Energy Levels of Light Nuclei
$A = 12$

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Abstract: An evaluation of $A = 11$–12 was published in *Nuclear Physics A*114 (1968), p. 1. This version of $A = 12$ differs from the published version in that we have corrected some errors discovered after the article went to press. Figures and introductory tables have been omitted from this manuscript. Reference key numbers have been changed to the NNDC/TUNL format.

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^{12}Be

(Fig. 8)

An activity of $\tau_{1/2} = 11.4 \pm 0.5$ msec, ascribed to ^{12}Be, is observed in the GeV proton irradiation of ^{15}N, ^{16}O, ^{18}O, ^{19}F, ^{23}Na and ^{27}Al targets (1965PO03). A peak in the particle-identifier spectrum from 5.3 GeV protons on U confirms the existence of ^{12}Be, but the assignment of the 11.4 msec half-life is rendered uncertain by the discovery of ^{11}Li (1966PO09). A calculation by Kurath (see ref [8] in (1965PO03)) suggests $\log ft = 3.5$ for the ground state; E_{β^-}(max) is then ≈ 11.7 MeV for the above $\tau_{1/2}$. $(M - A)$ for ^{12}Be is then ≈ 25.1 MeV, which would mean that ^{12}Be is bound with respect to ^{11}Be + n by ≈ 3.2 MeV. See also (1960GO1B, 1960ZE03, 1961BA1C, 1967AU1B).

^{12}B

(Figs. 5 and 8)

GENERAL:

See (1956KU1A, 1959FL41, 1960TA1C, 1963RE1C, 1963RU1C, 1964MA2A, 1964NA1G, 1964ST1B, 1965UB1C, 1966MA1P, 1967HA10, 1967KE1K, 1967KE1L, 1967MO1R, 1968HI1C).

$$\mu = +1.003 \pm 0.001 \text{ nm (1967SU03).}$$

1. ^{12}B(β^-)^{12}C $\qquad Q_{\rm m} = 13.370$

Measured values of the half-life are displayed in Table 12.2. The decay is complex; ^{12}B decays to the ground state of ^{12}C and to several excited states: see ^{12}C. The transition to ^{12}C$_{\rm g.s.}$ and (4.4) are allowed: hence $J(^{12}\text{B}) = 1^+$.

2. ^{6}Li(^{7}Li, p)^{12}B $\qquad Q_{\rm m} = 8.337$

At $E(^7\text{Li}) = 2$ MeV, eleven groups of protons are reported to known states of ^{12}B (1959MO12). At $E(^7\text{Li}) = 2.6$ MeV, a 1.67 MeV γ-ray is reported by (1962BE24). Angular distributions of protons have been determined by (1967GA06: $E(^6\text{Li}) = 3.5$ MeV; p_0, p_1, p_2, p_3) and by (1967KI03: $E(^7\text{Li}) = 3.78$ to 5.95 MeV; p_0, p_1, p_2, p_{3+4}, p_5). Except for p_2, the distributions are nearly isotropic. See also (1957NO14, 1962BE16).

Table 12.1: Energy levels of ^{12}B

E_x in ^{12}B (MeV $\pm$ keV)	J^π	τ or Γ (keV)	Decay	Reactions
g.s.	1^+	$\tau_{1/2} = 20.41 \pm 0.06$ msec	β^-	1, 2, 3, 5, 6, 7, 8, 9, 12, 15, 17, 22, 24
0.95314 ± 0.60	2^+	$\tau_m = 300 \pm 33$ fsec	γ	2, 3, 6, 8, 12
1.67365 ± 0.60	2^-	< 50 fsec	γ	2, 3, 6, 8, 12
2.6208 ± 1.2	1^-	< 70 fsec	γ	2, 3, 6, 8, 12
2.723 ± 11	$(\leq 3^+)$		γ	2, 3, 8, 12
3.388 ± 7	$(\leq 3^+)$	< 1.5	n, γ	2, 6, 8, 9, 12
3.756 ± 7	2^+	37 ± 4	n, γ	2, 6, 8, 9, 10, 12
4.303 ± 7	$(1)^-$	9 ± 4	n, γ	2, 6, 8, 9, 10
4.540 ± 20	3^-	110 ± 20	n, γ	2, 6, 8, 9, 10, 12
5.00 ± 20	$1^{(+)}$	60 ± 20	n, γ	2, 6, 8, 9, 10
5.610 ± 20	2	110 ± 20	n	2, 6, 8, 10
5.730 ± 20	3	60 ± 15	n	6, 8, 10
6.6	> 0	140	n	6, 10
(6.76)		65	n	6, 10
7.54	> 3	≤ 14	n	6, 10
(7.66)	> 0	45	n	10
7.77	> 0	90	n	6, 10
(7.96)	> 0	27	n	6, 10
8.23	> 1	65	n	10
8.40		110	n	6, 10
8.49	> 1	75	n	10
9.03	> 1	120	n	6, 10
9.95	> 0	100	n	10
10.53	> 2	65	n	10
12.27	> 2	120	n	10
[a]				

[a] And thirteen resonances in ^{9}Be(t, n)^{11}B.

Table 12.2: Half-life of ^{12}B [a]

$\tau_{1/2}$ (msec)	Ref.
20.6 ± 0.2	(1958VE20)
$18^{+1.5}_{-1.3}$	(1957CO57)
20.7 ± 0.3	(1958BU1E)
20.4 ± 0.4	(1959FA03)
18.87 ± 0.50	(1959KR1B)
20.31 ± 0.20	(1961SC09)
20.15 ± 0.2	(1962PO02) [b]
20.80 ± 0.15	(1962NE14)
20.3 ± 0.1	(1963FI05)
20.2 ± 0.2	(1963PE10)
20.41 ± 0.06	Weighted average [c]

[a] See also (1955AJ61).
[b] See also (1962MA19).
[c] Excluding (1957CO57, 1959KR1B).

3. ^{7}Li(^{7}Li, d)^{12}B $\quad Q_{\rm m} = 3.309$

The gamma decay of the first four excited states has been studied by (1963CA09): besides the 0.95 MeV state, the states at 1.67 and 2.72 MeV decay primarily to the ground state ($> 98\%$ and $> 80\%$, respectively), while the 2.62 MeV state decays primarily via cascades through the 0.95 or 1.67 MeV states ($> 80\%$). $\tau_{\rm m}$(^{12}B*(0.95)) $= 295 \pm 40$ fsec; $\tau_{\rm m}$(^{12}B*(1.67)) < 50 fsec (1967THZX). See also ^{11}B(d, p)^{12}B. See also (1962BE24, 1967WY1B) and ^{14}C in (1970AJ04).

4. ^{9}Be(t, n)^{11}B $\quad Q_{\rm m} = 9.561 \quad E_{\rm b} = 12.930$

Reported resonances in the yield of neutrons at $\theta = 0°$ are listed in Table 12.3 (1961VA1C). See also (1962SE1A).

5. ^{9}Be(α, p)^{12}B $\quad Q_{\rm m} = -6.884$

See (1951MC57, 1955RA41, 1962WE1C).

Table 12.3: Resonances in ^{9}Be(t, n)^{11}B (1961VA1C)

E_t (MeV)	E_x in ^{12}B (MeV)	Γ_{cm} (keV)	E_t (MeV)	E_x in ^{12}B (MeV)	Γ_{cm} (keV)
1.00	13.679	100	1.880	14.339	45
1.130	13.777		1.932	14.378	40
1.350	13.942	60	2.045	14.462	70
1.405	13.983	50	2.130	14.526	75
1.505	14.058	70	2.210	14.586	60
1.585	14.118	65	2.325	14.672	50
1.765	14.253	110			

6. ^{9}Be(^{7}Li, α)^{12}B $\qquad Q_m = 10.463$

At $E(^{7}\text{Li}) = 3.5$ MeV, α-groups are seen to the ground state of ^{12}B and to levels at 0.90, 1.61, 2.58, 3.27, 3.60, 4.22, 4.39, 4.90, 5.60, 5.80, 6.61, 7.00, 7.42, 7.77, 8.05, 8.34 and 9.06 MeV. Angular distributions have been obtained for the first five states for $E(^{7}\text{Li}) = 3.3$, 3.5 and 3.75 MeV. The total cross sections range from 1.1 to 2.3 mb. All angular distributions are characterized by backward maxima (1961HO19). See also (1966RO1E).

