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Energy Levels of Light Nuclei
$A = 12$

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Abstract: An evaluation of $A = 12$ was published in *Nuclear Physics* A968 (2017), p. 71. This version of $A = 12$ 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.

(References closed, 2016)

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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;
DWBA:	Distorted-Wave Born Approximation;
DWIA:	Distorted-Wave Impulse Approximation;
FRDWBA:	Finite Range Distorted-Wave Born Approximation;
PWIA:	Plane Wave Impulse Approximation;
QRPA:	Quasi-particle Random Phase Approximation;
GDR:	Giant Dipole Resonance;
SFGDR:	Spin-Flip Giant Dipole Resonance;
GQR:	Giant Quadrupole Resonance;
ANC:	Asymptotic Normalization Constant;
CDCC:	Continuum Discretized Coupled Channels;
EWSR:	Energy Weighted Sum Rule;
FSI:	Final State Interactions;
IAS:	Isobaric Analog State;
IMME:	Isobaric Multiplet Mass Equation;
[u]:	Unresolved;
VAP:	Vector Analyzing Power.

Table 1: Parameters of the ground states of the light nuclei with $A = 12$

	Atomic mass excess [a] (keV)	$\mathrm{T}_{1/2}$ or Γ_{cm} [b]	Decay [b]	$J^{\pi}; T$ [c]
^{12}Li	48920 ± 15		n	(2^{-})
^{12}Be	25077.8 ± 1.9	$\mathrm{T}_{1/2} = 21.46 \pm 0.05$ ms	β^{-}	$0^{+}; 2$
^{12}B [c]	13369.4 ± 1.3	$\mathrm{T}_{1/2} = 20.20 \pm 0.02$ ms	β^{-}	$1^{+}; 1$
^{12}C	$\equiv 0$		stable	$0^{+}; 0$
^{12}N [d]	17338.1 ± 1.0	$\mathrm{T}_{1/2} = 11.000 \pm 0.016$ ms	β^{+}	$1^{+}; 1$
^{12}O	31915 ± 24	$\Gamma < 72$ keV	p	$0^{+}; 2$

[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 (2012WA38). 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] $\mu = +1.00272 \pm 0.00011$ nm (1990MI16), $Q = 13.21 \pm 0.26$ mb (1993OH05).

[d] $\mu = 4571 \pm 1$ nm (2010ZH03), $Q = +9.8 \pm 0.9$ mb (1998MI10).

Table 2: Some electromagnetic transitions in $A = 12$

Nucleus	$E_{\mathrm{xi}} \to E_{\mathrm{xf}}$ (MeV)	$J^{\pi}_{\mathrm{i}} \to J^{\pi}_{\mathrm{f}}$	Γ_{γ} (eV)	Mult.	$\Gamma_{\gamma}/\Gamma_{\mathrm{W}}$ (W.u.)
^{12}Be	$2.109 \to 0$	$2^{+} \to 0^{+}$	$(2.637 \pm 0.808) \times 10^{-4}$	E2	4.7 ± 1.4
	$2.251 \to 0$	$0^{+} \to 0^{+}$	$(1.520 \pm 0.096) \times 10^{-9}$	E0	e^{+}+e^{-}-decay
	$\to 2.109$	$\to 2^{+}$	$(3.269 \pm 0.341) \times 10^{-10}$	E2	4.21 ± 0.44
	$2.715 \to 0$	$1^{-} \to 0^{+}$	0.035 ± 0.009 [a]	E1	0.0049 ± 0.0013
^{12}B	$0.953 \to 0$	$2^{+} \to 1^{+}$	$(2.515 \pm 0.387) \times 10^{-3}$	M1	0.138 ± 0.021
^{12}C	$4.440 \to 0$	$2^{+} \to 0^{+}$	$(1.08 \pm 0.06) \times 10^{-2}$	E2	4.66 ± 0.26
	$7.654 \to 4.440$	$0^{+} \to 2^{+}$	$(3.81 \pm 0.39) \times 10^{-3}$	E2	8.26 ± 0.85
	$9.641 \to 0$	$3^{-} \to 0^{+}$	$(3.1 \pm 0.4) \times 10^{-4}$	E3	12.1 ± 1.6
	$12.710 \to 0$	$1^{+} \to 0^{+}$	0.35 ± 0.05	M1	$(8.1 \pm 1.2) \times 10^{-3}$
	$\to 4.440$	$\to 2^{+}$	0.053 ± 0.010	M1	$(4.5 \pm 0.8) \times 10^{-3}$
	$15.110 \to 0$	$1^{+} \to 0^{+}$	38.5 ± 0.8	M1	0.533 ± 0.011
	$\to 4.440$	$\to 2^{+}$	0.96 ± 0.13	M1	$(3.8 \pm 0.5) \times 10^{-2}$
	$\to 7.654$	$\to 0^{+}$	1.09 ± 0.30	M1	0.125 ± 0.035
	$\to 10.300$	$\to 0^{+}$	1.60 ± 0.67	M1	0.69 ± 0.29
	$\to 12.710$	$\to 1^{+}$	0.59 ± 0.17	M1	2.0 ± 0.6
	$16.106 \to 0$	$2^{+} \to 0^{+}$	0.59 ± 0.11	E2	0.41 ± 0.08
	$\to 4.440$	$\to 2^{+}$	12.8 ± 1.5	M1	0.385 ± 0.045
	$\to 9.641$	$\to 3^{-}$	0.31 ± 0.06	E1	$(3.2 \pm 0.6) \times 10^{-3}$
	$\to 10.847$	$\to 1^{-}$	0.48 ± 0.12	E1	$(9.3 \pm 2.3) \times 10^{-3}$
	$\to 12.710$	$\to 1^{+}$	0.19 ± 0.04	M1	0.231 ± 0.049
	$16.620 \to 0$	$2^{-} \to 0^{+}$	0.048 ± 0.008	M2	0.48 ± 0.08
	$\to 4.440$	$\to 2^{+}$	8.0	E1	1.244×10^{-2}

[a] Using $\tau_{\mathrm{m}} = 1.9 \pm 0.5$ fs from the B(E1) given in (2000IW03).

^{12}He

(Not illustrated)

The nucleus ^{12}He has not been observed. See (2015JO05) and (1985PO10, 2005GR38).

1. ^{14}Be(CH$_2$, ^{12}He $\rightarrow$ ^{8}He + 4n) $Q_{\rm m} = -38.5229$

It was suggested by (2014SH23) that data collected in ^{14}Be interactions on a CH$_2$ target (2012KO43) could be influenced by 2p removal reactions that would populate states in ^{12}He. A reanalysis of the data (2015JO05), which determined the full kinematics of ejected neutrons and charged He ions, showed no evidence for population of ^{12}He.

^{12}Li

(Table 12.1)

1. ^{1}H(^{14}Be, ^{12}Li)^{3}He $Q_{\rm m} = -16.6122$

The ground state of ^{12}Li was reported in the kinematic reconstruction of ^{11}Li + n events resulting from multi-nucleon knockout reactions of $E = 304$ MeV/A ^{14}Be ions impinging on a liquid hydrogen target (2008AK03). Analysis of the differential cross section as a function of relative energy indicates the ground state is an unbound "virtual" s-state with a scattering length of -13.7 ± 1.6 fm ($E_{\rm res} = 120 \pm 15$ keV). Since ^{11}Li has $J^{\pi} = \frac{3}{2}^-$, the ground state of ^{12}Li must then have either $J^{\pi} = (1^-, 2^-)$. In (2013KO03), it is suggested that ^{13}Li $\rightarrow$ ^{11}Li + 2n events contaminated the analysis primarily because the neutron array has a low efficiency for 2n-events with a small relative energy. In (2013KO03) $a_s > -4$ fm is deduced. See relevant discussion in reaction 2. See also (2011XU03, 1988POZS).

2. ^{9}Be(^{14}Be, ^{12}Li)^{11}B $Q_{\rm m} = -6.2895$

The neutron scattering length $a_s > -4$ fm was deduced from analysis of n+^{11}Li pairs produced in the ^{9}Be(^{14}Be, ^{12}Li) reaction at $E(^{14}\text{Be}) = 53.6$ MeV/A (2013KO03). Using this constraint the data of (2008AK03) was reanalyzed; it is suggested that the results were influenced by ^{13}Li $\rightarrow$ ^{11}Li + 2n events that were not fully excluded from the data due to a low efficiency for 2n-events with a small relative energy. Using the new scattering length, the data of (2010HA04) were reanalysed. See comments in reaction 3.

Table 12.1: Energy levels of ^{12}Li

E_x (MeV ± keV)	$E_{res}(^{11}\mathrm{Li} + \mathrm{n})$ (keV)	J^π	Γ (keV)	Decay	Reactions
0	120 ± 15 [a, b]	(2^-)		n	1, 2, 3
0.130 ± 25	250 ± 20	(4^-)	< 15	n	3
0.435 ± 25	555 ± 20	(1^-)	< 80	n	3
3.880 ± 201	4000 ± 200		1100 ± 400	(n)	4
≈ 6.500	6000 to 7000			(n)	4

[a] This resonance energy is based on $a_s = -13.7$ fm (2008AK03). The s-wave strength is accepted as the ground state since reactions 1, 2 and 3 report non-negligible s-wave strength. The most inclusive interpretation is accepted.

[b] The results of (2013KO03) indicate an incompatible value, $a_s > -4$ fm. There is no consensus between the GSI work (2008AK03) and the MSU work (2013KO03). Important details that are relevant for understanding the different interpretations include differences in the prescriptions used to extract the scattering lengths and the efficiencies for 2n-events at low relative energy. Further results are necessary to better constrain the s-wave strength parameters.

3. ^{9}Be(^{14}B, ^{12}Li)^{11}C $\quad Q_m = -24.5579$

Excited states in ^{12}Li were observed in the kinematic reconstruction of $^{11}\mathrm{Li}+\mathrm{n}$ events produced when a 53.4 MeV/A beam of ^{14}B ions impinged on a thick ^{9}Be target (2010HA04). The $^{11}\mathrm{Li} + \mathrm{n}$ relative energy spectrum was reproduced by fitting unbound resonances with $E_{res}(\mathrm{keV}) = 120 \pm 15$ (from (2008AK03)), 250 ± 20 and 555 ± 20; these states are presumably the ground and first two excited states of ^{12}Li. The detector resolution permitted upper limits of $\Gamma = 15$ and 80 keV for the first and second excited states, respectively. The ^{12}Li ground state is consistent with an s-wave neutron coupled to the $J^\pi = \frac{3}{2}^-$ ^{11}Li ground state; hence $J^\pi = (1^-, 2^-)$. A comparison with shell model predictions suggests $J^\pi = (2^-)$, (4^-) and (1^-) for the ground, first and second excited states, respectively.

These data were reanalyzed in (2013KO03). In the scenario where $a_s > -4$ fm, slightly lower values of $E_{res} = 210 \pm 30$ keV and 525 ± 25 keV were deduced for the resonances previously reported at $E_{res} = 250$ and 555 keV. However, a more significant impact of this reanalysis is the suggestion that only the two states at 210 and 525 keV should be accepted and that because of the broad width of the s-wave strength this group should not be considered the ground state.

4. ^{14}C(π^-, 2p)^{12}Li $\quad Q_m = 79.0921$

The ^{14}C(π^-, 2p) missing mass spectrum resulting from the capture of stopped π^- on a 76% enriched ^{14}C target (26 mg/cm^2) was measured and analyzed in a search for states in ^{12}Li (2010GU04, 2013CH30). Evidence is found for a broad peak with $E_{\rm res} = 4.0 \pm 0.2$ MeV and $\Gamma = 1.1 \pm 0.4$ MeV; in addition an excess of counts near $E_{\rm res} = 6$ to 7 MeV is present in the measured spectrum.

^{12}Be

(Table 12.2, Fig. 1)

$$< (r_{\rm rms}^{\rm matter})^2 >^{1/2} \approx 2.71 \pm 0.06 \text{ fm (2012IL01).}$$

We accept $\Delta M = 25077.8 \pm 1.9$ keV (2012WA38). See precise ^{12}Be mass measurements: $\Delta M = 25078.0 \pm 2.1$ keV (2010ET01: TITAN), $\Delta M = 25068 \pm 13$ keV (2009GA24: MISTRAL), $\Delta M = 25075.7 \pm 4.2$ keV (1994FO08: ^{10}Be(t, p)) and $\Delta M = 25078 \pm 15$ keV (1978AL10: ^{10}Be(t, p)). Earlier measurements indicated $\Delta M = 25050 \pm 50$ keV (1974BA15: ^{14}C(^{18}O, ^{20}Ne)) and $\Delta M = 24950 \pm 100$ keV (1971HO26: ^{7}Li(^{7}Li, 2p)).

An analysis of $T = 2$ isobaric analogue states for $A = 12$ nuclei is reported in (2012JA11) including quadratic, cubic and quartic forms of IMME. See also (2006KO02, 2009BA41, 2010ET01, 2014MA56).

The 2s$_{1/2}$ $\rightarrow$2p$_{(1/2,\ 3/2)}$ transition in ^{12}Be was measured and compared with that of ^{9}Be; based on the isotope shift data and R_c(^{9}Be) $= 2.519 \pm 0.012$ fm (1972JA10), R_c(^{12}Be) $= 2.503 \pm 0.015$ fm is deduced (2012KR04). See also (2015KA02).

1. ^{12}Be(β^-)^{12}B $\qquad Q_{\rm m} = 11.7084$

Measured values of the ^{12}Be half-life are $T_{1/2} = 21.49 \pm 0.03$ ms (2001BE53, 2002BE53), 26.1 ± 2.4 ms (1994KE06), 21.32 ± 0.06 ms (1994RE1R: see also (1991RE02)), 21.3 ± 2.2 ms (1986CU01) and 24.0 ± 1.0 ms (1984DU15), 24.4 ± 3.0 ms (1978AL10): the weighted average of these values is 21.46 ± 0.05 ms. The β-delayed neutron probability is $(0.50 \pm 0.03)\%$ (1999BE53). See also $P_{\rm n} = (0.9 \pm 0.4)\%$ (1991RE02); and earlier measurements which placed an upper limit of $P_{\rm n} \leq 1\%$ (1978AL10, 1984DU15). Observation of β-delayed neutrons provide evidence that at least two ^{12}B states are fed in the decay, though no detailed decay scheme has been experimentally confirmed (1994KE06). Assuming a $(99.50 \pm 0.03)\%$ branching ratio to the ground state gives $logft = 3.795 \pm 0.002$ for decay to ^{12}B$_{\rm g.s.}$. (1997SU12) suggest the large $\log ft$ indicates "tremendous breaking of the neutron closed shell core;" a 65% breaking of the closed p-shell is estimated in (1998SU17). See also (1993CH06).

2. (a) ^{1}H(^{12}Be, ^{12}Be) $\qquad E_{\rm b} = 15.8047$

   (b) ^{1}H(^{12}Be, ^{12}Be$'$)

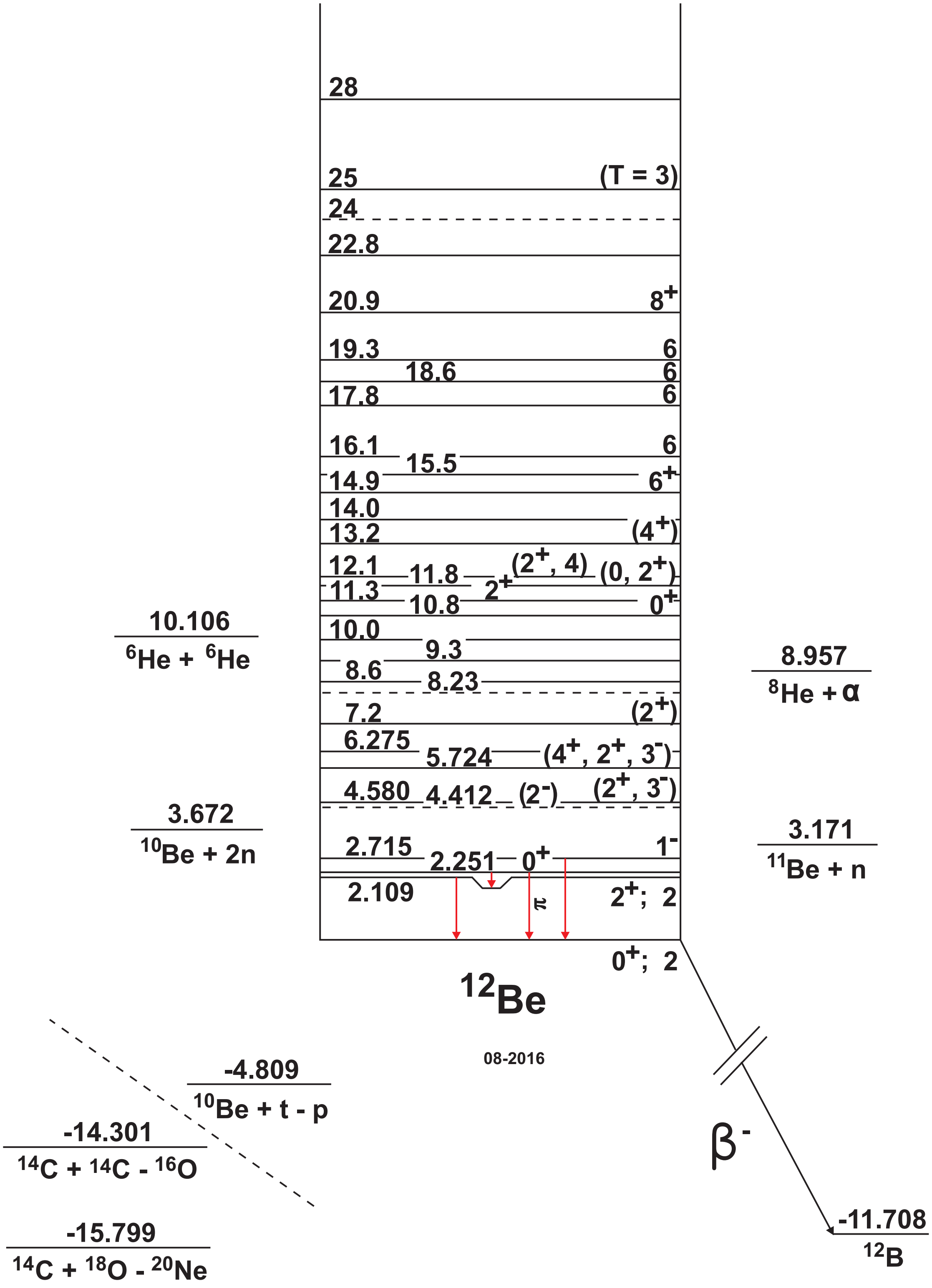


Fig. 1: Energy levels of ^{12}Be. For notation see Fig. 2.

At $E(^{12}\mathrm{Be}) = 53.8$ MeV the angular distribution for scattering to ^{12}Be*(2.1[$J^{\pi} = 2^{+}$]) was measured and analyzed in a coupled channels analysis (2000IW02). Scattered ^{12}Be ions and γ-rays were measured. Analysis indicates a deformation length, $\delta = 2.00 \pm 0.23$, and supports evidence that $N = 8$ shell closure is not present in ^{12}Be. See also (2008TA02). At $E(^{12}\mathrm{Be}) = 704$ MeV/A the differential cross sections for small-angle elastic scattering were measured (2012IL01); $R_{\mathrm{rms}}^{\mathrm{matter}} \approx 2.71 \pm 0.06$ fm is deduced. For calculations on p-Be elastic scattering see (2012FA14, 2012FO08, 2013CA04, 2014FA15).

Protons corresponding to ^{12}Be*(0, 2.1, 2.7, 4.56, 5.7, 8.60 ± 0.15, 10.00 ± 0.15, ≈ 14 MeV) were observed in elastic and inelastic scattering of 55 MeV/A ^{12}Be on ^{1}H (1995KO10, 1995KO27); states at 8.6 and 10.0 MeV have $\Gamma \leq 0.5$ MeV. He + He cluster structures are suggested for ^{12}Be*(10.0, ≈ 14) based on p + Be and p + He correlations observed in the particle-coincidence data. The kinematic reconstruction of $^{8}\mathrm{He} + \alpha$ and $^{6}\mathrm{He} + {}^{6}\mathrm{He}$ products, for example, from ^{12}Be breakup reactions on ^{1}H and ^{12}C targets yielded evidence for several states in the 10 MeV $\leq E_{\mathrm{x}} \leq$ 25 MeV region (1999FR04, 2001FR02, 2007CH81); see also (2005GA31, 2016KO22), reaction 18 and Table 12.4.

3. $^{1}\mathrm{H}(^{14}\mathrm{Be}, {}^{13}\mathrm{Be} \rightarrow {}^{12}\mathrm{Be} + \mathrm{n})$ $\qquad Q_{\mathrm{m}} = 0.9541$

States at ^{12}Be*(0, 2.1, 2.7) are involved in the decay of ^{13}Be states populated in the ^{1}H(^{14}Be, ^{13}Be) reaction at $E(^{14}\mathrm{Be}) = 304$ MeV/A (2013AK02).

4. $^{2}\mathrm{H}(^{11}\mathrm{Be}, {}^{12}\mathrm{Be} + \mathrm{p})$ $\qquad Q_{\mathrm{m}} = 0.9461$

In (2010KA03, 2010KA24), angular distributions of protons ($130^{\circ} \leq \theta_{\mathrm{lab}} \leq 160^{\circ}$) and ^{12}Be ($0.8^{\circ} \leq \theta_{\mathrm{lab}} \leq 2.7^{\circ}$) ejectiles were measured for $E(^{11}\mathrm{Be}) = 5$ MeV/A (2010KA03, 2010KA24). A DWBA analysis finds s-wave spectroscopic factors of $S = 0.28^{+0.03}_{-0.07}$, $0.10^{+0.09}_{-0.07}$, 0.73^{+27}_{-40} and ≈ 0.35 for ^{12}Be*(0[$J^{\pi} = 0^{+}$], 2.11[2^{+}], 2.24[0^{+}], 2.68[1^{-}]). The low neutron binding energy and sizeable spectroscopic factors are viewed as evidence for a possible halo structure for the isomeric ^{12}Be*(2.24) state. At $E(^{11}\mathrm{Be}) = 2.8$ MeV/A (2013JO06) the scattered protons ($8^{\circ} \leq \theta_{\mathrm{lab}} \leq 152^{\circ}$) and de-excitation γ-rays from ^{12}Be*(2.1, 2.7) were detected; spectroscopic factors of $S = 0.15^{+0.03}_{-0.05}$, 0.075 ± 0.025, 0.40 ± 0.13 and 0.27 ± 0.15 were deduced for ^{12}Be*(0, 2.11, 2.24, 2.68). In addition, analysis of the delayed radiations from ^{12}Be*(2.24) indicated $T_{1/2} = 247 \pm 15$ ns with $(87.3 \pm 3.5)\%$ decay to $^{12}\mathrm{Be}_{\mathrm{g.s.}}$ via pair production and 12.7% via γ-decay to ^{12}Be*(2.11). See also (2009JOZY). See comments on the spectroscopic factors in (2012FO11) and (2003ZE06).

5. $^{4}\mathrm{He}(^{12}\mathrm{Be}, {}^{12}\mathrm{Be}')$

Table 12.2: Energy levels of ^{12}Be

E_x (MeV ± keV)	$J^\pi; T$	$T_{1/2}$ or Γ	Decay	Reactions
0	$0^+; 2$	$T_{1/2} = 21.46 \pm 0.05$ ms	β^-	1, 2, 3, 4, 5, 7, 10, 11, 13, 14, 15, 16, 17, 20, 21, 22, 23
2.109 ± 2	$2^+; 2$	1.73 ± 0.53 ps	γ	2, 3, 4, 5, 7, 10, 11, 13, 14, 20, 21, 23, 24
2.251 ± 1	0^+	247 ± 15 ns	γ, π	4, 6, 10, 11
2.715 ± 15 [a]	1^-	1.3 ± 0.4 fs	γ	2, 3, 4, 5, 11, 14, 20, 23, 24
(4.412 ± 16)	(2^-)	$\Gamma = 634 \pm 60$ keV	n	8
4.580 ± 5	$(2^+, 3^-)$ [b]	101 ± 17 keV		2, 7, 11, 13, 20, 21
5.724 ± 6	$(4^+, 2^+, 3^-)$ [b]	85 ± 15 keV		2, 7, 9, 11, 12, 20, 21
6.275 ± 50				7, 9, 13
7.2 ± 100	(2^+)			7, 9, 20
(8.230)				7
8.600 ± 150		< 500 keV		2, 7
9.300		2 ± 0.3 MeV		9, 20
10.0		1.5 ± 0.2 MeV	α	2, 5, 7, 18
10.8	0^+		^{6}He	5, 7, 9
11.3	2^+			5, 7, 13
11.8	$(0, 2^+)$	≈ 1 MeV	^{6}He	5, 18, 19
12.1	$(2^+, 4)$		α	7, 18
13.2 ± 500	(4^+)	≈ 1 MeV	α, ^{6}He	2, 18, 19
14.0			α, ^{6}He	2, 18
14.9 ± 500	6^+		α, ^{6}He	2, 7, 9, 18, 19
15.5		1.5 MeV	α, ^{6}He	2, 18, 19
16.1 ± 500	$J = 6$		α	2, 7, 18
17.8 ± 500	$J = 6$	350 keV	α, (^{6}He)	2, 18
18.6 ± 500	$J = 6$		α, (^{6}He)	2, 18, 20
19.3 ± 500	$J = 6$		α, (^{6}He)	2, 9, 18
20.9 ± 500	8^+		α, (^{6}He)	2, 9, 18
22.8			(α, ^{6}He)	2, 18
(24)			(α, ^{6}He)	2, 18
25	$(T = 3)$	370 keV	p	2, 18
28		2.7 MeV	p	2, 18

[a] Limit of weighted means.

[b] (2011FO04, 2013FO30, 2014FO04) suggest $J^\pi = (3^-)$ and (4^+) for ^{12}Be*(4.6, 5.7), respectively. But for ^{12}Be*(4.6) $J^\pi = 2^+$ is indicated in reaction 7. $J^\pi = 4^+$ is preferred for ^{12}Be*(5.7).

At $E(^{12}\text{Be}) = 60$ MeV/A angular distributions for scattering to ^{12}Be*(2.1, 2.7) were measured (2004SH24, 2004SH29). DWBA analysis is consistent with $J^\pi = 2^+$ and 1^-, respectively. Angular distributions for the corresponding γ-rays are measured and analyzed in (2002MA79).

Invariant mass spectroscopy of the ^{6}He-^{6}He and $\alpha + {}^8$He particle coincidences populated with $E(^{12}\text{Be}) = 60$ MeV/A projectiles (2004SA32) resolved peaks at ^{12}Be*(10.9, 11.3); DWBA analysis indicates $J^\pi = 0^+$ and 2^+, respectively. Further evidence of a peak at $E_\text{x} = 11.8$ MeV is observed in the ^{6}He-^{6}He data, and evidence of a peak at $E_\text{x} \approx 10$ MeV is found in the $\alpha + {}^8$He data. See also (2011OG09).

6. ^{7}Li(^{12}B, ^{7}Be)^{12}Be $\qquad Q_\text{m} = -12.5703$

Angular distributions for the ^{12}B(^{7}Li, ^{7}Be) charge exchange reaction were measured in inverse kinematics at $E(^{12}\text{B}) = 80$ MeV/A (2012ME05) as a means to determine $B(\text{GT}) = 0.214 \pm 0.051$ for the transition between ^{12}Be*(2.25) and $^{12}\text{B}_\text{g.s.}$. The value is deduced by normalization to the known $B(\text{GT}) = 0.184 \pm 0.008$ for the $^{12}\text{Be}_\text{g.s.} \rightarrow {}^{12}\text{B}_\text{g.s.}$ transition.

7. ^{9}Be(^{12}C, ^{9}C)^{12}Be $\qquad Q_\text{m} = -42.6404$

States at ^{12}Be*(0[$J^\pi = 0^+$], 2.1[2^+], 4.56[2^+], 5.70[4^+, 3^-], 6.30 ± 0.05, 7.53, 8.23, 8.81, 10.18, 10.83, 11.44, 12.46, 14.7, 16.7) were populated in the 3-neutron stripping reaction at $E(^{12}\text{C}) = 231$ MeV (2004BO23, 2008BO37). The ^{12}Be*(7.53, 8.23, 8.81, 10.18, 12.46) states are suggested as a $K = 1^-$ rotational band. Level spacing suggests $J^\pi = 6^+$ for ^{12}Be*(14.7) if it is a member of the ground state rotational band.

8. ^{9}Be(^{13}B, ^{12}Be)^{10}B $\qquad Q_\text{m} = -9.2180$

Single-proton removal reactions from ^{13}B were utilized in a search for neutron unbound states in ^{12}Be (2014SM03). A state at $E(^{11}\text{Be}+\text{n}) = 1243 \pm 12$ keV ($E_\text{x} = 4412 \pm 16$ keV) was observed with $L = 1$ and $\Gamma = 634 \pm 60$ keV; it is presumed that $^{11}\text{Be}_\text{g.s.}$ is populated implying $J = (2^-)$. No states are observed in the ^{10}Be+2n analysis. Theoretical opinions given in (2016FO02, 2016FO03, 2016FO26) suggest the state is either a $J^\pi = 0^+$ or $J^\pi = 2^+$ state that likely decays to ^{11}Be*(0.32).

9. ^{9}Be(^{15}N, ^{12}N)^{12}Be $\qquad Q_\text{m} = -30.9660$

At $E = 240$ MeV states at ^{12}Be*(5.7, (6.4[$J^\pi = 0^+$]), 7.40[2^+], 9.3, 10.7[4^+], 14.6[6^+], 19.2, 21.7[8^+]) are observed (2002BO16). The J^π values are assumed based on systematics corresponding to a rotational band built on ^{12}Be*(6.4). See also (2003BO24, 2003BO38, 2003BO50, 2008BO37).

10. ^{9}Be(^{18}O, ^{12}Be)^{15}O $\qquad Q_\mathrm{m} = -17.3678$

In (2003SH06) a ^{12}Be beam was produced by fragmenting 100 MeV/A ^{18}O projectiles in a ^{9}Be target. The first report of ^{12}Be*(2.25) found evidence in the in-flight decay of the state via detection of the sequentially emitted γ-rays,$^{12\mathrm{m}}$Be*(2.25) $\rightarrow$ ^{12}Be*(2.107) $\rightarrow$ ^{12}Be$_{\mathrm{g.s.}}$. The ^{12}Be ions were detected in coincidence with the γ-rays. The angular correlations of the two γ-rays determine $J^\pi = 0^+$ for the state. Furthermore, 511 keV annihilation γ rays were also detected following e$^+$+e$^-$-decay, indicating a E0($0^+ \rightarrow 0^+$) decay branch to the ground state. The branching ratio for decay to either ^{12}Be*(2.107)[2^+] or ^{12}Be$_{\mathrm{g.s.}}$ was found as E2 $= (17 \pm 2)\%$ and E0 $= (82 \pm 2)\%$, respectively.

A subsequent endeavor also produced a ^{12}Be beam via fragmentation of a $E(^{18}\mathrm{O}) = 100$ MeV/A beam; the ^{12}Be ions were implanted in a thick polyethylene block (2007SH34). Decay of the $^{12\mathrm{m}}$Be*(2.251) state was observed via the γ-ray emission cascade through ^{12}Be*(2.107), as well as observation of the 511 keV annihilation γ-rays following e$^+$+e$^-$-pair emission. The γ-ray energies of 144 and 2107 keV in the $J^\pi = 0^+ \rightarrow 2^+ \rightarrow 0^+$ decay cascade lead to $E_\mathrm{x} = 2251 \pm 1$ keV for $^{12\mathrm{m}}$Be. The mean lifetime for the two decay branches is $\tau_\mathrm{m} = 331 \pm 12$ ns. The branching ratio E2 $= (18.3 \pm 1.4)\%$ and E0 $= (81.7 \pm 1.4)\%$ is observed; when combined with (2003SH06) the average is E2 $= (17.7 \pm 1.5)\%$ and E0 $= (82.3 \pm 1.5)\%$, which yields $B(\mathrm{E0}) = 0.87 \pm 0.03$ $e \cdot \mathrm{fm}^2$ and $B(\mathrm{E2}) = 7.0 \pm 0.6$ $e^2 \cdot \mathrm{fm}^4$. See also (2003SH35, 2007HA50) and (2012FO08). See (2008RO03) for the prediction of a $J^\pi = 0^-$ isomeric state near $E_\mathrm{x} = 2.5$ MeV.

11. ^{10}Be(t, p)^{12}Be $\qquad Q_\mathrm{m} = -4.8095$

Levels are reported in measurements at $E_\mathrm{t} = 12$ to 17 MeV; see Table 12.3. At $E_\mathrm{t} = 12$ MeV ^{12}Be*(2.10) is populated [$E_\mathrm{x} = 2110 \pm 15$ keV], and (p, γ) angular correlations lead to $J = 2$ (1978AL10). The Q-value 4808.3 ± 4.2 keV was deduced in (1994FO08), which compares with $Q = 4809\pm$ 15 keV from (1978AL10). See also (2006FO11, 2011FO04, 2013FO30, 2013GA48, 2014FO04, 2014FO11, 2014PO08, 2015FO06) and (1980AJ01).

12. ^{10}Be(^{14}C, ^{12}Be)^{12}C $\qquad Q_\mathrm{m} = -9.4504$

At $E(^{14}\mathrm{C}) = 87.7$ MeV analysis of the invariant mass spectra constructed from the ^{6}He + ^{6}He and ^{4}He + ^{8}He relative energies found no evidence for ^{12}Be excited states (2006CU01).

Table 12.3: States populated in ^{10}Be(t, p)

E_x ^{a} (keV)	J^π ^{a}	Γ ^{a} (keV)	E_x ^{b} (keV)	E_x ^{c} (keV)
0	0^+		0	0
2111 ± 3	2^+		2110 ± 15	2089 ± 20
				(2240 ± 20) ^{d}
2730 ± 3	(0^+)		0	(2712 ± 20)
4580 ± 5	$(2^+, 3^-)$ ^{e}	101 ± 17		(4559 ± 25)
5724 ± 6	$(2^+, 3^-, 4^+)$ $^{e, f}$	86 ± 15		5703 ± 25

[a] (1994FO08): $E_t = 15$ and 17 MeV.

[b] (1978AL10): $E_t = 12$ MeV. ^{12}Be*(2.11) has $J = 2$ from (t, pγ).

[c] (1978AL29): $E_t = 12$ MeV.

[d] (2003SH06, 2007SH34) confirm this $J^\pi = 0^+$ state.

[e] (2011FO04, 2013FO30, 2014FO04) suggest $J^\pi = (3^-)$ and (4^+) for ^{12}Be*(4.6, 5.7), respectively.

[f] $J^\pi = 4^+$ is preferred.

13. ^{10}Be(^{14}N, ^{12}N)^{12}Be $\quad Q_m = -26.9450$

States at ^{12}Be*(0, 2.1, 4.56, 5.70, 6.25$\pm$0.05, (11.2)) were populated in the 2-neutron stripping reaction at $E(^{14}\text{N}) = 216$ MeV (2003BO24, 2008BO37).

14. ^{12}C(π^-, π^+)^{12}Be $\quad Q_m = -25.0778$

At $E_{\pi^-} = 164$ MeV, ^{12}Be*(0, 2.10 + (2.71)) are populated (1978SE07). See also (2007FO05) for $E_{\pi^-} = 120$, 180 and 240 MeV.

15. ^{12}C(^{12}Be, ^{10}Be)^{14}C $\quad Q_m = 9.4504$

The width of the ^{10}Be longitudinal momentum distribution following $E(^{12}\text{Be}) = 56.75$ MeV/A breakup on a ^{12}C target is FWHM = 194 ± 9 MeV/c (1993ZA04). See also (1990LI39, 1997OR03, 2000BH09, 2003TI10, 2004YA05, 2010BA03).

16. $^{\text{nat}}$C(^{12}Be, ^{11}Be)^{13}C $\quad Q_m = 1.7756$

The neutron removal cross sections was measured at $E(^{12}\text{Be}) = 39.3$ 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 ± 0.08, 0.48 ± 0.06, 0.40 ± 0.07 were deduced, respectively. The significant feeding of ^{11}Be*(1.78[$J^{\pi} = \frac{5}{2}^{+}$]) implies a $\nu(0\text{d}_{5/2})^2$ component in the $^{12}\text{Be}_{\text{g.s.}}$. See also (2004BR17, 2004GO23, 2004IT08).

17. ^{12}C(^{12}Be, ^{12}Be) $E_{\text{b}} = 31.0294$

The angular distribution for quasielastic scattering of ^{12}Be on ^{12}C was measured at $E(^{12}\text{Be}) = 56$ MeV/A (1994ZA02), and optical model parameters were deduced from a coupled-channels analysis. See also (1996TH01) who analyzed the data of (1994ZA02) and deduced a dominant $(\text{p}_{1/2})^2$ configuration in the ^{12}Be ground state with a possible 25% $(sd)^2$ admixture. See also (1994ME15, 1995BE26, 1995TH04, 1999KN04, 2000PA14, 2001OZ04).

18. (a) ^{12}C(^{12}Be, ^{12}Be′)
(b) ^{12}C(^{12}Be, Breakup)

Unbound ^{12}Be states with $E_{\text{x}} = 10$ to 25 MeV were studied by measuring ^{6}He + ^{6}He and α + ^{8}He breakup coincidences and reconstructing the excitation energy from kinematics (1999FR04, 1999OR07, 2001FR02: $E(^{12}\text{Be}) = 378$ MeV), (2007CH81: $E(^{12}\text{Be}) = 600$ MeV) and (2014YA08, 2015YA05: $E(^{12}\text{Be}) = 348$ MeV). ^{12}C and $(\text{CH}_2)_n$ targets were used. Observed states are shown in Table 12.4.

In (2001FR02) the states are associated with cluster rotational states that could indicate a quasi-molecular α-4n-α structure in ^{12}Be. However, the high statistics measurements of (2007CH81) failed to find evidence supporting many states observed by (2001FR02); specifically several key members of the suggested rotational band were absent from the spectra. In (2007CH81) the relative energies of p + ^{11}Li and t + ^{9}Li breakup particles were reconstructed; in the p + ^{11}Li data, a state at $E_{\text{x}} = 25$ MeV with $\Gamma \approx 370$ keV is suggested as the IAS of $^{12}\text{Li}_{\text{g.s.}}$. The array configuration used in (2014YA08, 2015YA05) emphasized a high sensitivity for low relative energy breakup events. New states were identified and the angular distributions were analyzed via DWBA to obtain J^{π} values. At $E_{\text{x}} = 10.3$, a $J^{\pi} = 0^{+}$ level is identified as the bandhead of a ^{4}He + ^{8}He molecular rotational band with a transition strength of 7.0 ± 1.0 fm^2 for the isoscalar monopole transition.

The cross sections for ^{12}Be breakup into ^{6}He + ^{6}He, α + ^{8}He, α + ^{6}He (+ 2n), ^{11}Be (+ n), ^{10}Be (+ 2n), ^{9}Be (+ 3n), and ^{8}Be (+ 4n) were measured at $E(^{12}\text{Be}) = 41.8$ MeV/A (2004AS02). The cluster cross sections are dominated by breakup into $2\alpha+$ neutrons, suggesting a α-4n-α structure. See also theoretical analysis of cluster states in (2000BB06, 2000IT07, 2001DE20, 2001IT05, 2002IT09, 2003FI15, 2004FI04, 2004FI11, 2004KA21, 2004KA34, 2005KA50, 2007FR22, 2007PE26,

2008IT05, 2008IT07, 2008RO12, 2010DU08, 2010WO02, 2011DU11, 2011IT02, 2012GA33, 2012IT01, 2012IT02, 2012IT04, 2013TA01, 2014IT02).

19. ^{12}C(^{14}Be, ^{12}Be$'$)^{14}C $\quad Q_{\mathrm{m}} = 11.8523$

At $E(^{14}\mathrm{Be}) = 75$ MeV/A the ^{6}He + ^{6}He breakup events were detected (2002SA65). Peaks at the decay energies $E(^{6}\mathrm{He} + {}^{6}\mathrm{He}) \approx 1.7$, 2.9, 4.6 and 5.6 MeV were observed; these correspond to $E_{\mathrm{x}} \approx 11.8$, 13.0, 14.7 and 15.7 MeV. Analysis of the angular correlation data for ^{12}Be*(11.8) suggests $J = 0$.

20. (a) ^{12}C(^{14}C, ^{14}O)^{12}Be $\quad Q_{\mathrm{m}} = -30.06534$
(b) ^{14}C(^{12}C, ^{14}O)^{12}Be $\quad Q_{\mathrm{m}} = -30.06534$

At $E(^{14}\mathrm{C}) = 335.9$ MeV ^{12}Be*(0, 2.1, 2.7, 4.56, 5.7, 7.2 ± 0.1, 9.3 [$\Gamma = 2.0 \pm 0.3$ MeV]) are populated (1995VO05, 2002BO16). For reaction (b) at 231 MeV, ^{12}Be*(0, 2.1, 4.56, 9.6, 18.95) are observed (2008BO37). Although the $E_{\mathrm{x}} = 2.24$ MeV state is unresolved from the strongly populated $E_{\mathrm{x}} = 2.1$ MeV state, the authors suggest a rotational band based on ^{12}Be*(2.24 [0_2^+], 4.56 [2_2^+], 9.6, 18.95). See also (2015MA03, 2015CA08).

21. ^{14}C(^{14}C, ^{16}O)^{12}Be $\quad Q_{\mathrm{m}} = -14.3010$

At $E(^{14}\mathrm{C}) = 335.9$ MeV, ^{12}Be*(0, 2.10, 4.56, ≈ 5.7) are populated (1995BO10).

22. (a) ^{28}Si(^{12}Be, X)
(b)^{208}Pb(^{12}Be, X)

At $E(^{12}\mathrm{Be}) = 30$ to 60 MeV/A the total reaction cross sections were measured on ^{28}Si and ^{208}Pb targets (2001WA40). Data are compared with a Glauber model. Neutron removal cross sections indicate $\sigma_{2n} > \sigma_{1n}$, owing to the ease of removing the second neutron.

See also measurements in (1988TA10) and (1990LI39, 1990LO10, 1993FE12, 1996AL24, 1999KN04, 2000BH09, 2000CA33, 2001OZ04, 2002BR01, 2003CA07, 2006BH01, 2006SH20).

23. ^{197}Au(^{12}Be, ^{12}Be$'\gamma$)

Table 12.4: He + He cluster states observed in ^{1}H, ^{12}C + ^{12}Be reactions

E_x [a] (MeV)	J [a]	E_x [b] (MeV)	J [b]	E_x [c] (MeV)	E_x [d] (MeV)	J^π [e]	E_x (MeV)	Γ [k] (MeV)	E_x (MeV)	J^π [n]	Γ [l, m] (MeV)
							10.2 [f]	broad	10.3 [l]	(0^+)	1.5 ± 0.2
									11.7 [m]	(2^+)	≈ 1
		12.1	4		12.1				12.1 [l]	(2^+)	
13.2	4	13.0	4			4^+	12.8 [f,j]	≈ 1.5			
									13.3 [m]	(4^+)	≈ 1
		13.9	4	14.1	14.1		13.5 [g]		13.6 [l]	(4^+)	
14.9		14.7					$\approx$ 14.5 [g]				
		(15.4)			15.1		15.5 [f,j]	≈ 1.5			
16.1	6	16.6		16.0	16.5	6^+					
17.8	6	(17.7)		17.4			(17.7) [h]	$\approx$ 350 keV			
18.6	6	(18.4)		18.2							
19.3	6	(19.3)		19.4							
20.9	8	(20.8)		20.7		8^+					
22.8											
(24.0)											
(25.1)							25 [i]	370 keV			
							28 [i]	2.7			

[a] ^{1}H, ^{12}C(^{12}Be, ^{6}He + ^{6}He): all data combined $\Delta E_\mathrm{x} \approx 0.5$ MeV (1999FR04, 2001FR02).

[b] ^{12}C(^{12}Be, $\alpha +$ ^{8}He) (1999FR04).

[c] ^{1}H(^{12}Be, $\alpha +$ ^{8}He) (2001FR02).

[d] ^{12}C(^{12}Be, $\alpha +$ ^{8}He) (2001FR02).

[e] (2001FR02).

[f] ^{1}H, ^{12}C(^{12}Be, $\alpha + {}^{8}$He) (2007CH81).

[g] ^{1}H, ^{12}C(^{12}Be, ^{6}He + ^{6}He) (2007CH81).

[h] ^{1}H, ^{12}C(^{12}Be, t + ^{9}Li) (2007CH81).

[i] ^{1}H, ^{12}C(^{12}Be, p + ^{11}Li) (2007CH81).

[j] Doublets.

[k] (2007CH81).

[l] ^{12}C(^{12}Be, ^{4}He + ^{8}He) (2015YA05).

[m] ^{12}C(^{12}Be, ^{6}He + ^{6}He) 2015YA05).

[n] From DWBA (2015YA05).

At $E(^{12}\text{Be}) = 42.9$ MeV/A, the γ-rays associated with inelastic scattering to ^{12}Be*(2107 ± 3, 2693 ± 5) on a 1 mm thick Au target were observed at $\theta_{\text{lab}} = 150°$ (2009IM01). Using $\tau_{\text{m}} = 1.9 \pm 0.5$ fs (2000IW03) for the lifetime of ^{12}Be*(2693), the spectrum was analyzed using the Doppler shift attenuation method (or DSAM technique) to deduce the lifetime of the $E_{\text{x}} = 2107$ keV $J^\pi = 2^+$ state. The mean lifetime $\tau_{\text{m}} = 2.5 \pm 0.7$ (stat.) $\pm\, 0.3$ (sys.) ps, which corresponds to $B(\text{E2}) = 8.0 \pm 2.2$ (stat.) $\pm\, 0.8$ (sys.) $e^2 \cdot \text{fm}^4$, was deduced in an analysis that considered cascade feeding from the higher-lying $E_{\text{x}} = 2251$ keV $J^\pi = 0^+$ isomeric state. See also discussion in (2004TH07, 2005TH06, 2008UM02, 2012FO08, 2012LI32, 2012YU07, 2013MA53, 2013MA60, 2014LI39).

24. ^{208}Pb(^{12}Be, ^{12}Be$'\gamma$)

At $E(^{12}\text{Be}) = 53.3$ MeV/A Coulomb excitation of the $E_{\text{x}} = 2110 \pm 20$ and 2680 ± 30 keV states of ^{12}Be was measured (2000IW03). The $E_{\text{x}} = 2.68$ MeV state was strongly populated, leading to a $J^\pi = 1^-$ assignment and $B(\text{E1}) = 0.051 \pm 0.013\ e^2 \cdot \text{fm}^2$. The low energy and significant strength of the 1^- state is seen as further evidence of the ending of $N = 8$ "magicity" in ^{12}Be. A further study in (2002IW01) deduced the quadrupole deformation parameter, $\delta = 2.00 \pm 0.23$ fm, for ^{12}Be*(2.11) which corresponds to $\beta_2 \approx 0.7$. See also (1995AN20, 1997BO08, 2001SA06, 2001SU10, 2002SA12, 2002SH44, 2003SH26, 2003SH35, 2005NA06, 2005NA42, 2006GU07, 2010BL08).

^{12}B

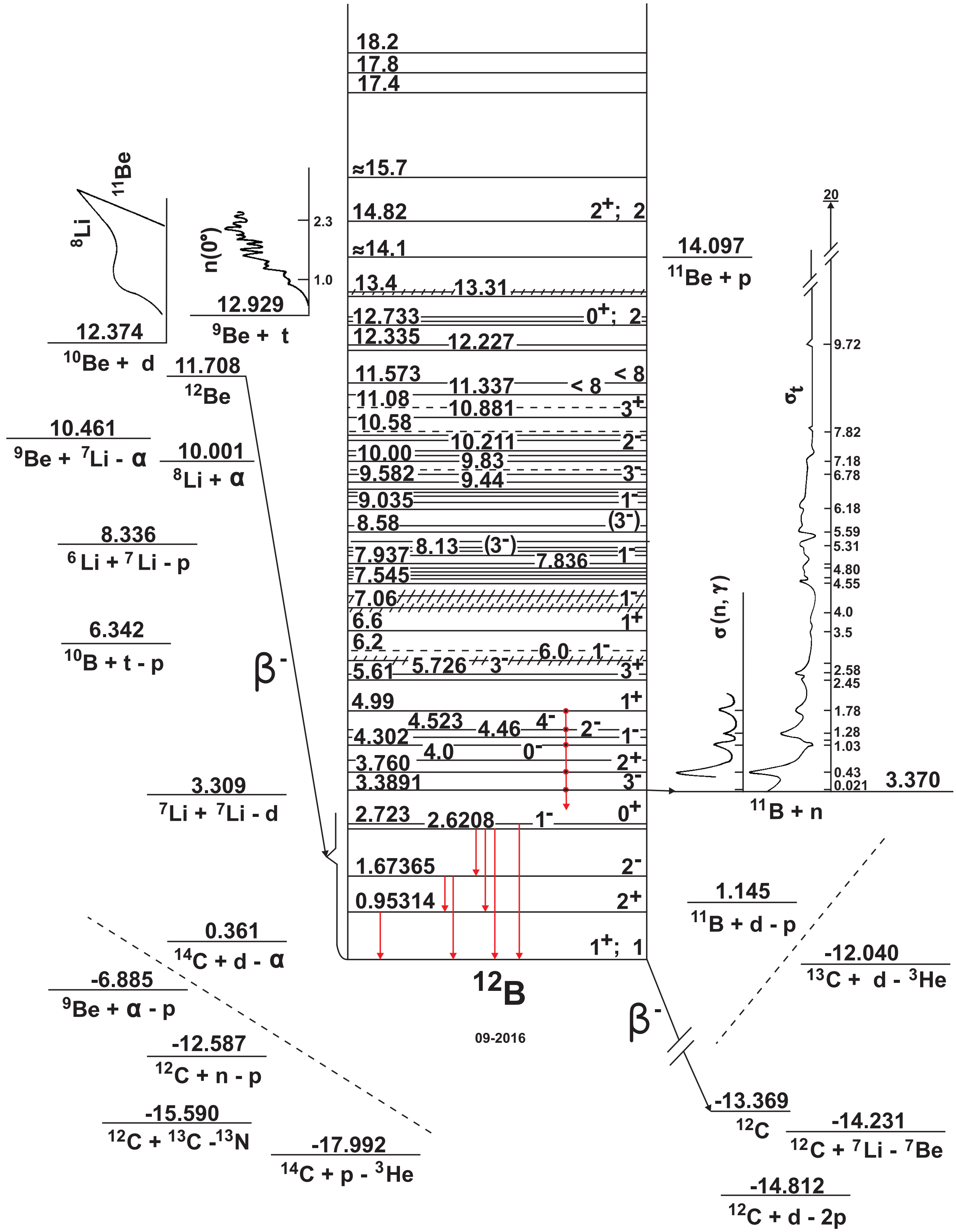
(Table 12.5, Fig. 2)

$\mu = +1.00272\ (11)$ nm (1990MI16). See also $+1.00306\ (^{+15}_{-14})$ nm (1970WI17), $+1.000\ (3)$ nm (2003ZH32), $+1.00\ (2)$ nm (2010ZH03) and comments in (2011STZZ).

$Q = 1.32 \pm 0.03\ \text{fm}^2$ (1993OH05). See also $1.34 \pm 0.14\ \text{fm}^2$ (1978MI19).

$< r^2_{\text{matter}} >^{1/2} \approx 2.31 - 2.35$ fm; i.e., see (1988TA10, 2010LI18, 2014ES07).

Fig. 2: Energy levels of ^{12}B. In these diagrams, energy values are plotted vertically in MeV, based on the ground state as zero. For the $A = 12$ 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 ^{12}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 (2012WA38). Further information on the levels illustrated, including a listing of the reactions in which each has been observed, is contained in Table 12.5.


18.2
17.8
17.4
≈15.7
14.82
2+; 2
≈14.1
13.4
13.31
12.733
0+; 2
12.335
12.227
11.573
11.337
< 8
< 8
11.08
10.881
3+
10.58
10.00
10.211
2-
9.582
9.83
3-
9.44
9.035
1-
8.58
(3-)
7.937
8.13
(3-)
7.836
1-
7.545
7.06
1-
6.6
1+
6.2
6.0
1-
5.61
5.726
3-
3+
4.99
1+
4.523
4.46
4-
2-
4.302
1-
4.0
0-
3.760
2+
3.3891
3-
2.723
2.6208
1-
0+
1.67365
2-
0.95314
2+
1+; 1
12B
09-2016
12.374
10Be + d
8Li
11Be
12.929
9Be + t
n(0°)
2.3
1.0
11.708
12Be
10.461
9Be + 7Li - α
10.001
8Li + α
8.336
6Li + 7Li - p
6.342
10B + t - p
β-
3.309
7Li + 7Li - d
0.361
14C + d - α
-6.885
9Be + α - p
-12.587
12C + n - p
-15.590
12C + 13C - 13N
-17.992
14C + p - 3He
14.097
11Be + p
σ(n, γ)
σt
20
9.72
7.82
7.18
6.78
6.18
5.59
5.31
4.80
4.55
4.0
3.5
2.58
2.45
1.78
1.28
1.03
0.43
0.021
3.370
11B + n
1.145
11B + d - p
-12.040
13C + d - 3He
β-
-13.369
12C
-14.231
12C + 7Li - 7Be
-14.812
12C + d - 2p

1. ^{12}B(β^-)^{12}C $Q_{\rm m} = 13.3694$

The half-life of ^{12}B is 20.20 ± 0.02 ms (1978AL01); earlier values are reported in (1968AJ02). ^{12}B decays to ^{12}C*(0, 4.4, 7.7, 10.3, 12.7); states in ^{12}C above $E_{\rm x} = 7366$ keV are unbound to α-decay: see details in Table 12.24. The transitions to ^{12}C$_{\rm g.s.}$[$J^\pi = 0^+$] and ^{12}C*(4.4[$J^\pi = 2^+$]) are allowed; hence the J^π of ^{12}B$_{\rm g.s.}$ is 1^+.

Values of the magnetic dipole moment, $\mu = 1.0002 \pm 0.0028\ \mu_{\rm N}$ (2003ZH32), $\mu = 1.003 \pm 0.001\ \mu_{\rm N}$ (1997MA21) and $\mu = 1.001 \pm 0.017\ \mu_{\rm N}$ (2010ZH03), were measured using β-NMR techniques, and the (electric) quadrupole moment, $Q = 13.22 \pm 0.26$ mb (1993MI36, 1993OH05, 1994OH03) was measured using β-NQR techniques; these compare well with the presently adopted values: see (2016ST14). A β-Level Mixing Resonance method, which simultaneously gives information on the nuclear alignment, μ and Q values, is applied to ^{12}B in (1997NE01, 1999CO09, 2001CO09).

Table 12.5: Energy levels of ^{12}B

$E_{\rm x}$ in ^{12}B (MeV $\pm$ keV)	$J^\pi; T$	τ or $\Gamma_{\rm cm}$ (keV)	Decay	Reactions
0	$1^+; 1$	$T_{1/2} = 20.20 \pm 0.02$ ms	β^-	1, 2, 3, 4, 7, 9, 10, 12, 14, 15, 18, 19, 20, 21, 22, 23, 24, 26, 27, 28, 30, 31, 32, 33, 35, 36, 37, 38, 39
0.95314 ± 0.6	2^+	$\tau_{\rm m} = 260 \pm 40$ fs	γ	2, 3, 4, 9, 10, 14, 15, 18, 19, 20, 21, 23, 26, 30, 31, 33, 35, 36, 37, 38, 39
1.67365 ± 0.6	2^-	< 50 fs	γ	3, 4, 9, 10, 14, 18, 19, 20, 21, 26, 31, 33, 35, 36
2.6208 ± 1.2	1^-	< 48 fs	γ	2, 3, 4, 10, 14, 18, 19, 20, 26, 31, 32, 33, 35, 36
2.723 ± 11	0^+		γ	3, 4, 10, 14, 19, 20, 38
3.3891 ± 1.6	3^-	$\Gamma = 3.1 \pm 0.6$ eV	γ, n	3, 9, 10, 14, 16, 18, 19, 20, 31, 33, 35, 36
3.760 ± 6	2^+	40 ± 4 keV	γ, n	2, 3, 9, 10, 14, 16, 18, 19, 31, 33, 38
4.0	0^-			31
4.302 ± 6	1^-	9 ± 4	γ, n	3, 10, 14, 16, 18, 19, 33

Table 12.5: Energy levels of ^{12}B (continued)

E_x in ^{12}B (MeV ± keV)	$J^\pi; T$	τ or Γ_{cm} (keV)	Decay	Reactions
4.46 [a]	2^-	260	n	16, 23, 30, 31, 33, 35, 36
4.523 ± 8 [a]	4^-	110 ± 20	γ, n	3, 10, 14, 16, 18, 19, 20, 23, 30, 31, 33, 35
4.990 ± 12	1^+	50 ± 15	γ, n	2, 3, 10, 14, 16, 18, 31, 38
5.610 ± 8	3^+	115 ± 20	n	2, 3, 10, 14, 16, 18, 20, 31, 35, 39
5.726 ± 8	3^-	58 ± 12	n	10, 14, 16, 20, 33
6.0	1^-	broad	n	16
(6.2)				
6.6	1^+	140	n	16
7.06	1^-	broad	n	16
7.3		very broad		32
7.545 ± 20		< 14	n	10, 14, 16
7.67	2^-	45	n	8, 16
7.7 ± 100 [a]	1^-	≈ 2 MeV		23, 30, 31, 35, 36
7.8 [b]		4.0 ± 0.5 MeV		30, 33, 36
7.836 ± 20	1^-	60 ± 40	n	8, 10, 16
7.937 ± 20	1^-	< 40	n	8, 10, 16
8.130 ± 15	(3^-)	260 ± 80	n	8, 10, 16
8.165 ± 25		45 ± 15		8, 10, 14
8.24 ± 30	3^-	65	n	10, 16
8.39 ± 20		40 ± 15		8, 10, 14
8.58 ± 30	(3^-)	75	n	10, 14, 16
8.707 ± 20	3^-		n	10, 16
9.035 ± 5	1^-	95 ± 20	n	8, 10, 14, 16
9.175 ± 20	(2^-)		n	10, 16
9.3 [e]	0^-	≈ 330		31
9.397 ± 6		35 ± 10		8
9.44 ± 8		60 ± 20		8, 10, 14

Table 12.5: Energy levels of ^{12}B (continued)

E_{x} in ^{12}B (MeV $\pm$ keV)	$J^{\pi}; T$	τ or Γ_{cm} (keV)	Decay	Reactions
9.582 ± 3	3^-	34 ± 4	n	8, 10, 14, 16
9.758 ± 20				10
(9.83)				10
10.00 ± 40		100	n	10, 16
10.115 ± 11	1^-	≈ 200		8, 10, 31
10.211 ± 12	2^-	9 ± 3		8, 10, 14, 19
10.42 ± 10	$< 4^-$	76 ± 20		8, 10
10.564 ± 3	2^-	11 ± 3		8, 10, 14, 19
(10.58)		200		17
10.881 ± 4	3^+	17 ± 4	α	5, 8, 10, 14, 19
(11.08)				10
11.337 ± 7	< 8	90 ± 25		8, 10
11.573 ± 6	< 8	60 ± 20	α	4, 5, 8, 10
12.227 ± 9		155 ± 60	n	8, 16
12.335 ± 15		62 ± 25		8, 10, 14
12.733 ± 40	$0^+; 2$	< 40	α	34, 39
12.76 ± 15		110 ± 35		8, 10
12.8 ± 500		3500 ± 500		33
13.31 ± 15		53 ± 12		8, 10
13.4 ± 100		broad	α	4, 5, 6, 14, 35
c				
≈ 14.1			(t), α	4, 5, 6, 10
14.82 ± 50	$2^+; 2$	< 100	p, t, α	34, 39
≈ 15.7			(t), α	4, 5, 6, 10
17.4				5, 10
17.8 ± 1500		3500 ± 1500		33
18.2				36
d				

[a] Spin Dipole.

[b] GDR.

[c] Thirteen states with $13.6 < E_x < 14.7$ are reported in ^{9}Be(t, n) (1961VA1C).

[d] See other neutron resonances shown in (1979AU07).

[e] A duplicate level at 9.0 MeV has been removed after publication.

See other theoretical work in (1993KI05, 1993KI22, 2012YU07, 2014RA17), and see discussion on methods for polarizing ^{12}B in (1984KO25, 1985DE54, 1990NO14, 1993SH37, 1997CO15, 1997MA21, 1998MA27, 1999MA24, 2002MO44, 2004NA37, 2007GR23) and references cited in (1985AJ01, 1990AJ01). See discussion on using TiO_2 (2001OG12, 2002OG08) and superfluid ^{4}He (1995SH22, 1996TA12, 1997TA13) as nuclear spin dewars. Quadrupole coupling constants of polarized ^{12}B in Mg and Zn were measured in (1993OH11).

The G-parity irregular induced tensor coefficient in the weak nucleon axial vector current $2Mf_T/f_A = -0.21 \pm 0.09$ (stat.) $\pm\, 0.07$ (sys.) $\pm\, 0.05$ (theory) (2002MI03) was deduced from the alignment correlation terms in spin aligned ^{12}B and ^{12}N decay. When combined with reanalyzed results from (1998MI14, 1999MI41, 2000MI11) the new analysis gives $2Mf_T/f_A = -0.15 \pm 0.12$ $\pm\, 0.05$ (theory) (2002MI03, 2002MI49, 2003MI24); see also (1987MI20) and (1995KO28: theory).

The axial charge in the weak nucleon axial vector current $y = 4.96 \pm 0.09$ (stat.) $\pm\, 0.05$ (sys.) (2002MI01, 2002MI36) was deduced from the alignment correlation terms in spin aligned ^{12}B and ^{12}N decay. When combined with reanalyzed results from (1993MI32, 1994MO23, 1998MA27, 1999MI04, 1999MI41, 2000MI11) the new analysis gives $y = 4.90 \pm 0.10$ (2002MI01). The large mesonic enhancement to the axial charge observed in the $A = 12$ triad may suggest an "in-medium" nucleon mass reduction of $\approx (16 \pm 4)\%$ (2002MI01). See also (2003SM02).

The β^- spectral shape following ^{12}B decay was measured (1987NA08, 1990CA10, 2000ST19) and compared with the β^+ spectral shape following ^{12}N decay to determine the weak magnetism correction to the beta spectra (1990CA10). Shape factors for β and ν spectra are compiled in (2015MO10). See Knight shifts measurements reported in (2007MI49) and other discussion in (1992BA11, 1993CH06).

2. ^{2}H(^{14}C, α)^{12}B $\quad Q_m = 0.3613$

At $E(^{14}\mathrm{C}) = 17.1$ MeV/A , ^{12}B states at $E_x = 0$, 953, 3759, 5000 and 5612 were populated using (d, α) reactions in inverse kinematics. The high spin selectivity of the reaction, which favors states with large J values, strongly populated the ^{12}B*(5612) $J^\pi = 3^+$ state (2014WU10).

3. ^{6}Li(^{7}Li, p)^{12}B $\quad Q_m = 8.3356$

Eleven groups of protons are reported to the known states at $E_x \leq 5.6$ MeV (1959MO12). Angular distributions have been measured at $E(^6\mathrm{Li}) = 3.5$ to 5.95 MeV. The distributions are generally featureless.

Table 12.6: States observed in ^{7}Li(^{7}Li, ^{8}Li + α) and ^{7}Li(^{7}Li, ^{9}Be + t)

E_x (MeV)	Breakup mode	Branching ratio
11.67	$\alpha + {}^8$Li	≈ 100
13.44	$\alpha + {}^8$Li	≈ 100
14.1	$\alpha + {}^8$Li	> 94.9
	t + ^{9}Be	< 5.1
15.90	$\alpha + {}^8$Li	99.6 ± 4.2
(15.87)	t + ^{9}Be	0.4 ± 0.2

4. (a) ^{7}Li(^{7}Li, d)^{12}B $Q_m = 3.3091$
   (b) ^{7}Li(^{7}Li, ^{12}B*)d $Q_m = 3.3091$

Angular distributions have been measured at $E(^7\text{Li}) = 2.10$ to 5.75 MeV (1969CA1A: d_0, d_1, d_2, d_{3+4}). The γ-decay of the first four excited states has been studied by (1963CA09): ^{12}B*(0.95) decays to the ground state. So, primarily, do ^{12}B*(1.67) [$> 98\%$] and ^{12}B*(2.72) [$> 80\%$], while ^{12}B*(2.62) decays [$> 90\%$] via ^{12}B*(0.95, 1.67). See also Table 12.7 in (1975AJ02). The mean lifetimes of ^{12}B*(0.95, 2.62) are 295 ± 37 fsec and < 48 fsec, respectively (1969TH01).

At $E(^7\text{Li}) = 58$ MeV the ^{7}Li(^{7}Li, ^{12}B*) $\rightarrow$ (^{9}Be + t and ^{8}Li + α) reactions were studied (2005CU06); see Table 12.6. Observations indicate α + Li clusters play an important role in the boron isotopes. See also (1984KO25).

