E2 d	1.26 ± 0.30
	$\to 4.445$	$\to \frac{5}{2}^-$	$(9.0 \pm 2.2) \times 10^{-3}$	M1	$(3.5 \pm 0.8) \times 10^{-2}$
	$6.792 \to 0$	$\frac{1}{2}^+ \to \frac{3}{2}^-$	0.26 ± 0.03	E1	$(2.5 \pm 0.3) \times 10^{-3}$
	$\to 2.125$	$\to \frac{1}{2}^-$	0.11 ± 0.02	E1	$(3.2 \pm 0.4) \times 10^{-3}$
	$\to 5.020$	$\to \frac{3}{2}^-$	$(1.56 \pm 0.23) \times 10^{-2}$	E1	$(8.3 \pm 1.2) \times 10^{-3}$
	$7.286 \to 0$	$\frac{5}{2}^+ \to \frac{3}{2}^-$	0.99 ± 0.07	E1	$(7.6 \pm 0.6) \times 10^{-3}$
		e	$(10^{+5000}_{-10}) \times 10^{-7}$	M2	≤ 0.33
	$\to 4.445$	$\to \frac{5}{2}^-$	$(6.2 \pm 1.2) \times 10^{-2}$	E1	$(8.1 \pm 1.6) \times 10^{-3}$
		f	$(4^{+24}_{-4}) \times 10^{-4}$	M2	≤ 180
	$\to 5.020$	$\to \frac{3}{2}^-$	$(8.5 \pm 1.3) \times 10^{-2}$	E1	$(2.2 \pm 0.3) \times 10^{-2}$
		g	$(7^{+77}_{-7}) \times 10^{-5}$	M2	≤ 190
	$7.978 \to 0$	$\frac{3}{2}^+ \to \frac{3}{2}^-$	0.53 ± 0.07	E1	$(3.1 \pm 0.4) \times 10^{-3}$
	$\to 2.125$	$\to \frac{1}{2}^-$	0.61 ± 0.08	E1	$(9.1 \pm 1.2) \times 10^{-3}$
	$\to 7.286$	$\to \frac{5}{2}^+$	$(9.8 \pm 1.4) \times 10^{-3}$	M1	1.4 ± 0.2
	$8.560 \to 0$	$\frac{3}{2}^- \to \frac{3}{2}^-$	0.56 ± 0.05	M1	$(4.3 \pm 0.4) \times 10^{-2}$
	$\to 2.125$	$\to \frac{1}{2}^-$	0.30 ± 0.03	M1	$(5.4 \pm 0.6) \times 10^{-2}$
	$\to 4.445$	$\to \frac{5}{2}^-$	$(5.0 \pm 1.1) \times 10^{-2}$	M1	$(3.4 \pm 0.8) \times 10^{-2}$
	$\to 5.020$	$\to \frac{3}{2}^-$	$(9.0 \pm 1.3) \times 10^{-2}$	M1	$(9.7 \pm 1.4) \times 10^{-2}$
	$8.920 \to 0$	$\frac{5}{2}^- \to \frac{3}{2}^-$	4.15 ± 0.05	M1	0.28 ± 0.03
		h	$(0^{+8}_{-0}) \times 10^{-4}$	E2	≤ 0.01
	$\to 4.445$	$\to \frac{5}{2}^-$	0.20 ± 0.02	M1	0.10 ± 0.01
		i	$(7.3 \pm 5.8) \times 10^{-4}$	E2	0.34 ± 0.27
	$9.184 \to 0$	$\frac{7}{2}^+ \to \frac{3}{2}^-$	$(1.5 \pm 0.7) \times 10^{-3}$	M2	0.32 ± 0.15
	$\to 4.445$	$\to \frac{5}{2}^-$	0.15 ± 0.05	E1	$(4.1 \pm 1.4) \times 10^{-3}$
	$\to 6.742$	$\to \frac{7}{2}^-$	$(2.1 \pm 0.8) \times 10^{-2}$	E1	$(4.3 \pm 1.6) \times 10^{-3}$
^{11}C	$2.000 \to 0$	$\frac{1}{2}^- \to \frac{3}{2}^-$	$(6.43 \pm 0.45) \times 10^{-2}$	M1	0.38 ± 0.03
	$8.105 \to 0$	$\frac{3}{2}^- \to \frac{3}{2}^-$	0.26 ± 0.06	M1	$(2.3 \pm 0.5) \times 10^{-2}$
	$\to 2.000$	$\to \frac{1}{2}^-$	$(9.1 \pm 2.3) \times 10^{-2}$	M1	$(1.9 \pm 0.5) \times 10^{-2}$
	$8.420 \to 0$	$\frac{5}{2}^- \to \frac{3}{2}^-$	3.0 ± 1.1	M1	0.25 ± 0.09

[a] $\delta = +0.158^{+0.025}_{-0.021}$ (2009RU04). See also $\delta = +0.19 \pm 0.03$ (1968BE03).
[b] $\delta = -0.036 \pm 0.013$ (2009RU04). See also $\delta = -0.03 \pm 0.05$ (1968BE03).
[c] $\delta = -0.19^{+0.10}_{-0.17}$ (2009RU04). See also $\delta = -0.05 \pm 0.20$ (1968BE03).
[d] $\delta = -0.45 \pm 0.18$. This value leads to too large a value of Γ_γ for an M3 transition (P.M. Endt, private communication with FAS).
[e] $\delta = +0.001^{+0.022}_{-0.021}$ (2009RU04).
[f] $\delta = -0.081^{+0.164}_{-0.126}$ (2009RU04).
[g] $\delta = +0.028^{+0.073}_{-0.075}$ (2009RU04).
[h] $\delta = 0.000 \pm 0.014$ (2009RU04). See also $\delta = -0.11 \pm 0.04$ (1968CO09).
[i] $\delta = -0.061^{+0.025}_{-0.022}$ (2009RU04).

^{11}He

(not illustrated)

^{11}He has not been reported: see (1980AJ01). The ground state of ^{11}He is predicted to have $J^\pi = \frac{1}{2}^+$ (1993PO11). Also see $J^\pi = \frac{5}{2}^+$ (1985PO10).

^{11}Li

(Table 11.1, Figs. 1 and 7)

$\mu = +3.6712 \pm 0.0003\ \mu_N$ (2008NE11)

$Q = -33.3 \pm 0.5$ mb (2008NE11); sign is from theory.

We accept the most precise measurement of the ^{11}Li mass $M = 11.04372361 \pm 0.00000069$ u which yields a mass excess of 40728.28 ± 0.64 keV (2008SM03: TITAN). This values differs from Audi et al. (2003AU03) by 70 keV and results in the value $S_{2n} = 369.15 \pm 0.65$ keV. Other precise mass measurements have indicated $\Delta M = 40719 \pm 5$ keV ($S_{2n} = 378 \pm 5$ keV) (2005BB01, 2008BA18, 2009GA24: MINSTRAL). Values derived from reaction Q-values, in terms of the 2-neutron separation energy, are $S_{2n} = 363 \pm 22$ keV (2009RO04), 295 ± 35 keV (1993YO07), 340 ± 50 keV (1991KO1U), 320 ± 120 keV (1988WO09) and 170 ± 80 keV (1975TH08).

The nuclear charge radius derived using $\Delta M = 40728.28 \pm 0.64$ keV is reported as, for example, $R^{\rm charge}_{\rm rms} = 2.427 \pm 0.016$ (measurement) ± 0.030 (reference) fm (2008SM03) and $R^{\rm charge}_{\rm rms} = 2.48 \pm 0.04$ (2011NO11); also see (2006PU03, 2006SA52, 2010PU01).

1. ^{11}Li(β^-)^{11}Be $\qquad Q_{\rm m} = 20.5513$

Published values of the ^{11}Li half-life are 8.99 ± 0.10 ms (1997MO35), 8.2 ± 0.2 ms (1996MU19), 8.5 ± 0.2 ms (1974RO31) [8.8 ± 1.2 ms and 9.0 ± 0.8 ms are also independently measured in (1974RO31)], 8.83 ± 0.12 ms (1981BJ01), 7.7 ± 0.6 ms (1986CU01) and 8.5 ± 1.0 ms (1969KL08). An unpublished value of 8.4 ± 0.2 ms (1995RE1M) is referenced in (2003AU03). The weighted average of all measurements is 8.75 ± 0.07 ms; however, this value has poor overlap with measurements and indicates that uncertainties are significantly underestimated in some cases. We accept the (2003AU03) value, 8.75 ± 0.14 ms, which is obtained by enlarging the uncertainty of the weighted average.

The β-decay is complex and details reported for branching ratios are ambiguous. Most of the decay populates low-lying states in ^{11}Be ($> 94\%$); all but ^{11}Be*(0, 0.32) are unstable with respect to neutron emission. At higher excitation energies the ^{11}Be states are also open to deuteron, triton,

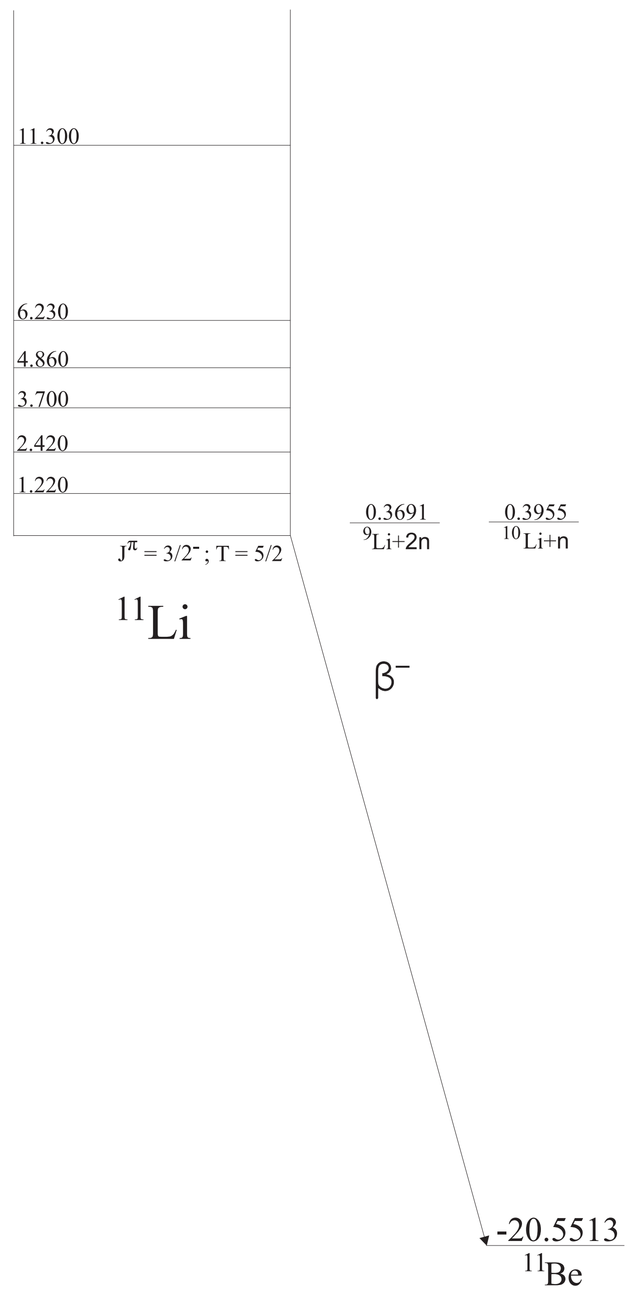

Fig. 1: Energy levels of ^{11}Li.

Table 11.1: Energy levels of ^{11}Li

E_x (MeV ± keV)	$J^\pi; T$	$T_{\frac{1}{2}}$ or Γ	Decay	Reactions
g.s.	$\frac{3}{2}^-; \frac{5}{2}$	$T_{\frac{1}{2}} = 8.75 \pm 0.14$ ms	β^-	1, 2, 4, 5, 6, 8, 9
1.220 ± 40		$\Gamma = 0.53 \pm 0.15$ MeV	n	2, 6, 7, 9, 10
2.420 ± 50		$\Gamma = 1.26 \pm 0.30$ MeV	n	2, 4, 6, 7, 9, 10
3.700 ± 130		$\Gamma < 200$ keV	n	7
4.860 ± 60		$\Gamma < 100$ keV	n	2, 4, 9
6.230 ± 60		$\Gamma < 100$ keV	n	2, 4, 9
11.300			n	2

α and ^{6}He emission. Measurements of γ-rays following ^{11}Li β-decay have provided new information on ^{10}Be and ^{11}Be states; see ^{11}Be reaction 15 and (1996MU19, 1997AO01, 1997AO04, 1997BO01, 1997BO03, 1997MO35, 1997MU06, 2003FY01, 2004FY01, 2004HI24, 2004SA46, 2005HI03, 2008MA34, 2009MA54).

The β-delayed particle emission branching ratios appear to show discrepancies. Details are given in Table 11.14. A summary suggests: β-1n $= 86.3 \pm 0.9$ %, β-2n $= 4.1 \pm 0.4$ %, β-3n $= 1.9 \pm 0.2$ % and $P_n = 100.3 \pm 1.4$ % using $P_{^{11}\mathrm{Be}^*(0.32)} = 7.7 \pm 0.8$ % (2005HI03). A precise determination of the β-d branch for low-energy deuterons is complicated by contamination from β-delayed alpha particles though published values indicate β-d $= (1.30 \pm 0.13) \times 10^{-2}$ % (2008RA23); β-t $= (0.93 \pm 0.08) \times 10^{-2}$ % (2009MA72); β-$\alpha = 1.7 \pm 0.3$ %. A theoretical analysis suggests β-(p + n) $\approx 10^{-10}$ which is roughly six orders of magnitude smaller than the β-d ratio (2010BA44).

Studies of β-decay to ^{11}Be states near $E_x = 18.5$ MeV (1996MU19, 1997BO03, 1997MU06, 2008MA34) have searched for β-delayed deuterons, which may indicate a deuteron-halo state in ^{11}Be that is analogous to the 2-neutron halo ground state of ^{11}Li; also see (1995OH02, 1995ZH31, 2004KU27, 2006BA73, 2011TU07). The β-decay shows retardation because of poor overlap of the initial and final wavefunctions (1995OT01). The s-wave and p-wave components in the 2-neutron valence wavefunctions are discussed in, for example, (1994SU12, 1996SU23, 1997BO01, 1997SU12, 2002SU16). See also (1997RI04, 2003SU04).

A β-NMR technique was used to measure the quadrupole moment of ^{11}Li (1992AR07). The measured quantity $|Q(^{11}\mathrm{Li})/Q(^9\mathrm{Li})| = 1.088 \pm 0.015$ implies $Q(^{11}\mathrm{Li}) = -33.3 \pm 0.5$ mb (2008NE11): negative sign assumed from theory. Also see $Q(^{11}\mathrm{Li}) = -31.2 \pm 4.5$ mb (1992AR07) and (1993NE08, 1994AR19).

2. ^{1}H(^{11}Li, ^{1}H)

Table 11.2: Measurements of ^{11}Li elastic and inelastic scattering

Target	^{11}Li Beam Energy (MeV/A)	Scatterings	References
^{1}H	62	elastic	(1997CO11)
^{1}H	62	elastic	(1992MO26, 1993KO11)
^{1}H	68	elastic and inelastic	(1997KO11)
^{1}H	75	elastic and inelastic	(1996KO02, 1997KO06)
^{1}H	700	elastic	(2001EG02, 2002EG02, 2003EG03)
^{1}H	700	small angle elastic	(2006DO02)
^{12}C	49	quasi-elastic	(1996ZA04)
^{12}C	50	elastic	(2003PE01)
^{12}C	60	quasi-elastic	(1992KO14)
^{28}Si	29	elastic	(1993AN13, 1993LE14, 1997PE03)

Scattering of ^{11}Li ions from ^{1}H has been measured at energies from 62 to 700 MeV/A (see Table 11.2). The elastic scattering distributions have been analyzed to evaluate possible signatures of the 2-neutron halo and to determine the nuclear size; $R^{\rm matter}_{\rm rms} = 3.62 \pm 0.19$ fm (2002EG02) and 3.71 ± 0.20 fm (2006AL16, 2006DO02). At $E(^{11}\text{Li}) = 75$ MeV/A states are reported at 0, 1.25 ± 0.15, 3.0 ± 0.2, (4.90 ± 0.25), (6.40 ± 0.25), and 11.3 ± 0.35 MeV (1996KO02, 1997KO06). Evidence for an $L = 1$ state with $E_{\rm x} = 1.3$ MeV ($\Gamma = 0.75 \pm 0.60$ MeV) is analyzed in (1992FAZV, 1997KA19, 1997KA42, 1997KO11, 1998KA33, 1999KA68, 2001CR06, 2002CR06, 2004ER07); the state is attributed to either the soft-dipole resonance or 2-neutron removal threshold effects. See (1993HI04, 1994CH07, 1996CR06) for comments on the influence of the ^{9}Li core. Also see (1991AL13, 1993AL06, 1993BE05, 1993KO44, 1993SU04, 1995SA33, 1996CR06, 1997CO11, 1997KN07, 1997KO12, 1998AN25, 1998DO16, 1999AL13, 1999CR02, 1999GR34, 2000GU19, 2000KA04, 2001CR02, 2001KI29, 2002CR02, 2002GU02, 2004AL09, 2004ER05, 2005KA21, 2005KI22, 2009HA04) and reaction ^{12}C(^{11}Li, ^{11}Li).

3. ^{1}H(^{11}Li, ^{9}Li)^{3}H $\qquad Q_{\rm m} = 8.1127$

Two techniques were used to determine the ^{1}H(^{11}Li, ^{9}Li)^{3}H reaction Q-value (2009RO04). First, a complete kinematic reconstruction of the ejectiles yielded $Q = 8.123 \pm 0.025$ MeV. Second, two-body reaction recoil energy kinematics of ejectiles at 180° yielded $Q = 8.106 \pm 0.042$ MeV. The weighted average is $Q = 8.119 \pm 0.022$ MeV, which corresponds to $S_{2\rm n} = 363 \pm 22$ keV.

At $E(^{11}\text{Li}) = 3$ MeV/A the two halo neutron transfer reaction is studied by measuring the angular distribution of ^{9}Li*(0, 2.69) (2008TA13); n-n correlations and the reaction mechanism are discussed. The population of ^{9}Li*(2.69: $J^\pi = \frac{1}{2}^-$) suggests a 1^+ or 2^+ configuration of the halo neutrons. Also see analysis of a proposed phonon mediated pairing interaction given in (2010PO08).

4. ^{10}Be(^{14}C, ^{13}N) $\qquad Q_m = -30.4465$

At $E(^{14}\text{C}) = 334.4$ MeV states corresponding to ^{11}Li*(0, 2.48 ± 0.07, 4.86 ± 0.07, 6.22 ± 0.08) were observed with $\Gamma = 1.2 \pm 0.2$, < 0.1 and < 0.1 MeV for the excited states, respectively (1995BO15, 1995VO05).

5. (a) ^{11}B(π^-, π^+) $\qquad Q_m = -32.0605$
   (b) ^{11}B(K$^-$, K$^+$) $\qquad Q_m = -32.0605$

The radius of ^{11}Li determined from pion double charge-exchange reactions on ^{11}B at $T_\pi = 164$ MeV is $R^{\text{neutrons}}_{\text{rms}} = 3.28^{+0.24}_{-0.33}$ fm, and the radius of the valence neutrons is $R^{\text{valence}}_{\text{rms}} = 5.1^{+0.6}_{-0.9}$ fm (1991GI06). See also (1992ES02, 1994LE06, 1995HA31). For reaction (b) see (1997YA11).

6. (a) ^{12}C(^{11}Li, ^{11}Li)
   (b) ^{28}Si(^{11}Li, ^{11}Li)

At $E(^{11}\text{Li}) = 246$ MeV/A, analysis of a complete three-body kinematical measurement of ^{11}Li breakup on a ^{12}C target indicates the reaction mechanism is ^{11}Li inelastic scattering to unbound states at $E_x = 1.31 \pm 0.05$ and 2.52 ± 0.27 MeV with $\Gamma = 0.26 \pm 0.24$ and 2.91 ± 0.72 MeV, respectively (2007SI24). Note: these excitation energies are adjusted upward by 70 keV to account for the change in the accepted ^{11}Li mass and 2n separation energy.

Elastic and quasi-elastic scattering of ^{11}Li ions on ^{12}C and ^{28}Si have been reported at energies from 30 to 60 MeV. Optical model analysis of the angular distributions yield parameters that are significantly different from standard parameters (reaction (a): 1992KO14, 2003PE01) and (reaction (b): 1993LE14). The effects of refraction and absorption are analyzed in (1991SA02, 1992AL05, 1993ME02, 1995DA05, 1995EV03, 1996EV01, 1997MO42, 2000MO34).

See also (1991CA14, 1991TA21, 1992TA16, 1992VE03, 1993DA09, 1993SU04, 1993TH01, 1994AL02, 1994CA07, 1994HU04, 1994SA16, 1994SK04, 1995AL01, 1995AL02, 1995AN06, 1995CO01, 1995FA17, 1995FO08, 1995GA24, 1995HU08, 1995KH11, 1996CA01, 1996KN02, 1996RA18, 1996UE01, 1997CH32, 1997KN07, 1997MO24, 1998CH18, 1998MO27, 2000BO45, 2000PA14, 2006DL01, 2011IB02) and reaction 2.

7. ^{14}C(π^-, p + d) $Q_m = 81.4370$

The kinematic reconstruction of p + d pairs resulting from the capture of stopped π^- on ^{14}C indicates population of ^{11}Li*(1.09 ± 0.07, 2.14 ± 0.12, 3.70 ± 0.13) (1998GO24) and ^{11}Li*(0.92 ± 0.15, 2.29 ± 0.25, 3.90 ± 0.25) with $\Gamma \approx 0.3$, ≈ 0.7 and < 0.2 MeV, respectively (2010GU04). There was no evidence for breakup into ^{9}Li$_{\text{g.s.}}$+ di-neutron; however in the high-excitation energy part of the spectrum the two neutron pairs corresponding to breakups via ^{9}Li*(2.69, 4.31) were strongly correlated. Note: these excitation energies are adjusted upward by 70 keV to account for the change in the accepted ^{11}Li mass and 2n separation energy.

8. ^{14}C(^{11}B, ^{11}Li) $Q_m = -37.0481$

At $E(^{11}\text{B}) = 32$ MeV the ground state of ^{11}Li was observed, and the Q-value for the reaction was measured as $Q = -37.120 \pm 0.035$ MeV (1993YO07, 1995BE30). This corresponds to $S_{2n} = 295 \pm 35$ keV. See also (1992PEZT, 1993BEZO).

9. ^{14}C(^{14}C, ^{17}F)^{11}Li $Q_m = -36.6403$

At $E(^{14}\text{C}) = 335.9$ MeV states corresponding to ^{11}Li*(0, (1.2), 2.45 ± 0.10, 4.84 ± 0.10, 6.22 ± 0.10) were populated with $\Gamma = 1.2 \pm 0.3$, < 0.1 and < 0.1 MeV for the states above 2 MeV, respectively (1995BO15, 1995VO05). These states were tentatively interpreted as excitations of the ^{9}Li core (1995VO05).

10. (a) ^{1}H, ^{9}Be, ^{12}C, ^{27}Al, Si, Pb(^{11}Li, n)
(b) ^{1}H, ^{2}H, ^{9}Be, ^{12}C, ^{27}Al, Si, Ni, ^{93}Nb, ^{181}Ta, ^{197}Au, Pb(^{11}Li, ^{9}Li)
(c) ^{1}H, ^{2}H, ^{9}Be, ^{12}C, ^{27}Al, Cu, Pb(^{11}Li, 2n + ^{9}Li)

Studies of ^{11}Li have been carried out via measurement of interaction cross sections and breakup reaction cross sections, see Table 11.3. The anomalously large cross sections observed in the studies can be related to the extent of the valence neutrons by various reaction models (1990HA15, 1990LI39, 1991MU19, 1992TA15, 1994BEZX, 1996AL13, 1996WA27, 2000EV03, 2001EG02, 2001OZ04). Also see (1990BE29, 1992OG02, 1992SA11, 1992SO15, 1992YA02, 1993BA71, 1993MA25, 1995PE19, 1996AL24, 1996BU09, 1997ES07, 1997FO04, 1997TO04, 1997ZA08, 1998BE09, 1998KN03, 1999KA67, 1999KN04, 2000GA20, 2000GA31, 2001BH02, 2003KH10, 2004CA18, 2004LO12). Measurements of the parallel and transverse momentum distributions of outgoing fragments can be related to the extent of the neutron spatial distribution using the

Table 11.3: Measurements of interaction cross sections, and (^{11}Li, n), (^{11}Li, ^{9}Li) and (^{11}Li, 2n + ^{9}Li) breakup reactions

Target	^{11}Li Beam Energy (MeV/A)	Measured	References
^{1}H, ^{2}H	800	^{9}Li $\perp$ momentum distribution	(1992TA15)
^{1}H, ^{2}H	800	interaction σ, ^{9}Li $\perp$ momentum distribution	(1992TA15)
^{9}Be, C	400	interaction σ, ^{9}Li $\perp$ momentum distribution	(1992TA15)
^{1}H	not given	$\parallel$ and $\perp$ momentum distributions	(1997KO07)
^{2}H, C	61	invariant mass spectrum	(2001PE27)
^{9}Be, Ni, ^{197}Au	30	2-neutron removal σ	(1990AN28, 1992RI01)
^{9}Be, ^{93}Nb, ^{181}Ta, ^{238}U	66	^{9}Li $\parallel$ momentum distribution	(1992OR03, 1995OR02)
^{9}Be	29.9	neutron $\parallel$ momentum distributions	(2001AX01)
^{9}Be	29.9	2 neutron-core correlations, neutron momentum distributions	(1999GR11)
C	30	2 neutron-core correlation functions	(2002MA21, 2002MA34)
C, Al, Cu, Pb	43, 75	interaction σ, 2 neutron-core dipole strength distribution	(1992INZZ, 1992SHZF, 1992SHZK)
C, Sn, Pb	80	interaction σ	(1991BL10, 1993BL04)
C, Sn, Pb	80	charge changing σ	(1992BL10)
C	264	neutron-core correlations, relative energy spectrum	(1999SC22, 2004SI12, 2007SI24)
C, ^{27}Al, Pb	280	^{9}Li $\perp$/$\parallel$ distributions	(1995HU06)
C	280, 460	n, ^{9}Li radial momentum distributions	(1995ZI03)
C, Pb	280	2 neutron-core invariant mass/dipole strength function	(1997ZI04)
^{12}C	287	2 neutron-core relative energy distribution	(1999SI08)
Si	13	2 neutron correlations, neutron energy spectrum	(2003PE19, 2004PE01, 2004PE08)
Si	11.2-15.2	neutron energy spectrum, $\perp$ momentum distribution	(1997PE14, 2004PE14)
Si	20-60	total reaction σ	(1996WA27)
Pb	30-60	total reaction σ	(2000WA23)
Pb	30	2 neutron-core correlation functions	(2000MA12)
Pb	30	2 neutron-core dipole strength function	(1996GA08, 1996IE01)
Pb	28	2 neutron correlation	(1993IE01)
Pb	28	neutron-core correlations	(1993SA21)
Pb	43	2 neutron-core dipole strength distribution	(1995IS04)
Pb	43	^{11}Li excitation spectrum	(1995SH14)
Pb	70	2 neutron-core relative energy spectrum	(2005NA40, 2006NA21, 2006NA39, 2007NA22)

uncertainty principle, but details of the reaction mechanism and final state interactions influence the measurements (1990UT01, 1992TA15, 1992ZH05, 1993BE45, 1993KO11, 1993LEZR, 1994JO04, 1995HA17, 1995OR02, 1995ZH13, 1995ZI03, 1996GA09, 1997GA04, 1997GA10, 1997OR03, 1997ZI04, 2001AX01, 2007SI24). Also see (1991ZH11, 1992BE43, 1992SH09, 1993ES02, 1993RO16, 1995BA32, 1995ES01, 1995OG04, 1996BA68, 2000BA47, 2001GA09, 2004BE45, 2009SH25). The measurements appear consistent with an $R_{\rm rms}^{\rm matter}$ size that is greater than 3 fm and a valence neutron "halo" that extends to $R_{\rm rms}^{\rm valence} = 5$ fm or more. Comments on the interference effects between nuclear and Coulomb breakup components are given in (1990BE29, 1993BA71, 1993EV02, 1993IV01, 1996DA03, 2000GA31).

The complete kinematical detection of ^{9}Li + 2n following Coulomb breakup on high-Z targets permits a determination of the dipole strength distribution in the region just above the neutron binding threshold. At $E(^{11}\text{Li}) = 280$ MeV/A (1997ZI04) the excitation strength function was decomposed into two Gaussian components; analysis indicates peaks at $E_{\rm x} = 1.1 \pm 0.1$ and 2.5 ± 0.2 MeV with $\Gamma = 0.7 \pm 0.2$ and 2.1 ± 0.6 MeV, respectively. Note: these excitation energies are adjusted upward by 70 keV to account for the change in the accepted ^{11}Li mass and 2n separation energy. The two peaks, which were assumed to have E1 character, carried 1.2 ± 0.3 % and 7 ± 2 % of the energy weighted sum rule. At $E(^{11}\text{Li}) = 30$ MeV/A (1996GA08, 1996IE01) report that the dipole strength function is consistent with a resonance at $E_{\rm res} = 0.7$ MeV, $\Gamma = 0.8$ MeV, but considering Coulomb re-acceleration of the charged particles in the Z-field of the target indicates a negligible lifetime for any resonant state and presents a contradiction to any soft-dipole resonant state behavior (2001GA22). A measurement of the relative three-body breakup energy at $E(^{11}\text{Li}) \approx 70$ MeV/A (2005NA40, 2006NA21, 2006NA39, 2007NA22) showed significant strength at low energies, peaking at $E_{\rm rel} \sim 0.3$ MeV. This corresponds to $E_{\rm x} \sim 0.6$ MeV with $\Gamma \sim 0.6$ MeV; the corresponding strength for $0 \leq E_{\rm x} \leq 3$ MeV is $B(\text{E1}) = 1.42 \pm 0.18\ e^2 \cdot \text{fm}^2$. Also see (1990BE04, 1990BE07, 1990HA33, 1990HO26, 1990SA41, 1990SU16, 1991FA09, 1991HO06, 1991HU03, 1991TE01, 1992BA63, 1992BE40, 1992CA20, 1992ES01, 1992SA10, 1992SU06, 1993BE05, 1993CA34, 1993GO17, 1993ZHZV, 1994TY02, 1995FU12, 1995RO13, 1996CA12, 1997BO08, 1998CO11, 1998CO22, 1999GA08, 1999KA68, 2000FO09, 2001FI14, 2001SA79, 2003MY03, 2003MY04, 2004ER05, 2004ER07, 2004MY01, 2006AO02, 2007BE58, 2007ES04, 2007MY04, 2007SA41, 2009HA30).

A simple interpretation of ^{11}Li describes the system as a ^{9}Li core with the two valence neutrons bound in a simple potential (1987HA30). In a search for possible evidence of a di-neutron, the data have been evaluated with an emphasis on measurements of the correlation of the valence neutrons after breakup (1992BE40, 1995IS04, 1995SH14, 1996CH38, 1996GA08, 1996IE01, 1997KU07, 1997LU08, 1997ZI04, 1998GA37, 2000EV03, 2000EV04, 2000MA12, 2001DA17, 2004PE01, 2004PE08, 2004WE05, 2009HA37, 2010HA10). Further studies emphasize the determination of s-wave to p-wave contributions for the valence neutron wavefunctions and implications for ^{10}Li (1992ZH05, 1995ZI03, 1996GA09, 1997GA04, 1999SI08, 2003MY03, 2004MY01). Overviews of the experimental work can be found in (1993KO11, 1994JO04, 1997OR03, 2001EG02, 2001OZ04, 2002BR01, 2002WA08). In all cases the emitted neutron pairs show no strong correlations, arguing against the existence of a di-neutron in ^{11}Li.

^{11}Be

(Table 11.4, Figs. 2 and 7)

$\mu = -1.6814 \pm 0.0004\ \mu_N$ from weighted average of $\mu = -1.6813 \pm 0.0005\ \mu_N$ (2009NO02) and $\mu = -1.6816 \pm 0.0008\ \mu_N$ (1999GE18, 2000NE11), also see (2009FO01).
$R^{\text{charge}}_{\text{rms}} = 2.463 \pm 0.015$ fm from isotope shift measurements (2009NO02, 2010ZA02). Also see (2010PU01).

We accept the most precise measurement of the ^{11}Be mass $M = 11.02166155 \pm 0.00000062$ u which yields a mass excess of 20177.60 ± 0.58 keV (2009RI03: TITAN). Other precise measurements have indicated $\Delta M = 20171 \pm 4$ keV (2005BB01: MINSTRAL), $\Delta M = 20170.1 \pm 3.3$ keV (2008BA18: MISTRAL) and $\Delta M = 20174.8 \pm 3.6$ keV (2009LU10: MISTRAL). These values compare with values measured in ^{9}Be(t, p): $\Delta M = 20175 \pm 15$ keV (1962PU01) and ^{10}Be(d, p): $\Delta M = 20174 \pm 7$ keV (1970GO11).

1. ^{11}Be(β^-)^{11}B $\qquad Q_m = 11.5092$

The half-life of ^{11}Be is 13.76 ± 0.07 sec; this is obtained from a weighted average of 13.81 ± 0.08 sec (1970AL21) and 13.57 ± 0.15 sec (1959WI49). The value 14.1 ± 0.3 sec has been reported by (1958NU40) who first identified ^{11}Be in the ^{11}B(n, p) reaction. Using $T_{1/2} = 13.76 \pm 0.07$ sec and the branching ratio given in Table 11.29 gives $\log ft = 6.826 \pm 0.016$ for decay to the ^{11}B ground state; see ^{11}B reaction 30 for further discussion on ^{11}B levels populated in ^{11}Be decay. The β-delayed alpha emission probability is 3.1 ± 0.4 % (1982MI08); see also (2011RA16). A discussion of β-delayed proton emission is given in (2011BA01) where a branching ratio of $\approx 3 \times 10^{-8}$ is estimated.

2. (a) ^{1}H(^{11}Li, ^{11}Be) $\qquad Q_m = 19.7689$
(b) ^{2}H(^{11}Li, ^{11}Be) $\qquad Q_m = 17.5443$

Complete kinematics were measured for charge exchange reactions on ^{1}H and ^{2}H targets at $E(^{11}\text{Li}) = 64$ MeV/A (1997SH12, 1997TE07, 1998SH06). The $^{11}\text{Li}_{\text{g.s.}}$ IAS state was identified at ^{11}Be*(21.16 ± 0.02) with $\Gamma = 0.49 \pm 0.07$ MeV; this gives $\Delta E_{\text{Coulomb}} = 1.32 \pm 0.02$ MeV (1997TE07, 1998SH06). An R-matrix analysis indicates the state decays mainly to ^{9}Li + p + n via the ^{10}Li + p channel. See (1991SU16) for more discussion on the isobaric analogue states of $A = 11$ nuclei.

3. ^{1}H(^{11}Be, ^{10}Be)d $\qquad Q_m = 1.7229$

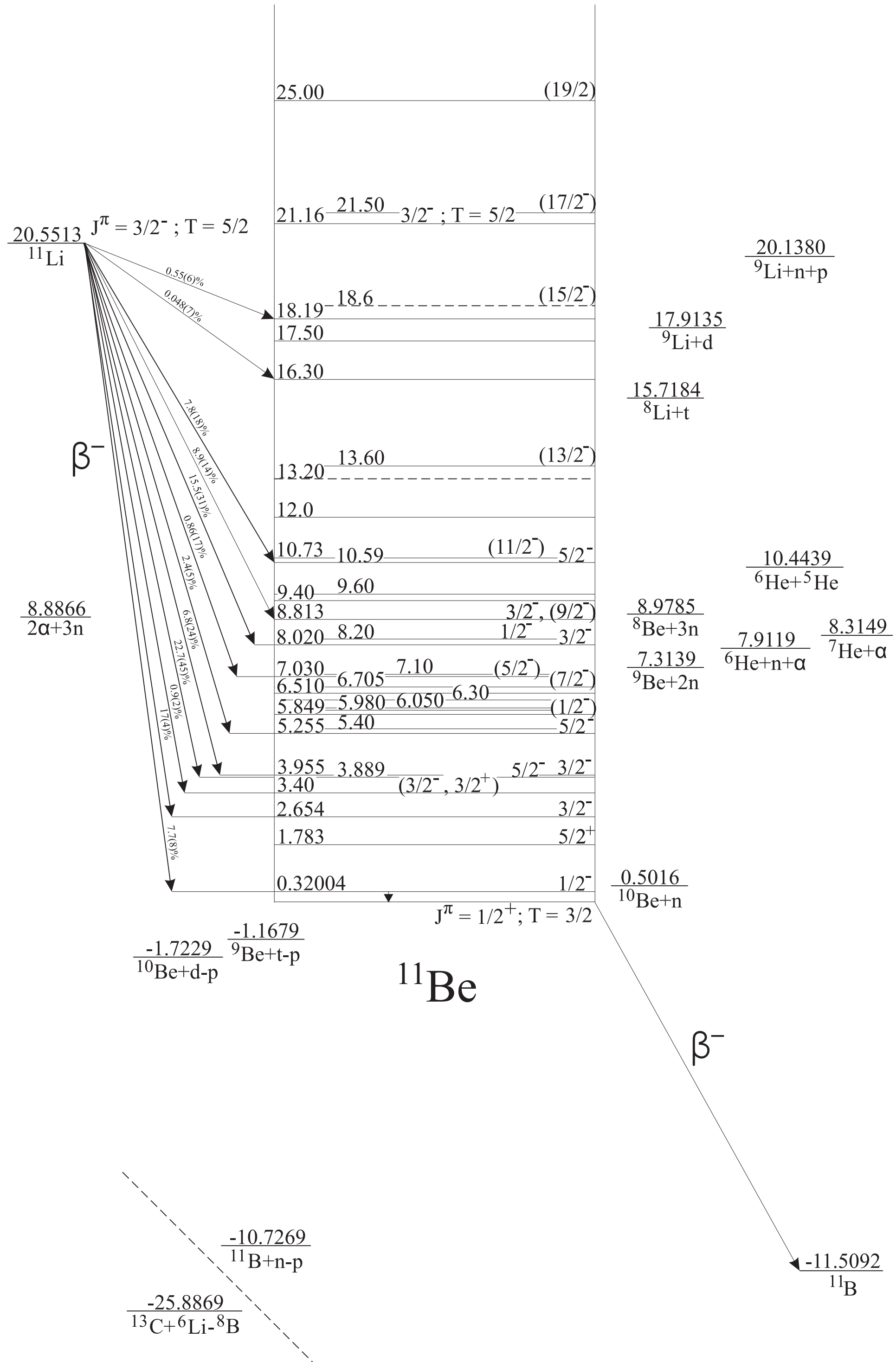

Fig. 2: Energy levels of ^{11}Be. For notation see Fig. 4.