7. ^{9}Be(^{11}B, 2α)^{12}B $\qquad Q_m = 1.799$

See (1963HO1E).

8. ^{10}B(t, p)^{12}B $\qquad Q_m = 6.343$

Eleven excited states of ^{12}B have been observed by (1960JA17) at $E_t = 5.5$ MeV and by (1964MI04) at $E_t = 10$ MeV. Widths and J^π values derived from angular distribution analyses (1964MI04) are displayed in Table 12.4. See also (1963HO19) and (1965SH1E, 1966SH1F, 1967BA1E; theor.).

9. ^{11}B(n, γ)^{12}B $\qquad Q_m = 3.369$

The thermal neutron capture cross section is 5 ± 3 mb (1962IM01). The excitation function of β^- particles (from ^{12}B decay) shows a resonance at $E_n = 20$ keV, with $\omega\Gamma_\gamma \approx 0.4$ eV, $\Gamma < 10$ keV (1964MO07). In the range 140 to 2325 keV, resonances are observed at $E_n = 0.43$, 1.03, 1.28 and 1.78 MeV, with radiation widths of 0.3, 0.3, 0.2 and 0.9 eV, respectively ($\pm 50\%$) (1962IM01).

Table 12.4: Parameters of ^{12}B states from ^{10}B(t, p)^{12}B

E_x in ^{12}B (MeV)	Γ (keV)		L [a]	J^π [a]
(1960JA17) [b]	(1964MI04)	(1960JA17)		
g.s.				
0.955			0	3^+
1.673				
2.627			0	3^+
2.73			(0)	(3^+)
3.393			0	3^+
3.754	42 ± 5	45	1	2^-, 3^-, 4^-
4.297	≤ 15			
4.514	100 ± 15	50	1	2^-, 3^-, 4^-
5.00	130 ± 40	≈ 40		
5.612	120 ± 20	145	0	3^+
5.724	70 ± 20		0	3^+

[a] (1964MI04).

[b] ±8 keV, except for the 2.73 and 5.00 MeV states.

10. ^{11}B(n, n)^{11}B $\qquad E_b = 3.369$

The thermal (bound) scattering cross section for B is 4.4 ± 0.2 b (1958HU18, 1961WI1A). The scattering amplitude (bound) is $a = 6.6 \pm 0.3$ fm (1965DO14), 6.53 ± 0.35 fm (1966DO11). Parameters of observed resonances in σ_{tot} are listed in Table 12.5. The resonance at $E_n = 20$ keV (1966MO09) is also observed in ^{11}B(n, γ)^{12}B (1964MO07). Angular distributions near the $E_n = 0.43$ MeV resonance $(J = 2)$ show $\cos\theta$ terms, indicating interference with s-wave potential scattering. The best fit to the data is obtained with $l = 1$ formation of the resonance, either all channel spin 1 or all channel spin 2 (1955WI25). Polarization results can be explained by interference of s- and p-wave neutrons at this resonance (1962EL01). The $E_n = 1.28$ MeV resonance can be fitted with $J = 3$, $l = 2$ with the partial width in channel spin 2 equal to 10 times that in channel spin 1. Potential scattering at $E_n = 1.5$ MeV is nearly all s-wave, $\delta_0 = -90°$ (1955WI25). A resonance not seen in earlier work is reported by (1962IM01) at $E_n = 1.027$ MeV. The observed cross section is consistent with s-wave formation, $J^\pi = (1)^-$. Polarization and differential cross section measurements have been carried out at 70 neutron energies from 0.075 to 2.25 MeV. Large polarizations are observed from the resonance at $E_n = 1.28$ MeV up to 2.25 MeV. Resonance behavior of the interference terms indicates that the parities of ^{12}B*(4.54) and (5.00) must be opposite (1967LA1N).

Total cross sections from $E_{\rm n} = 3.4$ to 15.5 MeV have been studied by (1961FO07): see Table 12.5. There is no evidence of sharp structure in the range $9.7 < E_{\rm x} < 17.3$ MeV. Limitations of statistical accuracy exclude observation of $J = 0$ levels above $E_{\rm n} = 4$ MeV, and of $J = 1$ levels above $E_{\rm n} = 12$ MeV in this work. Total cross sections from $E_{\rm n} = 14.1$ to 18.0 MeV are reported by (1954CO16).

See also (1963BA1F, 1963KU1F, 1963NE1H, 1965MO1J, 1967MA1K) and (1963LU10, 1966AG1A; theor.) and (1959AJ76).

11. (a) ^{11}B(n, d)^{10}Be	$Q_{\rm m} = -9.004$	$E_{\rm b} = 3.369$
(b) ^{11}B(n, t)^{9}Be	$Q_{\rm m} = -9.561$	
(c) ^{11}B(n, α)^{8}Li	$Q_{\rm m} = -6.632$	
(d) ^{11}B(n, p)^{11}Be	$Q_{\rm m} = -10.731$	

Reaction (a) has not been reported. At $E_{\rm n} = 14.1$ MeV, the cross section for reaction (b) is 15 ± 5 mb (1958WY67). The cross section for reaction (c) decreases from 27 mb at $E_{\rm n} = 12.6$ MeV to 16 mb at $E_{\rm n} = 20.0$ MeV (1956AR21). At $E_{\rm n} = 14.1$ MeV, the cross section is 35 ± 7 mb (1959SA04; see also (1962KA37, 1963CH20, 1966MO09)). The cross section for reaction (d) has been measured for $E_{\rm n} = 14.7$ to 16.9 MeV (1962KA37, 1966ST17). See also (1959AL83, 1964ST25).

12. ^{11}B(d, p)^{12}B $\qquad Q_{\rm m} = 1.144$

Observed proton groups and gamma rays are displayed in Table 12.6. Angular distributions of protons leading to the ground and 0.95 MeV states are of special interest because of the low Q-value: see studies by (1953HO48, 1961GO27, 1961GO28, 1961PU1B, 1962GO24, 1963RO22, 1963SE1F, 1963SE1G, 1964FI1D, 1964TI03, 1965BE1V, 1965FI05, 1965GA02, 1965LO02, 1965SA15, 1966GA09, 1966HA10, 1967BO17, 1967MO1Q, 1967SC29). Spectroscopic factors are listed by (1965GA02, 1966GA09, 1967MO1Q, 1967SC29). Polarization of the recoil ^{12}B is reported by (1959CH1D, 1967SU03).

The 0.95 MeV level is formed by p-wave capture, $J^\pi = 0^+, 1^+, 2^+$ or 3^+. The observed anisotropy of the γ-radiation (1960KO03, 1963WA20, 1965BE1V) excludes $J = 0$. The mean life of the state is 0.30 ± 0.033 psec (1968OL01). So short of a life excludes pure E2 radiation and hence $J \neq 3$, and limits $\delta^2 \equiv$ E2/M1 intensity ratio to < 0.02 for $J = 1$ or 2 (1963WA20). The observed polarization of the γ-ray also excludes $J = 3$ (1965BE1V). Gamma-γ correlations in the cascade $1.67 \to 0.95 \to$ g.s. fix $J = 2$; the amplitude mixing ratio $\delta \equiv$ E2/M1 for γ (0.95) is in the range $-0.124 \to 0.00$ (1968CH05). The energy of the level is 953.14 ± 0.60 keV (1966WI01). The observed $\Gamma_\gamma = 2.2 \pm 0.25$ meV and the mixing rates E2/M1 are in satisfactory agreement with IPM predictions (1968OL01). See also (1961GO27, 1961GO28, 1966BE31, 1967BO17).