5. ^{7}Li(^{9}Be, $\alpha + {}^8$Li)^{4}He $Q_m = 0.4599$

At $E(^9\text{Be}) = 70$ MeV α-cluster states at ^{12}B*(10.9, 11.6, 13.4, 14.1, 15.7, 17.4) were observed in the $\alpha + {}^8\text{Li}_{\text{g.s.}}$ breakup channel (2004SO19); see also reaction 10.

6. (a) ^{8}Li(α, n)^{11}B $Q_m = 6.6315$
   (b) ^{8}Li(α, α) $E_b = 10.0013$
   (c) ^{9}Li(α, n) $Q_m = 5.9391$

Reaction cross sections have been measured at $E_{cm} = 0.6$ to 2.7 MeV (2004HA54, 2006IS04), $E_{cm} = 0.6$ to 5 MeV (2016DE02), $E_{cm} = 0.64$ to 2.2 MeV (1995GU02), $E_{cm} = 0.9$ to 2.8 MeV

(2004MI34), $E_{\rm cm} = 1.05$ MeV (2008LA08, 2010LA07), $E_{\rm cm} = 1.25$ MeV, $E_{\rm cm} = 1.5$ to 7 MeV (2000MI34) and $E(^{8}{\rm Li}) = 10$ to 20 MeV (1992BO06). Various unresolved ^{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 Nucleosynthesis (1992BO06, 1993DE30, 2000MI34, 2004CH22). Early estimates for the ^{8}Li(α, n) reaction rate were based on the inverse reaction, ^{11}B(n, α), which only samples the ^{8}Li(α, n$_0$) rate. The direct measurements indicate the total σ to all ^{11}B excited states is roughly five times larger than the branch that feeds only ^{11}B$_{\rm g.s.}$ (1992BO06). 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 (2004CH22, 2008LA08, 2010LA07). See (2000MI34) for branching ratios to n$_0$ through n$_9$. Also see discussion in (1990DE21, 1992RA04, 1993OB01, 1994KU28, 1996DE02, 2012CO01, 2012LA20, 2016DE02). The fusion barrier is studied in (2016DE02).

Elastic α scattering on ^{8}Li was measured in thick target inverse kinematics by impinging a $E_{\rm cm} = 10.2$ MeV ^{8}Li on a ^{4}He gas cell and detecting the scattered α-particles (2011TO05, 2012DI22). Broad structures at $E_{\rm x} \approx 13.6$, 14.4, and 15.8 MeV dominate the excitation function.

The role of ^{9}Li(α, n)^{12}B(β^-)^{12}C in astrophysical processes is evaluated in (2010HO09).

7. (a) ^{9}Be(t, n)^{11}B $\quad Q_{\rm m} = 9.5590 \quad E_{\rm b} = 12.9289$
   (b) ^{9}Be(t, p)^{11}Be $\quad Q_{\rm m} = -1.1679$
   (c) ^{9}Be(t, d)^{10}Be $\quad Q_{\rm m} = 0.5550$
   (d) ^{9}Be(t, t)^{9}Be $\quad E_{\rm b} = 12.9289$
   (e) ^{9}Be(t, α)^{8}Li $\quad Q_{\rm m} = 2.9275$
   (f) ^{9}Be(t, ^{6}He)^{6}Li $\quad Q_{\rm m} = -5.3807$

Table 12.7: Resonances in ^{9}Be(t, n)^{11}B (1961VA1C)

$E_{\rm t}$ (MeV)	$E_{\rm x}$ in ^{12}B (MeV)	$\Gamma_{\rm cm}$ (keV)	$E_{\rm t}$ (MeV)	$E_{\rm x}$ in ^{12}B (MeV)	$\Gamma_{\rm cm}$ (keV)
1.00	13.677	100	1.880	14.337	45
1.130	13.775		1.932	14.375	40
1.350	13.939	60	2.045	14.460	70
1.405	13.981	50	2.130	14.524	75
1.505	14.056	70	2.210	14.584	60
1.585	14.116	65	2.325	14.670	50
1.765	14.250	110			

Table 12.8: Levels observed in ^{9}Be(α, p)

E_x [a] (MeV ± keV)	Γ [a] (keV)	E_x [b] (MeV ± keV)	L_{tr} [b]	Γ [b] (keV)	E_x [c] (MeV ± keV)	Γ [c] (keV)	J^π [c]	E_x [d, g] (MeV)	Γ [d] (keV)	J^π [d]
		7.61 ± 25	3, 4, 5, 6	30 ± 15						
		7.70 ± 25	3, 4, 5, 6	100 ± 30						
		7.87 ± 25	3, 4, 5, 6	80 ± 30						
		7.99 ± 25	3, 4, 5, 6	135 ± 40						
		8.15 ± 25 [e]	3, 4, 5, 6	260 ± 80						
		8.17 ± 25 [e]	3, 4, 5, 6	45 ± 15						
		8.41 ± 25	3, 4, 5, 6	40 ± 15						
					9.035 ± 5					
		9.42 ± 15 [f, j]	0, 1, 2	35 ± 10	9.393 ± 6 [j]					
		9.46 ± 15 [f, j]	0, 1, 2	60 ± 20	9.434 ± 8 [j]					
		9.60 ± 15	3, 4, 5, 6	45 ± 10	9.582 ± 4					
10.115 ± 11	180									
		10.22 ± 15	3, 4, 5, 6	15 ± 15	10.199 ± 3	9 ± 3	$(2\text{-}3)^-$	10.199	9 ± 3 [g]	2^-
10.418 ± 11	130	10.42 ± 15		115 ± 40	10.417 ± 14	61 ± 25	(0-8)	10.417		$< 4^-$
10.572 ± 11	< 20	10.57 ± 15	0, 1, 2	10 ± 10	10.564 ± 3	10 ± 3	$(2\text{-}3)^-$	10.564	11 ± 3 [h]	2^-
		10.90 ± 15	0, 1, 2	30 ± 20	10.880 ± 3	18 ± 4	$(0\text{-}3)^+$	10.880	17 ± 4 [i]	3^+
11.346 ± 11	140	11.35 ± 15	0, 1, 2	125 ± 60	11.328 ± 10	75 ± 25	≤ 8	11.328	75 ± 25	≤ 8
		11.58 ± 15	0, 1, 2	90 ± 30	11.571 ± 6	45 ± 15	≤ 8	11.571	45 ± 15	≤ 8
12.226 ± 11	160	12.23 ± 15	3, 4, 5, 6	155 ± 60						
		12.33 ± 15	3, 4, 5, 6	45 ± 20						
		12.76 ± 15	0, 1, 2	160 ± 60						
		13.31 ± 15	0, 1, 2	55 ± 15						

[a] $E_\alpha = 65$ MeV (1991KU10); $J^\pi = (1^-)$ for ^{12}B*(10.418, 10.572) is suggested.

[b] $E_\alpha = 65$ MeV (1992BO16). $\Delta E \approx 10$ keV, except at low excitation energy.

[c] $E_\alpha = 35.2, 39.7$ MeV (1994MA05).

[d] $E_\alpha = 29$ (1994MA06): ^{9}Be(α, p)^{12}B → ^{11}B + n where neutron angular distributions and partial widths are measured.

[e] Previously identified as a broad state at $E_x \approx 8.1$ MeV (1992BO16).

[f] Previously identified as a broad state at $E_x \approx 9.43$ MeV (1992BO16).

[g] $\Gamma_n = 8.6 \pm 2.9$ keV and $\Gamma_\alpha < 2.1 \times 10^{-3}$ keV (1994MA06).

[h] $\Gamma_n = 8.8 \pm 2.5$ keV and $\Gamma_\alpha = 2.2 \pm 0.8$ keV (1994MA06).

[i] $\Gamma_n = 13.6 \pm 3.3$ keV and $\Gamma_\alpha = 3.4 \pm 1.1$ keV (1994MA06).

[j] In (1994MA05) Table 1 and (2017KE05) Table 8, these states are incorrectly correlated. The present table is corrected.

Thirteen resonances have been reported in reaction (a) corresponding to $13.6 < E_x < 14.7$ MeV: see Table 12.7. Optical potentials for ^{9}Be + t are analyzed in (2007LI55, 2009PA07, 2015PA10). The yield of 2.12 MeV γ-rays has been measured for $E_t = 1.5$ to 3.3 MeV, $E_t = 2.96$ to 11.46 MeV (2001GE16), and $E(^9\text{Be}) = 10$ to 16 MeV: no resonances are observed. This is also the case for the yields of 0.32 MeV (reaction (b)), 0.98 MeV (reaction (e)) and 0.48 MeV γ-rays (from the (t, αn) reaction). Elastically scattered tritons have been studied for $E_t = 0.60$ to 2.1 MeV and $E_{\vec{t}} = 15$ and 17 MeV (also A_y). The yields of α_0 and α_1 have also been reported for $E_t = 0.52$ to 1.70 MeV: see (1975AJ02). The analyzing powers of the reactions leading to $^6\text{He}_{\text{g.s.}}$ and ^{6}Li*(0, 3.56) have been measured at $E_{\vec{t}} = 17$ MeV. For references see (1985AJ01). See also (1988AJ01).

8. ^{9}Be(α, p)^{12}B $\qquad Q_m = -6.8850$

Observed proton groups, above $E_x = 7.6$ MeV are displayed in Table 12.8. Early studies of low-lying states were carried out at $E_\alpha = 21.7$ MeV (1951MC57, 1955RA41). The later studies at $E_\alpha = 29$, 35.2 and 39.7 MeV (1994MA05, 1994MA06), $E_\alpha = 50.29$ (1991KU31) and $E_\alpha = 65$ MeV (1991KU10, 1992BO16) evaluated neutron unbound states that can participate in the astrophysically important ^{8}Li(α, n) and ^{9}Li(t, n) reactions. In (1991KU31, 1994MA06) the scattered protons, which determine the ^{12}B excitation energy, are measured in coincidence with neutrons, and the angular distributions of the n_{0-3}-decay neutrons are analyzed to constrain l and J^π values. The work of (1994MA06) studies the astrophysical significance of ^{12}B*(10.119 to 11.571) states by considering Γ, $\Gamma_{\text{n}_{0-3}}$, Γ_n, Γ_α, and allowed spin values deduced in their analysis. Of particular importance (1994MA05) find no evidence for a state at $E_x \approx 10.6$ MeV with $\Gamma \approx 200$ keV that is reported by (1990PA22) and is suggested to dominate the S-factor. See also unpublished work cited in (1985AJ01).

9. ^{9}Be(^{6}Li, ^{3}He)^{12}B $\qquad Q_m = -2.8653$

At $E(^6\text{Li}) = 32$ MeV ^{12}B*(0, 0.95, 1.67, 3.38, 3.76) and some unresolved states are populated (1986AS02).

10. ^{9}Be(^{7}Li, α)^{12}B $\qquad Q_m = 10.4612$

Observed α-particle groups are displayed in Table 12.9. Angular distributions have been measured at $E(^7\text{Li}) = 3.3$ to 6.2 MeV, at 20 MeV and at 30.3 MeV: see (1975AJ02, 1980AJ01). At $E(^7\text{Li}) = 20$ MeV angular distributions to the first seven states are rather featureless and have approximate symmetry about 90°. The integrated cross sections go as $2J_f + 1$ consistent with a compound nucleus mechanism for the transitions populating the low-lying states of ^{12}B. It is suggested that the sharp states of ^{12}B at high excitation energies correspond to states of high angular momenta with cluster configurations.

At $E(^{7}\mathrm{Li}) = 52$ MeV states at ^{12}B*(10.9, 11.6, 13.4, (14.1), 15.7, (17.7)) were observed in the complete kinematic reconstruction of $2\alpha + {}^{8}$Li ejectiles from ^{9}Be(^{7}Li, ^{12}B* $\rightarrow \alpha + {}^{8}$Li)$\alpha$ reactions (2003SO22, 2003SO29).

11. ^{9}Be, ^{12}C, ^{27}Al, Cu(^{12}B, X)

Total reaction and interaction cross sections are reported at $E(^{12}\mathrm{B}) = 54.4$ MeV/A on $^{\mathrm{nat}}$Si (2010LI18), at $E(^{12}\mathrm{B}) = 64$ MeV/A on $^{\mathrm{nat}}$C (2004SA14), at $E(^{12}\mathrm{B}) = 67$ MeV/A on $^{\mathrm{nat}}$C (2000SA47), at $E(^{12}\mathrm{B}) = 790$ MeV/A on ^{9}Be, $^{\mathrm{nat}}$C, ^{27}Al (1988TA10), at $E(^{12}\mathrm{B}) = 920$ MeV/A on ^{12}C (1999BO46), at $E(^{12}\mathrm{B}) = 930$ MeV/A on $^{\mathrm{nat}}$C (2000CH20), and on Cu (1989SA10). Glauber model analyses suggest $R^{\mathrm{matter}}_{\mathrm{rms}} \approx 2.33$ fm (2010LI18) and 2.31 ± 0.07 fm (2014ES07). See also (1990LI39, 1990LO10, 1999KN04, 2000BH09, 2000CA33, 2001OZ04, 2002BR01, 2003CA07, 2004CA45, 2006BH01, 2006SH20, 2011KU06).

Table 12.9: Levels of ^{12}B from ^{9}Be(^{7}Li, α) and ^{10}B(t, p) [a]

E_{x} [b] (MeV ± keV)	Γ_{cm} [b] (keV)	E_{x} [c] (MeV ± keV)	Γ_{cm} [c] (keV)	L [c]	J^{π} [c]
0		0		2	$(1, 2, 4, 5)^{+}$
0.951 ± 15		0.955 ± 8		2	$(1, 2, 4, 5)^{+}$
1.674 ± 15		1.673 ± 8		1	$(2, 3, 4)^{-}$
2.625 ± 15		2.627 ± 8		3	$(0, 1, 5, 6)^{-}$
2.724 ± 15		2.72 [f]		4	$(0, 6, 7)^{+}$
3.390 ± 15		3.393 ± 8			
3.77 ± 20 [d]	40 ± 20	3.754 ± 8	42 ± 5	2	$(1, 2, 4, 5)^{+}$
4.305 ± 15	< 30	4.297 ± 8	≤ 15		
4.534 ± 15		4.514 ± 8	95 ± 15		
4.982 ± 15 [d]	40 ± 20	5.00 [g]	130 ± 40		
5.57 ± 30 [d]		5.612 ± 8	120 ± 20		
5.728 ± 15	50 ± 20	5.724 ± 8	70 ± 20		
7.545 ± 20	< 30	7.55 [f]			
7.836 ± 20	60 ± 40				
7.937 ± 20	< 40				
(8.1 ± 100) [i]	900 ± 200				

Table 12.9: Levels of ^{12}B from ^{9}Be(^{7}Li, α) and ^{10}B(t, p) [a] (continued)

E_x [b] (MeV ± keV)	Γ_{cm} [b] (keV)	E_x [c] (MeV ± keV)	Γ_{cm} [c] (keV)	L [c]	J^{π} [c]
8.120 ± 20		8.16 ± 30			
8.24 ± 30					
8.376 ± 20	40 ± 20	8.38 [f]			
8.58 ± 30		8.58 [f]			
8.707 ± 20					
9.03 ± 20		9.07 ± 30	95 ± 20		
9.175 ± 20					
9.43 ± 20 [e]	85 ± 30	9.44 ± 30			
9.585 ± 20	60 ± 30	9.626 ± 20	34 ± 10		
9.758 ± 20					
(9.83)					
10.00 ± 40					
10.11 ± 40					
10.21 ± 30	50 ± 20	10.227 ± 20	< 25		
10.435 ± 20	75 ± 40				
10.58 ± 20	50 ± 30	10.61 ± 30	< 30		
10.887 ± 20 [h]	40 ± 20	10.91 ± 20	27 ± 10		
(11.08)					
11.31 ± 30	130 ± 60				
11.59 ± 20 [h]	75 ± 25				
12.33 ± 30	100 ± 30	12.36 ± 30			
12.77 ± 50	85 ± 40				
13.33 ± 30 [h]	50 ± 20	(13.4 ± 100)	broad		
15.5 [h]					

[a] For references see Tables 12.3 and 12.4 in (1980AJ01).
[b] ^{9}Be(^{7}Li, α)^{12}B.
[c] ^{10}B(t, p)^{12}B.
[d] $\theta^2_{\rm n} = 0.46 \pm 0.06$, 0.08 ± 0.03 and 0.10 ± 0.02 for ^{12}B*(3.76, 5.00, 5.61).
[e] Probably unresolved.
[f] Observed but $E_{\rm x}$ not determined.
[g] Not observed at $E_{\rm t} = 23$ MeV.
[h] Observed in ^{9}Be(^{7}Li, $2\alpha + {}^{8}$Li) (2003SO22).
[i] See discussion in (1992BO16).

12. (a) ^{9}Be(^{18}O, ^{12}B)^{15}N $\qquad Q_{\rm m} = -2.9052$
(b) ^{9}Be(^{40}Ar, ^{12}B)^{37}Cl $\qquad Q_{\rm m} = -5.2993$

Systematics for ^{12}B and other unstable isotope beam production are measured in, for example, (2000FA06, 2000OZ01, 2007NO13, 2012KW02, 2015MO17).

13. (a) ^{10}Be(d, p)^{11}Be $\qquad Q_{\rm m} = -1.7229 \qquad E_{\rm b} = 12.3738$
(b) ^{10}Be(d, α)^{8}Li $\qquad Q_{\rm m} = 2.3725$

The cross sections for production of ^{8}Li (reaction (b)) and of ^{11}Be (reaction (a)) have been measured for $E_{\rm d} = 0.67$ to 3.0 MeV and 2.3 to 12 MeV, respectively: the yields for both reactions vary smoothly with energy. No resonances are observed: see discussion in (1975AJ02). See also (2012UP01).

14. ^{10}B(t, p)^{12}B $\qquad Q_{\rm m} = 6.3421$

Observed excited states are displayed in Table 12.9. Angular distributions have been studied at $E_{\rm t} = 10$ and 23 MeV: see (1980AJ01). The angular distributions are analyzed in a search for manifestation of a ^{12}B neutron or dineutron halo (2008GA09, 2009GA33). See also (2012GA20: theory).

15. ^{11}B(n, γ)^{12}B $\qquad Q_{\rm m} = 3.3698$

The thermal neutron capture cross section, $\sigma_{\rm th} = 9.09 \pm 0.10$ mb, is reported by (2016FI06). This compares with $\sigma_{\rm th} = 5.5 \pm 3.3$ mb [see (1981MUZQ, 2003MOZU); see also the value $\sigma = 9.07 \pm 0.22$ mb from (2008FIZZ)]. In (2016FI06), the thermal capture state is reported to decay to ^{12}B*(0, 953) with $I_\gamma = (70.8 \pm 0.5)\%$ and $(29.2 \pm 0.5)\%$, respectively.

The capture cross section was deduced by measuring the ^{12}B decay activity and shows resonances at $E_{\rm n} = 20.8 \pm 0.5$ keV and at 0.43, 1.03, 1.28 and 1.78 MeV, with $\Gamma_\gamma = 25 \pm 8$ meV and 0.3, 0.3, 0.2 and 0.9 eV ($\pm 50\%$): see Table 12.10 and (1968AJ02). For a summary and the ENDF projections see (2010PR07, 2012PR13). See also (1988MA1U, 2010HU11, 2012CO01, 2014DU09: astrophys.).

16. ^{11}B(n, n)^{11}B $\qquad E_{\rm b} = 3.3698$

The thermal (bound) scattering cross section is 3.9 ± 0.2 b. The scattering amplitude (bound) is $a = 6.65 \pm 0.04$ fm, σ(free) $= 4.84 \pm 0.04$ b (1983KO17). The neutron spectroscopic factor is analyzed in (2009TI11). Total cross-section measurements have been reported for $E_{\rm n} = 0.3$ to 18.0 MeV: see (1995DO36) and references in (1968AJ02, 1980AJ01, 1985AJ01). Parameters of analyzed resonances are shown in Table 12.10. See additional structures observed in (1979AU07, 1995DO36). For a summary and the ENDF projections see (2010PR07, 2012PR13). High energy results are discussed in (2001AB14: $E_{\rm n} \leq 600$ MeV) and (2011SU23). For differential cross sections see ^{11}B. Polarization measurements have been carried out at $E_{\rm n} = 75$ keV to 2.2 MeV [see references in (1980AJ01)].

Results from R-matrix analysis are displayed in Table 12.10 (1983KO03). For a discussion of the earlier work see Table 12.5 in (1980AJ01). See also (1995XI06: theory).

17. (a) ^{11}B(n, p)^{11}Be $\qquad Q_{\rm m} = -10.7269 \qquad E_{\rm b} = 3.3698$

(b) ^{11}B(n, d)^{10}Be $\qquad Q_{\rm m} = -9.0040$

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

(d) ^{11}B(n, α)^{8}Li $\qquad Q_{\rm m} = -6.6315$

The cross sections for reaction (a) have been measured for $E_{\rm n} = 14.7$ to 16.9 MeV and those for reaction (b) have been investigated for $E_{\rm n} = 12.6$ to 20.0 MeV and at 25 and 38 MeV: see (1975AJ02). Reaction (d) was measured for $E_{\rm n} = 7.6$ to 12.6 MeV (1990PA22, 1991PA26) in an effort to evaluate the inverse ^{8}Li(α, n$_0$) reaction via the detailed balance theorem; a resonance at $E_{\rm cm}$(res) $= 580$ keV with $\Gamma_{\rm cm} \approx 200$ keV is reported to dominate the cross section; however such a resonance has not been observed in other studies; see (1994MA06) and ^{12}B reaction ^{8}Li(α, n). Earlier measurements are reported at $E_{\rm n} = 14.4$ MeV (1979AN18), and at $E_{\rm n} = 12$ to 38 MeV : see (1975AJ02); no resonances were observed. For a summary and the ENDF projections see (1988MCZT).

Table 12.10: Resonances in ^{11}B(n, n)^{11}B [a]

E_n (MeV ± keV)	Γ_{cm} (keV)	^{12}B* (MeV)	l [a, e]	J^{π} [a, e]
0.0208 ± 0.5 [b, d]	$\ll 1.4$	3.3889 [f]	2	3^-
0.43 ± 10 [c, d]	37 ± 5	3.764	1	2^+
1.027 ± 11 [c, d]	9 ± 4	4.311	0	1^-
1.19 [e]	broad	4.46	0, 2	2^-
1.28 ± 20 [c, e]	130 ± 20	4.54	2	4^-
1.78 ± 20 [c, e]	60 ± 20	5.00	1	1^+
2.45 ± 20 [e]	110 ± 40	5.62	1	3^+
2.58 ± 20 [e]	55 ± 20	5.73	2	3^-
2.9 [e]	broad	6.0	0, 2	1^-
3.5 [e]	140	6.6	1	1^+
4.03 [e]	broad	7.06	0, 2	1^-
4.55	≤ 14	7.54	> 3	
4.70 [e]	45	7.68	0, 2	2^-
4.80 [e]	90	7.77	0, 2	1^-
4.93 [e, i]		(7.89)	0, 2	1^-
5.19 [e, i]		(8.13)	2	3^-
5.31 [e]	65	8.24	2	3^-
5.59 [e]	75	8.49	2	3^-
5.82 [e]		(8.70)	2	3^-
6.18 [e]	120	9.03	0, 2	1^-
6.25 [e]		(9.10)	0, 2	2^-
6.78 [e]	34 ± 5	9.578 [g]	2	3^-
7.18	100	9.95	> 0	
7.3-8.5 [h]		10.11-11.06		
7.82	65	10.54	> 2	
9.72	120	12.28	> 2	

[a] For references see Tables 12.5 in (1980AJ01) and (1968AJ02).

[b] Also observed in ^{11}B(n,γ): $\Gamma_{\gamma} = 25 \pm 8$ meV, $\Gamma_n = 3.1 \pm 0.6$ eV (1969MO10).

[c] Also observed in ^{11}B(n, γ): see (1968AJ02).

[d] See also (1983KO03).

[e] From R-matrix analysis (1983KO03). See also (1980WH01) and the earlier work displayed in (1980AJ01).

[f] ±1.6 keV (1969MO10).

[g] ±5 keV (1979AU07).

[h] A measurement using the transmission method (1995DO36) reports resonances corresponding to ^{12}B*(10115, 10181, 10304, 10383, 10525, 10563, 10640, 10939, 11017, 11060) (±35 keV). See also (1979AU07).

[i] State at $E_n = (5.01)$ previously identified with $\Gamma \approx 27$ keV (1961FO07).

18. ^{11}B(p, π^+)^{12}B $\qquad Q_m = -136.9827$

The cross section for π^+ production near threshold has been measured. At $E_p = 200$ MeV ^{12}B*(0, 0.95, 1.67, 2.62, 3.39, 3.76, 4.30 + 4.52, 5.00, 5.61) are reported: see (1985AJ01).

19. ^{11}B(d, p)^{12}B $\qquad Q_m = 1.1453$

Table 12.11: ^{12}B states from ^{11}B(d, p)^{12}B [a]

^{12}B*(MeV ± keV)	l_n	J^π	S [b]	γ-decay (%)		τ_m (fs)
0	1	1^+	0.69			
0.95314 ± 0.60	1	2^+	0.55	→ g.s. [c]		260 ± 40
1.67365 ± 0.60	0	2^-	0.57	3.2 ± 0.4	[→ 0.95]	< 50
				96.8 ± 0.4	[→ g.s.]	
2.6208 ± 1.2	0	1^-	0.75	14 ± 3	[→ 1.67]	< 70
				80 ± 3	[→ 0.95]	
				6 ± 1	[→ g.s.]	
2.723 ± 11	1	0^+	0.21	> 85	[→ g.s.]	
3.383 ± 9	2	3^-	0.58 [d]			
3.76	1	2^+				
4.301 [d]	2 [d]	1^-	[d]			
4.52	2					
10.199 [e]	$2 + 4$	$(2\text{-}6)^-$				$\Gamma = 9 \pm 3$ keV
10.564 [e]	$0 + 2 + 4$	$(2\text{-}6)^-$				$\Gamma = 11 \pm 4$ keV
10.880 [e]	$1 + 3$	$(0\text{-}3)^+$				$\Gamma = 16 \pm 6$ keV

[a] For references see Table 12.6 in (1980AJ01).

[b] (1971MO14).

[c] δ E2/M1 $= -0.08 \pm 0.06$ (1968GO17).

[d] (2010LE02): $S = 0.50$ for ^{12}B*(3.39) and $S = 0.20$ for ^{12}B*(4.30).

[e] (1994MA05).

The ^{12}B nucleus was first identified in the analysis of β-decay species produced using this reaction (1935CR02, 2012TH01). Observed proton groups and γ-rays are displayed in Table 12.11. Angular distributions of cross sections to ^{12}B$_{\text{g.s.}}$ were measured at $E_d = 76$ to 144 keV (1997YA02, 1997YA08). A study in (2010LE02) analyzed angular distributions for protons leading to ^{12}B*(0, 0.95, 1.67, 2.62, 3.39, 4.30); revised spectroscopic factors were deduced for ^{12}B*(3.39, 4.30) and a partial width of $\Gamma_n/\Gamma_\gamma = 95 \pm 5$ was obtained for ^{12}B*(3.39); implications on the ^{11}B(n, γ) astrophysical reaction rate are discussed. See also (2012CO01). At $E_d = 26.3$ MeV angular distributions of protons to ^{12}B*(10.199, 10.564, 10.880) were analyzed to find total widths and to evaluate the spin quantum numbers via DWBA analysis (1994MA05); widths of $\Gamma = 9 \pm 3$ keV, 11 ± 4 keV and 16 ± 6 keV are deduced, respectively (1994MA05).

Discussion of this reaction in (1968AJ02) justifies $J^\pi = 2^+$, 2^- and 1^- assignments for ^{12}B*(0.95, 1.67, 2.62), respectively. See Table 12.12 in (1980AJ01) for a comparison of reduced widths and spectroscopic factors of the first seven $T = 1$ states in ^{12}B and in ^{12}C. Earlier work is referenced in Table 12.13 of (1975AJ02).

The ^{11}B + n $\rightarrow$ ^{12}B*(0, 2.62, 2.73) asymptotic normalization coefficients were deduced from DWBA analysis of angular distribution measurements at $E_d = 11.8$ MeV (2001LI42, 2001LI45); analysis suggests a neutron halo structure for the two higher states. In (2003LI50) analysis of the ANCs provides a result for the direct capture component of the ^{11}B(n, γ) reaction at astrophysical energies; see also reaction ^{11}B(n, γ). In (2007GU01), the existing ^{11}B(d, p) data is analyzed to extract ANCs for ^{11}B + n $\rightarrow$ ^{12}B*(0, 0.95, 1.67); then, using charge symmetry, the ANC for ^{12}N $\rightarrow$ ^{11}C + p is deduced and used to determine the direct capture component for ^{11}C(p, γ); see also (2010TI04, 2012OK02, 2013TI05) and ^{12}N reaction ^{11}C(p, γ).

Cross sections useful for boron depth profile studies were measured at $E_d = 0.7$ to 3.4 MeV (2000EL08: $\gamma_{1,2}$), $E_d = 0.6$ to 2 MeV (2006SZ07: p_0 and p_1 + γ), $E_d = 0.9$ to 1.2 MeV (2009KO09: p_0).

20. ^{11}B(^{7}Li, ^{6}Li)^{12}B $\quad Q_m = -3.8813$

At $E(^7\text{Li}) = 34$ MeV angular distributions to ^{12}B*(0, 0.95, 1.67, 2.62 + 2.72, 3.39, 4.52, 5.61 + 5.73) are measured, and spectroscopic factors are deduced (1987CO16).

21. ^{11}B(^{9}Be, ^{8}Be)^{12}B $\quad Q_m = 1.7053$

The cross sections for ^{12}B*(0.95, 1.67) de-excitation γ-rays were measured at $E_{cm} = 1.4$ to 4.4 MeV (1984DA17, 1986CU02).

22. ^{12}Be(β^-)^{12}B $\quad Q_m = 11.7084$

Observation of 4.44 MeV γ-rays from ^{12}B$_{g.s.}$ decay to ^{12}C and β-delayed neutrons from ^{12}B* decay to ^{11}B + n provide evidence that at least two ^{12}B states are fed in ^{12}Be decay; however no detailed decay scheme has been experimentally deduced (1994KE06). Using the ^{12}Be half-life, 21.46 ± 0.05 ms (see ^{12}Be reaction 1), and assuming a $(99.50 \pm 0.03)\%$ branching ratio to the ground state (1999BE53) gives $\log ft = 3.7952 \pm 0.0017$ for that decay.

23. (a) ^{12}C(γ, π^+)^{12}B $\quad Q_\mathrm{m} = -152.9396$
(b) ^{12}C(e, eπ^+)^{12}B $\quad Q_\mathrm{m} = -152.9396$
(c) ^{12}C(γ, $\pi_0\pi^+$)^{12}B $\quad Q_\mathrm{m} = -287.9162$

For reaction (a), angular distributions for the $\Delta S = 1$, $\Delta T = 1$ spin-isospin flip excitation states at ^{12}B*(0, 0.95, 4.5, 7.5, 10, 13) were measured using tagged $E_\mathrm{brem} = 187$ MeV (1990SO06) and 191 MeV (1994CH39, 1994CH43) beams. DWIA calculations of the angular distributions are used to analyze the transition multipolarities for states up to $E_\mathrm{x} = 7.5$ MeV. Earlier work with $E_\gamma = 210$ to 381 MeV (1982AR06) measured the total cross section for π^+ emission and the spectra of the positive pions; the $E_\gamma = 381$ MeV data show the influence of quasi-free pion production and FSI processes. See also DWIA (1990ER03, 1991OD04, 1995DO24), PWIA (2007TR04), Shell Model (1991ER06) and many-body (1992CA16) analyses.

At $E_\mathrm{e} = 195$ to 205 MeV the π^+ energy distributions show contributions from ^{12}B*(0, 0.95, ≈ 4.5, 7.0): see (1986SH14, 1988SH36) and references in (1985AJ01). The 2^- and 4^- states at $E_\mathrm{x} \approx 4.5$ MeV have been compared with their isobaric analogs in ^{12}C at $E_\mathrm{x} \approx 19.5$ MeV (1980MI08). At $E_\mathrm{e} = 400$ MeV, π^+ with $E_\pi = 32$ MeV have been studied: double differential cross sections are obtained for the transitions to ^{12}B*(0, 0.95, 1.67), and single differential cross sections to ^{12}B*(0, 0.95) (1983SC03, 1983SC11); the cross section (at $\theta = 54°$) is the same whether virtual or real photons are used in producing the pions (1983SC03). At $E_\gamma = 176$ to 187 MeV the giant resonance region, as well as some lower groups, has been studied by (1987MIZZ). Nuclear transparency vs. Q^2 was studied at $E_\mathrm{e} \approx 5.8$ GeV (2007CL04, 2009KA02, 2010QI02). See also (1988SH36, 1997GI13, 2002DI04, 2016LA08).

Differential cross sections for photoproduction of two pions were analyzed for $E_\gamma = 400$ to 460 MeV using a tagged Bremsstrahlung beam (2002ME22); see theoretical analysis in (2003ME32, 2003RO20, 2003VI09, 2003VI11, 2004MU17, 2006SC18).

24. (a) ^{12}C(γ, K$^+$)^{12}B $\quad Q_\mathrm{m} = -507.0464$
(b) ^{12}C(e, e$'$K$^+$)^{12}B $\quad Q_\mathrm{m} = -507.0464$

Strangeness electro-production measurements and discussion of nuclear medium effects are given in (1994MA42, 1994MO49, 1995YA10, 1998LE23) for reaction (a) and (1992AD09, 1998HI15, 2003MI11, 2004FU34, 2006YU03, 2007IO02) for reaction (b).

25. (a) ^{12}C(ν_e, e$^+$)$\bar{\nu}$ $\quad Q_\mathrm{m} = -13.37$
(b) ^{12}C(ν_μ, μ^+)$\bar{\nu}$ $\quad Q_\mathrm{m} = -119.0278$

Theoretical analysis is given on the neutrino induced Charge Current reactions ^{12}C($\nu_{\rm e}$, e$^+$)$\bar{\nu}$ (1982MI05, 1992KO07, 1995KO40, 2002JA03, 2005BO44, 2006CO15, 2006CO16, 2011SA04, 2013SO15) and ^{12}C(ν_μ, μ^+)$\bar{\nu}$ (1982MI05, 1995KO40, 1996EN06, 1996KO03, 2002JA03, 2008IV01, 2011KI06, 2014KI06, 2014PA06, 2016PA43). See also ^{12}N reactions 9 and 10 for more discussion.

26. (a) ^{12}C(μ^-, ν)^{12}B $\quad Q_{\rm m} = 92.2890$
(b) ^{12}C(μ^-, $\nu\gamma$)^{12}B $\quad Q_{\rm m} = 92.2890$

Observations of γ-transitions have led to the determination of the capture rates to ^{12}B*(0[$J^\pi = 1^+$], 0.95[2$^+$], 1.67[2$^-$], 2.62[1$^-$]) (1981GI08, 1981RO15); see also (1972MI15). The branching ratios for a variety of nuclides populated in ^{12}C$+\mu^-_{\rm stopped}$ reactions is reported in (2016AB02). See theoretical discussions in (1998MU17, 1998SI11, 2000HA17, 2002AU01, 2002JA03, 2005AM08, 2005NI01, 2006AM06, 2006VA09).

The ratio of the polarization of ^{12}B$_{\rm g.s.}$, $P_{\rm ave}$, and of the longitudinal polarization, $P_{\rm L}$, has been determined by (1981RO05, 1981RO15, 1982RO13): this ratio leads to a neutrino helicity, $h_\nu = -1.06 \pm 0.11$ (1981RO15), in agreement with the partial conservation of axial-vector current (PCAC) hypothesis. The polarization of ^{12}B has also been directly measured by (1984KU20): $P_{\rm ave}$ is deduced to be 0.462 ± 0.053 yielding a ratio of the induced pseudoscalar to the axial vector coupling constant in the hadronic weak current, $g_{\rm p}/g_{\rm a} = 10.1^{+2.4}_{-2.6}$, which is consistent with the prediction of ≈ 7 from Parity Conserved Axial-vector Current (1984KU20). See earlier measurements of $P_{\rm ave}$ and $P_{\rm L}$ in (1974PO05, 1977PO1B, 1979TR05) and (1989KA35, 1994KO27, 2002AU01: theory).

The branching ratio for "radiative muon capture" (reaction (b)) is $R_\gamma = (2.33 \pm 0.17) \times 10^{-5}$ when compared with the dominant process of "ordinary muon capture" (reaction (a)) (1991AR02). The branching ratio for radiative capture depends on the induced pseudoscalar coupling constant, $g_{\rm p}$, and measurements on ^{12}C, ^{16}O and ^{40}Ca show strong target dependence for the g_p/g_a values deduced from radiative capture ($16.2^{+1.3}_{-0.7}$, $13.6^{+1.6}_{-1.9}$, and 4.6 ± 1.8, respectively: 1991AR02 [in this result, renormalization is not strongly advocated, but rather more consistency in the theoretical treatment of the nuclear response]). See other results in (1988DO05) and (1989NA01, 1990GM01, 1990RO04, 2000KO06: theory).

27. ^{12}C(π^-, γ)^{12}B $\quad Q_{\rm m} = 126.2008$

The photon spectrum from stopped pions is dominated by peaks corresponding to ^{12}B*(0, 4.4, 7.9) (1970BI10). Branching ratios have been obtained for these and other unresolved transitions; that to ^{12}B$_{\rm g.s.}$ is $(6.22 \pm 0.35)\%$ (absolute branching ratio per stopped pion) (1986PE05); see also

(1997AM04: theory). The branching ratio for ^{12}C(π^-, 2γ) is $(1.2 \pm 0.2) \times 10^{-5}$ (1980MA39); see also (1995GI09: theory).

28. ^{12}C(π^-, π^0)^{12}B $\qquad Q_{\rm m} = -8.7758$

At $E_\pi = 165$ MeV, excitation of the ^{12}N and ^{12}B isovector analog giant E1 resonances, built on ^{12}C$_{\rm g.s.}$, is observed (1994HA41). Transitions to the ground states of ^{12}B and ^{12}N, via ^{12}C + $\pi^\mp$, are discussed as a means to understand the difference in ft-values for ^{12}B and ^{12}N decay to ^{12}C$_{\rm g.s.}$ (1970HI10). Studies of ($\pi^\pm$, π^0) evaluate the A and isospin dependence of the cross section for the Δ-nucleus interaction in (1983AS01, 1984AS05, 1990BE41); see also (1987CL02) for a study of delta production at $E_{\pi^-} = 475$ MeV. Analysis of scaling and scaling systems is given in (2013PE24). See (1996NA04) for a measurement with stopped pions.

29. (a) ^{12}C(π^-, $2\pi^0$) $\qquad Q_{\rm m} =$
(b) ^{12}C(π^-, $\pi^+\pi^-$) $\qquad Q_{\rm m} =$
(c) ^{12}C(π^+, $2\pi^+$) $\qquad Q_{\rm m} =$

Experimental studies at $E_{\pi^+} = 283$ MeV (1996BO09, 1999BO25, 2000BO38, 2000GR28, 2005GR28), $E_{\pi^-} = 292$ MeV (1991RA08), $E_{\pi^-} = 408$ MeV/c (2000ST31) and $E_{\pi^-} = 750$ MeV/c (2003ST28) have analyzed the nuclear medium effect on the $\pi^-\pi$ system. See also (2001CA53).

30. ^{12}C(n, p)^{12}B $\qquad Q_{\rm m} = -12.5871$

At $E_{\rm n} = 59.6$ MeV (1982BR04) have determined the angular distribution of the p$_0$ group. The 0° differential cross section to ^{12}B$_{\rm g.s.}$ at $E_{\rm n} = 198$ MeV has been measured; its ratio to that for the H(n, p) reaction, R, is 0.180 ± 0.006 (1988JA01). The angular distribution of the $J^\pi = 4^-$ ^{12}B*(4.52) 1p-1h "stretched" state was studied at $E_{\rm n} = 300$ MeV (1993PO05). See (1991BR10: $E_{\rm n} = 60$ and 65 MeV) for analysis of cross sections to ^{12}B*(0, 0.95, 4.4, 7.7) and a comparison of the lowest 1^+ and 2^+ states populated in ^{12}C(n, p), (p, p) and (p, n) reactions; see also (1990MI10: $E_{\rm n} = 280$ MeV), (2000DA22: $E_{\rm n} = 98$ MeV) and measurements reported in (1975AJ02, 1980AJ01, 1990AJ01). At $E_{\rm n} = 60$ to 260 MeV, differential cross sections were analyzed for data up to $E_{\rm x} \approx 40$ MeV; results on ground state population are analyzed to determine the volume integral of the spin-isospin term of the effective N-N interaction (1992SO02),

Table 12.12: Summary of experimental work on ^{12}C(d, 2p)

$E_{\rm d}$ (MeV)	Measurement	References
55	^{12}B*(0, 0.95, 4.5[u]); $\sigma(\theta$: ^{12}B*(0, 4.5))	(1979ST15)
70	^{12}B*(0, 0.95, 4.5[u], 8.2); $\sigma(\theta)$, VAP and TAP to ^{12}B*(0, 4.5)	(1986MO27, 1988MO11)
70	σ, $A_{\rm y}$, $A_{\rm yy}$ to ^{12}B*(0, 4.5)	(1993SA09)
99.2	^{12}B*(0, 4.5)	(1982BE33)
170	$\sigma(0^\circ)$ to ^{12}B*(0, 0.95, 1.7, 2.6, 3.4, 3.8, 4.5, 5.0, 5.6, 7.5)	(2001WO07, 2002RA12, 2002RA15)
171	$\sigma(0^\circ)$ to ^{12}B*(0, 0.95, 1.7, 2.6, 3.4, 3.8, 4.5, 5.0, 5.6, 7.5, 9, 10.7)	(2007DE28, 2008WOZZ)
200	$\sigma(0^\circ)$ to ^{12}B*(0, 0.95, 1.67, 2.62, $\approx$ 4.5, $\approx$ 7.7)	(1998IN02)
260	$\sigma(\theta_{\rm lab} < 10^\circ)$ to ^{12}B*(0, 4.4, 7.7)	(1993OH01)
270	σ, $A_{\rm y}$, $A_{\rm yy}$, $A_{\rm xx}(\theta_{\rm cm} < 20^\circ)$ to ^{12}B*(0, 0.95, 2.62, 4.5, 7.5, 9.3, $\approx$ 11)	(1994OK02, 1996SA11, 2002OK02)

while the Giant Dipole strength is analyzed via DWIA analysis (1993YA11). A similar review article describing measurements at $E_{\rm n} = 98$ MeV gives additional details on the dipole and spin-dipole strength distributions (1993OL03, 1996OL01). Results from an $E_{\rm n}$ = threshold to 10 GeV white source activation experiment are given in (2014ZU03, 2016ZU01). See also (2002KL14, 2008SU21).

31. ^{12}C(d, 2p)^{12}B $\qquad\qquad Q_{\rm m} = -14.8116$

This reaction has been measured at $E_{\rm d} = 55$ to 270 MeV; see Table 12.12. The $\theta \approx 0^\circ$ cross section for population of ^{12}B$_{\rm g.s.}$ is evaluated to analyze the correlation with the Gamow-Teller matrix element for β-decay transitions (1993OH01, 2002RA12). At $E_{\vec{\rm d}} = 270$ MeV the state at $E_{\rm x} = 7.5$ MeV is dominated by $J^\pi = 2^-$ strength, while $J^\pi = 0^-$ is supported for a peak at $E_{\rm x} = 9.3$ MeV (1996SA11, 2002OK02). To resolve uncertainty of the ^{12}B*(7.7 MeV) state character, ^{12}B* states were populated using 200 MeV deuterons (1998IN02); the decay neutrons were detected in coincidence with the ^{2}He ejectiles. Analysis of the neutron angular distributions confirm the $J^\pi = 1^-$ character of ^{12}B*(7.7 MeV). Subsequent studies at $E_{\vec{\rm d}} = 170$ MeV measured the angular distributions of cross section and analyzing powers for structures up to $E_{\rm x} < 11$ MeV and analyzed the isovector spin-dipole resonance strength distribution; $J^\pi = 0^-$, 1^- and 2^- strength that was observed near $E_{\rm x} = 4.0$ and 9.3 MeV, $E_{\rm x} = 7.85$ MeV, and $E_{\rm x} = 4.5$ and 7.5 MeV, respectively. Further analysis decomposes the structures around 4.4 MeV with $E_{\rm x} = 4.21 \pm 0.01$ MeV and 4.47 ± 0.01 MeV with $\Gamma \approx 260$ and 209 keV respectively, and indicates $\Gamma \approx 330$ keV for ^{12}B*(9.3), and there is evidence for $J^\pi = 1^-$ strength at $E_{\rm x} = 10.05 \pm 0.08$ MeV with $\Gamma \approx 470$ keV (2007DE28, 2008WOZZ). See also (1992SA07, 1999OK02, 1999RU07: theory), and see proton-pair spin correlation studies in (2004HA12, 2004PO03).

32. ^{12}C(t, ^{3}He)^{12}B $\qquad\qquad Q_{\rm m} = -13.3508$

This reaction was studied at E$_t$ = 129 MeV (2006GU02, 2007GU21), E_t = 345 MeV (2006CO14, 2011PE12), $E_t = 350$ MeV (1999SH30) and $E_t = 381$ MeV (1996FU06, 1997DA28, 1998DA05) for $\theta_{\rm cm}$(^{3}He) $< 10°$. Groups are observed at ^{12}B*(0, 2.6, 4.5, 7.3) with $J^\pi = 1^+$, 1^-, 2^-, 1^-, respectively. Studies have shown a relation between the $\sigma(\theta = 0°)$ cross sections for Gamow-Teller transitions and the B(GT) value for β-decay transitions such as the ^{12}B$_{\rm g.s.}(1^+)$ to ^{12}C$_{\rm g.s.}(0^+)$ transition; notably (2011PE12) analyzed data for targets up to ^{120}Sn and found a simple relation between the unit cross sections and the target masses for G-T transitions: $\hat{\sigma}_{\rm GT} = 109/A^{0.65}$. Discussion in (1999SH30) evaluates the $J^\pi = 2^-$ spin-flip dipole resonance at $E_x = 4.45$ MeV, while (1997DA28) finds that the strength near $E_x = 7.3$ MeV can be separated into a narrower spin-flip component that is populated in (d, ^{2}He) reactions and a broader non-spin-flip component that is populated in (t, ^{3}He) reactions.

33. ^{12}C(^{7}Li, ^{7}Be)^{12}B $\qquad Q_m = -14.2313$

At $E(^7$Li$) = 82$ MeV, a study of the angular distributions for ^{12}B*(0, 0.95, 1.67, 2.62, 4.5, 5.7, 7.6) states deduced that, at this low energy, 2-step processes are dominant (2006SA28). A measurement at $E(^7$Li$) = 14$ to 26 MeV/A and $\theta = 0°$ populated states at ^{12}B*(0, 0.95, 1.67, 2.62, 3.39, 3.76, 4.30, 4.37 4.5, 5.7, (6.2), 7.6); DWBA analysis suggests the reactions proceed via 1-step processes at incident energies above 21 MeV/A (1990NA03, 1990NA24).

Using the spin selectivities of the $\Delta T = 1$ (^{7}Li, ^{7}Be$_{\rm g.s.}[J^\pi = \frac{3}{2}^-]$) and (^{7}Li, ^{7}Be*(0.42[$J^\pi = \frac{1}{2}^-$])γ) reactions the spinflip ($\Delta S = 1$) and non-spinflip ($\Delta S = 0$) components of the cross sections are analyzed at $E(^7$Li$) = 26$ MeV; the peak at ≈ 4.5 MeV is attributed to Spin Dipole Resonance (SDR) states at ^{12}B*(4.37[$J^\pi = 2^-$]) and ^{12}B*(4.52[$J^\pi = 4^-$]) while the peak at $\approx$ 7.6 MeV is attributed to a $J^\pi = 1^-$ SDR at $E_x = 7.6$ MeV with $\Gamma = 2.1$ MeV and the Giant Dipole Resonance (GDR) at $E_x = 7.8$ MeV with $\Gamma = 3.2$ MeV (1991NA12, 1991NA17, 1994NA17); see also the $E(^7$Li$) = 50$ MeV/A measurements of (1996JA08, 1999AN13). Further analysis of the $E(^7$Li$) = 26$ MeV data reveals the GDR at $E_x = 7.8$ with $\Gamma = 4.0 \pm 0.5$ MeV (^{12}C*(23.0 ± 0.5 MeV)), the Isovector Giant Monopole Resonance (IVGMR) at $E_x = 17.8 \pm 1.5$ with $\Gamma = 3.5 \pm 1.5$ MeV (^{12}C*(33 ± 1.5)) and the Isovector Giant Quadrupole Resonance at $E_x = 12.8 \pm 0.5$ MeV with $\Gamma = 3.5 \pm 0.5$ MeV (^{12}C*(28.0 ± 0.5)) (1992NA13); see also (1987NA16) who found resonances with slightly lower excitation energies. Later studies at $E(^7$Li)=65 MeV/A (1998NA14, 1998NA16, 1999NA36, 2001NA18) analyzed the $\theta = 0°$ cross sections, which are found to be proportional to the GT strengths deduced from β-decay. The reaction is found to be a good spin probe for isovector excitations. See also (1996WI05).

34. ^{1}H(^{12}Be, ^{12}B)n $\qquad Q_m = 10.9261$

Particle decay spectroscopy was used to reconstruct the excitation energies of ^{12}B $T = 2$ particle unbound states at $E_x = 12.74 \pm 0.05$ MeV ($\Gamma < 40$ keV, $J^\pi = 0^+$) and 14.82 ± 0.05 MeV

($\Gamma < 100$ keV, $J^{\pi} = 2^{+}$) (2008CH28). Discussion suggests that the ^{12}B*(12.74) state observed here in the $\alpha + {}^{8}$Li breakup channel is a different state than the one observed in ^{9}Be(^{7}Li, α) (1975AJ03). The ^{12}B*(14.82) state is observed to have breakup cross sections of $\sigma = 522 \pm 150$, 190 ± 57 and 59 ± 17 μb into the p + ^{11}Be, $\alpha + {}^{8}$Li and ^{3}H + ^{9}Be decay channels, respectively.

35. ^{12}C(^{12}C, ^{12}N)^{12}B $\qquad Q_{\rm m} = -30.7075$

This reaction has been studied at energies between 30 and 900 MeV/A, see (1999BO26: $E = 357$ MeV), (1991AN12: 70 MeV/A), (1994IC01, 1994IC03, 1995IC01: $E = 135$ MeV/A) and references in (1990AJ01). At $E(^{12}\mathrm{C}) = 357$ MeV states are populated at ^{12}B*(0, 0.95, 1.67, 2.62, 3.39, 4.46[u], 4.52[u], 5.6, 7.4, 8.14, 10.5, 13.4).

Forward-angle differential cross sections have been measured for the groups to ^{12}B*(0, 0.95, 1.67, 4.5[u]); a broad peak near $E_{\rm x} = 7.8$ MeV is also populated. The unresolved groups near $E_{\rm x} \approx 4.5$ MeV dominate the spectra, see (1986WI05: 35 MeV/A) and (1999BO26: 30 MeV/A). At $E(^{12}\mathrm{C}) = 70$ MeV/A the $J^{\pi} = 0^{+} \rightarrow 1^{+}$ cross sections, at small angles, were analyzed to determine the correlation between $\theta \approx 0°$ cross section and B(GT) strength (1991AN12); a slight A dependence was observed. At $E(^{12}\mathrm{C}) = 135$ MeV/A the angular distribution for the GT transition to the ^{12}B ground state was analyzed and found to still be dominated by $L = 0$ components (1994IC01), subsequent analysis of transitions to the $E_{\rm x} = 4.5$ and 7.5 MeV states (1994IC03, 1995IC01) indicate the $J^{\pi} = 2^{-}$ and 4^{-} strength for the states near ^{12}B*(4.5) and a dominant $J^{\pi} = 2^{-}$ strength at the ^{12}B*(7.5) Spin Dipole Resonance with some additional $J^{\pi} = 0^{-}$ and 1^{-} strength. See theoretical analysis of the ^{12}B*(0, 0.95) angular distributions in (1999MA18), and see comments on the excitation of the Δ-resonance in (1986BA16, 1988RO1H, 1988RO17: and references therein).

36. ^{12}C(^{13}C, ^{13}N)^{12}B $\qquad Q_{\rm m} = -15.5899$

At $E(^{13}\mathrm{C}) = 29.2$ MeV/A and $\theta \leq 2°$ states at ^{12}B*(0, 0.95, 1.67, 2.62, 3.39, 4.46, 7.77) are populated (1988VO06, 1999BO26). The $E(^{13}\mathrm{C}) = 30$ MeV/A differential cross sections at $\theta = 1.8°$ are evaluated for the groups to ^{12}B*(0, 0.95, 4.5[u]) and to structures at $E_{\rm x} \approx 5.5$, 7.8, 10.1 and 18.2 MeV (1987AD07); See also (1986VO02, 1988VO08). At $E(^{13}\mathrm{C}) = 50$ MeV/A forward-angle differential cross sections have been measured for $\theta < 10°$ for ^{12}B*(0, 0.95, 7.7) (1989BE50, 1993BE19); the GDR peak is located at 7.7 ± 0.1 MeV with $\Gamma_{\rm cm} = 1.9 \pm 0.1$ MeV. The spin transfer selectivity of the $J^{\pi} = \frac{1}{2}^{-} \rightarrow \frac{1}{2}^{-}$ ($\Delta S = 0, 1$, $\Delta T = 1$) ^{12}C(^{13}C, ^{13}N) reaction and the $J^{\pi} = 0^{+} \rightarrow 1^{+}$ ($\Delta S = \Delta T = 1$) ^{12}C(^{12}C, ^{12}N) reaction are compared in (1999BO26, 1995IC01); exploiting these two reactions permits the determination of the spin-flip and non-spin-flip isovector excitations. The spin selectivity appears to identify the $E_{\rm x} \approx 7.5$ MeV peak observed in the ^{12}C(^{12}C, ^{12}N) as the Spin Dipole Resonance, while the $E_{\rm x} \approx 8$ MeV peak observed in the ^{12}C(^{13}C, ^{13}N) reaction is identified as the GDR (1995IC01). See also (1999MA18: theory).

37. ^{13}C(γ, p)^{12}B $\quad Q_{\rm m} = -17.5334$

The isospin components of the ^{13}C GDR are deduced in (1993MC02) by analyzing the ^{13}C(γ, p)^{12}B*(0, 0.95) data of (1975PA09, 1983ZU02) and the photo-neutron cross section data of (1975PA09, 1977WO04, 1979JU01).

38. ^{13}C(d, ^{3}He)^{12}B $\quad Q_{\rm m} = -12.0399$

Angular distributions have been measured for the transitions to ^{12}B*(0, 0.95) at $E_{\rm d} = 24.1$ to 29 and at 52 MeV; see references in (1980AJ01). Analysis of the ^{12}B*(2.72, 3.76, 5.00) states at $E_{\rm d} = 52$ MeV lead to $C^2S = 1.09$ [assuming 1p$_{3/2}$], 2.17, 0.14, 0.07, 0.22 [assuming 1p$_{1/2}$] for ^{12}B*(0, 0.95, 2.72, 3.76, 5.00): see (1975MA41). The spectroscopic factors for ^{12}B*(0, 0.95) are $S = 1.1 \pm 0.2$ and 2.0 ± 0.5 (1977LI02). For a summary of information on analog states of ^{12}B and ^{12}C see Table 12.12 in (1980AJ01).

39. ^{14}C(p, ^{3}He)^{12}B $\quad Q_{\rm m} = -17.9918$

At $E_{\rm p} = 54$ MeV, in addition to transitions to ^{12}B*(0, 0.95, 5.61), the population of $T = 2$ states at $E_{\rm x} = 12.72 \pm 0.07$ and 14.82 ± 0.10 MeV is reported. The angular distribution of ^{3}He ions to ^{12}B*(12.75) is fitted by $L = 0$; that to ^{12}B*(14.82) is rather featureless [its $T = 2$ character is assigned from the energies of the analog states]: both states have $\Gamma_{\rm cm} \lesssim 200$ keV (1976AS01).

^{12}C

(Table 12.13, Fig. 3)

Isotopic abundance: $(98.93 \pm 0.08)\%$.
$< r^2_{\text{charge}} >^{1/2} = 2.4829 \pm 0.0019$ fm (1984RU12: charge radius). See also reaction 40.
$< r^2_{\text{matter}} >^{1/2} \approx 2.35 - 2.48$ fm; i.e., see (1985TA18, 2001OZ04, 2011AL23, 2016KA37).
^{12}C*(4.44): $Q = 6 \pm 3\ e \cdot \text{fm}^2$, indicating a substantial oblate deformation (1983VE01).
$g_J(^{12}\text{C}^{5+})$[electronic g-factor] $= 2.0010415963\ (10)_{\text{exp}}\ (44) m_{\text{e}}$ (2002BE82).

1. ^{6}Li(^{6}Li, γ)^{12}C $\quad Q_{\text{m}} = 28.1738$

The γ_{0-3} excitation functions from the $^6\text{Li} + {}^6\text{Li}$ capture reaction were measured for $E_{\text{cm}} = 1$ to 8 MeV (1991EU01). Evidence is found for a state at $E_{\text{x}} = 30.33$ MeV with $\Gamma \approx 0.8$ MeV. A comparison with other data, mainly from other $^6\text{Li} + {}^6\text{Li}$ decay channels and ^{9}He(^{3}He, γ) suggests the resonance results from a concentration of $J^\pi; T = 2^+; 0$ and $2^-; 1$ strength.

2. (a) ^{6}Li(^{6}Li, n)^{11}C $\quad Q_{\text{m}} = 9.4521 \quad E_{\text{b}} = 28.1738$
(b) ^{6}Li(^{6}Li, p)^{11}B $\quad Q_{\text{m}} = 12.2169$
(c) ^{6}Li(^{6}Li, d)^{10}B $\quad Q_{\text{m}} = 2.9873$
(d) ^{6}Li(^{6}Li, α)^{8}Be $\quad Q_{\text{m}} = 20.8072$
(e) ^{6}Li (^{6}Li, 2α)^{4}He $\quad Q_{\text{m}} = 20.8990$
(f) ^{6}Li (^{6}Li, 2d)^{4}He^{4}He $\quad Q_{\text{m}} = -2.9475$
(g) ^{6}Li(^{6}Li, ^{6}Li)^{6}Li $\quad E_{\text{b}} = 28.1738$

The excitation functions for some final states in ^{11}B and ^{11}C (reactions (a) and (b)) are structureless while others (to states with $J^\pi = \frac{3}{2}^-, \frac{5}{2}^-, \frac{5}{2}^+$) exhibit pronounced structures. The most prominent of these is observed at $E(^6\text{Li}) = 8.4$ MeV [^{12}C*(32.4)] in the p_2 and n_2 yields with a width $\Gamma_{\text{cm}} \approx 1$ MeV (1987DO05). Reaction (d) has been studied in kinematically complete experiments at $E(^6\text{Li}) = 2.4$ to 6.7 MeV (1988LA11) and at $E(^6\text{Li}) = 2.5$ and 3.1 MeV (2015SP01, 2015TU06). See also (1984LA19, 1987LA25). For reactions (e) and (f) see (1983WA09). Broad structures have been observed in the elastic scattering at $E(^6\text{Li}) \approx 13$ and 26 MeV: see (1980AJ01). See also (1990AJ01).

3. ^{8}Be(α, γ)^{12}C $\quad Q_{\text{m}} = 7.3666$

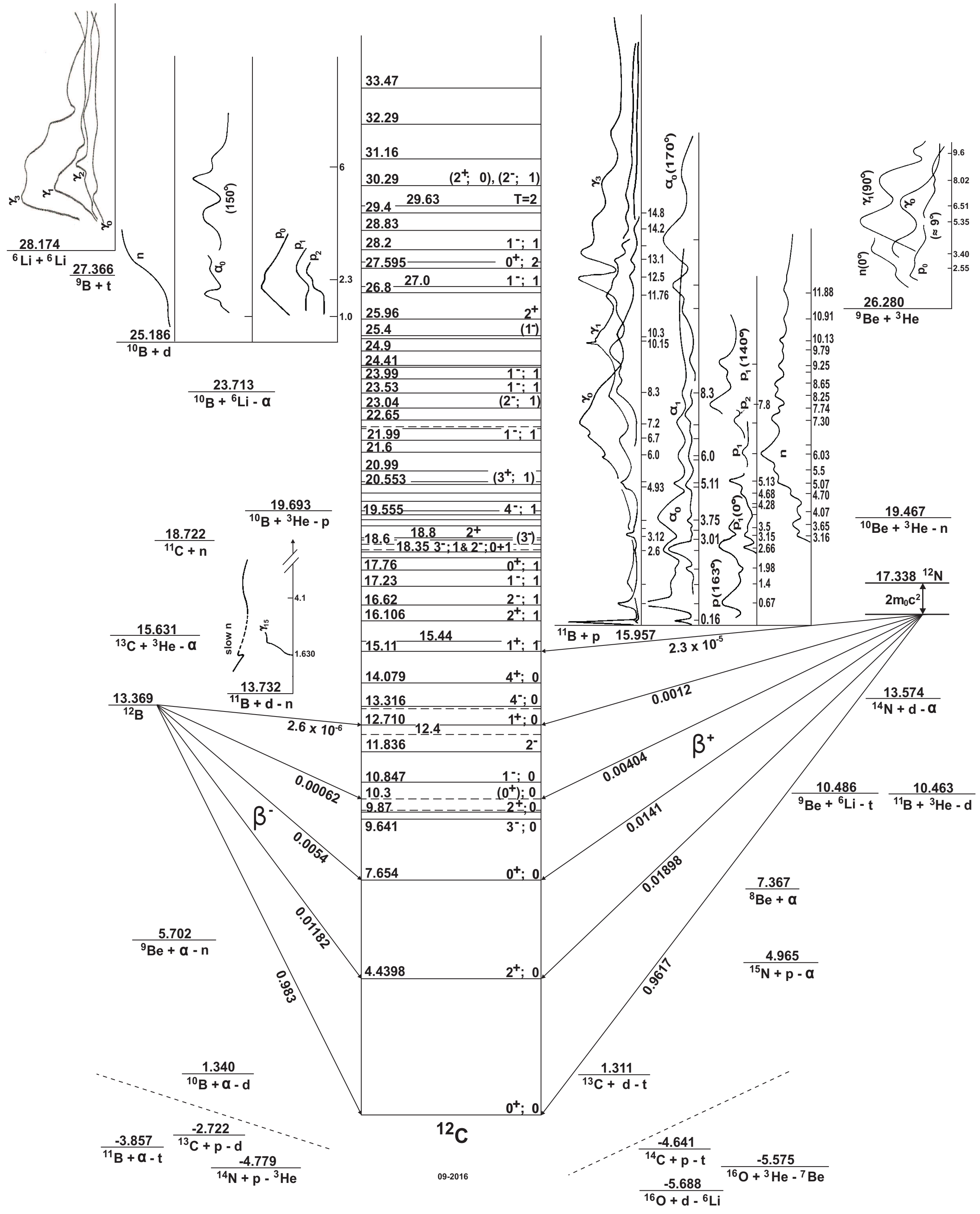


Fig. 3: Energy levels of ^{12}C. For notation see Fig. 2.

This reaction and the Hoyle state ^{12}C*(7.65) resonance state are of great importance to nucleosynthesis and the formation of heavy elements; see (1985CA41, 1987DE13, 1998TH07, 2000FI14, 2001CS04, 2010OGZX, 2010UM01, 2013EP01, 2013NG01, 2015FI03, 2016ME03, 2016SU25). In (2010UM01), non-resonant capture to a linear configuration that transitions to a triangular orientation is suggested. Production rate sensitivities to stellar environment variables are investigated in (2010DE18, 2011AU01), and the impact of time variation of the fundamental constants is studied in (2012CO19). Also see a prediction for the $J^\pi = 0_3^+$ state at $E_{\rm res} = 1.66$ MeV in (2010KAZK).