Table 11.4: Energy levels of ^{11}Be

E_x (MeV ± keV)	$J^\pi; T$	$T_{\frac{1}{2}}$ or Γ_{cm} (keV)	Decay	Reactions
0	$\frac{1}{2}^+; \frac{3}{2}$	$T_{\frac{1}{2}} = 13.76 \pm 0.07$ s	β^-	1, 3, 4, 5, 6, 8, 9, 10, 12, 14, 16, 17, 19, 23, 24, 25, 26, 27, 28, 30, 31, 32
0.32004 ± 0.1	$\frac{1}{2}^-$	$T_{\frac{1}{2}} = 115 \pm 10$ fs	γ	4, 5, 6, 8, 9, 10, 14, 15, 16, 17, 19, 21, 22, 23, 26, 28, 29, 30, 33
1.783 ± 4	$\frac{5}{2}^+$	$\Gamma = 100 \pm 10$	n	4, 5, 6, 9, 10, 14, 23, 26, 28
2.654 ± 10	$\frac{3}{2}^-$ [a]	206 ± 8	n	5, 6, 9, 10, 15, 16, 21, 22, 23, 28, 29
3.40 ± 6	$(\frac{3}{2}^-, \frac{3}{2}^+)$ [c]	122 ± 8	n	5, 9, (10), 15, 23, 26
3.889 ± 1	$\frac{5}{2}^-$ [c]	< 8	n	5, (6), 10, 11, 15, 21, 22, 23, (28), (29)
3.955 ± 1	$\frac{3}{2}^-$ [c]	10 ± 5	n	5, (6), 9, 10, 11, 15, 23, (28), (29)
5.255 ± 3	$\frac{5}{2}^-$ [a]	45 ± 10	n	5, 6, 9, 10, 15, 16
5.40			(n)	(21)
5.849 ± 10	$(\frac{1}{2}^-)$	139 ± 17	(n)	5
5.980 ± 40			(n)	9, 10
6.050 ± 40		320 ± 40	(n)	23
6.30			(n)	21
6.510 ± 50		120 ± 50	(n)	5
6.705 ± 21	$(\frac{7}{2}^-)$ [a, b]	40 ± 20	n	5, 6, 9, 10, 16
7.030 ± 50	$(\frac{5}{2}^-)$	300 ± 100	n	5, 15
7.10			(n)	10, (21)
8.020 ± 20	$\frac{3}{2}^-$	230 ± 55	n	15
8.20	$\frac{1}{2}^-$		(n)	21
8.813 ± 25	$\frac{3}{2}^-$, $(\frac{9}{2}^-$ [b]$)$	200 ± 50	n	5, 6, 9, 10, 15
9.40 ± 500		7000 ± 500	(n)	20, 21, 22, 23
9.60	[a]		(n)	9, 16, 21
10.59 ± 50	$\frac{5}{2}^-$	210 ± 40	n, α	5, 6, 15
10.73	$(\frac{11}{2}^-)$ [b]		(n)	9, 10
12.0	[a]		(n)	9, 16, 20, 21
(13.20)			(n)	(21)
13.60	$(\frac{13}{2}^-)$ [b]		(n)	9
16.30 ± 100	[a]	700 ± 100	n, α	15, 16
17.50	[a]		(n)	16

Table 11.4: Energy Levels of ^{11}Be (continued)

E_x (MeV ± keV)	$J^\pi; T$	$T_{\frac{1}{2}}$ or Γ_{cm} (keV)	Decay	Reactions
18.19 ± 140		1500 ± 400	n, d, t, α	15
(18.60)	$(\frac{15}{2}^-)$ [b]		(n)	9
21.16 ± 20	$\frac{3}{2}^-; \frac{5}{2}$	490 ± 70	(n, p)	2
21.50	$(\frac{17}{2}^-)$ [b]		(n)	9
25.0	$(\frac{19}{2})$ [b]		(n)	9

[a] Alternate J^π values for these levels are deduced in reaction ^{11}B(e, e$'\pi^+$).

[b] A speculative J^π is assumed based on a systematic level spacing analysis considering that the $K = \frac{3}{2}$ molecular rotational band is based on ^{11}Be*(3.96, 5.25, 6.70, etc.).

[c] From $^{11}\vec{\text{Li}}$ β-decay study (2005HI03). For ^{11}Be*(3.41) (2005HI03) deduce $J^\pi = (\frac{3}{2}^-)$; also see Pb(^{11}Be, ^{10}Be + n) (2004FU29) who deduce $J^\pi = \frac{3}{2}^+$ for ^{11}Be*(3.41).

The ^{11}Be(p, d)^{10}Be reaction was measured in inverse kinematics using an $E(^{11}\text{Be}) = 35.3$ MeV/A beam (1999FO09, 1999WI04, 2001WI05). The ^{10}Be*(0, 3.4, 6(multiplet)) states are populated. Coupled Channels DWBA analysis of the results indicate 16% core excitations for $^{11}\text{Be}_{\text{g.s.}}$, i.e. [84% $(0^+ \otimes s_{1/2}) + 16\% (2^+ \otimes d_{5/2})$]. See also (2000GO39, 2005TS03).

4. (a) ^{1}H(^{11}Be, ^{11}Be)^{1}H
   (b) ^{1}H(^{11}Be, ^{11}Be$'$)^{1}H

At $E(^{11}\text{Be}) = 63.7$ MeV/A elastic and inelastic scattering cross sections were measured up to $E_x = 7$ MeV (2004SH28). The ^{11}Be*$(0 + 0.32)$ states were unresolved; analysis of quasi-elastic scattering data in a Continuum Discretized Coupled Channels (CDCC) model reproduces the observations. Higher lying excited states are unbound, though measurement of the p + ^{10}Be particles permitted a construction of the ^{11}Be* scattering cross sections. A prominent peak corresponding to ^{11}Be*(1.78 [$J^\pi = \frac{5}{2}^+$]) is observed, other unresolved states at ^{11}Be*(2.67, 3.41, 3.89, 3.96, 5.25) were included in the CDCC analysis. The calculations underpredict the inelastic data. It is suggested that ^{10}Be core deformation and excitations play a sizeable role in the ^{11}Be breakup process (2004SH28, 2007SU11, 2007SU17, 2008KE01). See (1997CO04, 1997CO11) for elastic scattering measurements at $E(^{11}\text{Be}) = 49.3$ MeV/A. Also see (2007CR04) for a theoretical analysis at $E_p = 100$ to 200 MeV.

5. ^{9}Be(t, p)^{11}Be $\qquad Q_m = -1.1679$

Table 11.5: ^{11}Be levels observed in ^{9}Be(t, p)

E_x [a] (MeV ± keV)	Γ_{lab} [a] (keV)	E_x [b] (MeV ± keV)	Γ [b] (keV)	E_x [c] (MeV ± keV)	Γ [c] (keV)	L [c]	J^{π} [c]
0		0		0		1	$\frac{1}{2}^+$
0.3198 ± 0.2 [d]		0.322 ± 10		0.320 ± 2		2	$\frac{1}{2}^-$
1.780 ± 20	110 ± 15	1.790 ± 20	130 ± 25	1.784 ± 4	104 ± 21	$1+3$	$\frac{5}{2}^+$
2.700 ± 25	250 ± 20	2.680 ± 30	250 ± 50	2.642 ± 9	228 ± 21	$0+2$	$\frac{3}{2}^-$
3.410 ± 25	250 ± 20	3.410 ± 30	145 ± 30	3.398 ± 6	104 ± 17	0	$\frac{3}{2}^-$
3.890 ± 20	< 10	3.890 ± 30	≤ 10	3.888 ± 1		1	$\frac{3}{2}^+$
3.960 ± 20	< 10	3.960 ± 30	15 ± 5	3.955 ± 1		2	$\frac{3}{2}^-$
		5.250 ± 30	45 ± 10	5.255 ± 3		2	$\frac{5}{2}^-$
		(5.860)	≈ 300	5.849 ± 10	139 ± 17	1	$(\frac{1}{2}^-)$ [e]
		6.510 ± 50	120 ± 50				
		6.720 ± 30	40 ± 20				
		7.030 ± 50	300 ± 100				
		8.840 ± 50	200 ± 50				
		10.590 ± 50 [f]	210 ± 40 [f]				

[a] (1962PU01): $E_t = 14$ MeV.
[b] (1972AJ01): $E_t = 20$ MeV.
[c] (1990LI19): $E_t = 15$ MeV, L and J^{π} from DWBA analysis.
[d] (1971HA25).
[e] $E_x = 5.850$ and $J^{\pi} = \frac{1}{2}^+$ [^{10}B(2^+) $\otimes$ ($d_{5/2}$)] was also evaluated, but a $J^{\pi} = \frac{1}{2}^-$ solution where the configuration of the ^{11}Be*(5.85) level [^{9}Be$_{g.s.}$ $\otimes$ $(sd)^2_{2^+}$] is mixed with ^{11}Be*(0.32) is preferred.
[f] (1978AJ02): $E_t = 23$ MeV.

Proton groups have been observed to the states displayed in Table 11.5. The $E = 320.04 \pm 0.10$ keV γ-ray from the deexcitation of ^{11}Be*(0.32) was analyzed using the DSAM technique which indicates the mean lifetime $\tau_{\rm m} = 166 \pm 15$ fs (1983MI08). This corresponds to $B({\rm E1}) = 0.36 \pm 0.03$ W.u.. Also see (1997VO06).

6. ^{9}Be(^{6}He, ^{11}Be)^{4}He $\qquad Q_{\rm m} = 6.3392$

At $E(^{6}{\rm He}) = 16.8$ MeV angular distributions of α particles and complex α + fragment events were measured (2010MA29). ^{11}Be*(0, 0.32, 1.78, 2.69, ≈ 3.9, 5.24, 6.71, 8.82, 10.6) were populated. Analysis of the $\alpha + {}^{6}$He and $\alpha + {}^{9,\,10}$Be data suggests that ^{11}Be*(10.6) likely n-decays to ^{10}Be excited states which subsequently decay to either $\alpha + {}^{6}$He or n + ^{9}Be.

At $E(^{6}{\rm He}) = 25$ MeV/A angular distributions of ^{10,11}Be ions produced in the 1-neutron and 2-neutron transfer reactions were measured. The 1-neutron transfer reaction cross section was found to be larger than the 2-neutron transfer cross section, which is surprising since ^{6}He is a 2-neutron halo nucleus (2003GE05). Also see ^{15}C in (1970AJ04).

7. (a) ^{1}H, ^{9}Be, C, ^{27}Al, ^{28}Si, Ti, Nb, Ta, ^{197}Au, ^{208}Pb, ^{238}U(^{11}Be, n)
(b) ^{1}H, ^{9}Be, C, ^{27}Al, ^{28}Si, Ti, Nb, Ta, ^{197}Au, ^{208}Pb, ^{238}U(^{11}Be, ^{10}Be)

Studies of ^{11}Be have been carried out via measurement of interaction cross sections and one neutron breakup cross sections, see Table 11.6. The anomalously large cross sections observed can be related to the extent of the valence neutrons by various reaction models (1990LI39, 1991MU19, 1993FE02, 1993FE12, 1993MA25, 1995PE19, 1996AL13, 1997FO04, 1997YA07, 1999SE15, 2000BH09, 2000CA33, 2001LE21, 2002BR01, 2003CA07, 2006BH01). Measurements of the parallel and transverse momentum distributions of outgoing fragments can also be related to the extent of the neutron spatial distribution using the uncertainty principle, but details of the reaction mechanism and final state interactions influence the measurements (1992BE43, 1993BA64, 1994PO15, 1994SA30, 1995BA32, 1995ZA12, 1995ZA13, 1996BA40, 1996BA68, 1996CH38, 1996ES01, 1996HA29, 1996HE23, 1997RI04, 1998BA45, 1998BO01, 1998BO28, 1999FO13, 2000PA53, 2001ES05, 2003AB05, 2003CH65, 2004BE45). The measurements appear consistent with an $R^{\rm matter}_{\rm rms}$ size of 2.73 ± 0.05 fm (2001OZ04) and a valence neutron "halo" that extends to $R^{\rm halo}_{\rm rms} = 5.66 \pm 0.20$ fm (1988TA10). Overviews of the experimental work can be found in (1993KO11, 1994JO04, 1994MU14, 1995HA17, 1995JO09, 1997OR03, 1999KA67, 1999KN04, 2001OZ04, 2002BR01, 2005AU09). Also see theoretical analysis of diffraction dissociation, absorption and other relevant breakup mechanism effects (1993EV02, 1995EV01, 1996EV01, 1996VO04, 1999TO07, 2000BA47, 2000BO04, 2002CH60, 2002FA02, 2002MA26, 2002YA19, 2004AB29, 2004BO04, 2004CA50, 2004UE04, 2004WE04, 2005BA54, 2005BA72, 2005HO28, 2006MO03, 2006SU05).

Table 11.6: Measurements of interaction cross sections, and (^{11}Be, n) and (^{11}Be, ^{10}Be) breakup reactions

Target	^{11}Be Beam Energy (MeV/A)	Measured	Reference
^{1}H	$\approx$ 35-81	reaction σ	(2002DE29)
^{12}C, ^{27}Al	33	reaction σ and fragmentation σ	(1991FU10)
^{9}Be, C, ^{27}Al	800	interaction σ	(1988TA10)
^{9}Be, Ti, ^{197}Au	41	neutron angular distributions	(1993AN05, 1994AN12)
C	30.9, 41.7	neutron removal σ and cluster breakup σ	(2004AS02, 2004FR20)
^{9}Be, ^{93}Nb, ^{181}Ta, ^{238}U	63	$P_{\parallel}$ distribution	(1995KE02)
^{9}Be	60	$P_{\parallel}$ distribution and ^{10}Be levels populated	(2000AU02, 2002TO18)
^{9}Be	38.5	neutron $P_{\parallel}$ distribution	(2001AX01)
^{9}Be	29.9	neutron angular distribution and energy spectrum	(1999GR11)
^{9}Be, ^{197}Au	41	^{10}Be fragment energy and angle distribution, and γ-ray coincidence	(1998BU11)
^{28}Si	30-60	reaction σ and neutron removal σ	(2001WA40)
^{28}Si	$\leq$ 60	breakup σ, neutron angular momentum distribution and ^{10}Be fragment energy and angle distribution	(1999NE04, 1999SK06)
Pb, C	68	n + ^{10}Be relative energy spectra	(2002FU20, 2003NA37, 2004FU29, 2004NA11, 2004NA21, 2005NA40)
Pb	72	n + ^{10}Be relative energy, Dipole strength distribution	(1994NA22, 1995NA11)
Pb	$\approx$ 520 MeV	CD σ, Dipole excitation function, and ^{11}Be$_{\rm g.s.}$ spectroscopic factors	(2001AU04, 2003PA31, 2004PA08, 2004PA23)

The complete kinematical detection of ^{10}Be + n following breakup on high-Z targets provides a determination of the dipole strength distribution in the region just above the neutron binding threshold, but the nuclear breakup and higher-order Coulomb breakup components must be understood. See Table 11.6 for a summary of ^{11}Be breakup measurements.

At $E(^{11}\text{Be}) = 68$ MeV/A the nuclear and Coulomb breakup contributions on carbon and lead targets are analyzed by measuring the complete kinematics in ^{11}Be breakup (2004FU29). On the $^{\rm nat}$C target, the ^{11}Be*(1.78, 3.41) states are found to participate in the breakup reaction with $L = 2$ angular distributions; this implies $J^{\pi} = \frac{5}{2}^{+}$ and $\frac{3}{2}^{+}$ for these states, respectively. Further analysis and comparison with the breakup data from the ^{208}Pb target implies that at very forward angles the E1 Coulomb direct breakup mechanism is dominant. The dipole transition spectrum shows a strong peak near the neutron separation threshold, which is associated with the low neutron binding energy. The Pb target Coulomb breakup data with $\theta(^{11}\text{Be}) \leq 1.3°$ were analyzed using ECIS; a neutron spectroscopic factor $S = 0.72 \pm 0.04$ and $\Sigma_{E_x<4\ \mathrm{MeV}} B(\mathrm{E1}) = 1.05 \pm 0.06\ e^2 \cdot \mathrm{fm}^2$ were deduced. At $E(^{11}\mathrm{Be}) = 520$ MeV/A a similar experiment was carried out (2003PA31); ^{10}Be + breakup neutrons and γ-rays from ^{10}Be*(3.37, 5.96, 6.26) were found in coincidence. In this case, $S = 0.61 \pm 0.05$, $\Sigma_{E_x<4\ \mathrm{MeV}} B(\mathrm{E1}) = 0.83 \pm 0.06\ e^2 \cdot \mathrm{fm}^2$ and $\Sigma_{E_x<6.1\ \mathrm{MeV}} B(\mathrm{E1}) = 0.90 \pm 0.06\ e^2 \cdot \mathrm{fm}^2$ are deduced.

See (1991HO06, 1994KI12, 1995BE26, 1995ES01, 1995IS02, 1995IS04, 1995SA32, 1996KA06, 1996KI04, 1997DE07, 1998BA45, 1999BA29, 1999DA02, 1999ME12, 2000CH27, 2001ME18, 2001SH21, 2001TY01, 2001TY02, 2002BA60, 2002CH60, 2002FA02, 2002MA26, 2002SU34, 2002ZA10, 2003BE54, 2003CA01, 2003CA25, 2003MA20, 2003TA06, 2004AB29, 2004ZA12, 2005BA72, 2005CA22, 2005IB01, 2006CA06, 2006GO05, 2007BL02, 2010OG02, 2011HA41) for theoretical analysis of the Coulomb dissociation mechanism and other issues related to the near threshold dipole strength distribution.

8. ^{9}Be(^{12}Be, ^{11}Be + γ) $\qquad Q_\mathrm{m} = 3.6404$

Spectroscopic factors of $S = 0.42 \pm 0.06$ and 0.37 ± 0.06 were deduced for ^{11}Be(0 [$J^\pi = \frac{1}{2}^+$]) and ^{11}Be*(0.32 [$J^\pi = \frac{1}{2}^-$]), respectively, from measurements at $E(^{12}\mathrm{Be}) = 78$ MeV/A (2000NA23). The large $\mathrm{s}_{1/2}$ component in the ^{12}Be ground state appears to indicate that, in this case, $N = 8$ is not a good closed shell.

A beam of 90 MeV/A ^{12}Be ions impinged on a ^{9}Be target where 1-neutron knockout reactions populated ^{11}Be*(0, 1.778, 2.690, 3.949) (2011PE13). A kinematic energy reconstruction of the ^{10}Be + n products permitted an analysis of these states; decay modes and spectroscopic factors were analyzed and discussed. The state at 3949 keV decays evenly via neutron emission to the ^{10}Be*(0, 3.896) states, and the measured $S_\mathrm{n} = 80 \pm 2$ keV for feeding of the ^{10}Be*(3.896) state implies $E_\mathrm{x} = 3949 \pm 2$ keV ($\Gamma < 40$ keV).

9. (a) ^{9}Be(^{13}C, ^{11}C) $\qquad Q_\mathrm{m} = -16.3541$
(b) ^{9}Be(^{14}N, ^{12}N) $\qquad Q_\mathrm{m} = -23.3034$
(c) ^{9}Be(^{15}N, ^{13}N) $\qquad Q_\mathrm{m} = -14.0728$

At $E(^{13}\mathrm{C}) = 379$ MeV, ^{11}Be*(0, 0.32, 1.78, 2.69, 3.96, 5.26, 5.90, 6.72, 8.82, (9.3), 10.73, 11.6, 13.6, 18.6, 21.5, 25.0) are populated (1998BO38, 1999BO26, 2002BO16, 2003BO24, 2003BO38). It is suggested, based on level spacing systematics, that the $K = \frac{3}{2}^-$ molecular rotational band is built on ^{11}Be*(3.96 [$J^\pi = \frac{3}{2}^-$], 5.25 [$\frac{5}{2}^-$], 6.72 [$\frac{7}{2}^-$], 8.82 [$\frac{9}{2}^-$], 10.80 [$\frac{11}{2}^-$], 13.8 [$\frac{13}{2}^-$], 18.6 [$\frac{15}{2}^-$], 21.6 [$\frac{17}{2}^-$], 25.0 [$\frac{19}{2}^-$]). The moment of inertia deduced for the rotational system is consistent with a 2α-3n structure with large deformation. Also see (1997VO06).

Measurements for reaction (b) at $E(^{14}\mathrm{N}) = 217$ MeV (2002BO16) populated ^{11}Be*(0, 0.32, 1.78, 2.69, 3.42, 3.92, 5.25, 5.98(4), 6.72, 8.82, 10.80, (11.75), 14.0) and reaction (c) at $E(^{15}\mathrm{N}) =$

240 MeV (2002BO16) confirmed the presence of three new states at ^{11}Be*(10.8, 13.8, 21.6) that were reported in reaction (a).

10. (a) ^{9}Be(^{16}O, ^{14}O) $Q_{\rm m} = -21.5732$
(b) ^{10}Be(^{14}N, ^{13}N) $Q_{\rm m} = -10.0518$
(c) ^{13}C(^{12}C, ^{14}O) $Q_{\rm m} = -25.0596$

An experiment measuring reaction (a) at $E = 234$ MeV was configured to detect the ^{14}O ejectile momenta in coincidence with the ^{10}Be decay recoil from ^{11}Be* neutron decay in order to determine neutron decay widths for excited ^{11}Be states (2009HA01, 2010FR03). Neutron unbound levels at ^{11}Be*(1.78, 2.69, (3.41), 3.96, 5.24, 5.96, 6.72, 7.10, 8.82, 10.70) are observed and decay branching ratios are reported, see Table 11.7. The branching ratios are in poor agreement with those indicated in ^{11}Li decay to ^{11}Be states. A rotational band based on ^{11}Be*(3.96 [$J^{\pi} = \frac{3}{2}^{-}$], 5.24 [$\frac{5}{2}^{-}$], 6.72 [$\frac{7}{2}^{-}$]) is suggested with further indications that the $E_{\rm x} = 8.82$ MeV may also form a $\frac{3}{2}^{-}$ molecular cluster bandhead.

The angular distributions of $E_{\rm x} < 4$ MeV states populated in reactions (a) at $E(^{16}{\rm O}) = 233.5$ MeV: ^{11}Be*(0.32, 1.78, 3.96), (b) at $E(^{14}{\rm N}) = 217$ MeV: ^{11}Be*(0, 0.32, 1.78, 2.69, 3.41) and (c) at $E(^{12}{\rm C}) = 230.7$ MeV: ^{11}Be*(0.32, 2.7, 3.90) (2003BO24, 2003BO38, 2004BO12) are analyzed in an attempt to resolve the discrepancy in the J^{π} assignments for ^{11}Be*(3.41, 3.90, 3.96). Reactions (a) and (c) have a common property which is that the angular momentum transferred to the target is $l_{\rm t} = 0$. In the 2-neutron transfer reaction (a) the angular distribution of ^{11}Be*(3.96) is consistent with $l_{\rm t} = 2$, 0, which is consistent with $J^{\pi} = \frac{3}{2}^{-}$ and in agreement with the results from reaction ^{9}Be(t, p) (1990LI19). In the two-proton pickup reaction (c) the angular distributions of ^{11}Be*(2.7, 3.90) are in-phase, which indicates similar (negative) parity for the two states. Systematics described, for example, in (2001MI29) indicate that $\frac{3}{2}^{+}$ and $\frac{5}{2}^{-}$ states should be present near this excitation energy leading to conjecture that ^{11}Be*(3.41, 3.90) have $J^{\pi} = \frac{3}{2}^{+}$ and $\frac{5}{2}^{-}$, respectively (2003BO24, 2003BO38, 2004BO12). See Table 11.8 for an overview of analysis of J^{π} values in this region, also see (2005FO01, 2011FO07).

11. ^{9}Be(^{48}Ca, ^{11}Be) $Q_{\rm m} = 34.3113$

Neutron unbound states in ^{11}Be were populated in the fragmentation of ^{48}Ca on a ^{9}Be target at $E(^{48}{\rm Ca}) = 60$ MeV/A (2008CH07). The excited states near 4 MeV were observed in the kinematic reconstruction of coincident neutron plus ^{10}Be ejectiles; the decays populated ^{10}Be*(3.368). A fit including two known $\Gamma < 10$ keV resonances at ^{11}Be*(3.887, 3.956), from $E_{\rm res} = 19 \pm 15$ keV and 84 ± 15 keV, reproduced the data; however the data were also reasonably well fit with a single resonance at $E_{\rm res} = 30$ keV with $\Gamma = 65$ keV.

Table 11.7: Branching ratios for the neutron decay of ^{11}Be states populated in ^{9}Be(^{16}O, ^{14}O) (2009HA01)

E_x(^{11}Be) (MeV)	J^π	Branching ratios (%) to n + ^{10}Be*			
		0_1^+	2_1^+	6-MeV group	3_1^-, 2_3^+
1.78	$\frac{5}{2}^+$	105 ± 14			
3.96	$\frac{3}{2}^-$	48 ± 6	54 ± 7		
5.24	$\frac{5}{2}^-$	< 27	81 ± 16		
5.96	$(\geq \frac{5}{2})$	< 13	97 ± 16		
6.72	$(\geq \frac{7}{2})$	< 18	88 ± 15	9 ± 4	
8.82		< 15	< 6	52 ± 16	59 ± 28

Table 11.8: Summary of analyses of ^{11}Be*(3.41, 3.89, 3.96) J^π values

E_x (MeV)	(1990LI19)	(2001MI29)	(2003BO24, 2003BO38, 2004BO12)	(2004FU29)	(2005HI03)
3.41	$\frac{3}{2}^-$	$\frac{3}{2}^-$	$\frac{3}{2}^+$	$(\frac{3}{2}^+, \frac{5}{2}^+)$	$(\frac{3}{2}^-)$
3.89	$\frac{3}{2}^+$	$\frac{3}{2}^+$	$\frac{5}{2}^-$		$\frac{5}{2}^-$
3.96	$\frac{3}{2}^-$	$\frac{5}{2}^-$	$\frac{3}{2}^-$		$\frac{3}{2}^-$

Table 11.9: ^{10}Be and ^{11}Be γ-ray transition intensities (per 100 decays) observed following ^{11}Li β-decay: measurements prior to DBLA analysis

E_γ (keV)	^{10}Be($E_i \to E_f$)	I [a]	I [b]	I [c]	I [d]	I [e]
219.2	$6180.3 \to 5961.1$	0.78 ± 0.06	0.55 ± 0.10	0.5		0.95 ± 0.35
320.0	^{11}Be*($0.320 \to 0$)	7.8 ± 0.8	6.3 ± 0.6	7.6 ± 0.8	9.2 ± 0.7	5.2 ± 1.4
2590.3	$5958.4 \to 3368.0$	6 ± 1	8.0 ± 1.2	8.5		3.5 ± 1.0
2592.7	$5961.1 \to 3368.0$					
2811.8	$6180.3 \to 3368.0$	2.8 ± 0.3	0.8 ± 0.2	1.0		1.6 ± 0.7
2896.0	$6264.5 \to 3368.0$					
3367.1	$3368.0 \to 0$	33 ± 3	29 ± 3	33.3	35 ± 3	21 ± 6
5956.5	$5958.4 \to 0$					
5959.2	$5961.1 \to 0$					

[a] (1997MO35).
[b] (1997BO01).
[c] (1997AO01, 1997AO04).
[d] (1981BJ01).
[e] (1980DE39).

12. ^{10}Be(n, γ) $Q_{\rm m} = 0.5016$

The thermal neutron capture cross section is < 1 mb (see (1975AJ02)). Also see (2004LI04, 2005LI32) who use the Asymptotic Normalization Coefficient method to determine $\sigma(E_{\rm n})$ for $E = 0$ to 1 MeV.

13. ^{10}Be(n, n)

An *ab initio* no-core shell model was used to calculate the binding energies for the lowest $J^\pi = \frac{1}{2}^+$ and $\frac{1}{2}^-$ states in ^{11}Be and the n + ^{10}Be phase shifts (2008QU03, 2009QU02).

14. ^{10}Be(d, p)^{11}Be $Q_{\rm m} = -1.7229$

Angular distributions have been measured at $E_{\rm d} = 6$ MeV (1970GO11: p_1). At $E_{\rm d} = 12$ MeV (1970AU02) p_0 is populated with $l_{\rm n} = 0$ [and therefore $J^\pi = \frac{1}{2}^+$ for ^{11}Be$_{\rm g.s.}$] and p_1 is populated with $l = 1$; $S = 0.73 \pm 0.06$ and 0.63 ± 0.15, respectively (1970AU02). At $E_{\rm d} = 25$ MeV ^{11}Be*(0, 0.32, 1.78) are strongly populated: $S = 0.77$, 0.96, 0.50, respectively, $J^\pi = (\frac{5}{2}, \frac{3}{2})^+$ for ^{11}Be*(1.78) [$l_{\rm n} = 2$] (1979ZW01). Also see the analyses of (1999TI04, 2004KE08, 2009DE15, 2009MO39).

Table 11.10: ^{11}Li β-decay scheme deduced in (2004FY01)

β-decay to ^{11}Be* (MeV)	Branching ratio to [a] ^{11}Be excited states (%)	^{11}Be n-decay to ^{10}Be (MeV)	Branching ratio (%)
0.320	6.3 ± 0.6		
3.96(+3.88)	7.5 ± 1.1	3.368	7.5 ± 1.1
5.85	6.6 ± 1.3	3.368	6.6 ± 1.3
8.82	$8.0 \pm$	5.958	6.45 ± 0.30
		6.265	1.47 ± 0.25
9.6-10.0	8.0 ± 1.5	3.368	8.0 ± 1.5
11-16	3.5 ± 0.8	5.960	3.5 ± 0.8
13.5-16	1.15 ± 0.1	5.958	1.15 ± 0.1
13.5-20	1.38 ± 0.25	6.179	1.38 ± 0.25

[a] Branching ratios renormalized to give $I(^{10}\text{Be*}(3.368 \rightarrow 0)) = 33\%$ as in (1997MO35).

15. ^{11}Li(β^-)^{11}Be $\qquad Q_\text{m} = 20.5513$

The beta-decay of ^{11}Li populates ^{11}Be*(0, 0.32) and higher-lying neutron unbound ^{11}Be states that γ, n, d, t, α and ^{6}He decay. The beta delayed 1-neutron emission branching ratio is $\%\beta$-1n $= 86.2 \pm 0.9$, which is deduced using $I_\gamma(^{11}\text{Be*}(0.32 \rightarrow 0)) = 7.7 \pm 0.8$ % (2005HI03), $P_{2n}/P_{1n} = 0.048 \pm 0.005$ and $P_{3n}/P_{1n} = 0.022 \pm 0.002$ (1980AZ01). Also see (1974RO31, 1980AZ01, 1980DE39, 1981BJ01, 1997BO01) for $\%\beta$-n values based on different $I_\gamma(^{11}\text{Be*}(0.32 \rightarrow 0))$ values; notably $I_\gamma(^{11}\text{Be*}(0.32 \rightarrow 0)) = 6.3 \pm 0.6$ % (1997BO01) implies $\%\beta$-1n $= 87.6 \pm 0.8$. The data related to states involved in neutron emission have ambiguous interpretation connected with uncertainty in placement of neutron decay branches; the observed decay γ-ray intensities from reported measurements are also in poor agreement (see Table 11.9). See (1977BA11, 1994JO04, 1994SU12, 1995OH02, 1995ZH31, 1996SU23, 1997SU12, 2001KA31, 2002KA44, 2003SU04, 2003SU28) for theoretical discussion.

The measurements of (1997MO35) utilized β-γ and β-n coincidence data to deduce the branching ratios populating ^{11}Be and ^{10}Be states, while (1997AO01, 1997AO04) obtained β-γ, β-n and β-n-γ coincidence data in their measurements. Similar γ-ray and neutron energy spectra were observed by each experimenter, however the evaluation of the β-n-γ triple coincidence data of (1997AO01, 1997AO04) required a new, previously unobserved level at ^{11}Be*(8.03 ± 0.05) that populates ^{10}Be*(5.958, 6.179). This observation indicated a significantly different interpretation of the ^{11}Li decay scheme than in previous evaluations such as (1990AJ01).

Table 11.11: ^{11}Li β-decay scheme deduced in (2004SA46)

β-decay to ^{11}Be* (MeV)	Branching ratio to [a] ^{11}Be excited states (%)	^{11}Be n-decay to ^{10}Be (MeV)	Branching ratio (%)
0.320	7.69 ± 0.40		
3.41(+3.88 + 3.96)	20.92 ± 0.69	3.368	20.92 ± 0.69
8.03 ± 0.07	8.35 ± 0.20	6.180	1.71 ± 0.05
		5.958	6.63 ± 0.20
8.81 ± 0.04	5.12 ± 0.20	6.264	2.05 ± 0.05
		5.958	3.07 ± 0.20

[a] Branching ratios renormalized to give $I(^{10}\text{Be*}(3.368 \to 0)) = 33\%$ as in (1997MO35).

Table 11.12: ^{10}Be and ^{11}Be γ-ray transition intensities (per 100 decays) observed following ^{11}Li β-decay: implementing DBLA analysis

E_γ [a] (keV)	^{10}Be($E_i \to E_f$) [a]	I [a]	I [b]	I [c]	I [d]
219.2 ± 0.5	$6180.3 \pm 0.5 \to 5961.1 \pm 0.5$	0.67 ± 0.03	0.31 ± 0.05	0.46 ± 0.09	0.521 ± 0.026
320.0 ± 0.5	^{11}Be*($0.320 \to 0$)	7.69 ± 0.40	6.3 ± 0.6	7.7 ± 0.8	7.62 ± 0.40
2590.3 ± 0.5	$5958.4 \pm 0.5 \to 3368.0$ [e, f]	0.23 ± 0.10	7.6 ± 0.3	9.3 ± 1.4	8.28 ± 0.60
2592.7 ± 0.5	$5961.1 \pm 0.5 \to 3368.0$ [e, f]	8.75 ± 0.20	0.8 ± 0.1	0.08^{+3}_{-5}	0.294 ± 0.046
2811.8 ± 0.5	$6180.3 \pm 0.5 \to 3368.0$ [e, f]	1.03 ± 0.03	1.07 ± 0.20	1.2 ± 0.2	0.997 ± 0.020
2896.0 ± 0.5	$6264.5 \pm 0.5 \to 3368.0$ [e, f, g]	1.05 ± 0.53	1.47 ± 0.25 [h]	2.2 ± 0.4 [i]	2.08 ± 0.043
3367.1 ± 0.5	$3368.0 \to 0$	33 [a]	33 [a]	37.0 ± 5.5	33
5956.5 ± 1.0	$5958.4 \to 0$	0.96 ± 0.3	3.0 ± 0.7	0.36 ± 0.20	0.818 ± 0.059
5959.2 ± 1.0	$5961.1 \pm 0.5 \to 0$	0.43 ± 0.10		0.38 ± 0.09	0.568 ± 0.092

[a] (2004SA46). Intensity normalized here to give $I(3368) = 33\%$.
[b] (2004FY01), assuming $I(3368) = 33\%$ from (1997MO35, 1997AO01).
[c] (2004HI12).
[d] (2009MA54).
[e] (2004SA46) deduce $T_{1/2} = 85 \pm 6$ (stat.) ± 10 (sys.) fs, $870 \pm 70 \pm 160$ fs , less than a few hundred fs, and $60.0 \pm 1.6 \pm 6.0$ fs for ^{10}Be*(6.264, 6.180, 5.961, 5.958), respectively.
[f] (2004FY01) deduce $T_{1/2} = 230 \pm 60$ fs, 1.10 ± 0.25 ps, 330 ± 130 fs, and > 50 fs for ^{10}Be*(6.264, 6.180, 5.961, 5.958), respectively.
[g] (2004FY01) measured $E_i = 6264.5 \pm 2.0$.
[h] (1980DE39).
[i] $T_{1/2} = 85^{+27}_{-17}$ fs.