Table 12.5: Resonances in ^{11}B(n, n)^{11}B [a]

E_n (MeV $\pm$ keV)	Γ_r (lab) (keV)	^{12}B* (MeV)	l [b]	θ_n^2 [c]	J^π
0.02 [d]	< 1.5	3.387			
0.43 ± 10 [e]	40 ± 5	3.76	1	0.036	2^+ [h]
1.027 ± 11 [f]	10 ± 4	4.310	0		$(1)^-$
1.28 ± 20 [e]	140 ± 20	4.54	2	0.28	3^- [h]
1.78 ± 20 [e]	65 ± 20	5.00	1	0.012	1 [c,i]
			(2)	0.056	
2.45 ± 20 [e]	120 ± 40	5.61	1	0.017	2 [c]
			2	0.053	
2.58 ± 20 [e]	60 ± 20	5.73	1	0.008	3 [c]
			2	0.025	
3.5 [g]	140 (c.m.)	6.6			> 0
(3.70)	65 (c.m.)	(6.76)			≥ 0
4.55	≤ 14 (c.m.)	7.54			> 3
(4.68)	45 (c.m.)	(7.66)			> 0
4.80	90 (c.m.)	7.77			> 0
(5.01)	27 (c.m.)	(7.96)			> 0
5.31	65 (c.m.)	8.23			> 1
5.49	110 (c.m.)	8.40			
5.59	75 (c.m.)	8.49			> 1
6.18	120 (c.m.)	9.03			> 1
7.18	100 (c.m.)	9.95			> 0
7.82	65 (c.m.)	10.53			> 2
9.72	120 (c.m.)	12.27			> 2

[a] (1964ST25).
[b] (1951BO45, 1955WI25, 1964ST25).
[c] (1951BO45); $R = 4.5$ fm.
[d] (1964MO07, 1966MO09).
[e] (1951BO45, 1958HU18, 1964ST25).
[f] (1962IM01).
[g] This resonance and all the higher energy ones have been observed by (1961FO07).
[h] (1955WI25, 1966MO09).
[i] The parity appears to be even: see (1967LA1N).

Table 12.6: ^{12}B levels from ^{11}B(d, p)^{12}B

^{12}B* (MeV ± keV)	l_n [f]	J^π [g]	Gamma decay [d] (%)	τ_m [d] (fsec)
0	1	1^+	–	
0.95314 ± 0.60 [a]	1	2^+	to g.s.	300 ± 33
0.947 ± 5 [b]				
0.952 ± 3 [c]				
1.67365 ± 0.60 [a]	0	2^-	$(3.2 \pm 0.4) \rightarrow 0.95$	< 50
1.674 ± 11 [b]			$(96.8 \pm 0.4) \rightarrow$ g.s.	
2.6185 ± 3.5 [a]	0	1^-	$(14 \pm 3) \rightarrow 1.67$	
2.6208 ± 1.2 [d]			$(80 \pm 3) \rightarrow 0.95$	< 70
2.618 ± 11 [b]			$(6 \pm 1) \rightarrow$ g.s.	
2.723 ± 11 [b]	(1)	$(\leq 3^+)$	$(> 85\%) \rightarrow$ g.s.	
3.383 ± 9 [b]	1	$(\leq 3^+)$	$\Gamma_\gamma < 0.1\,\Gamma$ [g]	
3.76 [e]				
4.53 [e]	2			

[a] (1966WI01).
[b] (1950BU1A, 1953EL12).
[c] (1961JA23).
[d] (1968OL01).
[e] (1953HO48).
[f] (1953HO48, 1961GO27, 1961GO28, 1962GO24, 1965GA02, 1966GA09).
[g] See (1965GA02, 1968CH05).

The 1.67 MeV state is formed by s-wave capture, $J^\pi = 1^-$ or 2^-. The gamma decay is mainly direct, with a (3.2 ± 0.5)% (1968OL01), 3.0 ± 0.6% (1968CH05) branch via ^{12}B*(0.95): $\tau_m < 50$ fsec (1968OL01). See also (1964CH04, 1963WA20, 1965GA02). Gamma-γ correlations lead to an assignment $J^\pi = 2^-$ (1964CH04, 1965GA02, 1968CH05). The energy of the level is 1673.65 ± 0.60 keV (1966WI01).

The 2.62 MeV level is formed by s-wave capture, $J^\pi = 1^-$ or 2^- (1962GO24, 1965GA02). The level decays mainly via ^{12}B*(0.95) (80 ± 3)%. The ground-state branch is (6 ± 1)% (1968OL01): $\tau_m < 70$ fsec (1968OL01). See also (1963WA20, 1965GA02). Gamma-γ correlations lead to $J^\pi = 1^-$. $E_x = 2620.8 \pm 1.2$ keV (1968OL01), 2618.5 ± 3.5 keV (1964CH04, 1966WI01). See also (1965GA02).

The 2.72 MeV level is only weakly excited; most probably $l_{\rm n} = 1$, $J^\pi \leq 3^+$, although $l_{\rm n} = 0$, 2 are not excluded (1965GA02). The decay is mainly, if not entirely, (> 85%) to the g.s. (1968OL01): see also ^{7}Li(^{7}Li, d)^{12}B.

The 3.39 MeV state is formed by $l_{\rm n} = 1$ (1953HO48); $\Gamma_\gamma/\Gamma < 0.1$ (1965GA02). See also (1963BR16, 1966BE1E, 1966GO1L, 1966SC23, 1967CH19).

13. ^{11}B(t, d)^{12}B $\qquad Q_{\rm m} = -2.888$

Not reported.

14. ^{11}B(α, ^{3}He)^{12}B $\qquad Q_{\rm m} = -17.209$

Not reported.

15. ^{12}C(n, p)^{12}B $\qquad Q_{\rm m} = -12.588$

See (1948JE03, 1959AL83, 1967ME11) and ^{13}C in (1970AJ04).

16. ^{12}C(t, ^{3}He)^{12}B $\qquad Q_{\rm m} = -13.352$

Not reported.

17. ^{13}C(γ, p)^{12}B $\qquad Q_{\rm m} = -17.535$

See (1963NE02) and ^{13}C in (1970AJ04).

18. ^{13}C(d, ^{3}He)^{12}B $\qquad Q_{\rm m} = -12.041$

Not reported.

19. ^{13}C(t, α)^{12}B $\qquad Q_{\rm m} = 2.280$

Not reported.

20. ^{14}C(n, t)^{12}B $Q_{\rm m} = -17.229$

Not reported.

21. ^{14}C(p, ^{3}He)^{12}B $Q_{\rm m} = -17.993$

Not reported.

22. ^{14}C(d, α)^{12}B $Q_{\rm m} = 0.361$

See (1950HU72, 1956DO41).

23. ^{14}N(n, ^{3}He)^{12}B $Q_{\rm m} = -17.366$

Not reported.

24. ^{15}N(n, α)^{12}B $Q_{\rm m} = -7.623$

See (1948JE03).

^{12}C
(Figs. 6 and 8)

GENERAL:

Shell model : (1956KU1A, 1956PE1A, 1957KU58, 1960ME1C, 1960TA1C, 1960WE1C, 1961BA1E, 1961TR1B, 1963NA04, 1963VI1A, 1964AM1D, 1964CL1A, 1964GI1B, 1964GI1C, 1964NE1E, 1965BA2E, 1965CO25, 1965FA1C, 1965NE1C, 1966GI1A, 1966HA18, 1966VA1D, 1966YO1B, 1967CO32, 1967EV1C, 1967KU1N, 1968HI1H).

Collective model : (1959BA1F, 1959BR1E, 1961CL10, 1962CL13, 1962GO1R, 1962WA17, 1963GO1Q, 1964BR1H, 1964VO1B, 1965ST22, 1965UB1B, 1965UB1A, 1965VO1A, 1966BO1X, 1966DA1F, 1966DR1F, 1966KR02, 1967BA2N, 1967BO1G, 1967BO04, 1967BR1E, 1967KR1C, 1967LA09, 1967LA1G, 1967PA10, 1967RI1B, 1967RO1G, 1967SA1K, 1967SO1A, 1967SO07, 1967BA1K, 1967BA12, 1967BA2D, 1968MI1E, 1968SO1B).