Table 12.13: Energy levels of ^{12}C [a]

$E_{\rm x}$ in ^{12}C (MeV ± keV)	J^π ; T	$\Gamma_{\rm cm}$ (keV)	Decay	Reactions
g.s.	0^+; 0	-	stable	4, 6, 7, 8, 10, 16, 17, 18, 19, 20, 24, 25, 26, 27, 28, 29, 30, 32, 34, 35, 39, 40, 43, 44, 45, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 103, 104, 105, 106, 107, 108
4.43982 ± 0.21	2^+; 0	10.8 ± 0.6 meV	γ	1, 4, 6, 7, 8, 10, 16, 17, 18, 19, 20, 24, 25, 26, 27, 28, 29, 30, 32, 39, 40, 43, 44, 45, 47, 49, 50, 51, 52, 56, 58, 60, 61, 64, 66, 68, 69, 70, 71, 72, 76, 77, 78, 79, 80, 81, 82, 83, 84, 87, 88, 89, 90, 91, 92, 93, 95, 96, 97, 98, 99, 101, 102, 103, 104

Table 12.13: Energy levels of ^{12}C [a] (continued)

E_x in ^{12}C (MeV ± keV)	J^π ; T	Γ_{cm} (keV)	Decay	Reactions
7.65407 ± 0.19 [g]	$0^+; 0$	9.3 ± 0.9 eV	π, γ, α	1, 4, 6, 7, 8, 9, 10, 16, 18, 20, 25, 26, 27, 29, 32, 40, 43, 44, 45, 47, 49, 50, 52, 56, 58, 60, 64, 76, 80, 81, 82, 83, 84, 87, 88, 90, 92, 97, 98, 99
9.641 ± 5	$3^-; 0$	46 ± 3 [b]	γ, α	1, 4, 6, 7, 8, 9, 16, 18, 20, 24, 25, 26, 27, 29, 30, 39, 40, 43, 44, 45, 47, 49, 50, 52, 56, 58, 60, 64, 66, 80, 81, 83, 84, 88, 90, 97, 98, 99
9.870 ± 60	$2^+; 0$	850 ± 85	γ, α	38, 45, 50
(9.930 ± 30) [h]	0^+	2710 ± 80		(32), 50, (76)
(10.3 ± 300) [q]	$(0^+); 0$	3000 ± 700	α	6, 32, 38, 44, 47, 52, 58, 60, 76, 81
10.847 ± 4	$1^-; 0$	273 ± 5 [c]	α	6, 7, 16, 20, 24, 25, 27, 40, 43, 45, 47, 49, 50, 52, 58, 60, 64, 66, 83, 90
11.836 ± 4	2^-	230 ± 8 [c]	γ, α	6, 7, 16, 18, 24, 25, 27, 39, 40, 44, 45, 47, 50, 58, 64, 83, 90
(12.4)	$(5^+, 4^-, 6^-, 7^+)$	broad	α	16
12.710 ± 6	$1^+; 0$	18.1 ± 2.8 eV	γ, α	6, 7, 16, 17, 18, 20, 24, 25, 26, 27, 32, 39, 40, 43, 44, 45, 46, 47, 49, 50, 58, 64, 76, 79, 80, 81, 82, 83, 84, 88, 89, 90
(13.3 ± 200)	$4^+; 0$	1700 ± 200		6, 50
13.316 ± 20	$4^-; 0$	360 ± 43 [d]	γ, α	8, 16, 25, 39, 44, 45, 58, 60, 64, 83, 90

Table 12.13: Energy levels of ^{12}C [a] (continued)

E_x in ^{12}C (MeV ± keV)	J^π ; T	Γ_{cm} (keV)	Decay	Reactions
14.079 ± 5	4^+; 0	272 ± 6 [e]	α	6, 7, 8, 16, 40, 43, 44, 45, 46, 47, 49, 50, 58, 60, 64, 66, 80, 81, 88, 89, 90, 92, 96, 97, 99
15.110 ± 3	1^+; 1	$(43.6 \pm 1) \times 10^{-3}$	γ, α	11, 16, 17, 18, 20, 24, 25, 27, 29, 39, 40, 43, 44, 45, 47, 49, 76, 78, 79, 80, 81, 82, 83, 88, 89, 90
15.44 ± 40 [f]	(2^+; 0)	1770 ± 200 [e]		40, 43, 45, 47, 49, 50, 81
16.1060 ± 0.8	2^+; 1	5.3 ± 0.2	γ, p, α	10, 16, 20, 24, 25, 27, 39, 40, 43, 44, 45, 47, 49, 78, 80, 81, 82, 83, 88, 89, 90, 92
16.62 ± 50	2^-; 1	280 ± 28	γ, p, α	16, 20, 22, 24, 40, 45, 49, 81
17.23	1^-; 1	1150	γ, p, α	20, 22, 24, 39, 49
17.76 ± 20 [i]	0^+; 1	96 ± 5	p, α	10, 20, 22, 40, 81, 88, 92
18.16 ± 70	(1^+; 0)	240 ± 50	γ, p	20, 81
18.35 ± 50 [j]	3^-; 1	220 ± 50	γ, p, α	20, 22, 24, 25, 27, 39, 60
18.35 ± 50 [j]	2^-; $0 + 1$	350 ± 50	p	21, 22, 24, 25, 27, 39, 40, 43, 45, 46, 47, 49, 50, 60
(18.39)	0^-; (1)	43	p	22
(18.6 ± 100)	(3^-)	$\Gamma_{\mathrm{calc}} = 300$		40
18.71	($T = 1$)	100	p, α	20
18.80 ± 40	2^+	100 ± 15	γ, n, p	20, 21, 22, 49, 81, 88
19.2 ± 600	(1^-; 1)	≈ 1100	γ, n, p, α	20, 21, 22, 25, 46, 80
19.40 ± 25	2^-; 1	490 ± 30	γ, p, α	20, (21), 22, 40, 43, 45, 46, 90

Table 12.13: Energy levels of ^{12}C [a] (continued)

E_x in ^{12}C (MeV ± keV)	J^π ; T	Γ_{cm} (keV)	Decay	Reactions
19.555 ± 25	4^-; 1	485 ± 40	γ, p, α	24, 25, 40, 43, 49, 90
19.69	1^+	230 ± 35	n, p	21, 22, 43, 46, 49, 50
20.0 ± 100	2^+	375 ± 100	γ, n, p	21, 22, 40, 81
20.27 ± 50	(1^+; 1)	215 ± 45 [e]	n, p	(20), 21, 22, 45, 46, 81
20.553 ± 5	(3^+; 1)	300 ± 50	γ, p, α	16, 20, 39, 40, 80, 81, 90
20.60 ± 30	(3^-; 1)	280 ± 75 [k]	γ, n, p, α	20, 21, 22, 24, 25, 45, 46, 47, 80, 81, 90
20.99		≈ 370	n, p	21
21.60 ± 100 [l]	(2^+, 3^-); 0	1200 ± 150	γ, n, p, α	20, 21, 22, 40, 41, 45, 46, 49, 50, 66, 81
21.99 ± 50	1^-; 1	610 ± 110 [e]	γ, n, p	20, 21, 22, 40, 45, 46, 47
22.37 ± 50	(1^-; 1)	290 ± 40	n, p	21, 22, 25, 45, 50, 81, 90
(22.40 ± 200)	(5^-); 1		α	50
22.65 ± 100 [m]	1^-; 1	3200	γ, n, p, α	20, 21, 34, 35, 39, 40, 43, 45, 46, 80
23.04	(2^-; 1)	60	n, p	(20), 21, 80
23.53 ± 30	1^-; 1	238 ± 24	γ, n, p, α	10, 20, 21, 40, 45, 49, 80
23.99 ± 50 [e]	1^-; 1	570 ± 120 [e]	γ, n, p	21, 38, 40, 45, 46, 47, 50, 80
24.38 ± 50	2^+; 0	671 ± 67	n, p	21, 46
24.41 ± 150		1300 ± 300 [n]	γ, n, p	20, 21
24.90 ± 200		920	n, p	(20), 21, 40, 47
25.3 ± 150	(1^-; 1)	510 ± 100	n, p	21, 45, 80
25.40 ± 100 [o]	(1^-)	2 MeV	γ, n, p	13, 20, 34, 35, 40, 49, 50, 66, 80, 81
25.96	2^+	710	n, p, d, α	13, 14, 15, 21, 45, 49
26.80		275	n, p, d, α	14, 15, 20, 21
27.00 ± 300	(1^-; 1)	1400 ± 200	γ, p	13, 20, (38), 45, 47, 50

Table 12.13: Energy levels of ^{12}C [a] (continued)

E_x in ^{12}C (MeV ± keV)	J^π ; T	Γ_{cm} (keV)	Decay	Reactions
27.595 ± 2.4	0^+; 2	≤ 30	p, d, α	10, 88
27.8 ± 200		≈ 350	γ, n, p, ^{3}He	5, 20, 40
28.2	1^-; 1	1600	γ, ^{3}He	4
28.83 ± 40		1540 ± 90 [p]	γ, p, d, ^{3}He, α	4, 15, 20, 49, 50
29.4 ± 300	$(2^+; 1)$	≈ 800	γ, n, p, t, ^{3}He	4, 20, 38, 39, 45
29.63 ± 50	$T = 2$	≤ 200		88
30.29 ± 30	$(2^+; 0)$, $(2^-; 1)$	1540 ± 90	γ, ^{3}He, α	1, 4, 40
31.16 ± 30		2100 ± 150	γ, ^{3}He	4
32.29 ± 40		1320 ± 230	γ, n, p, ^{3}He, ^{6}Li	2, 4, 40
33.47 ± 210		1930 ± 50	γ, ^{3}He	4

[a] See also Table 12.14.

[b] Weighted average of (1956DO41, 1962BR10, 2012AL22, 2013KO14) with external errors.

[c] Average of Γ_{lab} values from (1961HI08, 1971RE03) and Γ_{cm} values from (1962BR10, 2012AL22).

[d] Average of Γ_{lab} value from (1971RE03) and Γ_{cm} values from (1962BR10, 1966WA16). See also $\Gamma = 550 \pm 80$ (1961HI08).

[e] Weighted average with external errors.

[f] Mainly from (1983DE53); see also 15380 ± 50 from (1997TE14).

[g] See (1976NO02).

[h] Support for a group at $E_x = 9.93$ MeV is found separately in the ^{12}C(α, α') works of (2003JO07) and (2011IT08). In (2011IT08) the group is suggested as a 0_3^+ and 0_4^+ doublet with $E_x = 9.04 \pm 0.09$ MeV and $\Gamma = 1.45 \pm 0.18$ MeV and $E_x = 10.56 \pm 0.06$ MeV and $\Gamma = 1.42 \pm 0.08$ MeV, respectively. Additional support for strength in this region is found in the R-matrix analysis of ^{12}B and ^{12}N β-decay data, (2010HY01) report evidence for $J^\pi = 2^+$ and 0^+ states at $E_x = 11.1 \pm 0.3$ and 11.2 ± 0.3 MeV, respectively. Differences in assumptions and analysis techniques may suggest the $J^\pi = 0^+$ state seen in (2010HY01) could be the same as the one in (2011IT08). In the present evaluation, the higher precision $E_x = 9.93 \pm 0.03$ is accepted. See discussion in reaction 50.

[i] See also values in reaction ^{11}B(p, p).

[j] At least two levels are present at $E_x = 18.35$ MeV. In (1983NE11), the discussion describes an interpretation with two similar width states having $J^\pi = 2^-$ and 3^-. At present, Γ for the 3^- state is taken from (1971RE03) while Γ of the 2^- state is taken from (1983NE11). However, $J^\pi = (2^+)$ has been reported in (1977BU19, 1987KI16).

[k] From method of best representation averaging technique (2014BI13).

[l] Possible unresolved states with $\Gamma = 1450$ and $\Gamma = 450$ keV.

[m] The GDR: In ^{12}C(γ, p) the resonance appears around 22.5 MeV with $\Gamma \approx 3.2$ MeV; in ^{12}C(γ, n) the resonance is fragmented into two peaks at 22.3 MeV and 23.3 MeV with $\Gamma \approx 1$ MeV and 2 MeV, respectively.

[n] $(2J+1)\Gamma_{p_0}\Gamma_\gamma/\Gamma = 20.8 \pm 2.8$.

[o] (2005RU16) suggest this Giant Dipole Resonance is fragmented into three components at 25.50, 25.69 and 26.53 MeV with $\Gamma = 0.37$, 0.37 and 1.24 MeV, respectively.

[p] $(2J+1)\Gamma_{p_0}\Gamma_\gamma/\Gamma = 150 \pm 18$ eV.

[q] The R-matrix analysis of (2010HY01) indicates the origin of the 10.3 MeV group is related to interference between the $J^\pi = 0^+$ state at $E_x = 7.65$ and higher-lying strength near 11 MeV that, "gives the very broad component from 8.5 to 11 MeV, which has been mistaken for a 10.3-MeV resonance with a 3-MeV width". We continue to list this state because of the value of the historic record of reports and studies of the $E_x = 10.3$ MeV group, and because of still unresolved questions on the $J^\pi = 0^+$ (and 2^+) strength in the $E_x = 9$-13 MeV region. However, future studies may provide different and more complete interpretation of this region. See discussion in reactions 32, 50, 76.

Table 12.14: The decay of some ^{12}C levels [a]

E_x (MeV)	Widths
4.44	$\Gamma_\gamma = 10.8 \pm 0.6$ meV
7.65	$\Gamma_\pi/\Gamma = (6.7 \pm 0.6) \times 10^{-6}$ [j]
	$\Gamma_{E0} = \Gamma_\pi = (62.3 \pm 2.0)$ μeV [k]
	$\Gamma = \Gamma_\pi \times \Gamma/\Gamma_\pi = 9.3 \pm 0.9$ eV
	Γ_{rad}/Γ [b] $= (4.16 \pm 0.11) \times 10^{-4}$ [l]
	$\Gamma_{rad} = \Gamma_{rad}/\Gamma \times \Gamma = 3.87 \pm 0.39$ meV
	$\Gamma_{E2} = \Gamma_\gamma = \Gamma_{rad} - \Gamma_\pi = 3.81 \pm 0.39$ meV
9.64	$\Gamma_{rad}/\Gamma < 4.1 \times 10^{-7}$ [n]
	$\Gamma_{rad} < 19$ meV [h,n]
	$\Gamma_{\gamma 0} = (3.1 \pm 0.4) \times 10^{-4}$ eV [m]
9.87	$\Gamma_\gamma = 60 \pm 10$ meV [o]
12.71	$\Gamma_{\gamma 0} = 0.35 \pm 0.05$ eV [q]
	$\Gamma_{\gamma 0}/\Gamma = (1.93 \pm 0.12) \times 10^{-2}$ [p]
	$\Gamma_{\gamma 1}/\Gamma_{\gamma 0} = 0.150 \pm 0.018$ [c]
	$\Gamma_{\gamma 1} = 0.053 \pm 0.010$ eV [h,p,q]
	$\Gamma = 18.1 \pm 2.8$ eV [h,p]
	$\Gamma_\alpha/\Gamma = 0.978 \pm 0.001$ [d,h,p]
	$\Gamma_\alpha = 17.7 \pm 2.8$ eV [d,h,p]
15.11	$\Gamma_{\gamma 0} = 38.5 \pm 0.8$ eV [g]
	$\Gamma_{\gamma 1} = 0.96 \pm 0.13$ eV [e,h]
	$\Gamma_\gamma(15.11 \rightarrow 7.65) = 1.09 \pm 0.3$ eV [e,h]

Table 12.14: The decay of some ^{12}C levels [a] (continued)

E_x (MeV)	Widths
	$\Gamma_\gamma(15.11 \rightarrow 10.3) = 1.60 \pm 0.67$ eV [h]
	$\Gamma_\gamma(15.11 \rightarrow 12.71) = 0.59 \pm 0.17$ eV [e,h]
	$\Gamma_\gamma = 41.8 \pm 1.1$ eV [e,h]
	$\Gamma_\alpha/\Gamma = \Gamma_{\alpha_1}/\Gamma = 0.041 \pm 0.009$ [i]
	$\Gamma_\gamma/\Gamma = 0.959 \pm 0.009$ [i,r]
	$\Gamma_\alpha = 1.79 \pm 0.39$ eV [h,i]
	$\Gamma = 43.6 \pm 1.0$ eV [h]
16.11 [f]	$\Gamma = 5.3 \pm 0.2$ keV
	$\Gamma_{\gamma_0}/\Gamma_{\gamma_1} = (4.6 \pm 0.7)\%$ [p]
	$\Gamma_{\gamma_1}/\Gamma = (2.42 \pm 0.29) \times 10^{-3}$ [p]
	$\Gamma_\gamma(16.11 \rightarrow 9.64)/\Gamma_{\gamma_1} = (2.4 \pm 0.4)\%$ [p]
	$\Gamma_\gamma(16.11 \rightarrow 12.71)/\Gamma_{\gamma_1} = (1.46 \pm 0.25)\%$ [p]
	$\Gamma_{\gamma_0} = 0.59 \pm 0.11$ eV [h,‡]
	$\Gamma_{\gamma_1} = 12.8 \pm 1.5$ eV [h,§]
	$\Gamma_\gamma(16.11 \rightarrow 9.64) = 0.31 \pm 0.06$ eV [h]
	$\Gamma_\gamma(16.11 \rightarrow 10.8) = 0.48 \pm 0.12$ eV [†]
	$\Gamma_\gamma(16.11 \rightarrow 12.71) = 0.19 \pm 0.04$ eV [h]
	$\Gamma_\gamma = 14.4 \pm 1.7$ eV [h]
	$\Gamma_\mathrm{p} = 21.5 \pm 3.3$ eV [¶]
	$\Gamma_{\alpha_0}/\Gamma_{\alpha_1} = 0.051 \pm 0.005$ [£]
	$\Gamma_{\alpha_0} = 0.26 \pm 0.03$ eV [h]
	$\Gamma_{\alpha_1} = 5.0 \pm 0.2$ eV [h]
16.62 [w,x]	$\Gamma_{\mathrm{p}0}/\Gamma = 0.5$
	$\Gamma_{\alpha_1}/\Gamma = 0.5$
	$\Gamma_{\gamma_0} = (48 \pm 8) \times 10^{-3}$ eV
	$\Gamma_{\gamma_1} = 8.0$ eV
17.23 [s,y]	$\Gamma_{\mathrm{p}0}/\Gamma = 0.87$
	$\Gamma_{\alpha_0}/\Gamma = 0.0087$
	$\Gamma_{\alpha_1}/\Gamma = 0.122$
	$\Gamma_{\gamma_0} = 44$ eV
	$\Gamma_{\gamma_1} = 5$ eV

Table 12.14: The decay of some ^{12}C levels [a] (continued)

E_x (MeV)	Widths
17.76 [w]	$\Gamma_{\mathrm{p}_0}/\Gamma = 0.82$
	$\Gamma_{\alpha_0}/\Gamma = 0.05$
	$\Gamma_{\alpha_1}/\Gamma = 0.124$
	$\Gamma_\gamma = 3.7 \pm 1.5$ eV [t]
18.16	$(2J+1)\Gamma_{\gamma_{15.1}} \geq 2.8 \pm 0.6$ eV
18.35 [w,z]	$\Gamma_{\mathrm{p}_0}/\Gamma = 0.22$
	$\Gamma_{\alpha_0}/\Gamma = 0.21$
	$\Gamma_{\alpha_1}/\Gamma = 0.57$
	$\Gamma_{\gamma_1} = 3.2$ eV
	$\Gamma_{\gamma_{9.61}} = 5.7 \pm 2.3$ eV
18.4 [w]	$\Gamma_{\mathrm{p}_0}/\Gamma = 0.79$
	$\Gamma_{\mathrm{p}_1}/\Gamma = 0.21$
18.80 [w]	$\Gamma_{\mathrm{p}_0}/\Gamma = 0.97$
	$\Gamma_{\mathrm{p}_1}/\Gamma = 0.02$
	$\Gamma_\mathrm{n}/\Gamma = 0.011$
	$\Gamma_{\gamma_0} = (0.4)$ eV
	$\Gamma_{\gamma_1} = 2$ eV
19.2 [w]	$\Gamma_{\mathrm{p}_0}/\Gamma = 0.27$
	$\Gamma_{\mathrm{p}_1}/\Gamma = 0.36$
	$\Gamma_\mathrm{n}/\Gamma = 0.14$
	$\Gamma_{\alpha_0}/\Gamma = 0.05$
	$\Gamma_{\alpha_1}/\Gamma = 0.18$
	$\Gamma_{\gamma_0} = 25$ eV
	$\Gamma_{\gamma_1} = 10$ eV
19.4 [w]	$\Gamma_{\mathrm{p}_0}/\Gamma = 0.41$
	$\Gamma_{\mathrm{p}_1}/\Gamma = 0.05$
	$\Gamma_\mathrm{n}/\Gamma = 0.09$
	$\Gamma_{\alpha_0}/\Gamma = 0.02$
	$\Gamma_{\alpha_1}/\Gamma = 0.41$
	$\Gamma_{\gamma_1} = 3$ eV
27.595 [u]	$\Gamma_{\alpha_0}/\Gamma = 0.105 \pm 0.030$

Table 12.14: The decay of some ^{12}C levels [a] (continued)

E_x (MeV)	Widths
	$\Gamma_{\alpha+^8\text{Be}^*}/\Gamma = 0.091 \pm 0.035$
	$\Gamma_{p_0}/\Gamma = 0.030 \pm 0.022$
	$\Gamma_{p_1}/\Gamma = 0.080 \pm 0.023$
	$\Gamma_{p_2}/\Gamma = 0 \pm 0.033$
	$\Gamma_{p_3}/\Gamma = 0.084 \pm 0.032$
	$\Gamma_{p_{4+5}}/\Gamma = 0.08 \pm 0.05$
	$\Gamma_d/\Gamma = 0.028 \pm 0.020$
28.20	$\Gamma \approx \Gamma_{^3\text{He}}$
	$\Gamma_{\gamma_0} \geq 11.8$ eV
	$\Gamma_{\gamma_1} \geq 4.6$ eV
	$\Gamma_{\gamma_2} \geq 11.3$ eV
29.63 [v]	$\Gamma_p/\Gamma = 0.8 \pm 0.2$
	$\Gamma_{p_0}/\Gamma \approx 0.4$
	$\Gamma_\alpha/\Gamma \approx 0.2$

[a] For references see Table 12.8 in (1980AJ01). See also Tables 12.15, 12.19, 12.20 and 12.26 here.

[b] $\Gamma_{\text{rad}} \equiv \Gamma_\gamma + \Gamma_\pi(e^+ + e^-)$.

[c] The branching ratios for the 12.71 → 4.44 and 12.71 → 0 transitions are $(13.0 \pm 1.4)\%$ and $(87.0 \pm 1.4)\%$ respectively (1977AD02). See earlier reported values in Table 12.9 of (1975AJ02).

[d] Assuming $\Gamma_\alpha + \Gamma_{\gamma_0} + \Gamma_{\gamma_1} = \Gamma$.

[e] Based on Γ_{γ_0} of (1983DE53) and on branching ratios of (1972AL03): ^{12}C*(15.11) $\rightarrow ^{12}$C*(0, 4.4, 7.65, 12.71) are $(92 \pm 2)\%$, $(2.3 \pm 0.3)\%$, $(2.6 \pm 0.7)\%$ and $(1.4 \pm 0.4)\%$, respectively. In addition, an undetected branching of 1.6% to ^{12}C*(10.3) is indicated by the β-decay work (1972AL03) and is included. See also (1980AJ01) and Table 12.9 of (1975AJ02).

[f] F. Ajzenberg-Selove private communication with E.G. Adelberger.

[g] (1983DE53) analyzed new data along with those of (1973CH16) ($\Gamma_\gamma = 37.0 \pm 1.1$ eV). The combined analysis result is adopted. See earlier results listed in Table 12.8 of (1968AJ02).

[h] Deduced. [i] From (1974BA42). See reaction 83.

[j] Weighted average of (1972OB01, 1977RO05, 1977AL31).

[k] From analysis of world (e, e′) data given in (2010CH17, 2011VO16).

[l] From $10^4 \times \Gamma_{\rm rad}/\Gamma = 3.3 \pm 0.9$ (1961AL23), 3.5 ± 1.2 (1964HA23), 4.20 ± 0.22 (1974CH03), 4.4 ± 0.2 (1975DA08), 4.15 ± 0.34 (1975MA34), 4.09 ± 0.27 (1976OB03), 3.87 ± 0.25 (1976MA46). The value from (1961AL23) has sometimes been miscopied as 3.4, which has no impact on the average. The value of (1975DA08) has been corrected, as indicated in (1976OB03). The value $(2.82 \pm 0.29) \times 10^{-4}$ (1963SE23) is a statistical outlier; including this value yields the average $(3.99 \pm 0.18) \times 10^{-4}$ that is the weighted average using the external uncertainty. The value in (1990AJ01) did not use the corrected (1975DA08) value. In (2014FR09), the value $(4.19 \pm 0.10) \times 10^{-4}$ is deduced by rounding the above values to the nearest tenth.

[m] (1967CR01). [n] (1974CH32). [o] (2013ZI03). [p] (1977AD02).

[q] (1974CE01). [r] Assume $\Gamma_\gamma/\Gamma = 1 - \Gamma_\alpha/\Gamma$.

[s] (1965SE06). $(2J + 1)\Gamma_{\gamma_0} \geq 115$ eV.

[t] Decays to ^{12}C*(12.71) (1982HA12).

[u] From (1979FR04). [v] From (1976AS01). [w] From (1965SE06).

[x] I_γ(rel. at $\theta = 55^\circ$) $= 15.7 \pm 1.6$, $\equiv 100$, < 0.07, 6.8 ± 0.4 and 0.16 ± 0.03 to ^{12}C*(0, 4.4, 7.65, 12.71, 15.11), respectively (1990ZI02).

[y] I_γ(rel. at $\theta = 55^\circ$) $= 168 \pm 17$, $\equiv 100$, 1.9 ± 0.2, 1.36 ± 0.07 and 2.09 ± 0.13 to ^{12}C*(0, 4.4, 7.65, 12.71, 15.11), respectively (1990ZI02).

[z] I_γ(rel. at $\theta = 55^\circ$) $= 104 \pm 11$, $\equiv 100$, < 0.02, 68 ± 1, 14.0 ± 1.2 and 10 ± 3 to ^{12}C*(0, 4.4, 7.65, 9.64, 12.71, 15.11), respectively (1990ZI02).

[†] (2016LA27).

[‡] Discrepancies in Γ_{γ_0} values measured in electron scattering and nuclear reactions are reviewed in (1978FR03). The results do not appear to converge. $\Gamma_{\gamma_0} = 0.59 \pm 0.11$ eV [(1977AD02): ^{10}B(^{3}He, pγ)] and $\Gamma_{\gamma_0} = 0.35 \pm 0.04$ eV [(1978FR03): ^{12}C(e, e$'$)] are most widely quoted. In the present case we accept (1977AD02), but we highlight the different analysis of decay partial widths using $\Gamma_{\gamma_0} = 0.35 \pm 0.04$ eV given in (2016LA27).

[§] In the analysis of (2016LA27) the value $\Gamma_{\gamma_1} = 10.5 \pm 1.6$ eV is deduced from Γ and the thick target ^{11}B(p, α) and ^{11}B(p, γ) yield studies of (1992CE02).

[¶] Deduced from Γ, σ(p, γ_{0+1}), $\Gamma_{\rm p}\Gamma_{\gamma_{0+1}}/\Gamma^2$ and $\Gamma_{\gamma_{0+1}}/\Gamma$.

[£] (2016LA24). See other values such as 0.078 ± 0.010 (2012AL22) and 0.045 ± 0.006 (1961SE10).

4. ^{9}Be(^{3}He, γ)^{12}C $\qquad$ $Q_{\rm m} = 26.2797$

Excitation functions and angular distribution studies have been carried out at E(^{3}He) $= 1.0$ to 6.0 MeV (1972BL17: γ_0, γ_1, γ_2), E(^{3}He) $= 1.5$ to 11 MeV (1972LI29: γ_0, γ_1, γ_2, γ_3), E(^{3}He) $= 2$ to 4.5 MeV (1964BL12: γ_0, γ_1) and E(^{3}He) $= 3$ to 26 MeV (1974SH01: γ_0, γ_1, γ_2, γ_3). Observed resonances are shown in Table 12.15. See (1980AJ01) for references.

Table 12.15: Resonances in ^{9}Be(^{3}He, γ)^{12}C [a]

$E(^{3}\mathrm{He})$ (MeV ± keV)	Res.	E_{x} (MeV)	Γ_{cm} (MeV)
2.55 [b]	γ_0, γ_2	28.2	1.6
3.40 ± 40	γ_0, γ_2	28.83	1.54 ± 0.09
5.35 ± 30	γ_1	30.29	1.96 ± 0.15
6.51 ± 30	γ_0	31.16	2.10 ± 0.15
8.02 ± 40	γ_1, γ_2	32.29	1.32 ± 0.23
9.60 ± 210	γ_1, γ_2	33.47	1.93 ± 0.05

[a] See (1975AJ02) for references.

[b] $\Gamma_\gamma \geq 11.8$ eV [γ_0], ≥ 4.6 eV [γ_1], ≥ 11.3 eV [γ_2], assuming $J = 1$, $\Gamma(^{3}\mathrm{He}) = \Gamma$; $J^\pi = 1^-; T = 1$.

^{12}C*(28.2) appears to be formed by s- and d-wave capture. The γ_0 and γ_2 transitions to the 0^+ states ^{12}C*(0, 7.7) are strong and show a similar energy dependence. A strong non-resonant contribution is necessary to account for the γ_1 yield (1972BL17). The resonance structure reported by (1974SH01) appears to confirm the role of 3p-3h configurations for ^{12}C excitations somewhat above the giant resonance region. The γ_3 yield is relatively unstructured (1972LI29, 1974SH01: to $E(^{3}\mathrm{He}) = 26$ MeV). See also (1975AJ02).

(1970BL09) had reported a capture resonance at $E(^{3}\mathrm{He}) = 1.74$ MeV which subsequently decayed via ^{12}C*(15.11) and which was assumed to correspond to the first $J^\pi = 0^+; T = 2$ state in ^{12}C [$E_{\mathrm{x}} = 27.585 \pm 0.005$ MeV]. However, neither (1972HA63) nor (1972WA18) have been able to repeat this observation: $\Gamma_{^{3}\mathrm{He}}\Gamma_\gamma/\Gamma < 1.5$ meV (1972WA18), < 2 meV (1972HA63).

5. (a) ^{9}Be(^{3}He, n)^{11}C	$Q_{\mathrm{m}} = 7.5580$	$E_{\mathrm{b}} = 26.2797$
(b) ^{9}Be(^{3}He, p)^{11}B	$Q_{\mathrm{m}} = 10.3228$	
(c) ^{9}Be(^{3}He, d)^{10}B	$Q_{\mathrm{m}} = 1.0932$	
(d) ^{9}Be(^{3}He, t)^{9}B	$Q_{\mathrm{m}} = -1.0866$	
(e) ^{9}Be(^{3}He, ^{3}He)^{9}Be		
(f) ^{9}Be(^{3}He, α)^{8}Be	$Q_{\mathrm{m}} = 18.9131$	
(g) ^{9}Be(^{3}He, α)^{4}He^{4}He	$Q_{\mathrm{m}} = 19.0049$	

Excitation functions for neutrons, production cross sections for ^{11}C and polarization observables have been measured at $E(^{3}\mathrm{He}) = 1.2$ to 10 MeV for several neutron groups. No sharp structure is observed, but there is some suggestion, from angular distribution data and the excitation function at forward angles, for a structure ($\Gamma \approx 350$ keV) at $E(^3\text{He}) \approx 2$ MeV: $E_\text{x} = 27.8$ MeV (1963DU12, 1965DI06). The total cross section for ^{11}C production shows a broad maximum, $\sigma = 113$ mb at $E(^3\text{He}) = 4.3$ MeV. In the range $E(^3\text{He}) = 5.7$ to 40.7 MeV the yield decreases monotonically. Excitation functions and angular distributions for protons (reaction (b)) have been measured for $E(^3\text{He}) = 1.0$ to 10.2 MeV for a number of proton groups. No pronounced structures are reported.

Analyzing powers have been measured at $E(^3\overrightarrow{\text{He}}) = 33.3$ MeV for nine deuteron groups (reaction (c)). The cross section for ground-state tritons (reaction (d)) increases monotonically for $E(^3\text{He}) = 2.5$ to 4.2 MeV and then shows a broad maximum at $E(^3\text{He}) \approx 4.5$ MeV. See also (1993AR14, 1996AR07: $E = 22.3$ to 34 MeV).

The excitation function for elastic scattering (reaction (e)) decreases monotonically for $E(^3\text{He}) = 4.0$ to 9.0 MeV and 15.0 to 21.0 MeV. See also (1992AD06: $E = 50, 60$ MeV). At $\theta_\text{cm} = 111°$ a slight rise is observed for $E(^3\text{He}) = 19$ to 21 MeV. Polarization observables have been reported at $E(^3\text{He}) = 18$, 31.4 and 32.8 MeV.

Excitation functions for the α_0 group (reaction (f)) have been reported for $E(^3\text{He}) = 2$ to 10 MeV (1978BI15): evidence is found for a resonance at $E_\text{x} \approx 29.3$ MeV. See also (1992AD06). Analyzing powers have been measured at $E(^3\overrightarrow{\text{He}}) = 33.3$ MeV. For reaction (g) see (1986LA26, 1987WA25).

See references and additional work in (1968AJ02, 1975AJ02, 1980AJ01, 1985AJ01, 1990AJ01).

6. (a) $^9\text{Be}(\alpha, \text{n})^{12}\text{C}$ $\qquad Q_\text{m} = 5.7020$

(b) $^9\text{Be}(\alpha, {}^{12}\text{C})\text{n}$ $\qquad Q_\text{m} = 5.7020$

Neutron groups have been observed to ^{12}C*(0, 4.4, 7.7, 9.6, (10.1), (10.8)). Angular distributions of neutrons, mainly for n_{0-3}, have been measured at energies in the range $E_\alpha = 1.75$ to 32 MeV. Gamma-ray angular distributions have been studied by (1955TA28, 1959SM98, 1963SE04). Observation of the γ-decay of the 15.1 MeV level is reported by (1954RA35, 1957WA04). At $E_\alpha = 35$ MeV the members of the $K^\pi = 0^+$ band and ^{12}C*(9.63) are strongly populated (1981HAZV).

Doppler shift measurements on the transition ^{12}C*(4.4 → g.s.) yield mean life values of $\tau_\text{m} = 50 \pm 6$ fsec (1961DE38); 57^{+23}_{-17} fsec, $\Gamma_\gamma = (11.5^{+5}_{-3.2})$ meV (1966WA10); $< 48 \pm 10$ fsec (1967CA02). The internal pair conversion coefficient indicates an E2 transition (1954MI68): the pair angular correlation permits M1 or E2 and favors the latter (1954HA07, 1956GO1K, 1956GO73, 1958AR1B). Angular distributions of n_1 and n_1-γ correlations strongly indicate a direct interaction mechanism even at $E_\alpha = 3.3$ and 5.5 MeV (1960GA14, 1962KJ01); also see correlation studies at $E_\alpha = 1.4$ to 4.5 MeV (2010GI07). ^{12}C*(7.65[$J^\pi = 0^+$]) decays predominantly into $^8\text{Be} + \alpha$ with a small radiative branch. In (1960AL04, 1972OB01) the pair decay is measured $\Gamma_\pi/\Gamma = (6.9 \pm 2.1) \times 10^{-6}$; this supercedes the earlier value $\Gamma_\pi/\Gamma = (6.6 \pm 2.2) \times 10^{-6}$ (1959AL97, 1960AJ04, 1960AL04, 1961GA03). However, see Table 12.14.

Neutron catalyzed helium burning, i.e. $^4\text{He}(\alpha\text{n}, \gamma)^9\text{Be}(\alpha, \text{n})^{12}\text{C}$, is analyzed in (1994WR01, 1996KU07, 2009GI03, 2011GI05). The ratio, Yield($E_\gamma = 4.44$ MeV)/Yield(neutrons) $= 0.596 \pm$

0.017, was measured for an AmBe source in (2004MO18). The energy dependent reaction cross sections have been evaluated at $E < 10$ MeV for actinide-Be neutron source energy distributions (2003SH22). Also see (1997HE11, 2000MI34, 2007AH07, 2007MA58, 2015VL01).

Reaction (b) was measured at $E_{\alpha} = 22$ to 30 MeV, along with ^{12}C(α, 3α)^{4}He, in search of ^{12}C resonances above $E_{\rm x} = 7$ MeV that could have structures related to the Hoyle state (2011FR02). The analysis separately considered both events populating natural parity states involving ^{12}C* $\rightarrow$ ^{8}Be$_{\rm g.s.}$($J^{\pi} = 0^{+}$) $+\ \alpha$ and events that excluded ^{12}C* $\rightarrow$ ^{8}Be$_{\rm g.s.}$ $+\ \alpha$. Known states at $E_{\rm x} = 9.64$, 10.84, 11.83, 12.71, 14.08 are observed in the ^{9}Be(α, ^{12}C) reaction along with a state consistent with $E_{\rm x} = 13.3 \pm 0.2$ MeV and $\Gamma = 1.7 \pm 0.2$ MeV. Analysis of the angular correlations from the ^{12}C(α, 3α) reaction support $J^{\pi} = 4^{+}$ for the new state.

7. ^{9}Be(^{6}Li, t)^{12}C $\qquad$ $Q_{\rm m} = 10.4855$

At E(^{6}Li) $= 32$ MeV angular distributions have been studied to ^{12}C*(0, 4.4, 7.7, 9.6, 10.8, 11.8, 12.7, 14.1); ^{12}C*(9.64) is relatively strongly populated. There is no indication of the $T = 1$ states (1986AS02: FRDWBA). Similar results are found for E(^{9}Be) $= 26$ MeV in (1975VE10).

8. ^{9}Be(^{9}Be, ^{6}He)^{12}C $\qquad$ $Q_{\rm m} = 5.1048$

At E(^{9}Be) $= 40$ MeV, angular distributions to ^{12}C*(0, 4.44, 7.65, 9.64, 13.35, 14.08) were measured (1992CO05); the data are consistent with direct ^{3}He cluster transfer. Cluster spectroscopic factors are deduced. Also see measurements at E(^{9}Be) $= 26$ MeV, $\theta = 10°$ to ^{12}C*(4.4, 7.7, 9.6) (1975VE10).

9. ^{9}Be(^{10}C, ^{12}C)^{7}Be $\qquad$ $Q_{\rm m} = 11.2783$

At E(^{10}C) $= 10.7$ MeV, the α-particle correlations from ^{12}C*(7.65, 9.64) were studied in search of evidence supporting direct 3-body breakup (2012MA10), as suggested in (2011RA43). Results were consistent with 100% decay via ^{8}Be$_{\rm g.s.}$ $+\ \alpha$ in both cases.

10. ^{10}Be(^{3}He, n)^{12}C $\qquad$ $Q_{\rm m} = 19.4674$

At E(^{3}He) $= 13$ MeV neutron groups are observed to ^{12}C*(0, 4.4, 7.7, 16.1, 17.8) and to excited states at $E_{\rm x} = 23.53 \pm 0.04$ [$\Gamma < 0.4$ MeV] and 27.611 ± 0.020 MeV. The latter is formed with a $0°$ cross section of ≈ 200 μb/sr and is taken to be the first 0^{+}; $T = 2$ state of ^{12}C (1974GO23).

11. ^{10}B(d, γ)^{12}C $Q_{\rm m} = 25.1864$

The (d, $\gamma\gamma$) excitation function [via the $J^{\pi} = 1^{+}$; $T = 1$ state at $E_{\rm x} = 15.1$ MeV] has been measured for $E_{\rm d} = 2.655$ to 2.84 MeV. The non-resonant yield of 15 MeV γ-rays is due to direct capture processes or to a very broad resonance: no sharp resonances are observed corresponding to the $E_{\rm x} \approx 27.6$, $T = 2$ state reported in other reactions [$\Gamma_{\rm d_0}\Gamma_{\gamma}/\Gamma \lesssim 0.2$ eV] (1970BL09).

12. ^{10}B(d, n)^{11}C $Q_{\rm m} = 6.4648$ $E_{\rm b} = 25.1864$

The thin-target excitation function, measured at $E_{\rm d} = 0.3$ to 4.6 MeV, shows some indication of a broad resonance in the forward direction near $E_{\rm d} = 0.9$ MeV. Above $E_{\rm d} = 2.4$ MeV, the cross section increases rapidly to 210 mb/sr at 3.8 MeV and then remains constant to 4.6 MeV (1954BU06, 1955MA76). Also see activation measurements reported at $E_{\rm d} = 0.5$ to 6 MeV (1990MI11). The 0° excitation function for ground state neutrons shows no structure for $E_{\rm d} = 3.2$ to 9.0 MeV (1967DI01). Excitation functions have been measured for $E_{\rm d} = 7.0$ to 16.0 MeV (1981AN16). The excitation function for neutrons to ^{11}C*(6.48) increases monotonically for $E_{\rm d} = 4.0$ to 4.8 MeV (1972TH14). The branching ratios at 90° for the transitions to the ground states of ^{11}C and ^{11}B [$\rm n_0/p_0$] have been measured for $E_{\rm d} = 1.0$ to 2.0 MeV by (1973BR24). At $E_{\rm d} = 1$ to 5 MeV, cross sections have been obtained for the neutrons and protons to the second, third, fourth, and fifth excited states of the ^{11}B and ^{11}C mirror nuclei (1967SC1K). The angular distributions all show a sharp peak around 20° and a smaller contribution in the backward direction; DWBA produces a satisfactory fit to these distributions (1967DI01).

Polarization measurements have been carried out for $E_{\vec{\rm d}} = 2.5$ to 4.0 MeV (1967ME1N), $E_{\vec{\rm d}} = 1.20$ to 2.90 MeV (1968BR26: $\rm n_0$) and $E_{\vec{\rm d}} = 2.4$ to 4.0 MeV (1972ME06: $\rm n_0$, $\rm n_1$, $\rm n_{2+3}$). The transitions to ^{11}C*(0, 4.32 + 4.80) appear to involve a direct reaction mechanism (1972ME06).

Cross sections and astrophysical S-factors for $\rm n_0$ are reported for $E_{\rm d} < 160$ keV (2008ST10). Thick-target yields and astrophysical S-factors are reported for neutrons at $E_{\rm d} = 24$ to 111 keV (2001HO23) and for 4.3 MeV γ-rays at $E_{\rm d} = 111$ to 170 keV (1982CE02).

Methods of ^{11}C production for position emission tomography are discussed in (1989ST09, 2005VO15, 2011KI04).

13. ^{10}B(d, p)^{11}B $Q_{\rm m} = 9.2296$

Angular distributions and yields of protons have been measured for $E_{\rm d} = 0.9$ to 2 MeV (2007KO69) and $E_{\rm d} = 15.3$ MeV (2005GA59); also see results reported at $E_{\rm d} = 0.18$ to 3.1 MeV (1959AJ76), 0.14 to 12 MeV (1968AJ02) and 0.7 to 2.9 MeV (1975AJ02). Although the excitation functions show several broad peaks, no clear resonances can be identified, and it is assumed that many overlapping resonances are involved (1956MA69) except possibly at $E_{\rm d} = 2.3$ MeV ($E_{\rm x} = 27.1$ MeV) where the effect of a broad resonance influences the cross section of the

p_1 and p_3 groups. An analysis given in (2005RU16) suggests the broad peaks correspond to fragmented $J^\pi = 1^-$ components of the GDR at $E_{\rm res}({\rm cm}) = 0.38, 0.61, 1.61$ MeV with $\Gamma = 0.37, 0.37$ and 1.24 MeV, respectively, as well as a $J^\pi = 2^+$ contribution from the GQR at $E_{\rm res}({\rm cm}) = 1.36$ MeV with $\Gamma = 710$ keV. The p_2-γ-ray correlations were measured in (2005GA59). Cross section ratios for the (d, n) and (d, p) reactions to mirror states have been measured by (1967SC1K, 1973BR24).

The astrophysical relevant region has been studied at $E_{\rm d} = 57$ to 141 keV (1993CE02, 1997YA02, 1997YA08), 91 to 161 keV (1981CE04) and 120 to 340 keV (2001HO22) and at $E_{\rm cm} = 100$ to 300 keV (2004RU10).

Polarization studies have been carried out at $E_{\vec{\rm d}} = 6.9$, 10, 11 to 13.8, 11.4 and 21 MeV [See (1968AJ02)] and at $E_{\vec{\rm d}} = 1.15$, 1.40 and 1.85, 10, 12 and 13.6 MeV [see (1975AJ02)].

14. ^{10}B(d, d)^{10}B $\qquad E_{\rm b} = 25.1864$

The yield of elastically scattered deuterons has been measured for $E_{\rm d} = 1.0$ to 2.0 MeV: resonances at $E_{\rm d} = 1.0$ and 1.9 MeV are suggested by (1969LO01). Excitation functions for the deuterons to ^{10}B*(1.74, 2.16) [J^π; $T = 0^+$; 1 and 1^+; 0, respectively] have been measured at several angles for $E_{\rm d} = 4.2$ to 16 MeV: they are characterized by rather broad, slowly varying structures. The ratio $\sigma_{1.74}/\sigma_{2.16}$ varies from $(0.69 \pm 0.04)\%$ at $E_{\rm d} = 6.5$ MeV to $(0.16 \pm 0.04)\%$ at $E_{\rm d} = 12.0$ MeV corresponding, respectively, to isospin impurities of $\approx 2\%$ and $\approx 0.5\%$ (1974ST01). No resonance structure is observed in the elastic yield for $E_{\rm d} = 14.0$ to 15.5 MeV (1974BU06). Polarization measurements are reported at $E_{\vec{\rm d}} = 12.5$ MeV (1975ZA08) and at 15 MeV (1974BU06).

15. (a) ^{10}B(d, α)^{8}Be $\qquad Q_{\rm m} = 17.8198 \qquad E_{\rm b} = 25.1864$
(b) ^{10}B(d, 2α)^{4}He $\qquad Q_{\rm m} = 17.9117$

Excitation functions have been measured for the α_0 and α_1 groups for $E_{\rm d} = 0.4$ to 12 MeV [see (1968AJ02, 1975AJ02, 1980AJ01)] and for $E_{\rm d} = 0.9$ to 2.0 MeV (2007KO70: α_0). Maxima in the α_0 yields are reported at $E_{\rm d} = 1$, 2, 4.5 and (6) MeV. The first is attributed to an s-wave resonance corresponding to a state with $E_{\rm x} \approx 26.0$ MeV, $\Gamma \approx 0.5$ MeV (1968FR07). The resonance structures at ≈ 2.0 and 4.5 MeV ($\Gamma \gtrsim 1$ MeV) may both involve the isoscalar giant resonance: $E_{\rm x} \approx 28$ MeV, $\Gamma \approx 4$ MeV (1978BU04). No evidence for the $T = 2$ state was found in the α_0 and α_1 yield curves taken in 2 keV steps for $27.35 < E_{\rm x} < 27.65$ MeV (1970BL09). For yields of the α-particles to ^{8}Be*(17.6, 18.1) see (1970CA12). Cross sections, angular distributions and S-factors are deduced in (2001HO22: $E_{\rm d} = 120$ to 340 keV) and (1993CE02, 1997YA02, 1997YA08: $E_{\rm d} = 57$ to 141 keV).

Reaction (b) has been studied for $E_{\rm d} = 2.7$ to 5.0 MeV (1975RO09, 1975VA04, 1977GO16), $E_{\rm d} = 0.36$ MeV (1977NO10), $E_{\rm d} = 2.5$ and 3 MeV (1992KO26), $E_{\rm d} = 13.6$ MeV (1981NE08, 1992PU06) and $E_\mathrm{d} = 48$ MeV (1993PA31). The work of (1977NO10) suggests that $J^\pi = 3^-$ and 4^+ ^{12}C compound states with unidentifiable energies and widths contribute dominantly to the sequential decay. Also see (1990NE15, 1991AS02).

16. (a) ^{10}B(^{3}He, p)^{12}C $\quad Q_\mathrm{m} = 19.6929$
    (b) ^{10}B(^{3}He, pα)^{8}Be $\quad Q_\mathrm{m} = 12.3264$
    (c) ^{10}B(^{3}He, 2p)^{11}B $\quad Q_\mathrm{m} = 3.7361$
    (d) ^{10}B(^{3}He, pn)^{11}C $\quad Q_\mathrm{m} = 0.9713$

Observed proton groups are displayed in Table 12.16. Angular distributions of many of these groups have been measured for $E(^3\mathrm{He}) = 2.0$ to 3.0 MeV (1965BH1A), 3.7 MeV (1962BR10), 10.1 MeV (1962AL01) and 14 MeV (1967CO1F). Also see Table 12.17, which has results from complete kinematics studies of ^{10}B(^{3}He, p3α) and ^{11}B(^{3}He, d3α) given in (2007BO49, 2009KI13, 2010KI08, 2011AL28, 2012AL22, 2012KI07, 2013KI07). Table 12.14 summarizes the electromagnetic decay parameters of some of the excited states of ^{12}C including results below.

Pair emission from ^{12}C*(7.65) has been measured: $\Gamma_\pi/\Gamma = (6.6 \pm 2.2) \times 10^{-6}$ [see Table 12.14] as has the cascade through ^{12}C*(4.4): $\Gamma_\gamma/\Gamma = (3.3 \pm 0.9) \times 10^{-4}$ (1961AL27). By observation of ^{12}C recoils, a value $\Gamma_\mathrm{rad}/\Gamma = (3.5 \pm 1.2) \times 10^{-4}$ is found by (1964HA23).

For ^{12}C*(12.71) $\Gamma_{\gamma_0}/\Gamma = (1.93 \pm 0.12)\%$, $\Gamma_{\gamma_1}/\Gamma_{\gamma_0} = (15.0 \pm 1.8)\%$ and $\Gamma_\alpha/\Gamma = (97.8 \pm 0.1)\%$ (1977AD02). See earlier reported results of $\Gamma_\gamma/\Gamma_\alpha = (3 \pm 1)\%$ (1958MO99) and $(2 \pm 1)\%$ (1959AL96): the γ-decay branching ratios are reported; see comments in Table 12.16. The α breakup of ^{12}C*(12.71) shows a triple-peaked α-particle spectrum, characteristic of the breakup of a $J^\pi = 1^+$ state (1967BH1B).

For ^{12}C*(14.08) the branching ratio Γ_{α_0}/Γ is 0.1-0.4. Proton-α correlations require $J \geq 2$ (1966WA16).

^{12}C*(15.11: $J^\pi = 1^+$; $T = 1$) decays by γ-emission mainly to ^{12}C$_\mathrm{g.s.}$ and has weaker transitions to ^{12}C*(4.4, 7.7, (10.3), 12.7) (1972AL03, 2009KI13): see Table 12.16. Earlier measurements reported the feeding to ^{12}C$_\mathrm{g.s.}$ as 97% and to ^{12}C*(4.4) as $(3.1 \pm 0.6)\%$ (1959AL96), $(4 \pm 1)\%$ (1960AL14); $\Gamma_\alpha/\Gamma < 0.2$ (1960MI1E), < 0.05 (1965AL1B), < 0.10 (1966WA16), respectively. The strong inhibition of the transition to ^{8}Be*(2.9) is cited as evidence for a high isospin purity (1965AL1B). For a study of the charge-dependent matrix element between ^{12}C*(12.7, 15.1) see Table 12.18.

Decays of ^{12}C*(16.11, 16.57) populate both ^{8}Be*(0, 2.9). The consequent assignment of natural parity is consistent with $J^\pi = 2^+$ for the former but not with the accepted $J^\pi = 2^-$ for the latter. For ^{12}C*(16.1) $\Gamma_{\gamma_1}/\Gamma = (2.42 \pm 0.29) \times 10^{-3}$, $\Gamma_{\gamma_0}/\Gamma_{\gamma_1} = (4.6 \pm 0.7)\%$, $\Gamma_\gamma(16.1 \rightarrow 9.6)/\Gamma_{\gamma_1} = (2.4 \pm 0.4)\%$, and $\Gamma_\gamma(16.1 \rightarrow 12.7)/\Gamma_{\gamma_1} = (1.46 \pm 0.25)\%$ (1976AD03, 1977AD02). Also see (1974AN19) who reported $\Gamma_\mathrm{p}/\Gamma = (3.24 \pm 0.27) \times 10^{-3}$ and $\Gamma_\gamma/\Gamma = (3.23 \pm 0.50) \times 10^{-3}$. Reported values of Γ_{α_0}/Γ are 0.05-0.12; the decay to 3α occurs rarely, if at all (1966WA16: see however, ^{11}B(p, α)^{8}Be: (1965DE1A)).

Table 12.16: ^{12}C states from ^{10}B(^{3}He, p)^{12}C

E_x [a] (MeV ± keV)	Γ_{cm} [c] (keV)	Γ_γ/Γ [e]	α-decay [d,j]		Parity [d,k]	$J^\pi; T$
			^{8}Be$_{g.s.}$	^{8}Be*(2.9)		
4.44						
7.655 ± 6		3×10^{-4} [m]	yes		natural	0^+
9.645 ± 6	36 ± 6		yes	yes	natural	
10.849 ± 25	320 ± 30		strong	yes	natural	
11.841 ± 25	245 ± 30		no	yes	unnatural	
12.713 ± 6	≈ 350 [o]	0.025 ± 0.01 [f]	no	yes	unnatural	1^+
13.29 ± 30	430 ± 100		no	yes	unnatural	≥ 1 [d]
	290 ± 70 [d]					
14.083 ± 15	252 ± 15		yes	yes	natural	≤ 2 [g]
	320 ± 50 [d]					
15.108 ± 6		> 0.95 [h,i]				$1^+; 1$
16.108 ± 6		$(2.6 \pm 0.5) \times 10^{-3}$ [l]	weak	strong	natural	2^+
16.58			yes	yes	natural [n]	
≈ 18.5 [p]	broad		(yes)			
≈ 19.5 [p]	broad			(yes)		
20.5 ± 100 [b]				yes [p]		(3^+) [b]
22 [p,q]			(yes)			

[a] (1962BR10): excitation energies based on $Q_0 = 19.693$ MeV.

[b] A (^{3}He, pn) study suggests $J^\pi = 3^+; T = 1$ for this state (1970BO39).

[c] (1962BR10).

[d] (1966WA16).

[e] See also Table 12.14.

[f] Branching ratios to ^{12}C*(0, 4.4) are $(85 \pm 4)\%$ and $(15 \pm 4)\%$, respectively (1972AL03). See also Table 12.14.

[g] From proton-α correlations (1966WA16).

[h] (1965AL1B): $\Gamma_\alpha/\Gamma < 0.05$.

[i] Branching ratios to ^{12}C*(0, 4.4, 7.7, 12.7) are, respectively, $(92 \pm 2)\%$, $(2.3 \pm 0.9)\%$, $(2.6 \pm 0.7)\%$, $(1.4 \pm 0.4)\%$ (1972AL03): see earlier results in (1959AL96).

[j] (1968KR02).

[k] (1965AL1B).

[l] (1977AD02): see, however, Table 12.14.

[m] (1961AL23): The cascade decay (via 4.44) is $(3.3 \pm 0.9) \times 10^{-4}$ of the total decay. This is 50 times stronger than the direct g.s. decay (via e$^+$+e$^-$-pairs). $\Gamma_{rad}/\Gamma = (3.5 \pm 1.2) \times 10^{-4}$ (1964HA23): see Table 12.14.

[n] Inconsistent with $J^\pi = 2^-$.

[o] $\Gamma \approx 350$ for ^{12}C*(12.713) appears in (1985AJ01), but the value is untraceable. It may be associated with (1982KA1M).

[p] (1982KA1M: private communication) $E(^3\text{He}) = 19$ MeV. The p$_0$-decay of ^{12}C*(18.3, 20.6) and the p$_2$ [to ^{11}B*(4.45)] decay of ^{12}C*(20.6, 22) are reported.

[q] The α_0-decay of states with $20 < E_x < 25$ MeV is very unlikely, consistent with the population of $T = 1$ states in this region: see reaction 21 in (1980AJ01).

Table 12.17: ^{12}C states observed in complete kinematics studies of both ^{10}B(^{3}He, p3α) and ^{11}B(^{3}He, d3α) reactions

$E_{\rm x}$ (MeV ± keV) [a]	Γ (keV) [a]	J^{π} [b]	Γ_{α_0}/Γ [a]
7.65			1.0000 ± 0.0001 [c]
9.64	43 ± 4	3^-	1.000 ± 0.004
10.847 ± 4	272 ± 5	1^-	1.00 ± 0.03
11.837 ± 4	229 ± 8	2^-	
(12.4) [d]	broad [d]	Unnatural [d]	
12.71	[e]	1^+	
13.305 ± 9	510 ± 40	4^- [f]	
14.078 ± 5	273 ± 5		0.25 ± 0.03; $\Gamma_{\alpha_0} = 68 \pm 8$ keV
15.1	[g]		
16.1			0.072 ± 0.009 [h]; $\Gamma_{\alpha_0} = 0.38 \pm 0.05$ keV
16.58			
18.38			
20.553 ± 5			

[a] From (2012AL22): for Γ, Γ_{α_0}/Γ the values are corrected for contributions from the "ghost" of the ^{8}Be ground state. Neglecting these corrections yields $\Gamma_{\alpha_0}/\Gamma = 0.980 \pm 0.004$, 0.943 ± 0.009, 0.22 ± 0.03 and 0.058 ± 0.009 for ^{12}C*(9.64, 10.84, 14.08, 16.11) respectively.

[b] From Dalitz plot analysis in (2010KI08).

[c] Decay is consistent with 100% decay to $\alpha + {}^{8}\mathrm{Be}_{\rm g.s.}$ (2012KI07). Limits on: direct breakup into 3 equal energy α particles was $< 0.9 \times 10^{-3}$, direct breakup with one α particle at rest and two equal energy α's was $< 0.9 \times 10^{-3}$, and decay into 3-body phase space was $< 5 \times 10^{-3}$.

[d] Previously unobserved state with Γ = 300-900 keV, and $J^{\pi} = 4^-, 5^+, 6^-, 7^+$ (5^+ is preferred: 2013KI07).

[e] $\Gamma_{\alpha}/\Gamma = 0.974 \pm 0.003$ and $\Gamma_{\gamma}/\Gamma = 0.026 \pm 0.004$ (2009KI13). The γ-decay branching ratios are $(84 \pm 12)\%$, $(12.7 \pm 2.4)\%$, $(2.6^{+1.6}_{-1.2})\%$ and $(0.9^{+0.6}_{-0.5})\%$ to ^{12}C*(0, 4.4, 7.65, 10.3), respectively. In (2009KI13) the γ-decay energies are deduced by taking the difference in excitation energy, deduced from the p- or d-ejectile and the reconstructed 3α-decay energy.

[f] See also (2007BO49).

[g] $\Gamma_{\alpha}/\Gamma = 0.028 \pm 0.012$ (2009KI13). The γ-decay branching ratios are $(90.4 \pm 1.0)\%$, $(2.3 \pm 0.3)\%$, $(4.4 \pm 0.8)\%$, $(1.4 \pm 0.2)\%$, $< 0.13\%$, $(0.32 \pm 0.12)\%$ and $(1.2 \pm 0.2)\%$ to ^{12}C*(0, 4.4, 7.65, 10.3, 10.84, 11.83, 12.71), respectively. In addition, the charge dependent matrix element between ^{12}C*(12.71, 15.11) is determined as 260 ± 60 keV.

[h] See also (2016LA24).

Table 12.18: Charge-dependent matrix element between ^{12}C*(12.71, 15.11) ($J^{\pi} = 1^{+}$; $T = 0$ and 1, respectively) [a]

Charge-dependent matrix element (keV)	Reaction	Reference
110 ± 30	^{10}B(^{3}He, p)	(1977AD02)
260 ± 60	^{10}B(^{3}He, p), ^{11}B(^{3}He, d)	(2009KI13)
285 ± 30	^{10}B(α, d)	(1977LI02)
130-165	^{12}C(e, e)	(1979FL08)
$+118 \pm 8$	^{12}C(e, e)	(2000VO04)
148 ± 29	^{12}C($\pi^{\pm}$, $\pi^{\pm}$)	(1981MO07)
157 ± 35	^{12}C($\pi^{\pm}$, $\pi^{\pm}$)	(1990JA05)
324 ± 33	^{12}C(d, d)	(1977LI02)
180 ± 80	^{13}C(d, t)	(1977LI02)
120 ± 30	^{13}C(d, t)	(1979CO08)
340 ± 60	^{13}C(^{3}He, α)	(1974BA42)

[a] See also reactions 44 and 86 in (1980AJ01).

An unpublished result at $E(^{3}\text{He}) = 14$ MeV, referenced in (1968AJ02), reported two peaks in the giant resonance excitation region corresponding to ^{12}C* ≈ 20.6 and 24.5 MeV, with $\Gamma \approx 200$ and 50 keV, respectively; the angular distributions show forward maxima.

Reactions (c) and (d) have been studied by (1970BO39). The latter, at $E(^{3}\text{He}) = 11$ MeV, appears to proceed via a state in ^{12}C at $E_{\text{x}} = 20.5 \pm 0.1$ MeV, which is suggested to be $J^{\pi} = 3^{+}$; $T = 1$. The relative intensities of the decays of ^{12}C states with $20 < E_{\text{x}} < 25$ MeV via channels (c) and (d) is estimated. The α_0-decay is very small, consistent with the expected population of $T = 1$ states (1970BO39).

17. ^{10}B(α, d)^{12}C $\qquad Q_{\text{m}} = 1.3399$

Angular distributions of the deuterons corresponding to ^{12}C*(0, 4.4) have been measured at $E_{\alpha} = 15$ to 31 MeV [see references in (1968AJ02, 1980AJ01, 1985AJ01, 1990AJ01)]. The d$\gamma_{4.4}$ angular correlations have been measured for $E_{\alpha} = 19$ to 30 MeV [see references in (1975AJ02, 1990AJ01)], and see (1989VA07, 2001LE50: $E_{\alpha} = 25$ MeV). Thick target γ-ray yields were measured in (1995HE40, 1997HE11). At $E_{\alpha} = 39.9$ MeV, the relative populations of ^{12}C*(12.71, 15.11) [both 1^{+}; the latter isospin forbidden] leads to the value of 285 ± 30 keV (1977LI02) for the charge-dependent matrix element between these two states. The spin-tensor components for ^{12}C*(4.44) formation (1990BO54, 1991BA23, 1998GA46) and induced polarization effects (1999GA43, 2003ZE06) are deduced from analysis of angular distributions at $E_\alpha = 25$ and 30 MeV.

18. ^{10}B(^{6}Li, α)^{12}C $Q_{\rm m} = 23.7127$

At $E(^6{\rm Li}) = 4.9$ MeV (1966MC05) angular distributions have been obtained for the α-particles to ^{12}C*(0, 4.4, 7.7, 9.6); the population of ^{12}C*(11.8, 12.7) is also reported. At $E(^6{\rm Li}) = 3.8$ MeV the intensity ratio for populating the isospin forbidden ^{12}C*(15.11; $T = 1$) state is $(3 \pm 2)\%$ of the intensity to ^{12}C*(12.7; $T = 0$) (1964CA18).

19. ^{10}B(^{14}N, ^{12}C)^{12}C $Q_{\rm m} = 14.9141$

Angular distributions involving ^{12}C*(0, 4.4) have been measured at several energies to $E(^{14}{\rm N}) =$ 93.6 MeV (1969IS01, 1977MO1A).

20. (a) ^{11}B(p, γ)^{12}C $Q_{\rm m} = 15.9569$
(b) ^{11}B(p, e$^+$+e$^-$)^{12}C $Q_{\rm m} = 14.9349$
(c) ^{11}B(p, α)^{8}Be $Q_{\rm m} = 8.5903$ $E_{\rm b} = 15.9569$

(a) Measurements relevant to the astrophysical capture reaction have been carried out at $E_{\rm p} =$ 40 to 180 keV (1992CE02), $E_{\vec{\rm p}} =$ 80 to 100 keV (2000KE10), $E_{\rm p} =$ 140 to 260 keV (1993AN06) and $E_{\rm p} =$ 160 to 310 keV (2016HE05). (1992CE02) produced γ_0 and γ_1 yields and S-factor related to the measured α-particle yields. A study of the $E_{\rm x} = 16.1$ MeV state in (2016HE05) found $E_{\rm res} = 150.0 \pm 0.5$ keV and $\Gamma = 5.0 \pm 0.8$ keV. See related discussion in (1990BR12, 1996RE16, 1999AN35, 2000LI06, 2012CO19, 2012MI24, 2014DU09).

In (2012DI19, 2012FY01), a kinematic energy reconstruction of the 3α energy was used to study α-unbound states populated in the γ-decay of ^{12}C*(16.1, 16.57). Capture reactions with $E_{\rm p} = 165$ keV and 350 keV beams populated the higher-states, while ^{12}C*(9.63, 10.8, 12.7) were observed in the low-energy region of the 3α spectrum. In (2012DI19), the $E_{\rm x} =$ 11.5-12 MeV region shows evidence for a state that may be associated with $J^\pi = 2^+$ strength. An update of this work, (2016LA27) observed evidence for ^{12}C*(16.1) decay to ^{12}C*(10.8) with $\Gamma_\gamma = 0.48 \pm 0.04$ (stat.) $\pm$ 0.11 (sys.) eV; in that work, they gave an overview of the partial decay widths for ^{12}C*(16.1). At $E_{\rm p} =$ 0.675, 1388, 2626 keV ($E_{\rm x} =$ 16.58, 17.23, 18.37 MeV), the relative intensities of the capture γ rays to ^{12}C*(0, 4.44, 7.65, 9.64, 12.71, 15.11) were measured at $\theta_{\rm lab} =$ 55° (1990ZI02). See also (1992HO11).

In the range $4 < E_\mathrm{p} < 14.5$ MeV, $\sigma(\gamma_0)$ is dominated by the giant dipole resonance at $E_\mathrm{p} = 7.2$ MeV ($E_\mathrm{x} = 22.6$ MeV, $\Gamma_\mathrm{cm} = 3.2$ MeV), while the giant resonance in γ_1 occurs at $E_\mathrm{p} \approx 10.3$ MeV ($E_\mathrm{x} = 25.4$ MeV, $\Gamma_\mathrm{cm} \approx 6.5$ MeV): see (1964AL20). Absolute cross-section measurements from $E_\mathrm{p} = 5$ to 14 MeV suggest that $\mathrm{d}\sigma/\mathrm{d}\Omega(90°) = 13.1 \pm 1.3$ μb/sr be used as a standard at the $E_\mathrm{p} = 7.25$ MeV peak of the GDR (1982CO11; also derived σ(E2) for $E_\mathrm{p} = 7$ to 14 MeV). The E2 strength is found to be centered near $E_\mathrm{p} = 12$ MeV: it exhausts $\gtrsim 30\%$ of the isoscalar E2 sum rule (1976MAZG, 1976MAZL).