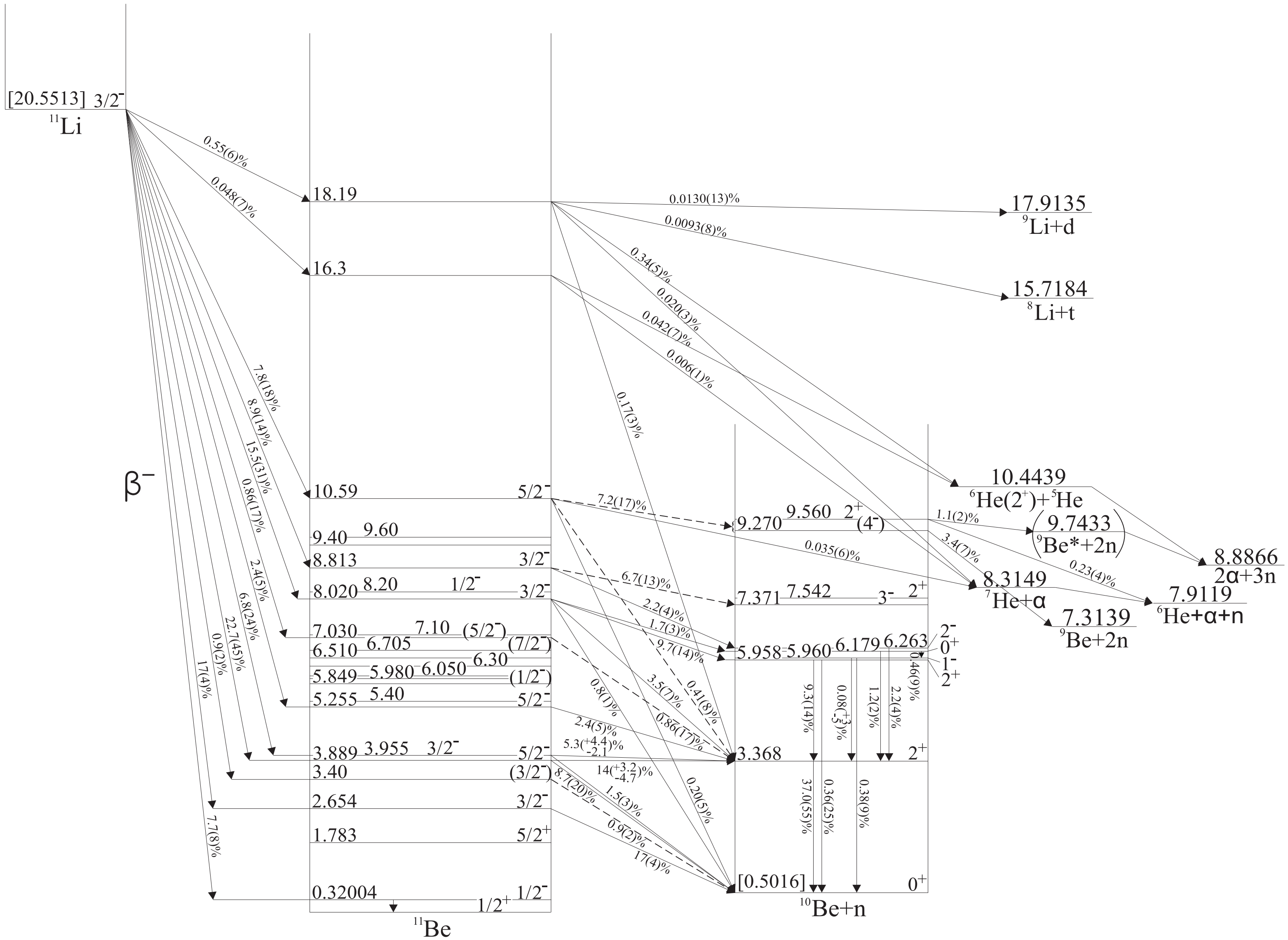

Fig. 3: γ-ray transitions and decay branching ratios observed in ^{11}Li decay. For notation see Fig. 4. (*Footnotes on next page*)

[a] Branching ratios for γ-ray transitions in ^{10}Be and ^{11}Be, and associated β-delayed neutron emission that populates those levels is from the DBLA of (2005HI03); see also other work of (2004FY01, 2004SA46, 2009MA54).

[b] Decay to ^{11}Be$_{\rm g.s.}$ is taken as zero; the upper limit on population is $< 2\%$.

[c] The 7.2(17)% branch for delayed neutron emission from ^{11}Be to ^{10}Be*(9.27, 9.56) is found by (2005HI03); they also deduced the 3.4(7)% decay of ^{10}Be*(9.27) into ^{9}Be + 2n.

[d] (2008MA34) find that ^{11}Be*(10.59) neutron decays partly to ^{10}Be*(9.52(2) MeV: Γ = 0.30(4) MeV) before breaking into $2\alpha + 3$n with 1.1(2)% and ^{6}He + α + n with 0.23(4)%.

[e] (1984LA27) suggested that ^{11}Be*(10.59) has a decay branch via ^{9}Be + 2n before breaking into $2\alpha + 3$n.

[f] The ^{11}Be*(16.3) level is reported only by (2009MA31). Their analysis suggests that decay and breakup strength that was previously attributed to ^{11}Be*(18.2) is shared with ^{11}Be*(16.3). It is presumed that ^{11}Be*(16.3) decay to $2\alpha + 3$n proceeds through ^{6}He(2^{+}) + ^{5}He, as was indicated in their analysis of ^{11}Be*(18.2) decay (2008MA34).

[g] The decay branching ratios for ^{11}Be*(18.2) were first measured by (1997BO03), however subsequent analysis (2009MA31) that accounts for the ^{11}Be*(16.3) state is accepted here.

[h] The ^{11}Be*(18.2) decay to ^{9}Li + d and ^{8}Li + t are measured by (2008RA23, 2009MA72), respectively. In each case a systematic uncertainty from the detector threshold is present.

[i] Transitions shown with dashed lines are deduced by (2005HI03) to provide a best fit of the β-n Time-of-Flight spectrum.

In (2003FY01, 2004FY01), Doppler Broadened Line shape Analysis (DBLA) of ^{10}Be γ-ray lines, was used to determine the excitation energy of parent states in ^{11}Be. A rigorous analysis of the line shape of emitted γ-rays yields details on the lifetime of ^{10}Be states populated in β-delayed neutron emission and on the recoil velocity of ^{10}Be atoms, which is connected to the energy of the emitted neutrons and therefore to the ^{11}Be parent level energy; this analysis also depends on the stopping power of the implantation medium. Analysis given in (2003FY01) supports the interpretation of (1997AO01, 1997AO04), but they suggest that the observed ^{11}Be*(8.03) branch corresponds to decay from the known level ^{11}Be*(8.82) with $T_{1/2} = 61 \pm 18$ fs to ^{10}Be*(5.958). In (2004FY01) γ-ray transitions corresponding to ^{10}Be*(5.958 $\rightarrow$ 0) and ^{10}Be*(6.263 $\rightarrow$ 3.368) were observed for the first time in ^{11}Li decay, and a more complete DBLA analysis is given for branches that populate ^{10}Be*(3.368, 5.958, 5.960, 6.179, 6.263); see Table 11.10.

The 8π spectrometer at TRIUMF-ISAC measured γ-rays from ^{11}Li decay (2004SA46). Improved γ-ray decay branching ratios were obtained for the levels of ^{10}Be. A DBLA analysis was performed, see Table 11.11. The high efficiency and resolution of the detector array provided sufficient information to confirm participation of both ^{11}Be*(8.03, 8.81) in the decay of ^{11}Li.

Finally, β-γ, β-n and β-n-γ coincidence data were measured in the decay of polarized ^{11}Li atoms (2004HI12, 2005HI03); see Tables 11.12 and 11.13. In the β-n and β-γ coincidence measurements, the β asymmetry unambiguously determined the spins and parities of ^{11}Be levels populated in the decay, and the asymmetry was used to resolve the origins of overlapping peaks in the delayed neutron energy spectrum. Although serious conflicts remain amongst the present measurements, the results of (2004HI12, 2004HI24, 2005HI03) are based on the most rigorous set of β-asymmetry plus β-n-γ coincidence constraints; see Fig. 3.

Table 11.13: ^{11}Li β-decay scheme deduced in (2005HI03)

Decay to ^{11}Be* (MeV ± keV)	J^π	Branching ratio (%)	log ft	^{11}Be n-decay to ^{10}Be* (MeV)	Branching ratio (%)
0.32	$\frac{1}{2}^{-\,a}$	7.7 ± 0.8	5.67 ± 0.04		
2.69	$\frac{3}{2}^-$	17 ± 4	5.06 ± 0.10	0	17 ± 4
3.41	$(\frac{3}{2}^-)$	0.9 ± 0.4	6.25 ± 0.10	0	0.9 ± 0.4 [c]
3.890 ± 1	$\frac{5}{2}^-$	22.7 ± 4.5	$4.78^{+0.07}_{-0.10}$	0	8.7 ± 2.0
				3.368	$14^{+3.2}_{-4.7}$
3.969^{+20}_{-9}	$\frac{3}{2}^-$	6.8 ± 2.4	$5.30^{+0.28}_{-0.13}$	0	1.5 ± 0.3
				3.368	$5.3^{+4.4}_{-2.1}$
5.24	$\frac{5}{2}^-$	2.4 ± 0.5	5.55 ± 0.08	3.368	2.4 ± 0.5
7.03	$(\frac{5}{2}^-)$	0.86 ± 0.17	5.77 ± 0.09	3.368	0.86 ± 0.17 [c]
8.020 ± 20 [b]	$\frac{3}{2}^-$	15.5 ± 3.1	4.30 ± 0.08	0	0.8 ± 0.1
				3.368	3.5 ± 0.7
				5.958	9.7 ± 1.4
				6.179	1.7 ± 0.3
8.82	$\frac{3}{2}^-$	8.9 ± 1.4	4.46 ± 0.07	6.263	2.2 ± 0.4
				7.371	6.7 ± 1.3 [c]
10.6	$\frac{5}{2}^-$	7.8 ± 1.8	4.18 ± 0.12	0	0.20 ± 0.05
				3.368	0.41 ± 0.08 [c]
				(9.27 [c] + 9.4) [d]	(7.2 ± 1.7)
16.3 [e]		0.048 ± 0.007	4.65 ± 0.08		
18.19 [f]		0.55 ± 0.06	2.45 ± 0.13		

[a] From Adopted Levels.
[b] $\Gamma = 230 \pm 55$ keV.
[c] Decay path assumed to account for neutron energy spectrum.
[d] Decays to ^{9}Be + n with intensity 3.4 ± 0.7 per 100 ^{11}Li decays.
[e] From (2009MA31).
[f] From (1997BO03, 2008RA23, 2009MA31, 2009MA72).

Table 11.14: Summary of ^{11}Li β-delayed particle emission measurements

(1974RO31): Measured $P_{\rm n}(^{11}{\rm Li})$, the neutron emission probability, relative to $P_{\rm n}(^{9}{\rm Li})$. Using $P_{\rm n}(^{9}{\rm Li}) = 50.8\%$ (2004TI06) gives $P_{\rm n}(^{11}{\rm Li}) = 88 \pm 10$ %. The original manuscript gives a lower value, $P_{\rm n} = 60.8 \pm 7.2$ %, based on $P_{\rm n}(^{9}{\rm Li}) = 35\%$ (1970CH07).
(1979AZ03): Measured the β-2n branching ratio using n-n coincidence counting. The singles neutron rate was 1.54 s^{-1} and the n-n coincidence rate was 0.0225 s^{-1}, using $P_{\rm n} > 95\%$ i.e. (1981BJ01) gives $P_{\rm 2n} > 13\%$. The text had used $P_{\rm n} = 60.8\%$ from (1974RO31) which gave a lower $P_{\rm 2n}$ value. The presently accepted value for $P_{\rm 2n}$ is smaller than these $P_{\rm 2n}$ values by more than a factor of two.
(1980AZ01): Measured $P_{\rm 3n}$ using n-n-n coincidence counting. The relative ratios were measured. $P_{\rm 2n}/P_{\rm 1n} = (4.8 \pm 0.5) \times 10^{-2}$ and $P_{\rm 3n}/P_{\rm 1n} = (2.2 \pm 0.2) \times 10^{-2}$. Using $P_{\rm n} = 95\%$ and $P_{\rm n} = \sum_i iP_{in}$ they found $P_{\rm 1n} = 82 \pm 7$ %, $P_{\rm 2n} = 3.9 \pm 0.5$ %, $P_{\rm 3n} = 1.8 \pm 0.2$ %. Note: the formula $P_{\rm n} = \sum_i P_{in}$ is used in some references.
(1980DE39): Measured $P_{^{11}{\rm Be}^*(0.32)} = 5.2 \pm 1.4$ % and $P_{^{10}{\rm Be}^*(3.32)} = 21 \pm 6$ % using β-γ counting; they deduced an upper limit of $\leq 2\%$ on population of the ^{11}Be ground state.
(1981BJ01): Measured $P_{^{11}{\rm Be}^*(0.32)} = 9.2 \pm 0.7$ % and $P_{^{10}{\rm Be}^*(3.32)} = 35 \pm 3$ % using β-γ counting. The rate of ^{11}B*(2.12) decay, fed from ^{11}Be decay, placed an upper limit of $\leq 2\%$ on population of the ^{11}Be ground state. Using $P_{^{11}{\rm Be}^*(0.32)}$ and the ratios from (1980AZ01), they deduced $P_{\rm 1n} = 85 \pm 1$, $P_{\rm 2n} = 4.1 \pm 0.4$, $P_{\rm 3n} = 1.9 \pm 0.2$ %, and using the correct formula, $P_{\rm n} = \sum_i iP_{in}$, they deduce $P_{\rm n} = 98 \pm 1$ %. From standard β-n counting they deduce a less precise value, $P_{\rm n} = 95 \pm 8$ %, but they note that a systematic error is present for multiple neutron emissions.
(1981LA11): Measured E and E-E coincident spectra for β-delayed charged particles using Si Detectors. They deduced: ^{11}Li $\rightarrow$ ^{11}Be*($\approx$ 18.5) $\rightarrow$ ^{8}Be*(3.0) + 3n $\rightarrow$ 2α + 3n : 0.30 ± 0.05 %; ^{11}Li $\rightarrow$ ^{11}Be*(10.59) $\rightarrow$ n + ^{10}Be*(9.4) $\rightarrow$ 2n + ^{9}Be*(2.43) $\rightarrow$ 2α + 3n: 2.0 ± 0.6 %; ^{11}Li $\rightarrow$ ^{11}Be*(10.59) $\rightarrow$ n + ^{10}Be*(9.4) $\rightarrow$ n + α + ^{6}He: 0.9 ± 0.3 %; Revised $P_{\rm 3n} = 2.3 \pm 0.6$ %, which implies $P_{\rm 1n} = 104 \pm 30$ % and $P_{\rm 2n} = 5.0 \pm 1.5$ % using the ratios from (1980AZ01).
(1984LA27): Using a single ΔE-E telescope they measured β-delayed charged particles. The lower level threshold was $\sim$ 800 keV. They deduced: ^{11}Li $\rightarrow$ ^{11}Be*($\approx$ 18.5, $\Gamma \approx 0.5$ MeV) $\rightarrow$ ^{8}Li + t_0/t_1: 0.010 ± 0.004 %; ^{11}Li $\rightarrow$ ^{11}Be*($\approx$ 18.5) $\rightarrow$ ^{10}Be*(11.76) + n $\rightarrow$ n + α + ^{6}He: 0.10 ± 0.03 %; ^{11}Li $\rightarrow$ ^{11}Be*($\approx$ 18.5) $\rightarrow$ ^{10}Be*(11.76) + n $\rightarrow$ 2α + 3n: 0.20 ± 0.05 %; ^{11}Li $\rightarrow$ ^{11}Be*(10.59) $\rightarrow$ n + ^{10}Be*(9.4) $\rightarrow$ 2n + ^{9}Be*(2.43) $\rightarrow$ 2α + 3n: 2.0 ± 0.6 %; ^{11}Li $\rightarrow$ ^{11}Be*(10.59) $\rightarrow$ n + ^{10}Be*(9.4) $\rightarrow$ n + α + ^{6}He: 0.9 ± 0.3 %; ^{11}Li $\rightarrow$ ^{11}Be*(0-8.4 MeV): 97%.
(1996MU19): Measured ΔE-E of emitted particles with an emphasis on β-d and β-t decays. The decay of subsequent daughters, implanted in the E detectors was also recorded. The lower level threshold was $\sim$ 500 keV. They found $P_{^{8}{\rm Li+t}} = (2.0 \pm 0.5) \times 10^{-2}$ % and $P_{^{9}{\rm Li+d}} \sim (1.5 \pm 0.5) \times 10^{-2}$ %.

Table 11.14: Summary of ^{11}Li β-delayed particle emission measurements (continued)

(1997BO01): Using β-γ coincidence counting they measured $P_{^{11}\mathrm{Be}^*(0.32)} = 6.3 \pm 0.6$ % and using the ratios from (1980AZ01) they deduced: $P_{1\mathrm{n}} = 87.6 \pm 0.8$ %, $P_{2\mathrm{n}} = 4.2 \pm 0.4$ %, $P_{3\mathrm{n}} = 1.9 \pm 0.2$ %. This implies $P_{\mathrm{n}} = 101.7 \pm 1.3$ %.
(1997BO03): Measured β-delayed neutrons, charged particles and γ-rays with an emphasis on determining the branching ratios of the ^{11}Be*(18.15 $\pm$ 0.15 MeV) state. $d +^9$ Li : 20%, ^{10}Be(2$^+$) + n : 19%, ^{9}Be + 2n : $\leq$ 5%, n + α +^{6} He : 24%; $t +^8$ Li : 13%, ^{10}Be + n : $\leq$ 0.6%, 2α + 3n : 38%. They suggest that much of the d + ^{9}Li decay proceeds through the continuum.
(2005HI03): Using β-γ coincidence counting they measured $P_{^{11}\mathrm{Be}^*(0.32)} = 7.7 \pm 0.8$ %; implying $P_{1\mathrm{n}} = 86.3 \pm 0.9$ %, $P_{2\mathrm{n}} = 4.1 \pm 0.4$ %, $P_{3\mathrm{n}} = 1.9 \pm 0.2$ % and $P_{\mathrm{n}} = 100.3 \pm 1.4$ %.
(2008RA23, 2011RA16): Implanted ^{11}Li in Double-Sided-Si-Strip-Detector (DSSSD) and selected ^{9}Li + d decay events by measuring the subsequent ^{9}Li β-decay. They measured $P_{^9\mathrm{Li+d}} = (1.30 \pm 0.13) \times 10^{-2}$ % with an energy threshold of $E_{\mathrm{cm}} = 200$ keV. They further suggest that the β-d events proceed through the ^{11}Be*(18.2 MeV) state and through the continuum. Preliminary results from this measurement appear to have been given in (2007RAZS).
(2008MA34): Implanted ^{11}Li in DSSSD and selected on subsequent daughter decays. They measured $P_{^8\mathrm{Li+t}} = 0.014 \pm 0.003$ % (improved to $(0.93 \pm 0.08) \times 10^{-2}$ % in (2009MA72)) and further suggest: ^{11}Li $\rightarrow$ ^{11}Be*(18.15) $\rightarrow$ ^{6}He(2$^+$) + ^{5}He $\rightarrow$ 2α + 3n: 0.34 $\pm$ 0.05 %; ^{11}Li $\rightarrow$ ^{11}Be*(18.15) $\rightarrow$ α + ^{7}He $\rightarrow$ n + α + ^{6}He: 0.057 $\pm$ 0.009 %; ^{11}Li $\rightarrow$ ^{11}Be*(10.59) $\rightarrow$ n + ^{10}Be*(9.5) $\rightarrow$ n + α + ^{6}He: 0.23 $\pm$ 0.04 %; ^{11}Li $\rightarrow$ ^{11}Be*(10.59) $\rightarrow$ n + ^{10}Be*(9.5) $\rightarrow$ 3n + 2α: 1.1 $\pm$ 0.2 % (but part of the distribution is below their threshold); ^{11}Li $\rightarrow$ ^{11}Be*(10.59) $\rightarrow$ α + ^{7}He $\rightarrow$ n + α + ^{6}He: 0.035 $\pm$ 0.006 %. In (2009MA72) the values ^{11}Be*(18.35 $\pm$ 0.30 MeV, Γ = 1.5 $\pm$ 0.4 MeV) are deduced.
(2009MA31): Implanted ^{11}Li in DSSSD and selected subsequent daughter decays corresponding to ^{7}He + α decay. Evidence for a previously unknown ^{11}Be state at $E_{\mathrm{x}} = 16.3$ MeV was observed. They deduced: ^{11}Li $\rightarrow$ ^{11}Be*(16.3 $\pm$ 0.1, Γ = 0.7 $\pm$ 0.1 MeV) $\rightarrow$ ^{6}He + n + α: 0.006 $\pm$ 0.001 %; ^{11}Li $\rightarrow$ ^{11}Be*(16.3) $\rightarrow$ ^{6}He(2$^+$) + ^{5}He $\rightarrow$ 2α + 3n: 0.042 $\pm$ 0.007 %; ^{11}Li $\rightarrow$ ^{11}Be*(18.4 $\pm$ 0.3, Γ = 1.6 $\pm$ 0.6 MeV) $\rightarrow$ ^{6}He + n + α: 0.020 $\pm$ 0.003 %.

More complex contributions to the ^{11}Li decay scheme are associated with weak population of higher lying ^{11}Be states. β-delayed α and triton emission from ^{11}Be*(10.6, 18.5) were first reported in (1981LA11, 1984LA27). A summary of β-delayed particle emission measurements is given in Table 11.14 and Fig. 3.

The state at ^{11}Be*(18.15) is a candidate for having a ^{9}Li + d "halo" structure analogous to the ^{9}Li + 2n structure of the ^{11}Li$_{\mathrm{g.s.}}$ (1995ZH31), and the strong feeding of the state in β-decay implies

Table 11.15: ^{11}Be states populated in electron induced photo-pion production (1995YA01)

E_x (MeV)	J^π	E1 strength (fm^2)
0	$\frac{1}{2}^+$	0.11
0.3		
2.7	$(\frac{3}{2}^+, \frac{5}{2}^+)$	0.022, 0.015
5.2	$(\frac{3}{2}^+, \frac{5}{2}^+)$	0.052, 0.035
6.8	$\frac{1}{2}^+$	0.31
9.4	$(\frac{3}{2}^+, \frac{5}{2}^+)$	0.13, 0.085
12.0	$\frac{1}{2}^+$	0.56
	$(\frac{3}{2}^+, \frac{5}{2}^+)$	0.067, 0.047
16.4	$(\frac{3}{2}^+, \frac{5}{2}^+)$	0.10, 0.07
17.5	$(\frac{3}{2}^+, \frac{5}{2}^+)$	0.13, 0.09

a large overlap with ^{11}Li$_{\rm g.s.}$ (1996MU19, 1997MU06). After the discovery of the ^{11}Li halo, investigation of possible ^{11}Li decay directly to the ^{9}Li + d continuum received special attention, since it could be sensitive to the ^{11}Li halo (1991BO31, 1995OH02, 1996MU19, 1997MU06, 1997RI04) and might indicate the presence of a deuteron-halo state in ^{11}Be (1995ZH31, 2004KU27); however the analysis of (1997BO03) provided no conclusive evidence to support this decay mode. Also see (2008RA23).

See (2010KA06) for an analysis of G-T transitions in ^{11}Li β-decay.

16. ^{11}B(e, e$'\pi^+$)^{11}Be $\qquad Q_{\rm m} = -139.5702$

At $E_{\rm e} = 200$ MeV, photo-pion production on ^{11}B populates states listed in Table 11.15. A PWIA analysis of measured differential cross sections was used to deduce spin-flip charge exchange E1 strengths (1995YA01).

17. ^{11}B(μ^-, γ)^{11}Be $\qquad Q_{\rm m} = 94.1491$

The time dependence of μ^- capture from the hyperfine levels of muonic-^{11}B leading to ^{11}Be*(0.32) determined $J^\pi = \frac{1}{2}^-$ for that state (1968DE20). The ratio of the capture cross section from the hyperfine levels to ^{11}Be*(0.32) can also be related to the ratio of the induced pseudoscalar to axial vector form factor, $g_p/g_A = 4.3^{+2.8}_{-4.3}$ (stat.) $\pm$ 0.5 (sys.) (1998WI26, 2002WI02); this agrees with partial conservation of the axial current. Also see (1998MU17).

18. ^{11}B(μ^-, ν)^{11}Be($\frac{1}{2}^-$) $\qquad Q_m = 94.1491$

The ^{11}B(μ^-, ν)^{11}Be($\frac{1}{2}^-$) capture reaction is sensitive to the pseudoscalar coupling constant, g_p; see discussion in (1994KU32, 1995KU35).

19. ^{11}B(π^-, γ)^{11}Be $\qquad Q_m = 128.0609$

The photon spectrum from stopped pion capture on ^{11}B includes a peak corresponding to ^{11}Be*($0 + 0.32$) (1986PE05).

20. ^{11}B(n, p) $\qquad Q_m = -10.7269$

The cross section has been measured for $E_n = 14$ MeV (2001KAZY) and $E_n = 14$ to 16.9 MeV; see references in (1975AJ02), and see ^{12}B. At $E_n = 96$ MeV, angular dependent cross sections were measured for $\theta < 30°$ (2001RI02). A DWBA analysis was used to deduce the G-T strength distribution, and a multipole decomposition was used to analyze the data up to $E_x = 35$ MeV; while a broad $\Delta L = 0$ peak is observed near $E_x = 9$ MeV, the higher excitation spectrum is dominated by a $\Delta L = 1$ peak at $E_x = 12$ MeV.

21. ^{11}B(d, ^{2}He) $\qquad Q_m = -12.9515$

At $E_d = 70$ MeV angular distributions of cross section and analyzing power were measured and G-T transitions populating ^{11}Be*(0.3, 2.7, 3.8) were identified with $J^\pi = \frac{1}{2}^-$, ($\frac{3}{2}^-$) and ($\frac{5}{2}^-$), respectively (1993SA09, 1994SA11); a broad bump at $E_x \approx 10$ MeV ($\Gamma \approx 7$ MeV) apparently having $\Delta L = 1$ is suggested as a spin-flip dipole transition. At $E_d = 270$ MeV angular distributions of cross section and analyzing power were measured (2001OH07). Peaks corresponding to ^{11}Be*(0.32, 2.7, 3.9, (5.4), 6.3, (7.3), 8.2, 9.2, (10.2), 11.6, (13.2)) were evaluated in a DWBA analysis to identify G-T, spin and isospin flip dipole transitions. The states at $E_x = 0.3, 2.7, 3.9$, 5.4, 7.3, 8.2 MeV were found to have G-T character.

22. ^{11}B(t, ^{3}He) $\qquad Q_m = -11.4906$

Table 11.16: ^{11}Be states observed in ^{11}B(^{7}Li, ^{7}Be) at 57 MeV (2001CA45, 2004CA29)

E_x (MeV)	Γ (keV)	J^{π} [a]
0		$\frac{1}{2}^+$
0.32 ± 0.02		$\frac{1}{2}^-$
1.77 ± 0.02	100 ± 10	$\frac{5}{2}^+$
2.67 ± 0.02	200 ± 10	$\frac{3}{2}^-$
3.41 ± 0.02	130 ± 10	$\frac{3}{2}^-$
3.89 ± 0.02	< 50	$\frac{3}{2}^+$, $\frac{5}{2}^-$
3.96 ± 0.02	< 50	$\frac{3}{2}^-$
6.05 ± 0.04	320 ± 40	
9.4 ± 0.5 [b]	7.0 ± 0.5 MeV [b]	

[a] See (1964AL22, 1990LI19).
[b] See (2004CA29).

At $E_t = 127$ MeV, the cross sections for populating ^{11}Be*(0.32, 2.69, 3.89, 8.94) were measured at 0°, and B(GT) $= 0.23 \pm 0.05$, 0.17 ± 0.05, 0.07 ± 0.03 values were deduced for ^{11}Be*(0.32 [$J^{\pi} = \frac{1}{2}^-$], 2.69 [$(\frac{3}{2}^-)$], 3.89 [$(\frac{5}{2}^-)$]), respectively (1998DA05).

23. ^{11}B(^{7}Li, ^{7}Be) $Q_m = -12.3711$

At $E(^{7}$Li$) = 57$ MeV, the charge-exchange reaction on ^{11}B populated states shown in Table 11.16 (2001CA45). The measurements were at $\theta \leq 35°$ and the experimental resolution separated ^{7}Be and ^{7}Be*(0.429). Results were compared with QRPA calculations. A subsequent analysis of the data indicated a resonance at $E_x = 9.4 \pm 0.5$ MeV with $\Gamma = 7.0 \pm 0.5$ MeV (2004CA29).

24. ^{12}C(μ, X)^{11}Be

A study of muon induced backgrounds in large volume scintillators measured σ(100 MeV) $<$ 1.22 μb and σ(190 MeV) $<$ 2.34 μb for production of ^{11}Be (2000HA33). See (2010AB05) for analysis of production rates in the KamLAND detector.

25. ^{12}C(π^-, p)^{11}Be $Q_m = 112.1040$

Proton emission following pion π^- capture on ^{12}C was measured at $E_{\pi^-} = 145$ MeV (1987BL07). Also see (1975CO06: $E_{\pi^-} = 27$ MeV), (1977JA15: $E_{\pi^-} = 60$, 100, 200 MeV), (1977AB09: $E_{\pi^-} = 1.43$ GeV/c), (1975CO06, 1980MC03, 1981MC09: $E_{\pi^-} = 100$, 160, 220 MeV), (1980KA13, 1981AN14: $E_{\pi} = 40$ GeV/c), (1981KA43: $E_{\pi^-} = 400$, 475 MeV), and (1976DE39, 1978DE30, 1979ME07, 1979SC02, 1981PR02: E_{π^-} = stopped).

26. ^{12}C(^{7}Li, ^{8}B)^{11}Be $\qquad Q_{\rm m} = -28.1916$

At $E(^7$Li$) = 82$ to 83 MeV, groups corresponding to ^{11}Be*($0 + 0.32$, 1.8, 3.4) are reported by (1982AL08, 1983AL20).

27. ^{12}C(^{11}Be, ^{11}Be)

Angular distributions of quasi-elastic scattering of ^{11}Be on ^{1}H and ^{12}C targets were measured at $E(^{11}$Be$) = 38.4$ MeV/A (2008LA01). The results are interpreted as purely elastic scattering since population of ^{11}Be* is expected to be two orders of magnitude smaller than elastic scattering. The impact of the weak binding energy on the interaction potentials was studied. While data on the ^{1}H target was reasonably reproduced by reducing the real part of the potential, the ^{12}C target data required modifications to the so-called "Virtual Coupling Potential" and requires further measurements to determine the dependency on coupling to excited states and the continuum. Earlier unpublished work from GANIL is discussed in (1997AL05, 1997JO16, 1998TO05, 2000JO21, 2002BO25, 2002TA31, 2003AB05, 2003TA04, 2005BA72, 2005TA34). Also see analysis in (1995EV01, 1996EV01, 1996VO04, 1999BR09, 1999FO13, 2000BO45, 2002AL25, 2002SU18, 2009HA18).

28. $^{\rm nat}$C(^{12}Be, ^{11}Be)

Neutron removal cross sections were measured at $E(^{12}$Be$) = 39.3$ MeV/A. States at ^{11}Be*(0, 0.32, 1.78, 2.69, ~ 4) were populated (2005PA68, 2006PA04). The spectroscopic factors $S = 0.56 \pm 0.18, 0.44 \pm 0.08, 0.48 \pm 0.06, 0.40 \pm 0.07$ were deduced for the first four states, respectively. The significant feeding of ^{11}Be*(1.78 [$J^\pi = \frac{5}{2}^+$]) implies a $\nu(0{\rm d}_{5/2})^2$ component in the ^{12}Be$_{\rm g.s.}$.

29. ^{13}C(^{6}Li, ^{8}B)^{11}Be $\qquad Q_{\rm m} = -25.8869$

At $E(^6$Li$) = 80$ MeV, ^{11}Be*(0.32) is strongly populated and the angular distribution to this state has been measured; ^{11}Be*(2.69, 4.0) are also observed (1977WE03). It is suggested that these states have odd parity (1977WE1B; thesis); however, see (1972AJ01): ^{9}Be(t, p)^{11}Be where positive parity was deduced for ^{11}Be*(2.69).

30. ^{14}C(^{18}O, ^{21}Ne) $Q_{\rm m} = -12.2083$

At $E(^{18}{\rm O}) = 88.7$ MeV, ^{11}Be*($0 + 0.32$) appear to be involved in the reaction which populates ^{21}Ne(0, 0.35, 1.75, 2.87, 4.43, 6.45) (1974BA15).

31. ^{64}Zn(^{11}Be, ^{11}Be)

Elastic and quasi-elastic scattering angular distributions were measured for $10° \leq \theta \leq 110°$ at $E_{\rm cm} = 24.5$ MeV ^{9,10,11}Be on 550-1000 μg/cm^2 targets using a large solid angle ΔE-E Si detector array (2010DI08, 2010SC12). Comparison of the angular distributions reveals a significant reduction of the so-called "Coulomb-nuclear interference peak" for ^{11}Be at $\theta_{\rm cm} \approx 40$ degrees. An optical model analysis indicates the interference peak is suppressed by absorption, related to the diffuse halo. A total reaction cross section of $\sigma_{\rm R} = 2730$ mb is deduced for ^{11}Be, compared with $\sigma_{\rm R} = 1090$ and 1260 mb for ^{9,10}Be, respectively; a sizeable ^{10}Be breakup component from ^{11}Be reactions indicates that about 40% of the ^{11}Be total reaction σ is attributed to transfer and/or breakup reactions.

32. ^{120}Sn(^{11}Be, ^{11}Be)

The ^{11}Be*(0, 0.32 MeV) quasi-elastic scattering angular distributions were measured in a large solid angle ΔE-E Si detector array for reactions on a 3.5 mg/cm^2 ^{120}Sn target at $E = 32$ MeV, which is just above the Coulomb barrier energy (2009AC02). In the angular range $15° \leq \theta \leq 38°$, the scattering events were separated from the breakup events via ΔE-E reaction product identification, while for $52° \leq \theta \leq 86°$ the ^{10}Be ejectiles were not distinguishable from the ^{11}Be events. The angular distribution has a "pronounced deviation from the typical Fresnel-type scattering," and the Coulomb-nuclear interference appears strongly damped. Coupled Channels calculations suggest that couplings to the p-states just above the breakup threshold may be important.

33. (a) ^{197}Au(^{11}Be, ^{11}Be$'$)
(b) ^{208}Pb(^{11}Be, ^{11}Be$'$)

Coulomb excitation measurements populating ^{11}Be*(0.32) have been carried out and the resulting B(E1) values are displayed in Table 11.17. These compare with 0.116 ± 0.012 $e^2\cdot$ fm^2 deduced from lifetime measurements. Also see (1995BE26, 1995BE47, 1995TY01, 1997AN01, 1997AN18, 1997DE07, 1997NA19, 2003BE54, 2003TA06, 2004TY01, 2005BA72, 2005TY02, 2007BE54, 2008ES04).

Table 11.17: The B(E1) values of ^{11}Be*(0.32) deduced from Coulomb excitation

$E(^{11}\text{Be})$ (MeV/A)	Target	B(E1) ($e^2\cdot$ fm^2)	References
43	^{208}Pb	0.06 ± 0.01	(1995AN20)
64	^{208}Pb	0.099 ± 0.010	(1997NA08)
57-60	^{197}Au	0.079 ± 0.008	(1997FA11)
57-60	^{208}Pb	0.094 ± 0.011	(1997FA11)
38.6	^{208}Pb	0.105 ± 0.012	(2007SU18)

34. ^{209}Bi(^{11}Be, ^{11}Be)

The elastic scattering angular distributions were measured for $E(^{11}\text{Be}) = 40$ MeV (2006MA51) and $E(^{11}\text{Be}) = 40$ to 48 MeV (2007MA90). Results are compared with ^{9}Be elastic scattering on ^{209}Bi. Near the Coulomb barrier the ^{11}Be cross sections are larger than the ^{9}Be cross sections, but at higher energies they become more similar, suggesting that direct processes related to the halo structure are more relevant at near-barrier energies.

35.(a) ^{209}Bi(^{11}Be, F)

(b) ^{238}U(^{11}Be, F)

Fusion cross sections were measured for $^{209}\text{Bi} + {}^{11}\text{Be}$ at $E(^{11}\text{Be}) = 30$ to 70 MeV (1995YO03, 1996YO08) and $E(^{11}\text{Be}) = 35$ to 50 MeV (1998SI16, 1998SI38). At $E(^{11}\text{Be}) = 35$ to 68 MeV fusion cross sections were measured for $^{11}\text{Be} + {}^{238}\text{U}$ (1995FE02, 1997FE08, 1999FE12). Also see (1995IM01, 1997SI07, 1997SI25, 1997ZA04, 1999DA02, 1999PE07, 2000HA14, 2000WA37, 2002AL12, 2002DI02, 2002SI07, 2002VI12, 2003BB07, 2003YA17, 2004DI16, 2005LI64).

^{11}B

(Tables 11.18 and 11.19, Figs. 4 and 7)

$$\mu = +2.6886489\ (10)\text{ nm (1989RA17)},$$
$$Q = 40.65 \pm 0.26\text{ mb (1970NE05)},$$
$$B(\text{E2}; \tfrac{3}{2}^- \rightarrow \tfrac{1}{2}^-) = 2.6 \pm 0.4\ e^2\cdot\text{ fm}^4\text{ (1980FE07)}.$$

1. ^{4}He(^{7}Li, α_0) $E_b = 8.6641$

A 13.7 MeV ^{7}Li beam impinged on a thick ^{4}He gas filled chamber and the spectrum of elastically scattered α particles, measured in a position sensitive ΔE-E Si telescope, was evaluated to determine the ^{7}Li(α, α) excitation function (2011YA02). An array of NaI detectors surrounding the target excluded participation of ^{7}Li*(0.48). States deduced from an R-matrix analysis are presented in Table 11.20.

2. ^{6}Li(^{6}Li, p)^{11}B $Q_m = 12.2169$

At $E(^6\text{Li}) = 2$ to 16 MeV, angular distributions have been measured for the proton groups corresponding to the first eight states of ^{11}B (1987DO05) and for p_0, p_1, p_2, p_6, p_7 and p_9 (1990LE05). For the earlier work see (1980AJ01). For excitation functions see ^{12}C. See also (1987DO07).

3. ^{7}Li(α, γ)^{11}B $Q_m = 8.6641$

Resonances for capture radiation are displayed in Table 11.21. See also (1995DE05, 1996RE16, 1999AN35, 2004GY02, 2010ZH21).