Cluster model : (1956GL1B, 1956PE1A, 1959PI1B, 1960BI1E, 1960IN1B, 1960SH1A, 1966HE1C, 1962MA1H, 1963MA1D, 1963MA1E, 1964GR1M, 1964MA1G, 1965BA2D, 1965BE1H, 1965FA1C, 1965IN1A, 1965KU1E, 1965NE1B, 1965SH11, 1966DA1J, 1966DU1D, 1966HA1R, 1966HE1C, 1966KA1A, 1966BR1U, 1967NO1C, 1967TA1C, 1967UI01, 1968GO01).

Special levels : (1959BA1D, 1960BA38, 1960WE1C, 1960ZE1B, 1961YO1A, 1962BA1C, 1963DU1C, 1963SE17, 1964LI1B, 1964NA1G, 1964PA1H, 1966BR2E, 1966ME05, 1966MO08, 1967RO1L).

E1 giant resonance : (1960SA1F, 1962NI1D, 1962VI01, 1963MI1B, 1963PE04, 1964GI1C, 1964MI1E, 1966DR1F, 1966LE1J, 1967BA2N, 1967DA1H, 1967DR1D, 1967KE1L, 1967ME1G, 1967MU1F, 1967YO04, 1968KA1M).

Special reactions : (1961BE1E, 1961JA1H, 1964AF1A, 1964DU1D, 1964PA1H, 1964RE1B, 1965KR1A, 1965MA1X, 1966DE1G, 1966DU1D, 1966PH1C, 1967AU1B, 1967KA1C, 1967ZI1A).

Transition probabilities : (1956EL1C, 1957KU58, 1962KU1D, 1962WA17, 1963BO1D, 1963KI1D, 1963KU03, 1963MA1E, 1964CL1D, 1965GR1H, 1965ST22, 1967HS1A, 1967KU1N).

Muon capture : (1965FO1F, 1965UB1A, 1966FR1J, 1967BA78, 1968BA2G).

Other topics : (1959CA1B, 1964RA1A, 1966BA42, 1966BO1P, 1966WI1E, 1966YO1C, 1967BL1D, 1967EL1E, 1967NE1G).

1. (a) ^{6}Li(^{6}Li, α)^{8}Be	$Q_{\rm m} = 20.808$	$E_{\rm b} = 28.177$
(b) ^{6}Li(^{6}Li, n)^{11}C	$Q_{\rm m} = 9.457$	
(c) ^{6}Li(^{6}Li, p)^{11}B	$Q_{\rm m} = 12.220$	

(d) ^{6}Li(^{6}Li, d)^{10}B $\quad Q_{\rm m} = 2.989$

(e) ^{6}Li(^{6}Li, nα)^{7}Be $\quad Q_{\rm m} = 1.912$

(f) ^{6}Li(^{6}Li, pα)^{7}Li $\quad Q_{\rm m} = 3.556$

(g) ^{6}Li(^{6}Li, ^{6}Li)^{6}Li

Table 12.7: Energy levels of ^{12}C

$E_{\rm x}$ in ^{12}C (MeV $\pm$ keV)	$J^{\pi}; T$	Γ (keV)	Decay	Reactions
0	0^{+}; 0	–	stable	3, 4, 6, 15, 16, 17, 18, 19, 23, 24, 25, 26, 27, 28, 29, 36, 38, 39, 40, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 72, 73, 74, 75, 76, 77, 78
4.4392 ± 0.3	2^{+}; 0	11.7 ± 0.5 meV	γ	6, 15, 16, 17, 19, 23, 24, 25, 28, 29, 36, 38, 39, 40, 43, 44, 47, 48, 49, 51, 53, 54, 55, 60, 61, 63, 65, 66, 68
7.653 ± 3	0^{+}; 0	9.7 ± 3.3 eV	γ, π, α	6, 15, 17, 23, 24, 28, 36, 38, 39, 40, 43, 44, 51, 54, 55, 61, 65
9.638 ± 5	3^{-}; 0	34 ± 5 keV	γ, α	6, 15, 17, 19, 23, 24, 36, 38, 39, 40, 44, 47, 55, 61, 65
10.3 ± 300	(0^{+}); 0	3000 ± 700	α	6, 24, 28, 38, 51
10.844 ± 16	1^{-}; 0	320 ± 20	α	6, 15, 23, 24, 38, 39, 55, 61, 65
11.828 ± 16	2^{-}; 0	274 ± 20	α	15, 17, 23, 24, 38, 39, 44
12.713 ± 6	1^{+}; 0		γ_0, γ_1, α	15, 17, 23, 24, 39, 44, 51, 53, 61
13.352 ± 17	(2^{-}); 0	400 ± 50	α	15, 23, 24, 61
14.083 ± 15	(4^{+}); 0	258 ± 15	α	15, 23, 39, 44, 47, 61,
14.71 ± 10		< 15		24
15.109 ± 4	1^{+}; 1	39.4 ± 1.5 eV	γ_0, γ_1	2, 6, 15, 17, 23, 30, 36, 39, 51, 53, 55, 61
16.106 ± 1	2^{+}; 1	6 ± 0.6 keV	γ_0, γ_1, γ_3, α_0, α_1, p	15, 19, 23, 29, 36, 39, 61
16.577 ± 20	2^{-}; (1)	300	γ_1, α_1, p	15, 19, 21, 30, 53
17.23	1^{-}; 1	1150	γ_0, γ_1, α_0, α_1, p	19, 21, 23, 29
17.77	0^{+}; (1)	100	α_0, α_1, p	19, 21
(18.1)	(1^{-})	500	γ_0, α, p	34, 36, 39
18.36	(3^{-}; 0)	310	γ_1, α_0, α_1, p	19, 21

Table 12.7: Energy levels of ^{12}C (continued)

E_x in ^{12}C (MeV ± keV)	$J^\pi; T$	$\Gamma_{c.m.}$ (keV)	Decay	Reactions
18.39	0^-	42	p	21
18.71	(; 1)	100	α_0, p	19
18.84	2^+; 1	100	γ_1, p, n	19, 20, 21
19.2	(1^-; 1)	1100	γ_0, γ_1, α_0, α_1, p, n	19, 20, 21, 30, 36
19.2	(2^-; 1)	500		36, 39
19.39	(2^+; 0)	(1100)	γ_1, α_0, α_1, p	19, 21
(19.42)		45	p	21
(19.69)		180	p, n	20
19.88		90	p	21
20.24		150	p, n	20, 21
20.47		180	γ_1, α_1, p	19, 39
20.64	(3^-; 1)	200	γ_1, α_0, p, n	15, 19, 20, 21
20.99		270	p, n	20, 39
21.49		430	γ_0, p, n	19, 20, 39
22.1			γ_0, γ_1, α_0, p, n	19, 20, 30, 39
22.6	(1^-; 1)	3200	γ_0, p	19, 29, 30, 31, 36, 39
22.64		330	p, n	20
23.04		60	p, n	20
23.52		350	p, n	20, 30, 39
23.6			γ_0, γ_1, α_0, p, n	19, 20
23.89		170	p, n	20
(24.2)			p, n	20
24.44		80	p, n	15, 20
24.93		900	p, n	20
25.25	(; 2)	115	γ_1, p, n	19, 20
25.4	(1^-; 1)	≈ 6500	γ_0, γ_1	19, 29, 30
25.96		400	p, n, d, α	9, 12, 20, 39
26.9		270	γ_1, p, n	19, 20
27.45			γ_0, p, n, d	10, 19, 30
28.0		350	γ_0, p_1, p, n, ^{3}He	5, 19
28.45			γ_1, p	19
28.9			γ_0, p, α, n	19, 29, 30, 34

Table 12.7: Energy levels of ^{12}C (continued)

E_x in ^{12}C (MeV $\pm$ keV)	$J^\pi; T$	$\Gamma_{c.m.}$ (keV)	Decay	Reactions
32.4			γ_0, n	31
34.4	$(1^-; 1)$	≈ 4000	γ_0, γ_1, p	19, 30, 36

Elastic scattering, studied for $E(^6\text{Li}) = 3.2$ to 7.0 MeV follows the Mott formula at low energies, but deviates at energies $\gtrsim$ 4.0 MeV. Angular distributions can be accounted for by the Blair cut-off model, but the parameters are not sharply defined (1966PI02).