A study of the giant dipole resonance region with polarized protons ($E_{\vec{\mathrm{p}}} = 6$ to 14 MeV) sets limits on the configuration mixing in the γ_0 giant resonance (1972GL01). The analysis of γ_1 is more complicated: the asymmetry results are constant either with a single $J^\pi = 2^-$ state or with interference of pairs of states such as (1^-, 3^-), (2^-, 3^-) and (1^-, 2^-) (1972GL01). The 90° yield of γ_0, γ_1, γ_2 and γ_3 [to ^{12}C*(0, 4.4, 7.7, 9.6)] has been studied by (1977SN01): the γ_2 yield shows a peak at $E_\mathrm{p} \approx 14.3$ MeV with a cross section $\approx 2.3\%$ that of γ_0 [in γ_0 yield, $E_\mathrm{res} = 15.0$ MeV (1977SN01)] and perhaps a low-intensity structure at $E_\mathrm{p} = 11.8$ MeV as well. The γ_3 yield exhibits two asymmetric peaks at $E_\mathrm{p} = 12.5$ and 13.8 MeV ($\Gamma \approx 0.7$ and 2.5 MeV) and a weaker structure at ≈ 9.8 MeV (1977SN01).

Resonances populated with $E_\mathrm{p} = 7$ to 24.5 MeV beams were studied via γ-γ techniques by measuring the cascades feeding into the ^{12}C*(15.1) state. In (2008CH13) peaks were found in the excitation function corresponding to E1 transitions from $E_\mathrm{x} = 24.41 \pm 0.15$ and 28.81 ± 0.10 MeV with $\Gamma_\mathrm{cm} = 1.3 \pm 0.3$ MeV and 2.0 ± 0.2 MeV, and $(2J + 1)\,\Gamma_{\mathrm{p}0}\Gamma_\gamma/\Gamma = 20.8 \pm 2.8$ and 150 ± 18 eV, respectively. The peaks were found on a smooth excitation function that had previously been analyzed in (2004CH06).

(1983AN09, 1983AN16) have measured the cross sections for γ_0 and γ_1 for $E_\mathrm{p} = 18$ to 43 MeV. They report giant resonances based on various excited states of ^{12}C at $E_\mathrm{x} = 22.5$ and 25.5 MeV (γ_0), 25.5, 27.4 and (31) MeV (γ_1), 27.4, 31 and (37) MeV (γ_3), as well as in the γ-yield to higher states. At $E_\mathrm{p} = 40$, 60 and 80 MeV, radiative capture is observed to a state, or a narrow group of states, at $E_\mathrm{x} = 19.2 \pm 0.6$ MeV (1979KO05); see also (1982WE08). At $E_{\vec{\mathrm{p}}} = 50$ MeV, angular distributions and analyzing power measurements are reported to ^{12}C*(0, 4.4, 9.6, 18.8 ± 0.5 [u], 22.3 ± 1.0 [u]) by (1985NO01) [u = unresolved].

At $E_\mathrm{p} = 98$ MeV, radiative capture to ^{12}C*(0,4.4, 7.6, 9.6, 12.7, 15.1, 16.1 + 16.6, ≈ 19) (1990HO23, 1992HO04, 1996BR20: $E_\mathrm{p} = 98$ and 176 MeV) and internal pair production to ^{12}C*(0, 4.4, 9.64) (1993HO07, 1997TR01) are studied to gain insight into exchange current effects. See also (2000LI06). See other measurements in (1991CA25: $E_\mathrm{p} = 14.24$ MeV, 1992KE03: $E_\mathrm{p} = 7$ MeV, 1998MA85: $E_\mathrm{p} = 7.2$ MeV).

Table 12.19: Resonance cross sections in ^{11}B(p, γ)^{12}C and ^{11}B(p, α)^{8}Be [a]

E_p (MeV)	Γ_cm (keV)	$\sigma(\gamma_0)$ (μb)	$\sigma(\gamma_1)$ (μb)	$\sigma(\alpha_0)$ (mb)	$\sigma(\alpha_1)$ (mb)	^{12}C* (MeV)	$J^\pi; T$
0.162	5.3 ± 0.2	5.5	152	res.	res.	16.1060 ± 0.0008	$2^+; 1$
0.675	300	non-res.	48	non-res.	600	16.576	$2^-; 1$

Table 12.19: Resonances [a] in ^{11}B(p, γ)^{12}C and ^{11}B(p, α)^{8}Be (continued)

E_p (MeV)	Γ_{cm} (keV)	$\sigma(\gamma_0)$ (μb)	$\sigma(\gamma_1)$ (μb)	$\sigma(\alpha_0)$ (mb)	$\sigma(\alpha_1)$ (mb)	^{12}C* (MeV)	$J^\pi; T$
1.388	1150	[27] [b]	3	3.3	≈ 180	17.230	1^-; 1
2.00	96 ± 5	non-res.	non-res.	9.0	(25)	17.79	0^+; 1
2.37	600 ± 100		0.77			18.13	(1^+; 0)
2.64	≈ 400	weak	res.	32.4 ± 4.8	270 ± 40	18.38	3^-; 1
2.66	43	non-res.	non-res.	non-res.	non-res.	18.39	0^-
3.01	100	non-res.	non-res.	3.4		18.71	n.π.[d]; (1)
3.12	100	weak	[20] [b]	non-res.	non-res.	18.81	2^+; 1
3.5	1100	[20] [b]	res.	5.2	res.	19.2	(1^-; 1)
3.75	(1100)	non-res.	res.	7.4 ± 1.1	300 ± 40	19.39	(2^+; 0)
4.93	180	non-res.	res.	res.	170 ± 40	20.47	
5.11	275	non-res.	[35] [b]	6.0 ± 0.9	non-res.	20.64	(3^-; 1)
5.85	300			res.		(21.31)	
6.0		res.	non-res.	res.		21.5	
6.7	500	res.	[35] [b]	res.		22.1	
7.25	3200	120	non-res.		res.	22.6	(1^-; 1)
8.3		res.	res.	res.		23.6	
10.3	≈ 6500	[60] [b]	83			25.4	
11.76 [e]		non-res.	45 [c]	res.		26.72	(1^-)
12.5 [f]	≈ 700	21 [c]	non-res.			27.4	
13.0	≈ 6000			res.		27.9	
13.09		19 [c]	38 [c]			27.94	
13.8 [f]	≈ 2500	non-res.	25 [c]			28.6	
14.3 [e]		16 [c]	non-res.			29.0	
14.8	broad	res.				29.5	

[a] For references see (1975AJ02, 1980AJ01). See also (1985KI16: theory).

[b] Estimated.

[c] $4\pi \times \sigma(90^\circ)$.

[d] Natural parity.

[e] Resonant in γ_2.

[f] Resonant in γ_3.

Table 12.20: Some resonance partial widths in ^{11}B(p, γ)^{12}C and ^{11}B(p, α)^{8}Be [a]

E_p (MeV)	Γ_{cm} (keV)	Γ_{γ_0} (eV)	Γ_{γ_1} (eV)	Γ_{α_0} (keV)	Γ_{α_1} (keV)	Γ_p (keV)	^{12}C* (MeV)	$J^\pi; T$
0.162 [b]	5.3 ± 0.2	0.59 [c]	12.8 ± 1.5 [c]	0.26 ± 0.03	5.0 ± 0.2	0.0215 ± 0.0033	16.1060 ± 0.0008	$2^+; 1$
0.675	300	< 0.4	8.0	< 0.27	150	150	16.576	$2^-; 1$
1.388	1150	44	5	10	140	1000	17.230	$1^-; 1$
2.00 [d]	96 ± 5			4.6	11.4	76	17.79	$0^+; 1$
2.37 [h]	600 ± 1000						18.13	$(1^+; 0)$
2.64 [e]	≈ 400	$\approx 2 \times 10^{-3}$	3.2	65	177	68	18.38	$3^-; 1$
2.66	43	< 0.5	< 0.5	< 1	< 5	33	18.39	0^-
3.01	100					< 10	18.71	n.π. [g]; (1)
3.12	100	(0.4)	2.0	< 0.2	< 1.5	97	18.81	$2^+; 1$
3.5	1100	25	10	50	200	300	19.2	$(1^-; 1)$
3.75	(1100)	< 3	3	20	450	450	19.39	$(2^+; 0)$
7.25	3200	≥ 2500 [f]					22.6	$(1^-; 1)$

[a] For references see (1975AJ02, 1980AJ01). See also (1985KI16: theory).

[b] $E_{res.}(\text{cm}) = 149.1 \pm 0.7$ keV. This is the weighted average (Limitation of Statistical Weights Method) of the value quoted in reaction 20(a) and the two values in 20(c). This value corresponds to $E_x = 16106.0 \pm 0.8$ keV.

[c] See Tables 12.14 here and 12.7 in (1990AJ01).

[d] Decays via ^{12}C*(12.71) [$J^\pi; T = 1^+; 0$]: $\Gamma_\gamma = 3.7 \pm 1.5$ eV.

[e] Γ_γ to ^{12}C*(9.6) $= 5.7 \pm 2.3$ eV, consistent with $J^\pi = 3^-; T = 1$.

[f] Assuming a single resonance.

[g] Natural parity.

[h] Decays via ^{12}C*(15.11) [$1^+; 1$]: $(2J + 1)\,\Gamma_\gamma \geq 2.8 \pm 0.6$ eV.

(b) In (1993HO07, 1997TR01) radiative capture at $E_{\mathrm{p}} = 98$ MeV followed by decay via internal pair conversion to ^{12}C*(0, 4.4, 9.64) was measured; the internal conversion cross section was roughly two times larger than expected. At $E_{\mathrm{p}} = 1.6$ MeV, the pair decay of ^{12}C*(17.2) was studied (1996DE51) in a search for evidence of a massive neutral boson. See also (1994VA17).

(c) Excitation functions have been measured for $E_{\mathrm{p}} = 0.15$ to 18.9 MeV (see 1975AJ02), 35.4 keV to 18 MeV (see 1980AJ01), 4.5 to 24 MeV (see 1985AJ01). Also see references listed below and in the comments of Tables 12.19, 12.20 and 12.21.

Astrophysically relevant ^{11}B(p, α) cross sections were measured in (1993AN06: $E_{\mathrm{p}} = 17$ to 134 keV); see additional comments on electron screening in (1993AN06, 1997BA95, 2002HA51, 2002BA77) and other discussions in (1995YA07, 1996RA14, 2004RO27, 2004SP03, 2008LA18, 2010LA11, 2011ST01, 2012CO19, 2013KI06). The use of this reaction for clean fusion energy generation is discussed in (1996YU04: $E_{\mathrm{p}} = 0.165$ to 2.58 MeV, 1998LI51: $E_{\mathrm{p}} = 667$ and 1370 keV, 1999LI13, 2015BE28). Surface analysis techniques and related cross sections are given in (1991BA61: $E_{\mathrm{p}} = 660$ keV, 1992LA08: $E_{\mathrm{p}} = 650$ keV, 1996VO23: $E_{\mathrm{p}} = 160$ to 800 keV, 1998MA54: $E_{\mathrm{p}} = 1.7$ to 2.7 MeV, 2002LI29: $E_{\mathrm{p}} = 0.4$ to 1.6 MeV, 2010KO33: $E_{\mathrm{p}} = 2.2$ to 4.2 MeV). See additional theoretical analysis in (1992KO26, 1994SH21, 2006DM01).

The total cross section shows the 162 keV resonance and a broad peak centered at 600 keV. At $E_{\mathrm{cm}} = 300$ keV $\sigma(\alpha_0) = 1.03 \pm 0.06$ mb and $\sigma(\alpha_1) = 165 \pm 10$ mb (1987BE17). The parameters of the 162 keV resonance are E_{res}(cm) $= 148.3 \pm 0.1$ keV, $\Gamma_{\mathrm{cm}} = 5.3 \pm 0.2$ keV (1987BE17), 149.8 ± 0.2 keV, $5.2^{+0.5}_{-0.3}$ keV (1979DA03). Derived S-values lead to $S(0) = 197 \pm 12$ MeV $\cdot$ b (1987BE17).

The reaction proceeding via 3α breakup into the 3-body continuum is of astrophysical importance; however the reaction proceeds predominantly by sequential two-body decays via ^{8}Be*(0, 2.9). In past reviews, the reactions ^{11}B(p, α)^{8}Be and ^{11}B(p, α)^{4}He^{4}He were distinct in that experiments grouped with the later reaction detected both α particles from the decay of ^{8}Be.

In (2016LA27) the 3-body decay of ^{12}C*(16.11) was analyzed using Dalitz plots, which indicated primarily sequential decay. Analysis of the multiplicity $= 2\alpha$ and 3α events yields $\Gamma_{\alpha_0}/\Gamma = 0.054 \pm 0.011$ and 0.051 ± 0.005 respectively. The text includes discussion on the “ghost” of the ground state; it is suggested that a correction for the “ghost” could raise the Γ_{α_0}/Γ value by $\approx 25\%$ to around 0.065, as in (2012AL22).

Beams of $E_{\mathrm{p}} = 0.675$ and 2.64 MeV protons were used to study the decay mechanisms of ^{12}C*(16.576, 18.38) (2011ST01); the decays were found to proceed primarily via $l = 3$ and 1 α_1 emission, respectively.

At higher energies, resonances are observed at $E_{\mathrm{p}} = 4.68$, 5.10, 6.08, 6.58 and 7.11 MeV [$E_{\mathrm{x}} =$ 20.25 to 22.47 MeV] (1983BO19) and some broad structures are reported by (1983BU06). Contributions from ^{12}C*(23.0, 23.6, 25.4) are reported in (1975VA04). A wide resonance-like structure centered at $E_{\mathrm{p}} = 13$ MeV [^{12}C*(28)] with $\Gamma \approx 6$ MeV is reported by (1977BU07): the angular distributions of α_0 show prominent backward peaking. No marked structure is observed above $E_{\mathrm{x}} = 28$ MeV (1972TH1C: Ph.D. thesis).

The parameters of the observed resonances are displayed in Tables 12.19 and 12.20. The following summarizes the information on the low-lying resonances: for a full list of references see (1968AJ02, 1980AJ01).

$E_\mathrm{p} = \mathit{0.16\ MeV}$ [^{12}C*(16.11)]. This is the $J^\pi = 2^+$; $T = 1$ analog of the first excited states of ^{12}B and ^{12}N. The γ-decay is to ^{12}C*(0, 4.4, 9.6): the angular distribution of γ_3, together with the known α-decay of ^{12}C*(9.6), fix $J^\pi = 3^-$ for the latter (1961CA13).

$E_\mathrm{p} = \mathit{0.67\ MeV}$ [^{12}C*(16.58)]. The proton width [$\Gamma_\mathrm{p} \approx 150$ keV] indicates s-wave protons and therefore $J^\pi = 1^-$ or 2^-. This is supported by the near isotropy of the two resonant exit channels, α_1 and γ_1. The α_1 cross section indicates $2J + 1 \geq 5$: therefore $J^\pi = 2^-$. [This is consistent with the results of an α-α correlation study via ^{8}Be*(2.9) (1972TR07)]. The γ_1 E1 transition has $|M|^2 \approx 0.01$ W.u., suggesting $T = 1$ (1957DE11, 1965SE06). (1962BL10) report a γ branch to ^{12}C*(12.71) ($\approx$ 6% of the intensity of the γ_1 transition). Such a branch may also be present for ^{12}C*(17.23).

$E_\mathrm{p} = \mathit{1.4\ MeV}$ [^{12}C*(17.23)]. $(2J + 1)\, \Gamma_{\gamma_0} \geq 115$ eV. This indicates $J^\pi = 1^-$, with $T = 1$ most probable (1965SE06). $J^\pi = 1^-$ is also required to account for the interference at lower energies in α_0 and γ_0: see (1957DE11) and is consistent with the α-α correlation results of (1972TR07). Two solutions for Γ_p are possible; the larger (chosen for Tables 12.19 and 12.20) is favored by elastic scattering data (1965SE06).

$E_\mathrm{p} = \mathit{2.0\ MeV}$ [^{12}C*(17.76)]. The resonance in the yield of α_0 requires natural parity, the small α-widths suggest $T = 1$. For $J^\pi = 1^-$ or 3^- the small γ-widths would be surprising; $J^\pi = 2^+$ would lead to a larger anomaly than is observed. J^π is then 0^+; $T = 1$ (1965SE06). A study of $E_\mathrm{p} = 0.82$ to 2.83 MeV reports that $E_\mathrm{x} = 17.80$ MeV [$\Gamma_\mathrm{cm} = 96 \pm 5$ keV] decays via a 5.10 ± 0.03 MeV γ-ray to ^{12}C*(12.71): $\Gamma_\gamma = 3.7 \pm 1.5$ eV. The angular distribution is isotropic, as expected (1982HA12).

$E_\mathrm{p} = \mathit{2.37\ MeV}$ [^{12}C*(18.13)]. Seen as a resonance in the yield of 15.1 MeV γ-rays: $\sigma_\mathrm{R} = 0.77 \pm 0.15$ μb, $\Gamma_\mathrm{cm} = 600 \pm 100$ keV, $(2J + 1)\, \Gamma_\gamma \geq 2.8 \pm 0.6$ eV. The results are consistent with $J^\pi = 1^+$; $T = 0$, but interference with a non-resonant background excludes a definite assignment (1972SU08).

$E_\mathrm{p} = \mathit{2.64\ MeV}$ [^{12}C*(18.38)]. The resonance for α_0 requires natural parity; the presence of a large P_4 term in the angular distribution requires $J \geq 2$ and $l_\mathrm{p} \geq 2$. The assignment $J^\pi = 3^-$ is consistent with the data (1965SE06, 1972CH35, 1972VO01, 1974GO21). (1982HA12) report $E_\mathrm{x} = 18.38$ MeV, $\Gamma_\mathrm{cm} \approx 400$ keV, Γ_γ (to ^{12}C*(9.6)) $= 5.7 \pm 2.3$ eV, consistent with $J^\pi = 3^-$; $T = 1$. The total peak cross section is 4.2 ± 1.7 μb. Transitions to ^{12}C*(0, 4.4) are also observed: $\Gamma_\gamma \approx 2 \times 10^{-3}$ eV and 3.2 ± 1.0 eV, respectively.

$E_\mathrm{p} = \mathit{2.66\ MeV}$ [^{12}C*(18.40)] is not observed in these reactions: see ^{11}B(p, p).

$E_\mathrm{p} = \mathit{3.12\ MeV}$ [^{12}C*(18.80)]. The angular distribution of γ_0 indicates E2 radiation, $J^\pi = 2^+$. This assignment is supported by the angular correlation in the cascade γ_1 and by the behavior of $\sigma(\alpha_0)$; $T = 1$ is suggested by the small Γ_α (1965SE06). The yield of γ_3 (to ^{12}C*(9.6)) shows a peak corresponding to $E_\mathrm{x} \approx 18.9$ to 19.0 MeV. It may be due to ^{12}C*(18.8) with an energy shift due to interference (1982WR01).

The structure near $E_\mathrm{p} = 3.5$ to 3.7 MeV [^{12}C*(19.2, 19.4)] seems to require at least two levels. The large Γ_{γ_0} requires that one be $J^\pi = 1^-$; $T = 1$ and interference terms in $\sigma(\alpha_0)$ require the other to have even spin and even parity: $J^\pi = 2^+$; $T = 0$ is favored (1963SY01, 1965SE06). (1982WR01) do not observe any evidence for an isospin mixed doublet near $E_\mathrm{x} = 19.5$ MeV [$E_\mathrm{p} = 2.9$ to 4.6 MeV (60° and 90°)].

Levels at $E_p = 4.93$ and 5.11 MeV, seen in $\sigma(\gamma_1)$ (1955BA22) also appear in $\sigma(\alpha_1)$, but not in $\sigma(\alpha_0)$. Angular distributions suggest $J^\pi = 2^+$ or 3^- for the latter [^{12}C*(20.64)]; the strength of γ_1 and absence of γ_0 favors $J^\pi = 3^-$; $T = 1$ (1963SY01, 1965SE06).

The first seven $T = 1$ states in ^{12}B and ^{12}C have been identified by comparing reduced proton widths obtained from this reaction and reduced widths obtained from the (d, p) and (d, n) reactions: see Table 12.12 of (1980AJ01) and (1971MO14, 1974AN19).

21. ^{11}B(p, n)^{11}C $\quad Q_m = -2.7647 \quad E_b = 15.9569$

Excitation functions have been studied at $E_p = 2$ to 5, 2.6 to 5.5, 3 to 4, 4 to 11.5, 4 to 14 and 4.9 to 11.4 MeV [see (1968AJ02)], from threshold to 6.0, 5.4 to 7.5 and 10.87 to 27.50 MeV [see (1985AJ01)], $E_p = 13.7$ to 14.7 and 16 to 26 MeV [see (1990AJ01)]. At the higher energies the excitation function decreases essentially monotonically (1981AN16). At the lower energies many peaks are observed whose positions correspond with structures seen in ^{11}B(p, γ)^{12}C and ^{11}B(p, α)^{8}Be and ^{12}C(γ, n) and ^{12}C(γ, p) reactions, suggesting that resonances, and not fluctuations, are involved; see Table 12.21. Angular distributions do not change as rapidly as might be expected from the pronounced structures in the excitation function (1965OV01). The strength of the pronounced peak at $E_p = 6.03$ MeV ($E_x = 21.49$ MeV) appears to demand $J \geq 4$ (1961LE11). See also (1994SH21, 1995SH44, 1999AN35, 2009EL09).

Polarization measurements have been carried out for $E_{\vec{p}} = 186$ MeV (1994RA23, 1994WA22, 1995YA12) and 295 MeV (1995WA16) and at $E_{\vec{p}} = 7.0$ to 26.5 MeV [see articles cited in (1975AJ02, 1980AJ01, 1985AJ01)]. For high-energy interactions see (1994GA40, 1994GA49) and work cited in (1990AJ01).

22. ^{11}B(p, p)^{11}B $\quad E_b = 15.9569$

States shown in Table 12.21 are revealed in the excitation functions, which have been studied at $E_p = 0.3$ to 1.0, 0.6 to 2.0, 2 to 5.3 MeV [see (1959AJ76)], $E_p = 0.5$ to 4.0, 1.8 to 4.1 MeV [see (1968AJ02)], $E_p = 1.9$ to 3.0, 3.5 to 10.5, 7.5 to 21.5 MeV [see (1975AJ02)], $E_p = 1.8$ to 3.1, 1.9 to 3.0, 3.0 to 5.2, 3 to 8, 7.5 to 10.5 and 19.2 to 47.4 MeV [see (1980AJ01)], $E_p = 4.5$ to 7.5, and 5.4 to 7.0 MeV [see (1985AJ01)], and $E_{cm} \approx 0.15$ to 1.1 MeV (1990AJ01), $E_p = 0.3$ to 1.05 MeV (2011AM02), 0.5 to 3.3 MeV (2001CH78), 1.7 to 2.7 MeV (1998MA54), 2.2 to 4.2 MeV (2010KO33). No pronounced structure is observed above $E_x = 28$ MeV (1969TH1B, 1971TH1F, 1972TH1C). It is reported that in all the channels and throughout this energy range a strong 2^+ background is observed. It is suggested that it may be the low-energy tail of the isoscalar giant quadrupole resonance (1983BO19).

Table 12.21: Anomalies and maxima in ^{11}B(p, n)^{11}C and ^{11}B(p, p)^{11}B yields [a]

A			B			J^π	E_x [l]
E_p (MeV)	Γ_{lab} [b] (keV)	Res. in [b]	E_p (MeV)	Γ_{lab} (keV)	Res. in		(MeV)
			0.67 [k]	330	p_0	2^-	16.57
			1.4 [k]	1270	p_0	1^-	17.24
			2.08 ± 0.02	86 ± 20	p_0	0^+	17.87
			2.62 ± 0.01 [n]	290 ± 20	p_0	3^-; (1)	18.36
2.664	48 [h]		2.66 ± 0.01 [n]	46	p_0, p_1	0^-	18.40
3.16 [c]	100 [h]		3.15	110 ± 10	p_0, p_1		18.85
3.5	500 [h]		3.4	broad	p_1	2^-	19.1
3.78 [c]	50 [h]		3.85	400 ± 55	p_0, p_1	2^-	19.42
4.08 [c]	200 [h]	n_0	4.10	250 ± 35	p_0	1^+	19.70
4.28	100 [h]		4.35	400	p_1		19.88
4.68 [c]	170 [h,i]	n_0	4.68 [f]	330 ± 40	p_0, p_1	(1^+; 1)	20.25
5.065 [c]	190 [h,i,j]	n_0	5.10 [f,g]	350 ± 15	p_0, p_1	3^-; 1	20.60
5.49 [c]	400 [d]	n_0					20.99
6.02	560 [i,j]	n_0, n_1	6.08 [f]	290 ± 25	p_0, p_1, p_2	3^-	21.50
6.4 [b]	wide	n_0	6.58 [f]	7800 ± 1100	p_0, p_2, p_3	1^-; 1	21.98
≈ 7.0 [d]	340	n_0	7.11 [f]	720 ± 90	p_0, p_2, p_3	3^-	22.47
7.29	360 [j]	n_0, n_1					22.64
7.74	65 [i,j]	n_0, n_1				(2^-; 1) [m]	23.05
8.25	380 [i,j]	n_0, n_1					23.52
8.65	180 [i,j]	n_0, n_2					23.89
9.0 [e]							24.2
9.25	110 [i,j]	n_0, n_2					24.44
9.79	1000 [j]	n_0, n_1					24.93
10.14	180 [i,j]	n_0, n_2					25.25
10.91	440 [i,j]	n_0					25.96
11.88	300 [i]						26.85

A: From the (p, n) reaction. B: From the (p, p) reaction.

[a] See also Tables 12.11 in (1968AJ02), 12.13 in (1980AJ01) and 12.12 in (1985AJ01) for additional work. The earlier references are listed there. Note: in (1985AJ01) the (p, n) work of (1955BA22) was wrongly distributed into columns A and B. [b] See also (1965OV01) and see (1965SE06) for γ, n, p and α particle widths.

[c] See also (1980RA16).

[d] (1981HO13); see also for possible additional structures. See $\Gamma_{\rm lab} = 300$ keV in (1961LE11).

[e] Also resonance in $K_{\rm y}^{\rm y}(0°)$.

[f] (1983BO19). From R-matrix analysis; $\Gamma_{\rm FWHM} = 350$, 320, 310, 710 and 330 keV are observed for $E_{\rm p} = 4.68$, 5.10, 6.08, 6.58 and 7.11 MeV, respectively.

[g] See also α-decay in Tables 12.19 and 12.20.

[h] From (1955BA22). [i] From (1964BA16). [j] From (1961LE11).

[k] From (1957DE11) $\Gamma_{\rm p}/\Gamma = 0.5$ and 0.05 for $E_{\rm p} = 0.67$, 1.27 MeV, respectively. See (1953BE61) for different $\Gamma_{\rm p}/\Gamma$ values. [l] See also (1977RI01) and (1988ABZW).

[m] From ($\vec{\rm p}$, p) and ($\vec{\rm p}$, p$'$): $J^\pi = 2^-$; $T = 1$ is consistent with the data, see (1975AJ02).

[n] (1977MA37) suggest two resonances at $E_{\rm p} = 2.620$ and 2.660 MeV (± 10 keV) [$J^\pi = 3^-$ ($T = 1$) and 0^-], $\Gamma = 290 \pm 20$ and 30 ± 5 keV, respectively. In addition, a resonance at $E_{\rm p} = 2.80 \pm 0.01$ MeV [$J^\pi = 3^+$], $\Gamma = 300 \pm 50$ keV, is also reported.

Polarization measurements are reported in (1975AJ02, 1980AJ01, 1990AJ01) and in (2003HA11, 2003HA12, 2004KA53). For studies of high-energy interactions see (2004KA53, 2004KA56). Applied uses of this reaction are discussed in (1990BO15, 1994MI21, 1998MA54, 2010KO33) Also see (1994SH21, 1998DO16, 2013HA17).

23. ^{11}B(p, d)^{10}B $\qquad Q_{\rm m} = -9.2296$

At $E_{\vec{\rm p}} = 11.34$ to 11.94 MeV the VAP angular distributions and excitation functions of the deuterons have been studied by (1982BU03). See also (1991AB04, 1994SH21).

24. ^{11}B(d, n)^{12}C $\qquad Q_{\rm m} = 13.7323$

Angular distributions of the neutrons to many ^{12}C states up to $E_{\rm x} = 17.23$ MeV have been reported (see Table 12.22) for energies in the range $E_{\rm d} = 0.5$ to 10 MeV [see (1968AJ02)], $E_{\rm d} = 2.5$ to 4 MeV (1972ME06), $E_{\rm d} = 5.5$, 6 and 11.8 MeV [see (1975AJ02)], $E_{\rm d} = 0.9$ and 1.2 MeV (1975SI22), $E_{\rm d} = 7$ to 16 MeV (1981AN16), $E_{\rm d} = 12$ MeV (1983NE11), $E_{\vec{\rm d}} = 79$ MeV (1985FO05, 1987FO22), and $E_{\rm d} = 111$ keV (2001HO23), $E_{\rm d} = 120$ to 160 keV (2006PA27) and $E_{\rm d} < 5$ MeV (2013CO12).

Proton- and α-decay from excited states are reported in (1965OL01, 1985NE01). $J^\pi = 3^-$ for the 9.64 MeV state is favored on the basis of the angular distribution of the α-particles to

^{8}Be$_{\rm g.s.}$. There is no evidence for direct 3α-decay of ^{12}C levels in the range $E_{\rm x} = 9$ to 13 MeV, nor does ^{12}C*(10.3) appear to participate in this reaction (1965OL01). Relative spectroscopic factors obtained in several (d, n) and (^{3}He, d) studies are summarized in (1975AJ02), but see (1971MU18) for a discussion of the problems involved in comparing spectroscopic factors obtained in these different reactions.

See a comparison of cross section calculations from the TALYS nuclear reaction code with reaction rates from the NACRE data base in (2012CO01). Angular correlations of neutrons and 4.4 MeV γ-rays and neutrons and 15.1 MeV γ-rays are reported in (1968AJ02, 1975AJ02). For polarization measurements see references in (1990AJ01).

25. (a) ^{11}B(^{3}He, d)^{12}C $\quad Q_{\rm m} = 10.4634$
(b) ^{11}B(^{3}He, np)^{12}C $\quad Q_{\rm m} = 8.2388$

Table 12.22: States in ^{12}C from ^{11}B(d, n)^{12}C and ^{11}B(^{3}He, d)^{12}C [a]

$E_{\rm x}$ (MeV $\pm$ keV)	$\Gamma_{\rm lab}$ [c] (keV)	$l_{\rm p}$ [b]	l [c]	$J^{\pi}; T$	Decay branching ratios
g.s.		1	1	$0^{+}; 0$	
4.44		1	1	$2^{+}; 0$	
7.65			1	$0^{+}; 0$	
9.629 ± 10 [a]		2	2	$3^{-}; 0$	
10.84 ± 20	330 ± 30	$0 + 2$	0	$1^{-}; 0$	primarily α_0 (1965OL01)
$[11.16 \pm 50]$ [j]			(1)	$(2^{+}); 0$	
11.82 ± 20	290 ± 40	$0 + 2$	2	$2^{-}; 0$	α_0 (10%), α_1 (90%) (1965OL01)
12.70 ± 10		1	1	$1^{+}; 0$	α_1 (1965OL01, 1985NE01)
13.38 ± 20	500 ± 80		((0))	$(2^{-}); 0$	
(14.71 ± 10) [d]	< 15		0		
15.110 ± 3 [e]		1	1	$1^{+}; 1$	
16.11		1	1	$2^{+}; 1$	α_0 (3%), α_1 (97%) (1985NE01)
16.58 [l]				$2^{-}; 1$	
17.23 [e, f]	broad	> 1		$1^{-}; 1$	
18.27 ± 50 [d]	350 ± 50		(2)	$(4^{-}; 0)$	
18.38 ± 60 [h,k]	350 ± 50 [k]		(2)	$3^{-}; 1$ & $2^{-}; 0 + 1$	α_0 (5%), α_1 (32%), p_0 (63%) (1983NE11, 1985NE01)

Table 12.22: States in ^{12}C from ^{11}B(d, n)^{12}C and ^{11}B(^{3}He, d)^{12}C [a] (continued)

E_x (MeV ± keV)	Γ_{lab} [c] (keV)	l_p [b]	l [c]	$J^\pi; T$	Relative Decay
19.25 [d]			(2)	$(1^-; 1)$	
19.55 ± 50 [g,k]	575 ± 60 [k]		(2)	$(4^-; 1) + (2^-)$	α_0 (1%), α_1 (41%), p_0 (52%), p_1 (6%) (1983NE11, 1985NE01)
20.62 ± 60 [i,k]	525 ± 60 [k]		(2)	$(3^-; 0)$	α_0 (2%), α_1 (30%), p_0 (56%), p_1 (12%) (1983NE11, 1985NE01)
22.40 ± 80	350 ± 50		(2)	$(1^-; 1)$	

[a] See Tables 12.14 in (1980AJ01) and 12.13 in (1985AJ01) for the earlier references. See also (1983NE11).

[b] (d, n): see also Table 12.12 in (1968AJ02).

[c] (^{3}He, d): see also Table 12.13 in (1968AJ02) and (1971RE03).

[d] Not reported in (d, n): see Table 12.14 in (1980AJ01).

[e] From a study of slow neutron thresholds at $E_d = 1.627 \pm 0.004$ and ≈ 4.1 MeV [$E_x = 15.107 \pm 0.005$ and 17.2 MeV (broad) (1955MA76)]. In another study at the lower threshold [$E_d = 1.633 \pm 0.003$ MeV, $E_x = 15.112$ MeV, $\Gamma < 2$ keV] 15.1 MeV γ-rays are observed (1958KA31).

[f] Not reported in (^{3}He, d): see Table 12.14 in (1980AJ01).

[g] ^{12}C*(19.55) is composed of at least two states separated by $\approx$ 300 keV, the lower of which α-decays. The p_0 angular correlation suggests (2^-) (1983NE11, 1985NE01).

[h] (1983NE11) find that this group is due to unresolved states with $J^\pi; T = 3^-; 1$ and $2^-; T = 0 + 1$. $\Gamma(3^-) = 220 \pm 50$ keV is taken from (1971RE03) while $\Gamma(2^-) = 350 \pm 50$ keV is from (1983NE11, 1985NE01).

[i] A broader α-decaying region may lie under this peak (1985NE01).

[j] This level was reported in (1971RE03), but a recent study (2012SM06) found evidence against its existence.

[k] From (d, n) in (1983NE11); also see values reported in (1971RE03).

[l] (d, n), see (1974AN19).

Observed deuteron groups are displayed in Table 12.22. Also see Table 12.17, which has results from ^{10}B(^{3}He, p3α) and ^{11}B(^{3}He, d3α) complete kinematics studies given in (2007BO49, 2009KI13, 2010KI08, 2011AL28, 2012AL22, 2012KI07, 2013KI07). Angular distributions have been measured at $E(^{3}\text{He}) = 5.1$ to 44 MeV [see (1968AJ02)], 10, 11, 12, 18 and 44 MeV [see (1975AJ02)], 23.2 MeV [see (1980AJ01)], 43.6 MeV [see (1985AJ01)], 18.3 and 22.3 MeV [see (1990AJ01)] and 44 MeV (2012SM06). The angular distributions exhibit characteristic direct interaction features (1967CR04). A $J^\pi = 2^+$ state at $E_x = 11.16$ was reported at $E(^{3}\text{He}) = 44$ MeV in (1971RE03): the group appeared as an enhancement on the high energy side of the $E_x = 10.84$ MeV peak; however a study under the same kinematic conditions found no evidence for such a peak (2012SM06). The R-matrix analysis of (2012SM06) showed that the fit to their data was improved by including a $J^\pi = 2^+$ resonance at $E_x = 9.7$ MeV: note there is no visible peak in the spectrum at this energy. At $E(^3\mathrm{He}) = 22.3$ MeV, spectroscopic factors of $S = 1.6$ and 0.33 are deduced for ^{12}C*(0,4.4), respectively (1993AR14); See Table 12.14 in (1980AJ01) for earlier reported values and see (2010TI04, 2016CO14). The d_1-γ angular correlations are studied in (1988IG03).

26. $^{11}\mathrm{B}(\alpha, \mathrm{t})^{12}\mathrm{C}$ $\quad Q_\mathrm{m} = -3.8570$

Angular distributions of t_{0-3} and to ^{12}C*(12.7) have been measured at several energy between $E_\alpha = 15.1$ to 120 MeV [see references in (1968AJ02, 1975AJ02, 1980AJ01, 1985AJ01 1990AJ01)]. Single-proton transfer seems to be the dominant reaction mode (1967DE1K). Angular correlation measurements of t_1-γ are reported at $E_\alpha = 21$ to 30 MeV: see (1972EL09, 1987VA04, 1988IG04). See also reaction mechanism studies in (1989BA86, 1990BO23, 1990BA62, 1991BA23, 1998GA46, 1999GA43, 1999LE48).

27. $^{11}\mathrm{B}(^7\mathrm{Li}, ^6\mathrm{He})^{12}\mathrm{C}$ $\quad Q_\mathrm{m} = 5.9829$

At $E(^7\mathrm{Li}) = 18.3$ and 28.3 MeV, angular distributions to $^{12}\mathrm{C}_\mathrm{g.s.}$ were measured and analyzed via DWBA to determine the $^6\mathrm{He} + {}^{12}\mathrm{C}$ and $^7\mathrm{Li} + {}^{11}\mathrm{B}$ optical Model parameters (2009WU01). At $E(^7\mathrm{Li}) = 34$ MeV, angular distributions have been measured and spectroscopic factors deduced for the groups to ^{12}C*(0, 4.4, 7.7, 9.6, 10.8, 11.8, 12.7, 15.1, 16.1, 18.35) (1983NE11, 1987CO16). It is concluded on the basis of these and other works, that the group corresponding to $E_\mathrm{x} = 18.35 \pm 0.05$ MeV ($\Gamma = 350 \pm 50$ keV) consists of unresolved ^{12}C states with $J^\pi = 3^-$ ($T = 1$) and 2^- ($T = 0$ plus some mixing of $T = 1$). No states were observed with $E_\mathrm{x} > 18.35$ MeV.

28. $^{11}\mathrm{B}(^{11}\mathrm{B}, ^{10}\mathrm{Be})^{12}\mathrm{C}$ $\quad Q_\mathrm{m} = 4.7283$

Angular distributions involving ^{12}C*(0, 4.4) and ^{10}Be*(0, 3.4) have been measured at $E(^{11}\mathrm{B}) =$ 11 MeV (1985PO02).

29. $^{11}\mathrm{B}(^{13}\mathrm{N}, ^{12}\mathrm{C})^{12}\mathrm{C}$ $\quad Q_\mathrm{m} = 14.0134$

The ^{13}N valence proton wave function was evaluated using the (^{13}N, ^{12}C) reaction on ^{11}B at $E(^{13}\mathrm{N}) = 29.5$ and 45 MeV (1998DI14). States at ^{12}C*(0, 4.44, 15.1) are found to participate, along with 3α unbound states. Further studies on ^{24}Mg states, some of which are found to possess significant components of $3_1^- + 3_1^-$, $3_1^- + 1_1^-$ and $0_2^+ + 3_1^-$, are given in (1999DI04, 2001DI12).

30. (a) ^{11}B(^{14}N, ^{13}C)^{12}C $\quad Q_{\mathrm{m}} = 8.4063$
(b) ^{11}B(^{16}O, ^{15}N)^{12}C $\quad Q_{\mathrm{m}} = 3.8295$

Angular distributions to ^{12}C$_{\mathrm{g.s.}}$ were measured at $E(^{14}\mathrm{N}) = 41$, 77 and 113 MeV (1971LI11) and optical model parameters were deduced. For reaction (b), angular distributions to ^{12}C*(0, 4.44, 9.6) have been measured at $E(^{16}\mathrm{O}) = 27$, 30, 32.5, 35 and 60 MeV (1972SC03): at the highest energy the ratio of relative spectroscopic factors, $\theta^2/\theta^2_{\mathrm{g.s.}}$, for the transitions ^{11}B$_{\mathrm{g.s.}}$ + p $\rightarrow$ ^{12}C* is 0.12 and 0.05, respectively, for ^{12}C*(4.4, 9.6). See (1975SC35) for analysis of reactions to the ground state at $E(^{16}\mathrm{O}) = 27$ to 35 MeV, and see (1992KA19) for analysis of multi-cluster transfer processes in the reaction.

31. ^{11}C(d, p)^{12}C $\quad Q_{\mathrm{m}} = 16.4971$

The impact of reactions such as ^{11}C(n, γ), ^{11}C(n, α) and ^{11}C(d, p) on nucleosynthesis is analyzed (2012CO01).

32. ^{12}B(β^-)^{12}C $\quad Q_{\mathrm{m}} = 13.3694$

^{12}B decay to ^{12}C is complex. Most of the decay populates ^{12}C$_{\mathrm{g.s.}}$ with small branches populating ^{12}C*(4.4) and several α-particle unbound states (see Table 12.24). See general discussion in (1992BA11, 1993CH06). The ground state decay branch is determined by subtracting all other observed decay branches from unity. Early studies were motivated by evaluation of the ^{12}B and ^{12}N mirror decays to states in ^{12}C and by parity violation studies. The decay rates to ^{12}C*(4.4) measured in (1981KA31) are deduced while taking significant care to decrease systematic effects that could distort the results; they are the most precise and have been used as normalization factors in modern experiments to deduce the relative and absolute branching ratios of weaker decay branches. We adopt the branching ratios of (1981KA31) to ^{12}C*(4.4).

Significant efforts have focused mainly on the ratio of the β-decay branches of ^{12}B and ^{12}N to ^{12}C*(4.4) and the relevance of mirror asymmetries in β-decay; see Table 12.23. In the case of ^{12}N, the measurement is complicated because the high-energy 17.3 MeV β^+ particles can produce Bremsstrahlung photons and give rise to a huge background. A lower Q-value in the case of ^{12}B β^--decay makes these measurements less complicated. Discussion on systematic effects in the measurements is given in (1974MC11, 1978AL01).

In (1963PE10, 1963WI05) the experimental layout used a scintillator β-counter that covered only part of the total solid angle along with NaI detectors; the β-γ coincidence data were analyzed. Other experimental efforts surrounded the targets with well-type scintillators while also detecting γ-rays in a NaI detector and analyzing the β-γ coincidence events (1972AL31, 1974MC11). The use of Ge(Li) and HPGe detectors significantly improved results from the measurements reported

Table 12.23: Intensity ratio (R) for ^{12}N/^{12}B decay to ^{12}C*(4.44)

R	Reference	Absolute Intensity (%)	
		^{12}B	^{12}N
1.84 ± 0.10	(1963PE10)	1.3 ± 0.1	2.4 ± 0.2
1.72 ± 0.15	(1963WI05)		
1.52 ± 0.06	(1972AL31)	1.27 ± 0.06	(1.93 ± 0.11) [a]
1.74 ± 0.08	(1974MC11)		
1.56 ± 0.05	(1978AL01)	1.276 ± 0.050	(1.99 ± 0.10) [a]
1.607 ± 0.021	(1981KA31)	1.182 ± 0.019	1.898 ± 0.032
1.528 ± 0.027	(1988NA09)		

[a] Absolute intensity calculated from R and measured $^{12}\text{B} \rightarrow {}^{12}$C*(4.44) intensity.

in (1978AL01, 1981KA31, 1988NA09). In most cases, the ratio of ^{12}B-to-^{12}N β-γ(4.44) coincidences was measured by using an essentially identical configuration for the two decays; then in some cases the configuration was modified to permit an absolute measurement of the ^{12}B decay branch to ^{12}C*(4.4) (1978AL01). In (1963PE10, 1981KA31) absolute ^{12}N decay intensities were measured along with the mirror decay ratio.

In the early study of (1957CO59) β-delayed α particles were studied in an effort to validate the prediction of a narrow "3α" state located just above the breakup threshold. The Hoyle state was reported in ^{12}B decay with the branching ratio (1.3 ± 0.4)%, $J^\pi = 0^+$ and $Q(^{12}\text{C-}^{8}\text{Be-}\alpha) = 278 \pm 4$ keV ($E_\text{x} = 7.65$ MeV). Analysis of a higher energy α group (1958CO66) was consistent with a broad $J^\pi = 0^+$ (or 2^+) state near 10.1 MeV with a (0.13 ± 0.04)% branching ratio. Later, in (1963WI05) the α, β and γ products were measured and analyzed for evidence of states in the $E_\text{x} =$ 9 to 12 MeV region; their best fit included states at $E_\text{x} = 10.1$ and ≈ 11.8 MeV. It is later pointed out in (1967AL03, 2009HY02) that the early works such as (1958CO66, 1963WI05) assigned too much intensity to the $E_\text{x} = 10.3$ MeV strength because they were unaware of the presence of the $E_\text{x} = 12.71$ MeV state. The work of (1966SC23) found evidence for ^{12}C*(10.3 ± 0.3) decaying primarily to $^8\text{Be}_\text{g.s.} + \alpha_0$ with a likely $J^\pi = 0^+$ and for ^{12}C*(12.71) decaying $> 96\%$ to ^{8}Be*(2^+) $+ \alpha$, hence $J^\pi = 1^+$. The relative ratio of I_β(10.3)/I_β(12.7) was found as 0.20 ± 0.05.

On the other hand, the studies of (1962MA22, 1963GL04) used magnetic spectrometers to measure the $\beta^\mp$-particle energy spectra. While the main thrust of these measurements focused on the energy dependence of the shape factors, results on intensities to ^{12}C*(7.65, 10.3) were also obtained in the analysis. See also (2015MO10).

In (1963AL15), the $\gamma_{3.23}$-$\gamma_{4.44}$ sequential de-excitation γ rays from ^{12}C*(7.65) and the β-$\gamma_{3.23}$-$\gamma_{4.44}$ events are analyzed to determine $\Gamma_\gamma/\Gamma(7.65) = (3.8 \pm 1.5) \times 10^{-4}$ and the (1.7 ± 0.5)% for the ^{12}B β-decay branching ratio to ^{12}C*(7.65). A similar measurement was carried out using the Gammasphere array (2016MU06); in that work (0.64 ± 11)% is determined for the β-decay branching ratio to ^{12}C*(7.65) and $E_\gamma = 3216.9 \pm 0.4$ (stat.) ± 0.7 (sys.) keV and 4439.5 ± 0.7 (sys.) keV are determined for the transitions between the $J^\pi = 0^+_2 \rightarrow 2^+_1$ and $J^\pi = 2^+_1 \rightarrow 0^+_1$ states. This corresponds to $E_{\rm x} = 7657.8 \pm 1.0$ keV, which is in poor agreement with the adopted value in Table 12.13, $E_{\rm x} = 7654.07 \pm 0.19$ keV (1976NO02). In Table 12.24 it is highlighted that some of the differences in published branching ratios are connected with the use of updated values in their computations.

In (1973BA73) the energy of the Hoyle state was determined by implanting ^{12}B activity, produced via the ^{11}B(d, ^{12}B) reaction, into a thick Si detector and measuring the 3-α breakup energy, $Q = 379.6 \pm 2.0$ keV.

Prior to development of rare isotope facilities, the ^{12}B and ^{12}N activities were typically produced in the target using the ^{11}B(d, n) and ^{10}B(^{3}He, n) reactions, respectively. These approaches have the disadvantage of producing unwanted activities such as ^{11}C, ^{13}N and ^{14}O in the targets. Renewed interest in the higher-lying $J^\pi = 0^+$ and 2^+ states led to measurements where ^{12}B and ^{12}N were produced at rare isotope facilities. An early series of experiments (2002FY02, 2003FY02, 2003FY04, 2004BO43, 2004FY02, 2004FY03) focused on identifying ^{12}C*(10.3) $\rightarrow$ ^{8}Be$_{\rm g.s.} + \alpha$ and ^{12}C*(12.71) $\rightarrow$ ^{8}Be*(2^+) $+ \alpha_1$ as the dominant breakup mechanisms for these states by analyzing the α-particle correlations. These data also gave indications of important interference effects between the $E_{\rm x} = 7.65$ and 10.3 MeV $J^\pi = 0^+$ states, as had been suggested in (1963WI05). In follow up measurements, two different experimental approaches enhanced the available data (2005DI16, 2009DI06, 2009HY01, 2009HY02, 2014TE01); in one case the ions were implanted into a thin carbon foil and the full decay kinematics of breakup α-particles was measured. Analysis yielded the decay intensity of ^{12}C excited states along with an assessment of the decay mechanism. In the second approach, ions were implanted in a segmented strip detector whose thickness stopped the full decay energy of breakup α-particles; this calorimeter approach provided a measure of the energies populated in ^{12}C with fewer systematic effects than prior experiments. The general shapes of spectra observed in (2009HY01, 2009HY02) were found in reasonable agreement with prior results. Implementation of HPGe detectors in the setups of (2009HY01, 2009HY02) permitted a simultaneous and absolute normalization of the β branching ratios to all unbound states using the known branching ratio to the ^{12}C*(4.44) state. In this case, the total intensities of ^{12}C*(12.71, 15.11) must be adjusted to account for the Γ_γ decay branches. See Table 12.24.

The work of (2009HY01, 2009HY02, 2010HY01) focused on a search for unknown and unresolved $J^\pi = 0^+$ and 2^+ strength in the $E_{\rm x} =$ 9-16 MeV region. Their analysis found that interference of the $J^\pi = 0^+_2$ state with other $J^\pi = 0^+$ strength around $E_{\rm x} \approx 11.2$ MeV leads to “the very broad component from 8.5 to 11 MeV, which has been mistaken for a 10.3-MeV resonance with a 3-MeV width”. Rather than attribute their observed strength to a 10.3 MeV group, they provided the β feeding strength for the $E_{\rm x} =$ 9-12 MeV and 12-16.3 MeV regions [excluding the 12.7 MeV state]. In (2010HY01), a multi-level many-channel R-matrix analysis of the data was carried out. The data was best fit with a $J^\pi = 0^+$ state at $E_{\rm x} = 11.2 \pm 0.3$ MeV with $\Gamma = 1.5 \pm 0.6$ MeV and B(GT) $= 0.06 \pm 0.02$ and a $J^\pi = 2^+$ state at $E_{\rm x} = 11.1 \pm 0.3$ MeV with $\Gamma = 1.4 \pm 0.4$ MeV and B(GT) $= 0.05 \pm 0.03$.

Table 12.24: Branching in ^{12}B(β^-)^{12}C

Decay to ^{12}C* (MeV ± keV)	Branch (%)	log ft [a]	Refs.
g.s.	**98.216 ± 0.028** [b]	4.0617 ± 0.0005	
$E_\gamma = 4.43891 \pm 0.31$ [c]	**1.182 ± 0.019** [d]	5.143 ± 0.007	(1981KA31)
7.6543 ± 2.0 [e, f]	**0.54 ± 0.02**	4.574 ± 0.017	
	1.3 ± 0.4		(1957CO59)
	1.1 ± 0.3 [g]		(1963AL15)
	0.54 ± 0.02 [h, m]		(2009HY01)
	0.63 ± 0.11 [i]		(2016MU06)
10.3 ± 0.3 [j]	**0.062 ± 0.003**	4.29 ± 0.20	
	0.13 ± 0.04 [k]		(1958CO66)
	0.07 ± 0.02 [k]		(1963WI05)
[9-12 MeV] [n]	0.063 ± 0.003 [h, m]		(2009HY01)
	0.055 ± 0.007 [l, m]		(2009HY01)
12.7	**$(2.6 \pm 0.2) \times 10^{-4}$**	3.91 ± 0.04	
	$(2.6 \pm 0.2) \times 10^{-4}$ [h, m]		(2009HY01)
	$(3.2 \pm 0.7) \times 10^{-4}$ [l, m]		(2009HY01)

[a] Based on $Q_{\rm m} = 13369.4 \pm 1.3$ keV and $T_{1/2} = 20.20 \pm 0.02$ ms.

[b] 100% minus the branching ratios measured to excited states.

[c] (1967CH19)

[d] See Table 12.23.

[e] Based on (2012WA38) and $Q = 379.6 \pm 2.0$ keV (1973BA73).

[f] See also $E_{\rm x} = 7657.8 \pm 1.0$ value from (2016MU06).

[g] In the original manuscript, the value (1.7 ± 0.5)% is calculated using $\Gamma_\gamma/\Gamma = (2.9 \pm 0.3) \times 10^{-4}$ and $B(4.4) = (1.3 \pm 0.1)$%. Here we used $\Gamma_\gamma/\Gamma = 4.16$ and $B(4.4) = (1.182 \pm 0.019)$%.

[h] Analysis of KVI data in (2009HY01).

[i] In the original manuscript, the value (0.64 ± 0.11)% is calculated using $\Gamma_\gamma/\Gamma = (4.07 \pm 0.11) \times 10^{-4}$. Here we used $\Gamma_\gamma/\Gamma = (4.16 \pm 0.11) \times 10^{-4}$.

[j] $\Gamma = 3.0 \pm 0.7$ MeV and $\theta^2_\alpha \approx 1.5$ (1966SC23).

[k] The analysis neglected β feeding to ^{12}C*(12.71).

[l] Analysis of JYFL data in (2009HY01).

[m] In (2009HY01) the branching ratios are normalized to $B(4.44) = (1.28 \pm 0.04)$% from (1990AJ01). In the present evaluation we adopted (1.182 ± 0.019)%. In the table the (2009HY01) values have been renormalized (decreased) to the updated $B(4.44)$.

[n] (2009HY01) integrated the strength in the $E_{\rm x}$ = 9-12 MeV region rather than attributing the strength to a 10.3 MeV group, see discussion.

33. ^{12}C decay

Violation of the Pauli exclusion principle could permit ^{12}C to decay by converting a p-shell nucleon into as $1s_{1/2}$-shell nucleon followed by emission of a $\approx$ 20 MeV γ ray. The reaction has not been observed. The limit on the mean lifetime of ^{12}C for this decay is $\tau_m \geq 5.0 \times 10^{31}$ yr (2010BE08); see also (1979LO13, 1998BA57, 1999AR22). Lifetimes for other ^{12}C$_{\rm g.s.}$ exotic decays are $> 8.9 \times 10^{29}$ yr (2010BE08); see also (2003BA42).

34. (a) ^{12}C(γ, n)^{11}C $\qquad Q_m = -18.7217$
(b) ^{12}C(γ, 2n)^{10}C $\qquad Q_m = -31.8414$

The total absorption, mainly (γ, n)+(γ, p), is dominated by a giant resonance peak at $E_x = 23.2$ MeV, $\Gamma = 3.2$ MeV [$\sigma_{\rm max} = 21$ mb] and by a smaller structure at $E_x = 25.6$ MeV, $\Gamma \approx 2$ MeV [$\sigma_{\rm max} \approx 13$ mb]: see (1975AH06) and references tabulated in (1968AJ02, 1975AJ02).

The (γ, n) cross section shows a giant resonance, $\sigma_{\rm max} \approx$ 7-8 mb, centered at about 23 MeV and consisting of an $\approx$ 1 MeV-wide group at 22.3 MeV and an $\approx$ 2 MeV-wide group at $\approx$ 23.3 MeV. A secondary maximum occurs at 25.5 MeV, $\Gamma \approx 2$ MeV with evidence for other structures at $\approx$ 30-31 and possibly at $\approx$ 35 MeV (1966FU02, 1966LO04); see also (1999AB39, 1999AB40, 2000AB35: $E_{\rm brem}$ = 20 MeV), (2003CH80, 2016HE07) and the atlas of photo-neutron cross sections (1988DI02).

The (γ, n_0) cross section has been measured at $\theta = 90°$ for $21 < E_x < 40$ MeV and compared with the (γ, p_0) cross section (1968WU01): the isospin mixing averages about 2% in intensity and shows structure at the giant resonance. Angular distributions of n_0 measured over the giant resonance region indicate that the main excitation mechanism is of a $1p_{3/2} \rightarrow d_{5/2}$ E1 single-particle character. No significant E2 strength is observed (1968RA21). At $E_\gamma = 60$ MeV a comparison of the (γ, n_0) and (γ, p_0) cross sections indicates the reaction mechanism is absorption and suggests the reaction is useful for studying correlated n-p pairs (1980GO13). A comparison of the ^{12}C(γ, p)^{3}H2α and ^{12}C(γ, n)^{3}He2α reactions at E_γ = 30 to 120 MeV is given in (2007AF02). See also results in (1993AN17: $E_{\rm brem}$ = 58 MeV), (2001KO62: $E_{\rm brem}$ = 70 to 140 MeV) and (1994RY03, 2000LE38, 2003VA20, 2011DZ02).

The (γ, 2n) cross section (reaction (b)) is much smaller than that for (γ, n): the highest value is 0.15% of the maximum value for reaction (a) in the energy range E_γ = 20 to 140 MeV (1970KA37). The reaction has been studied for $E_{\rm brem}$ = 100 to 800 MeV with an emphasis on ^{11}C production (1977JO02): see other references in (1975AJ02, 1980AJ01, 1985AJ01, 1990AJ01).

35. ^{12}C(γ, p)^{11}B $\qquad Q_m = -15.9569$

The photoproton cross section exhibits two broad peaks, the giant resonance peak at 22.5 MeV, $\Gamma = 3.2$ MeV, $\sigma_{\rm max} = 13.1 \pm 0.8$ mb and a 2 MeV broad peak at 25.2 MeV, $\sigma_{\rm max} = 5.6 \pm 0.3$ mb: see (1976CA21) and values listed in Table 12.19 in (1968AJ02). The (γ, p_0) cross section at the giant resonance is 11.0 ± 1.1 mb (1986KE06). While the E1 component dominates in the GDR, a 2% E2 contribution may be present (1976CA21). In contrast with the giant resonance peak in the (γ, n) cross section, the (γ, p) cross section shows a sharp peak in the center of the broad giant resonance peak. See also (1991IS09). Above 24.5 MeV the ground state (γ, p) and (γ, n) excitation functions have the same shape up to at least 36 MeV: see (1985FU1C).

The (γ, p) results of (1968FR12, 1968FR14, 1969CA22) are in good agreement with those of (1964AL20) for the inverse reaction, ^{11}B(p, γ_0)^{12}C [see reaction 20], when the population of ^{11}B*(4.4, 5.0) is taken into account: the required cross sections for the (γ, p_2) and (γ, p_3) processes peak at 1.5 mb at 29 and 30 MeV, respectively (1973DI1C, 1974DI17).

The population of ^{11}B states has been determined at various energies. The ground state is predominantly populated in these reactions; see measurements and discussion in (1980AJ01, 1985AJ01, 1990AJ01) and (1986AN25, 1986MC15, 1990SP06, 1990VA07, 1990VA09, 1991IS09, 1993IR01, 1994NI04, 1994ZO01, 1995HA03, 1995MO18, 1996KU36, 1996RU15, 1997AS01, 1997ZO02, 1998KU23, 1998SO18, 2001ME29, 2006MO11). Nuclear transparency, as well as the roles of different reaction mechanisms, including quasi-deuteron knockout, are investigated in (1990VA07, 1992RY02, 1992VA01, 1993HA12, 1993IR01, 1994IR01, 1994NI04, 1994RY03, 1995MO18, 1996AS02, 1996JO15, 1996RU15, 1997AS01, 1997BO22, 1997JO07, 2000LE38, 2002ME17, 2005GL05, 2005KA54, 2006CO19, 2013RO17).

Reactions in the Δ resonance region are discussed in (1992BA57, 1992GL04, 1995CR04, 1997JO07, 1997LI30, 1998GL14, 1999FI01, 2000DE58, 2000GL08, 2001MA31, 2002ME17, 2003GL03, 2006AN22, 2008GL05, 2010GL02, 2012GL02, 2013GL03, 2014GL03). In this region peaks corresponding to the removal of s-shell or p-shell protons from ^{12}C are observed in the missing mass spectrum, and quasi-free photo pion production is an important reaction mechanism. Searches for Δ components in the ^{12}C$_{\rm g.s.}$ are discussed in (2001BY01, 2002BY03). Evidence for η-mesic ^{11}B atoms is claimed in (1999SO18, 2000SO19, 2000YO02, 2002BA21); also see (1995LE26, 1996LE11, 1996RO06, 1997FI07, 1997HE14, 1998AB13, 1998EF09, 1998HE18, 1998PE12, 1999LE35, 1999TR09, 2000EF04, 2001BL13, 2001TR06, 2003HE18, 2003VA08, 2004MA27, 2005MO04, 2005NA17, 2005NA25, 2005NA35, 2006NA34, 2007HE29, 2008JI06, 2008ME15, 2015NE10).

36. (a) ^{12}C(γ, π^0)^{12}C $\qquad Q_{\rm m} = -134.9766$
(b) ^{12}C(γ, π^+)^{12}B $\qquad Q_{\rm m} = -152.9396$
(c) ^{12}C(γ, π^-)^{12}N $\qquad Q_{\rm m} = -156.9083$

Photo-pion production has been measured at $E_\gamma = 111$ to 160 MeV (1997BE22), 120 to 819 MeV (2008TA05), 130 to 165 MeV (1995VO17), 141 to 159 MeV (2008BA24), 170 to 177 MeV (1995GO27, 2008GO20), 200 to 350 MeV (2002KR02), 200 to 800 MeV (1998KR28, 2004KR16), 300 to 400 MeV (1991BE16) and 4.5 GeV (1993EG06). The $2\pi^0$ correlations were measured at $E_\gamma = 200$ to 820 MeV (2003ME32) and at 400 to 460 MeV (2002JA10, 2002ME22). General discussion, for example on photo-pion production in the Δ-resonance region, can be found in (1991TR02, 1992CA16, 1994BE31, 1994KO23, 1994OS02, 1995BA92, 1995HO12, 1996MA20, 1997EF03, 2000GL08, 2002BA23, 2004MU17, 2006DA17, 2007TR04, 2008CO04). Coherent photo-pion production is discussed in (1991BO26, 1993CA35, 1993LA07, 1993OL06, 1996TR07, 1997KA65, 1998PE09, 1999AB42, 1999DR17, 2005KR18, 2010NA04, 2012ZH39), and in-medium effects are discussed in (1996OS02, 1999LE35, 2002RO28, 2003RO20, 2003VI09, 2003VI11, 2005KR10, 2005RO13, 2006SC18). For ^{12}C(γ, π^+) see ^{12}B reaction 23 and for ^{12}C(γ, π^-) see ^{12}N reaction 8.

37. (a) ^{12}C(γ, d)^{10}B $\quad Q_{\rm m} = -25.1864$
(b) ^{12}C(γ, pn)^{10}B $\quad Q_{\rm m} = -27.4110$
(c) ^{12}C(γ, t)^{9}B $\quad Q_{\rm m} = -27.3663$
(d) ^{12}C(γ, pd)^{9}Be $\quad Q_{\rm m} = -31.7731$

Cross sections and angular distributions of the deuterons corresponding to transitions to ^{10}B$_{\rm g.s.}$ and/or low excited states have been measured at $E_\gamma \approx 40$ MeV: the results are consistent with E2 strength. There is some evidence for the excitation of higher states of ^{10}B via non-E2 transitions (1972SK08). For $E_{\rm brem} = 90$ MeV, the ratio of the yields of deuterons to protons is $\approx 2\%$, for particle energies 15 to 30 MeV. For higher particle energies, the ratio decreases (1962CH26). The excitation function for deuterons to $E_\gamma = 1.4$ GeV is given in (1969AN10, 1971AN15, 1972AN09, 1972AN22). The (γ, pn) reaction has been studied at $E_\gamma = 83$ to 133 MeV by (1988DA16), at $E_{\rm brem} = 150$ MeV by (1999KH06) and in the Δ-resonance region by (1987KA13, 1996HA17, 1996LA15, 1998HA01, 1998MA02, 1998YA05, 1999FR32, 2000WA20, 2001PO19); see also (1996OS01, 1998RY01, 1999IR01, 2000GR13, 2003WA01).

Momentum spectra for deuterons and tritons (reactions (a) and (c)) are reported at $E_\gamma = 300$ to 600 MeV by (1986BA07). The yield of tritons has been measured for $E_\gamma = 35$ to 50 MeV: see (1967KR05) and $E_\gamma < 1.2$ GeV (1972AN09). For reaction (d) see (1987VO08: $E_{\rm brem} = 80$ MeV), (1999MC06: $E_{\rm brem} = 150$ to 400 MeV) and (2007WA12: $E_{\overrightarrow{\rm brem}} = 170$ to 350 MeV).

38. ^{12}C(γ, α)^{8}Be $\quad Q_{\rm m} = -7.3666$

A study of the α breakup cross section using quasi-monoenergetic and polarized beams with $E_\gamma = 9.0$ to 10.7 MeV found enhanced E2 strength corresponding to $E_{\rm x} = 10.03 \pm 0.11$ MeV with $\Gamma = 0.80 \pm 0.13$ MeV and $\Gamma_\gamma = 60 \pm 10$ meV (2013ZI03); in the analysis the α-^{8}Be breakup angular distribution was analyzed to determine the E1/E2 contributions and the mixing phase. This state is interpreted as the $J^\pi = 2^+$ excitation of the $E_{\rm x} = 7.65$ MeV astrophysically important Hoyle state.