Fig. 4: Energy levels of ^{11}B. 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 ^{11}B 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 (2011AUZZ). Further information on the levels illustrated, including a listing of the reactions in which each has been observed, is contained in Table 11.18.

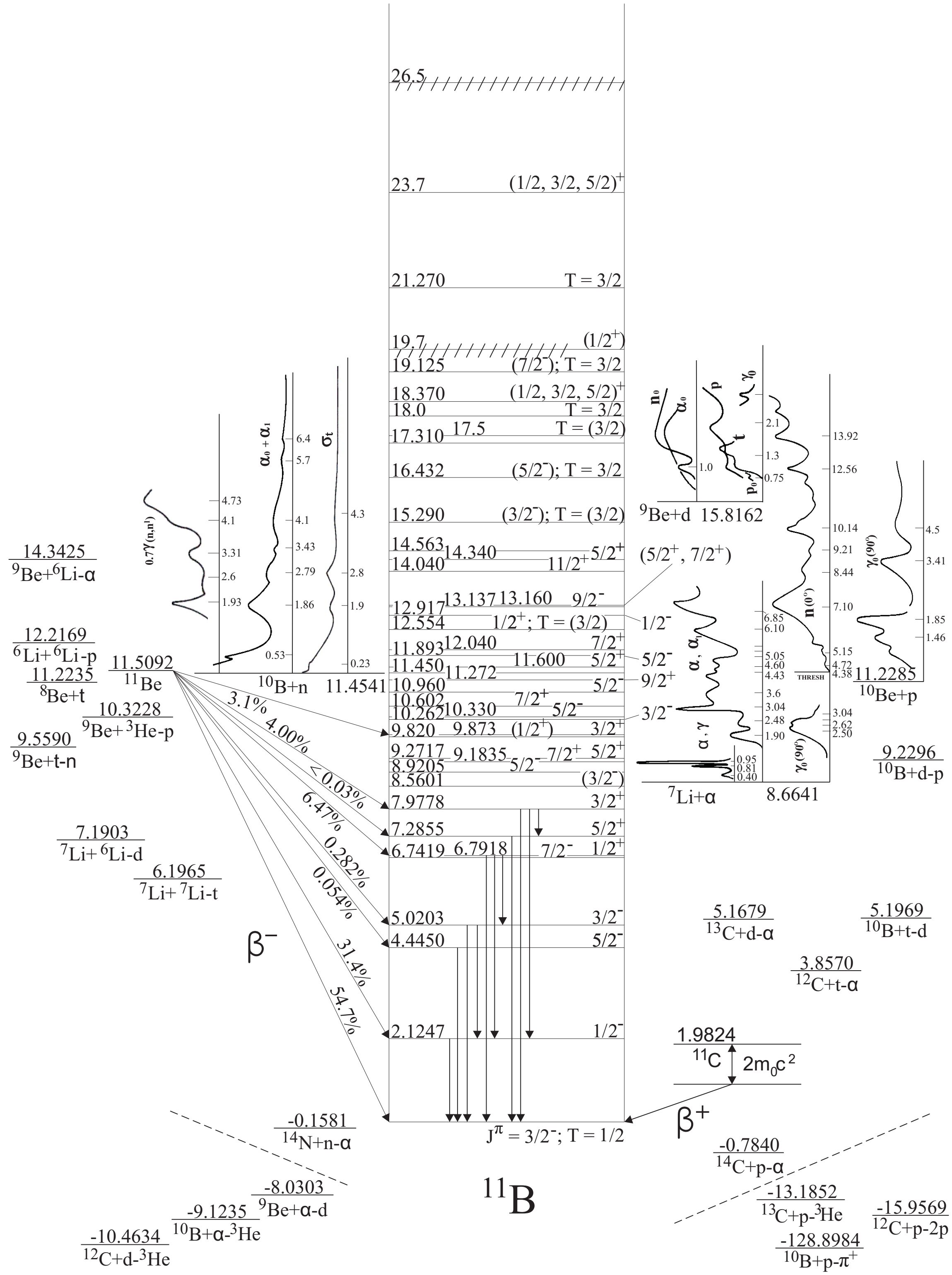

Fig. 4: Energy levels of ^{11}B.

Table 11.18: Energy levels of ^{11}B

E_x (MeV ± keV)	$J^\pi; T$	Γ_{cm} (keV)	Decay	Reactions
0	$\frac{3}{2}^-; \frac{1}{2}$	stable		2, 3, 7, 8, 11, 15, 16, 17, 18, 19, 22, 26, 27, 28, 29, 30, 32, 33, 34, 35, 36, 37, 39, 40, 42, 44, 45, 46, 47, 48, 49, 50, 51, 53, 54, 55, 56, 57, 58, 59, 60, 61, 63, 67, 68, 69, 70, 71, 72, 73, 74
2.124693 ± 0.027	$\frac{1}{2}^-$	0.117 ± 0.004 eV	γ	2, 7, 8, 11, 15, 16, 17, 18, 19, 26, 27, 28, 30, 32, 33, 35, 36, 37, 39, 40, 42, 44, 51, 53, 54, 55, 56, 57, 58, 59, 60, 61, 63, 67, 68, 69, 70, 71, 72, 73, 74
4.44498 ± 0.07	$\frac{5}{2}^-$	0.55 ± 0.05 eV	γ	2, 3, 7, 8, 11, 15, 16, 17, 18, 19, 22, 26, 27, 28, 29, 30, 32, 33, 35, 36, 37, 39, 40, 42, 44, 51, 53, 54, 55, 56, 58, 59, 63, 67, 68, 69, 70, 71, 72, 73, 74
5.02030 ± 0.30	$\frac{3}{2}^-$	1.97 ± 0.07 eV	γ	2, 7, 8, 11, 16, 17, 18, 19, 26, 27, 28, 29, 30, 32, 33, 35, 36, 37, 39, 40, 42, 51, 53, 55, 56, 57, 58, 59, 61, 63, 67, 68, 69, 70, 71, 72, 74
6.74185 ± 0.08	$\frac{7}{2}^-$	0.030 ± 0.007 eV	γ	2, 3, 7, 11, 16, 17, 18, 19, 22, 26, 27, 28, 29, 32, 36, 37, 39, 40, 42, 51, 53, 59, 61, 67, 68, 69, 70, 71, 73, 74
6.79180 ± 0.30	$\frac{1}{2}^+$	0.39 ± 0.05 eV	γ	2, 3, 7, 11, 16, 17, 18, 19, 26, 27, 28, 30, 32, 36, 39, 40, 44, 51, 53, 56, 61, 68, 69, 71, 74

Table 11.18: Energy levels of ^{11}B (continued)

E_x (MeV ± keV)	$J^\pi; T$	Γ_{cm} (keV)	Decay	Reactions
7.28551 ± 0.43	$\frac{5}{2}^+$	1.14 ± 0.08 eV	γ	2, 3, 7, 8, 15, 16, 17, 18, 19, 26, 27, 28, 30, 32, 33, 35, 36, 39, 40, 51, 53, 58, 59, 69, 71, 74
7.97784 ± 0.42	$\frac{3}{2}^+$	1.15 ± 0.15 eV	γ	2, 3, 7, 16, 18, 19, 26, 27, 30, 32, 33, 35, 36, 39, 42, 51, 53, 58, 59, 69, 71
8.5601 ± 1.7	$(\frac{3}{2}^-)$	1.00 ± 0.09 eV	γ	2, 7, 8, 15, 16, 18, 19, 26, 27, 32, 33, 35, 36, 37, 39, 40, 42, 51, 53, 59, 68, 69, 70, 71
8.92047 ± 0.11	$\frac{5}{2}^-$	4.374 ± 0.023 eV	γ, α	2, 3, 7, 15, 16, 18, 22, 26, 27, 29, 32, 33, 35, 36, 37, 39, 42, 59, 61, 67, 68, 70
9.1835 ± 1.0	$\frac{7}{2}^+$	$1.8^{+1.5}_{-1.1}$ eV	γ, α	2, 3, 8, 16, 18, 26, 27, 29, 31, 36, 39, 63, 72
9.2717 ± 1.0	$\frac{5}{2}^+$	≈ 4	γ, α	2, 3, 9, 16, 18, 26, 27, 33, 36, 39, 62, 63, 72
9.820 ± 25	$(\frac{1}{2}^+)$			53
9.873 ± 4	$\frac{3}{2}^+$	109 ± 14	α	6, 16, 30, 59, 72
10.262 ± 8	$\frac{3}{2}^-$	163 ± 22	γ, α	1, 3, 6, 9, 16, 39, 62, 63, 72
10.330 ± 8	$\frac{5}{2}^-$	112 ± 10	γ, α	1, 3, 6, 8, 16, 27, 62, 70
10.602 ± 4	$\frac{7}{2}^+$	91 ± 20	γ, α	1, 3, 6, 9, 16, 25, 33, 36, 39, 63, 72
(10.960 ± 50)	$\frac{5}{2}^-$	≈ 4500	α	6, 72
11.272 ± 14	$\frac{9}{2}^+$	110 ± 20	α	1, 6, 9, 16, 33, 39, 72
11.450 ± 17		93 ± 17	α	6, 8, 16, 18
11.600 ± 20	$\frac{5}{2}^+$	180 ± 20	n, α	4, 6, 16, 25, 70
11.893 ± 13	$\frac{5}{2}^-$	194 ± 6	n, α	4, 6, 9, 16, 25
12.040 ± 130	$\frac{7}{2}^+$	≈ 1000	n, α	6, 25
12.554 ± 13	$\frac{1}{2}^+; (\frac{3}{2})$ [a]	205 ± 20	γ, p, α	6, 8, 9, 16, 18, 20, 21, 31, 39

Table 11.18: Energy levels of ^{11}B (continued)

E_x (MeV ± keV)	$J^\pi; T$	Γ_{cm} (keV)	Decay	Reactions
12.917 ± 11	$\frac{1}{2}^{-\,b}; \frac{3}{2}$	230 ± 20	γ, p, α	6, 9, 16, 20, 21, 36, 67, 70
13.137 ± 40	$\frac{9}{2}^-$	426 ± 40	n t, α	1, 4, 8, 9, 16, 23, 24, 25
13.16	$(\frac{5}{2}^+, \frac{7}{2}^+)$	363	n, α	18, 23, 25
14.040 ± 80	$\frac{11}{2}^+$	500 ± 200	n, α	4, 6, 9, 23, 25
14.340 ± 20	$\frac{5}{2}^+; (\frac{3}{2})^{\,a}$	253 ± 19	γ, p	9, 16, 17, 20, 39
14.563 ± 11		≤ 30	n, t, α	4, 8, 16, 17, 23, 24, 39, 70
15.290 ± 25	$(\frac{3}{2}^-)^{\,b}; (\frac{3}{2})$	282 ± 15	γ, p, n, α	20, 23, 25, 36, 70
16.432 ± 10	$(\frac{5}{2}^-)^{\,b}; \frac{3}{2}$	≤ 30	p, d, α	11, 13, 16, 36, 70
17.31		≈ 1000	n, d, t, α	13, 24, 25
17.500 ± 30	$T = (\frac{3}{2})^{\,a}$	116 ± 25	γ, n, p, d, α	4, 9, 11, 13, 16
18.000 ± 100	$T = \frac{3}{2}$	870 ± 100		16
18.370 ± 50	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^+$	260 ± 80	γ, d	11
19.125 ± 26	$(\frac{7}{2}^-)^{\,b}; \frac{3}{2}$	115 ± 25		16, 70
19.7	$(\frac{1}{2}^+)$	broad	γ, d	11, 21
21.270 ± 50	$T = \frac{3}{2}$	300 ± 30		16
23.7	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^+$		γ, d	11
26.5		broad	γ, n	31

[a] See reactions 8(b) and 9(a).

[b] From ^{14}C(p, α), also see $J^\pi = (\frac{7}{2})^+$ for ^{11}B*(15.290) from ^{10}B(n, n); see (1975AJ02, 1985AR03, 1990SA24)

4. ^{7}Li(α, n)^{10}B $\qquad Q_m = -2.7900 \qquad E_b = 8.6641$

The total cross section has been measured from threshold to $E_\alpha = 5.67$ MeV [see also reaction 25]: a broad maximum at $E_\alpha \approx 5.1$ MeV ($\sigma_{max} = 40$ mb) is observed (1984OL05). The neutron spectrum and neutron-to-γ-ray radiation yield of Li-^{241}Am$_2$O$_3$ and Li-^{238}PuO$_2$ sources are evaluated in (1993VL02). For the earlier work see Table 11.7 in (1985AJ01). See also (1985CA41; astrophys.).

Table 11.19: Electromagnetic transitions in ^{11}B [a]

Initial state	J^π	Γ_γ (total) (eV)	Branching ratios (%) to final state [h]						
			g.s.	2.12	4.44	5.02	6.74	6.79	7.29
2.12 [b]	$\frac{1}{2}^-$	0.117 ± 0.004	100						
4.44 [b]	$\frac{5}{2}^-$	0.55 ± 0.05	100 [i]						
5.02 [c]	$\frac{3}{2}^-$	1.97 ± 0.07	85.6 ± 0.6 [j]	14.4 ± 0.6 [k]					
6.74 [d]	$\frac{7}{2}^-$	0.030 ± 0.007	70 ± 2 [l]	< 3	30 ± 2	< 1			
6.79 [c]	$\frac{1}{2}^+$	0.39 ± 0.05	67.5 ± 1.1	28.5 ± 1.1	< 0.04	4.0 ± 0.3			
7.29 [d]	$\frac{5}{2}^+$	1.14 ± 0.08	87.0 ± 2.0 [m]	< 1	5.5 ± 1 [n]	7.5 ± 1 [o]			
7.98 [e]	$\frac{3}{2}^+$	1.15 ± 0.15	46.2 ± 1.1	53.2 ± 1.2	< 0.06	< 0.09		< 0.10	0.85 ± 0.04
8.56 [d]	$(\frac{3}{2}^-)$ [p]	1.00 ± 0.09	56 ± 2	30 ± 2	5 ± 1	9 ± 1			
8.92 [f]	$\frac{5}{2}^-$	4.368 ± 0.021	95 ± 1 [q]	< 1	4.5 ± 0.5 [r]	< 1	< 1	< 1	
9.19 [g]	$\frac{7}{2}^+$	$0.17^{+0.06}_{-0.03}$	0.9 ± 0.3		86.6 ± 2.3		12.5 ± 1.1	< 1.3	
9.27 [g]	$\frac{5}{2}^+$	1.15 ± 0.16	18.4 ± 0.9		69.7 ± 1.4		11.9 ± 0.6	< 0.6	

[a] See Table 11.4 in (1980AJ01), Tables 11.21 and 11.30 here and (1965OL03).

[b] Γ_γ from ^{11}B(γ, γ'). The mean of values given in Table 11.14 in (1985AJ01).

[c] Γ_γ from ^{11}B(γ, γ') (1980MO23). Branching Ratios (BR) from discussion in (1982MI08).

[d] Γ_γ from ^{11}B(γ, γ') (1980MO23). BR from ^{9}Be(^{3}He, pγ), ^{10}B(d, pγ) and analysis of prior results (1965OL03). See also ^{11}B(n, nγ) (1972NI05).

[e] Γ_γ from ^{11}B(γ, γ') (1980MO23). BR from discussion in (1982MI08). See also ^{9}Be(^{3}He, pγ) and ^{10}B(d, pγ) (1965OL03) and ^{11}B(n, n$'\gamma$) (1972NI05).

[f] Γ_γ from discussion in (1984HA13). BR from (1965OL03).

[g] Γ_γ from ^{7}Li(α, γ) (1984HA13). BR from (1985AJ01) analysis of (1962GR07, 1984HA13) and earlier results.

[h] Mixing ratios are given in the Krane-Steffen convention. Values from (1968BE03) have been converted here from the Rose and Brink convention.

[i] $\delta = +0.158^{+0.025}_{-0.021}$ (2009RU04). See also $\delta = +0.19 \pm 0.03$ (1968BE03).

[j] $\delta = -0.036 \pm 0.013$ (2009RU04). See also $\delta = -0.03 \pm 0.05$ (1968BE03).

[k] $\delta = -0.19^{+0.10}_{-0.17}$ (2009RU04). See also $\delta = -0.05 \pm 0.20$ (1968BE03).

[l] $\delta = -0.45 \pm 0.18$. This value leads to too large a value of Γ_γ for an M3 transition (P.M. Endt, private communication with FAS).

[m] $\delta = +0.001^{+0.022}_{-0.021}$ (2009RU04).
[n] $\delta = -0.081^{+0.164}_{-0.126}$ (2009RU04).
[o] $\delta = +0.028^{+0.073}_{-0.075}$ (2009RU04).
[p] This is probably the ^{11}B analog of ^{11}C*(8.10). If so $J^{\pi} = \frac{3}{2}^{-}$.
[q] $\delta = 0.000 \pm 0.014$ (2009RU04). See also $\delta = -0.11 \pm 0.04$ (1968CO09).
[r] $\delta = -0.061^{+0.025}_{-0.022}$ (2009RU04).

Comments [mainly from (1962GR07, 1965OL03)]

(1) *4.44 MeV*. $9.28 \to 4.44 \to 0$ angular distribution fixes $J = \frac{5}{2}$. Odd parity determined from direct interaction assignments.

(2) *5.02 MeV*. Internal pair correlation permit M1, E2 for the g.s. transition: $J^{\pi} \leq \frac{7}{2}^{-}$ (parity from l-assignments). $\tau_{\rm m}$ excludes $\frac{7}{2}$, branch to 2.12, $\frac{5}{2}$. Angular correlation fixes $\frac{3}{2}^{-}$.

(3) *6.74 MeV*. Internal pairs indicate practically pure E2 g.s. radiation. Angular distributions and branching ratios (and l-assignments) all lead to $\frac{7}{2}^{-}$.

(4) *6.79 MeV*. The allowed β-decay from ^{11}Be [$J^{\pi} = \frac{1}{2}^{+}$] requires $J^{\pi} \leq \frac{3}{2}^{+}$. The relatively strong γ-branch to ^{11}B*(2.12) favors $\frac{1}{2}^{+}$, $\frac{3}{2}^{+}$. All γ-rays from this level are isotropic, suggesting $J^{\pi} = \frac{1}{2}^{+}$, but not excluding $\frac{3}{2}^{+}$.

(5) *7.29 MeV*. The g.s. transition is mainly E1, so $J^{\pi} \leq \frac{5}{2}^{+}$. The assignment $\frac{1}{2}^{+}$ is excluded by the strength of (7.29→4.44). $J^{\pi} = \frac{5}{2}^{+}$ is consistent with $\log ft > 8.04$ in the ^{11}Be β-decay.

(6) *7.98 MeV*. Transitions to ^{11}B(0, 2.12) are predominantly E1; thus ^{11}B*(7.98) has even parity, and the odd parity of ^{11}B*(2.12) is confirmed. The transition to ^{11}B*(2.12) is not isotropic, so $J^{\pi} = \frac{3}{2}^{+}$.

(7) *8.56 MeV*. Correlation of internal pairs indicate that the g.s. transition is M1 + E2 or E1 + M2, $J^{\pi} =\leq \frac{5}{2}^{+}$ or $\leq \frac{7}{2}^{+}$; the lifetime to ^{11}B*(2.12) excludes $\frac{7}{2}^{-}$. If the level has even parity, the required M2 admixture is excessive. $J^{\pi} \leq \frac{5}{2}^{-}$ is favored. See also footnote [p].

(8) *8.92 MeV*. From ^{7}Li(α, γ)^{11}B, $J^{\pi} = \frac{3}{2}^{+}$, $\frac{5}{2}^{+}$, $\frac{5}{2}^{-}$. The internal pair correlation confirms $\frac{5}{2}^{-}$. For higher states see comments under individual reactions and (1968AJ02).

Table 11.20: States deduced from R-matrix analysis of ^{4}He(^{7}Li, α_0)

E_x [a] (MeV ± keV)	L [b]	J^π [a]	Γ_α [b] (keV)	Γ [d] (keV)
10.24	2	$\frac{3}{2}^-$	4 (< 9) [c]	163 ± 22
10.34	2	$\frac{5}{2}^-$	19 ± 4 [c]	112 ± 10
10.60	3	$\frac{7}{2}^+$	10 ± 3 [c]	91 ± 20
11.06 ± 40 [b]	3	$\frac{5}{2}^+$ ($\frac{3}{2}^+$, $\frac{7}{2}^+$, $\frac{9}{2}^+$) [b]	32 ± 20 [c]	broad
11.29	3	$\frac{9}{2}^+$	35 ± 4	110 ± 20
(11.59) [b]	4	($\frac{7}{2}^-$) [b]	270 ($\Gamma_n = 580$)	180 ± 20
12.63 ± 40 [b, e]	3	($\frac{3}{2}^+$, $\frac{5}{2}^+$, $\frac{7}{2}^+$, $\frac{9}{2}^+$) [b]	33-400	
13.03	4	($\frac{9}{2}^-$)	140^{+110}_{-80}	426 ± 40

[a] From (1990AJ01, 2004TI06).
[b] From (2011YA02).
[c] For these states $\Gamma = \Gamma_\alpha + \Gamma_\gamma$, but the deduced Γ_α is much less than the accepted Γ_{tot}.
[d] From Table 11.18.
[e] Multiplet.

5. ^{7}Li(α, t)^{8}Be $\quad Q_m = -2.5595 \quad E_b = 8.6641$

Excitation functions have been measured for $E_\alpha = 14$ to 25 MeV (t_0) and 18 to 25 MeV (t_1): see (1980AJ01). See also ^{8}Be in (2004TI06) and (1987DM1C).

6. ^{7}Li(α, α)^{7}Li $\quad E_b = 8.6641$

The elastic scattering and the scattering to ^{7}Li*(0.48) have been studied at many energies up to $E_\alpha = 22.5$ MeV: see (1975AJ02, 1980AJ01, 1985AJ01). Observed resonances are displayed in Table 11.22. For α-^{7}Li correlations see (1987PO03).

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

Angular distributions have been measured for $E(^7\text{Li}) = 3.3$ to 5.95 MeV: see (1975AJ02).

Table 11.21: Resonances deduced from ^{7}Li(α, γ)^{11}B [a]

E_{α} (keV)	$\Gamma_{\rm cm}$ (keV)	^{11}B* (MeV)	J^{π}	$\omega\gamma$ (eV)	Γ_{γ_0} (eV)	Percentage decay to ^{11}B*			
						0	4.44	6.74	6.79
401 ± 3 [b]	4.37 ± 0.02 eV	8.919	$\frac{5}{2}^{-}$	$(8.8 \pm 1.4) \times 10^{-3}$	4.15 ± 0.02 [c]	95 ± 1	4.5 ± 0.5		
814 ± 2 [b]	$1.8^{+1.5}_{-1.1}$ eV	9.182	$\frac{7}{2}^{+}$	0.303 ± 0.26 [g]	$0.17^{+0.05}_{-0.01}$ [d]	0.9 ± 0.3	90.8 ± 4.0	8.3 ± 1.0	< 1.3
953 ± 2 [b]	4	9.271	$\frac{5}{2}^{+}$	1.72 ± 0.24	0.20 ± 0.03 [c]	17.1 ± 1.0	71.7 ± 1.8	11.2 ± 0.6	< 0.6 [e]
2500 ± 20	433	10.26			17	[f]			
2620 ± 20	100	10.33			1.0	[f]			
2800 ± 80	≈ 140	10.45			$10/(2J+1)$				
(3040)	90	(10.60)			< 0.2	[f]			

[a] See Table 11.6 in (1980AJ01) for comments and references.

[b] Γ_{α}(cm)=$(5.9 \pm 0.9) \times 10^{-3}$, $1.6^{+1.5}_{-1.1}$, and 4×10^{3} eV for ^{11}B*(8.92, 9.19, 9.27) (1984HA13). See also Table 11.19.

[c] See Table 11.19.

[d] Γ_{γ}, not Γ_{γ_0}. See also Table 11.19.

[e] The decay to ^{11}B*(7.29, 7.98) [$J^{\pi} = \frac{5}{2}^{+}, \frac{3}{2}^{+}$] is also observed: $\approx 1\%$ and $\approx 0.03\%$ respectively.

[f] $< 10\%$ to ^{11}B*(2.12).

[g] Weighted average of 0.300 ± 0.032 (2004GY02) and 0.310 ± 0.047 (1984HA13).

Table 11.22: Resonant structures in ^{7}Li(α, α)^{7}Li and ^{7}Li(α, α')^{7}Li [a]

E_α [b] (keV)	E_α [c] (keV)	Γ_{cm} (keV)	E_x (MeV $\pm$ keV)	J^π
1900 ± 10		130 ± 30	9.873 ± 10	$\frac{3}{2}^+$
2480 ± 50		150 ± 40	10.24 ± 50	$\frac{3}{2}^{(-)}, \frac{1}{2}$
	2630 ± 30	80 ± 30	10.34 ± 30	$\frac{5}{2}^-, \frac{7}{2}$
3040 ± 10	3040	70 ± 10	10.599 ± 10	$\frac{7}{2}^+$
(3600 ± 50) [e]		(4500)	(10.96 ± 50)	$\frac{5}{2}^-$
	4120 ± 30	90 ± 50	11.29 ± 30	$\frac{9}{2}^+$
4430 ± 50	4430		11.49 ± 50	
4600 ± 50		150 ± 50	11.59 ± 50	
5050 ± 30		150 ± 50	11.88 ± 30	
	5300 ± 200	≈ 1000	12.0 ± 200	
	5500 ± 100	60 ± 50	(12.17 ± 100) [d]	
6100 ± 30		150 ± 50	12.55 ± 30	
6850 ± 60		270 ± 50	13.03 ± 60	
(7200 ± 50) [e]		50 ± 50	(13.25 ± 50) [d]	
	7800 ± 100	500 ± 200	(13.63 ± 100) [d]	
(8450 ± 200) [f]		500 ± 200	(14.0 ± 200)	
(9450 ± 200) [f]		≤ 250	(14.7 ± 200)	
	9950 ± 20	500 ± 200	(15.00 ± 20) [d]	
(11200 ± 200) [f]			(15.8 ± 200)	

[a] Mostly from (1966CU02). For other parameters see Table 11.9 in (1975AJ02). See also Table 11.8 in (1985AJ01).

[b] ^{7}Li(α, $\alpha'\gamma$)^{7}Li: σ (total).

[c] ^{7}Li(α, α_0)^{7}Li.

[d] ^{7}Li(α, n)^{10}B threshold.

[e] Anomaly in angular distribution.

[f] Observed at $\theta = 60°$.

Table 11.23: States populated in ^{7}Li(^{7}Li, ^{11}B*) and their breakup decay branching ratios (2005CU06)

E (MeV)	($\alpha + {}^{7}$Li) (%)	(t $+ {}^{8}$Be) (%)	(d $+ {}^{9}$Be) (%)
9.18	100		
10.36	100		
11.42	100		
12.65	> 99.8	< 0.2	
13.21	> 99.8	< 0.2	
≈ 14.5	97.7 ± 8.3	2.3 ± 0.2	
≈ 15.5	96.7 ± 10.6	3.3 ± 0.6	
≈ 17.7		< 31.0	> 69.0
≈ 18.3		< 18.1	> 81.9
≈ 19.6		< 34.8	> 65.2

8. (a) ^{7}Li(^{7}Li, t)^{11}B $Q_{\rm m} = 6.1965$
   (b) ^{7}Li(^{7}Li, ^{11}B*)

For reaction (a), angular distributions have been measured at $E(^{7}$Li$) = 2.10$ to 16 MeV. See (1975AJ02) for references. At $E(^{7}$Li$) = 2$ to 16 MeV angular distributions and excitation functions for p, t and α cluster transfer were measured and evaluated using a DWBA analysis (2010RO09). While proton transfer was found to be nearly a 100% direct process, the α-particle transfer, to ^{11}B was more complex. On average the ^{11}B$_{\rm g.s.}$ and states at ^{11}B*(2.12, 4.44, 5.02) were populated 20 to 60 % by direct processes; compound nucleus processes were found to be less than 20%. At $E(^{7}$Li$) = 79.6$ MeV transitions are observed to several ^{11}B states; ^{11}B$_{\rm g.s.}$ is particularly strongly populated (1974CE06).

For reaction (b) at $E(^{7}$Li$) = 50.9$ MeV (2003FL02), states at ^{11}B*(11.3, 12.5, 14.3) were observed in the ^{7}Li $+ \alpha$ relative energy spectra, and at $E(^{7}$Li$) = 58$ MeV (2005CU06) states shown in Table 11.23 were populated. The observations confirm the $T = \frac{1}{2}$ nature of the 12.6 MeV and 14.3 MeV states, and the small $\Gamma_{\rm t}/\Gamma_{\alpha}$ ratio for ^{11}B*(12.6) supports the suggestion of (2004SO28) that this state is the $\frac{9}{2}^{+}$ member of the $K^{\pi} = \frac{3}{2}^{+}$ cluster band.

9. (a) ^{7}Li(^{9}Be, $\alpha +$ ^{7}Li) $Q_{\rm m} = -2.3077$
   (b) ^{7}Li(^{9}Be, $\alpha + \alpha +$ t)

At $E(^9\text{Be}) = 55$ MeV (2005SO13) and 70 MeV (2004SO19, 2004SO28, 2005SO13) states at ^{11}B*(9.3, 10.2, 10.55, 11.2, (11.4), 11.8, 12.5, (13.0), 13.1, (14.0), 14.35, (17.4) and (18.6)) are observed in reaction (a). It is suggested that these states may have a $2\alpha + t$ cluster structure. These $T = \frac{1}{2}$ states have some overlap with $T = \frac{3}{2}$ states and may indicate isospin mixing. The states at $E_x = 12.5$, 14.35, 17.45 MeV are believed to be IAS of low-lying ^{11}Be states.

For reaction (b), participation of ^{8}Be*(0, 3.04) and ^{7}Li*(4.65, 6.6) is found in the reconstruction of ^{11}B*(13.1, 14.4, 17.5) states from $\alpha + \alpha + \text{t}$ coincidences. Also see (2007FR22).

10. ^{8}Li(α, n)^{11}B $\qquad Q_m = 6.6315$

Reaction cross sections have been measured at $E_{cm} = 0.9$ to 2.8 MeV (2004MI34), $E_{cm} = 0.6$ to 2.7 MeV (2004HA54, 2006IS04), $E_{cm} = 1.05$ MeV (2008LA08, 2010LA07), $E_{cm} = 1.25$ MeV, $E_{cm} = 1.5$ to 7 MeV (2000MI34) and $E(^8\text{Li}) = 10$ to 20 MeV (1992BO06). Various ^{12}B resonances are observed. Rates for the reaction path ^{8}Li(α, n)^{11}B(n, γ)^{12}B(β)^{12}C are crucial for computing the formation of $A > 12$ nuclei in inhomogeneous Big Bang Nucelosynthesis (1992BO06, 1993DE30, 2000MI34, 2004CH22). Early estimates for the ^{8}Li(α, n) reaction rate were based on the inverse reaction, ^{11}B(n, α), see i.e. (1990PA22, 1991PA26); however, such measurements are only sensitive to the n_0 contribution to the total cross section. The direct measurements with ^{8}Li beams indicate participation of ^{11}B excited states and a much larger total cross section. Systematic issues are evident when comparing inclusive (^{8}Li, n) and exclusive (^{8}Li, n + ^{11}B) results: see (2006IS04). A novel experiment approached the issue by impinging a ^{8}Li beam on a ^{4}He gas target that was located inside a zero-energy-threshold 4π ^{3}He proportional counter embedded in a polyethylene moderator (2008LA08, 2010LA07). See (2000MI34) for branching ratios to n_0 through n_9. Also see discussion in (1992RA04, 1993OB01, 1994KU28, 1996DE02, 2003SO22), and see (2011AU01) for a discussion of ^{11}B production in core-collapse supernovae.

11. ^{9}Be(d, γ)^{11}B $\qquad Q_m = 15.8162$

The $\theta = 90^\circ$ γ_0 differential cross section has been measured for $E_d = 0.5$ to 11.9 MeV: see (1975AJ02). The behavior of the γ_0, γ_1, and γ_{2+3} total cross sections and of the angular distributions of these γ-rays indicate two resonances at $E_d = 1.98 \pm 0.05$ and 3.12 ± 0.05 MeV with $\Gamma_{lab} = 225 \pm 50$ and 320 ± 100 keV, corresponding to ^{11}B*(17.43, 18.37). The higher resonance was not observable in the $\gamma_2 + \gamma_3$ cross section which was not measured beyond $E_d = 2.5$ MeV. The maximum γ_0 cross section observed is 10.1 ± 3.5 μb at $E_d \approx 0.96$ MeV. Resonant behavior is observed in the $\theta = 90^\circ$ γ_0 cross section at $E_d \approx 3.4$ and 9.65 MeV (^{11}B*(18.6, 23.7)) in addition to a wide structure at 4.7 MeV (^{11}B*(19.7)). The angular distributions of γ_0 from ^{11}B*(18.6, 23.7) are typical of E1 transitions. The (d, γ_0) reaction appears to proceed via excitation of the $T = \frac{1}{2}$ component of the giant dipole resonance in ^{11}B (1974DE01).

12. ^{9}Be(d, n)^{10}B $Q_{\rm m} = 4.3621$ $E_{\rm b} = 15.8162$

The cross section follows the Gamow function for $E_{\rm d} = 70$ to 110 keV. The fast neutron and γ-yield rise smoothly to $E_{\rm d} = 1.8$ MeV except for a possible "resonance" at $E_{\rm d} \approx 0.94$ MeV. The fast neutron yield then remains approximately constant to 3 MeV: see (1968AJ02) for references. The excitation functions for $\rm n_0 \rightarrow n_4$, and n to ^{10}B*(5.1, 6.57) have been measured for $E_{\rm d} = 14$ to 16 MeV; no strong fluctuations are observed: see (1975AJ02). Thick target yields for γ-rays have been measured at $E_{\rm d} = 48$ to 170 keV: see (1985AJ01). Thick target yields are also reported at $E_{\rm d} = 14.8$, 18.0 and 23.0 MeV: see (1980AJ01). Polarization measurements have been carried out at $E_{\rm d} = 0.4$ to 5.5 MeV [see (1975AJ02, 1980AJ01)] and at $E_{\vec{\rm d}} = 12.3$ MeV: see (1985AJ01). See also ^{10}B in (2004TI06).

13. (a) ^{9}Be(d, p)^{10}Be $Q_{\rm m} = 4.5877$ $E_{\rm b} = 15.8162$

(b) ^{9}Be(d, α)^{7}Li $Q_{\rm m} = 7.1521$

(c) ^{9}Be(d, t)^{8}Be $Q_{\rm m} = 4.5927$

Measurements of proton yields have been carried out at $E_{\rm d} \leq 6.0$ MeV for $\rm p_0$ and $\rm p_1$ [see (1975AJ02, 1980AJ01, 1985AJ01)]. The $\rm p_0$ and $\rm p_1$ yields show a resonance at $E_{\rm d} = 750 \pm 15$ keV [^{11}B*(16.43), $\Gamma \approx 40$ keV] and the $\rm p_1$ yield resonates at 1.85 MeV [^{11}B*(17.33), $\Gamma_{\rm cm} \approx 1.0$ MeV] and 2.3 MeV [^{11}B*(17.70), sharp]. See also (1975AJ02, 1985AJ01) for other possible structures. Polarization of the protons has been measured at $E_{\rm d} = 1$ to 21 MeV [see (1975AJ02, 1980AJ01, 1985AJ01, 1990AJ01)] and at $E_{\vec{\rm d}} = 2.5$ to 3.0 MeV (1995LY03). See also ^{10}Be in (2004TI06).

The yield of α-particles (reaction (b)) has been measured for $E_{\rm d} = 0.3$ to 14.43 MeV [see (1975AJ02, 1980AJ01, 1985AJ01)]. The 0.75 MeV resonance, observed in reaction (a), is weakly populated in the α_0 yield. The VAP was measured for α_{0+1} at $E_{\rm d} = 2.0$ to 3.0 MeV and compiled for 1.4 to 3.0 MeV (1994LY02); analysis shows influence from ^{11}B*(17.33, 17.43, 17.7, 18.0). For other polarization measurements see references in (1985AJ01, 1990AJ01). Also see ^{7}Li in (2002TI10).

The cross section for reaction (c) has been measured for $E_{\rm d} = 0.15$ to 19 MeV: see (1968AJ02, 1975AJ02, 1980AJ01), and for $E_{\rm d} = 3$ to 11 MeV (1995AB41). Resonant structures are reported by (1995AB41) near ^{11}B*(18.1, 19.5, 22.4, 24.4). Polarization measurements are reported at $E_{\vec{\rm d}} =$ 12 and 15 MeV [see (1980AJ01, 1990AJ01)] and at $E_{\vec{\rm d}} = 2.5$ to 3.0 MeV (1994LY02). In the analysis of (1994LY02), which included VAPs for $E_{\rm d} = 1.4$ to 3.0 MeV, an anomaly near $E_{\rm d} = 2.4$ MeV is attributed to a resonance at $E(^{11}\rm B) \approx 17.8$ MeV, which could be the IAS to ^{11}Be*(5.25). See also ^{8}Be in (2004TI06).

See (1997YA02, 1997YA08) for measurements of ^{9}Be + d astrophysical S-factors at $E_{\rm d} = 57$ to 139 keV.

14. ^{9}Be(d, d)^{9}Be $E_{\rm b} = 15.8162$

Excitation functions for elastically scattered deuterons have been measured for $E_{\rm d} = 0.4$ to 7.0 MeV and for 12.17 to 14.43 MeV (also $\rm d_1, d_2$) [see (1975AJ02, 1980AJ01)]. Polarization measurements have been reported at $E_{\vec{\rm d}} = 6.3$ to 15 MeV [see (1975AJ02, 1980AJ01, 1990AJ01)]. See also ^{9}Be in (1988AJ01).

15. ^{9}Be(t, n)^{11}B $\qquad Q_{\rm m} = 9.5590$

Angular distributions have been measured at $E_{\rm t} = 1.1$ to 1.7 MeV ($\rm n_0, n_1, n_2, n_6, n_8, n_9$): see (1980AJ01).