For $E(^6\text{Li}) = 1.2$ to 2.8 MeV, population ratios of ^{7}Be*(0.43), ^{7}Li*(0.48) and ^{10}B*(0.72) remain approximately constant. Simple tunneling or compound nucleus models are not compatible with the data and a direct interaction through long-range tails is suggested (1962MC12). Absolute reaction cross sections at $E(^6\text{Li}) = 2.1$ MeV are in reasonable agreement with estimates based on barrier penetration. A strong preference for α-emission suggests that the favored mechanism involves interacting clusters (1963HU02). A conspicuous feature of the α-spectrum involves a transition through highly excited states of ^{8}Be, possibly those at $E_x = 22.2$ and 22.9 MeV with large ^{6}Li + d parentage (1963KA20, 1964MA26). Angular distributions of α_0 and α_1 indicate stripping (1964MA26: 2.0 to 4.4 MeV). Noticeable fluctuations of protons angular distributions and of $0°$ α-yields in the range $E(^6\text{Li}) = 2.4$ to 9.0 MeV (1966KI09), and 2.2 to 14.5 MeV (1967AL1F), indicate compound nucleus effects. See also (1962DE1F, 1963BA1Q, 1963CO35, 1963LE19, 1964CA1G, 1964GA1E, 1965NO1A), ^{8}Be and ^{10}B in (1966LA04), and ^{11}B and ^{11}C here.

2. ^{6}Li(^{7}Li, n)^{12}C $\qquad Q_m = 20.924$

At $E(^7\text{Li}) = 2.6$ MeV, population of the ^{12}C states at 15.11 and 4.44 MeV is reported (1962BE24). See also (1957NO17, 1963KA1E).

3. ^{6}Li(^{11}B, αn)^{12}C $\qquad Q_m = 12.260$

See (1963HO1E).

4. ^{7}Li(^{7}Li, 2n)^{12}C $\qquad Q_m = 13.672$

See (1962BE16, 1962BE24).

5. (a) ^{9}Be(^{3}He, γ)^{12}C $Q_m = 26.282$ $E_b = 26.282$
(b) ^{9}Be(^{3}He, n)^{11}C $Q_m = 7.562$
(c) ^{9}Be(^{3}He, p)^{11}B $Q_m = 10.325$
(d) ^{9}Be(^{3}He, d)^{10}B $Q_m = 1.094$
(e) ^{9}Be(^{3}He, t)^{9}B $Q_m = -1.087$
(f) ^{9}Be(^{3}He, α)^{8}Be $Q_m = 18.913$
(g) ^{9}Be(^{3}He, ^{3}He)^{9}Be

The yield of capture γ-rays to the ground and 4.4 MeV states (reaction (a)) has been measured for $E(^3\text{He}) = 2$ to 4.5 MeV. The cross section increases monotonically; at 4.5 MeV, $\sigma(\gamma_0)$ is ≈ 4 μb. A strong 17.6 MeV γ-ray is ascribed to reaction (f) (1964BL12). Evidence for decays via higher states of ^{12}C is not conclusive (1963BL05, 1964BL12).

Excitation functions for neutrons (reaction (b)) have been determined by (1963DU12: 1.2 to 2.7 MeV; n_0, n_1, n_2, n_3, n_{4+5}; $\theta = 0°$ and $81.5°$), (1965DI06: 1.3 to 4.9 MeV; n_0, n_1; $\theta = 0°$, $90°$ and $160°$), (1965TO06: 3.5 to 5.8 MeV; n_0, n_1, n_{2+3}, n_{4+5}, n_6, n_7, n_8; $\theta = 5°$ and $90°$) and (1968OK1D: 3.5 to 9.9 MeV; n_0, n_1). See also (1959MA1D, 1962SE1A, 1966MA1R, 1967HA20). No sharp structure is observed but there is some suggestion from angular distribution data and excitation functions at forward angles for a broad structure ($\Gamma \approx 350$ keV) at $E(^3\text{He}) \approx 2$ MeV: $E_x = 27.8$ MeV (1963DU12, 1965DI06). Comparison with (^{3}He, p) shows reasonable similarity at low energies, but strong differences for $E(^3\text{He}) > 2.5$ MeV (1965DI06, 1965TO06). For $E(^3\text{He}) = 3.5$ to 5.8 MeV the reaction proceeds predominantly by direct interaction (1965TO06). The total cross section for ^{11}C production shows a broad maximum, $\sigma = 113$ mb, at $E(^3\text{He}) = 4.3$ MeV (1966HA21: 3.2 to 10 MeV). See also (1965BR42, 1967HA20). Angular distributions of the polarization of neutrons to ^{11}C*(0, 2.0, $4.3 + 4.8$) have been measured at nine ^{3}He energies from 2.1 to 3.9 MeV by (1967TH1H). See also ^{11}C.

Excitation functions and angular distributions for protons (reaction (c)) have been measured for $E(^3\text{He}) = 1.0$ to 2 MeV (1967CO03: $90°$; p_2 to p_9), 1.8 to 4.9 MeV (1959WO53: total and differential cross sections; p_0 and p_1), 3 to 5 MeV (1959WO53: p_2 and p_3) and 5.7 to 10.2 MeV (1960HI08: $10°$, p_0 to p_9; $90°$, p_0, p_1). From $E(^3\text{He}) = 5.7$ to 10 MeV the majority of angular distributions are essentially independent of energy, showing pronounced forward peaking, consistent with a predominantly direct process. The excitation curves show only a slow and smooth increase (1960HI08). See also ^{11}B.

Excitation functions for ground-state tritons (reaction (e)) for $E(^3\text{He}) = 2.4$ to 4.1 MeV ($\theta = 20°$, $40°$, $55°$ and $90°$) show a smooth rise with energy in the region explored (1960TA04). At $\theta = 20°$ the cross section then shows a broad maximum at $E(^3\text{He}) \approx 4.5$ MeV. Following this maximum, the cross section decreases to $E(^3\text{He}) \approx 7.5$ MeV and then rises slowly to 9 MeV. Angular distributions of ground-state tritons have been measured at 1 MeV intervals between $E(^3\text{He}) = 5.0$ and 9.0 MeV (1967EA01). Near $E(^3\text{He}) = 10$ MeV, excitation functions for tritons and deuterons show no detailed structure; angular distributions show characteristic direct interaction features. DWBA fits for tritons are less satisfactory than those for deuterons (1967CR04). See also (1960HI08).

The elastic scattering excitation function (reaction (g)) has been measured at $45°$ for $E(^3\text{He}) = 4.0$ to 9.0 MeV: it decreases monotonically over this energy region (1967EA01). For reaction (f), see (1964BL12) and ^{8}Be in (1966LA04).

6. $^9\text{Be}(\alpha, \text{n})^{12}\text{C}$ $\qquad Q_\text{m} = 5.704$

Neutron groups corresponding to ^{12}C levels at 0, 4.4, 7.7, 9.6, (10.1) and (10.8) MeV are reported: see (1960AJ04, 1962NI02). Observation of the γ-decay of the 15.1 MeV level is reported by (1954RA35, 1957WA04, 1957WA1F). Angular distributions have been studied by (1959SM98: 1.9 to 2.7 MeV; n_0, n_1), (1960RE02: 2 to 5.6 MeV; n_0, n_1, n_2), (1960GA14: 3.35 and 5.10 MeV; n_1), (1963ME11: 5.3 MeV; n_1), (1960AJ04: 5.6 and 5.8 MeV; n_0, n_1, n_2), (1961GA03: 5.5, 5.8 and 6.0 MeV; n_0, n_1, n_2), (1967VE1D: 6 to 10 MeV; n_0, n_1, n_2), (1962KJ02, 1962KJ04, 1962NI02: 9.8 to 14.2 MeV; n_0, n_1, n_2, n_{3+4}), (1962DE1G, 1963DE27, 1965DE1F: 12.9 to 23 MeV; n_0, n_1) and (1963KO03: 17.5 to 22.1 MeV; n_0, n_1, n_3).