Table 12.25: Some states populated in ^{12}C(γ, α) reactions to discrete states in ^{8}Be (2008AF04)

$E_{\rm x}$ (MeV)	Γ (MeV) [a]	Decay Radiation
10.31	1.5	α_0
18.67	3.5	α_0, α_1
24.05	0.5	α_0, α_2
27.30	2.0	α_0, α_{3+4}
29.47	0.8	α_0, α_{3+4}
32.72	broad	^{8}Be*($19.9 < E_{\rm x} < 25.2$)

[a] Γ from decay to ^{8}Be$_{\rm g.s.}$. Also see $\Gamma(18.67) = 3.81$ MeV from α_1; $\Gamma(24.05) = 3.54$ MeV from α_2, and $\Gamma(29.47) = 0.90$ from α_{3+4}.

Also see (2011GA09, 2012GA39), (2016HA05: theory) and (1994OB03, 2011GA47, 2011IS14, 2013IS05, 2014IS06, 2015GA17: astrophys.).

At higher energies, the total cross section exhibits broad peaks at $E_{\rm x} = 17.47 \pm 0.12$ MeV with $\Gamma = 6.12 \pm 0.14$ MeV and 27.12 ± 0.34 MeV with $\Gamma = 4.56 \pm 0.14$ MeV (2008AF04). A pronounced minimum occurs at 20.5 MeV: to what extent the peaks have fine structure is not clear; see (1964TO1A) and references in (1968AJ02). Alpha energy distributions show surprisingly strong E1 contributions below $E_\gamma \approx 17$ MeV (1955GO59, 1964TO1A). For $E_\gamma < 22$ MeV, transitions are mainly to ^{8}Be$_{\rm g.s.}$ and ^{8}Be*(2.9) with the g.s. transition dominating for $E_\gamma \lesssim 14$ MeV. For $E_\gamma > 26.4$ MeV, ^{8}Be ($T = 1$) levels near 17 MeV are strongly excited (1955GO59, 2008AF04). The mechanism for formation of various ^{8}Be excited states up to $E_{\rm x} \approx 23$ MeV was carefully studied for photon energies below $E_{\rm brem} = 40$ MeV (2008AF04), and resonances have been deduced; see Table 12.25. See also (1992DZ02, 1993KI15, 1997GO16, 1998KO77, 2001KI33, 2002KO65).

The ratio for $\sigma(\gamma, \alpha_0)/\sigma(\gamma, {\rm p}_0)$ is 0.029 ± 0.012 at $E_\gamma = 28$ MeV (1989FE01). For other breakup processes see (1975AJ02, 1985AJ01).

39. ^{12}C(γ, γ)^{12}C

Inelastic scattering has also been reported to ^{12}C*(4.4, 9.6 ± 0.2, 11.8 ± 0.2, 12.7, 13.3 ± 0.2, 17.2 ± 0.2, 18.3 ± 0.2, 20.5 ± 0.2, 22-24 (giant resonance), 26.5 ± 0.4, 29.5 ± 0.3): see details in (1980AJ01) and (1980IS09, 1980IS13, 1982NOZV).

The $E_{\rm x}$ of ^{12}C*(4.4) is reported as 4439.4 ± 1.6 keV (1977WE1C), and the lifetime of the 4.4 MeV state was determined as $\tau_{\rm m} = 65 \pm 12$ fsec (1958RA14).

Resonance scattering and absorption by ^{12}C*(15.11) have been studied by many groups: see Table 12.15 in (1968AJ02). The branching ratios and partial widths are displayed in Table 12.9 in (1975AJ02) and Table 12.14. The scattering angular distribution indicates dipole radiation (1959GA09), the azimuthal distribution of scattered polarized radiation indicates M1 (1960JA01) and the large Γ_γ indicates $T = 1$. The branching ratio for the cascade decay via ^{12}C*(4.4) was reported as $(3.6 \pm 0.7)\%$ (1970AH02).

The ground-state width of ^{12}C*(16.11) was first reported as $\Gamma_{\gamma_0} = 7.5 \pm 1.9$ eV (1959KE19): see, however, Table 12.14 which shows a much smaller accepted value. For ^{12}C*(17.22), the scattering cross section is 1.0 ± 1.0 μb, consistent with Γ_γ from ^{11}B(p, γ) (1963SC21).

At higher energies, elastic scattering studies show the giant resonance peak at $\approx$ 24 MeV. A considerable tail is visible, extending to $>$ 40 MeV (1959PE32). At $E_\gamma = 23.5$ MeV, the peak of the giant resonance, the total photonuclear absorption cross section is 19.7 ± 0.4 mb (1983DO05), and $\Gamma_1/\Gamma_0 = 0.23 \pm 0.07$.

In (1990SC02) the cross sections were measured for $E_\gamma = 15$ to 140 MeV using tagged Bremsstrahlung photons. At low energies, ^{12}C*(15.1) and the GDR are prominent, while the scattering cross section is essentially flat above $E_\gamma = 30$ MeV. The ^{12}C*(16.1) state and additional strength are observed in the inelastic scattering to ^{12}C*(4.4). The ratio of dσ(150°)/dσ(60°) was studied in this range to reveal E1/E2 interference effects; E2 states are suggested near $E_{\rm x} = 28$ and 32 MeV. Previous measurements of the cross section at $\theta = 90°$ and 135° for $E_\gamma = 23.5$ to 39 MeV indicated a significant E2 strength [$1.9^{+0.8}_{-0.7}$ total isoscalar + isovector energy weighted sum rule] in addition to the dominant E1 strength (1980DO04, 1983DO05). However, measurements of the elastic differential cross sections for $E_\gamma = 22.5$ to 52.0 MeV ($\theta = 45°$, 90°, 135°) reported by (1984WR01, 1985WR02) were inconsistent with the results of (1980DO04, 1983DO05). The difference between the measured energy-integrated values of $\sigma(\gamma)$ and the E1 part of the photo-absorption cross section $\sigma_{E1}(\gamma)$ was small and not sufficient to verify E2 strength (1985WR02).

The scattering cross section has been measured for $E_\gamma = 150$ to 400 MeV by (1984HA08). Angular distributions for elastic and inelastic scattering are measured at $E_{\rm brem} = 158.8$, 195.2, 197.2, 247.2 and 290.2 MeV (1995IG01). Measurements of elastic and inelastic scattering to ^{12}C*(4.4) at $E_\gamma = 200$ to 500 MeV, including the Δ-resonance region, are given in (1993AH01, 1994WI13). A measurement of the total photoabsorption cross section for $E_\gamma = 600$ to 1500 MeV is given in (2010RU16). See theoretical analyses in (1996PA06, 1998HU01, 2002SC15, 2002VA01). For pair-production measurements at $E_{\rm brem} = 4.2$ to 31.1 MeV see (1983NO06).

The polarizabilities of bound nucleons in ^{12}C and ^{16}O were measured at $E_\gamma = 61$ and 77 MeV (1992LU01). The deduced values, $\tilde{\alpha}_{\rm N} = (11.5 \pm 0.8\ ({\rm stat.}) \pm 2.1\ ({\rm sys.})) \times 10^{-4}$ fm^3 and $\tilde{\beta}_{\rm N} = (2.5 \mp 0.8\ ({\rm stat.})\ \pm 2.1\ ({\rm sys.})) \times 10^{-4}$ fm^3, are in close agreement with the values for free nucleons. However, see the analysis of (2001WA24: $E_\gamma = 84$ to 105 MeV), which suggests that definite conclusions are severely hampered by model dependencies. See also (1995HA23: $E_\gamma = 58$ and 75 MeV, 2014MY01: $E_\gamma = 65$ to 115 MeV).

40. ^{12}C(e, e)^{12}C

Elastic scattering has been studied up to several GeV. The form factor is well accounted for by a harmonic-well model. Measurements of the elastic scattering form factor indicate the nuclear charge radius is $< r^2 >^{1/2} = 2.471 \pm 0.009$ fm [2.478 fm with dispersion corrections] (1991OF01), 2.464 ± 0.012 fm [2.468 fm with dispersion corrections] (1982RE12) and 2.472 ± 0.015 fm (1980CA07). This compares with $< r^2 >^{1/2} = 2.4829 \pm 0.0019$ fm from muonic X-ray studies (1984RU12). Other values are reported in (1968AJ02, 1975AJ02). See also (1995AN02, 1995AN13, 2010HA14). (1991OF01) reports evidence for an energy dependence of the elastic form factors.

The isoscalar vector hadronic coupling constant, $\gamma = 0.136 \pm 0.032$ (stat.) ± 0.009 (sys.) (1990KO47, 1990SO03, 1991SO08), is determined from analysis of parity violating electro-weak asymmetry in elastic scattering. Use of the parity violating elastic scattering asymmetries to obtain neutron densities is discussed in (2011MO35, 2012AB04, 2014MO03). See also (1990SU15, 1992MI09, 1993AL07, 1993AL20, 1993HO03, 1995KA14, 1998HO12, 2005ME10, 2009MO35).

Sharp inelastic peaks are reported along with widths in Table 12.26. See also (2009DE14, 2011AN17).

Table 12.26: States of ^{12}C from ^{12}C(e, e′)^{12}C [a]

E_x (MeV)	$J^\pi; T$	Γ_{γ_0} (eV)
4.44	$2^+; 0$ [i]	$(10.8 \pm 0.6) \times 10^{-3}$
7.65 [b]	$0^+; 0$ [i]	$(62.3 \pm 2.0) \times 10^{-6}$ [b]
9.64	$3^-; 0$ [i]	$(3.1 \pm 0.4) \times 10^{-4}$
10.84	$1^-; 0$	
11.83 [c]	$2^-; 0$	
12.71 [c, d]	$1^+; 0$	0.32 ± 0.02 [k]
14.08 [e]	$4^+; 0$	
15.11 [c, f]	$1^+; 1$	35.9 ± 0.6 [k]
15.44 ± 0.04		$\Gamma = 1.5 \pm 0.2$ MeV [g]
16.11 [c]	$2^+; 1$	0.35 ± 0.04 [m] 0.83 ± 0.06 [n]
16.57 [c, f, l]	$2^-; 1$	$(48 \pm 8) \times 10^{-3}$
17.6 ± 0.2		$(\Gamma_{\rm calc} = 100$ keV) [l]
18.20 ± 0.05 [c]	$(2^-; 0)$	$\Gamma = 300 \pm 100$ keV [h]
18.6 ± 0.1	(3^-)	$(\Gamma_{\rm calc} = 300$ keV) [l]
19.35 ± 0.10 [c, l]	$2^-; 1$	$\Gamma = 400 \pm 100$ keV [h]
19.59 ± 0.04 [c]	$4^-; 1$	$\Gamma = 550 \pm 70$ keV [h]
20.0 ± 0.1	(2^+)	
20.56 ± 0.05 [c]	$3^+; 1$	$\Gamma = 300 \pm 50$ keV [h]

Table 12.26: States of ^{12}C from ^{12}C(e, e)^{12}C [a] (continued)

E_x(MeV)	$J^\pi; T$	Γ_{γ_0}(eV)
21.6 ± 0.1	(3^-)	
22.0 ± 0.1	(1^-)	$(\Gamma_{\rm calc} = $2-3 MeV) [l]
22.7 ± 0.1 [c]	$(2^-; 1)$	$\Gamma = 450 \pm 150$ keV [h]
23.8 ± 0.1	(1^-) [j]	
24.9 ± 0.2		
25.5	(1^-)	
25.5	(3^-)	
26.4 ± 0.3		
27.8 ± 0.2		
30.2 ± 0.4		
32.3 ± 0.3		

[a] See also Tables 12.18 in (1975AJ02), 12.16 in (1980AJ01) and 12.15 in (1985AJ01) for additional information and for the earlier references.

[b] Γ from (2011VO16). The matrix element is 5.48 ± 0.22 fm^2 for the E0 decay by pair emission to ^{12}C$_{\rm g.s.}$ (1968ST20): see (1980AJ01). The value listed under Γ_{γ_0} is Γ_π.

[c] Form factors have been studied at back angles: see (1984HI06: $E_e = 50.7$ to 338 MeV) and (1987HI09: $E_e = 415$ MeV). See also Table 12.15 in (1985AJ01).

[d] $\Gamma_{\rm tot} = 14.6 \pm 2.6$ eV (1974CE01).

[e] $\Gamma \approx 0.3$ MeV.

[f] The Γ_{γ_0} shown are from (1983DE53).

[g] From (1983DE53).

[h] From (1984HI06).

[i] (1960BA38, 1964CR11, 1967HA1U).

[j] The giant dipole resonance has an average $E_x = 23.0 \pm 0.7$ MeV and $\Gamma = 5.7 \pm 0.7$ MeV. It may involve fine structure at $E_x = 22.2$, 22.8, 23.4 and 23.8 MeV. A strong and relatively narrow peak is reported at 23.6 MeV by (1987HI09).

[k] (2000VO04) measured at $q < 0.5$ fm^{-1}.

[l] See (1972AN03).

[m] (1978FR03).

[n] (1969GU05).

A study of the (e, e$'\gamma$) reaction by (1985PA01) shows that the relative phase of the longitudinal and transverse form factors of ^{12}C*(4.4) is negative.

Inelastic scattering data for the ^{12}C*(7.65) Hoyle state at $E_{\rm e} = 73$ MeV was collected and analyzed along with the world data resulting in the value $\Gamma_\pi = 62.3 \pm 2.0$ μeV for radiative decay (2009CHZX, 2010CH17, 2011VO16). This value is compared with prior measurements and other analyses; see (2005CR03) and (2014FR09) for references. Analysis of data in (2007CH04) suggests that the Hoyle state is dilute with a radius about 1.5 times larger than that of the ground state.

The longitudinal form factor for the $J^\pi; T = 1^-; 0$ isospin forbidden transition to ^{12}C*(10.84), which is sensitive to isospin mixing, was analyzed and indicates a transition strength B(E1) $= 0.39 \pm 0.20 \times 10^{-5}$ $e^2 \cdot$ fm^2 (1995CA14).

The isospin mixing between ^{12}C*(12.71) and ^{12}C*(15.11) [both $J^\pi = 1^+$; $T = 0$ and 1, respectively] has been measured by (1974CE01): $\beta = 0.19 \pm 0.01$ or 0.05 ± 0.01. The inelastic scattering to ^{12}C*(12.71, 15.11) was analyzed at $q < 0.5$ fm^{-1}, $\Gamma_{\gamma_0} = 0.32 \pm 0.02$ eV and 35.0 ± 1.1 eV were deduced, respectively (2000VO04). The results were combined with (1972SP1C) and (1973CH16) (other low q results) and produced an average of 35.9 ± 0.06 eV for the later transition. These compare with 38.5 ± 0.8 eV from (1983DE53). The Coulomb matrix element was also analyzed in (2000VO04); ME $= +118 \pm 8$ keV was deduced.

The longitudinal form factors show ^{12}C*(16.1, 18.6, 20.0, 21.6, 22.0, 23.8, 25.5) while the transverse form factors show ^{12}C*(15.1, 16.1, 16.6, 18.1, 19.3, 19.6, 20.6, 22.7, (25.5)). At $E_{\rm e} = 150.6$ MeV ($\theta = 180°$) two peaks are observed at 16.1 and at 19.6 MeV corresponding to E2 and M2-M4 excitations (1984RY01).

There appears to be evidence for structures at 18.1 ± 0.05, 19.5 ± 0.05 ($\Gamma = 0.5 \pm 0.1$), ≈ 24 and ≈ 34 MeV (1964GO14). The variation of F(q^2) with q^2 in the range 0-0.6 fm^{-2} shows good agreement with the calculations of (1964LE1D) which assumes four 1- particle-hole states at $E_{\rm x} = 19.6$, 23.3, 25.0 and 35.8 MeV (see also (1967CR02)). The behavior of the 19.2 MeV level suggests ascription to the expected giant magnetic quadrupole state $J^\pi = 2^-$; this state is not likely to have been seen in ^{11}B(p, γ)^{12}C (1965DE1C, 1965DE1K, 1967BI1K, 1967CR02). A positive parity state with a large longitudinal matrix element may also be present (1967BI1K).

No $\Delta T = 2$ excitations were observed in a search for isotensor components of the electromagnetic interaction (1993LO13).

Results and general analysis on scattering at medium to high energies are given in (1990DA14, 1991BR13, 1991BU04, 1991DE32, 1991ER06, 1991TA23, 1992PR01, 1992WA19, 1993AM11, 1993AR06, 1993DE33, 1994AM06, 1994JE04, 1995AV01, 1995DO23, 1995JO21, 1995MO11, 1995VA12, 1995VA33, 1997GI12, 1998RI01, 1999GU20, 2001CA04, 2001GU16, 2002CA26, 2003KI06, 2003KI09, 2003ME09, 2004KI21, 2005KI26, 2006KU01, 2006MA62, 2008CE01, 2009LI04, 2010AM01, 2010HA14, 2014KI06, 2015LO05, 2015MO24, 2015PA35, 2016RO32).

Reviews on the scaling and superscaling behavior of quasielastic electron scattering reaction cross sections are found in (2009MA57, 2010CA14). See other detailed discussion on scaling approaches in (1999DO05, 2003HA44, 2005AM03, 2005NA03, 2006BA62, 2006CA22, 2006CO15, 2007AM01, 2007KI16, 2007MA18, 2009AN06, 2009CI01, 2009MA57, 2009ME07, 2010AM01, 2011AN09, 2015AM02, 2015BE26, 2015KI01, 2016IV03).

Electro-production of hypernuclei is discussed in (1998HI15, 2003MI11, 2003TA41, 2005GA09, 2006YU03, 2007IO02, 2007TA25, 2008HA14, 2008LE08, 2010FU13, 2010GA29, 2014TA26).

41. (a) ^{12}C(e, e$'$p)^{11}B $Q_{\rm m} = -15.9569$
(b) ^{12}C(e, e$'$n)^{11}C $Q_{\rm m} = -18.7216$
(c) ^{12}C(e, e$'\alpha$)^{8}Be $Q_{\rm m} = -7.3666$
(d) ^{12}C(e, eπ^+)^{12}B $Q_{\rm m} = -152.9396$
(e) ^{12}C(e, eπ^-)^{12}N $Q_{\rm m} = -156.9083$

In (1984CA34) evidence for a monopole, $J^\pi = 0^+$, state near $E_{\rm x} \approx 20.5$ MeV which exhausts at least 1% of the energy weighted sum rule is found in (e, e$'$p$_0$). The decay of states in the giant resonance region via α-particles has been studied by (1993DE10, 1995DE23): the E2 decay is primarily to ^{8}Be*(2.9[$J^\pi = 2^+$]) and reveals a peak with $E_{\rm x} = 21.6$ and $\Gamma \approx 1.5$ MeV; see also (1991PO06, 1994CA08, 1999SA27).

Electron spectra in the region of large energy loss show a broad peak which is attributed to quasi-elastic processes involving ejection of single nucleons from bound shells; studies of e$'$-p coincidences reveal peaks corresponding to ejection of 1p and 1s protons (at 700 MeV the energies of the peaks are 15.5 ± 0.1 and 36.9 ± 0.3 MeV with $\Gamma = 6.9 \pm 0.1$ and 19.8 ± 0.5 MeV, respectively [1976NA17: DWIA]). Spectroscopic factors for 1s [$= 1.50 \pm 0.08$ (2000LA23)] and 1p [$= 3.56 \pm 0.12$ (2000LA23)] shell single-particle knockout reactions are discussed in (1990CA14, 1990DE16, 1990WE06, 1991WE10, 1991WE16, 1994IR01, 1994IR02, 1995BL10, 1995KE03, 1998WO01, 1999DO30, 1999RY06, 2000DU12, 2000LA23, 2002MA12).

At 500 MeV the quasi-elastic scattering cross section has been analyzed and indicates the Fermi momentum is 221 ± 5 MeV/c (1971MO06).

Studies of the quasielastic longitudinal and transverse response functions versus missing energy have been carried out. (1987UL03) find in the longitudinal response a broad bump at missing energies between 28 and 48 MeV, attributed to knockout from the s-shell. In the transverse response they find this bump on top of a broader feature with a threshold at 28 MeV extending beyond 65 MeV. This broad feature is attributed to two-particle knockout, a non-quasielastic reaction mechanism; it may account for the observed (e, e$'$) transverse-longitudinal difference. This feature is also observed in unseparated data at larger momentum transfers: it appears to grow with momentum transfer (1988WE1E). See also (1992BO10, 1992WA19, 1994MA26, 1995JO21, 2003AN15, 2003DE10, 2005MO04).

Multi-nucleon correlations and few-body interactions are discussed in (1993KE02, 1995KE03, 1995KE06, 1996KE03, 1996RY04, 1997RY01, 1998AL03, 1998BL06, 1998RY05, 2000DE58, 2000RO17, 2004MU29, 2005HO18, 2005KE06, 2006EG02, 2007PI05, 2009CI01, 2014CO05). Nucleon excitation studies are discussed in (1993RO13, 1995NI01, 1995ZO01, 1997GI02, 1997GI12, 1998GA25, 1999BA31, 2004BO47, 2008BO24, 2011VA11).

Effects such as transparency of the nuclear medium have been studied by (1990FR11, 1992BE23, 1992FR17, 1992GA02, 1992JE03, 1992PA03, 1993LO01, 1993NI11, 1994FR12, 1994FR16, 1994GR05, 1994IR02, 1994KO21, 1994MA23, 1994NI05, 1995FR04, 1996KE14, 1996NI13, 1997AL20, 1997IW03, 1999RY06, 2000DU12, 2000LA23, 2001FR06, 2002DE11, 2002GA43, 2002ME11, 2002ME17, 2003DU23, 2003RY02, 2004BA99, 2004BO47, 2004HA63, 2004LA13, 2005RO38, 2006RO37, 2007CL04, 2009KA02, 2010QI02, 2013RO06). Discussion on other final state effects is given in (1991CA09, 1994IR02, 1994JE04, 1994RY04, 1995BI07, 1995BI19, 1995NI02, 1996BI01, 1996BI21, 1996JE04, 1999KE04, 2002DE07, 2004BA99, 2004BB15, 2005BA07, 2005BA23, 2005PR02, 2007AL14, 2007PI05), and discussion on the reaction mechanism is found in (1990LO09, 1991VA05, 1992DR02, 1993CI05, 1993OF01, 1994IR01, 1994RY03, 1994TA11, 1994WE06, 1999MO02, 2002ME17, 2004FR27, 2004MU29, 2004RO35, 2004TA18, 2011RY03). See also (1993KE02, 1993KO12, 1994BI05, 1994VE08, 1994WA19, 1995RY02, 1996JO15, 1997BI06, 1997GI13, 1998HO20, 1999JO06, 2000DE38, 2000UD01, 2005KE04, 2009TA34, 2014MO25, 2014TO14).

42. (a) ^{12}C($\mu^{\pm}$, $\mu^{\pm}$)^{12}C
    (b) ^{12}C($\mu^{\pm}$, X)

Parity violating muon scattering is discussed in (1993MI03). A review of μ^--e$^-$ conversion reactions is given in (2006DE31). Cosmogenic production of nuclides, such as ^{11}C, is discussed in (2005GA19, 2006BA66, 2000HA33).

43. (a) ^{12}C($\pi^{\pm}$, $\pi^{\pm}$)^{12}C
    (b) ^{12}C($\pi^{\pm}$, $\pi^{\pm}$p)^{11}B $\qquad Q_{\rm m} = -15.9569$

Angular distributions of the elastic and inelastically scattered pions have been measured at many energies: see Table 12.27. See theoretical analysis in (1990BE53, 1990ER06, 1990FR02, 1990LI10, 1990MI08, 1990TA13, 1991AL01, 1991AR12, 1991OS01, 1991TA01, 1992BI06, 1993CH04, 1993CH16, 1993CH25, 1993MO27, 1993NI02, 1993PE09, 1994CH30, 1995AR02, 1995BA92, 1995KA49, 1996BI12, 1996CH16, 1996EB02, 1997SC09, 1998AH06, 1998CH42, 1998NU02, 1998PE09, 1998RO15, 1999HO13, 1999TA33, 2000EB05, 2000KH17, 2002NO13, 2004SA28, 2005EB03, 2005HA26, 2006AH02, 2006KA47, 2009FA02, 2010IO02, 2011EB03, 2013EB02, 2013KH17).

Angular correlations for π'-$\gamma_{4.4}$ and π'-$\gamma_{15.1}$ reactions have been studied by (1984SO12, 1984VO04, 1986OL07, 1988OL02) and (1988BA27), respectively. A detailed analysis of the sum rules for population of the $J^{\pi} = 1^-; T = 0$ ^{12}C*(10.84) state is given in (1993KO17). The possible group to ^{12}C*(15.4) has a width of ≈ 2 MeV (1981MO07); ^{12}C*(14.1, 16.1) were also populated. $J^{\pi} = 2^-$ for ^{12}C*(18.25, 19.4) and $J = 4$ for ^{12}C*(19.25) are suggested in (1987CO17); ^{12}C*(19.65) is also populated. Study of the giant resonance region suggests states at $E_{\rm x} = 19.85$, 22.10, 22.94, 23.70 and 25.40 MeV with $\Gamma \approx 330$, 198, 192, 79 and 232 keV, respectively (1993KO17). See also $E_{\rm x} = 20.0 \pm 0.2$ and 22.7 ± 0.4 MeV, with $\Gamma = 3.2 \pm 0.3$ and 1.0 ± 0.2 MeV (1984BL12) and $E_{\rm x} \approx 18.3$, 19.3, 22.1, 23.7 and 25.6 MeV (1982MO25).

A strong energy-dependent enhancement in the pion scattering to ^{12}C*(15.1) but not to ^{12}C*(12.7) is observed at $E_{\pi^{\pm}} = 100$, 180 and 230 MeV: this is interpreted as possible evidence for direct (Δ-h) components in the wave function of the $T = 1$ state (1982MO01). The charge-dependent matrix

Table 12.27: Summary of recent ^{12}C(π, π) angular distributions

E_{π^+} (MeV)	E_{π^-} (MeV)	Angular distribution to ^{12}C	References
13.9-200	29-280	g.s., 4.44, 7.7, 9.6, 12.7, 15.1, 18.3, 19.3, 22.1, 23.7, 25.6	See references in (1985AJ01)
50-673	19.5-673	g.s., 4.44, 7.7, 9.6, 12.7, 15.1, 16.1, 18.3, 19.3	See references in (1990AJ01)
18.8-43.5		g.s.	(1998AL08)
	20, 40	g.s.	(1994BU09)
30, 50	30, 50	g.s.	(1990SE04)
40, 50, 65	40,50, 65	g.s., 4.4, 7.7, 10.84, 19.85, 22.10, 22.94, 23.70, 25.40	(1993KO17)
50	50	g.s., 4.4, 7.7, 9.6, 12.7, 15.1	(1990RI04)
50	50	g.s., 4.4, 7.7, 12.7, 15.1, 16.1	(1990JA05)
400, 500		g.s.	(1997KA22)
	610-895	g.s.	(1995TA11)

element between the $J^\pi = 1^+; T = 0$ and $1^+; T = 1$ states, ^{12}C*(12.71, 15.11), was studied by (1990JA05); ME $= 157 \pm 35$ keV was deduced. See the results of (1981MO07) along with other values in Table 12.18. The ratio of the cross sections to, ^{12}C*(12.7, 15.1) at $E_{\pi^\pm} = 50$ MeV is 7.1 ± 1 [isospin averaged] (1988RI03). The excitation of these two states has also been studied for $E_{\pi^\pm} = 80$ to 295 MeV by (1988OA03). A preliminary value for the isospin mixing matrix element between ^{12}C*(18.4, 19.4), 250 ± 50 keV, was given in (1979BO2D, 1979MO1W: $E_\pi = 116, 180$ MeV).

The emission of 2 photons in the capture of stopped pions, i.e. (π^-, $\gamma\gamma$), occurs at a rate of $(1.3 \pm 0.3) \times 10^{-5}$/capture (1979DE06).

Strong energy dependence is observed in the π^+ absorption (1981AS07, 1983NA18). At $E_{\pi^\pm} = 50$ MeV the absorption of π^- is about twice that of π^+ (1983NA18). Analysis of 4.4 MeV γ-rays produced at $E_\pi = 73$ MeV yields $\sigma(\pi^+) = 14.5 \pm 3.0$ mb and a cross section ratio, $\sigma(\pi^-)/\sigma(\pi^+)$, of 1.23 ± 0.22 (1970HI10).

The Fermi-momentum distribution of protons was measured using reaction (b) at $E_{\pi^-} = 0.7$, 0.9 and 1.25 GeV (2000AB25).

44. (a) ^{12}C(n, n)^{12}C

(b) ^{12}C(n, nα)^{8}Be $\qquad Q_{\rm m} = -7.3666$

Table 12.28: Summary of ^{12}C(n, n) angular distributions studies

E_n (MeV)	^{12}C States	References
0.05-350	g.s., 4.4, 7.65, 9.6, 10.3, 10.8, 11.8	See references in (1968AJ02)
0.5-19.9	g.s., 4.4, 7.65, 9.6	See references in (1975AJ02)
1.5-14.93	g.s., 4.4	See references in (1980AJ01)
8.9-35	g.s., 4.4, 7.7, 9.6, 10.8, 11.8, 12.7, 13.4, 14.1, 15.1, 16.1	See references in (1985AJ01)
11-40.3	g.s., 4.4, 7.7, 9.6, 10.8, 11.8, 13.4, 14.1, 15.1, 16.1	See references in (1990AJ01)
2.2-8.5 (pol. n, n)	g.s.	(2005RO29)
5-18 (n, n$'\gamma$)	4.4	(2014NE09)
6-8.5 (n, n$'\gamma$)	4.4	(1994BE61, 1995BE69)
13-16	g.s., 4.4, 7.65, 9.64	(1994SC38)
14.2	7.65, 9.64, 10.3, 10.84, 11.83	(2008KO02)
15.57-17.29 (pol. n, n)	g.s., 4.4	(1993CH23)
28.2	g.s., 4.4, 9.6	(1997CH39)
65-225	g.s.	(2004OS02)
95	g.s., 4.4, 9.6	(2006ME26)
96	g.s.	(2002KL14, 2003KL05, 2003KL19, 2007BL10, 2008OHZT, 2011OH05)

Angular distributions and differential cross sections of elastically and inelastically scattered neutrons have been measured at many energies up to 350 MeV [see Table 12.28]. See other results in (1995TI10, 1995ZH49, 2013NE11). Discussion on polarization measurements is given in (1995CH12, 1995CH44, 2005CH58, 2006SV01, 2010WE06). For Optical Potential analyses see (1990NI02, 1991SH08, 1997EL13, 2001KA58, 2009WE04, 2011JA09, 2011RA34, 2012JA03, 2012PA09, 2015GH04, 2016AL14, 2016XU07); for Coupled Channels analyses see (2003AM08, 2005CA16, 2006SV01); for other analyses see (1990BE54, 1991BA39, 1992GA26, 1992KA14, 1992KA21, 1994IS08, 1994XI04, 1996CH33, 1996CH49, 1996GO48, 1997HA21, 1998SU23, 1999SU01, 2000CH31, 2000KE13, 2005PI16, 2008FR02, 2008FR11, 2008GE04, 2009AL05, 2009AL10, 2010NA18, 2016AR13, 2016FR09).

Angular correlations of (n, n$'\gamma_{4.4}$) have been studied at $E_n = 13.9$ MeV (1973DE45) and 15.0 MeV (1971SP01), and at 14 to 14.7 MeV [see (1968AJ02)]. The spin-flip probability for the transition to ^{12}C*(4.4) has been studied at $E_n = 7.48$ MeV (1971MC1K, 1972MC20) and at 15.0 and 16.9 MeV (1973TH08, 1974ME29). Its shape at $E_n = 7.48$ MeV is similar to that measured by (1964SC07) in the (p, p$'$) reaction at $E_p = 10$ MeV (1972MC20); while that at $E_n = 16.9$ MeV the shape is similar to that measured by (1969KO07) at $E_p = 20$ MeV (1974ME29). The quadrupole deformation parameter $\beta_2 = -0.67 \pm 0.04$ (1983WO02).

For reaction (b), complete kinematics involving ^{12}C*(7.65, 9.64, 10.84, 11.8, 12.7, 14.0, 15.1, 16.1) were studied at energies between $E_n = 11.5$ to 19 MeV (1991AN06). At $E_n = 14.4$ MeV ^{12}C*(9.6, 10.8, 11.8, 12.7) have been reported: see (1975AJ02). A detailed study on the population of ^{12}C*(9.6) at $E_n = 11$ to 35 MeV is given in (1983AN02): the decay is dominated by sequential feeding of ^{8}Be$_{\mathrm{g.s.}}$ at the higher energies; see also (1953JA1C). The α-decay of the 10.8 and 11.8 MeV states, together with stripping results, suggest $J^{\pi} = 1^{-}$ and 2^{-} for these states (1964BR25, 1971DO1K, 1975AN01, 1975AN02; see also (1966MO05)).

45. (a) ^{12}C(p, p)^{12}C
(b) ^{12}C(p, p$'$)^{12}C

Angular distributions of elastically and inelastically scattered protons have been measured at many energies up to $E_{\mathrm{p}} = 1040$ MeV: see Table 12.29. Table 12.30 displays the information on excited states of ^{12}C. A summary of the decay of some excited states is shown in Table 12.14.

Table 12.29: Recent work on ^{12}C(p, p) angular distributions

E_{p} (MeV)	Angular distribution to ^{12}C	References
2.4-1000	g.s., 4.4, 7.7, 9.6, 10.8, 11.8, 12.7, 14.0, 15.1, 16.1, 18.4, 19.3, 20.8	See references in (1968AJ02)
5.9-1040	g.s., 4.4, 7.7, 9.6, 10.8, (11.8), 12.7, 14.05, 15.1, 16.1, 18.2, 18.8, 19.3, 20.4, 21.5, 22.1, (22.4), 22.6, 23.5, 23.9, 25.3, (25.8), 27, 29.4	See references in (1975AJ02)
1.5-1000	g.s., 4.4, 7.7, 9.6, 12.7, 15.1, 15.4, 16.1	See references in (1980AJ01)
6.6-1000	g.s., 4.4, 7.7, 9.6, 10.8, 11.8, 12.7, 13.4, 14.05, 15.1, 15.3, 16.1, 16.6, 18.3, 19.2, 20.5	See references in (1985AJ01)
12.1-1000	g.s., 4.4, 7.7, 9.6, 12.7, 14.1, 15.1	See references in (1990AJ01)
0.45-2.2	g.s.	(1993LI62)
$\overrightarrow{1.0}$-$\overrightarrow{2.1}$	g.s. [a]	(1992BA30)
1.0-8.0	g.s., 4.4	(2011GU31)
1.5-1.8	g.s.	(1993DA16)
< 1.9	g.s.	(1990ER02)
1.8, 1.83	g.s.	(1994FA05)
2.5-3.6	g.s.	(1991YA10)
2.7-7.0	g.s.	(2011AB05)
< 3	g.s.	(2004JI10)
3-7	g.s.	(2006CA19)
$\overrightarrow{3.5}$-$\overrightarrow{7.5}$	g.s.	(1993SY01)
4.6-6.6	g.s.	(2000TO15)
4.9-6.1	g.s.: backscatter analysis	(2010TO03)
7.5	g.s., 4.4: $\theta_{\mathrm{p}-\gamma}$	(2006LE45)
8.4-20	4.44 (γ)	(1998KI15)
11-13	g.s., 4.44 [a]	(1991KA12)
14.23	g.s. [a]	(1992WI13)
16.5-20	g.s.	(1994AI04)

Table 12.29: Recent work on ^{12}C(p, p) angular distributions (continued)

E_p (MeV)	Angular distribution to ^{12}C	References
20	15.11: $\alpha_\pi = N_{e^+ + e^-}/N_{\gamma_0} = (3.3 \pm 0.5) \times 10^{-3}$	(1993BU23)
21	10.6, 12.7, 15.1	(1995SU30)
22	g.s. [a]	(2003AN11)
25	7.65, 9.64, ≈ 9.75, 10.8, 11.8, 12.71	(2011ZI01)
$\overrightarrow{35}$	12.7, 15.1, 16.1	(1990IE01)
50	g.s., 4.44, 7.65, 9.61	(1994HA61)
65-400	12.7, 15.1	(1995SA28)
66	7.654, 9.641: $\Gamma(9.641) = 48 \pm 2$ keV	(2013KO14)
66	g.s., 4.4, 7.65, 9.64, 9.75, 10.84, 11.83	(2009FR07, 2010FR03, 2012FR05)
71.2	g.s.	(1990EV01)
$\overrightarrow{100}$-$\overrightarrow{180}$	15.1: $\theta_{p-\gamma}$	(1990PL06)
100-400	12.7, 15.11	(1994SA42)
$\overrightarrow{150}$	g.s.	(2003HA12)
156	15.1, 16.1, 18.3, 19.4, 20.6, 21.6, 22.0, 22.7	(1997TE14)
170	15.1, 16.1, 18.35, 19.4, 21.6	(2001WO07)
$\overrightarrow{189}$	g.s.	(1992WI01)
$\overrightarrow{198}$	12.7, 15.11	(2001OP01)
$\overrightarrow{200}$	15.11	(1995WE10)
200	g.s.: $\theta = 160°$-$180°$	(1996YU02)
$\overrightarrow{200}$	g.s.	(1999CA11, 1999CA15)
$\overrightarrow{200}$-$\overrightarrow{800}$	4.44, 9.64, 10.84, 12.71, 15.11, 16.11, 16.58, 18.3, 19.4, 19.29, 19.65	(1994JO07)
280	15.11	(1990MI10)
$\overrightarrow{290}$, $\overrightarrow{420}$	g.s.: quasielastic	(1990CH16)
295	12.7, 15.11	(2007TA27, 2009TA13)
$\overrightarrow{319}$	12.7, 15.11	(1990BA14, 1990BA61)
300	g.s., 4.44, 7.65, 9.64, 12.71, 15.11	(2010OK01)
$\overrightarrow{318}$	15.11: $\theta_{p-\gamma}$	(1992LY01)
$\overrightarrow{318}$	g.s., 9.6, 12.7, 15.11, 18.3, 19.28, 19.65, 21.5, 22.0, 22.7, 23.8, 25.5	(1993BA37)
$\overrightarrow{392}$	7.65, 12.7, 15.1, 18.4, 19.5, 20.5, 22.5	(1999TA22)
$\overrightarrow{500}$	12.71, 15.11	(1991CH31)
$\overrightarrow{500}$	g.s.	(1990HO06, 1991BA45, 1996HO08)
800	Δ	(1995EN06)
1000	g.s.	(2004AN01)

[a] Analyzed resonances in ^{13}N.

Table 12.30: ^{12}C levels from ^{12}C(p, p′)^{12}C* [a]

E_x (MeV $\pm$ keV)	Γ (MeV)	$J^{\pi}; T$	E_x (MeV $\pm$ keV)	Γ (MeV)	$J^{\pi}; T$
4.4390 ± 1.1 [b,c]	[d]	$2^+; 0$	(19.65 ± 50)	(0.44 ± 0.1)	$(4^+; 0)$
7.65400 ± 0.20 [e]	[g,q]	$0^+; 0$	20.27 ± 50 [o]	0.14 ± 0.05	
9.63 ± 40 [h]	[f,g]	$3^-; 0$	20.57 ± 50	0.35 ± 0.1	$3^-; 1$
9.75 ± 0.15 [i]	0.75 ± 0.15	2^+	21.65 ± 100	1.20 ± 0.15	$3^-; 0$
10.78 ± 100 [h]		$1^-; 0$	(21.95 ± 150)	0.8 ± 0.1	$1^-; 1$
12.70 ± 80 [h]	[g]		(22.36 ± 50) [o]	0.3 ± 0.05	
14.05 ± 100 [h]		$4^+; 0$	(22.6 ± 100) [n]	0.9 ± 0.1	$1^-; 1$
15.11 ± 50 [h]	[g]	$1^+; 1$	23.50 ± 50	0.23 ± 0.1	$1^-; 1$
15.4 ± 100 [j,k]	1.41 ± 0.15	$2^+; 0$	23.92 ± 80	0.4 ± 0.1	$1^-; 1$
16.11			(25.3 ± 150)	0.51 ± 0.1	$1^-; 1$
16.57			(25.8 ± 300)	0.75 ± 0.15	$(1^-; 1)$
18.30 ± 30 [l]	0.38 ± 0.03	$(2^+, 2^-), 3^-$	(27.0 ± 300)	1.4 ± 0.2	$1^-; 1$
19.4 ± 30 [m]	0.48 ± 0.04	$2^-; 1$	(29.4 ± 300) [p]		$(2^+; 1)$

[a] See also Tables 12.18 in (1980AJ01, 1985AJ01) for the earlier references.

[b] On the basis of angular distributions to ^{12}C*(4.4, 12.7, 15.1) for $E_p = 22.2$ to 45 MeV, it is suggested that the E2 strength is fragmented with the major concentration, corresponding to the isoscalar E2 resonance, near 28 MeV, and subsidiary strength near 32 and 42 MeV, the latter possibly a part of the isovector quadrupole resonance.

[c] This state is identified at $E_x = 4437 \pm 7$ keV (1962BR10), 4440.0 ± 0.5 keV (1967KO14), 4442.2 ± 1.5 keV (1971ST22), 4439.2 ± 0.5 keV (1974NO07), and 4439.0 ± 1.1 (1974JO14).

[d] $\tau_m = 55 \pm 7$ fsec (1968RI16): $\Gamma_{\gamma} = 12.0 \pm 1.5$ eV.

[e] See $E_x = 7655.9 \pm 2.5$ keV (1971ST22), 7656.2 ± 2.1 keV (1971AU16), 7655.2 ± 1.1 keV (1974JO15), and 7654.00 ± 0.20 keV (1976NO02). Using the recommended value $E_x = 7654.07 \pm 0.19$ keV from (1976NO02) gives $Q(3\alpha) = 379.33 \pm 0.20$ keV.

[f] $\Gamma(9.641) = 48 \pm 2$ keV (2013KO14).

[g] See Table 12.14.

[h] (1965HA17, 1969SU03).

[i] (2012FR05).

[j] $\alpha_{\pi} = N_{e^+ + e^-}/N_{\gamma} = (3.3 \pm 0.5) \times 10^{-3}$ (1993BU23).

[k] $E_x = 15.3 \pm 0.2$ MeV (1977BU19) and 15.4 ± 0.1 MeV (1979GO16); $\Gamma = 2.0 \pm 0.2$ MeV (1977BU19) and 1.41 ± 0.15 MeV (1979GO16).

[l] $E_x = 18.20 \pm 0.10$ MeV (1965HA17, 1969SU03), 18.35 ± 0.05 MeV (1974BU17), 18.35 ± 0.03 MeV (1977BU19), and 18.30 ± 0.03 MeV (1983JO08); $\Gamma = 0.35 \pm 0.10$ MeV (1977BU19) and 0.38 ± 0.03 MeV (1983JO08). $J^{\pi} = 2^+$, 3^- (1977BU19) and 2^- (1983JO08).

[m] $E_x = 19.35 \pm 0.10$ MeV (1965HA17, 1969SU03), 19.40 ± 0.05 MeV (1977BU19), and 19.40 ± 0.03 MeV (1983JO08); $\Gamma = 0.53 \pm 0.1$ MeV (1977BU19) and 0.48 ± 0.04 MeV (1983JO08).

[n] (1977BU19): $E_p = 45$ and 155 MeV.

[o] Only at 45 MeV (1977BU19).

[p] Only at 155 MeV (1977BU19).

[q] $\Gamma_{\pi}/\Gamma = (6.0 \pm 1.1) \times 10^{-6}$ (1977RO05) and $(7.1 \pm 0.8) \times 10^{-6}$ (1977AL31).

The angular distributions have been analyzed by DWBA (and CCBA), DWIA (including microscopic calculations) and DWTA (DW t-matrix approximation with density-dependent interactions). Microscopic DWIA calculations give good results for transitions which proceed through the $S = T = 1$ part of the effective interaction and also give a reasonable description of the $S = T = 0$ transition. However the mechanism for the excitation of ^{12}C*(12.71) ($S = 1$, $T = 0$) remains a puzzle (1980CO05: $E_{\rm p} = 122$ MeV). The angular distributions of the inelastically scattered protons to ^{12}C*(12.71) are usually poorly fitted: see e.g. (1990IE01). In (1995SA28) the 0° cross sections were measured for ^{12}C*(12.71, 15.11) at $E_{\rm p} = 65$ to 400 MeV; the cross sections, which maintained a nearly consistent ratio at all energies, were evaluated via microscopic DWIA analysis that reproduced the data best by reducing the isovector tensor terms of the effective interactions. Also see the analysis of spin observables at $E_{\rm p} = 198$ MeV, for ^{12}C*(12.71, 15.11) up to $q \approx 200$ MeV/c (2001OP01).

At $E_{\rm p} = 402$ MeV the differential cross sections for ^{12}C*(12.7, 15.1) ($J^\pi = 1^+$) are very similar for large q. This may be due to the smallness of precursor effects [precursor to a pion condensate] (1981ES04).

The spin-flip probability (SFP) for the transition to ^{12}C*(4.4) has been measured for $E_{\rm p} = 15.9$ to 41.1 MeV: two bumps appear at $E_{\rm x} \approx 20$ and ≈ 29 MeV. It is suggested that the lower one is due to a substructure of the E1 giant dipole resonance while the upper one results from the E2 giant quadrupole resonance (1975DE32, 1982DE02). The SFP has also been studied at $E_{\vec{\rm p}} = 24.1, 26.2, 28.7$ MeV (1981FU12: to ^{12}C*(4.4)), at $E_{\rm p} = 42$ MeV (1981CO08: to ^{12}C*(12.7)), at $E_{\vec{\rm p}} = 397$ MeV (1982SE12: to ^{12}C*(9.6, 12.7, 15.1, 16.1)) [the SFP to ^{12}C*(9.6) is consistent with zero; the others exhibit large SFP at forward angles] and at $E_{\rm p} = 398$, 597 and 698 MeV (1983JO08: to ^{12}C*(18.3, 19.4)). The SFP has also been measured for ^{12}C*(12.71) at $E_{\rm p} = 42$ MeV (1977MO18) and for ^{12}C*(12.7, 15.1) at $E_{\rm p} = 23.5$ to 27 MeV (1978HOZJ) and $E_{\rm p} = 500$ MeV (1991CH31). The SFP was measured in the region of $5 < E_{\rm x} < 30$ MeV (1999TA22) and $10 < E_{\rm x} < 40$ MeV (1993BA37); see also (1990BA14, 1990BA61).

(1980HO07) have measured the angular distribution of γ-rays from the decay of ^{12}C*(12.7, 15.1) at $E_{\rm p} = 21.5$ to 27 MeV. Microscopic DW calculations were performed for the A_0 and a_2 coefficients from these and earlier data. The theoretical calculations underestimate A_0 for energies below 35 MeV and are in agreement with the experimental A_0 for higher energies. The calculations also predict significant differences in the a_2 values for the transitions from ^{12}C*(12.7, 15.1), and these are observed (1980HO07).

Angular distributions show that a large deformation exists: $\beta_2 = -0.72$ (1972DE13) and 0.6 (1967SA13); $\beta_2 = -0.663$ and $\beta_4 \approx 0$ (1983DE36); $\beta_2 = 55 \pm 11$, $\beta_0 = 0.15 \pm 3$ and $\beta_3 = 0.39 \pm 8$ (2010OK01). A DWBA analysis in (2010OK01) suggests ^{12}C*(7.65) has a structure that is consistent with the assumption of a dilute α-cluster condensed state as suggested by (2001TO23).

The p-$\gamma_{4.4}$ angular distributions have been studied at $E_{\rm p} = 7.5$ MeV (2006LE45). The p-$\gamma_{15.1}$ angular correlations have been studied at $E_{\vec{\rm p}} = 100$ to 180 (1990PI06) and $E_{\rm p} = 200$ MeV (1995WE10), 318 MeV (1992LY01) and 400 MeV by (1988HI12). See also (1990PI06, 1995SU30).

A study at $E_{\rm p} = 66$ MeV measured $\Gamma(9.64) = 48 \pm 2$ keV (2013KO14). Evidence for the $J^\pi = 2^+$ excitation of the $E_{\rm x} = 7.65$ MeV “Hoyle state” has been reported in (2009FR07, 2010FR03, 2012FR05: $E_x = 9.75 \pm 0.15$ MeV with $\Gamma = 0.75 \pm 0.15$ MeV) and (2011ZI01: $E_x \approx 9.6$ MeV). In these different experiments, the known states at (7.65, 9.6, 9.64, 10.83, 11.80, 12.71) were also observed. The $\Gamma \approx 600$ keV width initially reported in the (p, p′) work of (2009FR07) was reanalyzed in (2012FR05) along with the (α, α') data of (2011IT08) yielding the slightly higher $\Gamma = 0.75 \pm 0.15$ MeV value. In (2009FRZV), the authors question the validity of the $E_x = 11.16$ MeV state reported previously in ^{11}B(^{3}He, d) reactions and they reiterate the likely ^{12}C*(13.35) $J^\pi = 4^-$ spin assignment previously suggested in (2007FR17). In (1997TE14), inclusive (p, p′) and exclusive (p, p′p) and (p, p′α) reactions populated levels between $0 < E_x < 24.4$ MeV.

The GT$_+$ strength distribution in ^{12}B was analyzed in (2001WO07) by comparing the ^{12}C*(15.1, 16.1, 18.35, 19.4, 21.6) excitations with the corresponding $J^\pi = 1^+$, 2^+, 2^-, 2^- and 2^- excitations from ^{12}C(d, ^{2}He)^{12}B.

For theoretical analysis of elastic and inelastic scattering see (1990TA13, 1990TA16, 1991LI07, 1991TA01, 1992WA19, 1993BY02, 1993DE33, 1995MA23, 1996BE25, 1997DO02, 1997TE14, 1998GI01, 1998GU13, 1998KI17, 1998SU23, 1999GU17, 1999NA43, 2000CH31, 2000DE37, 2000LO20, 2004YA24, 2005PI16, 2006GU23, 2008FR02, 2013WE05, 2015TO11). Analyses of spin observables and polarized beam results are found in (1990BA14, 1990HA45, 1990ST32, 1990TA17, 1991BE45, 1992BE03, 1992BE24, 1992SH01, 1993CH14, 1993CO02, 1993KA45, 1993LA27, 1994DO03, 1994HI02, 1994PH02, 1994WI09, 1995BU37, 1995CH12, 1995CH44, 1995DE32, 1995DO31, 1995KA24, 1996DE31, 1996KA65, 1997BB17, 1997DO01, 1998DO16, 1998HI02, 1999AN32, 2000WE01, 2001HI10, 2001RA06, 2004CU02, 2005DE32, 2006ON03, 2007KH12, 2007YA13, 2008FU13, 2008KI13, 2009CO17, 2010NA18, 2011FU16, 2013PL02, 2014PL05). Global studies evaluating protons on a variety of targets are given in (1990BA14, 1990BA61, 1990HU09, 1990KA05, 1990PH02, 1990ST32, 1992KO04, 1993BE10, 1993CH14, 1993CO02, 1993KA45, 1994HA48, 1994WI09, 1995CH12, 1995CH44, 1995ER10, 1996GO48, 1997DO01, 1998DO16, 1999KU07, 2000DE43, 2000KE13, 2001KA58, 2002DI04, 2002FA14, 2002SA49, 2002TR12, 2005DE32, 2005KI04, 2005KO28, 2007KH12, 2007TA27, 2008FU13, 2008HA03, 2008KI13, 2009CO17, 2009WE04, 2010NA18, 2012DY01, 2012PA09, 2013ZU04, 2014HL01, 2015AR01, 2015BE12, 2016AR13). See also (1997IL02, 1998BA59, 1998KI15, 2001KI25, 2001WO07, 2010AZ01, 2011DU06: astrophysics).

46. (a) ^{12}C(p, 2p)^{11}B $Q_m = -15.9569$
(b) ^{12}C(p, pn)^{11}C $Q_m = -18.7216$
(c) ^{12}C(p, pd)^{10}B $Q_m = -25.1864$
(d) ^{12}C(p, pα)^{8}Be $Q_m = -7.3666$
(e) ^{12}C(p, 3p)^{10}Be $Q_m = -27.1854$

The (p, 2p) reaction has been studied up to energies above 1 GeV. At $E_p = 56.5$ MeV, p$_0$-decay from a state at ^{12}C*(20.3 ± 0.5) was reported (1969EP01). Table 12.31 shows states populated in reactions with 156 MeV protons. The analysis suggests the region above $E_x = 21$ MeV is dominated by $J^\pi = 1^-$; $T = 1$ resonances that mainly de-excite via single-nucleon emission. States

Table 12.31: ^{12}C states observed in inclusive ^{12}C(p, p$'$) and ^{12}C(p, p$'$p) and ^{12}C(p, p$'\alpha$) reactions at $E_{\rm p} = 156$ MeV (1997TE14)

$E_{\rm x}$ (MeV $\pm$ 50 keV)	Γ (MeV $\pm$ 10%)	$J^\pi; T$	$E_{\rm x}$ (MeV $\pm$ 50 keV)	Γ (MeV $\pm$ 10%)	$J^\pi; T$
15.38	2800	$2^+; 0$	21.61	1450	$2^+; 0$
16.1	narrow	$2^+; 1$	21.99	550	$1^-; 1$
16.62	280	$2^-; 1$	22.72	1200	$1^-; 1$
18.29	486	$2^-; 0$	23.57	238	$1^-; 1$
19.39	520	$2^-; 1$	24.04	659	$1^-; 1$
19.67	490	$4^-; 0+1$	24.38	671	$2^+; 0$
20.58	440				

in ^{11}B are studied in (2004YA20, 2004YO06). At higher energies, quasifree knockout reactions from distinct shells are observed; see experimental results reported in (1997HA15, 1998MA67, 1998NO04, 1999AC03, 1999CA11, 1999CA15, 2000NO03, 2003TA03, 2004AC08, 2004AN01, 2007RY02, 2008NO01). Discussions include p-p correlations, initial and final state effects, such as color transparency and nuclear modifications to the NN interaction; see (1992LE03, 1994FR12, 1994FR16, 1994KO21, 1995GA46, 1997GA16, 2000ST17, 2006DA15, 2006HI15, 2006VA08, 2007DA19, 2009CO10, 2011RY03, 2014CR05, 2015MO21, 2015OG03).

Although the shapes of the momentum distributions in the (p, pn) reaction (reaction (b)) at 400 MeV are consistent with quasifree knockout, the magnitude of the cross section relative to that for the (p, 2p) process is inconsistent with the PWIA model (1979JA20). However, a study of inclusive (p, p$'$) reactions along with exclusive (p, p$'$n) and (p, 2p) reactions at $E_{\rm p} = 200$ MeV (1999CA11, 1999CA15) found that a comprehensive accounting of p-shell knockout and s-shell knockout to excited states in the residuals was consistent with DWIA calculations, and apparently validated the impulse approach at this energy regime and lower. See also (2015MO21: theory) and ^{11}C yield measurements in (1993KO48).

The ^{12}C(p, pd) missing energy spectrum at $E_{\rm p} = 670$ MeV (reaction (c)) shows a strong bump at $E_{\rm miss} = 25$ MeV and a weaker one at $E_{\rm miss} = 45$ MeV, corresponding to the ^{10}B ground-state and ^{10}B*(20) regions, respectively (1981ER10). See also (1990LO18).

For reaction (d), at $E_{\rm p} = 56.5$ MeV (1969EP01) $T = 0$ states at ^{12}C*(22.2 $\pm$ 0.5, 26.3 $\pm$ 0.5) were reported to α_0-decay (natural parity) while states at ^{12}C*(19.7, 21.1, 26.3) were found to α_1-decay. It is suggested that ^{12}C*(21.1) has unnatural parity. At $E_{\rm p} = 44.2$ MeV ^{12}C*(12.7, 14.1, 21.6, 26.6) are observed in the angular correlations involving α_0; states at ^{12}C*(21.6, 24.1, 26.6) decay via α_1 to ^{8}Be*(3.0) [suggesting 2^+ for these states, assuming that only resolved states are involved (1981DE08)]. A detailed analysis of the ^{12}C(p, p3α) reaction at $E_{\rm p} = 14$, 18 and 26 MeV (1999HA27) indicates the involvement of ^{12}C(p, p$'\alpha$)^{8}Be and ^{12}C(p, α)^{9}B reaction channels. Other measurements at $E_{\rm p} = 101$ MeV (2009CO01, 2009MA21) and $E_{\rm p} = 296$ MeV (1998YO09) probed the cluster nature of ^{12}C by evaluating alpha cluster spectroscopic factors and

Table 12.32: Summary of ^{12}C(d, X) angular distributions studies

E_{d} (MeV)	^{12}C States	References
2.8-650	g.s., 4.4, 7.65, 9.6	See references in (1968AJ02)
1.39-80	g.s., 4.4, 7.65, 9.6, 12.7, 15.1	See references in (1975AJ02)
2.61-90	g.s., 4.4, 7.65, 9.6, 12.7, 14.1, 15.1, 16.1, 18.4	See references in (1980AJ01)
0.556-650	g.s.	See references in (1985AJ01)
35-70	g.s.	See references in (1990AJ01)
15.3	g.s., 4.4	(2007GA07)
37	GDR region	(2008GR22)
53	g.s., 4.4, 12.71, (γ)	(1993IS04)
$\overrightarrow{270}$	4.4, 7.65, 9.64, 12.7, (15.4), 18.35, 20.5, 21.7	(1999SA21, 2001SA68, 2002SA51)
110, 120	g.s.	(1993BE43)
170	g.s., 4.4	(2001BA18)
200, $\overrightarrow{200}$	g.s., 4.4, 7.65, 12.71	(2004KA53)
$\overrightarrow{393}$	12.71	(1995FU03)
$\overrightarrow{400}$	g.s., 4.4, 7.65, 9.6, 10.3, 11.83, 12.7, 15.4, 18.3, 20.4, 21.9, 23.8, 25.1, 26.5, 30 (35: $\Gamma \approx 5$ MeV)	(1990MO29, 1990MO38, 1990BA61, 1994MO21, 1995JO06, 1997BB17)
$\overrightarrow{1.8}$ GeV	g.s.	(1995TO15)
9 GeV/c	N*(2190)	(2001LA10, 2002LA06)

quasifree scattering; consistency with free scattering was found. See also (1994NE05, 1995GA39, 1995NE11, 1995TC01, 1997NE05, 1997SA04).

47. (a) ^{12}C(d, d)^{12}C

(b) ^{12}C(d, pn)^{12}C $\qquad Q_{\mathrm{m}} = -2.2246$

(c) ^{12}C(d, dα)^{8}Be $\qquad Q_{\mathrm{m}} = -7.3666$

The angular distribution of elastically and inelastically scattered deuterons has been studied at many energies: see Table 12.32. Measurements aimed at refining global model parameters are found in (1993BE43, 2001BA18); see also (1990GO28, 1990HU09, 1990ST32, 1992RA31, 2003EL08, 2004KE08, 2006AN14, 2006HA42, 2006PR13, 2008CHZT, 2010GU03, 2011MI20, 2012PA22, 2012UP01, 2016ZH26). Few-body and cluster model analyses are given in (1997MI29, 1999BR09, 2000MI36, 2007AL28, 2008FO06, 2009DE08, 2013BE27, 2014BE17). In (2009DA22, 2010OG03) a method is suggested for determining nuclear radii of unstable states by analysis of diffractive scattering; root-mean-square radii are estimated for ^{12}C*(7.65. 9.64, 9.9, 10.3, 10.84).

In addition to well-known states in ^{12}C such as ^{12}C*(4.4) [$E_{\mathrm{x}} = 4440.5 \pm 1.1$ keV (1974JO14)] and ^{12}C*(12.7, 15.1) [see Table 12.18 for charge-dependent matrix element results], the population of ^{12}C*((10.8 ± 0.2), (11.8 ± 0.2), 18.3 ± 0.3, 20.6 ± 0.3, 21.9 ± 0.3 (broad), ≈ 27 (broad)) is also reported (1975AS06). The $J^\pi = 2^-$ state here at 18.3 MeV is different from the 18.4 ± 0.2 MeV $J^\pi = 2^+$ state observed in α inelastic scattering (1995JO06). DWIA analysis indicates $J^\pi = (1^+)$ for $E_\mathrm{x} = 20.4$ MeV and $L = (1)$ for $E_\mathrm{x} \approx 30$ MeV (1994MO21). The GDR region was studied in (2008GR22). A preliminary report (1977CH1L) suggested two structures at $E_\mathrm{x} = 26 \pm 1$ and 29 ± 1 MeV, with $\Gamma = 2 \pm 1$ and 4 ± 1 MeV, respectively, and determine $L = 3$ in the excitation of ^{12}C*(18.4).

Isoscalar spin strengths and spin-flip probabilities are reported at $E_{\vec{\mathrm{d}}} = 53$ MeV (1993IS04), $E_{\vec{\mathrm{d}}} = 270$ MeV (2001SA68) and $E_{\vec{\mathrm{d}}} = 400$ MeV (1995JO06); S_1 shows peaks for $E_\mathrm{x} = 12.71$ and 18.35 MeV and suggestions of peaks above 20 MeV while S_2 is consistent with zero up to $E_\mathrm{x} = 24$ MeV range (2001SA68). Polarization observables are reported at, for example, $E_\mathrm{d} = 200$ MeV (2004KA53), $E_\mathrm{d} = 393$ MeV (1995FU03: $E_\mathrm{x} = 12.7$ MeV) and $E_\mathrm{d} = 1.8$ GeV (1995TO15). See also theoretical analysis in (1990SA45, 2001HI10, 2009DE02, 2009DE13).

The quadrupole deformation parameter is calculated to be $\beta_2 = -0.48 \pm 0.02$ independent of incident energy [$E_\mathrm{d} = 60.6$, 77.3, 90.0 MeV] (1975AS06: coupled channels analysis). (1971DU09: $E_\mathrm{d} = 80$ MeV) report $\beta_2 = 0.47 \pm 0.05$ and $\beta_3 = 0.35 \pm 0.06$ for ^{12}C*(4.4, 9.6), respectively. See also $\beta_2 = -0.5$ (2007GA07).

Reaction (b) was measured at $E_\mathrm{d} = 56$, 140 and 270 MeV (1994OK01, 1998OK04); the results indicate sensitivity to Coulomb-dissociation and dissociation-diffraction mechanisms (1990SA45, 1991EV03, 1995SA39, 1996SA10, 1998NA42, 1998TO08, 1998TO10, 2002ZA10, 2006EV05, 2012UP01). See also (2002EV01, 2003EV01, 2009DE08, 2014YE03, 2016OG02). Earlier results are reported at $E_\mathrm{d} = 5.00$ to 5.50, 9.20 and 9.85 MeV (1973SA03), 5.1 to 6.25 MeV (1973SH04), 5.4 and 6.0 MeV (1968BO02), 5.5 to 6.5 MeV (1972VA10), 56 MeV (1983BA37) and 2.1 GeV (1989PU01).

For reaction (c) see ^{8}Be in (1979HE06).

48. ^{12}C(t, t)^{12}C

Angular distributions of elastically scattered tritons have been measured at $E_\mathrm{t} = 1$ to 20 MeV. See (1968AJ02: $E_\mathrm{t} = 1$ to 12 MeV), (1975AJ02: $E_\mathrm{t} = 1.11$ to 20 MeV), (1980AJ01: $E_\mathrm{t} = 9.0$ to 17 MeV) and (1990AJ01: $E_\mathrm{t} = 33$, 36 MeV). See also the optical model analyses for $E_\mathrm{t} < 40$ MeV in (2007LI55, 2009PA07, 2015PA10).

49. ^{12}C(^{3}He, ^{3}He)^{12}C

Angular distributions of ^{3}He ions have been measured for $E(^3\mathrm{He}) = 2$ to 217 MeV: see Table 12.33. Parameters of observed ^{3}He groups are displayed in Table 12.34. See analysis on angular distributions in (1995GA22, 1997KH07, 2000MO34, 2001KU20, 2003BE70, 2003KH01,

Table 12.33: Summary of ^{12}C(^{3}He, ^{3}He) angular distributions studies

E(^{3}He) (MeV)	^{12}C States	References
2-32.6	g.s., 4.4, 7.65	See references in (1968AJ02)
3.6-217	g.s., 9.6, 12.7, 14.1, 15.1, 16.1	See references in (1975AJ02)
18-132	g.s.-16.1, 16.6, 18.4, 18.9, 19.6, 21.3, 23.5, 25.9, 28.8	See references in (1980AJ01)
1-132	g.s.	See references in (1985AJ01)
12-72	g.s., 4.4, 7.65, 9.6	See references in (1990AJ01)
22.4	4.44(γ)	(1994IG01)
46	7.65, 9.64, 10.84, 14.2, 15.2, 16.3, 17.2, 18.4, 19.7, 22.2, 25.1	(2014WH02)
50.5, 60	g.s, 4.4, 7.65, 9.64	(2013HA01)
50, 60	g.s. 9.6, 14.11	(1992AD06)
72	g.s, 4.4, 7.65, 9.64	(1992DE18)
98	g.s.	(1991GO25)
98	g.s., 4.44	(1995DA08, 1995DA21)
443	g.s.	(2003KA24, 2003KA26)
450	g.s.	(1995YA06)

2004BE42, 2007LU04, 2007OH01, 2008DE35, 2009GU16, 2009PA07, 2010HA19, 2015PA10). In (2003KH01), $E(^{3}\text{He}) = 72$ MeV data are analyzed and the deformation length $\delta_2 = 1.05$ fm is deduced for ^{12}C*(4.44). The ^{3}He-$\gamma_{4.44}$ angular correlations were measured in (1994IG01). See (2003KA24: $E = 443$ MeV) for polarization observables.