16. ^{9}Be(^{3}He, p)^{11}B $\qquad Q_{\rm m} = 10.3228$

Observed proton groups are displayed in Table 11.24. Angular distributions have been obtained at a number of energies in the range $E(^{3}{\rm He}) = 1.0$ to 38 MeV [see (1980AJ01, 1985AJ01, 1990AJ01)]. It is suggested that the $T = \frac{1}{2}$ strength is strongly fragmented (1982ZW02). See also ^{12}C in (1990AJ01).

Table 11.24: Energy levels of ^{11}B from ^{9}Be(^{3}He,p)^{11}B

$E_{\rm x}$ [a] MeV ± keV)	$E_{\rm x}$ [b] MeV ± keV)	$\Gamma_{\rm cm}$ [b] (keV)	L
0			0
2.1243 ± 0.9			0
4.4434 ± 1.8			0
5.0187 ± 2.3			0
6.7411 ± 3.0			
6.7909 ± 3.1			1
7.285 ± 10			
7.975 ± 10			
8.553 ± 10			0
8.909 ± 10	8.934 ± 15		$0 + 2$
9.175 ± 10	9.183 ± 15		$(1) + 3$
9.264 ± 10	9.265 ± 15	10 ± 10	$1 + 3$
9.86 ± 20	9.887 ± 15	104 ± 15	1
	10.265 ± 25	168 ± 25	2

Table 11.24: Energy levels of ^{11}B from ^{9}Be(^{3}He,p)^{11}B (continued)

E_x [a] MeV ± keV)	E_x [b] MeV ± keV)	Γ_{cm} [b] (keV)	L
	10.337 ± 20	123 ± 20	$0+2$
	10.580 ± 20	122 ± 20	$1+3$
	11.254 ± 20	110 ± 20	3
	11.437 ± 20	103 ± 20	$(0+2)$
	11.588 ± 30	180 ± 30	$1+3$
	11.889 ± 20	204 ± 20	$0+2$
	12.563 ± 20 [c]	202 ± 25	1
	12.920 ± 20 [c]	155 ± 25	2
	13.137 ± 40	426 ± 40	$1+3$
	$\equiv 14.40$ [d]	261 ± 25	$1+3$
	14.565 ± 15	≤ 30	(1)
	16.437 ± 20 [c, e]	≤ 30	
	$\equiv 17.69$ [c, e]	91 ± 25	$(0+2)$
	18.0 ± 100 [c, e]	870 ± 100	$(1+3)$
	19.146 ± 30 [c, e]	115 ± 25	3
	21.27 ± 50 [c]	300 ± 30	$(1+3)$

[a] See Table 11.9 in (1980AJ01) for references and Table 11.34 here.
[b] $E(^{3}\text{He}) = 38$ MeV; DWBA analysis.
[c] $T = \frac{3}{2}$ state.
[d] This state may have mixed isospin ($T = \frac{1}{2} + T = \frac{3}{2}$).
[e] Not observed in ^{9}Be(α, d)^{11}B.

17. ^{9}Be(α, d)^{11}B $\qquad Q_m = -8.0303$

Angular distributions have been measured at a number of energies in the range $E_\alpha = 23.4$ to 30.2 MeV [see (1980AJ01, 1990AJ01)]. The predominant L-transfers are $L = 0, 2; 0; 0$ for ^{11}B*(0, 2.12, 5.02). The angular distribution to ^{11}B*(4.44) is flat at $E_\alpha = 27$ MeV. At $E_\alpha = 48$ MeV, ^{11}B*(16.44, 17.69, 18.0, 19.15) are not excited suggesting that these states are rather pure $T = \frac{3}{2}$ states (1982ZW02): also see ^{9}Be(^{3}He, p)^{11}B Table 11.24.

Table 11.25: Levels of ^{11}B from the ^{10}Be(p,γ_0)^{11}B reaction (1970GO04)

E_p (MeV ± keV)	E_x (MeV)	Γ_{cm} (keV)	$(J+\frac{1}{2})(\Gamma_p/\Gamma)\Gamma_{\gamma_0}$ [a] (eV)	Γ_{γ_0} [a] (eV)	$\Gamma_{\gamma_1}/\Gamma_{\gamma_0}$	J^π
(1.05 ± 40) [b]	(12.18)	230 ± 90	$3.1^{+2.9}_{-2.0}$			
1.46 ± 30	12.56	230 ± 65	10^{+7}_{-5}	10^{+7}_{-5}	0.25 ± 0.08	$\frac{1}{2}^+(\frac{3}{2}^+)$
1.85 ± 20	12.91	235 ± 27	29 ± 9	29 ± 9 [c]	≤ 0.06	$\frac{1}{2}^-$
3.41 ± 20	14.33	255 ± 36	29 ± 9	14.5 ± 4.3	≤ 0.1	$\frac{5}{2}^{(+)}(\frac{3}{2}^-)$
4.5 ± 100	15.32	635 ± 180	53^{+34}_{-26} [d]			

[a] Values reported in (1970GO04)are here shown multiplied by 1.7: see (1973GO09). See also Table 11.34.
[b] May be due to ^{10}B*(0.7) + n threshold.
[c] In the (e, e′) work of (1975KA02) a strong group is observed at $E_x = 13.0 \pm 0.1$ MeV. If it corresponds to the excitation of ^{11}B*(12.91) with $J^\pi = \frac{1}{2}^-$; $T = \frac{3}{2}$, then $\Gamma_{\gamma_0} = 36 \pm 7$ eV (1975KA02).
[d] Assumes that $\sigma_{total} = 4\pi\, d\sigma/d\Omega(90°)$.

18. ^{9}Be(^{6}Li, α)^{11}B $\qquad Q_m = 14.3425$

Angular distributions have been determined for seven α-groups at $E(^6\mathrm{Li}) = 3$ to 4 MeV, and at 24 MeV to ^{11}B*(0, 2.12) and to a number of unresolved levels with $E_x \leq 13.2$ MeV: see (1968AJ02, 1975AJ02). For the breakup reactions see (1975AJ02).

19. ^{9}Be(^{11}B, ^{11}B)^{9}Be

Angular distributions for elastic and inelastic scattering have been measured at $E(^{11}\mathrm{B}) = 45$ MeV (2003RU02). Distributions for ^{11}B*(2.12, 4.445, 5.020, 6.743 + 6.792, 7.28, 7.978, and 8.560) were analyzed with an emphasis on determining the large angle scattering mechanism which is sensitive to the short range nucleus-nucleus interaction. Deformation parameters were deduced for ^{9}Be and ^{11}B states.

20. ^{10}Be(p, γ)^{11}B $\qquad Q_m = 11.2285$

The yield of γ_0 has been measured at 90° for $E_p = 0.6$ to 6.3 MeV. Observed resonances are displayed in Table 11.25. $T = \frac{3}{2}$ assignments are made for the states at $E_x = 12.56$, 12.91, 14.33 and 15.32 MeV whose energies match those of the first four states of ^{11}Be [compare with the $T = \frac{3}{2}$ states reported in ^{9}Be(^{3}He, p)^{11}B - Table 11.24 and Table 11.34]. Several known $T = \frac{1}{2}$ states in ^{11}B are not observed in this reaction: see Table 11.18. Parameters of the 12.56 MeV state are discussed in (2006FO14, 2007BA54).

21. ^{10}Be(p, n)^{10}B $\qquad Q_{\rm m} = -0.2256 \qquad E_{\rm b} = 11.2285$

The reaction cross section has been measured for $E_{\rm p} = 0.89$ to 1.93 MeV: the excitation of ^{11}B*(12.56, 12.91) is reported (1986TE1A and G.M. Ter-Akopian, private communication; 1987ERZY). See also (1988DU06; theor.).

22. ^{10}B(n, γ)^{11}B $\qquad Q_{\rm m} = 11.4541$

$Q_0 = 11454.1 \pm 0.2$ keV (1986KO19)

Table 11.26: Thermal neutron capture γ-ray transitions from ^{10}B + n [a]

E_γ (keV) [b]	I_γ [c]	I_γ [d]	I_γ [e]	Transition [f]
11447.72 ± 0.13	4.64 ± 0.61	4.6 ± 0.3	6 ± 1	capt.→g.s.
8916.67 ± 0.16	12.8 ± 1.6	13 ± 1	15 ± 2	8.92→g.s.
6739.53 ± 0.16	18.7 ± 2.2	19 ± 2	19 ± 1	6.74→g.s.
4444.03 ± 0.08	64.6 ± 7.0	67 ± 4	65 ± 3	4.44→g.s.
7006.75 ± 0.07	54.2 ± 5.7	56 ± 2	54 ± 3	capt.→4.44
4711.18 ± 0.07	25.7 ± 2.8	28 ± 2	25 ± 1	capt.→6.74
2533.40 ± 0.14	13.8 ± 2.2	12 ± 4	15 ± 2	capt.→8.92
2296.63 ± 0.13	8.95 ± 2.10	7 ± 4	10 ± 3	6.74→4.44

[a] Photons/100 captures.
[b] From weighted average of E_γ values from (1986KO19) and (2003LI1L).
[c] (2003LI1L).
[d] (1986KO19). For the earlier work see Table 11.12 in (1975AJ02): I_γ for 5.02→ g.s. and 2.12→g.s. are < 2 and < 3, respectively (1967TH05).
[e] (1967TH05).
[f] Level energies from a least squares fit to the γ-ray energies with recoil: $E_{\rm x} = 8920.47 \pm 0.11$, 6741.85 ± 0.08 and 4444.98 ± 0.07 keV.

Values reported for the thermal capture cross section are inconsistent. The *Atlas of Neutron Resonances* evaluation gives the value $\sigma_\gamma = 305 \pm 16$ mb (2006MUZX); an earlier evaluation of the thermal capture cross sections reported $\sigma_\gamma = 0.5 \pm 0.1$ b (2003MUZZ). At the same time, the results of the measurements and analysis for the *Evaluated Gamma-ray Activation File* (EGAF) project deduced $\sigma_\gamma = 303 \pm 20$ mb (2003LI1L), but the value $\sigma_\gamma = 390 \pm 11$ mb was later published by that group (2008FIZZ). The earlier reported values are $\sigma_\gamma = 0.29 \pm 0.04$ b (1986KO19) and 0.5 ± 0.2 (1957BA18, 1973MU14). Reviewing these reported values, we accept the value $\sigma_\gamma = 305 \pm 16$ mb from the *Atlas of Neutron Resonances* (2006MUZX). The observed capture γ-rays are displayed in Table 11.26. A compilation of thermal capture data is in (2002RE13).

23. (a) ^{10}B(n, n)^{10}B $\qquad E_b = 11.4541$

(b) ^{10}B(n, n$'$)^{10}B

Coherent neutron scattering lengths and free cross sections were measured to determine the spin-dependent scattering length (1983KO17, 2006MUZX). The coherent scattering length $b(^{10}\text{B}) = -0.2 \pm 0.4$ fm (1983KO17) and the total free scattering cross section $\sigma_0 = 2.23 \pm 0.06$ b (1970AS10) are used to deduce the spin state scattering lengths $a_+ = -3.8 \pm 0.4$ fm, $a_- = 4.7 \pm 0.4$ fm, $b_+ = -4.2 \pm 0.4$ fm and $b_- = 5.2 \pm 0.4$ fm which implies a vanishing coherent scattering cross section. Therefore neutron scattering on ^{10}B is totally incoherent (1983KO17). The total scattering cross section is constant at 2.23 ± 0.06 b for $E_n = 0.7$ to 10 keV and then rises to 2.97 b at $E_n = 127$ keV. For a display of cross sections and a listing of measurements see (1988MCZT).

Total cross section measurements in the range $E_n = 10$ to 500 keV show a broad maximum near $E_n = 0.23$ MeV, also observed in the (n, α) cross section. At higher energies the total cross section shows broad maxima at $E_n = 1.9$, 2.8 and 4.3 MeV: see Table 11.28. In the range $E_n = 5.5$ to 16 MeV σ_{tot} is constant at 1.5 b.

Elastic and inelastic cross sections have also been reported at $E_n = 4$ to 17 MeV [see (1980AJ01, 1990AJ01)], and at $E_n = 3.0$ to 12.0 MeV (1990SA24). Inelastic scattering cross sections for formation of the first five states of ^{10}B have been measured in the range $E_n = 3.0$ to 12 MeV (1990SA24); twelve levels in ^{11}B above $E_x = 13$ MeV were identified. See Table 11.27 for the R-matrix analysis of (n, n_{0-5}) and (n, $n_{\alpha_{0+1}}$) data given in (1990SA24). The yield of 0.7 MeV γ-rays has been studied from threshold to $E_n = 5.2$ MeV: observed resonances are displayed in Table 11.28. See Table 11.13 in (1980AJ01) for an R-matrix analysis of cross section and analyzing power measurements from $E_n = 0.075$ to 4.4 MeV, and see (1975AJ02) for an analysis of measurements from $E_n = 1.45$ to 14.8 MeV. See also ^{10}B in (1988AJ01).

See (2008MU23) for an analysis of the $E_n < 2$ MeV ^{10}B(n, n) International Cross Section Standard: (1996CH33) for an optical model analysis of elastic scattering up to $E_n = 200$ MeV: and (2001AB14) for measurements at $E_n \leq 600$ MeV. See (2008GE04) for an analysis on Mott-Schwinger scattering of $E = 0$ to 25 meV neutrons.

Table 11.27: R-matrix analysis of ^{11}B resonance states in ^{10}B + n (1990SA24) [a]

E_x (MeV)	J^π	Γ_{n0} (MeV)	Γ_{n1} (MeV)	Γ_{n2} (MeV)	Γ_{n3} (MeV)	Γ_{n4} (MeV)	Γ_{n5} (MeV)	$\Gamma_{\alpha0}$ (MeV)	$\Gamma_{\alpha1}$ (MeV)
10.6	$\frac{7}{2}^+$							0.003	0.006
11.6	$\frac{5}{2}^+$	0.004						0.296	0.100
11.8	$\frac{7}{2}^+$	1.339						0.002	0.113
11.9	$\frac{5}{2}^-$	0.001						0.080	0.090
13.1	$\frac{9}{2}^-$	0.200						0.275	0.050
13.2	$\frac{5}{2}^+$	0.020	0.033					0.194	0.116
13.7	$\frac{3}{2}^+$	0.250	0.250					0.125	0.125
13.9	$\frac{5}{2}^-$	0.125	0.500						
14.0	$\frac{11}{2}^+$	0.800						0.045	0.010
15.2	$\frac{7}{2}^+$	0.250	0.125		0.125			0.062	0.125
15.6	$\frac{5}{2}^+$	1.000	0.300	0.025	0.380			0.068	0.278
15.8	$\frac{9}{2}^-$	0.031	0.015		0.006			0.015	0.031
16.5	$\frac{7}{2}^-$	0.500	0.250	0.100	0.010	0.500			
16.9	$\frac{5}{2}^-$	0.500	0.500	0.100	0.063	0.250			
17.8	$\frac{9}{2}^-$	0.500	0.500		0.250	0.012	1.000		
17.9	$\frac{7}{2}^-$	0.500	0.250	0.125	0.250	0.500	0.250		
18.1	$\frac{9}{2}^+$	0.125				0.063	0.125		
19.5	$\frac{5}{2}^-$	0.500				0.500			

[a] Additional fit parameters are given in (1990SA24).

24. (a) ^{10}B(n, p)^{10}Be $\quad Q_m = 0.2256 \quad E_b = 11.4541$
(b) ^{10}B(n, t)^{4}He^{4}He $\quad Q_m = 0.3224$

The thermal cross section for reaction (a) is 6.4 ± 0.5 mb (1987LA16); that for reaction (b) is reported as $\sigma = 4.47 \pm 0.15$ mb (1989CL01: see also for other references) and $\sigma = 7 \pm 2$ mb (1987KA32). For reaction (a), differential cross sections were measured for $E_n = 70$ to 240 MeV (2007SO06); the stretched transition to ^{10}Be$_{g.s.}$ was studied in a DWIA analysis. The cross section for reaction (b) has also been studied for $E_n = 1.4$ to 8.2 MeV [see Table 11.28 and (1968AJ02)] and 3 to 8 MeV (1986QA01). For various breakup processes see (1984TU02). For a display of cross sections and a listing of measurements see (1988MCZT).

See (1997BRZV) for a measurement of the total ^{10}B(n, X) cross section for $E_n = 0.08$ to 2000 keV. Also see (2008MU23).

Table 11.28: Resonances in ^{10}B + n [a]

^{10}B(n,n$'\gamma$)^{10}B		^{10}B(n,α)^{7}Li		Yield	^{11}B*
E_n (MeV)	Γ (keV)	E_n (MeV)	Γ (keV)	of	(MeV)
		0.23 [b]		σ_t, α	11.66
		0.53 [b, c]	140	σ_0, α_1	11.94
1.93	260	1.86	570	σ_t, α_0, α_1, t, n$'$	13.2
(2.6)	broad	2.79	530	σ_t, α_0, α_1, n$'$	14.0
3.31	370	3.43	$<$ 120	α_0, t, n$'$	14.57
4.1		4.1	800	σ_t, α_0, α_1, n$'$	15.2
4.73				n$'$	15.75
		5.7	broad	α_0, t	16.6
		6.4	broad	α_0, t	17.3

[a] See also Table 11.27. For references see Table 11.12 in (1980AJ01).

[b] (1984OL05) [see reaction 24] report $E_R = 241 \pm 18$ and 493 ± 4 keV, $\Gamma = 166 \pm 40$ and 194 ± 6 keV: E_x are then 11.673 and 11.902 MeV.

[c] See footnote [b] in Table 11.11 of 1990AJ01.

25. ^{10}B(n, α)^{7}Li $\qquad Q_m = 2.7900 \qquad E_b = 11.4541$

The "recommended" value of the thermal isotopic absorption cross section is 3837 ± 9 b (1981MUZQ, 2006MUZX). Also see $\sigma = 3820 \pm 135$ b (2003MOZU). The k_0 factor for prompt 478 keV γ-rays from thermal neutron activation was measured in (2001AC04, 2003CHZX, 2004MA76).

The cross section for this reaction has been measured for $E_n = 4.17$ to 6.52 MeV (2002ZH35), $E_n = 1.5$ to 5.6 MeV (2005GI03, 2006GI03), $E_n = 4.0$ and 5.0 MeV (2008ZH20) and for $E_n = 0.025$ eV to 14.8 MeV [see (1975AJ02, 1980AJ01, 1985AJ01)]: for observed and deduced structures see Tables 11.27 and 11.28. A study of the reaction involving polarized thermal neutrons and a polarized ^{10}B target shows that the transition to ^{7}Li*(0.48) proceeds almost totally through the $J = \frac{7}{2}$ channel (1986KO19). For a display of cross sections and a listing of measurements see (1988MCZT). For a review see (1986CA28). "Detailed balance" [from ^{7}Li(α, n) measurements] has led to the determination of the ^{10}B(n, α_0) cross section from $0 < E_n \leq 0.78$ MeV: two resonances are inferred at $E_R = 241 \pm 18$ and 493 ± 4 keV, with $\sigma_R = 17 \pm 3$ and 112 ± 3 mb and $\Gamma = 166 \pm 40$ and 194 ± 6 keV (1984OL05). Also see (2008LA18) for an indirect determination of the astrophysical S-factor via ^{2}H(^{10}B, pα) at $E(^{10}$B$) = 27$ MeV.

The α_0/α_1 branching for thermal neutrons is $(6.723 \pm 0.011)\%$ [mean of values listed in (1985AJ01)]. At $E_{\rm n} = 2$ and 24 keV the α_0/α_1 ratios are $(7.05 \pm 0.16)\%$ and $(7.13 \pm 0.15)\%$, respectively (1979ST03). At $E_{\rm n}$ = thermal to 5.5 keV, ratio values are reported near 6.7 ± 0.3 % (2000GO03). The ratio is reported for $E_{\rm n} = 0.1$ keV to 1 MeV (2002HAZP, 2007HA06), $E_{\rm n} = 0.1$ to 2 MeV (2009HA19), $E_{\rm n} = 20$ keV to 1 MeV (1991WE11) and $E_{\rm n} = 0.2$ to 0.4 MeV (1993SC20). Sizeable discrepancies between the data and the ENDF/B-VII library exist above 1 MeV.

The ratio of the ^{10}B(n, α) cross section to the ^{6}Li(n, t) cross section has been measured from $E_{\rm n} \approx 1$ to 45 eV (1986CA29), and $E_{\rm n} < 1$ MeV (2008CA28).

Parity violation has been studied using polarized thermal neutrons: the P-odd asymmetries for the transitions to ^{7}Li*(0, 0.48) are $< 3.7 \times 10^{-6}$ (1986ER05) and $+(0.0 \pm 2.6\ (\mathrm{stat.}) \pm 1.1\ (\mathrm{sys.})) \times 10^{-8}$ (2011VE06), respectively: see also (1983VE10, 1994GL07, 1996VE02, 1999VE03, 2002VEZY, 2003VE10, 2005GI03, 2007NI05), and (1985AJ01) for the earlier work. See also ^{7}Li in (1988AJ01).

The T-odd asymmetry parameter, related to time reversal invariance, is discussed in (2000GA43, 2003BA36, 2007NI05); an upper limit of 3.2×10^{-4} is deduced from analysis of ^{10}B($\vec{\rm n}$, $\alpha\gamma$) at thermal energies (2000GA43).

Techniques of boron trace composition analysis are developed in (1994SA72, 1997SA70, 1998MA61).

26. ^{10}B(p, π^+)^{11}B $\qquad Q_{\rm m} = -128.8984$

Angular distributions have been obtained at $E_{\rm p} = 168$ to 800 MeV to several states of ^{11}B [see (1980AJ01, 1985AJ01)] as have cross sections for π^+ production near threshold. At $E_{\vec{\rm p}} = 200$ to 260 MeV, angular distributions and analyzing powers have been measured for the groups to ^{11}B*(0, 2.12) (1985ZI04). Angular distributions of pions have been measured at $E_{\rm p} = 209$, 247 and 364 MeV (1995BB15).

27. ^{10}B(d, p)^{11}B $\qquad Q_{\rm m} = 9.2296$

Reported proton groups are displayed in Table 11.14 of (1980AJ01). Angular distributions have been studied at energies in the range $E_{\rm d} = 0.17$ to 28 MeV [see (1968AJ02, 1975AJ02, 1980AJ01)]. The lowest five levels are formed by $l_{\rm n} = 1$ except for ^{11}B*(2.12) which appears to involve a spin-flip process. They are presumed to comprise the set $\frac{3}{2}^-, \frac{1}{2}^-, \frac{5}{2}^-, \frac{3}{2}^-, \frac{7}{2}^-$ expected as the lowest p^7 levels ($a/K \approx 4.0$). ^{11}B*(9.19, 9.27) [$J^\pi = \frac{7}{2}^+, \frac{5}{2}^+$] show strong $l = 0$ stripping and are ascribed to capture of a 2s neutron by ^{10}B: see (1968AJ02) for a listing of all the relevant references. At $E_{\rm d} = 15.3$ MeV, differential cross sections were measured for (d, p$_2\gamma$) to obtain the spin-tensor components of the density matrix (2005GA59); neutron stripping appears to be the dominant mechanism. Deformation parameters $\beta_2(^{10}\mathrm{B}) = -0.55$ and $\beta_2(^{11}\mathrm{B}) = 0.4$ were deduced.

A survey of ground state neutron spectroscopic parameters is given in (2005NI24, 2005TS03). Other studies of pγ correlations are discussed in reaction 14 of (1968AJ02) and displayed here in Table 11.19. See also ^{12}C.

Astrophysical S-factors are deduced from measurements at $E_{\rm d} = 60$ to 140 keV (1993CE02, 1997YA02, 1997YA08), at $E_{\rm d} = 100$ to 300 keV (2004RU10), and at $E_{\rm d} = 120$ to 340 keV (2001HO22). At $E_{\rm d} < 3$ MeV the p_0-p_3 reaction cross sections were analyzed to evaluate the impact of the ^{12}C GDR and GQR on the astrophysical rates (2005RU16). At $E_{\rm d} = 900$ to 2000 keV angular distributions and differential cross sections were measured for p_0-p_6, motivated mainly by boron composition depth profiling studies (2007KO69).

28. (a) ^{10}B(t, d)^{11}B $\qquad Q_{\rm m} = 5.1969$
(b) ^{10}B(α, ^{3}He)^{11}B $\qquad Q_{\rm m} = -9.1235$

See (1968AJ02, 1975AJ02).

29. (a) ^{10}B(^{7}Li, ^{6}Li)^{11}B $\qquad Q_{\rm m} = 4.2030$
(b) ^{10}B(^{9}Be, ^{8}Be)^{11}B $\qquad Q_{\rm m} = 9.7896$
(c) ^{10}B(^{13}C, ^{12}C)^{11}B $\qquad Q_{\rm m} = 6.5078$

Optical potentials for reaction (a) are deduced in (2009RO10). For other work see (1980AJ01, 1985AJ01).

30. ^{11}Be(β^-)^{11}B $\qquad Q_{\rm m} = 11.5092$

^{11}Be decays to many states of ^{11}B (1982MI08): see Table 11.29 for the observed β- and γ-transitions. ^{11}B*(9.88) decays via α-emission to ^{7}Li*(0, 0.48) with branching ratios $(87.4 \pm 1.2)\%$ and $(12.6 \pm 1.2)\%$, respectively (1981AL03). A study of the $\beta\nu$ angular correlation in the first-forbidden decay of ^{11}Be to the $J^\pi = \frac{1}{2}^-$ state ^{11}B*(2.12) has been performed; the β-transition is dominated by rank-0 matrix elements and is of interest as a test of meson-exchange effects: see (1982WA18, 1994WA01). See (1992HE12) who propose first forbidden β-decay as a probe of T-odd forces, and see (1993HA29) for discussion on β-decay isospin mixing probabilities and the ^{11}Be nuclear halo.

31. (a) ^{11}B(γ, n)^{10}B $\qquad Q_{\rm m} = -11.4541$
(b) ^{11}B(γ, p)^{10}Be $\qquad Q_{\rm m} = -11.2285$

Table 11.29: ^{11}Be β-decay scheme (1982MI08) [a]

^{11}B (keV)	J^{π} [b]	Branching [c] ratio (%)	log ft [d]	^{11}Be* decay E_γ (keV)	I_γ [c] (%)	Transition to ^{11}B* (MeV)
g.s.	$\frac{3}{2}^-$	54.7 ± 2.0 [e]	6.826 ± 0.016			
2124.693 ± 0.027 [f]	$\frac{1}{2}^-$	31.4 ± 1.8	6.644 ± 0.025	2124.473 ± 0.027	100	g.s.
4444.89 ± 0.50	$\frac{5}{2}^-$	0.054 ± 0.004	8.83 ± 0.04 [g]	4443.90 ± 0.50	100	g.s.
5020.31 ± 0.30	$\frac{3}{2}^-$	0.282 ± 0.020	7.93 ± 0.03	5018.98 ± 0.40	85.6 ± 0.6	g.s.
				2895.30 ± 0.40	14.4 ± 0.6	2.12
6791.80 ± 0.30 [h]	$\frac{1}{2}^+$	6.47 ± 0.45	5.93 ± 0.03	6789.81 ± 0.50	67.5 ± 1.1	g.s.
				4665.90 ± 0.40	28.5 ± 1.1	2.12
				1771.31 ± 0.30	4.0 ± 0.3	5.02
7285.51 ± 0.43	$\frac{5}{2}^+$	< 0.03	> 8.0	7282.92	87.0 ± 2.0	g.s.
7977.84 ± 0.42 [i]	$\frac{3}{2}^+$	4.00 ± 0.30	5.57 ± 0.04	7974.73	46.2 ± 1.1	g.s.
				5851.47 ± 0.42	53.2 ± 1.2	2.12
				692.31 ± 0.10	0.85 ± 0.04	7.29
9876	$\frac{3}{2}^+$	3.1 ± 0.4 [j]	4.23 ± 0.06			

[a] See also Tables 11.15 in (1980AJ01) and 11.13 in (1985AJ01).
[b] From Table 11.18.
[c] Adopted by (1982MI08); based on their work and on the earlier work.
[d] Using $T_{1/2} = 13.76 \pm 0.07$ sec.
[e] From the relative intensities of the γ-rays and $I_{2.12}/I_{\text{total }\beta} = 0.355 \pm 0.018$.
[f] See also (1980WA25, 1981AL03).
[g] Log $f_1 t \approx 10.93$.
[h] Branching ratio to ^{11}B*(4.44) is $< 0.04\%$.
[i] Branching ratios to ^{11}B*(4.44, 5.02, 6.79) are < 0.06, < 0.09 and $< 0.10\%$.
[j] From the relative intensities of the γ-rays and $I_\alpha/I_{2.12}$ of (1981AL03).

(c) ^{11}B(γ, d)^{9}Be $\qquad Q_{\text{m}} = -15.8162$

(d) ^{11}B(γ, t)^{8}Be $\qquad Q_{\text{m}} = -11.2235$

The giant dipole resonance is shown to consist mainly of $T = \frac{1}{2}$ states in the lower energy region and of $T = \frac{3}{2}$ states in the higher energy region by observing the decay to states in ^{10}B and ^{10}Be [reactions (a) and (b)]. Absolute measurements of the ^{11}B(γ, all n) cross section have been carried out from threshold to 35 MeV: the cross section exhibits a main peak at $E_\gamma = 25$ to 28 MeV and weak shoulders at 13 and 16 MeV. The integrated cross section up to 35 MeV is 69.1 ± 0.8 MeV · mb: see (1980AJ01) and (1988DI02). See also (1984AL22). For other structures reported in the (γ, n) and (γ, p) cross sections see (1975AJ02). The yield of 3.37 MeV γ-rays [from ^{10}Be*(3.37), reaction (b)] has been measured for $E_{\text{brem}} = 100$ to 800 MeV. See also (1984AL22, 1986AL24). The (γ, d_0) cross section peaks at ≈ 19 MeV, lower than it would be expected to if $T = \frac{3}{2}$ states were involved. For reaction (d) see (1986AL24). See (1980AJ01, 1985AJ01) for references and for other photonuclear processes.

Measurements at higher energies are reported for $E_\gamma = 4.5$ GeV (1990AR14) and for $E_\gamma = 30$ to 1200 MeV (1999SA08).

32. ^{11}B(γ, γ)^{11}B

Widths of excited states are displayed in Table 11.30. The mixing ratios measured in (2009RU04) are displayed in Table 11.31. See also (2000KA08, 2000ZI04).

33. (a) ^{11}B(e, e)^{11}B

(b) ^{11}B(e, ep)^{10}Be $\qquad Q_{\rm m} = -11.2285$

$$\langle r^2\rangle^{1/2} = 2.43 \pm 0.11 \text{ fm (1986DO1E).}$$

[See also unpublished result in (1980AJ01).]

Magnetic elastic scattering at $\theta = 180°$ shows strong M3 effects: the derived ratio of static M3/M1, 2.9 ± 0.2 fm^2, suggests a j-j coupling scheme for ^{11}B$_{\rm g.s.}$. The quadrupole contribution to the elastic form factor is best accounted for by the undeformed shell model, $Q = 3.72(\pm 20\%)$ fm^2, $\langle r^2\rangle^{1/2} = 2.42$ fm. See (1980AJ01) for references. A study of the elastic scattering for $q = 2.0$ to 3.9 fm^{-1} is reported by (1988HI02): the M3 component is dominant in the elastic form factor for $q > 1.5$ fm^{-1}. See also (1994AM01, 1994BO04).

The excitation of ^{11}B*(2.1, 4.4, 5.0, 8.6, 8.9) has been studied. The giant resonance region, centered at ≈ 18 MeV, is characterized by a lack of prominent features except for a pronounced peak at $E_{\rm x} = 13.0 \pm 0.1$ MeV (mixed M1-E2) and a broad transverse group at $E_{\rm x} = 15.5$ MeV. At $E_{\rm e} = 121$, 186 and 250 MeV form factors (and $B({\rm E}\lambda)\uparrow$) are obtained for ^{11}B*(4.4, 6.7, 8.5, 8.9, 13.00 ± 0.15) and the excitation of ^{11}B*(14.50 ± 0.15, 16.7 ± 0.2) is also reported: see (1985AJ01). See also (1994MO19).

For Γ_{γ_0} see Table 11.30. For reaction (b) see (1975AJ02).

34. ^{11}B(π^+, π^+)^{11}B

The proton matter distribution in ^{11}B$_{\rm g.s.}$ has a radius of 2.368 ± 0.021 fm, assuming that for ^{12}C to be 2.44 fm. The result is not sensitive to the details of the optical-model calculations (1980BA45: $E_{\pi^+} = 38.6$ and 47.7 MeV).

35. ^{11}B(n, n)^{11}B

Table 11.30: Gamma widths from ^{11}B(γ, γ)^{11}B and ^{11}B(e, e)^{11}B [a]

E_x (MeV)	J^π	Γ_{γ_0} (eV)	Reactions
2.12	$\frac{1}{2}^-$	0.120 ± 0.009 [b]	(γ, γ)
4.44	$\frac{5}{2}^-$	0.58 ± 0.04	(γ, γ)
		0.55 ± 0.02	(γ, γ)
		0.60 ± 0.09 (M1)	(e, e)
		$\pm 0.016 \pm 0.002$ (E2)	
		0.56 ± 0.02 [b]	
5.02	$\frac{3}{2}^-$	1.80 ± 0.13	(γ, γ)
		1.64 ± 0.07	(γ, γ)
		1.73 ± 0.14 (M1)	(e, e)
		< 0.0034 (E2)	
		1.68 ± 0.06 [b]	
6.74	$\frac{7}{2}^-$	0.021 ± 0.005	(γ, γ)
6.79	$\frac{1}{2}^+$	0.26 ± 0.03	(γ, γ)
7.29	$\frac{5}{2}^+$	1.00 ± 0.07 [b]	(γ, γ)
7.98	$\frac{3}{2}^+$	0.53 ± 0.07	(γ, γ)
8.56	$(\frac{3}{2}^-)$	0.53 ± 0.05	(γ, γ)
8.92	$\frac{5}{2}^-$	4.15 ± 0.20 [b]	(γ, γ); (e, e)

[a] See also Table 11.19 here, and Table 11.16 in (1980AJ01). For references see Table 11.14 in (1985AJ01).

[b] Mean of values shown in Table 11.14 (1985AJ01).

Angular distributions have been reported for $E_n = 75$ keV to 14.1 MeV [see (1980AJ01, 1985AJ01)] and at $E_n = 8.0$ to 13.9 MeV (1982GL02; $n_0 \to n_3$). Other work is reported for $E_n \leq 17$ MeV (1986MU08; n_0). See (1995XI06) for analysis of $E_n = 7.54$ to 20 MeV, (2000ZHZR) for $E_n < 20$ MeV, and (1996CH33) for $E_n < 200$ MeV. A measurement of the total cross section for ^{11}B(n, X) at $E_n \leq 600$ MeV is given in (2001AB14). See an analysis of Mott-Schwinger scattering of $E_n < 25$ meV in (2008GE04). See also ^{12}B.

36. (a) ^{11}B(p, p)^{11}B

(b) ^{11}B(p, 2p)^{10}Be $\qquad Q_m = -11.2285$

(c) ^{11}B(p, pn)^{10}B $\qquad Q_m = -11.4541$

Table 11.31: Transition mixing ratios deduced from ^{11}B(γ, γ') (2009RU04)

E_x (keV)	E_γ (keV)	Branching Ratio (%) [a]	Multiplicity	Mixing Ratio [b]
2124.7	2124.5	100	M1	
4444.8	4443.9	100	M1 + E2	$+0.158^{+0.025}_{-0.021}$
5020.3	2895.2	14.2 ± 0.6	M1 + E2	$-0.19^{+0.10}_{-0.17}$
	5019.1	85.8 ± 2.6	M1 + E2	-0.036 ± 0.013
7285.5	2264.9	6.3 ± 0.4	E1 + (M2)	$+0.028^{+0.073}_{-0.075}$
	2840.2	5.3 ± 0.4	E1 + (M2)	$-0.081^{+0.164}_{-0.126}$
	7282.9	88.4 ± 2.7	E1 + (M2)	$+0.001^{+0.022}_{-0.021}$
8920.2	4474.3	2.7 ± 0.1	M1 + E2	$-0.061^{+0.025}_{-0.022}$
	8916.3	97.3 ± 2.9	M1 + (E2)	0.000 ± 0.014

[a] G. Rusev, private communication (2011).

[b] Krane-Steffen phase convention.

Observed proton groups for reaction (a) are displayed in Table 11.32. Angular distributions have been measured for $E_p = 6$ to 185 MeV [see (1980AJ01)], $E_p = 0.5$ to 3.3 MeV (2001CH78), $E_p = 0.6$ to 1.2 MeV (2011AM02), $E_p = 1.7$ to 2.7 MeV (1998MA54), $E_p = 10$ to 17 MeV (1986MU08), $E_p = 392$ MeV (2004KA53, 2004KA56) and at $E_p = 1$ GeV (1985AL16). Spin-isovector M1 strengths are given in (2003HA11) for excitation of the first three states with $E_{\vec{p}} = 150$ MeV. Polarization transfer coefficients for p_0 and p_3 were measured at $E_p = 150$ MeV (2003HA12). At $E_p = 2.2$ to 4.2 MeV and $\theta = 135°$ to 160°, proton elastic scattering cross sections were measured to evaluate the suitability of the reaction for boron depth profiling (2010KO33). At $E_p = 3.2$ to 3.6 MeV, thick target γ-ray yields were measured for PIGE analysis (1990BO15). Also see (1998DO16). For reactions (b) and (c) at $E_p = 392$ MeV see (2005NO13) and at $E_p = 1$ GeV see (1985BE30, 1985DO16). For pion production see (1988AB05). See also ^{12}C, and (1985AJ01).