Doppler shift measurements on the transition ^{12}C*(4.4 $\rightarrow$ g.s.) yield a mean life $\tau_\text{m} = 50 \pm 6$ fsec (1961DE38); 57^{+23}_{-17} fsec, $\Gamma_\gamma = (11.5^{+5}_{-3.2})$ meV (1966WA10); $\leq 48 \pm 10$ fsec (1967CA02): see Table 12.8. 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 $\text{n}_1 - \gamma$ correlations strongly indicate a direct interaction mechanism even at $E_\alpha = 3.3$ and 5.5 MeV (1960GA14, 1962KJ01). Gamma ray angular distributions have been studied by (1955TA28, 1959SM98, 1963SE04). See also ^{13}C.

The 7.65 MeV state decays predominantly into $^8\text{Be}+\alpha$ (see reactions 15 and 28). The 7.7 MeV nuclear pairs have been observed: $\Gamma_\pi/\Gamma = (6.6 \pm 2.2) \times 10^{-6}$ (1959AL97, 1960AJ04, 1960AL04, 1961GA03). See also (1959AJ76) for a survey of the earlier work.

See also (1959HE1B, 1959LI1D, 1959NA1B, 1961DE08, 1961EL1A, 1962BR14, 1962EL1C, 1962GO1J, 1962HU1D, 1962ST12, 1963AN1B, 1964SA1J, 1965CL1B, 1967EL1D, 1967VA1J).

7. $^9\text{Be}(^7\text{Li}, ^4\text{H})^{12}\text{C}$

Not observed: see (1964CA05).

8. $^{10}\text{B}(\text{d}, \gamma)^{12}\text{C}$ $\qquad Q_\text{m} = 25.188$

At $E_\text{d} = 0.95$ MeV, the upper limit to the capture cross section is $0.1\ \mu$b (1955SA1B).

9. $^{10}\text{B}(\text{d}, \text{n})^{11}\text{C}$ $\qquad Q_\text{m} = 6.468$ $\qquad E_\text{b} = 25.188$

The thin-target excitation function in the forward direction in the range $E_\text{d} = 0.3$ to 4.6 MeV

Table 12.8: Electromagnetic decay of ^{12}C levels [a]

Level	Width	Reaction	Refs.
4.44	$\Gamma_\gamma = 12.5 \pm 2.5$ meV	^{12}C(e, e)	(1956HE83)
	11.2 ± 1.2	^{12}C(e, e)	(1964CR11)
	10.6 ± 1.1	^{12}C(e, e)	(1967CR01)
	12.2 ± 0.8	^{12}C(e, e)	(1967AR1A)
	13 ± 1.5	^{9}Be(α, n)	(1961DE38)
	$11.5^{+5}_{-3.2}$	^{9}Be(α, n)	(1966WA10)
	10.1 ± 2	^{12}C(γ, γ)	(1958RA14)
	11.7 ± 0.5 meV		mean
7.65	$\Gamma_\pi = 55 \pm 30$ μeV	^{12}C(e, e)	(1956FR27)
	65 ± 7	^{12}C(e, e)	(1964CR11)
	73 ± 13	^{12}C(e, e)	(1965GU04)
	62 ± 6	^{12}C(e, e)	(1967CR01)
	64 ± 4 μeV		mean
	$\Gamma_\pi/\Gamma = (6.6 \pm 2.2) \times 10^{-6}$	^{9}Be(α, n)	(1960AJ04, 1960AL04)
	$\Gamma_\gamma/\Gamma = (3.3 \pm 0.9) \times 10^{-4}$	^{10}B(^{3}He, p)	(1961AL23)
	(3.5 ± 1.2)	^{10}B(^{3}He, p)	(1964HA23)
	(2.8 ± 0.3)	^{14}N(d, α)	(1963SE23)
	$(2.9 \pm 0.3) \times 10^{-4}$		mean
	$\Gamma = \Gamma_\pi/(\Gamma_\pi/\Gamma) = (9.7 \pm 3.3)$ eV		
	$\Gamma_\gamma = \Gamma(\Gamma_\gamma/\Gamma) = (2.8 \pm 1.0)$ meV		
9.64	$\Gamma_\gamma = 0.36 \pm 0.04$ meV	^{12}C(e, e)	(1964CR11)
	0.31 ± 0.04	^{12}C(e, e)	(1967CR01)
	0.34 ± 0.03 meV		mean
12.71	$\Gamma_\gamma/\Gamma_\alpha = 0.025 \pm 0.007$	^{10}B(^{3}He, p)	(1958MO99, 1959AL96)
	$\Gamma_\gamma/\Gamma = 0.027 \pm 0.007$	^{12}C(p, p)	(1962WA31)
15.11 [b]	$\Gamma_{\gamma_0} = 54.5 \pm 9.3$ eV	^{12}C(γ, γ)	(1957HA13)
	59.2 ± 9.7	^{12}C(γ, γ)	(1959GA09)

Table 12.8: Electromagnetic decay of ^{12}C levels [a] (continued)

Level	Width	Reaction	Refs.
	40.2 ± 5.2	^{12}C(γ, γ)	(1963SC21)
	54 ± 6	^{12}C(γ, γ)	(1961BU1E)
	50.5 ± 7.1	^{12}C(γ, γ)	(1960HA1H)
	37 ± 5	^{12}C(γ, γ)	(1967KU11)
	40^{+8}_{-6}	^{12}C(e, e)	(1959BA36, 1960BA47)
	39 ± 4	^{12}C(e, e)	(1962ED02)
	34.4 ± 3	^{12}C(e, e)	(1964GU05)
	36.0 ± 3	^{12}C(e, e)	(1967PE07)
	39.4 ± 1.5 eV		mean
	$\Gamma_\alpha/\Gamma < 0.05$	^{10}B(^{3}He, p)	(1965AL1B)
	$\Gamma_\gamma/\Gamma = 1.15 \pm 0.3$	^{12}C(p, p)	(1962WA31)

[a] See also ^{11}B(p, γ)^{12}C and ^{12}C + γ.

[b] See also Table 12.15.

shows some indication of a broad resonance 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). The $0°$ excitation function for ground state neutrons shows no structure for $E_{\rm d} = 3.2$ to 9.0 MeV. The angular distributions all show a sharp peak around $20°$ and a smaller contribution in the background direction. DWBA produces a satisfactory fit to these distributions, but the parameters vary with energy (1967DI01). Cross-section ratios have been obtained at $E_{\rm d} = 1$ to 5 MeV for the neutrons and protons to the second, third, fourth, and fifth excited states of the ^{11}B and ^{11}C mirror nuclei (1967SC1K). Polarization measurements have been carried out for $E_{\rm d} = 2.5$ to 4.0 MeV (1967ME1N). See also (1955SA1B) and ^{11}C.

10. ^{10}B(d, p)^{11}B $\qquad Q_{\rm m} = 9.231 \qquad E_{\rm b} = 25.188$

Absolute yields and angular distributions are reported for various proton groups by (1952EN19, 1954BU06, 1954PA28, 1956MA69, 1956VA17, 1959CR1A, 1960CR1A, 1960HA08, 1964BR1A, 1965LE1B, 1967PO01) for $E_{\rm d} = 0.14$ to 12 MeV. 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 (to ^{11}B*(2.14, 5.03)) (1964BR1A). Studies of plane wave, distorted wave and Coulomb wave Born approximation angular distributions are reported by (1967PO01: see also (1966MO1H, 1967MO1N). There are no significant fluctuations in the yield of protons for $E_d = 5$ to 12 MeV (1965LE1B: $\theta = 50°$ and $150°$). See also (1965BA31). Yields of gamma rays have been measured by (1955SA1B). Cross section ratios for the (d, n) and (d, p) reactions to mirror states have been measured by (1967SC1K) [see reaction 9].