Table 12.34: States of ^{12}C from ^{12}C(^{3}He, ^{3}He), ^{12}C(α, α) and ^{14}N(d, α) [a]

E_x [b,c,d] (MeV ± keV)	Γ [d] MeV	Γ_{α_0}/Γ [p]	L [c,d] (MeV)	E_x [b,g] (MeV ± keV)	Γ (MeV)	$J^{\pi}; T$ [u]
0			0	0		$0^{+}; 0$
4.4422 ± 1.5 [e]			2	4.44 [h,y]		$2^{+}; 0$
7.67				7.67 [h]		$0^{+}; 0$
9.64			3	9.642 ± 14 [h,i,z]	0.030 ± 0.008 [i]	$3^{-}; 0$
				9.84 ± 60 [†]	1.01 ± 0.15	2^{+}
				9.93 ± 30 [‡]	2.71 ± 0.08	0^{+}
10.84			[j]	10.96 ± 0.10 [§]		$1^{-}; 0$ [v]
11.83			[j]	11.83 [j]		$2^{-}; 0$
12.71			0	12.7 ± 70 [j,k]		$1^{+}; 0$
				13.29 [l]	0.355 ± 0.050 [l]	
				13.3 ± 200 [#]	1.7 ± 0.2	(4^{+})
14.08		0.20 ± 0.10		14.08 ± 30 [m]		4^{+} [n,v]; 0
15.11 [f]		< 0.08	0			$1^{+}; 1$
15.2 ± 300 [d]	1.8 ± 0.3		2	15.5 ± 100 [o,q]	2.1 ± 0.3 [o]	$(2^{+}; 0)$ [o]

Table 12.34: States of ^{12}C from ^{12}C(^{3}He, ^{3}He), ^{12}C(α, α) and ^{14}N(d, α) [a] (continued)

E_x [b,c,d] (MeV ± keV)	Γ [d] MeV	Γ_{α_0}/Γ [p]	L [c,d] (MeV)	E_x [b,g] (MeV ± keV)	Γ (MeV)	$J^\pi; T$ [u]
16.11 [f]		0.18 ± 0.10	2			$2^+; 1$
16.58 [f]						$2^-; 1$
18.40 ± 60 [c,d,f]	0.4 ± 0.1	0.25 ± 0.10 [w]	2	18.5 ± 150 [j,o,q]		(2^+) [d]
18.9 ± 150 [d,f]	0.7 ± 0.15		2			(2^+) [d,&]
				19.50 ± 100 [o,r]	≈ 0.25 [r]	$(1, 2, 3)^+$ [r]
19.58 ± 60 [c,f]		0.21 ± 0.10 [x]				
				20.55 ± 100 [r]	≈ 0.2 [r]	$(2, 3)^+$ [r]
21.3 ± 150 [d,s]	1.4 ± 0.2 [s]		2	21.65 ± 100 [j,o,p,q]	0.43 ± 0.08 [g,s]	2^+ [d,v]
		[x]		22.35 ± 100 [o,r]	≈ 0.25	2^+ [d,r]
				22.4 ± 200		(5^-)
23.5 ± 200 [d]	0.6 ± 0.2		2	23.9 ± 100 [j,r,t]	≈ 0.4	
25.9 ± 300 [d]	2.2 ± 0.3	[x]	2	[q]		(2^+) [d]
28.8 ± 400 [d]	2.7 ± 0.4		2			(2^+) [d]

[a] See also Table 12.23 in (1975AJ02). [b] When no errors are shown, values are from Table 12.8 of (1980AJ01).

[c] $E(^3\text{He}) = 49.8$ MeV (1969BA06). [d] $E(^3\text{He}) = 130$ MeV (1977BU03).

[e] (1971ST22). [f] $T = 1$ (1969BA06).

[g] (1972FA07): $E_\alpha = 90$ MeV and $E_d = 52$ MeV; above $E_x = 15.5$ values are taken from other references, see footnotes.

[h] See Table 12.8 of (1980AJ01). [i] (1956DO41): ^{14}N(d, α)^{12}C. [j] Angular distribution not obtained.

[k] (1965PE17): ^{14}N(d, α)^{12}C. [l] (1965SC12): ^{14}N(d, α)^{12}C; see also (1965BR08).

[m] (1972FA07) suggests $J^\pi = 3^-$ for ^{12}C*(14.08) and 4^+ for ^{12}C*(15.6).

[n] (1977MC07): the decay is (9 ± 3)% to $^8\text{Be}_{\text{g.s.}}$ [this branching ratio is somewhat uncertain because there may be an appreciable effect due to continuum breakup].

[o] (1975BU1F, 1977BU19): $E_\alpha = 60$ MeV. [p] From (^{3}He, ^{3}He)^{12}C* → ^{8}Be + α (2014WH02).

[q] (1976KN05): $E_\alpha = 150$ MeV. [r] (1976VA07): $E_d = 40$ MeV.

[s] Possibly unresolved states with $\Gamma = 1.4 \pm 0.2$ MeV and $\Gamma = 0.43 \pm 0.08$ MeV. [t] Weakly populated.

[u] Best values: see Table 12.7 of (1980AJ01) when other footnotes are not given. [v] (1978RI03): $E_\alpha = 104$ MeV.

[w] Corresponds to $E_x = 18.35$ MeV; $J^\pi = 3^-$ state (2014WH02).

[x] (2014WH02) report states at $E_x = 19.7$, 22.2 and 25.1 MeV.

[y] $B(\text{E2}) = 37 \pm 1\ e^2 \cdot \text{fm}^4$ (2011IT08). [z] $B(\text{E3}) = 251 \pm 10\ e^2 \cdot \text{fm}^6$ (2011IT08).

[†] $B(\text{E2}) = 1.6 \pm 0.2\ e^2 \cdot \text{fm}^4$ (2011IT08); see also (2012FR05) who simultaneously fit (2012FR05) and (2009FR07: (p, p′)) and find $E_x = 9.75 \pm 0.15$ MeV and $\Gamma = 0.75 \pm 0.15$ MeV.

[‡] (2011IT08) suggested a 0^+_3 and 0^+_4 doublet with $E_x = 9.04 \pm 0.09$ MeV and $\Gamma = 1.45 \pm 0.18$ MeV and $E_x = 10.56 \pm 0.06$ MeV and $\Gamma = 1.42 \pm 0.08$ MeV, respectively. See other values in (1998YO02, 2003JO07).

[§] (1998YO02). [#] (2011FR02). Possible rotational band member with $J^\pi = 0^+_2, 2^+_2$ states.

[&] (1987KI16): ^{12}C(α, α').

Rainbow effects and Airy patterns are discussed in (1990DE31, 1990KU25, 1991GO25, 1991KU29, 1992AD06, 1992DE18, 1995DA08, 1995DA21, 1995GA22, 2010OG03). The radius of the ^{12}C*(7.65) Hoyle state is reported as 2.94 fm or 1.2-1.3 times larger than the g.s. radius (2008DE35); see additional comments on the dilute nature of the Hoyle state structure in (2006OG04, 2007OH01, 2008DE35, 2009DA22, 2010OG03, 2013HA01).

Angular distributions of the ^{3}He groups to ^{12}C*(15.11, 16.11, 16.58, 19.56) have been compared with those for the tritons to ^{12}N*(0, 0.96, 1.19, 4.25) in the analog (^{3}He, t) reaction: the correspondence is excellent and suggests strongly that these are $T = 1$ isobaric analog states (1969BA06: $E(^{3}\text{He}) = 49.8$ MeV). See also Tables 12.12 in (1980AJ01) and 12.34. At $E(^{3}\text{He}) = 46$ MeV, the inelastically scattered ^{3}He projectiles were detected along with the 3α particles from the breakup of α-unbound states (2014WH02); levels up to $E_{\text{x}} = 25.1$ MeV are observed.

The states reported by (1977BU03) at $E(^{3}\text{He}) = 130$ MeV [see Table 12.34]: ^{12}C*(4.4, 15.2, 18.4, 18.9, 21.3, 23.5, 25.9, 28.8) are all suggested to correspond to E2 transitions: their strengths add up to 46% of the EWSR (energy-weighted sum rule). The quadrupole deformation parameter $\beta_2 = 0.30$ can account for both the elastic and inelastic data providing that the ratio of the spin orbit and central deformation $\beta_{s.o.}/\beta_{cent.}$ is energy dependent ($E(^{3}\text{He}) = 20.5$ to 33 MeV) (1977KA25).

In (1980LE25) states were reported at $E_{\text{x}} = 9.15 \pm 0.2$ and 20.3 ± 0.2 MeV [$\Gamma = 1.8 \pm 0.2$ and 1.1 ± 0.2 MeV, respectively]: it was suggested that both are E0 states whose intensities are $(2.1 \pm 0.4)\%$ and $(2.6 \pm 0.2)\%$ of the EWSR: however these states are not confirmed, see (1981EY02, 1981YO04) in reaction 46 of (1985AJ01).

Cross sections are discussed in (1998BO39, 2008KO29, 2009LI01, 2011CH11).

For discussion on Δ-resonance excitation and coherent π^{+} production see (1990UD01, 1991DE31, 1992HE08, 1993DM01, 1993FE10, 1993HE03, 1993OL06, 1993RO09, 1993RO30, 1994DM03, 1994JA12, 1994KO23, 1994OS02, 1994OS03, 1994SN01, 1994UD01, 1995KE13, 1995ST29, 1996GA20, 1996OS02, 1997KA52, 1998DA25, 2000BO47, 2002DA20, 2005AL37, 2005BO22).

50. (a) $^{12}\text{C}(\alpha, \alpha)^{12}\text{C}$
(b) $^{12}\text{C}(\alpha, 2\alpha)^{8}\text{Be}$ $Q_{\text{m}} = -7.3666$

Angular distributions have been measured at many energies up to 1.37 GeV: see Table 12.35. Parameters of observed states of ^{12}C are displayed in Table 12.34. See general theoretical analyses of the angular distributions in (1990AB10, 1990AL05, 1990BO23, 1990CO29, 1990HU09, 1990LE18, 1991AN21, 1991BA23, 1991KU30, 1991LI25, 1991OK02, 1991ZH27, 1992ZH06, 1992ZH40, 1993AL10, 1993TA30, 1994AH05, 1994IN01, 1994RU12, 1994RU15, 1995AI03, 1995KH07, 1996ZH36, 1997CH48, 1998EL14, 1998GA46, 1999GA43, 1999IG02, 2000AB16, 2000EB02, 2000EL03, 2000GU07, 2001EL05, 2001KH02, 2001KI25, 2002HI07, 2002KH01, 2003MO11, 2003ZE06, 2004YA03, 2005AL18, 2005GR40, 2005KU23, 2006FA09, 2006FU11, 2006KU16, 2008KH14, 2008ZO03, 2010IZ01, 2010KA21, 2011AL23, 2011BE20, 2011BE42, 2011GU15, 2012DY01, 2012GI01, 2012PA22, 2013LA28, 2015SU14, 2016AN08, 2016HU08, 2016MI13, 2017BE01). Structures in large angle scattering are discussed in (1990DA23, 1991GO25,

1994DA32, 1995DA08, 2004OH13, 2008DE35, 2011BE42) and studies of backward angles scattering are emphasized in (1990TO09, 1994DA16, 1994YO06, 1995EN09, 1996SO20, 1998BE56, 2002AN26, 2002AR16, 2004JI10, 2012MA26). The large radii deduced for ^{12}C*(7.65), $R_{\text{rms}} = 2.89 \pm 0.04$ fm and ^{12}C*(9.9: $J^\pi = 2^+$), $R_{\text{rms}}(2^+_2) = 3.07 \pm 0.13$ fm, are significantly larger than for ^{12}C*(4.44) and have been suggested as evidence for Bose-Einstein condensate structures (2008DE35, 2009DA22, 2010OG03, 2011OG10, 2013OG05); see also (2004IT09, 2006OG04, 2006TA27, 2008KH02, 2008OHZX, 2008TA21, 2010BE32, 2010OG03, 2011IT08, 2016NA22).

In (2004IT09), an $L = 2$ component of the reaction was identified near $E_{\text{x}} = 9.9$ MeV with $\Gamma \approx 1.0$ MeV; the strength is associated with a rotational excitation of the Hoyle state. In (2011IT08), the state is identified at $E_{\text{x}} = 9.84 \pm 0.06$ MeV with $\Gamma = 1.01 \pm 0.15$ MeV. In (2012FR05) the (p, p′) data from (2009FR07) and the (α, α') data from (2011IT08) are simultaneously analyzed via R-matrix analysis, and the $J^\pi = 2^+_2$ state is identified at $E_{\text{x}} = 9.75 \pm 0.15$ MeV with $\Gamma = 0.75 \pm 0.15$ MeV. The large α width associated with this $J^\pi = 2^+_2$ state suggests a highly clustered structure.

In addition to the discovery of the $J^\pi = 2^+_2$ state, evidence is observed for other previously unreported states in the $E_{\text{x}} = 9$-12 MeV region. A group at $E_{\text{x}} = 9.93 \pm 0.03$ MeV with $\Gamma = 2.71 \pm 0.08$ MeV is identified with $J^\pi = 0^+$ strength; it is suggested as a $J^\pi = 0^+_3 + 0^+_4$ doublet (2011IT08); this state is seen at $E_{\text{x}} = 9.8^{+0.2}_{-0.4}$ MeV with $\Gamma = 2.7 \pm 0.3$ MeV in (2003JO07). Analysis in (2011IT08) suggests $E_{\text{x}} = 9.04 \pm 0.09$ MeV and $\Gamma = 1.45 \pm 0.18$ MeV for 0^+_3 and $E_{\text{x}} = 10.56 \pm 0.06$ MeV and $\Gamma = 1.42 \pm 0.08$ MeV for 0^+_4 states. Additional support for the interpretation of doublet $J^\pi = 0^+$ states is found in the GCM calculations of (2016ZH43) and in the cluster model analyses of (2016FU07, 2016IS15). See also (2015FU09, 2016KA19, 2016YO09).

At $E_\alpha = 240$ MeV (2003JO07), some evidence for $J^\pi = 2^+$ strength at E_{x} is reported at $E_{\text{x}} = 11.46 \pm 0.20$, but no evidence was seen for this state in the $E_\alpha = 386$ MeV data of (2011IT08). In addition, the results of (2011IT08) don't find support for the $J^\pi = 0^+$ and 2^+ strength at $E_{\text{x}} = 11.2$ and 11.1 MeV, respectively, deduced in the analysis of the ^{12}B/^{12}N β decay data (2010HY01); however, differences in analysis approaches may explain the different findings. At present it is difficult to suggest a clear picture of the $J^\pi = 0^+$ and 2^+ strength has emerged. See a review of $E\lambda$ transition strengths for $E_{\text{x}} \leq 10.84$ MeV in (2013CU05).

Evidence for a $\Gamma = 1.7 \pm 0.2$ MeV broad $J^\pi = (4^+)$ state at $E_{\text{x}} = 13.3 \pm 0.2$ MeV is seen in the reconstructed kinematics of 3α ejectiles (2011FR02). It is suggested that this state, along with the $J^\pi = 0^+_2$ and 2^+_2 states form a rotational band. Alpha-alpha correlations from ^{12}C*(14.1) to ^{8}Be$_{\text{g.s.}}$ lead to an assignment of $J^\pi = 4^+$ for that state (1977MC07); see also (1978RI03).

States at $E_{\text{x}} = 7.65$, 9.64, 10.84 and 14.08 MeV were observed along with a new state at $E_{\text{x}} = 22.4 \pm 0.2$ MeV (2014MA37); the angular correlations of breakup α-particles indicate a $J^\pi = 5^-$ assignment for the later. A ground state rotational band including ^{12}C*(0[$J^\pi = 0^+$], 4.44[2^+], 9.64[3^-], 14.08[4^+] and 22.4[5^-]) is suggested.

In the region of the GDR, prominent structures are observed consisting of two ≈ 2 MeV wide peaks at 26.2 and 29.2 MeV (1987KI16: see also for a discussion of deformation parameters). J^π assignments have been suggested for ^{12}C states with $9.6 \leq E_{\text{x}} \leq 39.3$ MeV on the basis of their decay into 3α-particles: see (1973JA02: $E_\alpha = 90$ MeV).

Table 12.35: Recent work on ^{12}C(α, α) angular distributions

E_α (MeV)	^{12}C States	References
2.5-56	g.s., 4.4, 7.65, 9.6, 11.8, 12.7, 14.1	See references in (1968AJ02)
12.5-166	g.s., 4.4, 7.65, 9.6	See references in (1975AJ02)
	10.7, 11.8, (12.87), 14.1, 15.7, 18.36, 19.36, 21.8, 22.67, 24.24	(1972FA07)
3.0-1370	g.s., 4.4, 7.65, 9.6, 14.1, 15.5, 26.2, 27	See references in (1980AJ01)
5-172	g.s., 4.4, 7.65, 9.6, 14.1	See references in (1985AJ01)
1.4-172	g.s., 4.4, 7.7, 9.6, 10.8, 11.8, 14.0, 15.3, 18.4, 21.6, 24.0, 26.2, 29.2	See references in (1990AJ01)
0.4-1.8	g.s.	(1990TO09)
2.6-8.2	g.s.	(2001BU20, 2002TI03, 2009TI02)
2.6-8.2	g.s., 4.4	(2012DE08)
3.8-4.6	g.s.	(1996SO20)
4.1-4.4	g.s.	(2004JI10)
4.265	g.s.	(1995EN09)
5.5-5.8	g.s.	(1994DA16)
5.5-8	g.s.	(1994YO06)
5.7	g.s.	(1998BE56)
12-20	7.65, 9.64	(2013CU04)
14-21	7.65, 9.64	(2012SO20)
22-30	7.65, 9.64, 10.84, 11.83, 13.3, 14.08, 17	(2011FR02)
25	4.4	(1994IG01)
25.5-35.2	g.s., 4.4	(2002AR16)
27.2	g.s., 4,44, 7.65, 9.64	(1991KO40)
28	g.s.	(1990AR24)
40	7.65, 9.64, 10.84, 14.08, 22.4 ± 0.2 ($J^\pi = 5^-$)	(2014MA37)
50.5	g.s.	(1999BO58)
60	7.65, 9.64	(2013RA20)
72-90	g.s., 4.44	(1994DA32)
89.1	g.s.	(1997GO10)
90	g.s.	(1992DE47)
90, 139	g.s.	(1991GO25)
240	g.s., 4.44, 7.65, 9.641, 10.3, 10.84, (11.46) (E0 strength at 21.5 ± 0.4 MeV)	(2003JO07, 1998YO02)
386	4.44, 7.65, 9.64, (9.75 ± 0.15), $9.93 \pm 0.03[J^\pi = 0^+]$, 10.3, 10.84, 11.83	(2004IT09, 2011IT08, 2012FR05)
4.2 GeV	g.s. ($< r_m^2 >= 5.4 \pm 0.2$ fm^2)	(1994MO30)

The quadrupole deformation, β_2, is -0.29 ± 0.02 (1971SP08), -0.30 ± 0.02 (1976PA05), -0.40 ± 0.02 (1983YA01); $\beta_3 = 0.24$ (1973SM03), 0.23 (1977BU19) and $\beta_4 = +0.16 \pm 0.03$ (1983YA01: see also for a review of deformation parameters). In (2003JO07) $\beta_2 = 0.753 \pm 0.049$, $\beta_0(7.65) = 0.187 \pm 0.13$, $\beta_3 = 0.556 \pm 0.066$, $\beta_0(10.3) = 0.157 \pm 0.011$, $\beta_1 = 0.026 \pm 0.005$ deformation parameter values are deduced.

In (2003JO07) strength was identified corresponding to $(27 \pm 5)\%$, $(78 \pm 9)\%$, and $(51 \pm 7)\%$ of the isoscalar E0, E1, and E2 energy weighted sum rule (EWSR), respectively, with centroids of 21.9 ± 0.3, 27.5 ± 0.4, and 22.6 ± 0.5 MeV and rms widths of 4.8 ± 0.5, 7.6 ± 0.6, and 6.8 ± 0.6 MeV. Less than 7% of the E3 EWSR strength was identified. See also (1998YO02, 2008KH02) and earlier work in (1976KN05, 1978RI03, 1981EY02).

Angular correlation measurements α_1-$\gamma_{4.4}$ have been carried out for $E_\alpha = 10.2$ to 104 MeV (see 1980AJ01, 1985AJ01, 1990AJ01). Measurements of the radiative widths for ^{12}C*(7.7, 9.6) are reported in (1974CH32, 1976MA46) and Table 12.14. The value for Γ_{rad} for ^{12}C*(7.65) implies a 45% faster rate for the (3α) astrophysical process (1974CH32). A detailed study of the ^{12}C*(7.65) de-excitation finds the decay is 99.1% via sequential α-decay to ^{8}Be$_{\text{g.s.}}$ and $< 0.9\%$ via direct decay into 3α-particles (2013RA20).

For cross sections analyses relevant to ^{16}O see (1990AR24, 1991DE15, 1992SA26, 1993DE03, 1996VO18, 1997AB52, 1997GO10, 1999AN35, 2000AN17, 2001BU20, 2001HU14, 2002TI03, 2004SP02, 2004SP04, 2005PA58, 2005SP06, 2006BU32, 2007FR22, 2007ST21, 2009AS01, 2009TI02, 2010KA21, 2011DU06, 2011IR01, 2011SP03, 2012CU04, 2012DE08, 2012SO20, 2013CU04, 2013DE03, 2013GA05, 2013KA03, 2014CH06, 2015IR01, 2015SH22). For reaction (b) and α-cluster knockout studies see (1999NA05, 1999ST06, 2007FR22, 2012CU04, 2012SO20, 2013CU04: exp.) and (2008JA02, 2009JA07, 2011CO10, 2014JA07: theory).

51. ^{12}C(^{6}He, ^{6}He)^{12}C

Angular distributions of elastic scattering have been measured at $E(^6\text{He}) = 5.9$ to 492 MeV; see Table 12.36. At $E(^6\text{He}) = 10$ MeV (1995WA01) the elastic angular distribution was found to fall off more quickly than expected when compared with the Rutherford cross section; on the other hand, measurements at $E(^6\text{He}) = 38.3$ and 82 MeV/A found an enhancement of cross section at angles larger than about 15° (2002LA20, 2011LO07). At $E(^6\text{He}) = 30$ MeV, scattering to ^{12}C*(0, 4.4) was measured and analyzed for $\theta_{\text{cm}} \approx 20°$-$100°$ using a coupled-channels approach (2014SM01). The nuclear forward glory effect was studied at $E(^6\text{He}) = 5.9$ MeV in (1998OS02, 1999OS04, 2002OS04), and the analysis indicated the low ^{6}He binding energy leads to a loss of flux from the elastic channel, even at very forward scattering angles.

See theoretical analyses in (1993GO06, 1995GA24, 1998TO05, 2000BO45, 2000KR13, 2000MI36, 2002AB16, 2002SU18, 2003AB26, 2003LE25, 2003ZA15, 2004AB12, 2004AB13, 2004MA57, 2005AL18, 2005MI29, 2007RO29, 2008BO19, 2008DE38, 2008EL03, 2008KE06, 2008RO16, 2009DO20, 2009KU25, 2010AY08, 2010DEZW, 2010LA09, 2010LU08, 2010MA61, 2011BA03, 2011LU14, 2012AL24, 2012GI01, 2014KU09, 2015IS03, 2016IB01, 2016SU13).

Table 12.36: Summary of ^{12}C(^{6}He, ^{6}He), (^{7}Be, ^{7}Be), (^{8}Li, ^{8}Li), (^{8}B, ^{8}B), (^{9}Be, ^{9}Be), (^{10}Be, ^{10}Be), (^{10}B, ^{10}B), (^{11}Li, ^{11}Li), (^{11}Be, ^{11}Be), (^{11}B, ^{11}B) angular distributions studies

$E(^{6}\mathrm{He})$ (MeV)	^{12}C States	References
5.9	g.s.	(1998OS02, 1999OS04, 2002OS04)
10	g.s.	(1995WA01)
57	g.s.	(1997PE03)
41.6 MeV/A	g.s.	(1996AL11)
38.3 MeV/A	g.s.	(2002LA20)
18	g.s.	(2004MI05, 2006MI19)
30	g.s., 4.4	(2014SM01)
82 MeV/A	quasi-elastic	(2011LO07)
$E(^{7}\mathrm{Be})$ (MeV)	^{12}C States	References
8-22.4	g.s.	(1990SM04)
18.8	g.s.	(2011BA25, 2011ZA05)
140	g.s.	(1989YA02)
280	quasi-elastic, breakup	(1995PE09, 1996SK04, 1997PE03)
$E(^{8}\mathrm{Li})$ (MeV)	^{12}C States	References
13-20	g.s.	(1989BE28, 1993BE22)
23.9	g.s.	(2009BA42)
$E(^{8}\mathrm{B})$ (MeV)	^{12}C States	References
25.8	g.s.	(2011BA25)
320	quasi-elastic, breakup	(1995PE09, 1996SK04, 1997PE03)
$E(^{9}\mathrm{Be})$ (MeV)	^{12}C States	References
$E(^{12}\mathrm{C}) = 12$-21	g.s.	See references in (1975AJ02)
$E(^{12}\mathrm{C}) = 12$-21	g.s., 4.4, 7.65, 9.6	See references in (1980AJ01)
14-26, 39.7, 43.8	g.s., 4.4	See references in (1980AJ01)
20-158.3	g.s., 4.4	See references in (1985AJ01)
$E(^{12}\mathrm{C}) = 65$	g.s., 4.4, 7.7, 9.6	See references in (1990AJ01)
13-21	g.s.	(2011OL01)
26	g.s.	(2011ZA05)
40	g.s.	(2013LI09)
$E_{\mathrm{cm}} = 3$-16	g.s., 4.4	(1995CA26)
$E(^{10}\mathrm{Be})$ (MeV)	^{12}C States	References
23.2	g.s.	(2011ZA05)

Table 12.36: Summary of ^{12}C(^{6}He, ^{6}He), (^{7}Be, ^{7}Be), (^{8}Li, ^{8}Li), (^{8}B, ^{8}B), (^{9}Be, ^{9}Be), (^{10}Be, ^{10}Be), (^{10}B, ^{10}B), (^{11}Li, ^{11}Li), (^{11}Be, ^{11}Be), (^{11}B, ^{11}B) angular distributions studies (continued)

39.1 MeV/A	g.s.	(2008LA01)
$E(^{10}\mathrm{B})$ (MeV)	^{12}C States	References
18, 100	g.s., 4.4, 7.7, 9.6, 10.8, 11.8, 12.7, 13.4, 14.1, 14.8	See references in (1975AJ02)
100	g.s., 4.4, 9.6	See references in (1980AJ01)
18-46	g.s.	See references in (1985AJ01)
$E(^{11}\mathrm{Li})$ (MeV)	^{12}C States	References
550	g.s.	(2003PE01)
637, 660	quasi-elastic	(1992KO14, 1996ZA04)
$E(^{11}\mathrm{Be})$ (MeV)	^{12}C States	References
38.4 MeV/A	g.s.	(2008LA01)
$E(^{11}\mathrm{B})$ (MeV)	^{12}C States	References
$E(^{12}\mathrm{C}) = 15\text{-}24$	g.s.	See references in (1975AJ02)
28	g.s., 4.4	See references in (1975AJ02)
$E(^{12}\mathrm{C}) = 16\text{-}24, 87$	g.s.	See references in (1980AJ01)
25-50	g.s., 4.4	See references in (1985AJ01)
$E(^{12}\mathrm{C}) = 52.4$	g.s.	See references in (1990AJ01)
10.4-14.6, 42.5-100	g.s.	See references in (1990AJ01)
28-80	g.s., 4.4, 9.6, 10.3	(1991AL12, 1991JA09)
49	g.s., 4.4	(2001RU14)
50	g.s.	(2014LI49)
$E(^{12}\mathrm{C}) = 18$	g.s.	(2014HA34)
$E(^{12}\mathrm{C}) = 30.5\text{-}70$	[g.s., 4.4, 9.6, 10.3]	(1991AL12, 1991JA09)
$E(^{12}\mathrm{C}) = 344.5$	g.s., 4.4, 9.64	(1990JA12, 1992JA12)

52. (a) ^{12}C(^{6}Li, ^{6}Li)^{12}C
(b) ^{12}C(^{6}Li, αd) ^{12}C $Q_{\mathrm{m}} = -1.4738$
(c) ^{12}C(^{7}Li, ^{7}Li)^{12}C

See Table 12.37 for a summary of reported measurements on ^{12}C(^{6}Li, ^{6}Li) and ^{12}C(^{6}Li, dα). The inelastic angular distributions to ^{12}C*(4.4, 7.7, 9.6) have been used to obtain deformation parameters (1996KE09); see earlier work in (1994RE15, 1974BI04). Measurements of large angle scattering are reported in (1996GA29, 2004CA46) and analyzed in (1990DA23, 1990SA05,

1993GO06, 1995GA22, 2003LE25, 2005MI29, 2012CA21). A method for determining nuclear radii of excited states, such as ^{12}C*(7.65. 9.64, 9.9, 10.3, 10.84), is suggested in (2009DA22). A study of the E0 strength distribution determines 10%, $(5 \pm 1)\%$ and $(5 \pm 2)\%$ of the EWSR, respectively for ^{12}C*(7.7, 10.3) and for $19 < E_{\rm x} < 21.5$ MeV (1987EY01). See general theoretical analyses in (1990KA14, 1991BO48, 1991EV04, 1991SA26, 1992GA17, 1994NA03, 1994SA10, 1994SA33, 1994SK04, 1995BE60, 1995EM03, 1995GA24, 1995KH03, 1995MO28, 1996CA01, 1997SA57, 1997ZE04, 1998PI02, 1999BE59, 2000BE49, 2000EL11, 2000MI36, 2002EL01, 2002EL10, 2003ZA15, 2004EL02, 2005AL18, 2006DA05, 2008KE06, 2009DA22, 2011PA37, 2013BA13, 2015AY05, 2016CA36).

At $E(\overrightarrow{^6\rm Li}) = 30$ MeV the angular distributions and polarization observables corresponding to ^{12}C*(0, 4.4, 9.64) have been studied (1994RE01, 1994RE15); see also $E(\overrightarrow{^6\rm Li}) = 50$ MeV measurements to ^{12}C*(0, 4.4, 7.65, 9.64) reported in (1995KE10, 1996KE09) and theoretical analyses given in (1990FI12, 2011BA23, 2011PA37).

At $E(^6\rm Li) = 60$ MeV reaction (b) takes place via ^{12}C*(0, 4.4, 7.7) (1982AR20) and can involve structures in ^{16}O. See other measurements and analysis of the ^{6}Li breakup mechanism in (2000SC11, 2004SO23: exp.) and (1991EV04, 1991EV05).

See Table 12.37 for a summary of reported measurements on ^{12}C(^{7}Li, ^{7}Li). Analyses of elastic scattering distributions are given in (1991BO48, 1994SK04, 1997BE05, 2000EL11, 2002EL01, 2004EL02, 2005AL18, 2011BA23, 2014PI02) At $E(\overrightarrow{^7\rm Li}) = 34$ MeV the angular distributions and polarization observables corresponding to ^{12}C*(0, 4.4, 7.65, 9.64) and ^{12}C*(0, 4.4) + ^{7}Li*(0.48) have been studied (2000BA75, 2002KE04); see other results in (2001BA29, 2001BA57, 2006MO24) and (2011BA23: theory). For fusion and yield measurements see (2007PA33).

For the ^{6}Li and ^{7}Li + C interaction cross sections at 790 MeV/A see (1985TA18).

53. ^{12}C(^{7}Be, ^{7}Be)^{12}C

Angular distributions for elastic and inelastic scattering have been measured at $E(^7\rm Be) = 8$ to 280 MeV; see Table 12.36. See theoretical analyses and discussion in (1995FA17, 1996KN05, 1997KN07, 2006DA05, 2010HO08).

Reaction cross sections and interaction cross sections are reported at $E(^7\rm Be) = 245$ and 420 MeV (1999FU08) and 280 MeV (1995PE09). See also (1993FE12, 2000AB31, 2002AB16).

54. (a) ^{12}C(^{8}Li, ^{8}Li)^{12}C
(b) ^{12}C(^{8}Li, X)

Angular distributions for elastic and inelastic scattering have been measured at $E(^8\rm Li) = 13$ to 24 MeV; see Table 12.36. See theoretical analyses and discussion in (2014AY05).

Table 12.37: Summary of ^{12}C(^{6}Li, ^{6}Li), (^{7}Li, ^{7}Li) angular distributions studies

$E(^{6}\text{Li})$ (MeV)	^{12}C States	References
4.5-40	g.s., 4.4, 7.7, 9.6, 10.8, 11.8, 12.7, 13.4, 14.1	see references in (1975AJ02)
4.5-100	g.s., 4.4, 7.7	see references in (1980AJ01)
$\overrightarrow{20}$ and $\overrightarrow{22.8}$		(1976WE10)
9-156	g.s., 4.4, 9.6	see Table 12.20 in (1985AJ01)
24-210	g.s., 4.4, 7.7, 9.6. $\approx$ 10.2, 10.8	see Table 12.20 in (1990AJ01)
12.3	g.s.	(2011BA25)
13	g.s.	(2002LI67, 2013PO08)
20, 50	g.s., 4.44, 7.65, 9.64	(1990TR02)
25.5	g.s.	(2014RO04)
25.5	^{6}Li ($\rightarrow$ d + α)	(2004SO23, 2005SO14)
$\overrightarrow{30}$	g.s., 4.44, 7.65, 9.64	(1994RE01, 1994RE15)
$\overrightarrow{30}$	g.s., 4.44	(1996GA29)
$\overrightarrow{50}$	g.s., 4.4, 7.65, 9.64	(1995KE10, 1996KE09)
54	g.s.	(2004CA46)
63	g.s.	(2005MB12)
318	g.s.	(1993NA01)
600	g.s., ^{6}Li ($\rightarrow$ d + α)	(2000SC11)
$E(^{12}\text{C}) = 100$	g.s.	(1996KE09)
$E_{\text{cm}} =$ 2-16	g.s., 4.44	(1995CA26)

$E(^{7}\text{Li})$ (MeV)	^{12}C States	References
4.5-36	g.s., 4.4	see references in (1975AJ02)
4.5-89	g.s., 4.4 ($\beta_2^2 = 0.51 \pm 0.02$)	see references in (1980AJ01)
34-78.7	g.s., 4.4, 7.7, 9.6	see Table 12.20 in (1985AJ01)
34-131.8	g.s., 4.4, 7.7, 9.6	see Table 12.20 in (1990AJ01)
7.5, 9, 12, 15	g.s.	(2007PA33)
13	g.s.	(2002LI67)
$\overrightarrow{34}$	g.s.	(2001BA29, 2001BA57, 2006MO24)
$\overrightarrow{34}$	g.s., 4.4, 7.7, 9.6	(2000BA75, 2002KE04)
350	g.s.	(1995NA16)

Reaction cross sections and interaction cross sections are reported at $E(^8\text{B}) = 30$ to 110 MeV (2014FA18, 2015FA03). See also (2000AB31, 2000BH09, 2001BH02, 2002AB16, 2002WA08, 2003WE07, 2004KH06, 2006SH20).

55. (a) $^{12}\text{C}(^8\text{B}, {}^8\text{B})^{12}\text{C}$
(b) $^{12}\text{C}(^8\text{B}, \text{X})$

Angular distributions for elastic and inelastic scattering have been measured at $E(^8\text{B}) = 25.8$ to 320 MeV; see Table 12.36. See theoretical analyses and discussions in (1995FA17, 1996AL13, 1996KN05, 1997KN07, 2000BO45, 2006DA05, 2006DA27, 2010HO08).

Reaction cross sections and interaction cross sections are reported at $E(^8\text{B}) = 206.4$ MeV (2011BA25), 280 and 480 MeV (1999FU08), 288 MeV (2015JI07), 320 MeV (1995PE09) and 616 MeV (2003EN05). See also (1998KN03, 2000AB31, 2001LE21, 2002AB16, 2002PA51, 2004EV02, 2006HU12, 2006TR07, 2011HA38).

56. $^{12}\text{C}(^9\text{Be}, {}^9\text{Be})^{12}\text{C}$

Angular distributions for elastic scattering have been obtained at $E(^9\text{Be}) = 3$ to 158.3 MeV; see recent studies listed in Table 12.36. At $E(^9\text{Be}) = 158.3$ MeV angular distributions to $^{12}\text{C}^*(0, 4.4)$ were measured by (1984FU10), and at $E(^{12}\text{C}) = 65$ MeV angular distributions to $^{12}\text{C}^*(0, 4.4, 7.7, 9.6)$ were measured by (1985GO1H).

Excitation functions were measured for elastic scattering at $E_{\text{lab}} = 13$ to 21 MeV (2011OL01) and for elastic and inelastic scattering to $^9\text{Be}^*(2.43)$ or $^{12}\text{C}^*(4.44)$ at $E_{\text{cm}} = 2$ to 16 MeV (1995CA26); analysis indicated significant components of ^3He transfer in the reactions (1995CA26); see also (1998GR21).

The interaction cross section of ^9Be ions on ^{12}C at 790 MeV/A is reported in (1985TA18). See estimates of the total reaction cross sections for $E(^9\text{Be}) = 3$ to 26 MeV (2011ZA05); also see (1993FE12, 2000BH09, 2002AB16, 2002BR01, 2003CA07, 2006SH20, 2008KO29, 2013YA01, 2016TR10). For fusion and yield measurements see (1978CH02, 1981JA09, 1982DEZL, 1982HU06, 1983JA09, 1985DE22, 1992FI04, 1998CA27).

57. (a) $^{12}\text{C}(^{10}\text{Be}, {}^{10}\text{Be})^{12}\text{C}$
(b) $^{12}\text{C}(^{11}\text{Be}, {}^{11}\text{Be})^{12}\text{C}$

Angular distributions of ^{10}Be and ^{11}Be elastic scattering are summarized in Table 12.36. For theoretical analyses, see (^{10}Be: 1999BR09, 2000AB31, 2009RO31) and (^{11}Be: 1995EV01, 1996EV01, 1996VO04, 1997AL05, 1997JO16, 1998TO05, 1999BR09, 1999FO13, 2000BO45, 2000JO21,

2002AL25, 2002BO25, 2002SU18, 2002TA31, 2003TA04, 2005BA72, 2005TA34, 2009HA18, 2010LA09, 2011OG09, 2011OG10, 2015IS03, 2015LU04).

The interaction cross section of ^{10}Be ions on ^{12}C at 790 MeV/A is reported in (1985TA18). See estimates of the total reaction cross sections for $E_{\rm cm}$ = 12.7 MeV (2011ZA05); see also (1993FE12, 1996AL24, 2000BH09, 2002AB16, 2002BR01, 2006SH20). For ^{11}Be (reaction (b)), see measurements on the reaction cross sections in (1991FU10) and see other theoretical analyses in (1993FE02, 1993MA25, 1994SA30, 1996AL13, 1997FO04, 2000BH09, 2002BR01, 2003CA07, 2006GO05, 2006SH20, 2007SH33, 2008AL06, 2013SH17).

Table 12.38: ^{12}C spectroscopic factors from ^{12}C + ^{11}B reactions (1990JA12, 1992JA12)

	$C^2S(^{11}\mathrm{B}_{\rm g.s.} + \mathrm{p})$	$C^2S(^{11}\mathrm{B}^*(2.12) + \mathrm{p})$
$^{12}\mathrm{C}_{\rm g.s.}$	2.85 [a]	0.64
$^{12}\mathrm{C}_{4.4}$	0.79	0.36
$^{12}\mathrm{C}_{9.64}$	≤ 0.55	

[a] See also C^2S = 2.7-3.1 deduced in (2014HA34).

58. (a) ^{12}C(^{10}B, ^{10}B)^{12}C
    (b) ^{12}C(^{11}B, ^{11}B)^{12}C

Angular distributions in reaction (a) have been measured at $E_{\rm cm}$ = 3.18 to 6.82 MeV (1977HI01) and at $E(^{10}\mathrm{B})$ = 18 (1969VO10, 1988DI08) and 100 MeV (1977TO02).

The ^{11}B + ^{12}C reaction has been studied for $E(^{11}\mathrm{B})$ = 10 to 100 MeV and for $E(^{12}\mathrm{C})$ = 15 to 87 MeV; see Table 12.36, Tables 12.20 in (1985AJ01, 1990AJ01) and discussion in (1980AJ01). Proton spectroscopic factors for elastic transfer reactions ranging from C^2S = 2-5.6 have been deduced from measurements at $E_{\rm cm}$ = 15 to 40 MeV (1991AL12), and 2.15 ± 0.23 was deduced at $E(^{11}\mathrm{B})$ = 50 MeV (2014LI49). Spectroscopic factors for ^{12}C*(0, 4.4, 9.64) from analysis of measurements at $E(^{12}\mathrm{C})$ = 18 MeV (2014HA34) and $E(^{12}\mathrm{C})$ = 344.5 MeV (1990JA12, 1992JA12) are given in Table 12.38. See other analyses in (1990KA17, 1998KH16, 2001RU14, 2003ME36). For fusion and yield studies see references in (1985AJ01, 1990AJ01) and (1993HA14, 1994BA41, 1996JA12, 1996KI17, 1999CA50, 2000TAZK, 2006JI01, 2009JI04).

59. (a) ^{12}C(^{11}Li, ^{11}Li)^{12}C
    (b) ^{12}C(^{11}Li, X)

Angular distributions for elastic and inelastic scattering have been measured at $E(^{11}\mathrm{Li}) = 550$ to 660 MeV; see Table 12.36. See theoretical analyses and discussion in (1991CA14, 1992TA16, 1992YA04, 1993DA09, 1993ME02, 1993TH01, 1994AL02, 1994CA07, 1994HU04, 1994SA16, 1995AL01, 1995AL02, 1995CO01, 1995DA04, 1995EV03, 1995FA17, 1995FO08, 1995GA24, 1995HU08, 1995KH11, 1996CA01, 1996KH03, 1996KN05, 1996RA18, 1996UE01, 1996UE07, 1997CH32, 1997KN07, 1997MO42, 1998CH18, 1998MO27, 1999MO37, 2000MO34, 2000PA14).

Reaction cross sections are reported at $E(^{11}\mathrm{Li}) = 341$ and 451 MeV (2013MO21). See other theoretical analyses mainly related to the ^{11}Li density distribution and structure in (1992OG02, 1992YA02, 1993FE02, 1993MA17, 1993MA25, 1996AL13, 1996AL24, 1996BU09, 1997FO04, 1997ZA08, 1998BE09, 1998GA37, 1998KN03, 2000BO45, 2001BH02, 2001OG10, 2002WA08, 2004CA18, 2004LO12, 2007AL07, 2007SH33, 2008CA08, 2009SH25, 2011IB02).

60. (a) ^{12}C(^{12}C, ^{12}C)^{12}C

(b) ^{12}C(^{12}C, α^{8}Be)^{12}C $\quad Q_{\mathrm{m}} = -7.3666$

Angular distributions have been measured at $E(^{12}\mathrm{C}) = 10$ to 2400 MeV: see Table 12.39.

See analyses of elastic and inelastic scattering at $E < 100$ MeV (1990DE13, 1991AL03, 1991TR03, 1991VE02, 1992AP01, 1994AP01, 1995AP01, 1995LI27, 1997AP06, 1997BR05, 1998AP03, 2000EB03, 2001BO18, 2001BO41, 2001EL08, 2002BO17, 2003AL17, 2005ER05, 2006KU06, 2011HA36), at $E = 100$ MeV to 1 GeV (1990JA12, 1990WA01, 1991AL16, 1992AY03, 1992GA08, 1992KA36, 1992LE02, 1993LI13, 1993MC01, 1994KH02, 1995FA17, 1996BE25, 1996EL05, 1997BR04, 1997BR30, 1997CH48, 1997IN02, 1997KH04, 1997KN07, 1997SI21, 1997ZE04, 2000KH06, 2000KI05, 2001FA24, 2002AH05, 2002BO58, 2002YA15, 2004AH11, 2005AL18, 2005CH48, 2007KI19, 2010BA45, 2012FU04, 2012FU09, 2013FU01, 2013WE05, 2016MI03), and at $E > 1$ GeV (1990AL10, 1990AM02, 1990DA12, 1990DA23, 1991CE09, 1991ZH20, 1992CH30, 1993CE01, 1994CH35, 1994GU20, 1995BE26, 1995GA24, 1996FA08, 1998CH18, 1998EL14, 1999MA18, 2000AB31, 2000EL03, 2001LU09, 2002AB16, 2002AH02, 2002FA10, 2002VA17, 2003BE31, 2004FA08, 2004GH02, 2006CH45, 2007CH42, 2009FU11, 2012GI01, 2013WE05, 2014MI22, 2016FU13). See also (1991PU01, 1991SA29, 1996AD04, 1996RA25, 1997AB50, 2007CH62, 2011FU16, 2012FU04). For comments on "rainbow" scattering and Airy minima see (1991BR04, 1992MC07, 1995GA22, 2000ME04, 2000ME05, 2002KI15, 2003SZ12, 2004KI13, 2004MI12, 2010DE32, 2010FU12, 2016KH09).

The nuclear sizes of ^{12}C*(0, 4.4, 7.65) were determined by a Frauenhofer analysis of the small angle diffraction pattern at $E(^{12}\mathrm{C}) = 121.5$ MeV; results indicate $R_{\mathrm{diffraction}} = 6.35 \pm 0.09, 6.26 \pm 0.10$ and 6.86 ± 0.11 fm, respectively (2011MA04). See also (2009DA22), who evaluated ^{3}He, α, ^{6}Li and ^{12}C scattering data, deduced the diffractive radii for ^{12}C*(0, 4.4, 7.65, 9.64) and deduced $R_{\mathrm{rms}} = 2.34, 2.36 \pm 0.04, 2.89 \pm 0.04, 2.88 \pm 0.11$ fm for those states, respectively.

The relative population of elastic and inelastic channels is very energy dependent, for example, because of structure effects and molecular-like states in ^{24}Mg; see references listed in (1975AJ02, 1980AJ01, 1985AJ01, 1990AJ01), and see footnote [a] in Table 12.40. The spin alignment of ^{12}C*(9.64) was studied in (1993DA22, 1995DA05) and shows little energy dependence. See also

Table 12.39: ^{12}C + ^{12}C scattering

$E(^{12}\text{C})$ (MeV)	To states in ^{12}C at E_x (MeV)	References
6-126	g.s., 4.4, 14.0 ± 0.5	See references in (1968AJ02)
18.8-174	g.s., 4.4, 7.7, 9.6, 14.1, 19.6 and ^{12}C*(4.4) + ^{12}C*(4.4)	See references in (1975AJ02)
10-126.7	g.s., 4.4, 7.65, 9.64, 14.07	See references in (1980AJ01)
12 MeV-1.02 GeV	g.s., 44, 7.7, 9.6, 14.1, 18.5 and ^{12}C*(7.7) + ^{12}C*(7.7)	See references in (1985AJ01)
4 MeV-2.4 GeV	g.s., 44, 7.7, 9.6, 14.1	See references in (1990AJ01)
3.2-5	g.s.	(2001OS05)
4	g.s.	(1991VE02)
12.8-22.8	g.s.	(1991OS03)
24, 28	g.s.	(2012HA45)
33	^{12}C*(0, 4.4) [a]	(1997HA63)
50-80	g.s., 4.4, 7.65, 9.64 and mutual excitations [a]	(1993WU01, 1994WU07, 1994WU08, 1996WU11, 1997WU11, 2002WU01, 2003WU05, 2003WU12)
54-67	g.s., 4.4, 9.64	(1993DA22, 1995DA05)
60-68	g.s., 4.4, 7.65, 9.64 and mutual excitations [a]	(1997LE06)
60-70	g.s., 4.4, 7.7, 9.6, 14.1 and ^{12}C*(4.4) + ^{12}C*(4.4) [a]	(1997SZ01)
60-90	g.s., 4.4, 7.65, 9.64 and mutual excitations [a]	(1995CH07, 1996CH14, 1998CH48)
60-120	4.44, 9.64, 14.1 [a]	(1999SZ01)
60-120	g.s., 4.4, and ^{12}C*(4.4) + ^{12}C*(4.4)	(1991MO03)
80-120	g.s., 4.4, 7.65, 9.64, 14.1 and mutual excitations [a]	(2002BR43)
120-160	g.s., 4.4, 7.65, 9.64	(2010OG03)
121.5	g.s., 4.4, 7.65	(2011MA04)
240	g.s.	(2010DE32)
240	g.s., 4.4	(1995PE09, 1997PE03)
344.5	g.s., 4.4	(1990JA12)
1200	g.s., 4.4, unresolved states	(2015QU02)
1.62 GeV [b]	g.s.	(1994IC01)

[a] Studies involving analysis of ^{24}Mg resonance structures.

[b] See also Table 12.40.

Table 12.40: ^{12}C states populated in ^{12}C(^{12}C, 3α) reactions

E_{x} (MeV) [a]	E_{x} (MeV) [b]	E_{x} (MeV) [c]	E_{x} (MeV) [d]	J^{π} [e]	Γ [e]
7.65	7.65 [f]	7.65 [f]	7.65	0^+	
9.64 [f]	9.64 [f,g]	9.64 [f,g]	9.64	3^-	$\Gamma_{\alpha_0}/\Gamma = 0.972$, $\Gamma_{\alpha_1}/\Gamma = 0.027$
			10.30	0^+	
10.84 [f]	10.84 [f]	10.84 [f]	10.84	1^-	
			(11.16)	2^+	
			(11.80)	1^-	broad
11.83 [g]	11.83 [g]		11.83	(4^-) [h]	
			(12.50)	3^-	broad
12.71 [g]	12.71 [g]		12.71	1^+ [h]	
			13.35	$(2^-, 3^+, 4^-)$ [h,i]	
14.08 [f,g,j]	14.08 [f,g]		14.08	4^+	$\Gamma_{\alpha_0}/\Gamma = 0.17$, $\Gamma_{\alpha_1}/\Gamma = 0.83$

[a] $E(^{12}\mathrm{C}) = 90$ MeV (1991CA01).

[b] $E(^{12}\mathrm{C}) = 104, 106$ MeV (2007FR05).

[c] $E(^{12}\mathrm{C}) = 101.5$ MeV (2010MU05).

[d] $E(^{12}\mathrm{C}) =$ 82-106 MeV (2007FR17).

[e] From (2007FR17).

[f] Observed in $\alpha + {}^{8}\mathrm{Be}_{\mathrm{g.s.}}$ decay.

[g] Observed in $\alpha + {}^{8}\mathrm{Be}^*(3.03)$ decay.

[h] Unnatural parity state.

[i] $J^{\pi} = 4^-$ is preferred.

[j] $\Gamma_{\alpha 1}/\Gamma = 0.83 \pm 0.04$ (1991CA01).

(1990SA07, 1990SA48, 1992GR15, 1992RA25, 1993AB05, 1993ME04, 1994AD13, 1994ME18, 1994SA07, 1995BE33, 1995HI21, 1996AD04, 1996SC02, 1998KO29, 1999IT02, 2000SA57, 2001BO18, 2002IT05, 2003SA36, 2003SA39, 2003SZ12, 2005GA33, 2006PE23, 2007FR22).

For reaction (b), several states are observed by reconstructing the complete kinematics of decay α particles, see Table 12.40. In (2007FR17), the three-α breakup systematics are analyzed to determine spin values for states with $E_{\mathrm{x}} \geq 7.65$ MeV; the analysis found no evidence for the $J^{\pi} = 2^+$ excitation of the Hoyle state that is expected near 10 MeV. Contradictory results for previous J^{π} value assignments for states such as ^{12}C*(11.83, 13.35) were also found along with suggestive evidence for new broad states nears $E_{\mathrm{x}} = 11.8$ and 12.5 MeV. In (2007FR17) analysis of the $E_{\mathrm{x}} = 11.16$ MeV region is given that showed limited evidence for a previously accepted state; however, in light of the findings in (2012SM06), the result of (2007FR17) does not provide sufficient evidence for the state's existence (private communication, M. Freer, June 2017). In (2010MU05) analysis of the α-particle angular correlations found no evidence for excess $J^{\pi} = 2^+$ strength in the $E_{\mathrm{x}} \approx 9$ to 10 MeV excitation region.

In (1991CA01) no evidence for direct 3α-decay was observed from any state. Detailed measurements of the ^{12}C*(7.65) decay systematics, which are relevant for astrophysical ^{12}C formation, are given in (1994FR05, 2014IT01); see also (1996RA08). In (2014IT01) the decay kinematics of ^{12}C*(7.65) are analyzed, and the results are consistent with 100% sequential decay via ^{8}Be$_{\text{g.s.}}$, with limits of $< 0.2\%$ decay via 3-body phase space and $< 0.08\%$ decay into 3 equal energy α particles. The α-α correlation data is analyzed in (2007FR05), and discussion relating the correlations to the nuclear radii of excited states is given.

61. (a) ^{12}C(^{13}C, ^{13}C)^{12}C
(b) ^{12}C(^{14}C, ^{14}C)^{12}C

Elastic and inelastic angular distributions are reported at $E(^{12}\text{C}) = 127.2$ MeV (2010AL10) and $E(^{13}\text{C}) = 16.3$, 20, 29.5 MeV (1995LI23) and 240 MeV (2010DE32). See previous measurements reported at $E(^{12}\text{C}) = 15$ to 36 MeV and 87 MeV (1975AJ02), at $E(^{12}\text{C}) = 20$ to 35 MeV and $E(^{13}\text{C}) = 12$ and 36 MeV (1980AJ01), at $E(^{12}\text{C}) = 15$ MeV and $E(^{13}\text{C}) = 87$ MeV (1985AJ01), and at $E(^{12}\text{C}) = 94.5$ MeV and $E(^{13}\text{C}) = 16.3$ to 26.5 MeV, 36 MeV and 260 MeV (1990AJ01).

The spin-flip probability to ^{12}C*(4.4) has been studied at $E(^{13}\text{C}) = 36$ and 56 MeV by (1985BY01); also see (1981TA21). The mirror scattering reactions of $^{12}\text{C} + {}^{13}\text{C}$ and $^{12}\text{C} + {}^{13}\text{N}$ are compared in (1995LI10, 1995LI23, 1997IM01). Rainbow scattering and Airy minima are discussed in (2003BE70, 2004BE42, 2010DE32, 2015OH02). See also (1990BA03, 1993IM02, 1999RA24, 2010AL10).

For reaction (b) elastic angular distributions are reported at $E(^{12}\text{C}) = 12$ to 20 MeV (1972BO68) and $E(^{14}\text{C}) = 31.0$ to 56 MeV (1985KO04). Excitation functions to ^{26}Mg resonances are studied for ^{12}C(^{14}C, ^{14}C) at $E_{\text{cm}} = 22$ to 30 MeV (1992FR13) and $E_{\text{cm}} = 6$ to 35 MeV (2003SZ11).

62. ^{12}C(^{13}N, ^{13}N)^{12}C

Elastic and inelastic scattering has been measured at $E(^{13}\text{N}) = 16.3$, 20 and 29.5 MeV (1995LI10, 1995LI23) and at 153.4 MeV (2004TA15). The $^{12}\text{C} + {}^{13}\text{C}$ and $^{12}\text{C} + {}^{13}\text{N}$ systems appear to comply with charge symmetry, see (1995LI10, 1995LI23, 1997IM01).

63. ^{12}C(^{14}N, d)^{24}Mg* $\rightarrow$ $^{12}\text{C} + {}^{12}\text{C}$ $\quad Q_{\text{m}} = -10.2723$

This reaction has been used to populate ^{12}C-^{12}C quasi-molecular states in ^{24}Mg, see for example measurements at $E(^{14}\text{N}) = 30$ to 45 MeV (1994ZU03) and analyses in (1994BE55, 1999SA54, 2002BE71, 2002BE73).

64. (a) ^{12}C(^{14}N, ^{14}N)^{12}C
(b) ^{12}C(^{15}N, ^{15}N)^{12}C

Elastic and inelastic angular distributions are reported at $E(^{14}\text{N}) = 80.73, 100.3$ MeV (1990DE13), 116 MeV (1997ZI05) and 280 MeV (1990BR21). See previous measurements reported at $E(^{14}\text{N}) =$ 21.5 to 27.3 and 62.5 MeV (1968AJ02), $E(^{14}\text{N}) = 21$ to 155 MeV (1975AJ02), $E(^{14}\text{N}) =$ 37 to 155 MeV (1980AJ01), $E(^{14}\text{N}) = 48$ to 78 MeV (1985AJ01) and $E(^{14}\text{N}) = 150$ MeV (1990AJ01). At $E(^{14}\text{N}) = 155$ MeV ^{12}C*(0, 4.4, 7.7, 9.6, 10.8, 11.8, 12.7, 13.4, 14.1) are reported; see (1975AJ02). High-energy γ-ray emission has been studied at $E(^{14}\text{N}) = 280$ to 560 MeV (1986ST07). See also (1994AD08, 1997IN02, 2003AU04).

For reaction (b), angular distributions are reported at $E(^{15}\text{N}) = 31.5$ to 47 MeV (1978CO20) and the spin-flip probability to ^{12}C*(4.4) has been studied at $E(^{15}\text{N}) = 94$ MeV (1981TA21).

65. ^{12}C(^{16}C, ^{16}C)^{12}C

The angular distribution for quasielastic scattering at $E(^{16}\text{C}) = 47.5$ MeV/A is reported for $\theta_{\text{cm}} = 5°$-$40°$ (2009FA07).

66. (a) ^{12}C(^{16}O, ^{16}O)^{12}C
(b) ^{12}C(^{16}O, α)^{12}C^{12}C $\quad$ $Q_{\text{m}} = -7.1619$

Angular distributions involving ^{12}C and ^{16}O states have been measured at $E(^{16}\text{O}) = 17.3$ to 1503 MeV and at $E(^{12}\text{C})$ =65 to 76.8 MeV: see Table 12.41. See general analyses in (1990DA12, 1991ST07, 1992CH29, 1992CO01, 1993MA09, 1994KH02, 1994SA24, 1996EL05, 1997BR04, 1997CH23, 2000EL03, 2000KI30, 2000ME04, 2002AN35, 2002KU41, 2003BE31, 2005CH48, 2005KO52, 2006HO04, 2007GO35, 2009CH46, 2009FU11, 2011GR11, 2011MO07, 2012FU04, 2012GR16, 2013GR13, 2014FA04, 2014FA11, 2016FU13, 2016MA52).

The reaction dynamics leading to the Airy patterns at large scattering angles are discussed in (1997RI08, 2001AN04, 2001GO46, 2001MI06, 2002MI19, 2002MI39, 2002SZ03, 2003GO34, 2003OG04, 2003SZ12, 2008GR12, 2008GR14, 2008KO16, 2009KO05, 2010BA45, 2010DE10, 2014OH02, 2015MA12, 2016HA01).

In (1979DO01) excitation of the giant quadrupole resonance is observed in groups at ^{12}C*(25.3, 26.7) with $\Gamma \approx 4$ MeV that contain $(25^{+15}_{-10})\%$ of the energy-weighted E2 sum rule strength; states at ^{12}C*(0, 4.4, 9.6, 10.8, 15.8, 21.6) were also populated.

For fusion resonant excitation function studies to states in ^{28}Si see (1992SA21, 1993BE17, 1993ES01, 1994GA06, 1995BU29, 1995FR12, 1995SI13, 1997FU12, 1997GY02, 1998KE02, 2008LE27, 2011LE19, 2011CO05, 2012RU02, 2012LE04, 2013KU04, 2014KU06, 2014GO03) and (1994GR26, 2004KO38, 2007FR22: theory). For studies of other nuclides see (^{20}Ne: 1994RA04, 1995SU06), (^{24}Mg: 1991CO09, 1994CO01, 1994KU18, 1995FR12, 1997FU12, 1998FR03, 2001FR19, 2001TU06, 2001WI18, 2011JO02, 2012DI04 and theory: 2007FR22) and (^{26}Al: 1993BE17, 1997BA51, 1998BA19). See also (1993HA14, 1993WA16, 1994CZ03, 1994DE21, 1995SC30, 2006YA14, 2007GA43, 2009CH35, 2009LO01, 2012UM02, 2015AB01). For discussions on fragmentation reactions see (1990WE15, 1992MA13, 1992ME02, 1999BO46, 2000CH20, 2000FA12, 2001DE50, 2002MO22, 2008KU15, 2011DE09).

67. (a) ^{12}C(^{17}O, ^{17}O)^{12}C
    (b) ^{12}C(^{18}O, ^{18}O)^{12}C

Elastic and inelastic angular distributions are reported at $E(^{17}\text{O}) = 22$ to 38 MeV (1993TI05) and $E(^{18}\text{O}) = 66$ to 120 MeV (2001SZ05, 2006SZ06), 84 MeV (2011CA33), 94.5 MeV (2009AD08), 105 MeV (2010RU03, 2010RU13, 2010RU15, 2011RU07) and 216 MeV (2014AL05, 2014AL11). See previous measurements reported at $E(^{17}\text{O}) = 35$ MeV (1975AJ02), 30.5 and 33.8 MeV (1980AJ01), 40 to 70 MeV (1990AJ01), and $E(^{18}\text{O}) = 35$ MeV (1975AJ02), 32.3, 35, 47.5, 55 and 57.5 MeV (1980AJ01) and 32.0 to 140 MeV (1985AJ01). Fusion yields and other reactions to isotopes in, for example, Ne and Si are reported in (1990XE01, 1993BE17, 1993TI05, 1996FO16, 1999BO46, 2000CH20, 2000FA12, 2006FR16, 2006YI01, 2011BA22, 2011GI03, 2014ST22) and (1980AJ01, 1985AJ01, 1990AJ01). See also analyses in (1991TH02, 1991TH04, 1997KI22, 1999MA96, 2002BR01, 2004KH06, 2006BH01, 2008KO29, 2009AB07, 2011KU06, 2011SH26, 2012HO19, 2012RA29, 2014HO02).

68. (a) ^{12}C(^{17}F, ^{17}F)^{12}C
    (b) ^{12}C(^{19}F, ^{19}F)^{12}C

Angular distributions for elastic scattering and quasielastic scattering have been measured at $E(^{17}\text{F}) = 60$ MeV (2012ZH21) and 170 MeV (2005BL23). For reaction (b), elastic scattering and fusion angular distributions are reported at $E(^{19}\text{F}) = 10$ to 16 MeV (1990XE01), 19 to 56 MeV (1999CA50), 22 to 24 MeV (2004SU02), 48 to 72 MeV (2002AN11), 57 to 64 MeV (2002SU17), 83.6 MeV (2003WO17, 2004KI07, 2006WO04), 92 MeV (1997AI01, 1997AI06), 96 MeV (1996BH06, 1999BA11, 2001BB02, 2002BA50), 111 to 136.9 MeV (1997PO07, 2001PO01), 121.7 MeV (1995VA05) and 912 MeV (2001ME26). See previous measurements reported at $E(^{19}\text{F}) = 40$, 60 and 68.8 MeV (1975AJ02), $E(^{19}\text{F}) = 18.0$ to 60.1 MeV (1985AJ01) and $E(^{19}\text{F}) = 29.3$ to 60.1 MeV (1990AJ01). The substate population probability for ^{12}C*(4.4) has been studied by (1986IKZZ) at $E(^{19}\text{F}) = 63.8$ MeV.

69. (a) ^{12}C(^{20}Ne, ^{20}Ne)^{12}C
    (b) ^{12}C(^{22}Ne, ^{22}Ne)^{12}C

Table 12.41: Studies of elastic and inelastic ^{12}C + ^{16}O scattering reactions

E (MeV)	To states in ^{12}C at E_x (MeV)	References
$E(^{16}O) = 20\text{-}80$	g.s., 4.44	See references in (1975AJ02)
$E(^{16}O) = 17.29\text{-}315$ and $E(^{12}C) = 65, 76.8$	g.s., 4.4, 14.1, 26	See references in (1980AJ01)
$E(^{16}O) = 21\text{-}315$ and $E(^{12}C) = 77$	g.s.	See references in (1985AJ01)
$E(^{16}O) = 62\text{-}1503$	g.s., 4.44	See references in (1990AJ01)
$E_{cm} = 15\text{-}34$	7.65 [a]	(1999FO16)
$E_{cm} = 17.4\text{-}23.0$	g.s., 4.44	(2004SU10)
20, 24, 28	g.s.	(2011HA23)
$E(^{12}C) = 21$	g.s.	(2011HA23)
24	g.s.	(2002LI67)
28	g.s.	(2014HA34)
28.5-33.5	4.44 (m-state population) [a]	(1994SU09)
$E_{cm} \approx 30$	4.44 [a]	(2002FU14)
$E(^{16}O) = 47.5$	quasielastic	(2009FA07)
51-66	7.65, 9.64	(1996FR09)
62-124	g.s. [b]	(2000NI03, 2001SZ05)
62-124	g.s., 4.44	(2006SZ06)
99	g.s. 4.44	(1995FR05)
132	g.s. [b]	(1998OG02, 2007GL01)
170, 200, 230, 260	g.s. [b]	(2000OG06)
170, 181, 200, 230, 260, 281	g.s., 4.44 [b]	(2014OH04)
181, 281	g.s. [b]	(2001GL12)
300	g.s. [b]	(2001BR17)

[a] Studies of ^{28}Si resonances.