37. ^{11}B(d, d)^{11}B

Elastic scattering has been studied at $E_d = 5.5$ and 11.8 MeV: see (1980AJ01). At $E_d = 200$ MeV, angular distributions were measured for ^{11}B*(2.12, 4.44, 5.05, 6.74, 8.56, (8.92)) (2004KA53, 2007KA17, 2007KA49). Isoscalar M1 spin-flip strengths, $B(\sigma)$, were derived (2004KA53), and isoscalar monopole and quadrupole strengths were deduced (2007KA17): see Table 11.33. The large monopole strength for $E_x = 8.56$ MeV is interpreted as evidence for a developed 2α + t cluster structure. See (2011DE17) for a discussion of the radius of the ^{11}B*(8.56) state, and a comparison with the ^{12}C*(7.65) Hoyle state.

Table 11.32: States of ^{11}B from ^{11}B(p, p′)^{11}B*, ^{13}C(d, α)^{11}B and ^{14}C(p, α)^{11}B [a]

E_x (keV) [b]	E_x (keV) [c]	E_x (keV) [d]	J^π [d]; T	Γ_{cm} (keV) [d]
0	0	0	$\frac{3}{2}^-$	
2124.7 ± 0.5	2125.4 ± 1.4	2120 ± 10	$\frac{1}{2}^-$	
4445.2 ± 0.5	4444.5 ± 1.6	4450 ± 10	$(\frac{5}{2}^-)$	
5021.1 ± 0.6	5020.2 ± 1.9	5025 ± 8	$\frac{3}{2}^-$	
6743.0 ± 0.7 [e]	6745.8 ± 3.4	6746 ± 5 [f]	$\frac{7}{2}^-$	
6792.6 ± 1.6	6795 ± 3.0			
7285.6 ± 1.5				
7978.0 ± 1.7				
8559.4 ± 1.9	8520 ± 70	8560 ± 10 [g]	$\frac{1}{2}^-$	
8920.2 ± 2.0	8910 ± 60	8920 ± 10 [h]	$\frac{5}{2}^-$	
9185.0 ± 2.0				
9274.4 ± 2.0				
10450 ± 150		10300 ± 60 [i]	$\frac{5}{2}^-$	133 ± 10
11650 ± 150		11620 ± 30	$\frac{3}{2}^-$	186 ± 25
12850 ± 100		12920 ± 20	$\frac{1}{2}^-$; $\frac{3}{2}$	238 ± 15
		14560 ± 15	$(\frac{7}{2}^-, \frac{5}{2}^-)$	42 ± 27
15200 ± 150		15290 ± 25	$(\frac{3}{2}^-, \frac{5}{2}^-)$; $\frac{3}{2}$	282 ± 15
16400 ± 150		16500 ± 50	$(\frac{5}{2}^-, \frac{7}{2}^-)$; $\frac{3}{2}$	201 ± 10
		19070 ± 50	$(\frac{7}{2}^-, \frac{5}{2}^-)$; $\frac{3}{2}$	294 ± 10

[a] For references see Table 11.17 in (1980AJ01).

[b] ^{11}B(p, p′)^{11}B.

[c] ^{13}C(d, α)^{11}B.

[d] ^{14}C(p, α)^{11}B (1985AR03) at $E_p = 41.9$ MeV.

[e] Values below are normalized to $E_x = 4445.3$, 5020.0 and 6743.4 keV.

[f] Very strongly excited.

[g] Very weakly excited.

[h] On the basis of the similarity with the angular distribution to ^{11}B*(4.44), $J^\pi = \frac{5}{2}^-$ is assigned.

[i] This state and the ones below may be unresolved.

Table 11.33: Parameters derived from ^{11}B(d, d$'$)

E_x (MeV)	J^π	$B(E0,\ IS)$ fm^4 [a]	$B(E2,\ IS)$ fm^4 [a]	$B(\sigma)$ [b]
2.12	$\frac{1}{2}^-$		11 ± 2	0.037 ± 0.007
4.44	$\frac{5}{2}^-$		56 ± 6	
5.02	$\frac{3}{2}^-$	< 9	4.7 ± 1.5	0.035 ± 0.005
6.74	$\frac{7}{2}^-$		38 ± 4	
8.56	$\frac{3}{2}^-$	96 ± 16	< 6	≤ 0.003
8.92	$\frac{5}{2}^-$		0.4 ± 0.3	0.012 ± 0.003

[a] (2007KA49).
[b] (2004KA53).

38. ^{11}B(t, t)^{11}B

The elastic scattering has been studied at $E_t = 1.8$ and 2.1 MeV: see (1980AJ01).

39. ^{11}B(^{3}He, ^{3}He)^{11}B

The elastic scattering has been studied at $E(^3\text{He}) = 8$ to 74 MeV: see (1975AJ02, 1980AJ01). At $E(^3\text{He}) = 17.5$ and 40 MeV angular distributions have been studied for the ^{3}He ions to ^{11}B*(2.12, 4.44, 5.02, 6.74). $T = \frac{3}{2}$ states observed in this reaction are displayed in Table 11.34. See also (1985AJ01). There is a weak indication of a state at $E_x = 14.51$ MeV: see (1975AJ02).

40. ^{11}B(α, α)^{11}B

Angular distributions have been reported at $E_\alpha = 24$ to 54.1 MeV [see (1975AJ02, 1980AJ01, 1985AJ01, 1990AJ01)]. A review of α-particle scattering cross sections for $E_\alpha = 2$ to 8 MeV is given in (1991LE33). Elastic and inelastic scattering were measured at $E_\alpha = 40$ and 50 MeV (2005BU33); optical model, β_2 and β_4 deformation parameters were deduced. A DWBA analysis of data taken at $E_\alpha = 388$ MeV is given in (2010KAZZ). Depth profile studies on boron-doped materials have been carried at $E_\alpha = 3.5$ to 7.5 MeV (1990MO21) and at $E_\alpha = 1.0$ to 5.3 MeV (1996LI62, 1996ZH36).

41. ^{11}B(α, ^{7}Li) $Q_m = -8.7559$

Table 11.34: $T = \frac{3}{2}$ states in ^{11}B [a]

Reaction	E_x (MeV ± keV)	Γ_{cm} (keV)
^{7}Li(α, α)	*12.550 ± 20*	*150 ± 50*
^{9}Be(^{3}He, p)^{11}B	*12.563 ± 20*	*202 ± 25*
^{10}Be(p, γ)^{11}B	*12.56 ± 30*	*230 ± 65*
^{11}B(^{3}He, ^{3}He)^{11}B*	*12.51 ± 50*	*260 ± 50*
	12.554 ± 13 [b]	**205 ± 20** [b]
^{9}Be(^{3}He, p)^{11}B	*12.920 ± 20*	*155 ± 25*
^{10}Be(p, γ)^{11}B	*12.91 ± 20*	*235 ± 27*
^{13}C(p, ^{3}He)^{11}B	*12.94 ± 50*	*350 ± 50*
^{13}C(p, ^{3}He)^{11}B	*12.91 ± 30*	*260 ± 50*
^{14}C(p, α)^{11}B	*12.92 ± 20* [c]	238 ± 15
	12.917 ± 11 [b]	**230 ± 20** [b]
^{9}Be(^{3}He, p)^{11}B	*14.40* [e]	*261 ± 25*
^{10}Be(p, γ)^{11}B	*14.33 ± 20*	*255 ± 36*
^{11}B(^{3}He, ^{3}He)^{11}B*	*14.40 ± 50*	*220 ± 50*
	14.34 ± 20 [b]	**253 ± 19** [b]
^{14}C(p, α)^{11}B	**15.29 ± 25** [g]	**282 ± 15**
^{9}Be(d, p)	*16.430 ± 20*	*40*
^{9}Be(^{3}He, p)^{11}B	*16.437 ± 20*	*≤ 30*
	16.432 ± 10 [f]	**≤ 30**
^{7}Li(α, n)	*17.52 ± 30*	
^{9}Be(d, γ)	*17.44 ± 50*	*184 ± 41*
^{9}Be(^{3}He, p)^{11}B	*17.69*	*91 ± 25*
	17.50 ± 30 [b]	**116 ± 25** [b]
^{9}Be(^{3}He, p)^{11}B	**18.0 ± 100**	**870 ± 100**
^{9}Be(^{3}He, p)^{11}B	*19.146 ± 30*	*115 ± 25*
^{14}C(p, α)^{11}B	*19.070 ± 50*	*294 ± 10*
	19.125 ± 26 [b]	**115 ± 25** [d]
^{9}Be(^{3}He, p)^{11}B	**21.27 ± 50**	**300 ± 30**

[a] See also Table 11.18 in (1980AJ01). See Table 11.16 in (1985AJ01) for references.
[b] Mean value.
[c] See Table 11.18.
[d] "Best" value.
[e] May have mixed isospin ($T = \frac{1}{2} + T = \frac{3}{2}$).
[f] See also reaction 70 (1985AR03).
[g] See also ^{10}Be(p, γ) for $E_x = 15.32 \pm 0.10$ MeV and $\Gamma = 635 \pm 180$ keV.

Cluster configuration spectroscopic factors are deduced (1995BO31) at $E_\alpha = 27.2$ MeV.

42. (a) ^{11}B(^{6}Li, ^{6}Li)^{11}B
(b) ^{11}B(^{7}Li, ^{7}Li)^{11}B

The elastic scattering has been studied at $E(^6\text{Li}) = 28$ MeV: see (1975AJ02). At $E(^7\text{Li})=$ 34 MeV angular distributions have been reported to ^{11}B*(0, 2.12, 4.44, 5.02, 6.74, 7.29, 8.92) (1987CO02, 1987CO16); also see (2005RU17, 2005RU18). At $E(^{11}\text{B}) = 44$ MeV, scattering on a ^{7}Li target populated ^{11}B*(0, 2.12, 4.44, 5.02, 6.74, 7.29, 7.98, 8.56, 8.92) (2005RU18). Deformation parameters were deduced for ^{7}Li and ^{11}B states, and contributions from 1- and 2-step cluster transfers are found to be small in both the elastic and inelastic channels.

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

For reaction (a) see (1984DA17, 1986CU02). For fusion cross sections (reactions (b) and (c)) see (1989SZ01). See also (1975AJ02, 1980AJ01).

44. (a) ^{11}B(^{12}C, ^{12}C)^{11}B
(b) ^{11}B(^{13}C, ^{13}C)^{11}B

The elastic scattering has been studied at $E(^{11}\text{B}) = 18.8$ to 50 MeV and at $E(^{12}\text{C})= 15$ to 24 MeV and 87 MeV [see (1980AJ01, 1985AJ01)] as well as at $E(^{11}\text{B}) = 10.4$, 12.4 and 14.6 MeV (1985JA01), at $E_{\text{cm}} = 25$ MeV (1986MA13), at $E(^{11}\text{B}) = 42.5$ to 100 MeV (1985MA10) and at $E(^{12}\text{C}) = 65$ MeV (1985GO1H) [see ^{12}C]. The population of ^{11}B*(2.12, 4.44, 6.79) is reported. For yields, fusion and breakup studies see (1985AJ01) and (1985MA10, 1986MA13). For reaction (b) see (1984DEZX, 1984HAZK).

45. ^{11}B(^{14}N, ^{14}N)^{11}B

The elastic scattering has been investigated at $E(^{14}\text{N}) = 41$, 77 and 133 MeV: see (1975AJ02, 1985AJ01).

46. (a) ^{11}B(^{16}O, ^{16}O)^{11}B

(b) ^{11}B(^{17}O, ^{17}O)^{11}B

(c) ^{11}B(^{18}O, ^{18}O)^{11}B

The elastic scattering in reaction (a) has been studied at $E(^{16}\text{O}) = 14.5$ to 60 MeV and at $E(^{11}\text{B}) = 41.6$, 49.5 and 115 MeV; for references see (1975AJ02, 1980AJ01, 1985AJ01). Elastic and quasi-elastic scattering are reported in (1994AN05: $E(^{16}\text{O}) = 22$ to 64 MeV). Also see (1992KA19).

For reaction (b) see (1994AN05). For reaction (c), elastic and quasi-elastic scattering are reported at $E_{\text{cm}} = 18.8$ and 19.9 MeV (1992LE04), at $E(^{18}\text{O}) = 22$ to 64 MeV (1994AN05), and at $E(^{11}\text{B}) = 115$ MeV (1980PR09; elastic). Analysis in (1992LE04) evaluated evidence for long-lived orbiting phenomena in the compound system.

47. ^{11}B(^{20}Ne, ^{20}Ne)^{11}B

The elastic angular distribution has been studied at $E(^{11}\text{B}) = 115$ MeV: see (1985AJ01).

48. (a) ^{11}B(^{24}Mg, ^{24}Mg)^{11}B

(b) ^{11}B(^{25}Mg, ^{25}Mg)^{11}B

(c) ^{11}B(^{26}Mg, ^{26}Mg)^{11}B

(d) ^{11}B(^{27}Al, ^{27}Al)^{11}B

(e) ^{11}B(^{28}Si, ^{28}Si)^{11}B

The elastic angular distributions for reactions (a) to (d) have been studied at $E(^{11}\text{B}) = 79.6$ MeV: see (1985AJ01). See also (1987PO15). For reaction (e) see (1984TE1A).

49. (a) ^{11}B(^{40}Ar, ^{40}Ar)^{11}B

(b) ^{11}B(^{40}Ca, ^{40}Ca)^{11}B

For reaction (a) at $E(^{40}\text{Ar}) = 7$ MeV/A see (1986MO15). Angular distributions have been reported in reaction (b) at $E(^{11}\text{B}) = 51.5$ MeV to ^{11}B*(0, 2.12): see (1985AJ01).

50. ^{11}C(β^+)^{11}B $\qquad Q_{\text{m}} = 1.9824$

The β^+-decay of ^{11}C populates $^{11}\text{B}_{\text{g.s.}}$; see ^{11}C. A 4π-β-γ coincidence system to evaluate the activity of ^{11}C sources is discussed in (2004NI04).

51. ^{12}C(γ, p)^{11}B $\qquad Q_{\rm m} = -15.9569$

Angular distributions to the ground and to excited states of ^{11}B (and to ^{11}C states reached in the (γ, n) reaction) have been measured at various energies (see Table 11.35); the ground state is predominantly populated: see measurements and discussion in (1980AJ01, 1985AJ01, 1990AJ01) and (1986AN25, 1986MC15, 1990SP06, 1990VA07, 1990VA09, 1991IS09, 1993IR01, 1994NI04, 1994ZO01, 1995HA03, 1996RU15, 1997AS01, 1997ZO02, 1998KU23, 1998SO18, 2001ME29). Analog states are populated similarly in the (γ, n) and (γ, p) reactions. Also see (2000DE58).

Bremsstrahlung photons at $E_\gamma = 50$ to 70 MeV (tagged) were used to study ^{12}C(γ, pγ')^{11}B; states at ^{11}B*(2.12, 4.45, 5.02, 6.74, 6.79, 7.29) were resolved. The analysis centered on the mechanism for populating the $\approx$ 7 MeV triplet states (1998KU23). The relative population of ^{11}B*(6.8) is much greater than that reported in (e, ep) (1988SH08). The role of different reaction mechanisms, including quasi-deuteron knockout, is investigated in (1990VA07, 1992RY02, 1992VA01, 1993HA12, 1993IR01, 1994NI04, 1995MO18, 1996AS02, 1996JO15, 1996RU15, 1997AS01, 1997JO07, 2000LE38, 2002ME17, 2005KA54).

Table 11.35: Summary of ^{12}C(γ, p)^{11}B and ^{12}C(γ, π^+n) measurements since 1990

References	Energy (MeV)	Observable
(1996RU15)	25-75	$p_{0-3,4+5+6}$
(1997AS01)	41-57	$p_{0-3,4+5+6}$
(1995MO18)	44-98	$p_{0,1}$
(1990SP06)	49-78	$p_{0,1,3,4+5}$
(1996KU36, 1998KU23)	50-70	γ-ray de-excitation ^{11}B*(2.12-7.3)
(1993IR01)	60	$p_{0,1,3,4+5+6}$
(1994NI04)	61, 71	$p_{0,1,3,4+5+6}$
(1990VA07)	75, 95	$p_{0-3,4+5+6}$
(1993HA12, 1995HA03)	80-157	$p_{0,4+5+6}$, ^{11}B*($\approx$ 13, 17, 22.5 MeV)
(1996MA20)	114-792	(γ, π^+n) in $\Delta(1232)$ region
(1997LI30)	150-790	(γ, π^+n)/(γ, π^+p) ratio
(2000BR01, 2002BR38)	260-380	(γ, π^0p) in $\Delta(1232)$ region
(1999SO18, 2000SO19)	650-850	η-mesic ^{11}B atoms
(2003GL03)	900	(γ, π^0p)

Reactions in the "Delta" resonance region are discussed in (1992BA57, 1992GL04, 1995CR04, 1997JO07, 2000GL08, 2001MA31, 2002ME17, 2006AN22). In this region peaks corresponding to removal of s-shell and p-shell protons are observed in the missing mass spectrum, and quasi-free photo pion production is an important reaction mechanism. Evidence for η-mesic ^{11}B atoms is claimed in (1999SO18, 2000SO19, 2002BA21); also see (1995LE26, 1999LE35, 1999TR09, 2003HE18, 2005NA17, 2005NA25, 2005NA35, 2006NA34, 2008JI06).

52. ^{12}C(ν, p) $Q_{\rm m} = -15.9569$

Neutrino induced proton knockout reactions on ^{12}C are discussed in (1995UM02, 1995UM03, 2003KO50, 2008MA21, 2008ME03). Sensitivity to the strange quark content of the nucleon is given in (1993GA20, 2004ME18, 2004VA09, 2006LA13, 2006ME17, 2006ME24, 2006MA67). Enhancement of ^{11}B production in supernovae explosions is discussed in (2006SU15, 2007SU08).

53. ^{12}C(e, e′p)^{11}B $Q_{\rm m} = -15.9569$

Measurements reported at $E_{\rm e} = 21$ MeV to 14.5 GeV are listed in Table 11.36. Levels at ^{11}B*(0, 2.12, 4.44, 5.02, 6.74, 6.79, 7.28) are populated; see discussion in (1985VA16, 1988VA09, 1988VA21, 1990DE16, 1992BO10, 1994CA08, 1994IR01, 1994TA11, 1996KE03). ^{11}B*(0, 2.12, 5.02) are populated by $l = 1$ knockout (1988VA09). The relative population of ^{11}B*(6.8) is much less than that reported in (γ, p) (1988SH08). A high-resolution measurement reported in (1988VA21) observed weak transitions to 8.61 ± 0.05, 9.820 ± 0.025 MeV and to a broad structure at 11.5 MeV. $l = 0$ and 1 are suggested for the structures at 9.8 and 11.5 MeV. A structure at ≈ 12 MeV is reported in (1996KE03). One-third to one-half of the sum-rule strength predicted by the independent-particle shell model is observed (1988VA09). Weak population of ^{11}B*(4.44) by (1992BO10) is interpreted as arising almost completely from two-step processes.

Spectroscopic factors for 1s and 1p shell single-particle knockout reactions are discussed in (1990CA14, 1990DE16, 1990WE06, 1991WE10, 1991WE16, 1994IR01, 1994IR02, 1995BL10, 1995KE03, 1998WO01, 1999DO30, 1999RY06, 2000DU12, 2000LA23, 2002MA12). Effects such as transparency of the nuclear medium have been studied by (1990FR11, 1992BE23, 1992FR17, 1992GA02, 1992JE03, 1992PA03, 1993LO01, 1993NI11, 1994FR12, 1994FR16, 1994GR05, 1994IR02, 1994MA23, 1994NI05, 1995FR04, 1996KE14, 1996NI13, 1997IW03, 1999RY06, 2000DU12, 2000LA23, 2001FR06, 2002DE11, 2002GA43, 2002ME17, 2003DU23, 2003RY02, 2004LA13, 2004BA99, 2005RO38, 2006RO37). Discussion on other final state interactions is given in (1991CA09, 1994IR02, 1994JE04, 1994RY04, 1995BI07, 1995BI19, 1995NI02, 1996BI01, 1996BI21, 1996JE04, 1999KE04, 2002DE07, 2004BA99, 2004BB15, 2005BA23, 2007PI05), and discussion on the reaction mechanism influence is found in (1990LO09, 1991VA05, 1992DR02, 1993CI05, 1993OF01, 1994IR01, 1994RY03, 1994TA11, 1994WE06, 1999MO02, 2002ME17, 2004FR27, 2004MU29, 2004RO35, 2004TA18, 2011RY03). See also (1993KE02, 1994BI05, 1994VE08, 1994WA19, 1995RY02, 1997BI06, 1997GI13, 1998HO20, 2000DE38, 2000UD01, 2005KE04).

Table 11.36: Measurements of ^{12}C(e, e′p) at $E_e = 21$ MeV to 14.5 GeV

E_e (MeV)	References	E_e (MeV)	References
21, 25, 35, 45, 55	(1983HO15)	470	(1993KE02, 1995KE03, 1995KE06, 1996KE03)
43	(1971SH09)	500	(1971BU26, 1974BE12, 1976MO17, 1982BE02)
65, 75, 86, 100	(1975PL02)	509	(1995ZO01)
86, 118, 126	(1984CA34, 1994CA08)	0.55-1.0 GeV	(1969DE20)
100-225	(1984LI07, 1985LI15)	560 (polarized)	(1994MA26, 1999DO30)
100-250	(1971EG02, 1971EG03)	576	(1998HO20)
100, 150, 200	(1970VY01)	579	(1998WO01)
110-119	(1968BO46)	600, 855	(1999BA31)
124.1, 183.4	(1995DE23)	696, 796	(1999MO02)
129	(1994TA11)	700	(1976NA17)
160, 520	(1978MO19)	705	(1998BL06, 2000RO17, 2001WA31)
197	(2009TA34)	780	(1989GE04, 1992GA02)
200	(1981LO02)	845-3345	(2000DU12, 2003DU23)
280-480	(1988VA09, 1988VA21)	855	(1995BL02, 2004BO47)
283	(1985VA16)	1.6, 2.06 GeV	(1997AL20)
288, 443	(1987UL03)	1.94 GeV	(1998AL03)
312.8, 443.3	(1986VA17)	2.261, 4.461 GeV (polarized)	(2005PR02)
353	(1985VA05)	2.5, 2.7 GeV	(1974KO21)
379-585	(2005MO04)	3.1, 4.5, 5.6 GeV	(2002GA43)
460	(1986LO03, 1990WE06, 1991WE10)	3.3 GeV	(2004RO35, 2005RO38, 2006RO37)
461	(1992BO10)	4.627 GeV	(2007PI05)
460, 647	(1989BA03)	14.5 GeV	(1994DE17)
460-800	(1990LO09)		

The production of ^{11}B in astrophysical sites with large densities of high-energy electrons is discussed by (1983HO15).

54. (a) ^{12}C(π^+, π^+p)^{11}B $\qquad Q_{\rm m} = -15.9569$

(b) ^{12}C(π^-, π^-p)^{11}B $\qquad Q_{\rm m} = -15.9569$

At $E_{\pi^+} = 100$ to 200 MeV the reaction proceeds primarily to ^{11}B$_{\rm g.s.}$. At $E_\pi = 200$ MeV the ratios for $\sigma_{\rm n}/\sigma_{\rm p}$ for the first excited states in ^{11}C/^{11}B($J^\pi = \frac{1}{2}{}^-_1$) are 1.4 ± 0.2 for π^- and 1/1.8 ± 0.2 for π^+. At $E_{\pi^+} = 60$ to 300 MeV ^{11}B*(4.44) [$J^\pi = \frac{5}{2}^-$] is strongly populated as is the analog state in the mirror reaction: see (1980AJ01, 1985AJ01) for references. At $E_{\pi^\pm} = 220$ MeV the quasi-elastic nature of the scattering has been studied by (1984FA11). The proton Fermi-momentum distributions were analyzed at $E_{\pi^-} = 0.7$, 0.9 and 1.25 GeV/c (2000AB25). See also the studies by (1984ZI1B, 1987HU02, 1991BE43), ^{12}C.

55. ^{12}C(n, d)^{11}B $\qquad Q_{\rm m} = -13.7323$

See (1994MO41) and ^{13}C in (1986AJ01, 1991AJ01).

56. ^{12}C(p, 2p)^{11}B $\qquad Q_{\rm m} = -15.9569$

An overview of ^{12}C(p, 2p) measurements is given in Table 11.37. At $E_{\rm p} = 98.7$ MeV groups are observed to ^{11}B*(0, 2.12, 4.44, 5.02, 6.79); DWIA lead to relative spectroscopic factors of 2.0, 0.37, 0.15, 1.08, 0.25 for these states. No evidence is seen for multistep reaction processes which would be necessary to populate ^{11}B*(4.44, 6.74): see (1979DE35). At $E_{\rm p} = 392$ MeV (2003YO01) states at $E_{\rm x} \approx 8.5$ and ≈ 10 MeV are also observed in addition to the s-hole state in ^{11}B, which is split into three different components with $E_{\rm x} = 16.1 \pm 0.1$ MeV ($\Gamma = 5.3 \pm 0.3$ MeV), $E_{\rm x} = 21.9 \pm 0.2$ MeV ($\Gamma = 8.1 \pm 0.2$ MeV) and $E_{\rm x} = 28.7 \pm 0.7$ MeV ($\Gamma = 9.7 \pm 2.5$ MeV); also see (2001YA08, 2004YA20, 2004YO06, 2004YO08); see additional discussion on knockout spectroscopic factors in (2002BR26, 2011SI01).

At $E_{\rm p} = 1$ GeV the separation energy between 6 and 14 MeV broad 1p$_{3/2}$ and 1s$_{1/2}$ groups is 18 MeV (1985BE30, 1985DO16); also see (1967GO01, 1969JA05, 1970SI01, 1971LA16, 1976BH02, 2004AN01, 2008KO12, 2008NO01; exp.) and (1990LO18, 1995GA46, 2003TA03, 2006HI15; theor.). Initial and finial state effects, such as color transparency and nuclear modifications to the NN interaction are discussed in (1966TY01, 1978KO30, 1979JA20, 1988CO02, 1989CO17, 1989PI12, 1997HA15, 1998MA67, 1998NO04, 1999AC03, 1999CA11, 1999CA15, 2000NO03, 2003TA03, 2004AC08; exp.) and (1992LE03, 1994FR12, 1994FR16, 1994KO21, 1997GA16, 2000ST17, 2002DI04, 2004AC08, 2006DA15, 2006VA08, 2007DA19, 2007RY02, 2009CO10; theor.).

Table 11.37: Measurements of ^{12}C(p, 2p)

E_p (MeV)	References	E_p (MeV)	References
44	(1970WE07)	392	(1997HA15, 1998NO04, 2000NO03, 2001YA08, 2003YO01, 2004YO06, 2004YO08, 2008NO01)
50	(1965PU02, 1967PU01, 1971HA61, 1984VD01)		
57	(1969EP01)		
100	(1976BH02, 1979DE35)	400	(1979JA20)
120	(1967YU02)	460	(1966TY01)
156	(1971HO03, 1997TE14)	600	(1971LA16)
160	(1967GO01)	640	(1978KO30)
200	(1988CO02, 1989CO17, 1989PI12, 1999CA11, 1999CA15)	1 GeV	(1970SI01, 1985BE30, 1985DO16, 2004AN01)
		5.9-14.4 GeV	(1998MA67, 1999AC03, 2003TA03, 2004AC08)
250	(2008KO12)		
385	(1969JA05)		

57. ^{12}C(p, dπ^+) $Q_m = -154.0849$

Measurements were performed at E_p = 223 MeV (1992CO04) and E_p = 370 and 500 MeV (1998BE38). Population of ^{11}B*(0, 2.12, 5.02) and continuum excitations near 20 MeV, interpreted as 1s$_{\frac{1}{2}}$ hole excitations, were observed (1998BE38); spectroscopic factors were also deduced.

58. ^{12}C(d, ^{3}He)^{11}B $Q_m = -10.4634$

Angular distributions of ^{3}He ions have been measured for E_d = 20 to 80 MeV and spectroscopic factors have been derived for ^{11}B*(0, 2.12, 5.02): see references in (1975AJ02, 1980AJ01, 1985AJ01). The ^{12}B spin dipole resonance is studied via ^{12}C(d, ^{2}He + n) at E_d = 171 MeV (2007DE28). Also see (2001KR01).

59. ^{12}C (t, α)^{11}B $Q_m = 3.8570$

Angular distributions have been measured at E_t = 33 MeV (1987FO21, 1991PI09) and 38 MeV (1988SI08) to ^{11}B*(0, 2.12, 4.44, 5.02, 6.74, 7.29, 7.98, 8.56); spectroscopic factors are deduced.

As expected, the $J^\pi = \frac{5}{2}^-$ and $\frac{7}{2}^-$ states ^{11}B*(4.44, 6.74) are populated by two-step processes. The best J^π value for ^{11}B*(8.56) is $\frac{3}{2}^-$ but this assumes some direct population which may not be the case. For the earlier work at $E_t = 1$ to 3.4, 10.1 and 13 MeV see (1975AJ02).

60. ^{12}C(α,^{5}Li)^{11}B $\qquad Q_m = -17.9219$

See (1987GA20) and (1985AJ01).

61. (a) ^{12}C(^{6}He, ^{7}Li)^{11}B $\qquad Q_m = -5.9822$
(b) ^{12}C(^{6}Li, ^{7}Be)^{11}B $\qquad Q_m = -10.3500$

The ^{7}Li$_{g.s.}$ angular distribution was measured for reaction (a) at $E(^6\text{He}) = 36.4$ MeV. A DWBA analysis reproduces the data (2009LI27).

Reaction (b) was measured at $E(^6\text{Li})= 93$ MeV; ^{11}B*(0, 2.12, 5.0, 6.8, 8.9) are populated (1988BUZI). Polarization observables were measured at $E(^6\text{Li}) = 50$ MeV (1997KE04).

62. ^{12}C(^{10}Be, $^7\text{Li} + \alpha$) $\qquad Q_m = -13.3925$

Peaks corresponding to ^{11}B*(9.3 ± 0.1 and 10.3 ± 0.1 MeV) are observed in the kinematic energy spectrum of $^7\text{Li}_{g.s.} + \alpha$ particles following $^{12}\text{C} + {}^{10}\text{Be}$ reactions at $E(^{10}\text{Be}) = 302$ MeV (2004AH02, 2004AH06). The measurement could not resolve possible participation of ^{7}Li*(0.48).

63. (a) ^{12}C(^{11}B, ^{11}B)
(b) ^{12}C(^{11}B, $^7\text{Li} + \alpha$)

Angular distributions for elastic and inelastic scattering are reported for $E(^{11}\text{B}) = 49$ MeV ^{11}B*(0, 2.12, $4.45 + {}^{12}\text{C}(2^+)$, 5.02) (2001RU14, 2003ME36), $E_{cm} = 15$ to 40 MeV ^{11}B*(0, 2.12, 4.45) (1991JA09), and $E(^{11}\text{B}) = 344.5$ MeV ^{11}B*(0, 4.45) (1992JA12). Optical model parameters and spectroscopic factors are deduced. Quadrupole deformation parameters of $\delta_2 = 1.0$ and 0.8 fm are deduced for ^{11}B*(0, 5.02), respectively (2003ME36).

For reaction (b) at $E(^{11}\text{B}) = 87$ MeV, ^{11}B*(9.19, 9.27, 10.27, 10.61) states were observed at $E_{rel} = 527 \pm 10$ keV, 604 ± 10 keV, 1610 ± 14 keV and 1948 ± 7 keV with measured widths of $\Gamma = 30 \pm 11$, 37 ± 9, 337 ± 44 and 83 ± 22 keV, respectively (1994WO02). The broad widths of the first two levels are explained with the ≈ 41 keV energy resolution.

The measured interaction cross section for $^{11}\text{B} + {}^{12}\text{C}$ at $E(^{11}\text{B}) = 950$ MeV is 778 ± 30 mb; this implies $R^{\text{matter}}_{\text{rms}} = 2.09 \pm 0.12$ fm (2001OZ03, 2001OZ04).

64. ^{12}C(^{12}C, X)

At $E(^{12}\text{C}) = 344.5$ MeV angular distributions and spectroscopic factors involving ^{11}B*(0, 2.12) are reported in (1992JA10). Angular distributions involving $^{11}\text{B}_{\text{g.s.}}$ are reported in (1979FU04: $E(^{12}\text{C}) = 93.8$ MeV) and (1974AN36: $E(^{12}\text{C}) = 114$ MeV). See also (1995HO02).

65. ^{12}C(^{13}C, ^{14}N)^{11}B $\qquad Q_{\text{m}} = -8.4063$

See (1987AD07, 1988VO08) and ^{14}N in (1991AJ01).

66. ^{12}C(^{19}F, ^{20}Ne)^{11}B $\qquad Q_{\text{m}} = -3.1134$

At $E(^{19}\text{F}) = 40$, 60 and 68.8 MeV angular distributions involving ^{11}B*(0, 2.12) and ^{20}Ne*(0, 1.63) have been measured: see (1980AJ01).

67. ^{13}C(p,^{3}He)^{11}B $\qquad Q_{\text{m}} = -13.1852$

At $E_{\text{p}} = 50.5$ MeV, in addition to ^{11}B*(0, 2.12, 4.44, 5.02, 6.74, 8.92), a state is observed at $E_{\text{x}} = 12.94 \pm 0.05$ MeV, $\Gamma = 350 \pm 50$ keV. Comparison of the angular distributions of the ^{3}He and of the tritons [to the analog state] at $E_{\text{p}} = 43.7$ and 50.5 MeV lead to the assignments $J^{\pi} = \frac{1}{2}^{-}, T = \frac{3}{2}$ for this state and for ^{11}C*(12.50): the strong proton and the weak α-decay are consistent with this assignment: see Table 11.34. Angular distributions have been measured at $E_{\text{p}} = 26.9$ to 49.6 MeV involving the above states except for ^{11}B*(8.92) and at $E_{\vec{\text{p}}} = 65$ MeV (to ^{11}B*(0, 2.12)): see (1975AJ02, 1980AJ01, 1985AJ01). See also ^{14}N in (1986AJ01).

68. ^{13}C(d, α)^{11}B $\qquad Q_{\text{m}} = 5.1679$

Observed α groups are displayed in Table 11.32. Angular distributions are reported at $E_{\text{d}} = 150$ to 350 keV (1993MA45), $E_{\text{d}} = 180$ to 350 keV (1998NA38), $E_{\text{d}} = 0.5$ to 1.65 MeV (2007CO01), $E_{\text{d}} = 15.3$ MeV (2009GA19, 2010GA05), and $E_{\text{d}} = 0.41$ to 14.1 MeV; see references in (1975AJ02).

At $E_{\text{d}} = 15.3$ MeV analysis of the angular distributions indicates the 4.4 MeV $J^{\pi} = \frac{5}{2}^{-}$ state is mainly formed by deuteron pickup, while both deuteron pickup and ^{9}Be cluster-exchange are important for ^{11}B*(0, 2.12, 5.02) (2009GA19). In (2010GA05) the measurements were extended to include double differential cross sections for detecting $\gamma + \alpha$ coincidences. The angular dependences of the even components of density matrix spin tensors, magnetic sublevel populations, and components of multipole moment orientation tensors of the ^{11}B nucleus were obtained and analyzed for ^{11}B*(4.45).

69. ^{13}C(^{11}B, ^{11}B)

Scattering distributions for ^{11}B*(0, 2.125, 4.445, 5.020, $6.743+6.792$, 7.286, 7.978, 8.560) and other ^{13}C states were measured at $E(^{11}\text{B}) = 45$ MeV (2003ME13). The mechanism for anomalous large angle scattering was evaluated in Optical Model and Coupled Channels analyses.

70. ^{14}C(p, α)^{11}B $\qquad Q_{\text{m}} = -0.7840$

Observed states are displayed in Table 11.32 (1985AR03). It is suggested ^{11}B*(12.92, 15.29, 16.50, 19.07) are $T = \frac{3}{2}$, negative-parity states. Spectroscopic factors have also been derived (1985AR03).

71. ^{14}C(^{11}B, ^{11}B)

At $E(^{11}\text{B}) = 45$ MeV ^{11}B*(0, 2.12, 4.4, 5.02, $6.74 + 6.79$, 7.28, 7.97, 8.56) are observed in the scattering reactions (2005ME05).

72. (a) ^{14}N(n, α)^{11}B $\qquad Q_{\text{m}} = -0.1581$
(b) ^{14}N(n, 2α)^{7}Li $\qquad Q_{\text{m}} = -8.8222$

Angular distributions have been measured for $E_{\text{n}} = 4.9$ to 18.8 MeV [see (1975AJ02, 1980AJ01, 1985AJ01)], at $E_{\text{n}} = 1.7$ to 7 MeV (2011KHZW), at $E_{\text{n}} = 5.46$ to 7.2 MeV (2006KH12; α_{0-3}), and at $E_{\text{n}} = 12.2$, 14.1 and 18.0 MeV (1986RU1B; α_0, α_1). At $E_{\text{n}} = 14.1$ and 15.7 MeV various states of ^{11}B with $8.9 < E_{\text{x}} < 14.5$ MeV appear to be involved in the sequential decay to ^{7}Li. Angular correlation results are consistent with $J = \frac{7}{2}$ and $\frac{5}{2}$ for ^{11}B*(9.19, 9.27) respectively: see (1975AJ02). In (2006KH12) a comparison of the cross section with the ENDF/B VI values is given, and the impact of ^{14}N in nuclear reactors is discussed.

73. ^{14}N(p, p^{3}He)^{11}B $\qquad Q_{\text{m}} = -20.7357$

See (1986VDZY; $E_p = 50$ MeV).

74. ^{16}O(d, ^{7}Be)^{11}B $\qquad Q_m = -16.0382$

At $E_d = 80$ MeV angular distributions have been measured to ^{11}B* (0, 2.12, $4.44 + 5.02$, $6.74 + 6.79 + 7.29$): see (1980AJ01).

75. ^{208}Pb(^{11}B, ^{11}B$'$)

Coulomb excitation of ^{11}B*(2.2) is discussed in (2007BE54).