Polarization measurements have been made by (1959HI1E: 6.9 MeV; p_0), (1964BE08: 10 MeV; p_0, p_1, $p_2 + p_3$), (1962TA13, 1964PA1E: 11 to 13.8 MeV; p_0), (1960TA27: 11.4 MeV; p_0), (1963BO1J: 21 MeV; p_0). The circular polarization of 2.12 and 4.44 MeV γ-rays has been investigated at $E_d = 0.45$ MeV (1960ER1A, 1961ZI02, 1962ZI01, 1963ER1A). See also ^{11}B.

11. ^{10}B(d, d)^{10}B $\qquad E_b = 25.188$

See ^{10}B and (1965LE1B, 1967DI01, 1967PO01).

12. ^{10}B(d, α)^{8}Be $\qquad Q_m = 17.819$ $\qquad E_b = 25.188$

Excitation curves and angular distributions are reported for α_0 and α_1 groups (to ^{8}Be*(0, 2.9)) by (1956MA69, 1960BE15, 1961LE10, 1963PU02, 1964AL1Q, 1964BR1A, 1966LO18, 1967LO1J) for $E_d = 0.4$ to 3.3 MeV. Broad maxima are observed in both excitation curves above $E_d = 1$ MeV. Preliminary data at $E_d = 0.98$ MeV indicate the formation of a level in ^{12}C at 26.00 ± 0.01 MeV which decays via ^{8}Be*(2.9) and ^{8}Be$_{g.s.}$ (1967PE1B).

13. ^{10}B(d, ^{6}Li)^{6}Li $\qquad Q_m = -2.989$

This reaction has been studied for $E_d = 8$ to 13.5 MeV. A DWBA calculation with $L = 2$ α-transfer gives a qualitative account of the angular distribution (1964GE10).

14. ^{10}B(t, n)^{12}C $\qquad Q_m = 18.931$

Not reported.

15. ^{10}B(^{3}He, p)^{12}C $\qquad Q_m = 19.695$

$Q_0 = 19.6945 \pm 0.0036$ (1967OD01).

Table 12.9: ^{12}C states from ^{10}B(^{3}He, p)^{12}C

E_x [a] (MeV ± keV)	Γ (keV)	Γ_γ/Γ	Gamma branching to		Alpha decay [c] to		Parity [c,g]	$J^\pi;T$
			^{12}C$_{g.s.}$	^{12}C*(4.43)	^{8}Be$_{g.s.}$	^{8}Be*(2.9)		
4.43								
7.655 ± 6		3×10^{-4} [d]			yes		natural	0^+
9.645 ± 6	36 ± 6 [b]				yes		natural	
10.849 ± 25	320 ± 30 [b]				strong	no	natural	
11.841 ± 25	245 ± 30 [b]				no	yes	unnatural	
12.713 ± 6		0.025 ± 0.01		0.20 ± 0.07 [f]	no	yes	unnatural	1^+
13.29 ± 30	430 ± 100 [b]				no	yes	unnatural	≥ 1 [c]
	290 ± 70 [c]							
14.083 ± 15	252 ± 15 [b]				yes	yes	natural	(2^-) [c]
	320 ± 50 [c]							
15.108 ± 6		> 0.95 [g]	0.97 [e]	0.034 ± 0.005 [e,f]	($\Gamma_\alpha/\Gamma < 0.05$) [g]			$1^+; 1$
16.108 ± 6					weak	strong	natural	(2^-)
16.57					yes	yes	natural	
≈ 20.6	≈ 200							
≈ 24.5	≈ 50							

[a] (1962BR10): excitation energies based on $Q_0 = 19.693$ MeV and Po $\alpha = 5.3056$ MeV: see also (1958MO99, 1959AL96, 1967CO1F).
[b] (1962BR10).
[c] (1966WA16).
[d] (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 pairs). $\Gamma_{rad}/\Gamma = (3.5 \pm 1.2) \times 10^{-4}$ (1964HA23): see Table 12.8.
[e] (1959AL96).
[f] (1960AL14).
[g] (1965AL1B).

Proton groups observed by (1958MO99, 1959AL96, 1962BR10, 1967CO1F) are displayed in Table 12.9. Angular distributions of many of these groups have been measured for $E(^{3}\text{He}) = 2.0$ to 3.0 MeV (1965BH1A), 3.7 MeV (1962BR10), 10.1 MeV (1962AL01) and 14 MeV (1967CO1F). The following comments on individual levels derive largely from the ^{10}B(^{3}He, p)^{4}He^{4}He^{4}He studies of (1964ET02, 1965AL1B, 1966WA16): see Table 12.9.

^{12}C*(7.65, 9.6) are observed to decay to ^{8}Be$_{g.s.}$, confirming natural parity $\pi = (-1)^J$ for both states (1966WA16). Pair emission from ^{12}C*(7.66) has been measured: $\Gamma_\pi/\Gamma = (6.6 \pm 2.2) \times 10^{-6}$ [see Table 12.8] as has the cascade through ^{12}C*(4.4): $\Gamma_\gamma/\Gamma = (3.3 \pm 0.9) \times 10^{-4}$ (1961AL23). By observation of ^{12}C recoils, a value $\Gamma_{rad}/\Gamma = (3.5 \pm 1.2) \times 10^{-4}$ is found by (1964HA23): compare to ^{14}N(d, α)^{12}C.

^{12}C*(10.8) decays to both ^{8}Be*(0, 2.9), indicating natural parity. (1966WA1C) searched for ^{12}C*(10.1) with inconclusive results: see also (1962BR10).

^{12}C*(11.83, 12.71, 13.35) decay to ^{8}Be*(2.9) but not to the g.s., indicating unnatural parity: this result is inconsistant with the assignment (1^-) to ^{12}C*(11.83): see (1964BR25). For ^{12}C*(12.71) $\Gamma_\gamma/\Gamma_\alpha = (3 \pm 1)$% (1958MO99), (2 ± 1)% (1959AL96): the cascade through ^{12}C*(4.4) is (20 ± 7)% relative to the ground-state transition (1960AL14): see Table 12.9. The alpha breakup of ^{12}C*(12.71) shows a triple-peaked α-particle spectrum, characteristic of the breakup of a $J^\pi = 1^+$ state (1967BH1B).

^{12}C*(14.08) decays both to ^{8}Be*(0, 2.9); the branching ratio $\Gamma(\alpha_0)/\Gamma$ 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 to ^{12}C$_{\rm g.s.}$ 97% and to ^{12}C*(4.4) (3.1 ± 0.6)% (1959AL96), (4 ± 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): see, however, (1958KA31).

^{12}C*(16.11, 16.57) show decay to 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 [see reaction 19]. For ^{12}C*(16.11) observed 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: (1965DE1R)).

The giant resonance excitation region has been searched for levels with a resolution of ≈ 20 keV at $E(^{3}\text{He}) = 14$ MeV. Two peaks have been observed corresponding to ^{12}C* ≈ 20.6 and 24.5 MeV, with $\Gamma \approx 200$ and 50 keV, respectively. Angular distributions show forward maxima. peaks which could be associated with structure seen in photodisintigration experiments are not observed (1967CO1F). See also (1959JO1E, 1961AL10, 1961WO08, 1962KU02, 1965SI05, 1966BA01) and ^{13}N.

16. ^{10}B(α, d)^{12}C $\qquad Q_{\rm m} = 1.341$

$Q_0 = 1.3406 \pm 0.0015$ (1965BR28).

At $E_\alpha = 21.2$, 23.0 and 25.0 MeV angular distributions of the deuterons corresponding to ^{12}C*(0, 4.4) have been measured (1967AL16).

See also (1959HE1C, 1960ON01, 1965JA03, 1965NI1B) and ^{14}N.

17. ^{10}B(^{6}Li, α)^{12}C $\qquad Q_{\rm m} = 23.716$

At $E(^{6}\text{Li})_{\rm c.m.} = 3.05$ MeV, angular distributions have been obtained for α_0, α_1, α_2 and α_3. The α-particles to ^{12}C*(11.83) and (12.71) have also been observed (1966MC05). At $E(^{6}\text{Li}) = 3.8$ MeV, the population of the $T = 15.11$ MeV state is about 3 ± 2% of the $T = 0$ state at 12.71 MeV. It is pointed out that in this reaction the distance of closest approach is 15 fm and the dominant potential would be the Coulomb potential. It is therefore not neccessary to invoke a large $T = 0$ mixing in the 15.11 MeV state to explain the observation of the 15 MeV γ rays (1964CA18).