[b] Studies of large angle scattering and Airy structures.

Elastic angular distributions are reported at $E(^{20}\text{Ne}) = 390$ MeV (1993BO28) and $E(^{22}\text{Ne}) = 264$ MeV (2010AL10). See previous measurements for reaction (a) reported at $E(^{20}\text{Ne}) = 65.7$ MeV (1980AJ01) and at $E(^{12}\text{C}) = 37$ MeV (1975AJ02), 20 to 34.4, 60.7, 72.6 to 75.2 MeV [to ^{20}Ne*(0, 1.6)] and 77.4 MeV (1985AJ01). Fusion to sulfur, reaction cross section, fragmentation yield and evaporation residue studies are also reported in the literature. See also (1990SL01, 1997BR05, 1997FR04, 2004FA08, 2007FR22).

70. (a) ^{12}C(^{24}Mg, ^{24}Mg)^{12}C
    (b) ^{12}C(^{26}Mg, ^{26}Mg)^{12}C

Elastic angular distributions are reported for reaction (a) at $E(^{12}\text{C}) = 19$, 21 and 23 MeV (1993LE08), 32 to 48 MeV (1997SC14), 85 MeV (2000SI36) and 104 MeV (2017JO03), and at $E(^{24}\text{Mg}) = 130$ MeV (2004BE08, 2004BE18, 2009BE34) and 768 MeV (2001CH11, 2001CH56). See previous measurements for reaction (a) at $E(^{12}\text{C}) = 20$ to 36, 20 to 60, 24.8, 27.7 to 34.8 and 40 MeV (1985AJ01) and for reaction (b) at $E(^{12}\text{C}) = 20$ to 56 MeV (1985AJ01). The B(E2) values and deformation parameters for the first $J^{\pi} = 2^{+}$ states of ^{24,30,32}Mg are measured at $E \approx 32$ MeV (2001CH11, 2001CH56). See also analyses of scattering distributions given in (1991LI34, 1992GR15, 1994LI33, 1996FR23, 1997FR04, 1999KU01, 1999LE14, 1999LE38, 1999LI34, 2000LU03, 2001BO41, 2001BO46, 2001KU01, 2002BO17, 2002BO58, 2002KU33, 2004BE31, 2005BO28, 2005BO31, 2006KA23, 2006KA43, 2006MA33, 2007FR22). Reaction induced fission of ^{24}Mg to ^{12}C-^{12}C cluster states is studied at $E(^{24}\text{Mg}) = 170$ and 180 MeV (1991BE27, 1991FU03, 1991FU09, 1994CU05, 1995CU01, 1995LE22, 2000CU02, 2001SH08) and $E_{\text{cm}} = 43.3$ to 60 MeV (1994GY01). Studies on fusion to ^{32}S and ^{36}Ar, fragmentation yields, and other reaction cross sections can be found in the literature.

71. ^{12}C(^{27}Al, ^{27}Al)^{12}C

Elastic angular distributions have been measured at $E(^{12}\text{C}) = 21$ MeV (2011HA47) and 30.0 to 39.9 MeV (1979RO11), while that of the transition to ^{12}C*(4.4) has been studied at $E(^{12}\text{C}) = 82$ MeV (1977BE42) and $E = 344.5$ MeV (1990JA12). See also (2004FA08, 2004GA16, 2006ZA10). Results on fusion, fragmentation yield, and other reaction studies are found in the literature.

72. (a) ^{12}C(^{28}Si, ^{28}Si)^{12}C
    (b) ^{12}C(^{29}Si, ^{29}Si)^{12}C
    (c) ^{12}C(^{30}Si, ^{30}Si)^{12}C

Elastic scattering for reaction (a) was studied at $E(^{12}\text{C}) = 60$, 65, 75 and 85 MeV (1998YA02) and $E(^{28}\text{Si}) = 145$ and 160 MeV (1991RA05). See previous measurements at $E(^{12}\text{C}) = 19$ to

36, 24, 27, 30, 40.2, 49.3, 70 and 83.5 and 186.4 MeV and at $E(^{28}\text{Si}) = 58.3$ to 116.7 MeV see (1980AJ01), at $E(^{12}\text{C}) = 19$ to 48, 41.3, 56.0 to 69.5 and 131.5 MeV see (1985AJ01), and at $E(^{12}\text{C}) = 56$, 59, 66, 69.5 and 65 MeV see (1990AJ01). The α-γ angular correlations have been studied at $E(^{28}\text{Si}) = 112.3$ and 142.7 MeV: ^{12}C*(4.4) is found to be produced almost entirely in the $m = 0$ magnetic substate (1986RA08). Elastic and inelastic scattering on ^{29}Si was studied at $E(^{12}\text{C}) = 36.8$ MeV (1968AN21). See theoretical analysis of elastic scattering on ^{28}Si in (1992GR15, 1997CH41, 1999LE14, 1999LE38, 1999RA24, 2001EL08, 2004PA17, 2010BA45) and see specific discussion on "forward glory" scattering in (2000DA15, 2003LE25, 2004DA27, 2011DA04). Results on fusion, fragmentation yield, and other reaction studies on ^{28,29,30}Si targets are found in the literature.

73. $^{12}\text{C}(^{32}\text{S}, ^{32}\text{S})^{12}\text{C}$

Elastic and inelastic angular distributions and B(E2) values are reported at $E(^{32}\text{S}) = 65$ to 67 MeV (2006SP01). See previous measurements at $E(^{12}\text{C}) = 35.8$ MeV and $E(^{32}\text{S}) = 73.3$ to 128.3 MeV (1980AJ01), $E(^{32}\text{S}) = 60$ to 99 MeV and 160 MeV (1985AJ01), and $E(^{32}\text{S}) = 194$, 239 and 278 MeV (1990AJ01). See also (1990ME07, 1991AR15, 1991BE27, 1991FI04, 2001PI10, 2003BE75), references in (1980AJ01, 1985AJ01, 1990AJ01) and other references in the literature for discussion on fusion, fragmentation yield and other reaction studies.

74. (a) $^{12}\text{C}(^{39}\text{K}, ^{39}\text{K})^{12}\text{C}$
(b) $^{12}\text{C}(^{40}\text{Ar}, ^{40}\text{Ar})^{12}\text{C}$

Elastic angular distributions for reaction (a) have been studied at $E(^{12}\text{C}) = 54$ and 63 MeV (1980GL03). For reaction (b) see measurements in (1989PL02, 1990LE08, 1990LE10, 1991PA08, 1993YO03, 2004MO48).

75. (a) $^{12}\text{C}(^{40}\text{Ca}, ^{40}\text{Ca})^{12}\text{C}$
(b) $^{12}\text{C}(^{42}\text{Ca}, ^{42}\text{Ca})^{12}\text{C}$
(c) $^{12}\text{C}(^{48}\text{Ca}, ^{48}\text{Ca})^{12}\text{C}$

The elastic scattering in all three reactions has been studied at $E(^{12}\text{C}) = 51.0$, 49.9 and 49.9 MeV, respectively (1979RE03) and for reaction (a) at $E(^{12}\text{C}) = 180$, 300 and 420 MeV (1986SA29). See theoretical analysis of elastic scattering on a ^{40}Ca target in (1994SA37, 2003AL17, 2008KI20, 2013XU06). Results on fusion, fragmentation yield, and other reaction studies are found in the literature.

76. ^{12}N(β^+)^{12}C $\qquad$ $Q_{\rm m} = 17.3381$

^{12}N decay to ^{12}C is complex. Most of the decay populates ^{12}C$_{\rm g.s.}$ with small branches populating ^{12}C*(4.4) and several α-particle unbound states (see Table 12.42). The ground state decay branch is determined by subtracting all other observed decay branches from unity. Early studies were motivated by evaluation of the ^{12}B and ^{12}N mirror decays to states in ^{12}C and by parity violation studies. The decay rates to ^{12}C*(4.4) measured in (1981KA31) are most precise and have been used as normalization factors in modern experiments to deduce the relative and absolute branching ratios of weaker decay branches, see Table 12.23. In most articles, measurements on ^{12}N and ^{12}B were published together; see reaction 32 ^{12}B β^--decay for detailed discussion on the experiments.

Studies on ^{12}N decay are more complicated than those on ^{12}B decay because the high-energy 17.3 MeV β^+ particles can produce Bremsstrahlung photons while interacting in the β-counter, which can be detected in the γ-counter giving rise to a huge background under the discrete photopeaks. The Q-value for ^{12}B decay is 13.37 MeV, which leads to a significantly lower background radiation. In addition, the β^+ annihilation photons can sum with decay γ-rays in the detector causing a distortion away from the expected response function. Discussion on systematic effects is given in (1974MC11, 1978AL01).

A detailed study of the high-energy portion of the γ-ray spectrum identified decay branches populating the ^{12}C*(12.71, 15.11) states (1967AL03). The β-γ spectra were analyzed to determine the ratios $I(E_\gamma = 12.72)/I(E_\gamma = 4.4) = 2.9 \times 10^{-3} \pm (26\%)$ and $I(E_\gamma = 15.11)/I(E_\gamma = 4.4) = 1.78 \times 10^{-3} \pm (20\%)$. Using the known Γ_γ and γ-decay branching ratios the β-decay intensities to these states can be deduced.

Interest in the higher-lying $J^\pi = 0^+$ and 2^+ states led to measurements where ^{12}N and ^{12}B ions were produced at rare isotope facilities. Analysis of these data gave precise details on the α breakup channel for ^{12}C states up to $E_{\rm x} = 15.11$ MeV populated in the decays, see for example (2004FY03, 2005DI16, 2009DI06, 2014TE01). In (2009HY01, 2009HY02, 2010HY01) it is found that interference of the $J^\pi = 0^+_2$ state with other $J^\pi = 0^+$ strength around $E_{\rm x} \approx 11.2$ MeV leads to "the very broad component from 8.5 to 11 MeV, which has been mistaken for a 10.3-MeV resonance with a 3-MeV width". Rather than attribute their observed strength to a 10.3 MeV group, they provided the β feeding strength for the $E_{\rm x} =$ 9-12 MeV and 12-16.3 MeV regions [excluding the 12.7 MeV state]. A multi-level many-channel R-matrix analysis of the data (2010HY01) indicated a $J^\pi = 0^+$ state at $E_{\rm x} = 11.2 \pm 0.3$ MeV with $\Gamma = 1.5 \pm 0.6$ MeV and B(GT) $= 0.06 \pm 0.02$ and a $J^\pi = 2^+$ state at $E_{\rm x} = 11.1 \pm 0.3$ MeV with $\Gamma = 1.4 \pm 0.4$ MeV and B(GT) $= 0.05 \pm 0.03$.

77. ^{13}B(β^-n)^{12}C $\qquad$ $Q_{\rm m} = 8.4908$

The β-decay of ^{13}B primarily populates bound states in ^{13}C with an intensity $> 99\%$. However weak decay branches to ^{13}C*(7.54, 8.86, 9.90) and possibly ^{13}C*(9.50) lead to β-delayed neutron

Table 12.42: Branching in ^{12}N(β^+)^{12}C

Decay to ^{12}C* (MeV)	Branch (%)	log ft [a]	Reference.
g.s.	**96.15 ± 0.05** [b]	4.1107 ± 0.0007	
$E_\gamma = 4.43891 \pm 0.31$ [c]	**1.898 ± 0.032** [d]	5.148 ± 0.008	(1981KA31)
7.6543 ± 2.0 [e]	**1.41 ± 0.03**	4.622 ± 0.010	
	3.0 ± 0.4		(1962MA22)
	2.2 ± 0.6		(1963GL04)
	1.41 ± 0.03 [f]		(2009HY01)
10.3 ± 0.3 [g]	**0.404 ± 0.009**	4.42 ± 0.11	
	0.44 ± 0.15 [h]		(1963WI05)
	0.85 ± 0.6 [h]		(1963GL04)
[9-12] [n]	0.404 ± 0.009 [f]		(2009HY01)
	0.38 ± 0.05 [i]		(2009HY01)
12.7	**0.120 ± 0.003**	3.924 ± 0.012	
	≈ 2.0 [j]		(1966SC23)
	0.29 ± 0.08 [k]		(1967AL03)
	0.120 ± 0.003 [f]		(2009HY01)
	0.11 ± 0.02 [i]		(2009HY01)
[**$12 - 16.3$**] [n]	0.021 ± 0.006 [i]		(2009HY01)
	0.020 ± 0.003 [f]		(2009HY01)
15.11	**$(2.3 \pm 1.5) \times 10^{-3}$**	3.6 ± 0.3	
	$(3.8 \pm 0.8) \times 10^{-3}$ [l]		(1967AL03)
	$(0.8 \pm 0.3) \times 10^{-3}$ [m]		(2009HY01) [n]

[a] Based on $Q_{\rm m} = 17338.1 \pm 1.0$ keV and $T_{1/2} = 11.000 \pm 0.016$ ms.

[b] Taken as unity - branching ratios measured to excited states. [c] (1967CH19). [d] See Table 12.23.

[e] Based on (2012WA38) and $Q = 379.6 \pm 2.0$ keV (1973BA73). [f] Analysis of KVI data in (2009HY01): normalized to $B(4.44) = (1.90 \pm 0.03)\%$. [g] $\Gamma = 3.0 \pm 0.7$ MeV and $\theta^2_\alpha \approx 1.5$ (1966SC23).

[h] The presence of higher lying states was not taken into account.

[i] Analysis of JYFL data in (2009HY01): normalized to $B(4.44) = (1.90 \pm 0.03)\%$.

[j] From $I_\alpha(10.3)/I_\alpha(12.7) = 0.2$ (1966SC23).

[k] In the original manuscript, the value 0.29 ± 0.13 is calculated using $\Gamma_\gamma/\Gamma(12.7) = (3 \pm 1) \times 10^{-2}$, 0.80 ± 0.07 as the ground state branching fraction and assuming $B(4.4) = (2.4 \pm 0.2)\%$. The observable is $I_\gamma(12.7)/I_\gamma(4.4) = 2.9 \times 10^{-3}$ ($\pm 26\%$). We used the values in Table 12.14 and $B(4.4) = 1.89\%$.

[l] In the original manuscript, the value $(4.4 \pm 1.5) \times 10^{-3}$ is calculated using $\Gamma_\gamma/\Gamma = 1$ and 0.965 as the ground state branching fraction, and assuming $B(4.4) = (2.4 \pm 0.2)\%$. The observable is $I_\gamma(15.11)/I_\gamma(4.4) = 1.78 \times 10^{-3}$ ($\pm 20\%$). We used the values in Table 12.14 and $B(4.4) = (1.898 \pm 0.032)\%$.

[m] The value is $(3.2 \pm 1.0) \times 10^{-5} \cdot \Gamma/\Gamma_\alpha$.

[n] (2009HY01) integrated the strength in the $E_{\rm x}$ = 9-12 MeV and 12-16.3 MeV regions [excluding the 12.7 MeV state] rather than attributing the strength to a 10.3 MeV group, see discussion.

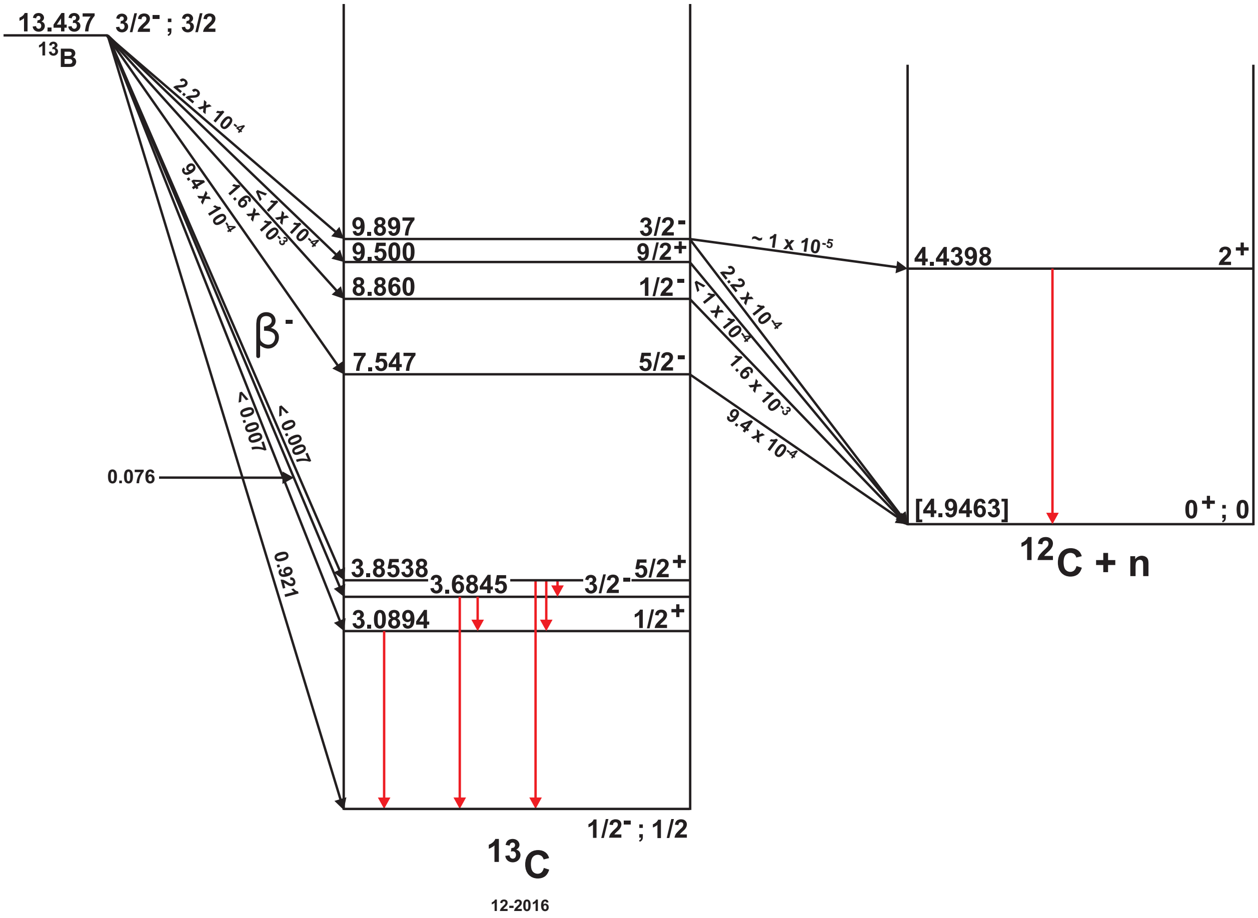


Fig. 4: ^{13}B β^-n-decay scheme. For notation see Fig. 2.

emission to ^{12}C*(0.4.4) with $P_{\rm n} = (0.28 \pm 0.04)\%$ (1962MA19, 1969JO21, 1974AL12); see Fig. 4.

78. ^{13}C(γ, n)^{12}C $\qquad Q_{\rm m} = -4.9463$

The decay of the giant resonance in ^{13}C takes place predominantly to ^{12}C*(15.1, 16.1) [and to their analogs in ^{12}B]. Below $E_\gamma = 21$ MeV transitions to ^{12}C*(4.4) are dominant (1975PA09). A review on isospin component splitting in ^{13}C up to $E_\gamma \approx 30$ MeV is given in (1993MC02).

79. ^{13}C(e, e′n)^{12}C $\qquad Q_{\rm m} = -4.9463$

The neutron decay of the pygmy and giant dipole resonances of ^{13}C were studied using $E_{\rm e} = 129$ MeV electron scattering (1999SU12). Neutron decay from the pygmy resonance tends to populate ^{12}C*(0, 4.4), while neutron decay from the GDR tends to populate ^{12}C*(12.7, 15.11).

80. ^{13}C(π^+, p)^{12}C $\qquad Q_{\rm m} = 135.4062$

Angular distributions have been measured at $E_{\pi^+} = 90$ to 170 MeV to ^{12}C*(0, 4.4, 7.7, 9.6, 12.7, 14.1, 15.1, 16.1, 19.1, 20.6, 22.9, 25.3) (1981AN10): an energy dependent ratio for the excitation of ^{12}C*(12.7, 15.1) is reported along with similarities in the population of states seen in this reaction and in the (p, d) reaction. Angular distributions are reported to ^{12}C*(0, 4.4) at $E_{\pi^+} = 32$ MeV (1982DO01). The population of ^{12}C*(4.4) is more than 10 times that of ^{12}C$_{\rm g.s.}$.

81. (a) ^{13}C(p, d)^{12}C $\qquad Q_{\rm m} = -2.7217$

(b) ^{13}C(p, pn)^{12}C $\qquad Q_{\rm m} = -4.9463$

Angular distributions have been measured at $E_{\rm p} = 8$ to 800 MeV; see (1995TO03) for $E_{\rm p} = 35$ MeV to ^{12}C*(0, 4.4), see (1982BU03) for $E_{\vec{\rm p}} = 123$ MeV† to ^{12}C*(0, 4.4), see (1990AJ01) for $E_{\rm p} = 18.6$ MeV† to ^{12}C*(0, 4.4), 41.3 MeV to ^{12}C*(0, 4.4, 12.7, 15.1, 16.1), 800 MeV to ^{12}C*(0, 4.4, 12.7, 14.1, 15.1, 16.1) and $E_{\vec{\rm p}} = 119$ MeV† to ^{12}C*(0, 4.4, 7.7, 9.6, 12.7, 14.1, 15.1, 16.1, 16.6, 17.8, 18.16 ± 0.07, 18.8, 19.9, 20.3, 20.6) and 500† MeV to ^{12}C$_{\rm g.s.}$, see (1985AJ01) for $E_{\rm p} = 800$ MeV to ^{12}C*(0, 4.4, 12.7, 14.1, 15.1, 16.1) and $E_{\vec{\rm p}} = 65^\dagger$ MeV to ^{12}C*(0, 12.7, 15.1, 16.1) and 200 and 400 MeV to ^{12}C*(0, 4.4), see (1980AJ01) for $E_{\rm p} = 16.7$ and 17.7 MeV to ^{12}C*(0, 4.4) and 200 to 500 MeV to ^{12}C*(0. 4.4), see (1975AJ02) for $E_{\rm p} = 50^\dagger$ and 54.9† to ^{12}C*(0, 4.4, 12.7, 15.1, 16.1), and 62† MeV to ^{12}C*(15.11, 16.1, 17.76, 18.8, 21.5, 22.55), and see (1968AJ02) for $E_{\rm p} = 8$, 12 and 17 MeV to ^{12}C*(0, 4.4). *Spectroscopic factors are deduced* *in measurements highlighted with the symbol* †. See also (1990GU26, 1990MU19, 1991AB04, 2004LI41, 2005DE33, 2005TS03, 2009DE02, 2009DE07, 2009DE13, 2012KU35).

The population of ^{12}C*(10.3, 15.4) is reported in (1987LE24) along with structures at E_x = 18.2, 18.8, 19.9, 20.3 and 20.6 MeV that have $\Gamma_{cm} = 240 \pm 50$, 120 ± 30, ≈ 400, ≈ 220 and ≈ 210 keV, respectively. (1984SM04) report structures at 20.61 ± 0.04 and 25.4 ± 0.1 MeV, the latter with $\Gamma \geq 0.5$ MeV. At $E_p = 62$ MeV, (1974PA01) report the excitation of states having widths [Γ (keV)] of $E_x = 15112{\pm}5$, $16110{\pm}5$ [< 20], $17760{\pm}20$ [$80{\pm}20$], $18800{\pm}40$ [$80{\pm}30$], $21500{\pm}100$ [< 200] and 22550 ± 50 [< 200] keV: $l_n = 1$ for all states except ^{12}C*(21.5) and (22.55) for which $l_p = (1)$ and $\neq 1$, respectively. ^{12}C*(14.1) is not excited, consistent with $J^\pi = 4^+$ (1970SC02, 1974PA01). For d-γ correlations via ^{12}C*(15.1) see (1987CA20).

For reaction (b), cross sections and angular distributions for deuterons and small-relative angle p-n pairs with small relative angles ($^1S_0$ state pairs) were measured at $E_p = 35$ MeV (1995TO03); both angular distributions were reproduced in coupled channels calculations, and the angular distribution for the singlet state pairs was found to fall off more slowly at large angles. Also see (1996GO07). In a kinematically complete experiment at $E_p = 7.9$ to 12.5 MeV (1971OT02), it was found that sequential decay via states in ^{13}C and ^{13}N is strongly involved in the reaction. Near $E_p = 12.5$ MeV there is some indication of sequential decay via singlet deuteron formation.

82. ^{13}C(d, t)^{12}C $\qquad Q_m = 1.3109$

Angular distributions, mainly for t_0, t_1 and t_2, have been measured for $E_d = 0.41$ to 29 MeV. See (1985AJ01) for $E_d = 18$ MeV, see (1980AJ01) for $E_d = 24.1$, 26.2 and 27.5 MeV and $E_{\vec{d}} = 13$ and 29 MeV, see (1975AJ02) for $E_d = 0.41$ to 0.81, 1.0 to 2.7, 2.2, 3.3 8, 12, 12.1, 13.3, 13.6, 14, 14.8, 15 and 28 MeV, see (1968AJ02) for $E_d = 2.2$, 3.3, 8, 12 and 14.8 MeV. Also see analyses in (1990GU26, 1995GU22, 2007CO01).

The relative yields of triton groups to ^{12}C*(12.7, 15.1, 16.1) [$(J^\pi; T) = (1^+; 0)$, $(1^+; 1)$ and $(2^+; 1)$, respectively] and ^{3}He groups to ^{12}B*(0, 0.95) [$(J^\pi; T) = (1^+; 1)$ and $(2^+; 1)$, respectively] give information on a possible short range charge dependent nuclear force. Ratios were measured at $E_d = 62$ MeV (1972BR27), 24.1 to 27.5 (1977LI02) and 29 MeV (1979CO08) yielding charge-dependent matrix element values of 250 ± 50 keV, 180 ± 80 keV and 120 ± 30 keV, respectively. If the $j = \frac{1}{2}$ component is excluded, which appears to be unwarranted, the charge dependent matrix element of (1979CO08) increases to 140 ± 40 keV. For a comparison of reported charge-dependent matrix element values between ^{12}C*(12.7, 15.1) see Table 12.18.

83. (a) ^{13}C(^{3}He, α)^{12}C $\qquad Q_m = 15.6313$
(b) ^{13}C(^{3}He, 2α)^{8}Be $\qquad Q_m = 8.2647$
(c) ^{13}C(^{3}He, pt)^{12}C $\qquad Q_m = -4.1826$

Angular distributions, mainly involving α_{0-3} have been measured at many energies up to 60 MeV; see (1990ES01): $E_{\rm cm}$ = 1.05 and 1.20 MeV, (1994BU01): $E(^3\text{He})$ = 37.9 MeV, (1990MU19): $E(^3\text{He})$ = 39.6 MeV, (1992AD06): $E(^3\text{He})$ = 50 and 60 MeV, (1959AJ76): $E(^3\text{He})$ = 2 and 4.5 MeV, (1968AJ02): $E(^3\text{He})$ = 1.6 to 3.3, 1.8, 4.5, 8.8, 9.4, 10.3, 12, 15, 18, 40 to 45 MeV, (1975AJ02): $E(^3\text{He})$ = 1.5 to 5.3, 19.1, 27.3, 35.7, 36.8 MeV, (1980AJ01): $E(^3\text{He})$ = 18, 20, 29.2 MeV, (1985AJ01): $E(^3\text{He})$ = 18.3 and 23.1 MeV and (1990AJ01): $E(^3\text{He})$ = 22.7 MeV. A DWBA analysis of α_{0-3} and ^{12}C*(10.84, 11.8, 12.7, 13.3) distributions (1966KE08) finds $l = 1$ or 0 for all the groups except α_3 (to ^{12}C*(9.6)) for which $l = 2$. Rainbow scattering effects are discussed in (1992AD06, 1994BU01). See also (1968AR12, 1990GU26).

Angular correlations of α-particles and 4.4 MeV γ-rays have been studied at $E(^3\text{He}) = 4.5$ MeV (1962HO13) and 29.2 MeV (1976FU1F). For ^{12}C*(15.1), angular correlations have been studied at $E = 9.4$ and 11.2 MeV (1969TA09) and at $E = 24$ and 25.5 MeV (1980BA1U): the average ratio between the $p_{1/2}$ and $p_{3/2}$ amplitudes is -0.086 ± 0.030 in the later measurement; see also (1999LE48, 2003ZE06). See (1990ES01, 2007GA24) for discussion on neutron stripping and ^{9}Be cluster transfer, and see (1984VA39, 1985VA1E, 1986ZE1C) for a study of the spin tensors for ^{12}C*(4.4). Ion beam analysis of surfaces is discussed in (2017MO06).

For a detailed analysis of the decays of ^{12}C*(12.7, 15.1) see (1970RE09) and Table 12.14. Attempts have been made to study the T mixing between the 1^+ states ^{12}C*(12.71, 15.11). Reported values for Γ_α/Γ for ^{12}C*(15.11) are $(1.2 \pm 0.7)\%$ (1970RE09, 1970RE1F), $(6.0 \pm 2.5)\%$ (1970AR30) and $(4.1 \pm 0.9)\%$ (1974BA42). The (1974BA42) value was obtained by observing the decay α-particles (only α_1) in reaction (b); using the ^{12}C*(15.11) Γ_{γ_0} (1983DE53) and γ-decay branching ratios (1972AL03) leads to $\Gamma_\alpha = \Gamma_{\alpha_1} = 1.8 \pm 0.3$ eV. If this isospin forbidden Γ_α is the result of the mixing between the 1^+ states ^{12}C*(12.71, 15.11) [$T = 0$ and 1, respectively] via a charge dependent interaction, the matrix element is 340 ± 60 keV (1974BA42): see, however, Table 12.18 and (1980AJ01).

For reaction (c), proton unbound states in ^{13}N that decay to ^{12}C*(0, 4.4, 7.65, 12.7, 14.08, 15.1, 16.1) were studied at $E(^3\text{He}) = 450$ MeV (2004FU12).

84. (a) $^{13}\text{C}(^6\text{Li}, ^7\text{Li})^{12}\text{C}$ $\quad Q_{\rm m} = 2.3048$
    (b) $^{13}\text{C}(^7\text{Li}, ^8\text{Li})^{12}\text{C}$ $\quad Q_{\rm m} = -2.9137$

At $E(^7\text{Li}) = 34$ MeV angular distributions have been observed for the reactions to ^{12}C*(0, 4.4) + ^{7}Li*(0, 0.48) and ^{8}Li*(0, 0.95) in all combinations. While ^{12}C*(0, 4.4) are dominant in the two spectra, ^{12}C*(7.7, 9.6) and, in reaction (a) at $E(^6\text{Li}) = 36$ MeV, ^{12}C*(12.7) are also populated (1973SC26). See also (1987CO16, 2003TR04, 2004CA46).

85. (a) $^{13}\text{C}(^{13}\text{C}, ^{14}\text{C})$ $\quad Q_{\rm m} = 3.2301$
    (b) $^{13}\text{C}(^{14}\text{C}, ^{15}\text{C})$ $\quad Q_{\rm m} = -3.7282$

Angular distributions have been reported at $E(^{13}\mathrm{C}) = 16.0$ to 50.0 MeV by (1983KO15) who have also studied the excitation functions over that energy range. For reaction (b), (2014MC03) deduced spectroscopic factors and asymptotic normalization coefficients at $E(^{14}\mathrm{C}) = 168$ MeV. See (1988BI11) for measurements at $E(^{13}\mathrm{C}) = 20.0$ to 27.5 MeV.

86. (a) $^{13}\mathrm{C}(^{16}\mathrm{O}, {}^{17}\mathrm{O})^{12}\mathrm{C}$ $Q_{\mathrm{m}} = -0.8032$
(b) $^{13}\mathrm{C}(^{17}\mathrm{O}, {}^{18}\mathrm{O})^{12}\mathrm{C}$ $Q_{\mathrm{m}} = 3.0991$
(c) $^{13}\mathrm{C}(^{18}\mathrm{O}, {}^{19}\mathrm{O})^{12}\mathrm{C}$ $Q_{\mathrm{m}} = -0.9907$

Angular distributions for neutron exchange reactions involving oxygen isotopes are reported at $E(^{16}\mathrm{O}) = 42$ to 65 MeV (1989FR04), 13 and 14 MeV (1976DU04), 14, 17 and 20 MeV (1971BA68) and 41.7 and 46.0 MeV (1973DE21); $E(^{17}\mathrm{O}) = 29.8$ and 32.3 MeV (1977CH22, 1978CH16), and $E(^{18}\mathrm{O}) = 15, 20$ and 24 MeV (1971BA68, 1971KN05) and 31.0 MeV (1978CH16). See also (1990IM01).

87. $^{13}\mathrm{O}(\beta^+\mathrm{p})^{12}\mathrm{C}$ $Q_{\mathrm{m}} = 15.8260$

The β-decay of $^{13}\mathrm{O}$ populates $^{13}\mathrm{N}_{\mathrm{g.s.}}$ in $(88.7 \pm 0.2)\%$ of all decays. The levels with $E_{\mathrm{x}} \geq 3.50$ MeV decay via proton emission to $^{12}\mathrm{C}$*(0, 4.4, 7.65) leading to $P_{\mathrm{p}} = (11.3 \pm 2.3)\%$. See (2005KN02) and Fig. 5. Also see (1965MC09, 1970ES03, 1990AS01, 2014TE01).

88. $^{14}\mathrm{C}(\mathrm{p, t})^{12}\mathrm{C}$ $Q_{\mathrm{m}} = -4.6409$

Angular distributions have been measured at $E_{\mathrm{p}} = 14.5$ (1971CU01), 18.5 (1963LE03), 39.8 (1973HO10), 40.3 (1990YA02), 45 (1978RO08), 46 (1979FR04), 50.5 [unpublished in (1975AJ02)] and 54 MeV (1976AS01).

At $E_{\mathrm{p}} = 40.3$ MeV, the states at $^{12}\mathrm{C}$*(0, 4.4, 7.65, 9.64, 12.71, 14.08, 15.11, 16.10, 17.76, 18.80) are populated; cross sections for natural parity $T = 0$ states are enhanced when compared with the $T = 1$ states (1990YA02). At $E_{\mathrm{p}} = 54$ MeV the first $T = 2$ states of $^{12}\mathrm{C}$ are observed at $E_{\mathrm{x}} = 27.57 \pm 0.03$ and 29.63 ± 0.05 MeV [$\Gamma_{\mathrm{cm}} \leq 200$ keV] (1976AS01): their identification is supported by the similar angular distributions to the first two $T = 2$ states in $^{12}\mathrm{B}$, reached in the (p, ^{3}He) reaction [see reaction $^{14}\mathrm{C}(\mathrm{p}, {}^3\mathrm{He})$ in $^{12}\mathrm{B}$]. The lower $T = 2$ state is well fitted by $L = 0$; the angular distribution to $^{12}\mathrm{C}$*(29.63) is rather featureless. It is suggested that its shape is more consistent with $L = 0$ than with $L = 2$. It is not excluded that the group to $^{12}\mathrm{C}$*(29.63) may be due to unresolved states. The states are observed with $\Gamma_{\mathrm{p}}/\Gamma = 0.3 \pm 0.1$ and $\Gamma_{\alpha_1}/\Gamma < 0.1$ for the first $T = 2$ state and $\Gamma_{\mathrm{p}}/\Gamma = 0.8 \pm 0.2$, $\Gamma_{\mathrm{p}_0}/\Gamma \approx 0.4$ and $\Gamma_{\alpha}/\Gamma \approx 0.2$ for $^{12}\mathrm{C}$*(29.63). (1976BA24) has suggested that the second $T = 2$ state in $A = 12$ may have $J^{\pi} = 0^+$.

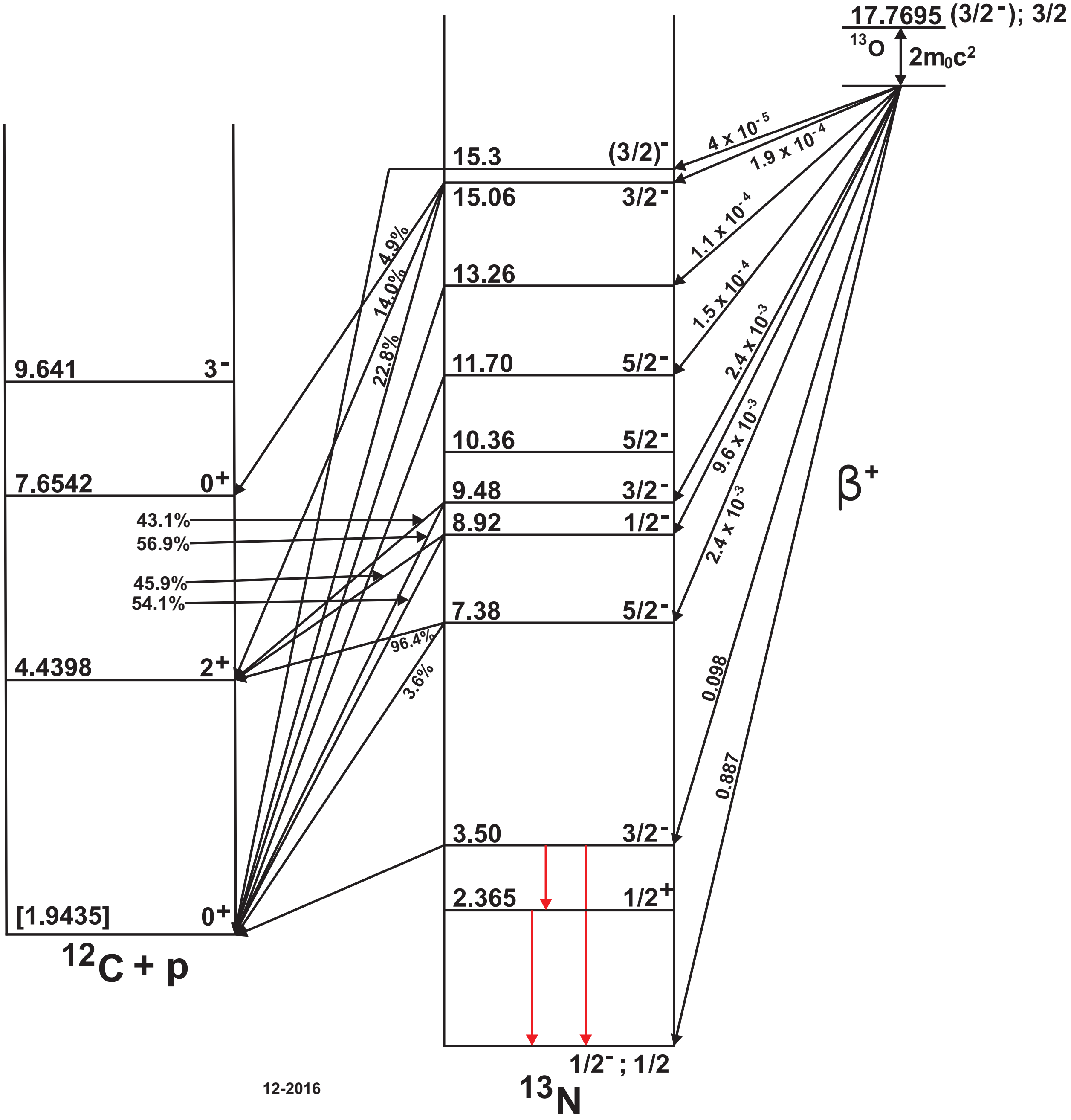


Fig. 5: ^{13}O β^+p-decay scheme. For notation see Fig. 2.

At $E_{\rm p} = 45$ MeV, (1978RO08) report $E_{\rm x} = 27595.0 \pm 2.4$ keV, $\Gamma \leq 30$ keV for the first $T = 2$ state and calculate the decay properties for two values of the total width, *narrow* and 30 keV. A subsequent measurement at $E_{\rm p} = 46$ MeV reported branching ratios for the decay of ^{12}C*(27.6) to ^{8}Be$_{\rm g.s.}$+α; ^{11}B*(0, 2.12, 4.45, 5.02, 6.74+6.79)+p; and ^{10}B$_{\rm g.s.}$+ d are, respectively, $(10.5{\pm}3.0)\%$; $(3.0 \pm 2.2)\%$, $(8.0 \pm 2.3)\%$, $(0 \pm 3.3)\%$, $(8.4 \pm 3.2)\%$, $(8 \pm 5)\%$; and $(2.8 \pm 2.0)\%$ (1979FR04). An additional $(9.1 \pm 3.5)\%$ of the decay feeds into the ^{8}Be* $+ \alpha$ continuum. See also (2006FO11).

89. (a) ^{14}N(p, ^{3}He)^{12}C $\qquad Q_{\rm m} = -4.7788$
(b) ^{14}N(p, pd)^{12}C $\qquad Q_{\rm m} = -10.2723$

Angular distributions of ^{3}He, mainly to ^{12}C*(0, 4.4) and also to ^{12}C*(12.7, 14.1, 15.1, 16.1), have been studied at $E_{\rm p} = 7.5$ to 52 MeV; see references in (1975AJ02, 1980AJ01). At $E_{\rm p} = 50$ MeV, the analysis indicates $J^{\pi} = 4^{+}$ for ^{12}C*(14.1) (1970SC02). The angular distributions to the first two $T = 1$ states in ^{12}C are compared with those of the analog states in ^{12}N obtained in the (p, t) reaction (1976YO03). For reaction (b) the transitions to ^{12}C*(0, 4.4) have been studied at $E_{\rm p} = 46$ MeV (1970WE1J, 1971WE05) and to ^{12}C*(4.4) at $E_{\rm p} = 58$ MeV (1985DE17).

90. ^{14}N(d, α)^{12}C $\qquad Q_{\rm m} = 13.5742$

Alpha groups have been observed corresponding to most known ^{12}C states up to ^{12}C*(16.11), see (1965BR08, 1965SC12) and Table 12.34. The reaction proceeds mainly via α_{0-3}. Angular distributions have been measured at several energies, see (1959AJ76): $E_{\rm d} = 10.8$ to 20 MeV, (1968AJ02): $E_{\rm d} = 0.5$ to 28.5 MeV, (1975AJ02): $E_{\rm d} = 1.0$ to 40 MeV, (1980AJ01): $E_{\rm d} = 2.7$ to 40 MeV, (2004PE10): $E_{\rm d} = 0.5$ to 2.0 MeV, (2008GU08): $E_{\rm d} = 0.7$ to 2.2 MeV and (1999IG03): $E_{\rm d} = 15.4$ MeV. The α-γ correlations give $J = 2^{+}$ for the 4.4 MeV state (1954ST1C). At $E_{\rm d} = 1.8$ MeV, the α-particles to the 7.65 MeV state were observed in coincidence with recoiling ^{12}C$_{\rm g.s.}$ nuclei; if $\Gamma_{\rm rad} = (\Gamma_{\gamma} + \Gamma_{\pi})$, then the ratio $\Gamma_{\rm rad}/\Gamma = (2.8 \pm 0.3) \times 10^{-4}$ was reported in (1963SE23). The width of the 9.6 MeV state $\Gamma_{\rm cm}$ is reported as 30 ± 8 keV (1953DU23, 1956AH32).

Analysis of the angular distributions at $E_{\rm d} = 40$ MeV, with a one-step, ZRDWBA, leads to $J^{\pi} = (1, 2, 3)^{+}$, $(2, 3)^{+}$ and $(2, 3)^{+}$, respectively for ^{12}C*(19.5, 20.6, 22.5) (1976VA07); spectroscopic factors were also deduced for all observed transitions. At $E_{\rm d} = 40$ MeV, the upper limits for the ratio of the cross sections to ^{12}C*(15.11) and ^{12}C*(12.71) are $\approx 0.3\%$ for $\theta_{\rm lab} = 6°$ to $10°$ and 0.5% at 40° and 50°: these results by (1974VA15) imply a lower isospin mixing between these two 1^{+} states than suggested by the work of (1965BR08, 1972BR27). See also (1991AP03, 1994IV01, 1996TA29: material profiling) and (1995HU15: meteorite analysis).

91. ^{14}N(α, ^{6}Li)^{12}C $\qquad Q_{\rm m} = -8.7985$

The angular distributions of ^{6}Li ions corresponding to transitions to ^{12}C*(0, 4.4) have been measured at $E_{\alpha} = 27.2$ (1995FA21) and 42 MeV (1964ZA1A). At 27.2 MeV, the contributions of the direct and statistical two-nucleon transfer processes are estimated by studying the (α, ^{6}Li) reaction on several targets.

92. (a) ^{15}N(p, α)^{12}C $Q_{\rm m} = 4.9655$
(b) ^{1}H(^{15}N, α)^{12}C $Q_{\rm m} = 4.9655$

Properties of ^{12}C states have been deduced from measurements of the angular distributions of α_0 and α_1 particles for $E_{\rm p} < 18$ MeV [see (1968AJ02)], at $E_{\rm p} = 2.99$ to 5.14 MeV (1977JA11), $E_{\rm p} = 19.85$ to 43.35 MeV (1971GU23) and $E_{\rm p} = 3.5$ to 7.5 MeV (2000IG05). Early results on the angular distributions of alpha particles and 4.4 MeV γ-radiation indicated that the 4.4 MeV state has $J = 2^{+}$ or > 4 (1953KR1B). The alpha particles to ^{12}C*(4.432 ± 0.010 MeV) were observed along with a transition corresponding to $E_{\gamma} = 4.443 \pm 0.020$ MeV (1952SC28). The lifetime of ^{12}C*(4.4) was reported as $\tau_{\rm m} = 65 \pm 9$ fsec (1970CO09). At $E_{\rm p} = 43.7$ MeV the angular distributions to the 0^{+} states ^{12}C*(0, 7.66, 17.76) are fitted by $L = 1$, while the distributions to ^{12}C*(14.1, 16.1) are consistent with $L = 3$ [$J^{\pi} = 4^{+}$ and 2^{+}, respectively] (1972MA21). The energy of the second excited state of ^{12}C is 7654.2 ± 1.6 keV (1973MC01), see additional discussion therein; such a high value leads to a sharply reduced rate for the (α-α-α) process.

At $E_{\rm p} = 7.5$ MeV, the α-γ correlations to ^{12}C*(4.44) were measured and analyzed for $\theta = 20°$-$160°$ to deduce spin tensor components and $M = 0$, 1 and 2 magnetic sublevel populations (2000IG05). The triton-cluster transfer spectroscopic factor amplitudes to ^{12}C*(0, 4.44, 7.65, 14.08, 16.1, 17.76) are deduced from analysis of angular distributions at $E_{\rm p} = 9$ to 43.7 MeV (2006AB20).

This reaction, which decreases proton and ^{15}N abundances in the ^{19}F production sequence, was studied in (1994KA02, 1998AD12, 2003HU10, 2008BA42, 2009LA13, 2011AD03, 2012DE06, 2012IM02); complementary analyses of this reaction using the Trojan Horse Method are found in (2006LA18, 2007LA37, 2008MU07, 2008MU15, 2008PIZZ, 2009LA13, 2010MU16).

Parity non-conserving alpha-decay reactions are discussed in (1990DU01, 1991DU04, 1991KN03, 2000MI37). Depth profiling and material composition studies using reactions (a) and (b) are discussed in (1990FU06, 1991DU04, 1991IW05, 1992FA04, 1992MA14, 1992MA22, 1994EN07, 1994JA16, 1994OL08, 1996MI28, 1996MI29, 2005KU36, 2010MA26, 2016RE12).

93. ^{15}N(α, ^{7}Li)^{12}C $Q_{\rm m} = -12.3808$

At $E_{\alpha} = 42$ MeV angular distributions have been obtained for all four of the transitions: ^{12}C$_{\rm g.s.}$ + ^{7}Li*(0, 0.48) and ^{12}C*(4.4) + ^{7}Li*(0, 0.48) (1968MI05). See (1995BO31) for a study of the ^{15}N cluster configurations at $E_{\alpha} = 27.3$ MeV.

Table 12.43: ^{16}N β-delayed α emission branching ratios to ^{12}C$_{\text{g.s.}}$

^{16}O Parent level (keV)	Branching ratio (%) for delayed α emission	Reference
8871: $J^\pi = 2^-$	$(5.7 \pm 1.1) \times 10^{-8}$	(1974NE10) [a]
9585: $J^\pi = 1^-$	$(1.49 \pm 0.05) \times 10^{-3}$	(2016RE01) [b]
9845: $J^\pi = 2^+$	$(8.1 \pm 1.5) \times 10^{-7}$	(1969HA42) [a]

[a] Revised: these values are determined relative to the ^{16}O*(9585) β-delayed α branching ratio. In the original manuscripts, the result of (1961KA06) was used resulting in branching ratios = $(4.6 \pm 0.9) \times 10^{-8}$% and $(6.5 \pm 1.4) \times 10^{-7}$% for ^{16}O*(8871, 9845), respectively.

[b] See also branching ratio = $(1.20 \pm 0.05) \times 10^{-3}$% (1961KA06).

94. ^{16}N decay

The β-delayed α-decay of ^{16}N can feed only ^{12}C$_{\text{g.s.}}$ from ^{16}O*(8.871, 9.585, 9.845) states. In early measurements such as (1959AL06, 1984WA07), a (1.0 ± 0.2)% β-decay branch to ^{16}O*(8.871) was deduced that was based on the beta spectrum following ^{16}N decay; a subsequent reanalysis by the authors resulted in a revised branching ratio (1.06 ± 0.07)% that was detailed in (1986AJ04). However, the small fraction of α-decay from these states yields a significantly lower α-particle intensity.

The decay to ^{16}O*(9.585), which α-decays 100% to ^{12}C$_{\text{g.s.}}$ dominates the delayed α spectrum; the branching ratio $(1.20 \pm 0.05) \times 10^{-5}$ (1961KA06) has been used extensively in the literature. However the result $(1.49 \pm 0.05) \times 10^{-5}$ (2016RE01) is in poor agreement. A third reported value $(1.3 \pm 0.3) \times 10^{-5}$ (1993ZH13) does little to resolve the discrepancy. In (1961KA06) a gas carrying radioactive ^{16}N passed sequentially through a proportional counter (α-counting) and a GM-tube counter (β-counting). The delayed α branching ratio was deduced from analysis that considered lifetimes, flow-rates and active volumes. On the other hand, (2016RE01) counted the number of ^{16}N nuclei deposited into a Si detector and the number of subsequent α-decays. At present, we accept the result of (2016RE01), though additional verification of this result would be useful.

The smaller decay branches to the neighboring states have been measured relative to the ^{16}O*(9.585) branching ratio, see Table 12.43. The α-decay of ^{16}O*(8.871) is parity forbidden, and detailed measurements of this decay branch have set limits on irregular parity amplitudes in the wavefunction (1961KA06, 1969HA42, 1970JO25, 1974NE10). In (1974NE10) $\Gamma_\alpha = (1.03 \pm 0.28) \times 10^{-10}$ eV is determined for ^{16}O*(8.87) (1974NE10).

It was proposed in, for example, (1971BA99) that the ^{16}N delayed α spectrum gives details on the E1 component of the ^{12}C + α capture cross section in the relevant $E_{\text{cm}} \approx 300$ keV region. At astrophysical energies the reaction is dominated by the tails of subthreshold states; the interference of these states gives rise to a, so called, “ghost peak” in the delayed α-particle energy spectrum that can be used to deduce the E1 component of the capture reaction. Significant efforts focused on determining the shape of the spectrum (1993BU03, 1993BU18, 1993BU21, 1993ZH06, 1994AZ03, 1997FR12, 1998GA20, 2007FR11, 2007TA34, 2009BU12, 2010TA05).

95. (a) ^{16}O(γ, α)^{12}C $Q_{\rm m} = -7.1619$
(b) ^{16}O(γ, 4α) $Q_{\rm m} = -14.4367$
(c) ^{16}O(e, e′α)^{12}C $Q_{\rm m} = -7.1619$

Reactions (a) and (b) have been studied using Bremstrahling beams with $E_\gamma < 42$ MeV (1981MA38), < 50 MeV (1997GO16, 2001KI33), < 100 MeV (1981CH28), < 150 MeV (2012AF07), < 300 MeV (1995GO10, 1995KI04), and with polarized quasi-monoenergetic beams at $E_\gamma = 9$ to 11 MeV (2013ZI03). There is evidence for the involvement of many ^{12}C states: see (1965RO05) and references therein. A test of time reversal invariance, via comparison of the ^{12}C(α, γ) vs. the ^{16}O(γ, α) rate found no evidence of T-invariance (1970VO13). Astrophysical implications of the photo-breakup reactions are discussed in (1953HO81).

For reaction (c), the dipole and quadrupole decay strengths measured in ^{16}O(e, e′α) reactions to ^{12}C states are discussed in (1990BU27, 1992FR05, 2001DE36, 2008DO15).

96. (a) ^{16}O(n, n′α)^{12}C $Q_{\rm m} = -7.1619$
(b) ^{16}O(p, p′α)^{12}C $Q_{\rm m} = -7.1619$

These reactions proceed mainly through ^{12}C*(0, 4.4). See references in (1968AJ02, 1975AJ02, 1980AJ01, 1985AJ01, 1990AJ01). ^{12}C*(14.1) is populated at $E_{\rm p} = 101.5$ MeV (1984CA09). See analysis of the $E_\gamma = 4.44$ MeV lineshape in (2001KI25). See also (2016OL04).

97. ^{16}O(d, ^{6}Li)^{12}C $Q_{\rm m} = -5.6882$

Angular distributions, mainly to ^{12}C*(0, 4,4), have been measured at $E_{\rm d} = 13$ to 55 MeV (1975AJ02), $E_{\rm d} = 12.7$ to 80 MeV (1980AJ01), $E_{\rm d} = 50$ to 80 MeV (1985AJ01) and $E_{\rm d} = 18$ to 55 MeV (1990AJ01). Spectroscopic factors are reported in (1984UM04: $E_{\rm d} = 54.2$ MeV to ^{12}C*(0, 4.4, 7.7, 9.6, 14.1)), (1978BE1T: $E_{\rm d} = 50$, 65 and 80 MeV to ^{12}C*(0, 4.4, 14.1)), (1978OE02, 1979OE04: $E_{\rm d} = 80$ MeV to ^{12}C*(0, 4.4, 7.7, 9.6, 14.1, and broad (or unresolved) structures at 14.1 ± 2.6, 19.5 ± 1.5 MeV)), (1980YA02, 1984UM04: $E_{\rm d} = 54.25$ MeV to ^{12}C*(0, 4.4, 7.7, 9.6, 14.1)).

98. ^{16}O(^{3}He, ^{7}Be)^{12}C $Q_{\rm m} = -5.5748$

Reactions involving ^{12}C*(0, 4.4, 9.6) + ^{7}Be*(0, 0.4) and ^{12}C*(7.6) + ^{7}Be$_{\rm g.s.}$ are reported at $E(^3{\rm He}) = 25.5$ to 30 MeV (1970DE12, 1972PI1A). The α-particle pickup spectroscopic factors are deduced at $E(^3{\rm He}) = 26$ MeV (1975AU01), 60 MeV (1995MA57) and 70 MeV (1976ST11). See also measurements at $E(^3{\rm He}) = 41$ MeV (1981LE01).

99. (a) ^{16}O(α, 2α)^{12}C $Q_{\rm m} = -7.1619$
(b) ^{16}O(α, ^{8}Be)^{12}C $Q_{\rm m} = -7.2538$

At $E_\alpha = 25$ MeV reaction (a) proceeds in part by sequential decay via states in ^{16}O and ^{20}Ne (1968PA12). Angular distributions involving ^{12}C*(0, 4.4) at $E_\alpha = 90$ MeV have been analyzed by PWIA and DWBA by (1976SH02): $S_\alpha = 2.9 \pm 0.5$ and 0.70 ± 0.23, respectively. In reaction (b), the angular distributions and integrated cross sections of ^{8}Be nuclei (identified through the α-decay) leading to the ground and 4.4 MeV states of ^{12}C have been determined for $E_\alpha = 35.5$ to 41.9 MeV (1965BR13). The α pickup spectroscopic factors have been measured at $E_\alpha = 55$ to 72.5 MeV (1973WO06, 1974WO1D, 1976WO11): $S_\alpha = 0.25$, 1.07, 0.05, 1.40 for ^{12}C*(0, 4.4, 7.7, 14.1) respectively; the excitation of ^{12}C*(9.6) is also reported. See also (1990JA09, 1992JA04, 2008JA02, 2009JA07, 2014JA07).

100. (a) ^{16}O(^{9}Be, ^{13}C)^{12}C $Q_{\rm m} = 3.4864$
(b) ^{16}O(^{16}O, ^{20}Ne)^{12}C $Q_{\rm m} = -2.4321$

Reaction (a) was measured at $E_{\rm cm} = 7.2$ to 10.2 MeV (1988WE17), see analysis in (1994OS08). For reaction (b), see measurements reported in (1974SP06: $E(^{16}{\rm O}) = 24$ MeV), (1974RO04: 49 to 64 MeV), (1977PO14, 1979PO14: 68 to 90 MeV), (1979MO14: 65 to 92 MeV), (1983ME13, 1984ME10: 50 to 72 MeV), (1988AU03: 72 MeV), (1996FR09: 51 to 66 MeV) and (1977KA26: $E_{\rm cm} = 17$ MeV).

101. ^{16}O(^{11}B, ^{12}C)^{15}N $Q_{\rm m} = 3.8295$

At $E(^{11}{\rm B}) = 41.25$ MeV the t_{20} and t_{40} polarization tensors of ^{12}C*(2_1^+) were measured for $\theta_{\rm cm} = 48°$-$62°$ (2000IK02). In addition, analysis of the measured transfer cross sections for reactions leading to $^{12}{\rm C}_{\rm g.s.} + {}^{15}{\rm N}_{\rm g.s.}$, $^{12}{\rm C}^*(4.44) + {}^{15}{\rm N}_{\rm g.s.}$ and $^{12}{\rm C}_{\rm g.s.} + {}^{15}{\rm N}^*(6.32[J^\pi = \frac{3}{2}^-])$ appears to indicate significant participation of multistep processes passing through ^{11}B states. See also optical model analysis of measurements at $E(^{11}{\rm B}) = 115$ MeV in (1979RA10).

102. ^{16}O(^{13}C, ^{12}C)^{17}O $Q_{\rm m} = -0.8032$

The γ-recoil method was used to extract the t_{20} and t_{40} polarization tensors of ^{12}C*(2_1^+) at $E(^{13}{\rm C}) = 50$ MeV for population of ^{12}C*(2_1^+) + ^{17}O$_{\rm g.s.}$ and ^{12}C*(2_1^+) + ^{17}O*(870) (2000IK01). An analysis of the spectroscopic amplitudes is also given. See earlier experimental results in (1975SE03, 1976WE21, 1977DU04, 1979BO36, 1979RA10).

103. ^{18}O(p, tα)^{12}C $Q_{\rm m} = -10.8686$

The decay of the lowest $T = 2$ state of ^{16}O to ^{12}C*(0, 4.4) has been studied by (1973KO02).

104. ^{19}F(d, ^{9}Be)^{12}C $Q_{\rm m} = 0.2998$

At $E_{\rm d} = 13.6$ MeV angular distributions have been obtained for the ^{9}Be groups to ^{12}C*(0, 4.4) (1981GO16). Angular distributions have also been measured at $E_{\rm d} = 9$ to 14.5 MeV: see (1964DA1B, 1967DE03, 1967DE14).

105. ^{20}Ne(α, ^{12}C)^{12}C $Q_{\rm m} = -4.6170$

Angular distributions for the α-induced fission of ^{20}Ne have been measured in the range $E_\alpha =$ 13.4 to 20.8 MeV (1981DA13). See also measurements at $E_\alpha = 12$ to 17 MeV (1962LA03, 1962LA05, 1962LA15).

106. ^{23}Na(p, ^{12}C)^{12}C $Q_{\rm m} = -2.2409$

Angular distributions involving ^{12}C$_{\rm g.s.}$ have been studied at $E_{\rm p} = 7.9$ to 18.6 MeV (1987KI26).

107. ^{24}Mg(α, ^{16}O)^{12}C $Q_{\rm m} = -6.7717$

Angular distributions have been reported in (1978SO10: $E_\alpha = 22$ to 26 MeV), (1980BE04, 1980BE15: 90.3 MeV), (1986SK01: 24.9 to 27.76 MeV) and (1989ES06: 26 to 37 MeV).

108. ^{24}Mg(^{16}O, ^{28}Si)^{12}C $Q_{\rm m} = 2.8222$

Angular distributions for reactions that mainly involve ^{40}Ca resonances have been reported in (1978PA04: $E = 47$ to 57 MeV), (1979LE02: 17 to 31 MeV), (1980PA08, 1980SA12, 1980SA31, 1985SA11: 24 to 54 MeV), (1981NU02: 32 to 48 MeV), (1982FU06: 32 to 36 MeV) and (1989LE19: 46.5 MeV). See also measurements and analyses of the α transfer reaction reported in (1972MA36, 1975ER02, 1976PE05).

^{12}N

(Table 12.44, Fig. 6)

$\mu = 4571$ (1) nm (2010ZH03). See also $\mu = 4573$ (5) nm (1968SU05) and (2013MA60).

$Q = +9.8 \pm 0.9$ mb (1998MI10).

$< (r_{\rm rms}^{\rm matter})^2 >^{1/2} = 2.40 - 2.50$ fm; i.e., see (2006WA18, 2010LI18).

An analysis of the $T = 1$ states of ^{12}B, ^{12}C and ^{12}N with $J^{\pi} = 1^+$, 2^+ and 0^+ using the quadratic form of the IMME is reported in (1998BR09). A similar report is given in (2013LA29) which also included the 2^- and 1^- states. See also (2009BA41, 2014MA56).

1. ^{12}N(β^+)^{12}C $\qquad Q_{\rm m} = 17.3381$

The half-life of ^{12}N is 11.000 ± 0.016 ms (1978AL01); see also $T_{1/2} = 10.95 \pm 0.05$ ms (1963FI05), 11.43 ± 0.05 ms (1958VE20), 11.0 ± 0.1 ms (1963PE10), 11.1 ± 0.2 ms (1962PO02) and 11.2 ± 0.4 ms (1959FA03). ^{12}N decays to ^{12}C*(0, 4.44, 7.65, 10.3, 12.71, 15.11): see Table 12.42. See (2015MO10) for discussion of the β and neutrino spectra shapes. Since the transitions to ^{12}C*(0, 4.4) are allowed, the J^{π} of ^{12}N$_{\rm g.s.}$ is 1^+. Measurement of the magnetic quadrupole moment, via β-NMR techniques, yields $Q = +9.8 \pm 0.9$ mb (1998MI10). See also (1998MI20).

Measurements of $\beta\gamma$ correlations in aligned ^{12}N (and ^{12}B) nuclei can provide information on conservation of vector currents without second-class currents (1985MI1A, 1985GR1A, 1995GO34: reviews) and (1978BR18, 1979MA31, 1987MI20, 1990CA10, 1993MI32, 1994MO23, 1995KO28, 1998MA27, 1999MI04, 2002MI01, 2003SM02). Analysis of modern experiments yields the axial charge, $y = 4.90 \pm 0.10$ (2002MI01), which is consistent with an in-medium renormalization of hadron masses; the data implies an in-medium nuclear mass reduction of $(16 \pm 4)\%$.

The longitudinal polarization of positrons emitted from polarized ^{12}N is analyzed and sets a lower limit M(W gauge boson) ≥ 310 GeV/c (1996AL23, 1998SE04, 2001TH18) for the right handed gauge boson contributing to electro-weak interaction; these results are consistent with the standard model.

Limits on the G-parity irregular induced tensor coefficient, $f_{\rm T}$, in the weak nucleon axial vector current are found as $2{\rm M}f_{\rm T}/f_{\rm A} = -0.15 \pm 0.12$ (stat.) ± 0.05 (theory) from analysis of β-ray angular distributions from spin aligned ^{12}N and ^{12}B ions (1998MI14, 1999MI41, 2000MI11, 2002MI03, 2002MI36, 2002MI49, 2003MI24).

See also (1991LI32, 1998MA27, 2013MI10) for ^{12}N polarization methods.