^{11}C

(Tables 11.38 and 11.39, Figs. 5 and 7)

$\mu = -0.964 \pm 0.001$ nm (1969WO03)
$Q = 34.26$ mb (1969SC34: calculated)

1. ^{11}C(β^+)^{11}B $\qquad Q_m = 1.9824$

The half-life of ^{11}C is 20.364 ± 0.014 min. The most significant measured values are 20.382 ± 0.020 (1975AZ01), 20.334 ± 0.024 (2002WO02), 20.40 ± 0.04 (1969AW02), 20.34 ± 0.04 (1964KA31) and 20.35 ± 0.08 min (1941SM11); the later value is omitted from the weighted average. Other measurements are tabulated in (1968AJ02). The decay populates the ^{11}B ground state; log $ft = 3.5921 \pm 0.0019$. The ratio of K-capture to positron emission is $(0.230^{+0.014}_{-0.011})\%$. See (1998BA57) for comments on Pauli principle violating anomalous atoms. See also (1995GO34, 2002WO02, 2003SU04) and (1985AJ01).

2. ^{1}H(^{11}C, ^{11}C)^{1}H

Elastic and inelastic scattering of ^{11}C + p was measured at $\theta_{cm} = 20$ to 50 degrees using $E(^{11}\text{C}) = 40.6$ and 45.3 MeV/A beams (2003JO09). The ground state and excited states at 2.03, 4.37 and 6.47 MeV were observed. The angular distributions for ^{11}C*(0, 4.37) were analyzed in AMD and QRPA models.

At $E(^{11}\text{C}) = 40.6$ MeV/A elastic and inelastic proton scattering on ^{11}C were measured in inverse kinematics (2005JO12). States at ^{11}C*(0, 2.02, 4.33, 6.48) were resolved. The elastic scattering data are consistent with $R^{\text{matter}}_{\text{rms}} = 2.33 \pm 0.10$ fm, and a Jeukenne-Lejeune-Mahaux (JLM) microscopic potential analysis of the $E_x = 4.33$ MeV ($\frac{5}{2}^-$) and 6.48 MeV ($\frac{7}{2}^-$) state angular distributions are consistent with E2 transition multipolarities.

Also see (2003TE12, 2006PE21, 2009UM05) and ^{12}N.

3. ^{6}Li(^{6}Li, n)^{11}C $\qquad Q_m = 9.4521$

At $E(^{6}\text{Li}) = 4.1$ MeV angular distributions have been obtained for the neutrons to ^{11}C*(2.00, 4.32, 4.80, $6.34 + 6.48$, 6.90, 7.50). In addition, nγ-coincidences via ^{11}C*(8.42) [and an 8.42 MeV γ-ray] are reported. ^{11}C*(8.10) was not observed. The mean lifetimes, τ_m, for ^{11}C*(4.32, 6.90, 7.50) are < 140, < 69 and < 91 fs, respectively. See (1980AJ01) for references. For yields see ^{12}C and (1987DO05).

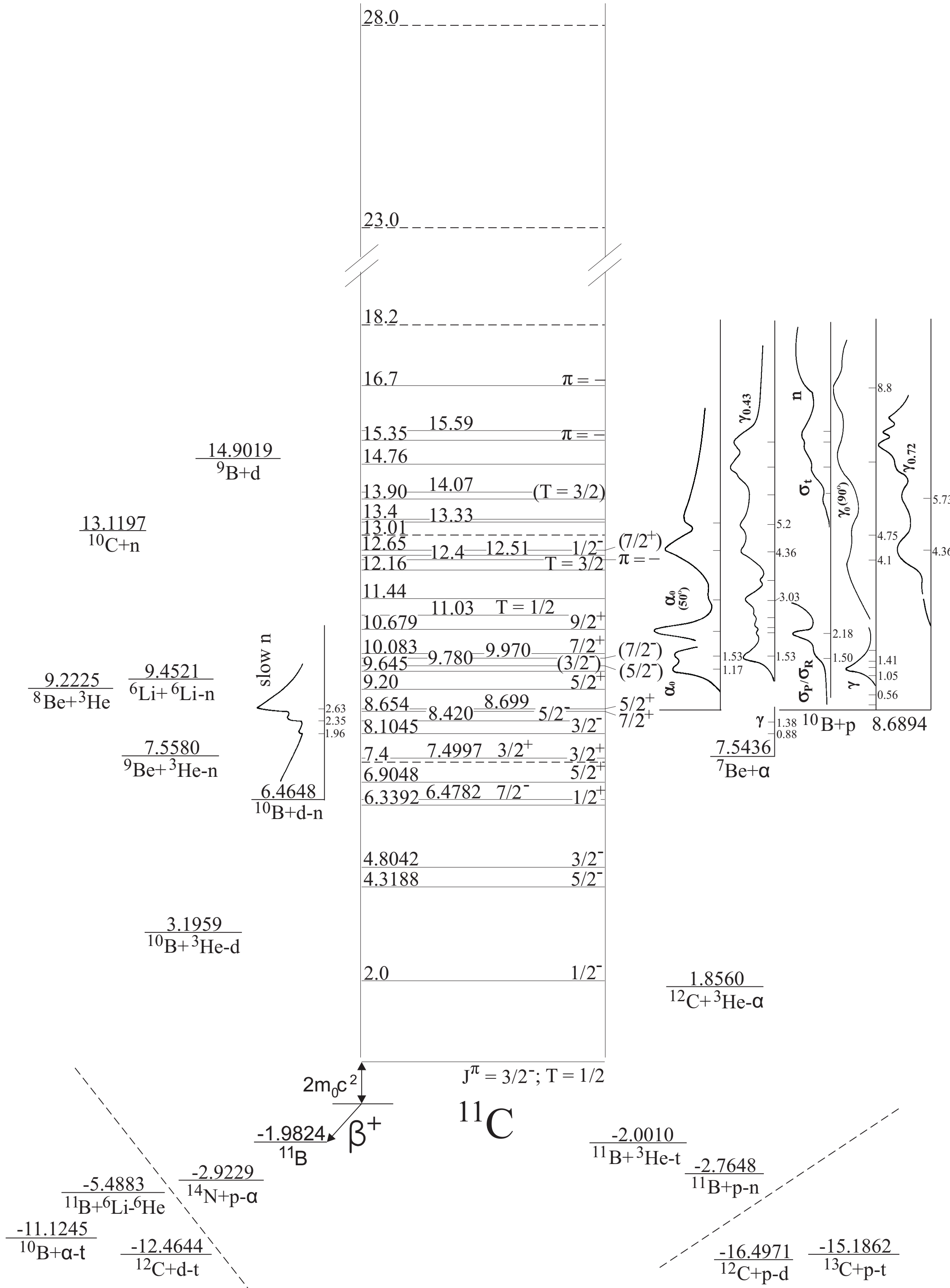

Fig. 5: Energy levels of ^{11}C. For notation see Fig. 4.

Table 11.38: Energy levels of ^{11}C [a]

E_x in ^{11}C (MeV ± keV)	$J^\pi; T$	$T_{\frac{1}{2}}$ or Γ_{cm}	Decay	Reactions
0	$\frac{3}{2}^-; \frac{1}{2}$	$T_{\frac{1}{2}} = 20.364 \pm 0.014$ min	β^+	1, 2, 6, 7, 10, 16, 17, 18, 19, 21, 22, 23, 24, 25, 26, 27, 28, 30, 31, 32, 33, 34, 35, 37, 38, 39, 40, 41, 43, 44
2.0000 ± 0.4	$\frac{1}{2}^-$	$T_{\frac{1}{2}} = 7.1 \pm 0.5$ fs	γ	2, 3, 6, 7, 10, 16, 17, 18, 19, 21, 22, 26, 28, 30, 31, 32, 33, 38, 39, 44
4.3188 ± 1.2	$\frac{5}{2}^-$	< 8.3 fs	γ	2, 3, 6, 7, 10, 16, 17, 19, 21, 22, 26, 28, 30, 31, 34, 38, 39, 44
4.8042 ± 1.2	$\frac{3}{2}^-$	< 7.6 fs	γ	3, 7, 10, 16, 17, 19, 21, 22, 26, 28, 31, 38, 39, 44
6.3392 ± 1.4	$\frac{1}{2}^+$	< 76.2 fs	γ	3, 7, 16, 17, 21, 28, 31, 44
6.4782 ± 1.3	$\frac{7}{2}^-$	< 5.5 fs	γ	2, 3, 7, 10, 16, 17, 19, 21, 22, 26, 28, 31, 37, 38, 44
6.9048 ± 1.4	$\frac{5}{2}^+$	< 48 fs	γ	3, 7, 16, 17, (19), 21, 22, 28, 31, 38, 44
(7.4)	$\frac{3}{2}^+$			16, 21
7.4997 ± 1.5	$\frac{3}{2}^+$	< 63 fs	γ	3, 7, 17, 22, 28, 31, 38
8.1045 ± 1.7	$\frac{3}{2}^-$	$\Gamma = 6^{+12}_{-2}$ eV	γ, α	4, 6, 7, 16, 17, 22, 28, 31
8.420 ± 2	$\frac{5}{2}^-$	0.030 ± 0.008 fs	γ, α	3, 4, 6, 7, 10, 16, 17, 19, 22, 28, 31, 38
8.654 ± 4	$\frac{7}{2}^+$	$\Gamma \leq 5$ keV	(γ)	4, 7, 10, 16, 17, (19), (22), 26, 28, 45
8.699 ± 2	$\frac{5}{2}^+$	15 ± 1	γ, p	7, 10, 16, 17, (19), (22), 28
9.200 ± 50	$\frac{5}{2}^+$	500 ± 90	γ, p	10, 28
9.645 ± 50	$(\frac{3}{2}^-)$	210 ± 40	γ, p, α	10, 12, 15, 28
9.780 ± 50	$(\frac{5}{2}^-)$	240 ± 50	γ, p	10, 12, 15, 22, 28, (45)
9.970 ± 50	$(\frac{7}{2}^-)$	120 ± 20	γ, p	10, (45)
10.083 ± 5	$\frac{7}{2}^+$	≈ 230	γ, p, α	10, 12, 15, 16, 17, 22, 28
10.679 ± 5	$\frac{9}{2}^+$	200 ± 30	γ, p, α	7, 10, 12, 15, 16, 17, 22, 28, 45
11.030 ± 30	$T = \frac{1}{2}$	300 ± 60		7, 22, 28, 31, 38

Table 11.38: Energy levels of ^{11}C [a] (continued)

E_x in ^{11}C (MeV ± keV)	$J^\pi; T$	$T_{\frac{1}{2}}$ or Γ_{cm}	Decay	Reactions
11.440 ± 10		360	p, α	15, 22, 28
12.160 ± 40	$T = \frac{3}{2}$ [b]	270 ± 50	p	7, 13, 22, 45
12.4	$\pi = -$	1400 ± 400	γ, p	10, 31
12.510 ± 30	$\frac{1}{2}^-; \frac{3}{2}$	500 ± 50	p	7, 13, 22, 26, 38
12.650 ± 20	$(\frac{7}{2}^+)$	360	p, ^{3}He, α	14, 15, 22, 45
(13.01)			γ, p	10
13.330 ± 60		270 ± 80		26, 38
13.4		1100 ± 100	p, α	15, 28, 45
13.900 ± 20	$(T = \frac{3}{2})$	200 ± 40	p	7, 13, 22, 38
14.070 ± 20		135 ± 50	n, p	11, 22, 38
14.760 ± 40		≈ 450	n, p, ^{3}He	7, 11, 13, 14, 22
15.350 ± 50	$\pi = -$	broad	γ, n, p	10, 11, 13, 31
15.590 ± 50		≈ 450	n, p	11, 13
16.7	$\pi = -$	820 ± 90	γ, p	10
(18.2)			γ, p	10
(23.0)				31
(28.0)				31

[a] See also Table 11.39.

[b] FAS private communication with F.C. Barker.

4. ^{6}Li(^{10}B, ^{7}Be + α) $Q_m = -3.2875$

Particle decay spectroscopy was used to study ^{11}C*(8.10, 8.42, 8.65) which were observed in the coincident ^{7}Be + α particle relative energy spectra (1998LE17). Upper limits for the $\Gamma_{\alpha_1}/\Gamma_{\alpha_0}$ decay branching ratios for these states were found to be ≤ 0.03, ≤ 0.01 and ≤ 0.01. A comparison with Γ_γ values given in (1990AJ01) indicates $\Gamma_{\alpha_0}/\Gamma = 0.97 \pm 0.03$, 0.80 ± 0.10 and ≈ 1.0 for these states, respectively. Excited states above 8.65 MeV are not observed, indicating small α decay branches.

Table 11.39: Electromagnetic transitions in ^{11}C [a]

Initial state	J^π	τ_m (fs)	Branching ratios (%) to final state				
			g.s.	2.00	4.32	4.80	6.48
2.00	$\frac{1}{2}^-$	10.3 ± 0.7 fs	100				
4.32 [b]	$\frac{5}{2}^-$	< 12 [l]	100	< 2			
4.80 [c]	$\frac{3}{2}^-$	< 11 [l]	85.2 ± 1.4	14.8 ± 1.4			
6.34 [d]	$\frac{1}{2}^+$	< 110	66.5 ± 2.1	33.5 ± 2.1	< 7	< 3	
6.48 [e]	$\frac{7}{2}^-$	< 8 [l]	88.5 ± 1.4	< 2	11.5 ± 1.4	< 2	
6.90 [f]	$\frac{5}{2}^+$	< 69	91 ± 2	< 1	4.5 ± 1	4.5 ± 1	
7.50 [g]	$\frac{3}{2}^+$	< 91	36 ± 2	64 ± 2	< 1	< 1	< 3
8.10 [h]	$\frac{3}{2}^-$	0.06 ± 0.04	74 ± 12	26 ± 5			
8.42 [h]	$\frac{5}{2}^-$	0.043 ± 0.011	100		< 7		
8.70 [i]	$\frac{5}{2}^+$		42 ± 10		42 ± 10	2.4 ± 1.5	13.6 ± 4.6
9.20 [i]	$\frac{5}{2}^+$		74 ± 18		6 ± 5		20 ± 10
9.65 [i,j,k]	$(\frac{3}{2}^-)$		60 ± 5		32 ± 10	8 ± 4	
9.78 [i,j,k]	$(\frac{5}{2}^-)$		76 ± 16		8 ± 2	4 ± 2	12 ± 4
9.97 [i]	$(\frac{7}{2}^-)$				90 ± 10		10 ± 7
10.08 [i]	$\frac{7}{2}^+$				67 ± 8		13 ± 6
10.68 [i]	$\frac{9}{2}^+$						100

[a] See Table 11.20 in (1980AJ01) for other references and additional information.

[b] Branching Ratios (BR) from (1961DO03): ^{10}B(p, γ) and (1968EA03): ^{12}C(^{3}He, α).

[c] BR from (1965OL03): ^{9}Be(^{3}He, n) and ^{10}B(d, n), (1961DO03), (1962FR06): ^{10}B(d, n) and (1968EA03).

[d] BR from (1965RO07): ^{9}Be(^{3}He, n) and (1968EA03).

[e] BR from (1962FR06, 1963BR1H): ^{10}B(d, n) and (1968EA03).

[f] BR to ^{11}C*(0, 2.0, 4.3, 4.8) from (1968EA03). See also (1965OL03) who report 89(3), < 2, 11(3), < 3, < 5, < 5 % for ^{11}C*(0, 2.0, 4.3, 4.8, 6.3, 6.8) respectively.

[g] BR from (1965OL03) who report 36(2), 64(2), < 3, < 3, < 3, < 3, < 4 % for ^{11}C*(0, 2.0, 4.32, 4.8, 6.3, 6.5, 6.9) respectively and (1968EA03) who report 37(3), 63(8), < 1, < 1 % for ^{11}C*(0, 2.0, 4.32, 4.8) respectively.

[h] BR from (1984HA13): ^{7}Be(α, γ).

[i] BR from (1983WI09): ^{10}B(p, γ).

[j] See also BR in (1979AN16).

[k] $\Gamma_\gamma/\Gamma = 0.20 \pm 0.05$, < 0.06 and ≤ 0.1 for ^{11}C*(8.42, 8.66, 8.70), respectively: $\Gamma_{\rm total}$(cm) ≤ 4.5, ≤ 4.5 and 15 ± 1 keV (1983WI09).

[l] (1979AN16). See also (1981CA06) for τ_m of ^{11}C*(4.32, 4.80, 6.48).

5. ^{7}Li(^{7}Li, 3n)^{11}C $\qquad Q_{\rm m} = -5.0501$

At $E(^7$Li)$= 82$ MeV no states of ^{11}C are populated (1987AL10).

6. ^{7}Be$(\alpha, \gamma)^{11}$C $\qquad Q_{\rm m} = 7.5436$

The resonances at $E_\alpha = 0.884 \pm 0.008$ and 1.376 ± 0.003 MeV [^{11}C*(8.106, 8.419)] have $\omega\gamma = 0.331 \pm 0.041$ and 3.80 ± 0.57 eV, $\Gamma_\gamma = 0.350 \pm 0.056$ and 3.1 ± 1.3 eV, and $\Gamma_\alpha = 6^{+12}_{-2}$ and 12.6 ± 3.8 eV, respectively (1984HA13). See also (1995DE05) for a 3-cluster-model analysis and discussion of the astrophysical importance of this reaction. Also see (1996RE16).

7. ^{9}Be(^{3}He, n)^{11}C $\qquad Q_{\rm m} = 7.5580$

Reported neutron groups are listed in Table 11.16 of (1968AJ02). Angular distributions have been studied in the range $E(^3$He$) = 1.3$ to 13 MeV: see (1980AJ01). The dominant L-values are 0 for ^{11}C*(0, 8.10), 1 for ^{11}C*(6.34, 7.50), 2 for ^{11}C*(2.00, 4.32, 4.80, 6.48, 8.42) and 3 for ^{11}C*(6.90). Neutron groups to $T = \frac{3}{2}$ states have been reported at $E_{\rm x} = 12.17 \pm 0.05$ [see however reaction 38], 12.55 ± 0.05 MeV and 14.7 ± 0.1 MeV: see Table 11.40.

Gamma-ray branching ratios and multipolarities for ^{11}C levels up to $E_{\rm x} = 7.5$ MeV have been studied by (1965OL03): see Table 11.39. Together with results from reactions 16 and 28 they lead to assignments of $J^\pi = \frac{1}{2}^-, \frac{5}{2}^-, \frac{3}{2}^-, \frac{1}{2}^+, \frac{7}{2}^-, \frac{5}{2}^+, \frac{3}{2}^+$ for ^{11}C*(2.00, 4.32, 4.80, 6.34, 6.48, 6.90, 7.50): see (1965OL03) and reaction 3 in (1968AJ02) for a summary of the evidence concerning these assignments. See (1980AJ01) for references. See also ^{12}C.

8. (a) ^{9}Be(^{11}C, ^{11}C)
(b) C(^{11}C, ^{11}C)
(c) Al(^{11}C, ^{11}C)

The ^{11}C interaction cross sections on Be, C and Al targets were measured at 730 MeV/A (1995OZZZ). Also see (1996KN05).

9. ^{9}Be(^{14}N, ^{12}B) $\qquad Q_{\rm m} = -9.8074$

At $E(^{14}$N$) = 39.3$ and 68.3 MeV/A, angular distributions and cross sections were measured and evaluated in a DWIA analysis (1997MIZO).

Table 11.40: $T = \frac{3}{2}$ states in ^{11}C [a]

Reaction	E_x (MeV)	Γ_{cm} (keV)
^{9}Be(^{3}He, n)^{11}C	*12.17 ± 0.05*	*200 ± 100*
^{10}B(p, p′)^{10}B*	*12.20 ± 0.10*	
^{11}B(^{3}He, t)^{11}C	*12.15 ± 0.05*	*290 ± 50*
	12.16 ± 0.04 [b]	**270 ± 50** [b]
^{9}Be(^{3}He, n)^{11}C	*12.55 ± 0.05*	*350 ± 100*
^{10}B(p, p_2)^{10}B*	*12.45 ± 0.10*	*400 ± 100*
^{11}B(^{3}He, t)^{11}C	*12.57 ± 0.07*	*370 ± 90*
^{13}C(p, t)^{11}C	*12.47 ± 0.06*	*550 ± 50*
^{13}C(p, t)^{11}C	*12.48 ± 0.04*	*540 ± 60*
	12.51 ± 0.03 [b]	**490 ± 40** [b]
^{10}B(p, p)^{10}B	*13.90 ± 0.02*	
^{11}B(^{3}He, t)^{11}C	*13.92 ± 0.05*	*260 ± 50*
^{13}C(p, t)^{11}C	*13.90 ± 0.04*	*150 ± 50*
	13.90 ± 0.02 [b, c]	**200 ± 40** [b]

[a] See also Table 11.34 for $T = \frac{3}{2}$ states in ^{11}B, and Table 11.21 in (1980AJ01). For references see Table 11.19 in (1985AJ01).

[b] Mean.

[c] See also $E_x = 13.7 \pm 0.1$ MeV from ^{9}Be(^{3}He, n).

10. ^{10}B(p, γ)^{11}C $\qquad Q_m = 8.6894$

This reaction has been investigated for $E_p = 0.07$ to 17.0 MeV. Reported resonances are displayed in Table 11.41. Observed capture γ-rays are displayed in Table 11.39 [see also for τ_m measurements]. Capture measurements for $E_p = 0.07$ to 2.20 MeV are consistent with five resonances (see Tables 11.39 and 11.41), the lowest two (at $E_p = 10$ and 560 keV) of which are s-wave resonances. Thermonuclear reaction rates for $T = (0.01 \to 5) \times 10^9$ K are deduced from the results (1983WI09; see also for spectroscopic factors). At $E_p = 100$, 130 and 160 keV analyzing powers of γ_0, γ_2 and γ_5 were measured (capture to ^{11}C*(0, 4.319, 6.417)) (2003TO21); a TME analysis indicates that the ^{11}C*(8.420) sub-threshold resonance influences the near threshold reaction cross sections.

The 90° yield of γ_0 has been measured for $E_p = 2.6$ to 17 MeV and angular distributions have been obtained for $E_p = 2.8$ to 14 MeV. The excitation function is consistent with the giant resonance centered at $E_x \approx 16$ MeV. In addition to weak structures at $E_p = 4.75$ MeV and 10.5

Table 11.41: Resonances in ^{10}B + p [a]

E_p (MeV±keV)	E_x (MeV)	J^π	Γ_{lab} (keV)	Decay
0.010 ± 2 [b]	8.699 ± 10	$\frac{5}{2}^+$	16 ± 1 [c]	γ
0.56 ± 60 [b]	9.20 ± 50	$\frac{5}{2}^+$	550 ± 100	γ
1.05 ± 60 [b]	9.64 ± 50	$(\frac{3}{2}^-)$	230 ± 50	γ, (p_0, α_0)
1.20 ± 50 [b]	9.78 ± 50	$(\frac{5}{2}^-)$	260 ± 60	γ, (p_0, α_0)
1.41 ± 50 [b]	9.97 ± 50	$(\frac{7}{2}^-)$	130 ± 20	γ
1.533 ± 5	10.083	$\frac{7}{2}^+$	≈ 250	p_0, α_0, α_1
2.189 ± 5	10.679	$\frac{9}{2}^+$	220 ± 30	p_0, α_0, α_1
3.03 ± 10	11.44		400	α_0, α_1
3.9 ± 10	12.20	$T = \frac{3}{2}$		p_2
4.1 ± 100	12.45	$T = \frac{3}{2}$	440 ± 100	p_2
4.1 [d, e]	12.4	$\pi = -$	1–2 MeV	γ_0
4.36 ± 20	12.65	$(\frac{7}{2}^+)$	400	γ_1, α_0, α_1, ^{3}He
(4.75)	(13.01)			γ_0
5.2	13.4		1200 ± 100	α_0, α_1
5.73 ± 20	13.90		≈ 500	γ_1, p
5.92 ± 20	14.07		broad	n
6.68 ± 40	14.76		≈ 500	n, p, ^{3}He
7.33 ± 50 [e]	15.35	$\pi = -$	broad	γ_0, n, p
7.60 ± 50	15.59		≈ 500	n, p
8.8 [e]	16.7	$\pi = -$	900 ± 100	γ_0
(10.5)	(18.2)			γ_0

[a] See also Table 11.39 here, and Tables 11.23 and 11.24 in (1975AJ02). Table 11.23 displays some other reported resonances; Table 11.24 gives detailed parameters for ^{11}C*(9.73, 10.08, 10.68, 12.65). For references see Table 11.22 in (1980AJ01). For unpublished work and other references see Table 11.20 in (1985AJ01). (1988ABZW) [in (p, p′γ) and (p, $\alpha\gamma$); $E_p = 2$ to 5 MeV] report 5 states with energies 11.84, 11.37(?), 12.63, 12.75, and 13.1 MeV.

[b] (1983WI09).

[c] $\Gamma_\gamma/\Gamma_{tot} = (2.6 \pm 0.15) \times 10^{-4}$: see (1983WI09). $\Gamma_\gamma/\Gamma_{tot} = 0.20 \pm 0.05$ and < 0.06, respectively for ^{11}C*(8.42, 8.66), respectively: $\Gamma_{tot} \leq 5$ keV for both states (1983WI09).

[d] $\Gamma_p\Gamma_\gamma/\Gamma \approx 20$ eV.

[e] Probably part of the E1 giant resonance.

MeV, there are three major peaks at $E_p = 4.1$, 7.0 and 8.8 MeV ($\Gamma = 1$ to 2 MeV) [$E_x = 12.4$, 15.0, 16.7 MeV]. At ^{11}C*(12.4), the γ_0 angular distribution is essentially isotropic: $\Gamma_p\Gamma_\gamma/\Gamma \approx 200$ eV, $\Gamma_\gamma \approx 5$ keV (assuming $\Gamma_p \approx 10$ keV). The $E_p = 4.1$ MeV resonance is probably part of the E1 giant resonance and is formed by s-wave capture. At the two higher resonances the angular distributions are characteristic of E1 giant resonances in light nuclei. The ^{10}B(p, γ_1) cross section is small for $E_p = 2.6$ to 17 MeV: see (1980AJ01).

11. ^{10}B(p, n)^{10}C $\quad Q_m = -4.4303 \quad E_b = 8.6894$

The total (p, n) cross section has been measured to $E_p = 10.6$ MeV: broad maxima are observed at $E_p = 5.92 \pm 0.02, 6.68 \pm 0.04, 7.33 \pm 0.05$ and 7.60 ± 0.05 MeV (see Table 11.41). The cross section for formation of ^{10}C$_{g.s.}$ shows a relatively smooth behavior rising up to $E_p \approx 8$ MeV where a sharp maximum is observed. The cross section for production of 3.35 MeV γ-rays (from ^{10}C*) does not appear to show structure for $E_p = 8.5$ to 12 MeV (1966SE03). For references see (1980AJ01). For n_0 and n_1 excitation curves from $E_p = 13.7$ to 14.7 MeV see (1985SC08). See also (1995YA12) for measurements at $E_p = 186$ MeV.

12. ^{10}B(p, p)^{10}B $\quad E_b = 8.6894$

Below $E_p = 0.7$ MeV the scattering can be explained in terms of pure s-wave potential scattering but the possibility of a state near $E_p = 0.27$ MeV ($E_x = 8.95$ MeV) cannot be excluded. The elastic scattering then shows two conspicuous anomalies at $E_p = 1.50 \pm 0.02$ MeV and at 2.18 MeV [$E_x = 10.05$ and 10.67 MeV] with $J^\pi = \frac{7}{2}^+$ and $\frac{9}{2}^+$: see Table 11.41. At higher energies (to $E_p = 10.5$ MeV) a single broad resonance is reported at $E_p \approx 5$ MeV. Polarization measurements are reported at 30.3 MeV: optical model parameters have been derived. The depolarization parameter D has been measured for polarized protons at 26 and 50 MeV. For references see (1980AJ01, 1985AJ01).

13. ^{10}B(p, p$'$)^{10}B $\quad E_b = 8.6894$

The yield of γ_1 [from ^{10}B*(0.72)] rises monotonically from $E_p = 1.5$ to 4.1 MeV and then shows resonance behavior at $E_p = 4.36$ and 5.73 MeV: see Table 11.41. For $E_p = 6$ to 12 MeV, the cross section for γ_1 shows several sharp maxima superposed on a broad maximum ($\Gamma \approx 2.5$ MeV) at $E_p \approx 7.2$ MeV. See however (1975AJ02). Yields of five other γ-rays involved in the decay of ^{10}B*(1.74, 2.16, 3.59, 5.18) have also been measured in the range $E_p = 4$ to 12 MeV [see (1975AJ02)].

Excitation curves for the p_1, p_2 and p_3 groups have been measured for E_p =3.5 to 5.0 MeV. Possible resonances are observed in the p_2 yield [to the $T = 1$ state ^{10}B*(1.74)] corresponding to the first $T = \frac{3}{2}$ states at $E_x = 12.16$ [see however reaction 38] and 12.50 MeV [see Table 11.40]: these do not occur in the yield of p_1 and p_3. Yield curves for inelastically scattered protons have also been measured at $E_p = 5.0$ to 16.4 MeV (p_1, p_2, p_3), 6.6 to 16.4 MeV (p_4), 8.9 to 16.4 MeV (p_5) and 10.9 to 16.4 MeV (p to ^{10}B*(6.03)): the principal feature for all groups, except that to ^{10}B*(6.03), is a structure at $E_p \approx 7.5$ MeV, $\Gamma \approx 4$ MeV. In addition narrower structures are observed, including three at $E_p = 5.75$, 6.90 and 7.80 MeV (± 0.2 MeV) and widths of ≈ 500 keV. For references see (1980AJ01, 1985AJ01).

14. (a) ^{10}B(p, d)^{9}B $\quad Q_m = -6.2125 \quad E_b = 8.6894$

(b) ^{10}B(p, ^{3}He)^{8}Be $\quad Q_m = -0.5332$

Polarization measurements (reaction (a)) have been carried out at $E_p = 49.6$ MeV for the deuterons to ^{9}B*(0, 2.36): see (1975AJ02). In reaction (b) two strong maxima are observed in the cross section at $E_p \approx 4.5$ and 6.5 MeV: see Table 11.41. See also (1975AJ02).

15. ^{10}B(p, α)^{7}Be $\quad Q_m = 1.1458 \quad E_b = 8.6894$

The total cross section for this reaction has been measured for $E_p = 60$ to 180 keV: the extrapolated cross section at the Gamow energy, taken to be 19.1 keV, is $\approx 10^{-12}$ b. The thick target yield for $E_p = 75$ keV to 3 MeV shows that the ^{7}Be yield constitutes a potential problem if natural boron is used as fuel in CTR devices (1975PE1A).

The parameters of observed resonances are displayed in Table 11.41. The ground state (α_0) α-particles exhibit broad resonances at $E_p = 1.17$, 1.53, 2.18, 3.0, 4.4, 5.1 and 6.3 MeV. Alpha particles to ^{7}Be*(0.43)[α_1] and 0.43-MeV γ-rays exhibit all but the 1.2 MeV resonance: see (1975AJ02). A broad maximum dominates the region from $E_p = 4$ MeV to about 7.5 MeV. A study of the yield of 0.43 MeV γ-rays for $E_p = 2.0$ to 4.1 MeV suggests that the 3.0 MeV resonance, where angular distribution is asymmetric, is due to two broad states. A weak structure at $E_p = 2.5$ MeV is also reported. For references see (1980AJ01, 1985AJ01). See also ^{7}Be in (2002TI10), and (1995SA52) for PIGE applications.

16. ^{10}B(d, n)^{11}C $\quad Q_m = 6.4648$

Table 11.42 presents the results obtained in this reaction and in the (^{3}He, d) reaction. Information on τ_m and on the γ-decay of ^{11}C states is displayed in Table 11.39: see (1968AJ02, 1975AJ02) for references. The thick target yields for ^{10}B(d, n_0) were measured for $E_d = 140$, 160 keV (2008ST10); cross sections were deduced and the practicality of developing a 6.3 MeV neutron source based on the ^{10}B(d, n) reaction is discussed. In (1990MI11) cross sections were measured for $E_d = 0.5$ to 0.6 MeV. Production of ^{11}C for PET is discussed in (2005VO15, 2011KI04). See also (2001HO23) and ^{12}C.

17. ^{10}B(^{3}He, d)^{11}C $\qquad Q_m = 3.1959$

Table 11.42 displays the information derived from this reaction and from the (d, n) reaction. The study of the angular distributions of the deuterons to ^{11}C*(8.66, 8.70) shows that these levels are the analogs, respectively, of ^{11}B*(9.19, 9.27) whose J^π are $\frac{7}{2}^+$ and $\frac{5}{2}^+$ [the ^{11}B states were studied in the (d, p) reaction]: Γ_{cm} are $\ll 9$ keV and 15 ± 1 keV, respectively, for ^{11}C*(8.66, 8.70): see (1975AJ02) for references.

Angular distributions of cross section were measured at $E(^3\text{He}) = 34$ MeV, and an optical model analysis was used to extract the ANCs for ^{11}C*(0, 4.319, 6.478) (2010AR03). The astrophysically relevant cross sections and S-factors were deduced from the ANCs. Also see (2010TI04) for a shell model analysis of ANCs for this reaction.

18. ^{10}B(α, t)^{11}C $\qquad Q_m = -11.1245$

Angular distributions have been measured at $E_\alpha = 25.1$ and 56 MeV [see (1980AJ01)] and at 24.8 and 30.1 MeV (1983VA28; t_0, t_1).

19. ^{10}B(^{7}Li, ^{6}He)^{11}C $\qquad Q_m = -1.2853$

Angular distributions of ^{6}He ions have been measured at $E(^7\text{Li}) = 3.0$ to 3.8 MeV and at 24 MeV [to ^{11}C*(0, 4.32, 6.48)]. ^{11}C*(2.0, 4.80, 8.42, $8.66 + 8.70$) are also populated: see (1980AJ01) for references.

20. ^{11}B(γ, π^-) $\qquad Q_m = -141.5526$

Pion production yields were measured at $E_{brem} = 0.03$ to 1.2 GeV (1994OUZZ).

21. ^{11}B(p, n)^{11}C $\qquad Q_m = -2.7648$

Table 11.42: Energy levels and spectroscopic factors of ^{11}C from ^{10}B(d,n)^{11}C and ^{10}B (^{3}He,d)^{11}C stripping reactions [a]

E_x (MeV±keV)	J^π	l [b]	l [c]	$S_{d,n}$ [c]	$S_{^3He,d}$ [c]	l [d]	$S_{^3He,d}$ [d]
0	$\frac{3}{2}^-$	1	1	1.12	0.88	1	1.09
2.0006 ± 0.9	$\frac{1}{2}^-$	(1)	(1)	(0.18)	(0.036)		
			(3)		≤ 0.09	(3)	< 0.40
4.322 ± 10	$\frac{5}{2}^-$	1	1	0.27	0.20	1	0.17, 0.19
4.808 ± 10	$\frac{3}{2}^-$	1	1	< 0.02		(1)	< 0.08
						(3)	< 0.35
6.345 ± 10	$\frac{1}{2}^+$		2		0.07	2	0.08
6.476 ± 10	$\frac{7}{2}^-$	1	1	0.86	0.56	1	0.73, 0.79
6.903 ± 10	$\frac{5}{2}^+$	(1)				2	0.06
						0	< 0.04
7.498 ± 10	$\frac{3}{2}^+$					2	0.08
8.107 ± 10	$\frac{3}{2}^-$					1	0.07
8.424 ± 8	$\frac{5}{2}^-$	1	1	0.65	0.46	1	0.73, 0.79
8.655 ± 8	$\frac{5}{2}^+$	0	0	0.84	0.45		
			2	0.8	0.32		
	$\frac{7}{2}^+$		0	0.63	0.33	2	0.41
			2	0.6	0.24	0	< 0.34
8.701 ± 20	$\frac{5}{2}^+$	(0)	0	0.40	0.14	0	< 0.8
			2	≤ 0.2	0.13		
	$\frac{7}{2}^+$		0	0.30	0.11		
			2	≤ 0.15	0.10		
10.08							
10.68 [e]			(0,2)				

[a] See Table 11.23 in (1980AJ01) for references.

[b] From (d, n) work summarized in Table 11.20 of (1968AJ02).

[c] $S_{d,n}$ obtained at $E_d = 5.8$ MeV, $S_{^3He,d}$ obtained at $E(^3He) = 11.0$ MeV [both ±30%]. When $S_{d,n}$ and $S_{^3He,d}$ differ appreciably, the more reliable value is underlined.

[d] $E(^3He) = 21$ MeV; when two values are shown for $S_{^3He,d}$, they are in order of descending j, i.e. $\frac{3}{2}$, $\frac{1}{2}$.

[e] $\Gamma \approx 200$ keV.

Table 11.43: B(GT) values obtained from 0° ^{11}B(^{3}He, t) measurements

E_x (MeV)	J^{π} [a]	B(GT) (2004FU16)	B(GT) (2004KA53) [b]	B(GT) (2004KA56)
0	$\frac{3}{2}^-$	0.345 (8) [a]	0.345 (8) [a]	0.345 (8) [a]
2.00	$\frac{1}{2}^-$	0.440 (22)	0.402 (31)	0.405 (9)
4.319	$\frac{5}{2}^-$	0.526 (27)	0.454 (26)	0.491 (8)
4.804	$\frac{3}{2}^-$	0.525 (27)	0.480 (31)	0.581 (8)
8.105	$\frac{3}{2}^-$	0.005 (2)	≤ 0.003	
8.420	$\frac{5}{2}^-$	0.461 (23)	0.406 (38)	

[a] From adopted table.

[b] Results shown use a central potential strength ratio $R^2 = 8.24$; using $R^2 = 5.24$ yields B(GT) = 0.345, 0.461 (36), 0.521 (31), 0.551 (36), ≤ 0.004 and 0.466 (45) respectively.

Angular distributions for transitions including n_0, n_1, n_2, n_3, n_{4+5}, n_6, n_7 have been measured up to 49.5 MeV [see (1980AJ01, 1985AJ01, 1990AJ01)]. Also see (1986MU08) $E_{\vec{p}} = 13$ to 17 MeV, (1990SAZL) $E_p = 50$, 80 MeV and (1994GA49) $E_p = 1$ GeV. At $E_p = 186$ MeV, angular dependent cross sections ($\theta = 0$ to 50 degrees) and polarization transfer coefficients, analyzing powers and induced polarization ($\theta = 0$ to 20 degrees) were measured (1994WA22, 1994RA23, 1995YA12). The quasi-free scattering data are found to agree with a simple Fermi gas model (1994WA22). A multipole decomposition analysis of the data enabled a DWBA investigation of the $\Delta L = 1$ transitions; peaks at $E_x = 13$ and 16 MeV are found to have $\Delta L = 0$, 1 and 2 components, while a broad peak around $E_x = 18$ to 23 MeV is dominated by $\Delta L = 1$ components (1995YA12).

The G-T matrix elements, which are related to the zero-degree cross sections, are discussed in (1985GR09, 1990TA15) for $E_p = 16$ to 26 MeV and 160 to 795 MeV, respectively. Polarization transfer coefficients are measured at $E_p = 160$ MeV (1990TA15) and $E_p = 295$ MeV (1994WAZW, 1995WA16). See also (1994SH21, 1995SH44, 2009EL09) and ^{12}C.

22. ^{11}B(^{3}He, t)^{11}C $\qquad Q_m = -2.0010$

Angular distributions of t_0 and t_1 have been measured at $E(^3\text{He}) = 10$, 14, and 217 MeV [the latter also for the triton groups to ^{11}C*(4.3, 4.8, 6.48, 8.10) and at $E(^3\vec{\text{He}}) = 33$ MeV; for references see (1980AJ01, 1985AJ01). At $E(^3\text{He}) = 26$ MeV, the $E_x = 6.9$ to 8.7, (9.78), 10.08 to 12.15, 12.57, 12.65, 13.92 and 14.15 MeV states of ^{11}C are populated including the possible $T = \frac{3}{2}$ states displayed in Table 11.40 (1971WA21). At $E(^3\text{He}) = 420$ MeV (2004FU16) and 450 MeV (2004KA53, 2004KA56) the 0° cross sections for populating ^{11}C states are related to the G-T transition strengths; see Table 11.43. In (2004KA53) peaks corresponding to ^{11}C*(11.0, 12.6, 14.7) are also observed. An AMD analysis of the $J^\pi = \frac{3}{2}^-_3$ and $\frac{5}{2}^-_2$ states near 8 MeV deduced that the $\frac{3}{2}^-$ state has a well developed cluster character with dilute density (2007KA07, 2008KA46).

23. (a) ^{12}C(γ, n)^{11}C $\quad Q_m = -18.7217$
(b) ^{12}C(e, e′n)^{11}C $\quad Q_m = -18.7217$

For reaction (a) the fraction of transitions to the ground and to excited states of ^{11}C [and to ^{11}B states reached in the (γ, p) reaction] has been measured at $E_{\rm brem}$ = 24.5, 27, 33 and 42 MeV: the ground state is predominantly populated. The population of analog states in the (γ, n) and (γ, p) reactions are similar. A significant decay strength is found to the positive-parity states with $6 < E_x < 8$ MeV. In general the main contribution to the strength of the transitions to the various excited states of ^{11}C (and ^{11}B) lies in rather localized energy bands in ^{12}C which are a few MeV wide (1970ME17). Measurements are reported at $E_{\rm brem}$ = 20 MeV (1999AB39, 1999AB40, 2000AB35) and $E_{\rm brem}$ = 58 MeV (1993AN17); see (1994RY03, 1994VAZX, 1994ZO01, 2000LE38) for comments on knockout reactions above the GDR, also see (1980AJ01, 1985AJ01) and ^{12}C.

For reaction (b), the excitation function for n_0 emission from the GDR region in ^{12}C was measured at E_e = 126 MeV (2000OI01) and E_e = 129 MeV (1992SU12, 1997SA17, 2002TA19). See also (1991SA14, 1992DR02, 2005SA37).

For reactions producing pions see (1990AN26, 1990AR14, 1993LI21, 1994JO05, 1998GL14, 1999BA31, 1999LE35, 2000GL08, 2000SO19, 2003GL03, 2004BO47, 2005GL05, 2006CO19, 2008GL05).

24. ^{12}C(ν, ν'n) $\quad Q_m = -18.7217$

Polarization effects in neutrino-nucleus scattering reactions are discussed in (2008ME03). An analysis of superscaling applied to quasi-elastic neutrino scattering is given in (2008MA21). Discussion of the impact of (ν, ν'n) reactions on ^{7}Li and ^{11}B production in supernovae explosions is given in (2006SU15, 2007SU08). Influence of the nuclear strong quark component on quasi-elastic neutrino scattering is discussed in (1992GA14). Also see (2004ME18, 2004VA09, 2006ME17, 2006ME24).

25. ^{12}C(μ, X)^{11}C $\quad Q_m = -18.7217$

A study of muon induced backgrounds in large volume scintillators measured σ(100 MeV) = 576 ± 45 μb and σ(190 MeV) = 905 ± 58 μb for production of ^{11}C, and σ(100 MeV) < 1.22 μb and σ(190 MeV) < 2.34 μb for production of ^{11}Be (2000HA33). See (2006BA66) for analysis of ^{11}C production rates in Borexino and (2010AB05) for analysis of production rates in KamLAND.

26. (a) ^{12}C(π^+, p)^{11}C $\quad Q_m = 121.6309$
(b) ^{12}C($\pi^\pm$, $\pi^\pm$n)^{11}C $\quad Q_m = -18.7217$

Angular distributions at $E_{\pi^+} = 49.3$, 90 and 180 MeV have been obtained to ^{11}C*(0, 2.0, 4.3+4.8, 6.5, 8.5). At the same momentum transfer, this reaction and the (p, d) reaction give similar intensities to the low lying states of ^{11}C. $T = \frac{3}{2}$ states have been suggested at $E_x = 12.5 \pm 0.3$ and 13.3 MeV: see (1985AJ01). See also (1991KI02, 1992BA57, 1997BO15, 1999KE04). For reaction (b) ^{11}C*(4.32)[$\frac{5}{2}^-$] (and the analog state in ^{11}B) is surprisingly strongly populated for $E_{\pi^+} = 60$ to 300 MeV: see (1980AJ01, 1985AJ01).

27. ^{12}C(n, 2n) $\quad Q_m = -18.7217$

The total cross sections for (n, 2n) reactions on ^{12}C were measured at $E_n = 15$ to 40 MeV (1996UN01), $E_n = 20$ to 50 MeV (1998KI21), and $E_n = 22.8$ to 33.6 MeV (1981AN16). Also see (1997HA21) and references in ^{13}C (1981AJ01, 1986AJ01).

28. ^{12}C(p, d)^{11}C $\quad Q_m = -16.4971$

Angular distributions have been measured for E_p =19 to 800 MeV [see (1968AJ02, 1975AJ02, 1980AJ01, 1985AJ01) for references], at $E_p = 45$ MeV (2005KI09; to ^{11}C*(0, 2.0, 4.3, 4.8)), at $E_{\vec{p}} = 497$ MeV (1984OH06; d$_0$; also A_y) and at $E_p = 800$ MeV (1984SM04; to ^{11}C* (0, 2.0, 4.3, 4.8, 6.5, 8.1, 8.66+8.70, 9.98±0.20, 10.56±0.20, 13.22±0.25)). In the latter experiment ^{11}C*(8.4) and a state at 13.22 ± 0.25 MeV ($\Gamma \approx 2$ MeV) are also reported (1984SM04). See (1991AB04) for an analysis of Cohen-Kurath wavefunctions at $E_p = 30.3$ MeV, and see (1998CA18) for a Glauber model analysis of $E_p = 800$ MeV data. States of ^{11}C previously observed in this reaction are displayed in Table 11.24 of (1980AJ01). See also ^{13}N in (1991AJ01).

29. ^{12}C(p, n + p) $\quad Q_m = -18.7217$

At 1 GeV the separation energy between $\Gamma \approx 6$ and 13 MeV broad 1p$_{3/2}$ and 1s$_{1/2}$ groups is ≈ 17 MeV (1985BE30, 1985DO16). At $E_p = 200$ MeV, angular distributions were evaluated in a study of the collective influence of the nuclear medium on the NN interaction (1999CA15).

At $E_{\vec{p}} = 200$ MeV, analyzing powers were measured (1999CA11). The study was evaluating the difference between free NN scattering and quasifree scattering to help improve the understanding of how the presence of a nuclear medium modifies the NN interaction.

The excitation function for ^{11}C production via proton spallation on carbon, nitrogen and oxygen was measured for E_p = threshold to 200 MeV (2004KE05) and $E_p = 60$ to 250 MeV (1999CH50). Measurement of the excitation function for $E_p = 95$ to 200 MeV determined cross sections for clinical proton therapy applications (1993KO48). Also see (1996MA53) for $E_p < 200$ MeV and see ^{12}C.

30. ^{12}C(d, t)^{11}C $\qquad Q_m = -12.4644$

At $E_d = 28$ MeV the t_0 angular distribution was measured, and a detailed comparison has been made with the results for the mirror reaction ^{12}C(d, ^{3}He)^{11}B. At $E_d = 29$ MeV the t_0 angular distribution leads to pick-up spectroscopic factor $C^2S = 2.82$ or 3.97 depending on different sets of parameters for $^{11}C_{g.s.}$; ^{11}C*(2.0, 4.32) are also populated; see (1980AJ01). At $E_{\vec{d}} = 200$ MeV angular distributions and analyzing powers were measured (1994VA28); a DWBA analysis deduced spectroscopic factors for ^{11}C*(0, 2.0). See also ^{14}N in (1986AJ01), (1980AJ01) for references.

31. (a) ^{12}C(^{3}He, α)^{11}C $\qquad Q_m = 1.8560$
(b) ^{12}C(^{3}He, tp)^{11}C $\qquad Q_m = -17.9579$

Angular distributions have been measured at many energies to $E(^3\text{He}) = 217$ MeV [see (1968AJ02, 1975AJ02, 1980AJ01, 1985AJ01) for references]. Observed states are displayed in Table 11.44. Excitation of additional states at $E_x = 11.2$, 12.4, 15.3, 23, and (28) MeV has also been suggested: see (1980AJ01).

At $E(^3\text{He}) = 35.6$ MeV DWBA analysis indicates good fits for strong $l = 1$ transitions, and reasonable agreement in the forward direction, as well as with S_{theor}, for weak $l = 1$ transitions. Transitions involving $l = 0$ or 2 (and 3) are weak and the agreement with theory is poor. It is suggested that ^{11}C*(8.10) $[\frac{3}{2}^-]$ is predominantly a $p_{3/2}$ hole state coupled to ^{12}C*(7.65)$[0^+]$: see (1980AJ01).

Alpha-γ correlations have been studied for $E(^3\text{He}) = 4.7$ to 12 MeV. The results are summarized in Table 11.39 and are discussed in detail in reaction 22 of (1968AJ02). A measurement of the linear polarization of the 2.00 MeV γ-ray (together with knowledge of the τ_m) fixes $J^\pi = \frac{1}{2}^-$ for ^{11}C*(2.00). $\tau_m = 10.3 \pm 0.7$ fs for ^{11}C*(2.00). See also ^{12}N, and ^{15}O in (1986AJ01).

Reaction (b) has been studied at $E(^3\text{He}) = 75$ MeV: transitions to ^{11}C*(0, 2.0, 4.3, 4.8, 6.3) are observed by analyzing p, t angular correlations: see (1985AJ01).

Nuclear rainbow effects are studied at $E(^3\text{He}) = 50$ and 60 MeV (1992AD06) and at $E(^3\text{He}) = 98$ MeV (1995DA08, 1995DA21). See (1997TE16) for applications in ^{12}C concentration depth profiling.

Table 11.44: Levels of ^{11}C and relative pick-up spectroscopic factors from ^{12}C(^{3}He, α)^{11}C [a]

E_x (MeV ± keV)	l	S_{rel}			
		$E(^3$He$) = 16$ MeV	24 MeV	28 MeV	35.6 MeV
0	1	1	1	1	1.00
1.999 ± 4	1	0.10	≤ 0.6	≤ 0.6	0.19
4.3188 ± 1.2	3	0.057	(0.04)	(0.06)	(0.031)
4.8042 ± 1.2	1	0.11	0.22	0.22	0.13
6.3392 ± 1.4	0	0.003 [b]	≤ 0.07	≤ 0.07	($\lesssim 0.2$)
6.4782 ± 1.4	3	0.11[b]	0.06	(0.06)	(0.21)
6.9048 ± 1.4	2	0.018	(0.15)	(0.17)	(0.054)
7.4997 ± 1.5	2	0.006[b]	(0.07)	(0.09)	(0.046)
8.1045 ± 1.7	1	0.017[b, c]			(0.035)
8.42	3	0.034[b, d]			(0.041)

[a] See Table 11.39 for γ-decay work. Higher excited states are also reported: see text. See Table 11.25 in (1980AJ01) for references and for additional information.
[b] At $E(^3$He$) = 18$ MeV.
[c] Assuming $J^\pi = \frac{3}{2}^-$.
[d] Assuming $J^\pi = \frac{5}{2}^-$.

32. (a) ^{12}C(^{6}Li, ^{7}Li)^{11}C $\qquad Q_m = -11.4706$
(b) ^{12}C(^{6}Li, ^{6}He + p)^{11}C $\qquad Q_m = -21.4452$

The angular distributions involving ^{7}Li$_{g.s.}$ + ^{11}C$_{g.s.}$ and ^{7}Li*(0.48) + ^{11}C*(2.00) have been studied at $E(^6$Li$) = 36$ MeV: see (1980AJ01). At $E(^6\vec{\text{Li}}) = 50$ MeV polarization observables were measured for the reaction populating ^{11}C$_{g.s.}$ (1997KE04). For reaction (b) see (1992SC10, 1993SC02) and ^{12}N.

33. ^{12}C(^{10}B, ^{11}B)^{11}C $\qquad Q_m = -7.2675$

At $E(^{10}$B$) = 100$ MeV, angular distributions have been measured involving ^{11}B$_{g.s.}$ + ^{11}C$_{g.s.}$, ^{11}B$_{g.s.}$ + ^{11}C*(2.00) and ^{11}C$_{g.s.}$ + ^{11}B*(2.12). See (1985AJ01).

34. ^{12}C(^{12}C, ^{13}C)^{11}C $\qquad Q_m = -13.7753$

Angular distributions involving $^{11}C_{g.s.}$ have been studied at $E(^{12}C)=$ 93.8 and 114 MeV [see (1980AJ01, 1985AJ01)], at 20 MeV/A (1985BO39), at 25, 35, and 50 MeV/A (1988WI09, 1989WI07) and at 344.5 MeV (1992JA10). The strongest peak observed is due to the unresolved ^{13}C*$(3.68 + 3.85)$+^{11}C*(4.32) states (1988WI09, 1989WI07). The results are in agreement with the predictions of the exact FRDWBA. Above $\approx$ 30 MeV/A the angle-integrated cross sections fall off with an approximately exponential shape (1988WI09).

A theoretical analysis of spin polarization in nuclei following one nucleon transfer for ^{12}C+^{12}C at $E_{\rm lab} = 140$ and 300 MeV is given in (1994YA01).

35. ^{12}C(^{28}Si, X)^{11}C

At $E(^{28}$Si$) = 13.4$ GeV/A the ^{11}C activation cross section is $\sigma = 73.5 \pm 1.4$ (stat.) $\pm\, 3.5$ (syst.) mb (1990WI09).

36. ^{13}C(γ, 2n) $Q_{\rm m} = -23.6680$

This reaction was measured at $E_{\rm brem} \approx 36$ MeV in the region of the ^{13}C GDR (1993MC02). Also see ^{13}C in (1991AJ01).

37. ^{13}C(π^+, d)^{11}C $Q_{\rm m} = 118.9091$

At $E_{\pi^+} = 32$ MeV angular distributions have been obtained for the deuterons to ^{11}C*(0, 6.48): see (1985AJ01).

38. ^{13}C(p, t)^{11}C $Q_{\rm m} = -15.1862$

Angular distributions have been measured for $E_{\rm p} = 26.9$ to 65 MeV [see (1980AJ01, 1985AJ01)]. At $E_{\rm p} = 43.7$ to 50.5 MeV the tritons have been studied to ^{11}C*(0, 2.00, 4.32, 4.80, 6.48, 6.90, 7.50) and to a $T = \frac{3}{2}$ state at $E_{\rm x} = 12.47$ MeV [see Table 11.40] whose J^π is determined to be $\frac{1}{2}^-$ [it is thus the analog of ^{11}Be*(0.32)]. The state primarily proton decays to ^{10}B*(1.74). Alpha decay to ^{7}Be*$(0 + 0.4)$ is also observed. At $E_{\rm p} = 46.7$ MeV the $T = \frac{3}{2}$ state is also observed by (1974BE20) who, in addition, report the population of states with $E_{\rm x} = 11.03 \pm 0.03$, 13.33 ± 0.06, 13.90 ± 0.04 and 14.07 ± 0.04 MeV [$\Gamma = 300 \pm 60$, 270 ± 80, 150 ± 50 and 135 ± 50 keV, respectively].

39. (a) ^{14}N(p, α)^{11}C $Q_{\rm m} = -2.9229$
(b) ^{14}N(p, pt)^{11}C $Q_{\rm m} = -22.7367$

Angular distributions have been reported at a number of energies in the range $E_{\rm p} = 5.0$ to 44.3 MeV for the α_0 and α_1 groups: see (1975AJ02, 1980AJ01). A DWBA analysis of angular distributions measured for ^{11}C*(0, 2.0, 4.3, 4.8) at $E_{\rm p} = 20$ to 45 MeV (2005AB17) found that the reaction proceeds mainly by the direct mechanism.

The astrophysical importance of this reaction is discussed in (1998AD12). The excitation function was evaluated as a method to produce ^{11}C for PET applications at $E_{\rm p} = 5$ to 25 MeV (2003TA17), and at $E_{\rm p} = 6$ to 19 MeV (2003KO72). Also see (1990KO21, 2006TR08). For reaction (b) see (1986VDZY; $E_{\rm p} = 50$ MeV).

40. ^{14}N(d, αn)^{11}C $Q_{\rm m} = -5.1474$

The excitation function of ^{14}N(d, αn) was measured from threshold to $E_{\rm d} = 12.3$ MeV using activation techniques (1998SZ01).

41. ^{14}N(^{10}B, ^{13}C)^{11}C $Q_{\rm m} = 1.1388$

This reaction has been studied at $E(^{10}$B$) = 100$ MeV; see (1980AJ01).

42. ^{16}O(ν, e$^-$ + p + α) $Q_{\rm m} = -25.6122$

Cross sections for neutrino induced reactions on ^{16}O are calculated in (2003KO50).

43. (a) ^{16}O(γ, ^{11}C)
(b) ^{181}Ta(γ, ^{11}C)

For reaction (a) γ-rays from $E_{\rm brem} = 1$ GeV were used to evaluate PET radioisotope production (1996BB09). For reaction (b) a 50 TWatt laser was focused on a Ta target, and the intense energy at the laser focus accelerated electrons in the target to relativistic energies; as the electrons stopped Bremsstrahlung photons were produced with energies above 10 MeV. The high energy photons induced photo-breakup reactions in the Ta and ^{11}C ions were produced (2000LE02).

44. (a) ^{16}O(d, ^{7}Li)^{11}C $\qquad Q_{\rm m} = -17.1587$

(b) ^{16}O(α, ^{9}Be)^{11}C $\qquad Q_{\rm m} = -24.3109$

At $E_{\rm d} = 80$ MeV, angular distributions for ^{11}C*(0, 2.0, 4.3 + 4.8, 6.3 + 6.5 + 6.9) have been measured (1978OE1A). At $E_\alpha = 42$ MeV, the angular distribution involving the two ground state transitions has been measured (1972RU03).

45. ^{16}O(^{9}Be, ^{7}Be $+ \alpha$) $\qquad Q_{\rm m} = -14.6024$

At $E(^{9}{\rm Be}) = 70$ MeV ^{11}C states at $E_{\rm x} = 8.65$, 9.85, 10.7 and 12.1 MeV were observed in the relative energy spectrum of ^{7}Be $+ \alpha$ particles (2004SO19, 2004SO28, 2005SO13). There is weak evidence for peaks corresponding to ^{11}C*(12.6, 13.4). Observation of ^{11}C*(12.1), which is assumed to be the $T = \frac{3}{2}$ analog of the ^{11}Be ground state, may indicate a significant $T = \frac{1}{2}$ isospin mixing.

46. ^{28}Si(^{11}C, X)

Total reaction cross sections for ^{11}C + ^{28}Si were measured at $E(^{11}{\rm C}) = 15$ to 53 MeV/A (2006WA18). A Glauber model analysis was used to deduce the ^{11}C $R^{\rm matter}_{\rm rms} = 2.18 \pm 0.26$ fm.

^{11}N

(Table 11.45, Figs. 6 and 7)

Experimental evidence supporting states in ^{11}N have produced a generally consistent picture of the ^{11}N structure. However, sizeable inconsistencies persist amongst measured values for the ground state energy (mass excess) and the widths of states. There are essentially three high resolution measurements of the ^{11}N ground state mass. They do not have overlap in their uncertainties. The measured values, in the ^{10}C + p relative energy system, are $E_{\rm res} = 1.54 \pm 0.02$ MeV from ^{1}H(^{10}C, ^{1}H) (2006CA05), 1.63 ± 0.05 MeV from ^{10}B(^{14}N, ^{13}B) (2000OL01) and 1.31 ± 0.05 MeV from ^{14}N(^{3}He, ^{6}He) (2003GU30). In the present evaluation, we have taken the unweighted average and assigned an uncertainty of 60 keV; this yields $^{11}{\rm N}_{\rm g.s.} = E_{\rm res} = 1.49 \pm 0.06$ MeV which is in reasonable agreement with each value and the average. This corresponds to a mass excess of 24477 ± 60 keV for ^{11}N, and compares with $\Delta M = 24303 \pm 46$ ($E_{\rm res} = 1315 \pm 46$ keV) from (2011AUZZ). See theoretical analysis relevant to ^{11}N and other $A = 11$ nuclei in (1995FO11, 1996BA13, 1997GR18, 2000AO06, 2001MU35, 2001SH39, 2002LE40).

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

The ^{1}H + ^{10}C resonant scattering excitation function was measured (1996AX01, 2000MA62). In (1996AX01) the 0° cross sections were evaluated in an R-matrix analysis which found evidence for three states at $E_{\rm res} = 1.3$, 2.04 and 3.72 MeV. Weak evidence was found for a state at 4.32 MeV [$\Gamma = 70$ keV, ($\frac{3}{2}^-$)] and higher-lying states above 5 MeV (not fully analyzed because of a limited sensitivity). In (2000MA62) the data of (1996AX01) are combined with additional measurements at $\theta_{\rm lab} = 12°$; the analysis of low-lying resonances is shown in Table 11.46. The resonance at 4.33 MeV is thought to be the analog of ^{11}Be*(2.69). A separate R-matrix analysis of the high-energy part of the resonant spectrum, which only distinctly shows the $E_{\rm res} = 4.33$ MeV resonances, was well fit by including resonances at $E_{\rm res} = 3.94$ MeV [$\Gamma = 580$ keV, $\frac{3}{2}^+$], 4.81 MeV [$\Gamma = 400$ keV, ($\frac{5}{2}^+$)] analogs of ^{11}Be*(3.41) and 5.4 MeV [$\Gamma = 250$ keV, ($\frac{7}{2}^-$)]. Additional measurements at $E(^{10}{\rm C}) = 25.5$ and 32 MeV (2004AN28, 2006ANZV, 2006CA05) find $E_{\rm res} = 1.54$ and 2.27 MeV for the $\frac{1}{2}^+$ and $\frac{1}{2}^-$ states; see Table 11.46. See also (1998AO01) for a discussion of the Thomas-Erman effect and a comparison of the low-lying ^{11}N and ^{11}Be states.

2. ^{9}Be(^{12}N, ^{10}C + p) $\qquad Q_{\rm m} = -6.9086$

Complete kinematics decay spectroscopy was used to determine the excitation energies of ^{11}N states populated in the fragmentation of 40 MeV/A ^{12}N on a ^{9}Be target (1998AZ01). In addition to a strong contribution apparently from the $J^\pi = \frac{1}{2}^-$ first excited state, an enhancement at low

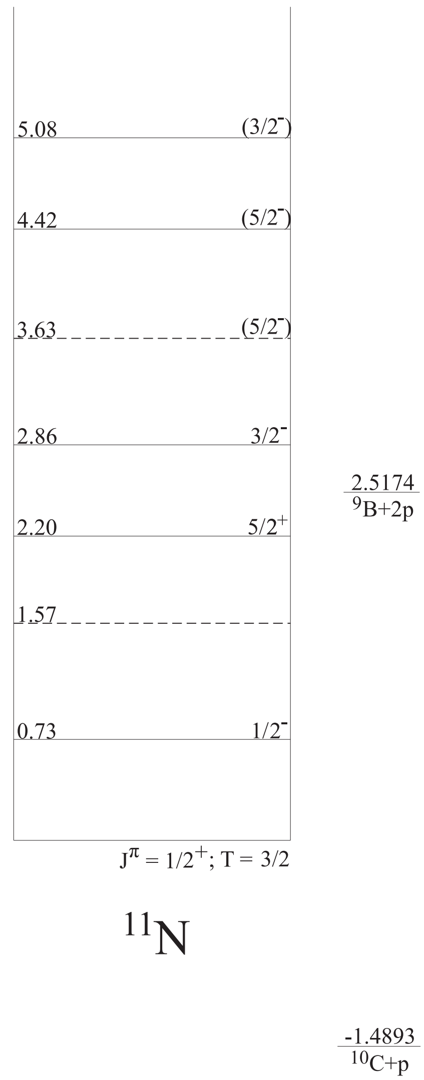

Fig. 6: Energy levels of ^{11}N. For notation see Fig. 4.

Table 11.45: Energy levels of ^{11}N

$E_{\rm res}$ (MeV ± keV)	$E_{\rm x}$ (MeV ± keV)	$J^\pi; T$	Γ (keV)	Decay	Reactions
1.49 ± 60	0	$\frac{1}{2}^+; \frac{3}{2}$	830 ± 30	p	1, 2, 3, 6
2.22 ± 30	0.73 ± 70	$\frac{1}{2}^-$	600 ± 100	p	1, 2, 3, 5, 6
3.06 ± 80	(1.57 ± 80)		< 100	p	3
3.69 ± 30	2.20 ± 70	$\frac{5}{2}^+$	540 ± 40	p	1, 3, 5, 6
4.35 ± 30	2.86 ± 70	$\frac{3}{2}^-$	340 ± 40	p	1, 3, 5, 6
5.12 ± 80	(3.63 ± 100)	$(\frac{5}{2}^-)$	< 220	p	5
5.91 ± 30	4.42 ± 70	$(\frac{5}{2}^-)$		p	3, 5, 6
6.57 ± 100	5.08 ± 120	$(\frac{3}{2}^-)$	100 ± 60	p	3, 6

Table 11.46: Resonances observed in ^{1}H(^{10}C, p)

$E_{\rm res}$ [a] (MeV)	$\Gamma_{\rm res}$ [a] (MeV)	$E_{\rm res}$ [b] (MeV)	$\Gamma_{\rm res}$ [b] (keV)	J^π	$E_{\rm x}$ [c] (MeV)
$1.27^{+0.18}_{-0.05}$	1.44 ± 0.20	1.54 ± 0.02	830 ± 30	$\frac{1}{2}^+$	0
$2.01^{+0.15}_{-0.05}$	0.84 ± 0.20	2.27 ± 0.05	1150 ± 250	$\frac{1}{2}^-$	0.7
3.75 ± 0.05	0.60 ± 0.05			$\frac{5}{2}^+$	5.1
4.33 ± 0.05	0.27			$\frac{3}{2}^-$ [a]	5.9

[a] (2000MA62).
[b] (2006CA05).
[c] From Table 11.45.

relative energies was attributed to ^{11}N at $E_{\rm res} = 1.45 \pm 0.40$ MeV with $\Gamma > 400$ keV. Further interpretation, involving predicted higher-lying $J^\pi = \frac{3}{2}^-$ and $\frac{5}{2}^-$ states that decay to ^{10}C + p_0 and ^{10}C*(3.36) + p_1 channels is also given.

3. ^{10}B(^{14}N, ^{13}B)^{11}N $\qquad Q_{\rm m} = -26.1250$

At $E(^{14}{\rm N}) = 30$ MeV/A the ^{11}N ground state and multiple excited states are observed (2000OL01, 2003LE26), see Table 11.47. The mass excess of 24618 ± 50 keV is deduced for the ^{11}N ground state. Shell model predictions suggest the peaks observed at 2.16, 4.33 and 5.98 MeV decay energy could be the $\frac{1}{2}^-$, $\frac{3}{2}^-$ and $\frac{5}{2}^-$ members of the K = $\frac{1}{2}$ rotational band.

4. ^{12}C(π^+, π^-p) $\qquad Q_{\rm m} = -31.7660$

Table 11.47: ^{11}N resonances populated in ^{10}B(^{14}N, ^{13}B)^{11}N (2000OL01)

E_{decay} (MeV)	Γ (MeV)	J^π	E_x [a] (MeV)
1.63(5)	0.4(1)	$\frac{1}{2}^+$	0
2.16(5)	0.25(8)	$\frac{1}{2}^-$	0.7
3.06(8)	$< 0.10(8)$		1.6
3.61(5)	0.50(8)	$\frac{5}{2}^+$	2.2
4.33(5)	0.45(8)	$(\frac{3}{2}^-)$	2.9
5.98(10)	0.10(6)	$(\frac{5}{2}^-)$	4.4
6.54(10)	0.10(6)		5.1

[a] From Table 11.45.

Table 11.48: ^{11}N resonances observed in ^{12}C(^{14}N, ^{15}C)^{11}N (1998LE06)

E_{res}	Γ (MeV)	l	σ (μb/sr)	J^π	E_x [a] (MeV)
2.18 ± 0.05	0.44 ± 0.08	1	0.6(3)	$\frac{1}{2}^-$	0.7
3.63 ± 0.05	0.40 ± 0.08	2	0.9(3)	$\frac{5}{2}^+$	2.2
4.39 ± 0.05	$\leq 0.22 \pm 0.10$		0.26(10)	$(\frac{3}{2}^-)$	2.9
5.12 ± 0.08	$\leq 0.22 \pm 0.10$			$(\frac{5}{2}^-)$	3.6
5.87 ± 0.15	0.7 ± 0.2			$(\frac{7}{2}^-)$	4.4

[a] From Table 11.45.

A search for evidence of Δ components in normal nuclear matter was carried out at $E(\pi^+) =$ 500 MeV (1998MO09).

5. ^{12}C(^{14}N, ^{15}C)^{11}N $\qquad Q_m = -31.4867$

At $E(^{14}\mathrm{N}) = 30$ MeV/A five levels in ^{11}N have been observed at $\theta_{lab} = 2.5°$ (1998BO38, 1998LE06, 1999LE37, 2003LE26). The observed resonances were evaluated in an R-matrix analysis to determine the probable J^π values, see Table 11.48. The $J^\pi = \frac{1}{2}^+$ ground state was not observed, though its population was expected to be strongly hindered.

6. ^{14}N(^{3}He, ^{6}He)^{11}N $\qquad Q_m = -24.2752$

Table 11.49: ^{11}N resonances observed in ^{14}N(^{3}He, ^{6}He)^{11}N (2003GU30)

E_{res}	Γ (MeV)	J^π	E_x [a] (MeV)
1.31 ± 0.05	0.24 ± 0.24	$\frac{1}{2}^+$	0
2.31 ± 0.02	0.73 ± 0.06	$\frac{1}{2}^-$	0.7
3.78 ± 0.05	0.56 ± 0.17	$\frac{5}{2}^+$	2.2
4.56 ± 0.01	0.30 ± 0.05	$\frac{3}{2}^-$	2.9
5.91 ± 0.03	1.30 ± 0.09	$(\frac{5}{2}^-)$	4.4
6.80 ± 0.30		$(\frac{3}{2}^-)$	5.1

[a] From Table 11.45.

At $E(^3\text{He}) = 70$ MeV a ^{6}He group was observed which was interpreted as the first observation of a ^{11}N state with an atomic mass excess of 25.23 ± 0.10 MeV and $\Gamma = 740 \pm 100$ keV (1974BE20). The cross section for forming this state is 0.5 μb/sr at $10°$. The observed state was interpreted as the $J^\pi = \frac{1}{2}^-$ mirror of ^{11}Be*(0.32) because of its width; the $\frac{1}{2}^+$ mirror of $^{11}\text{Be}_{\text{g.s.}}$ was expected to be much broader (1974BE20). A subsequent investigation (1995GU08) at $E(^3\text{He}) = 70$ MeV and at 6.8 to 25.0 degrees reported two resolved states thought to be the g.s. and first excited state, possibly having $J^\pi = \frac{1}{2}^+$ and $\frac{1}{2}^-$. Further measurements at $E(^3\text{He}) = 73.4$ MeV (2003GU06, 2003GU30), resolved the g.s. and first excited states and found evidence for several additional states, see Table 11.49. A DWBA analysis of the angular distributions was used to evaluate spin assignments for the resonances up to $E_{res} = 5.9$ MeV.

^{11}O, ^{11}F, ^{11}Ne

(Not illustrated)

These nuclei have not been observed: see (1980AJ01, 1985AJ01).

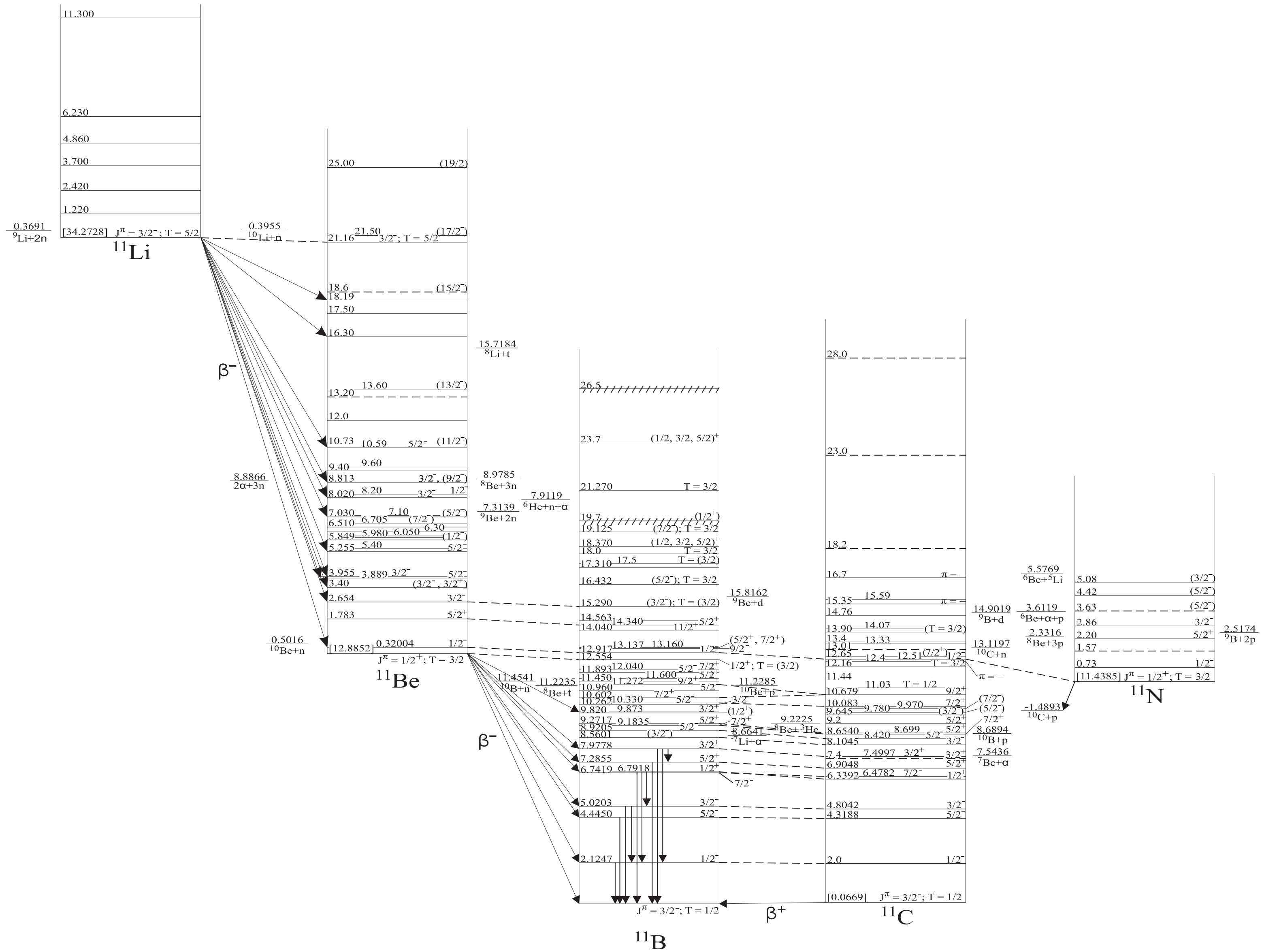

Fig. 7: Isobar diagram, $A = 11$. The diagrams for individual isobars have been shifted vertically to eliminate the neutron-proton mass difference and the Coulomb energy, taken as $E_C = 0.60Z(Z-1)/A^{1/3}$. Energies in square brackets represent the (approximate) nuclear energy, $E_N = M(Z,A) - ZM(\mathrm{H}) - NM(\mathrm{n}) - E_C$, minus the corresponding quantity for ^{11}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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