2. ^{1}H(^{11}C, $\alpha + {}^{8}$B) $\qquad Q_{\rm m} = -7.4072$

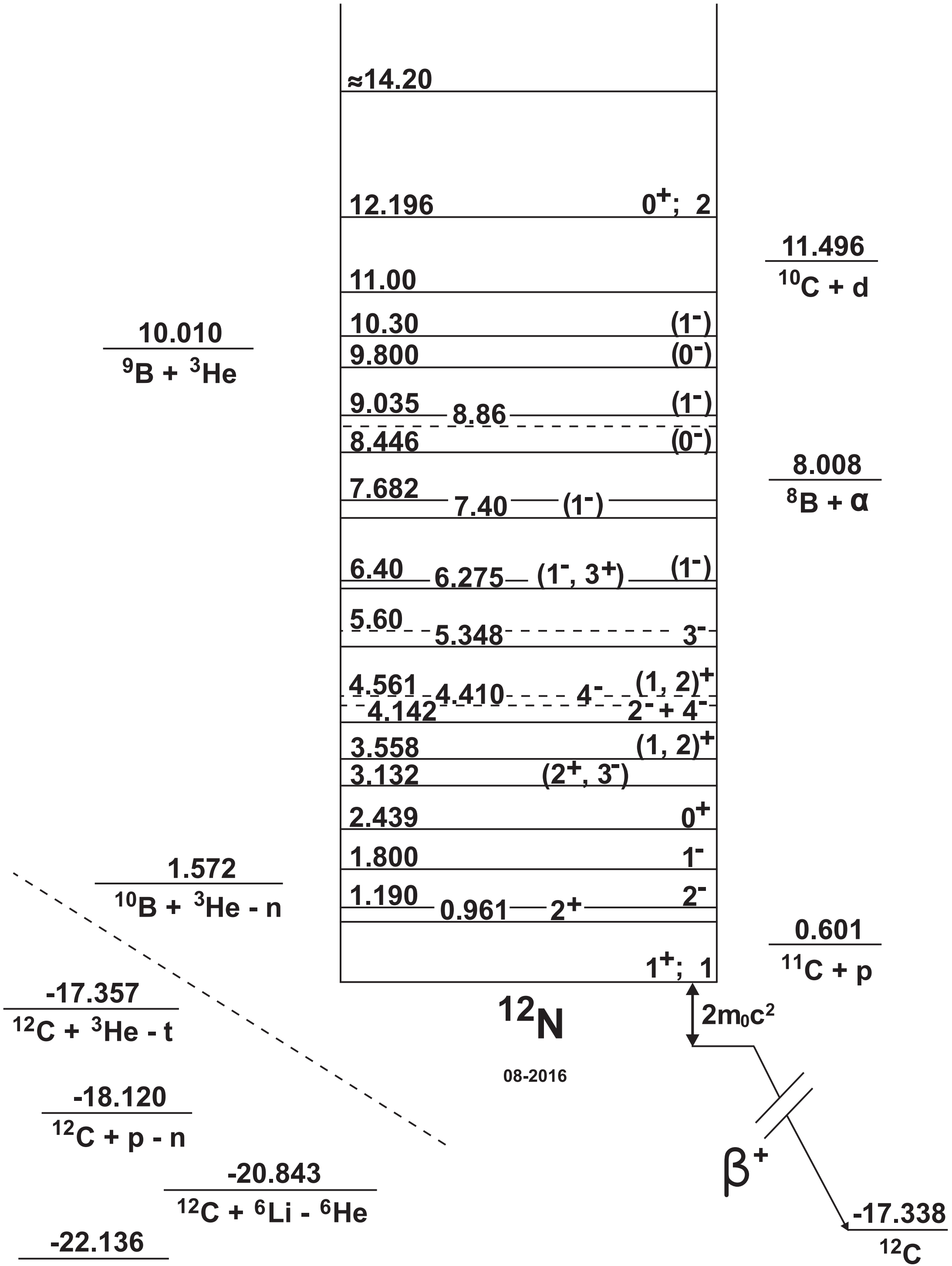


Fig. 6: Energy levels of ^{12}N. For notation see Fig. 2.

Table 12.44: Energy levels of ^{12}N

E_x (MeV $\pm$ keV)	$J^\pi; T$	$T_{1/2}$ or Γ (keV)	Decay	Reactions
0	$1^+; 1$	11.000 ± 0.016 ms	β^+	1, 3, 4, 7, 8, 9, 10, 11, 12, 14, 15, 16, 17, 18
0.961 ± 5	2^+	< 20 [a,e]	p	5, 7, 8, 11, 12, 14, 15, 16, 17
1.190 ± 7	2^-	100 ± 20	p	5, 6, 7, 11, 12, 17
1.800 ± 30	1^-	750 ± 250	p	6, 7, 11, 12
2.439 ± 8	0^+	69 ± 22	p	6, 7, 12, 17
3.132 ± 8	3^-	219 ± 20	p	6, 7, 11, 12, 17
3.558 ± 7	2^+	221 ± 30	p	6, 7, 11, 12, 17
4.142 ± 10 [b,c]	$2^- + 4^-$	825 ± 25	p	7, 8, 11, 12, 14, 16, 17
(4.410 ± 50)	4^-	744 ± 25	(p)	6, 11
(4.561 ± 24)	$(1, 2)^+$	517 ± 72	(p)	17
5.348 ± 15	3^-	270 ± 110 [d]	p	7, 11, 12, 14, 17
(5.60 ± 10)		120 ± 50	(p)	12
6.275 ± 21 [b]	$(1^-, 3^+)$	256 ± 88	(p)	17
6.40 ± 30 [b]	(1^-)	1200 ± 300	p	11, 12, 14
7.40 ± 50 [b]	(1^-)	1200 ± 500	p	11, 12, 14, 16, 17
7.682 ± 30 [b]		200 ± 30	(p)	7, 12
8.446 ± 17 [b]	(0^-)	90 ± 30		7, 11
(8.86 ± 100)		≈ 100		12
9.035 ± 12	(1^-)	16 ± 20		7, 11
9.800 ± 50	(0^-)	450 ± 100		12, 14
10.30 ± 50	(1^-)	450 ± 100		11, 12
11.00 ± 20		350 ± 100		12
12.196 ± 29	$0^+; 2$	< 110		5, 14
≈ 14.20				5

[a] Comparison with ^{12}B suggests $\Gamma = 0.91 \pm 0.29$ keV (2007GU01).

[b] Probably corresponds to unresolved states.

[c] This group includes the ^{10}B(^{3}He, n) state reported at $E_x = 4250$ keV.

[d] Method of Best Representation averaging technique (2014BI13).

[e] In (1995LE27), an upper limit of $\Gamma_p \leq 5.5$ keV is suggested based on the product of the Wigner limit and the analog ^{12}B state spectroscopic factor. See also (2015TI03).

The $E_x(^{12}\text{N}) = 8.7$ to 9.9 MeV region of the $^8\text{B}(\alpha, \text{p})$ reaction was studied in inverse kinematics by impinging $E(^{11}\text{C}) = 98$ to 110 MeV beams on 720 μg/cm^2 CH_2 targets ($\Delta E \approx 100$ keV) and detecting the $\alpha + {}^8\text{B}$ reaction products (2004RE31). The cross sections for the complementary reaction, deduced via the Detailed Balance equation, increase steadily from about 50 nb to 20 mb with only a slight enhancement of near 9.1 MeV. This cross section, which is relevant to the astrophysical hot pp-chain, is roughly two orders of magnitude larger than previously expected. See also (1990DE21).

3. $^2\text{H}(^{11}\text{C}, {}^{12}\text{N})\text{n}$ $\qquad Q_\text{m} = -1.6234$

Indirect studies of the astrophysically important $^{11}\text{C}(\text{p}, \gamma)$ reaction were carried out by analyzing angular dependent cross sections for the $^2\text{H}(^{11}\text{C}, {}^{12}\text{N}_{\text{g.s.}})$ reaction at ($\theta_\text{cm} \leq 33.8°$) and $E(^{11}\text{C}) = 9.8$ MeV (2003LI51, 2005LI40, 2006LI62), and at ($10.9° \leq \theta_\text{cm} \leq 72°$) and $E(^{11}\text{C}) = 150$ MeV (2011LE25). While the earlier measurement confirmed the dominant mechanism is direct capture to the ground state, their results (ANC $= 2.86 \pm 0.91$ fm^{-1}) are limited by low statistics. The later measurement found the ANC as $(C_\text{eff}^{^{12}\text{N}})^2 = 1.83 \pm 0.27$ fm^{-1}, and in calculations where they folded in resonant capture to the first and second excited states and interference contributions they obtained the astrophysical S-factor(0) $= 0.097 \pm 0.020$ keV $\cdot$ b, which is significantly higher than theoretical predictions.

Analogous to determination of the $^2\text{H}(^{11}\text{C}, \text{n})$ ANC, the $^2\text{H}(^{11}\text{B}, \text{p})$ $\theta \leq 160°$ angular distribution data from (1967SC29, 1974FI1D, 2001LI45) were analyzed in (2007GU01) to determine the $^{12}\text{B}^*(0, 0.95, 1.67) \rightarrow {}^{11}\text{B} + \text{n}$ ANCs; then by charge symmetry the corresponding $^{12}\text{N} \rightarrow {}^{11}\text{C} + \text{p}$ ANC values were deduced. In addition to determining astrophysical S-factors for capture to the ground, first and second excited states, $\Gamma_\text{p} = 0.91 \pm 0.29$ keV and 99 ± 20 keV were deduced for $^{12}\text{N}^*(0.95, 1.19)$, respectively. See also (2005SH39, 2005TI07, 2005TI14, 2012OK02).

4. ^9Be, C, ^{27}Al, Si(^{12}N, X)

The ^{12}N total reaction and interaction cross sections were measured on ^9Be, $^\text{nat}\text{C}$ and ^{27}Al at $E(^{12}\text{N}) = 730$ MeV/A (1995OZ01) and on $^\text{nat}\text{Si}$ at $E(^{12}\text{N}) = 20$ to 42 MeV/A (2006WA18) and $E(^{12}\text{N}) = 34.9$ MeV/A (2010LI18). The cross sections were analyzed in Glauber models to deduce matter radii of $R_\text{rms}^\text{matter} \approx 2.40$-$2.50$ fm. Spectroscopic factors to $^{11}\text{C}^*(0, 2.0, 4.32, 4.80)$ are calculated and compared with the data in (2006WA18). See also (2001OZ04).

5. $^9\text{Be}(^{13}\text{O}, {}^{12}\text{N}^*)^{10}\text{B}$ $\qquad Q_\text{m} = 5.0747$

An $E(^{13}\mathrm{O}) = 30.3$ MeV/A beam, produced via the ^{1}H(^{14}N, ^{13}O) reaction, impinged on a ^{9}Be target where 1n and 1p knockout reactions populated ^{12}N and ^{12}O (2012JA11). Excited ^{12}N decayed into $^{11}\mathrm{C}+\mathrm{p}$ and $^{10}\mathrm{B}+2\mathrm{p}$. In (2012JA11), kinematic reconstruction of the relative energies found evidence for ^{12}N states at $E_{\mathrm{x}} = 968 \pm 10$ keV [$^{11}\mathrm{C}+\mathrm{p}$] and $E_{\mathrm{x}} = 12196 \pm 29$ keV ($\Gamma < 110$ keV: $J^{\pi} = 0^{+}$) and ≈ 14200 keV [$^{10}\mathrm{B} + 2\mathrm{p}$]. A followup analysis (2013SO11) focused on ^{13}O and ^{12}N events involving the ^{12}N second excited state; $E_{\mathrm{x}} = 1.179 \pm 0.017$ MeV and $\Gamma = 55 \pm 20$ keV were deduced for this $J^{\pi} = 2^{-}$ resonance that decays 100% via $^{11}\mathrm{C} + \mathrm{p}$. In (2012JA11), the ^{12}N*(12196) state is interpreted as the IAS of $^{12}\mathrm{O}_{\mathrm{g.s.}}$, and a comparison using the IMME formula finds the $T = 2$ quintet for $A = 12$ can be fit with a quadratic form. See also ^{12}O reaction 1.

6. (a) ^{11}C(p, γ)^{12}N $\quad Q_{\mathrm{m}} = 0.6012$

(b) ^{11}C(p, p) $\quad E_{\mathrm{b}} = 0.6012$

The ^{11}C(p, γ) reaction is part of the hot pp chain (1989WI24), which can produce CNO seed nuclei earlier than the triple-α process; see discussion in (1990DE21, 2006LI62, 2011LE25). At present there are no direct measurements of the capture cross section, which is expected to be determined by direct capture and resonant capture to ^{12}N*(0.96[2^{+}], 1.19[2^{-}]). Estimates of $\Gamma_{\gamma} = 2.59$ meV and 1.91 meV were deduced in (1989WI24) by analogy with ^{12}B*(2^{+}) and from systematics given in (1979EN05), respectively. Subsequent experimental (i.e. see reaction 19) and theoretical (1990DE21, 1999DE03, 2003TI01) analysis suggests $\Gamma_{\gamma}(2^{-}) \gg 2$ meV leading to a much higher reaction rate than estimated in (1989WI24). See also (1993TI01, 2010HU11).

The $^{11}\mathrm{C}+$ p elastic scattering in thick target inverse kinematics (TTIK) has been used to provide important data for the capture reaction. An $E(^{11}\mathrm{C}) = 3.5$ MeV/A beam was stopped in a thick $(\mathrm{CH}_2)_{\mathrm{n}}$ target, and scattered protons were detected at $\theta_{\mathrm{lab}} < 5°$; using the p and ^{11}C stopping powers in the CH_2 target the $^{11}\mathrm{C}+\mathrm{p}$ excitation function was reconstructed from the observed proton energy spectrum. The ^{12}N*(1.2, 1.8, 2.4, 3.1, 3.6) levels are observed in the excitation spectrum, and $J^{\pi} = 3^{-}$ and $(2)^{+}$ are deduced for ^{12}N*(3.1, 3.6) (2003KU36, 2003TE01, 2003TE09, 2003TE12). TTIK was also employed to probe the $E_{\mathrm{x}} = 2$ to 11 MeV region (2006PE21); at $E(^{11}\mathrm{C}) = 73.8$ and 125 MeV, elastically scattered protons from a CH_2 target were detected at $\theta_{\mathrm{lab}} = 0°$, 5°, 10° and 15°, and at 99.8 MeV, protons elastically scattered in a CH_4 gas filled chamber were detected at $\theta_{\mathrm{lab}} = 0°$, 11.5°, 12.5° and 16.5°. Table 12.45 displays ^{12}N levels deduced from R-matrix analysis of the (2006PE21) excitation function that relied on known ^{12}N and ^{12}B levels. See also discussion in (2016HO14).

7. ^{10}B(^{3}He, n)^{12}N $\quad Q_{\mathrm{m}} = 1.5725$

Parameters for observed neutron groups, mainly from (1974FU11: $E(^{3}\mathrm{He}) = 12.5$ and 13 MeV) are displayed in Table 12.46. Angular distributions have been studied at $E(^{3}\mathrm{He}) = 2.5$ and

Table 12.45: ^{12}N levels deduced from an R-matrix analysis of ^{11}C(p, p′) (2006PE21)

E_x (MeV)	J^π	Γ (MeV)	E_x (MeV)	J^π	Γ (MeV)
0.0 [a]	1^+		4.340 [b]	4^-	0.572
0.960 [a]	2^+		5.015 [b]	1^+	0.445
1.195	2^-	0.109	5.275 [b]	3^+	0.490
1.796	1^-	0.581	5.331 [b]	3^-	0.480
2.428	0^+	0.079	5.410 [b]	1^+	0.207
3.127 [b]	3^-	0.227	5.500 [b]	1^-	
3.433	1^-	0.052	7.831	$(1^-, 2^+)$	0.078
3.480 [b]	2^+	0.211	8.200	$(1^-, 2^-, 3^-)$	1.270
3.983 [b]	2^-	1.056	10.026	(3^-)	0.605

[a] From adopted levels.

[b] Related to known ^{12}N or ^{12}B levels.

3.6, 2.4, 2.75 and 2.94, and 4.0 and 5.8 MeV: see references in (1968AJ02), and at $E(^3\text{He}) = 11$, and 12.5 and 13 MeV: see references in (1975AJ02).

8. (a) ^{12}C(γ, π^-)^{12}N $\quad$ $Q_m = -156.9083$
   (b) ^{12}C(γ, $\pi^0\pi^-$)^{12}N $\quad$ $Q_m = -291.8849$

States at $E_x \approx 0$, 1 and 4 MeV are populated in photo-pion production (1979PA06); see also (1976BE39: $E_{\text{brem}} = 170$ MeV), (1983SC11: $E_{\text{brem}} = 190$ MeV), and (1976WA07: $E_{\text{brem}} = 250$ MeV). At higher energies cross sections in the Δ resonance region were studied with (1974BO47: $E_{\text{brem}} = 345$ MeV), (1979BO23: $E_{\text{brem}} = 360$ MeV), (1974EP02: $E_{\text{brem}} = 375$ MeV), (1982AR06: $E_{\text{brem}} = 390$ MeV), (1982TO10, 1985TO14: $E_{\text{brem}} = 400$ MeV), (1990AN26: $E_{\text{brem}} = 450$ MeV); (1977BA60, 1978BA50: $E_{\text{brem}} = 850$ MeV), (1973GO44: $E_{\text{brem}} = 1200$ MeV), and (1980AL25: $E_{\text{brem}} = 4.5$ GeV); see a review in (1988KA41).

The reaction mechanism for ^{12}C(γ, $\pi^0\pi^-$) is investigated at $E_{\text{brem}} = 400$ to 460 MeV in (2002ME22); see also (2003ME32, 2003RO20, 2003VI09, 2003VI11, 2004MU17).

9. ^{12}C(ν_e, e$^-$) $\quad$ $Q_m = -17.34$

Table 12.46: States of ^{12}N from ^{10}B(^{3}He, n) and ^{12}C(^{3}He, t)

E_x [a] (MeV ± keV)	Γ_{cm} [a] (keV)	L [a]	E_x [b] (MeV ± keV)	Γ_{cm} [b] (keV)	E_x [d] (MeV ± keV)	Γ_{cm} [d] (keV)	J^π [e]
0	20 ± 20	2	0		0		(1^+)
0.960 ± 12	16 ± 20	2	$\equiv 0.964$	< 20 [h]	0.960		(2^+)
1.189 ± 12	140 ± 25 [c]	1	1.190 ± 20	80 ± 30 [h]	1.193 ± 10	120 ± 20	2^-
(1.72 ± 0.08)					1.80 ± 30	750 ± 250	1^-
2.4 ± 100			2.415 ± 20	45 ± 15 [h]	2.445 ± 10	110 ± 20	0^+
3.114 ± 15	200 ± 36 [c]	2	3.136 ± 30	240 ± 40	3.14 ± 10	220 ± 25	$2^+, 3^-$
3.533 ± 15	150 ± 40 [c]	2	3.55 ± 50	150 ± 100	3.57 ± 10	260 ± 30	1^+
4.250 ± 30 [f]	290 ± 70		4.15 ± 80 [f]	650 ± 100	4.14 ± 10 [f]	830 ± 20	$2^- + 4^-$
5.320 ± 12	180 ± 20	(0)	5.23 ± 80 [f]	400 ± 80	5.37 ± 10	150 ± 30	3^-
					(5.60 ± 11)	120 ± 50	
			6.10 ± 80 [f]	300 ± 100	6.40 ± 30	1200 ± 300	(1^-)
			7.13 ± 100 [f]	500 ± 100	7.40 ± 50	1200 ± 500	(1^-)
7.629 ± 20	200 ± 40		7.48 ± 100 [f]	180 ± 80	7.70 ± 11	200 ± 50	
8.446 ± 17	90 ± 30						
			(8.86 ± 100)	≈ 100			
9.035 ± 12	16 ± 20						
			9.42 ± 100	≈ 200	9.80 ± 20	450 ± 100	
			9.90 ± 100	100 ± 50	10.30 ± 20	450 ± 100	
			[g]		11.00 ± 20	350 ± 100	

[a] ^{10}B(^{3}He, n)^{12}N: from values given in Table 12.26 of (1975AJ02) [mainly (1974FU11)]. See also Table 12.29 of (1968AJ02).

[b] ^{12}C(^{3}He, t)^{12}N: see Table 12.23 in (1980AJ01) for references. See also reaction 12 here.

[c] Weighted means of values shown in Table 12.22 (1980AJ01).

[d] ^{12}C(^{3}He, t)^{12}N: (1983ST10: $E(^{3}\text{He}) = 75$ and 81 MeV), and M.N. Harakeh, private communication. See also (1984VA43, 1985VA1A).

[e] DWBA calculations (1983ST10). Some of the J^π assignments also reflect knowledge of the analog region in ^{12}B.

[f] May be due to unresolved states.

[g] No other states observed with $E_x < 13$ MeV.

[h] $J^\pi = 2^+$, (2^-), and (0^+) for ^{12}N*(0.96, 1.19, 2.42), respectively: see Table 12.23 in (1980AJ01).

Table 12.47: ^{12}C(ν_e, e$^-$)^{12}N flux averaged cross sections

Experiment	$\langle\sigma(^{12}\text{C}(\nu_e, e^-)^{12}\text{N}_{\text{g.s.}})\rangle$ (cm^2 × 10^{-42})	$\langle\sigma(^{12}\text{C}(\nu_e, e^-)^{12}\text{N*})\rangle$ (cm^2 × 10^{-42})
E225	10.5 ± 1.0 (stat.) ±1.0 (sys.) [a]	5.4 ± 1.9 [d]
KARMEN	9.6 ± 0.3 (stat.) ±0.7 (sys.) [b]	4.8 ± 0.6 (stat.) $^{+0.4}_{-0.5}$ (sys.) [b]
LSND	8.9 ± 0.3 (stat.) ±0.9 (sys.) [c]	4.3 ± 0.4 (stat.) ±0.6 (sys.) [c]

[a] (1992KR05).

[b] (2008EI01).

[c] (2001AU09).

[d] (1997AT02).

The q^2-dependence of the weak axial vector form factor, $F_A(q^2)$, was deduced from the decay electron energy spectrum; analysis indicates $F_A(q^2 = 0) = 0.73^{+0.11}_{-0.10}$, which compares well with $F_A(q^2 = 0) = 0.711$ deduced from β-decay (1994BO41: KARMEN Collaboration).

Neutrino beams produced via $\pi^+ \rightarrow \mu^+ + \nu_\mu$ followed by $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ ($E(\nu_e) \approx 26$ to 50 MeV) have been used to measure the flux averaged cross section for Charge Current interactions (CC); present results, which are important for systematics in neutrino oscillation experiments, are summarized in Table 12.47. The first measurement, E225 (1990AL09, 1992KR05), was carried out at LAMPF and produced cross section values for the exclusive ^{12}C(ν_e, e$^-$)^{12}N$_{\text{g.s.}}$ reaction (identified by a scattered electron in coincidence with the β^+ from ^{12}N decay) and inclusive ^{12}C(ν_e, e$^-$)[^{12}N$_{\text{g.s.}}$ + ^{12}N*] reaction; the cross sections are often evaluated to deduce the ^{12}C(ν_e, e$^-$)^{12}N* yields. Later efforts by the KARMEN collaboration (1992BO11, 1993BO12, 1994BO34, 1994BO41, 1994KR14, 1996KL07, 1998AR04, 2008EI01) and LSND collaboration (1997AT02, 2001AU09) have produced results in reasonable agreement. See an overview in (2003KO50).

In general, theoretical estimates of the reaction cross sections are in good agreement with measured values and have been carried out using QRPA/CRPA models (1992KO07, 1996KO32, 1997AU05, 1998IM02, 1999KO24, 2000VO13, 2001AU05, 2001VO18, 2002JA03, 2005BO44, 2005KR06, 2008PA06, 2010CH05, 2011SA04), Shell models (2000VO13, 2001AU05, 2001VO18, 2002AU01, 2003HA17, 2012SU15) and other approaches (1996EN06, 1996KO03, 2003HA44, 2004SA67, 2013PA06, 2013SO15, 2016GA35).

The role of neutrino interactions for nucleosynthesis in supernovae explosions is discussed in (2006SU15, 2007SU08, 2008PA05, 2009CH49, 2013PA06).

10. ^{12}C(ν_μ, μ^-)^{12}N $\qquad Q_{\text{m}} = -122.9965$

A beam of ν_μ from in-flight decay of π^+ was used to determine the flux averaged cross sections for populating ^{12}N ground and excited states (2002AU03: LSND Collaboration). Detectors searching for neutrino oscillations are mainly mineral oil (carbon) based scintillators, and hence cross sections on ^{12}C for neutrinos from pion decay are vital for data analysis. For these measurements, the neutrino beam energy spectrum extended to slightly above 250 MeV so reactions occurred for $E_\nu = 150$ (threshold) to 250 MeV. The exclusive cross section to $^{12}\mathrm{N}_{\mathrm{g.s.}}$, which requires the coincidence of a μ^- with a delayed β^+ from ^{12}N decay, is $\sigma = (5.6 \pm 0.8\ (\mathrm{stat.}) \pm 1.0\ (\mathrm{sys.})) \times 10^{-41}$ cm^2, while the inclusive cross sections, which required only detection of the emitted μ^-, is $\sigma = (10.6 \pm 0.3\ (\mathrm{stat.}) \pm 1.8\ (\mathrm{sys.})) \times 10^{-40}$ cm^2. The ^{12}N(ν_μ, μ^-)^{12}N* cross section is roughly 200 times greater than the ν_{e} induced reaction.

See prior results from the collaboration in (1997AT03). Note: an earlier LAMPF measurement had significantly fewer events (1992KO18) and was incompatible with the LSND results. See also (2003KO50).

Theoretical analyses of the cross sections have been carried out using QRPA/CRPA models (1996KO32, 1997AU05, 2001JA12, 2005BO44, 2005KR06, 2006CO15, 2006CO16, 2008PA06, 2011SA04), shell models (1999HA32, 2002AU01) and other approaches (2004ME12, 2004SA67, 2006JA04, 2006VA09, 2011KI06, 2014KI06, 2016PA43, 2016VA08). Special attention has been focused on the reaction channel populating ^{12}N*; this contribution to the reaction cross section is generally over predicted by roughly a factor of two (1995KO40, 1995UM02, 1996EN06, 1996KO03, 1997KO04, 1998IM02, 1999KO24, 2000HA17, 2000VO13, 2001AU05, 2001VO18, 2002JA03, 2003HA17).

The scaling and superscaling approaches for relating the relativistic (e, e′) and (ν_μ, μ^-) cross sections provide a reasonable description and are examined for energies up to the quasi-elastic scattering and Δ-resonance regions in (2003HA44, 2005AM09, 2005CA54, 2006BA17, 2006BA62, 2006CA22, 2008IV01, 2009AN06, 2015AM02, 2015PA35, 2016IV03).

11. ^{12}C(p, n)^{12}N $\qquad Q_{\mathrm{m}} = -18.1204$

States populated in ^{12}C(p, n) are displayed in Table 12.48. At $E_{\mathrm{p}} = 135$ MeV, J^π values are deduced from a DWIA analysis of $\theta = 0°$-$45°$ angular distributions (1996AN08); see earlier measurements and analysis at $E_{\mathrm{p}} = 30.5$ and 49.5 MeV (1970CL01) and at 160 MeV (1984GA11). At $E_{\vec{\mathrm{p}}} = 197$ and 295 MeV cross sections, angular distributions, and spin observables were measured (1996SA11). The peak at $E_{\mathrm{x}} = 4.5$ MeV is consistent with a $J^\pi = 2^-$ assignment, but at $E_{\mathrm{x}} = 7.5$ MeV the strength is inconsistent with the predicted $J^\pi = 1^-$ because the sign of D$_{NN}$ is negative; it should be positive. Contributions from additional states are suggested to explain the negative D$_{NN}$(0) (1996SA11). Unresolved angular distributions over the range $E_{\mathrm{x}} = 2$ to 17 MeV (and $\theta = 5°$-$13°$) are dominated by $l = 1$ transitions (1984GA11).

Angular distributions have also been studied at $E_{\mathrm{p}} = 35$ and 40 MeV (1987OH04: n$_0$, n$_1$, n$_2$; DWBA), 61.8 and 119.8 MeV (1979GO16, 1980AN05: n$_0$, n$_1$) , 99.1 MeV (1980KN02: n$_0$,

n_1), 120, 160 and 200 MeV (1981RA12: n_0, n_1) [the spin-isospin term of the effective interaction appears to be almost energy independent over the latter energy interval], and at 144 MeV (1980MO10: n_0). See also (1994GA49, 2010AD18). The backward angle scattering distribution for n_0 measured at $E_p = 200$ MeV was found to be five times larger than expected (1996YU02). At $E_p = 647$ and 800 MeV, the spectra show a narrow high energy peak and a broad bump at lower energies associated with pion production (1976CA17).

Table 12.48: ^{12}N States from ^{12}C(p, n)

E_x (MeV) [a]	E_x (MeV) [b]	J^π [b]	Γ (keV) [b]	E_x (MeV) [c]	J^π [c]
0	0	1^+			
1.0 ± 0.1	1.0	$2^+/2^-$	unresolved doublet		
	1.8	1^-			
	3.2	(3^-)			
3.7 ± 0.2	3.5	$(1^-, 2^+)$			
4.2 ± 0.2	4.18 ± 0.05	2^- [d]	836 ± 25	4.3	2^-
	4.41 ± 0.05	4^-	744 ± 25		
5.3 ± 0.2	5.40 ± 0.05	$3^+, 3^-$	385 ± 55		
	6.4	1^-		6.4	2^-
7.5 ± 0.3	7.3	1^- [d]		7.5	2^-
				8.4	(0^-)
				9.1	(1^-)
				10.2	(1^-)

[a] $E_p = 50$ MeV (1970CL01).

[b] $E_p = 135$ MeV and $\theta = 0°$-$45°$ (1996AN08).

[c] $E_p = 296$ MeV (2008DO02).

[d] See also (1984GA11, 1996SA11).

The $\theta = 0°$ ($L = 0$) cross sections to ^{12}N$_{\rm g.s.}$ at $E_p = 61.8$ and 119.8 MeV (1979GO16, 1980AN05), 280 MeV (1990MI10), 160, 200 and 795 MeV (2001PR02), 492 MeV(1989RA09) have been compared with the Gamow-Teller transition strengths and to the strengths for population of the ^{12}C*(15.11) (1982AN08) and ^{12}B$_{\rm g.s.}$ members of the $T = 1$ isospin triad (1990MI10). See also (1980AN05, 2002DM01). In (1987TA13) analysis of the $\theta = 0°$ ($L = 0$) cross sections measured for G-T transitions over a broad range of targets yielded a straightforward relationship between the cross section and B(GT). See also (1989RA09). A systematic analysis of $^{12-19}$C(p, n) reactions is given in (2016TA07).

At $E_{\vec{p}} = 160$ and 186 MeV spin observables were measured for $\theta_{\rm lab} = 0°$ to 50°; prominent peaks at ^{12}N*(0, 0.96, 1.2, 4.5, 7) were evaluated via multipole decomposition analysis

Table 12.49: Measurements of the ^{12}C($\vec{\mathrm{p}}$, n) polarization transfer coefficient

$\mathrm{D}_{NN}(0)$	E_{x} (MeV)	E_{p} (MeV)	Reference
-0.24 ± 0.11	0	50	(1994SA36)
-0.23 ± 0.05	0	80	(1994SA36)
-0.24 ± 0.03	0	160	(1984TA07)
-0.22 ± 0.02	0	295	(1995WA16)
-0.53 ± 0.06	0	318	(1993ME06)
0.69 ± 0.02	0	494	(1993ME06)

(1993YA11, 1994RA23, 1995YA12). At $E_{\mathrm{p}} = 296$ MeV, cross sections and polarization transfer observables were analyzed up to $E_{\mathrm{x}} \approx 10$ MeV; the $E_{\mathrm{x}} \approx 7$ MeV group is dominated by $J^{\pi} = 2^{-}$ strength and a strong spin-flip strength is found in the continuum (2008DO02). See also (2007WA40: $E_{\vec{\mathrm{p}}} = 296$ MeV) and (2005WA36).

The polarization transfer coefficients, $\mathrm{D}_{NN}(0°)$, were measured at $E_{\vec{\mathrm{p}}} = 295$ MeV (1995WA16), the large negative values measured for E_{x} up to 50 MeV suggest a stronger spin-flip strength than what has been observed at lower bombarding energies. Results at $E_{\vec{\mathrm{p}}} = 318$ and 494 (1993ME06) indicate that medium modified effective N-N interactions play a role. See also measurements at $E_{\vec{\mathrm{p}}} = 50$ and 72 MeV (1991LI32), $E_{\mathrm{p}} = 296$ MeV (2008DO02), Table 12.49, and analysis in (1998HI02, 1999AN32, 2000KI03).

Cross sections and analyzing powers have been measured for quasifree neutron knockout (1994WA22: $E_{\vec{\mathrm{p}}} = 186$ MeV, 1991TA13: $E_{\mathrm{p}} = 494$ and 795 MeV, 1993HI01: $E_{\vec{\mathrm{p}}} = 290$ and 420 MeV) and are found to be similar to those for free NN scattering (1993HI01). See also (1992WA19, 1993DE33, 1999NA43). Measurements on the spin-longitudinal and spin-transverse strength functions are given in (1984TA07: $E_{\mathrm{p}} = 160$ MeV, 2002HA14: $E_{\vec{\mathrm{p}}} = 197$ MeV, 2004WA14: $E_{\mathrm{p}} = 345$ MeV, 1999WA08: $E_{\vec{\mathrm{p}}} = 346$ MeV, 1993CH13, 1994TA24: $E_{\vec{\mathrm{p}}} = 495$ MeV, 1994PR08, 1995PR04: $E_{\vec{\mathrm{p}}} = 495$ and 795 MeV). See discussion in (1993HO04, 1993SA30, 1994DE29, 1994HO15, 1994HO18, 1994IC04, 1995DE44, 1996GA20, 1999YO02, 2001KA19, 2002IC02, 2002NA17).

At $E_{\vec{\mathrm{p}}} = 65$ MeV the spin transfer coefficient $\mathrm{K}_{\mathrm{y}}^{\mathrm{y}'}(0°)$ for $\vec{\mathrm{n}}_0 + \vec{\mathrm{n}}_1$ has been measured by (1984SA12). See also (1987LI29, 1987RA32). Evidence for pionic and ρ-mesonic correlation effects is deduced from analysis of polarization transfer coefficients measured at $E_{\mathrm{p}} = 296$ MeV (2009DO12). See also (1994DM03, 1994HE06, 1996OS02, 1996PR03, 1998DO15, 1998IO03, 2002DA20, 2002IC02, 2002TO07, 2016DE06).

12. ^{12}C(^{3}He, t)^{12}N $\qquad Q_{\mathrm{m}} = -17.3567$

Table 12.50: Measurements of ^{12}C(^{3}He, t)

Beam Energy (MeV)	Measured	Deduced	References
40-50	$\sigma(E_{^3\mathrm{He}}, \theta)$, $\sigma(E_\mathrm{t}, \theta)$ [a]	OM parameters, ^{12}C, ^{12}N levels	(1969BA06)
36	$\sigma(E_{^3\mathrm{He}}, \theta)$, $\sigma(E_\mathrm{t}, \theta)$ [a]	^{12}C, ^{12}N levels, J^π, isobaric analogs	(1970AR05)
217	$\sigma(E_\mathrm{t}, \theta)$	^{12}N levels reaction mechanism	(1974WI16, 1976WI05)
49.3	$\sigma(E_\mathrm{t}, \theta)$	^{12}N levels, Γ	(1976MA15)
44	$\sigma(E_{^3\mathrm{He}}, \theta)$, $\sigma(E_\mathrm{t}, \theta)$ [a]	^{12}N levels, Γ, J^π, T	(1976CE02)
52	$\sigma(E_\mathrm{t}, \theta)$	reaction mechanism	(1981AA01)
170	$\sigma(E_{^3\mathrm{He}}, \theta)$, $\sigma(E_\mathrm{t}, \theta)$ [a]	^{12}C, ^{12}N IAS of levels and GDR	(1982TA05)
75, 81	$\sigma(E_\mathrm{t}, \theta)$	^{12}N levels, $\Delta L = 1$ transition strength	(1984VA43, 1989VA09)
197	$\sigma(E_\mathrm{t}, \theta = 15^\circ)$	^{12}N IAS of ^{12}C GDR	(1984TA11)
0.6-2.3 GeV	$\sigma(E_\mathrm{t}, \theta)$	G-T, spin-flip and Δ isobar excitations	(1987BE25, 1988RO17)
76, 200	$\sigma(E_\mathrm{t}, \theta = 0^\circ)$	low-lying transition strengths	(1991JA04)
450	$\sigma(E_\mathrm{t}, \theta)$; ^{12}N* proton decay	^{12}N levels, J^π	(1994HA40, 1998IN02, 1998HA43)
420	$\sigma(E_\mathrm{t}, \theta < 2.5^\circ)$	^{12}N level transition strength, B(GT)	(2007ZE06)
140	$\sigma(E_\mathrm{t}, \theta = 0^\circ)$	^{12}N levels	(2009FU03)
4.37-10.78 GeV/c	$\sigma(\theta)$	Δ isobar excitations	(1984AB06, 1988AB08)
1.5, 2, 2.3 GeV	$\sigma(E_\mathrm{t}, \theta)$	Δ isobar excitations	(1986CO03)
0.2, 0.9, 2 GeV	$\sigma(E_\mathrm{t}, \theta)$	Δ isobar excitations	(1987EL14)
2 GeV	triton plus π^+ or p coincidence	Δ isobar resonance decay	(1991HE12, 1992HE08)
35	$\sigma(E_\mathrm{t}, \theta = 10^\circ)$	^{12}N levels	(2013HA39)

[a] Also measured (^{3}He, ^{3}He′).

Measurements of the ^{12}C(^{3}He, t) reaction are summarized in Table 12.50. Observed triton groups are displayed in Table 12.46. The ^{12}N*(0, 0.96, 1.19, 2.42, 4.25) triton group angular distributions (corrected for phase-space and isospin factors) are similar to those of inelastically scattered ^{3}He to ^{12}C*(15.11, 16.11, 16.58, 17.77, 19.57) strongly suggesting isobaric analogs (1969BA06, 1970AR05, 1976CE02, 1982TA05). Following this suggestion, if ^{12}C*(17.77) and ^{12}N*(2.42) are analogs, then the latter is a 0^+ state (1976CE02). Relatively narrow levels at ^{12}N*(4.25, 5.32, 6.10, 7.13) are reported in ^{10}B(^{3}He, n), while broader levels at ^{12}N*(4.15, 5.23) are observed in this reaction; it is therefore suggested that the selectivity is greater in the (^{3}He, n) reaction and that (^{3}He, t) populates unresolved states (1976MA15).

More states are observed in ^{12}B than in ^{12}N, indicating that some analog states are missing. With the possible exception of the relatively narrow states, ^{12}N*(9.42, 9.90), the other reported groups with $E_{\rm x} > 6$ MeV may be due to unresolved groups (1976MA15). See also (1975GO1L, 1978TA1M).

At $\theta \approx 0°$ the Gamow-Teller and spin-flip $\Delta L = 1$ resonances are strongly populated; cross sections have been measured (1991JA04: $E = 76$, 200 MeV), (1994AK02: 450 MeV), (2007ZE06: 420 MeV). The $J^\pi = 1^+, 2^+, 2^-, 0^+, 2^-, 3^-, 1^-$ values are deduced for ^{12}N*(0, 960, 1190, 2439, 4250, 5348, 7130), respectively (1991JA04). A broad study of the B(GT) systematics finds $\sigma_{\rm GT} = 109/A^{0.65}$, where the GT unit cross section, $\sigma_{\rm GT}$, is related to the known B(GT) values from β-decay and the $d\sigma/d\Omega_{\rm cm}$ cross section for zero momentum transfer (2011PE12).

In (1994AK02, 1994HA40, 1998IN02, 1998HA43: 450 MeV) proton decay from excited ^{12}N states was measured in coincidence with $\sigma(E_{\rm t}, \theta = 0°)$; ^{12}N*(4.16, 6.0, 9.9) were correlated with p_0-decay to the ^{11}C $J^\pi = \frac{3}{2}^-$ ground state, while ^{12}N*(7.4, 8.4, 9.9) were correlated with p_1-decay to ^{11}C*(2.0[$J^\pi = \frac{1}{2}^-$]). Preliminary analysis indicates $J^\pi = (2^-)$, (1^-) and (0^-) for ^{12}N*(6.4, 7.4, 9.9) respectively.

Angular distributions have been reported to many states. ^{12}N*(4, 7.1) are reached via an $l = 1$ transfer (1983EL05). At 81 MeV, (1983ST10) carried out a DWBA analysis for states up to $E_{\rm x} = 7.4$ MeV. At E(^{3}He) = 197 MeV ($\theta = 0°$) the spectrum shows ^{12}N*(0, 0.96), an ≈ 1 MeV wide state at 4.3 MeV (possibly 2^-, 4^-) and the GDR at ≈ 10 MeV (≈ 84% of the strength is 1^-) (1984TA11). ^{12}N*(4.) is assumed to be the analog of the $J^\pi = 2^-$ isovector magnetic dipole state while ^{12}N*(7.) corresponds to a group of states with $J^\pi = 1^-$ strength that is the analog of the GDR (1991GR03). The ^{12}N and ^{12}B spin-dipole resonances, populated via ^{12}C(^{3}He, t)^{12}N and ^{12}C(d, ^{2}He)^{12}B reactions, are compared and discussed in (1998IN02).

The spectra of inelastically scattered ^{3}He ions (see ^{12}C) and of tritons have been studied at E(^{3}He) = 170 MeV (1982TA05). The triton spectrum has been compared with photoabsorption results (1984TA11, 1991GR03, 1998IN02). (1982TA05) conclude that the isovector GDR is preferentially excited in the (^{3}He, t) process while the (^{3}He, ^{3}He) process preferentially excites the isoscalar giant multipole resonances. No structure is observed between $E_{\rm x} = 15$ and 70 MeV (1984TA11).

Analysis of data in the quasielastic scattering energy region (1987BE25) is given in (1996GA20, 1992WA19, 1996KE04). At E(^{3}He) = 0.6 to 2.3 GeV the reaction appears to be single-step direct and is well described by DWIA (1987BE25).

Delta isobar excitations have been studied at 1.5, 2.0 and 2.3 GeV (1986CO03) and at 4.4 to 10.8 GeV/c (1984AB06, 1988AB08). In later studies (1991HE12, 1992HE08, 1993RO09) π^++ protons were detected following decay of the Δ, and the width of the resonance was evaluated. The Δ excitation peak observed in the ^{12}C(^{3}He, t)^{12}N reaction is shifted from that found in the ^{12}C(d, ^{2}He)^{12}B reaction, see discussion in (1984GA36, 1984GE1A, 1985RO1N, 1986EL1C, 1986GA1P, 1987EL08, 1987EL14, 1988RO17). See also (1990AR05, 1990DE49, 1990GA19, 1991DE31, 1993DM01, 1993FE10, 1993OS03, 1994DM03, 1994HE06, 1994OS02, 1994SN01, 1994UD01, 2002DA20).

Measurements and discussion on $D_{nn}(0°) \approx \frac{1}{3}$, the spin transfer coefficient, are given in (1994DM03, 1998KI10, 2000KI03).

13. ^{12}C(π^+, π^0)^{12}N $\qquad Q_m = -12.7445$

At $E_{\pi^\pm} = 165$ MeV, excitation of the ^{12}N and ^{12}B isovector analog giant E1 resonances, built on ^{12}C$_{\rm g.s.}$, is observed (1994HA41). Earlier studies of ($\pi^\pm$, π^0) evaluated the A and isospin dependence of the cross section to investigate the Δ-nucleus interaction (1983AS01, 1984AS05, 1987OS05, 1990BE41, 1990IM02).

14. ^{12}C(^{6}Li, ^{6}He)^{12}N $\qquad Q_m = -20.8433$

Angular distributions have been studied to ^{12}N$_{\rm g.s.}$ at $E(^6\text{Li}) = 84$, 150 and 210 MeV (1987WI09), $E(^6\text{Li}) = 93$ MeV (1984GL06), $E(^6\text{Li}) = 100$ MeV (1994LA10), $E(^6\text{Li}) = 156$ MeV (1990MO13, 1993SC02) and $E(^6\text{Li}) = 210$ MeV (1986AN29). At bombarding energies up to 210 MeV the reaction mechanism is dominated by two-step processes, but it is suggested that one step processes will dominate above 300 MeV (1987WI09). At the higher beam energies ^{12}N*(1.0) is also populated as is a broad structure near 4.25 MeV. The forward angle cross sections for the GT transitions are found to be proportional to the β-decay strength for ^{12}C and other targets (1986AN29).

Proton angular distributions (p_0, p_1 and p_{2+3}) of groups near ^{12}N*(4.2, 5.35, 6.4, 7.4, 9.5, 12) were analyzed via Legendre polynomial fits (1993SC02) to deduce spin information; the results are consistent with the accepted spin values, with the exception of the $E_x = 6.4$ MeV resonance, where $J > 3$ is required while prior studies indicate $J^\pi = 1^-$.

15. ^{12}C(^{12}C, ^{12}N)^{12}B $\qquad Q_m = -30.7075$

The $E_x = 0$, 0.96 MeV states of ^{12}N and ^{12}B are populated in ^{12}C(^{12}C, ^{12}B) reactions at $E(^{12}\text{C}) = 70$ MeV (1986WI05, 1991AN12). Since only the ^{12}N$_{\rm g.s.}$ is bound, emphasis is typically placed on the ^{12}C(^{12}C, ^{12}N) reaction, which isolates ^{12}B excited states. See further discussion in ^{12}B reaction 35 ^{12}C(^{12}C, ^{12}N).

Coherent pion production was measured using the ^{12}C(^{12}C, ^{12}Nπ^+) reaction at 1.1 GeV/A (2005BO22).

16. ^{12}C(^{13}C, ^{13}B)^{12}N $\quad Q_{\text{m}} = -30.7752$

At $E(^{13}\text{C}) = 30$ MeV/A ^{12}N*(0, 1.0) are populated but the dominant groups in the forward direction are broad structures at $E_{\text{x}} = 4.2$ and 7.5 MeV attributed to $J^\pi = 2^-$ (SFGDR) and 1^- (GDR) states (1986VO02, 1988VO06). See analysis of the ground-state charge exchange reaction in (1999MA18).

17. ^{14}N(p, t)^{12}N $\quad Q_{\text{m}} = -22.1355$

At $E_{\text{p}} = 38$ MeV triton groups are reported to states up to $E_{\text{x}} = 7.3$ MeV (2015CH50); see Table 12.51; see also discussion in (2016HO14). At $E_{\text{p}} = 43.7$ MeV, triton groups are observed to ^{12}N$_{\text{g.s.}}$ and to the first excited state: $E_{\text{x}} = 0.963 \pm 0.030$ MeV (1967CE1B: private communication). At $E_{\text{p}} = 51.9$ MeV angular distributions of the tritons to ^{12}N*(0, 0.96) and of the ^{3}He ions to the analog $T = 1$ states [^{12}C*(15.11, 16.11)] have been measured (1976YO03). At $E_{\text{p}} = 52.5$ MeV the angular distribution to ^{12}N*(2.42) is consistent with $J^\pi = 0^+$ (1976CE02). The atomic mass excess of ^{12}N, 17338 ± 1 keV, is derived from this reaction in (1976NO1J).

18. ^{14}N(^{11}C, ^{12}N)^{13}C $\quad Q_{\text{m}} = -6.9494$

Angular distributions for ^{14}N(^{11}C, ^{12}N) were measured at $E(^{11}\text{C}) = 110$ MeV (2001TR04, 2002GA11, 2002GA44, 2003TA02) in order to determine the $^{12}\text{N} \rightarrow {}^{11}\text{C}+\text{p}$ ANC, which is related to the non-resonant ^{11}C(p, γ) reaction rate. The value $(C^{^{12}\text{N}}_{\text{p}_{\text{eff}}})^2 = (C^{^{12}\text{N}}_{\text{p}_{1/2}})^2 + (C^{^{12}\text{N}}_{\text{p}_{3/2}})^2 = 1.73 \pm 0.25$ fm^{-1} was deduced, implying a significantly larger astrophysical S-factor than previously deduced. See also (2003KR14, 2003TR09, 2005TI07, 2005TI14, 2006MU15, 2012OK02) and reaction ^{11}C(p, γ).

19. ^{208}Pb(^{12}N, ^{11}C + p) $\quad Q_{\text{m}} = -0.6012$

At $E(^{12}\text{N}) = 65.5$ MeV/A the Coulomb dissociation of ^{12}N was measured on a ^{208}Pb target and the photo-breakup excitation function was deduced from the kinematic reconstruction of the p + ^{11}C momenta (1995LE27). Analysis indicates $\Gamma_\gamma = 6.0^{+7.0}_{-3.5}$ meV for ^{12}N*(1.19) and $C^2S = 0.40 \pm 0.25$ for the direct capture spectroscopic factor. See measurements at $E(^{12}\text{N}) = 77$ MeV/A in (2004MIZW) and (2005TY02). See also discussion in (2015MU08).

Table 12.51: States reported in ^{14}N(p, t) (2015CH50)

E_x (MeV ± keV)	J^π	Γ (keV) [a]	L
g.s.	1^+	< 179	2
0.956 ± 8	2^+	< 179	2
1.195 ± 30	2^-	116 ± 74	1, 2
2.438 ± 16	0^+	77 ± 92	2 [b]
3.135 ± 19	2^+	217 ± 82	2
3.558 ± 7	1^+	245 ± 56	(2, 0) [b]
(4.160 ± 100) [c]			
4.561 ± 24	$(1, 2)^+$	517 ± 72	(2, 0) [b]
5.346 ± 9	$(1, 2, 3)^+$	340 ± 91	2
6.275 ± 21 [d]	$(1^-, 3^+)$	256 ± 88	(1, 2) [b]
(7.300 ± 110)		broad	

[a] The experimental resolution has been removed from all widths except for ^{12}N*(0, 956 keV).

[b] Likely admixture based on DWBA analysis.

[c] From $E_x = 4157 \pm 102$ keV.

[d] Likely multiplet.

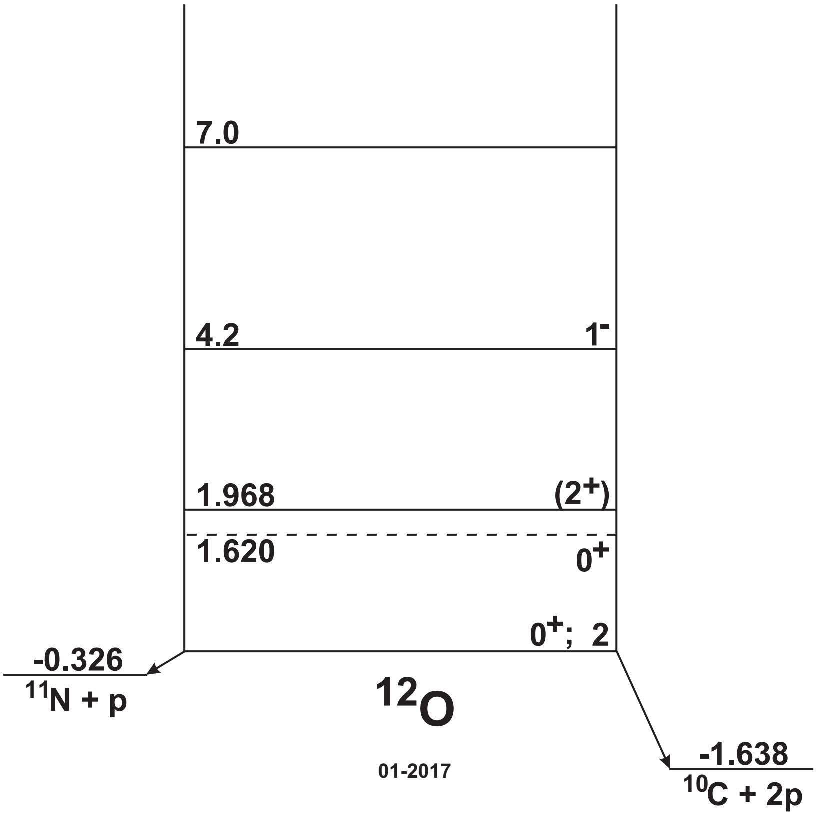


Fig. 7: Energy levels of ^{12}O. For notation see Fig. 2.

^{12}O

(Table 12.52, Fig. 7; see comparison of isobars in Fig. 8)

Theoretical studies on ^{12}O have focused on the location and width of the ground state (1988CO15, 1997KR10, 1999BA03, 1999SH43, 2001LE22, 2002GR03, 2003FO14, 2010FO08, 2013FO10, 2014ROZZ). In several approaches the analog states in ^{12}Be are utilized to gain an understanding of the expected ^{12}O structure (1999SH43, 2006FO11, 2011FO04). In most cases the expected width ($\approx$ 100 keV) is significantly smaller than the experimentally observed widths. The possibility for ^{2}He decay has been discussed in (2001BA31, 2001GR29, 2002GR03, 2002GR25, 2003BA99, 2003FO14, 2006CA05, 2009LE22). See also (2005JI04, 2006SA29, 2009BA41, 2011SH26, 2016PA05).

1. ^{9}Be(^{13}O, ^{12}O)^{10}Be $\quad Q_{\rm m} = -10.0590$

Table 12.52: Energy levels of ^{12}O

E_x (MeV ± keV)	J^π	Γ (keV)	$E(2p + ^{10}C)$ (keV)	Decay	Reactions
0 [a]	0^+	< 72	1638 ± 24	2p	1, 2, 3, 4
(1.620 ± 105) [b]	0^+	$1.2^{+0.3}_{-0.7}$	3258 ± 107	2p	2, 3
1.968 ± 52 [b]	(2^+) [c]	475 ± 110	3606 ± 60	2p	1, 2
4.2	1^-	2.2 MeV	5.8 MeV	2p	3
7.0		2.2 MeV	8.6 MeV	2p	3

[a] From (2012JA11) ($\Delta M = 31914 \pm 24$ keV). Other results suggest $\Delta M > 32$ MeV, but in these cases systematic effects appear greater than in (2012JA11).

[b] It is unclear whether the groups observed at $E_x = 1.62$ MeV and $E_x = 1.97$ MeV represent unique states or a closely spaced doublet.

[c] A state with $J^\pi = 2^+$ is expected in this energy region. J^π is from systematics.

At $E(^{13}\mathrm{O}) = 33.4$ MeV/A population of ^{12}O states was measured by stripping a single neutron from ^{13}O on a ^{9}Be target and measuring the $^{10}\mathrm{C} + 2\mathrm{p}$ products resulting from decay of the unbound ^{12}O nuclei (1995KR03, 1995KR24, 1998AZ03). The decay energy spectrum was deduced by reconstructing the $^{10}\mathrm{C} + 2\mathrm{p}$ relative energy spectrum; a peak corresponding to the ^{12}O ground state is found at $E^{\mathrm{rel}}_{\mathrm{cm}} = 1.77 \pm 0.02$ MeV with $\Gamma = 578 \pm 205$ keV. Evidence for ^{12}O excited states is present in the spectrum, however no resonance peaks are resolved. Analysis of the p-p angle correlations indicates that equal energy protons are emitted isotropically; this is consistent with direct three body breakup, though sequential decay through the ^{11}N ground state appears likely (1998AZ03). An upper limit of $\Gamma_{^2\mathrm{He}} \leq 7\%$ is deduced for diproton decay (1995KR03).

The reaction was also measured at $E(^{13}\mathrm{O}) = 30.3$ MeV/A, the beam impinged on a ^{9}Be target where 1n and 1p knockout reactions occurred yielding ^{12}N and ^{12}O reaction products (2012JA11). The ^{12}O nuclei decayed into $^{10}\mathrm{C} + 2\mathrm{p}$, which were detected in a position sensitive ΔE-E array. Kinematic reconstruction of the relative energies found evidence for ^{12}O*(0, 1968 ± 52 keV) at $E^{\mathrm{rel}}_{\mathrm{cm}} = 1.638 \pm 0.024$ MeV and 3.606 ± 0.060 MeV with $\Gamma = < 72$ keV and 475 ± 110 keV, respectively. For $^{12}\mathrm{O}_{\mathrm{g.s.}}$, $\Delta M = 31914 \pm 24$ keV. This mass excess is smaller than the previously reported values, but the measurement seems more reliable since the ground state peak is well separated and since the experimental resolution is improved. Comparison using the IMME formula finds the $T = 2$ quintet for $A = 12$ can be fit with a quadratic form. See also ^{12}N reaction 5 and see discussion in (2016FO19).

2. $^{12}\mathrm{C}(\pi^+, \pi^-)^{12}\mathrm{O}$ $\qquad Q_m = -31.9150$

At $E_{\pi^+} = 180$ MeV the mass excess of ^{12}O was measured as $\Delta M = 32059 \pm 48$ keV (1980BU15). In addition to observing the ^{12}O ground state, at $E_\pi = 164$ MeV (1985MO18) found

Table 12.53: Experimental studies of ^{12}C(π^+, π^-)^{12}O double charge exchange reactions

Reactions	E_π (MeV)	Measurements	Reference
$^{6,\,7}$Li, ^{9}Be, ^{12}C(π^+, π^-), (π^-, π^+)	120-270	$\sigma(\theta, E_{\pi^-})$	(2007FO05)
^{7}Li, ^{12}C, ^{16}O, ^{56}Fe(π^+, π^-)	30-90	$\sigma(\theta, E_{\pi^-})$	(2000DR19)
^{12}C, ^{24}Mg, ^{32}S, ^{40}Ca(π^+, π^-)	164	$\sigma(\theta)$	(1991WA04)
^{12}C, ^{16}O, ^{44}Ca, ^{56}Fe(π^+, π^-)	100-300	$\sigma(\theta)$ vs E in Δ resonance region	(1990SE11)
^{4}He, $^{6,\,7}$Li, ^{9}Be, ^{12}C, ^{16}O, ^{40}Ca, ^{103}Rh, ^{208}Pb(π^+, π^-), (π^-, π^+)	180, 240	σ, target A/Z systematics	(1989GR06)
^{12}C(π^+, π^-)	50-120	$\sigma(\theta)$, $\sigma(\theta)$ vs E, $\sigma(E_{\pi^-})$; deduced σ energy dependence	(1987FA05)
^{12}C, ^{24}Mg, ^{28}Si, ^{32}S, ^{40}Ca(π^+, π^-), (π^-, π^+)	120-210	$\sigma(\theta, E_{\pi^-})$	(1985MO18)
^{12}C, ^{24}Mg, ^{28}Si, ^{32}S, ^{40}Ca(π^+, π^-)	120-210	$\sigma(\theta = 5^\circ)$ vs E, target A/Z systematics	(1983BL08)
^{9}Be, $^{12,\,13}$C, ^{16}O, ^{24}Mg, ^{32}S(π^+, π^-)	180	$\sigma(\theta)$, ^{12}O mass	(1980BU15)
^{12}C, $^{40,\,44,\,48}$Ca(π^+, π^-), (π^-, π^+)	290	$\sigma(E_{\pi^-})$	(1979DA16)

additional cross section strength at $E_x = 1.7$ MeV and viewed this as evidence of the $J^\pi = 2^+$ first excited state. At $E_\pi = 59.4$ MeV, weak evidence for ^{12}O*(0, 1.3, 2.8) is found (1987FA05). See Table 12.53 for a summary of relevant (π^+, π^-) double charge exchange measurements. The table also includes some results that explored (π^+, π^-) reaction dynamics; also see theoretical analysis in (1979HU02, 1981DZ03, 1985OS08, 1986CH39, 1986FO03, 1986GI13, 1988MA27, 1989AU05, 1993CL03, 1992BI04, 1993GI03, 1994MO44).

3. ^{14}O(p, t)^{12}O $\qquad Q_m = -31.5684$

An $E(^{14}\text{O}) = 50$ MeV/A beam impinged on a cryogenic hydrogen target and the residual triton products were detected in a set of four position sensitive ΔE-E telescopes (2016SU05). The ^{12}O products decayed in flight to ^{10}C, which were detected in coincidence with the tritons using a ΔE-ΔE-E at $\theta < 1.6^\circ$. Excitation energies with $\Delta E = \pm 100$ keV were determined by constructing the missing mass spectrum. The ground state properties were assumed from (2012JA11). Peaks at $E_x = 0, 1620 \pm 30$ (stat.) ± 100 (sys.), 4200 and 7000 were observed with $\Gamma < 72$ keV (2012JA11), 1.2 ± 0.1 (stat.) $^{+0.3}_{-0.7}$ (sys.) MeV, 2.2 MeV and 2.2 MeV, respectively. A DWBA analysis of the angular distributions found $L = 0$, 0, 1 and (0, 1, 2) for these states, which implies $J^\pi = 0^+$, 0^+ and 1^- for the first three states. An earlier result in (2009SU14, 2012SU21) suggested $L = 0, 2$ in the $E_x = 1.8$ MeV region that could imply presence of a doublet; however the present result does not support this interpretation.

4. ^{16}O(α, ^{8}He)^{12}O $Q_{\rm m} = -65.8368$

At $E_\alpha = 117.4$ MeV the Q-value for the ^{16}O(α, ^{8}He) reaction was measured by detecting the ^{8}He recoils at $\theta_{\rm lab} = 8°$ (1978KE06). The energy spectrum indicated $Q = 66.02 \pm 0.12$ MeV and $\Gamma = 400 \pm 250$ keV for the reaction ($\Delta M = 32.10 \pm 0.12$ MeV). In addition five counts are attributed to an excited state at $E_{\rm x} = 1.0 \pm 0.1$ MeV, using the Wigner limit for reduced widths, the diproton decay branching ratio is 30 to 90 %.

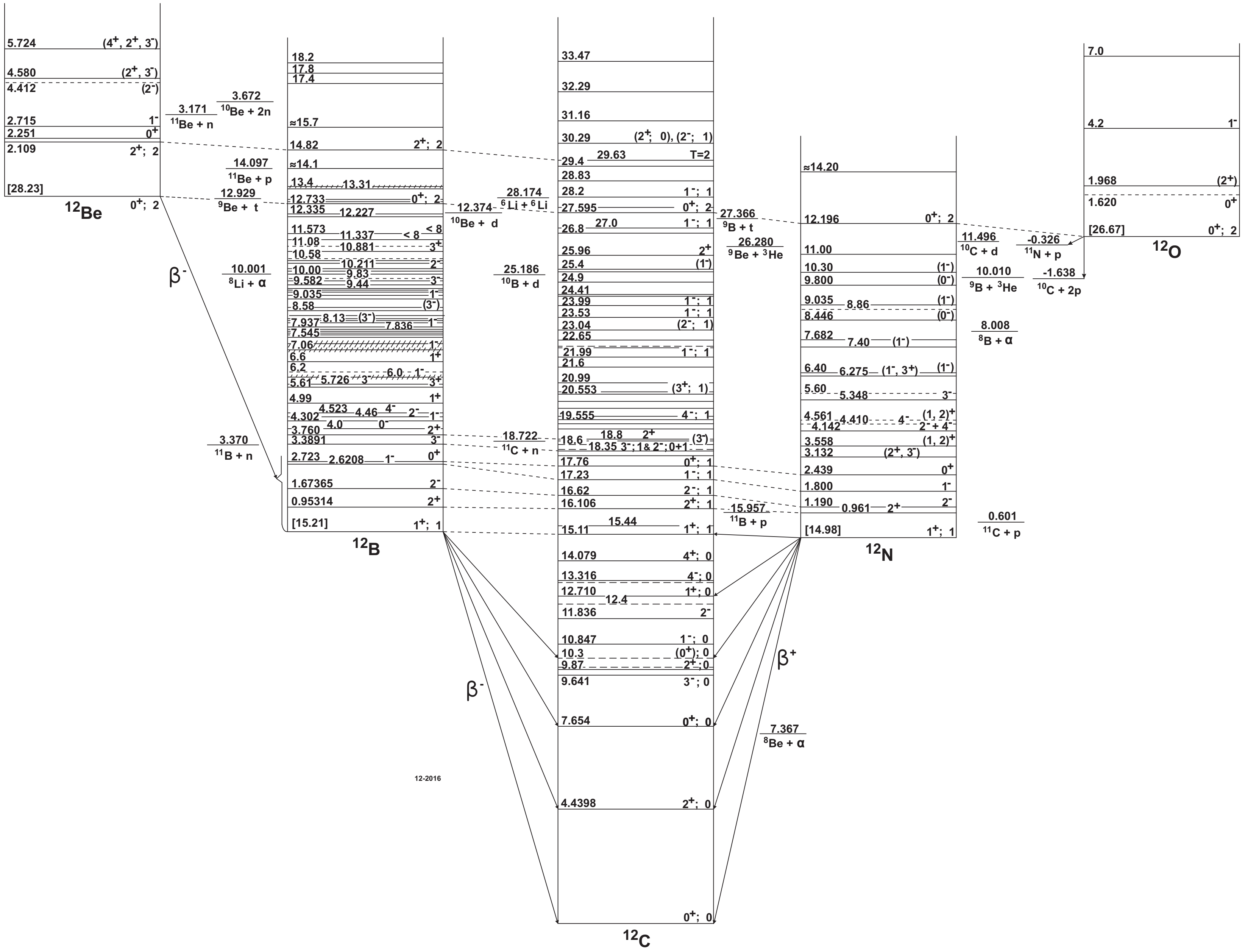


Fig. 8: Isobar diagram, $A = 12$. The diagrams for individual isobars have been shifted vertically to eliminate the neutron-proton mass difference and the Coulomb energy, taken as $E_C = 0.60Z(Z-1)/A^{1/3}$. Energies in square brackets represent the (approximate) nuclear energy, $E_N = M(Z, A) - ZM(\text{H}) - NM(\text{n}) - E_C$, minus the corresponding quantity for ^{12}C: 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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