See also (1963MI02, 1963MO1B, 1965GA1H, 1966BR1G, 1967SE08).

Table 12.10: Resonances in ^{11}B(p, γ)^{12}C and ^{11}B(p, α)^{8}Be

Peak number	$E_{\rm p}$ (MeV)	$\Gamma_{\rm c.m.}$ (keV)	$\sigma(\gamma_0)$ (μb)	$\sigma(\gamma_1)$ (μb)	$\sigma(\alpha_0)$ (mb)	$\sigma(\alpha_1)$ (mb)	Γ_{γ_0} (eV)	Γ_{γ_1} (eV)
1	0.163 [a]	6.4 [a]	5.5	152	res.	res.	0.22 ± 0.09 [b]	6.8 ± 1.1
2	0.675	300	non-res.	48 [f]	non-res.	600 [f]	< 0.4	8.0
3	1.388	1150	[27] [c]	3	3.3	≈ 180	44	5
4	1.98	100	non-res.	non-res.	9.0	(25)	< 0.5	< 0.5
5	2.62	310	weak?	res.	32.4 ± 4.8	270 ± 40	< 1.5	3.2
6	2.66	42	non-res.	non-res.	non-res.	non-res.	< 0.5	< 0.5
7	3.01	100	non-res.	non-res.	3.4			
8	3.12	100	weak	[20] [c]	non-res.	non-res.	(0.4)	2.0
9	3.5	1100	[20] [c]	res.	5.2	res.	25	10
10	3.75	(1100)	non-res.	res.	7.4 ± 1.1	300 ± 40	< 3	3
11	4.93	180	non-res.	res.	non-res.	170 ± 40		
12	5.11	275	non-res.	[35] [c]	6.0 ± 0.9	non-res.		
13	6.0		res.	non-res.				
14	6.7		res.	[35] [c]	res.			
15	7.2	3200	120	non-res.		(res.)	≥ 2500 [e]	
16	8.3		res.	res.	res.			
17	10.15	115	non-res.	res.				
18	10.3	≈ 6500	[60] [c]	83				
19	11.76		non-res.	45 [d]	res.			
20	12.55		21 [d]	non-res.				
21	13.09		19 [d]	38 [d]				
22	[13.6]		non-res.	25 [d]				
23	14.19		16 [d]	non-res.				
24	20.1	≈ 4000	≈ 9	≈ 20				

Table 12.10: Resonances in ^{11}B(p, γ)^{12}C and ^{11}B(p, α)^{8}Be (continued)

Peak number	$\Gamma_{\alpha 0}$ (keV)	Γ_{α_1} (keV)	Γ_{p} (keV)	^{12}C* (MeV)	$J^{\pi}; T$	Refs.
1	0.290 ± 0.045	6.3 ± 0.5	0.069 ± 0.015	16.11	2^+; 1	(1953HU29, 1961SE10)
2	< 0.27	150	150	16.58	2^-; (1)	(1953BE61, 1953HU29, 1965SE06)
3	10	140	1000	17.23	1^-; 1	(1953HU29, 1963SY01, 1965SE06)
4	4.6	11.4	76	17.77	0^+; (1)	(1955HO48, 1963SY01, 1965SE06)
5	65	177	68	18.36	(3^-; 0)	(1955BA22, 1963SY01, 1965SE06)
6	< 1	< 5	33	18.39	0^-	(1965SE06)
7			< 10	18.71	n.π. ^{g}; (1)	(1965SE06)
8	< 0.2	< 1.5	97	18.82	2^+; (1)	(1955BA22, 1965SE06)
9	50	200	300	19.2	(1^-; 1)	(1955BA22, 1965SE06)
10	20	450	450	19.40	(2^+; 0)	(1963SY01, 1965SE06)
11				20.47		(1955BA22, 1963SY01, 1964AL20)
12				20.64	(3^-; 1)	(1955BA22, 1963SY01, 1964AL20, 1964BL1D)
13				21.5		(1964AL20)
14				22.1		(1963BE18, 1964AL20)
15				22.6	(1^-; 1)	(1961GO13, 1963BE18, 1964AL20, 1964BL1D)
16				23.6		(1963BE18, 1964AL20, 1964BL1D)
17				25.26	($T = 2$)	(1964AL20)
18				25.5		(1961GO13, 1963BE18, 1964AL20, 1967FE04)
19				26.9		(1963BE18, 1964AL20, 1964BL1D, 1967FE04)

Table 12.10: Resonances in ^{11}B(p, γ)^{12}C and ^{11}B(p, α)^{8}Be (continued)

Peak number	$\Gamma_{\alpha 0}$ (keV)	$\Gamma_{\alpha 1}$ (keV)	Γ_{p} (keV)	^{12}C* (MeV)	$J^{\pi}; T$	Refs.
20				27.45		(1967FE04)
21				28.0		(1964AL20, 1967FE04)
22				28.45		(1967FE04)
23				28.9		(1967FE04)
24				34.4	$(1^{-}; 1)$	(1963RE09)

[a] 163.1 ± 0.2 keV, $\Gamma = 6.0 \pm 0.6$ keV: see text.
[b] 1% branch to ^{12}C*(9.63) (1961CA13).
[c] Estimated from graph (1964AL20).
[d] $4\pi \times \sigma(90°)$.
[e] Assuming a single resonance (1961GO13).
[f] (1953BE61, 1953HU29).
[g] n.π. = natural parity.

18. ^{10}B(^{7}Li, αn)^{12}C $\qquad Q_{m} = 16.463$

See (1964CA18).

19. (a) ^{11}B(p, γ)^{12}C $\qquad Q_{m} = 15.957$
(b) ^{11}B(p, α)^{8}Be $\qquad Q_{m} = 8.588$ $\qquad E_{b} = 15.957$

In the range $E_{p} = 0$ to 25 MeV, twenty-three resonances are reported. Their characteristics are displayed in Table 12.10. Cross sections of astrophysical interest are discussed by (1967FO1B).

The $E_{p} = 0.16$ MeV resonance (^{12}C* $= 16.11$ MeV) is well established as the $J^{\pi} = 2^{+}$; $T = 1$ analogue of the first excited states of ^{12}B and ^{12}N: see (1959AJ76). The resonant energy is 163.1 ± 0.2 keV; $\Gamma_{lab} = 6.5 \pm 0.6$ keV [see (1955AJ61)]. The gamma decay of the 16.11 MeV state takes place to ^{12}C*(0, 4.4, 9.6): see (1959AJ76, 1961CA13, 1961SE10). The decay to ^{12}C*(9.6) is via a 6.45 ± 0.05 MeV γ-ray whose angular distribution, together with the known α-decay properties of ^{12}C*(9.6), leads to $J^{\pi} = 3^{-}$. The intensity of the transition is 1% of the γ_{1} decay (1961CA13). See also (1961GR07, 1965CV1A, 1966SO1B).

The character of the α-decay at the $E_{p} = 0.16$ MeV resonance has been studied with coincidence techniques by (1961DE31, 1962DE1H, 1964DE1J, 1965DE1R). Immediately below and above the resonance, a Dalitz plot indicates sequential decay via ^{8}Be*(0, 2.9): in this region, the behavior is ascribed to tails of the $E_{p} = 0.675$ and 1.4 MeV resonances. At $E_{p} = 0.163$ MeV, the

Dalitz plot shows a striking increase in population near the center, indicative of direct 3α breakup. Some part of the reaction also goes through ^{8}Be$_{\text{g.s.}}$, and there is evidence for a final-state two-body interaction with $l = 2$ (1964DE1J): see, however, (1965MA1X, 1965PH1A, 1966CH1L, 1966WA16). See also (1959KA12, 1959KA13, 1960BO26, 1962BE21, 1964DE1H, 1964LO05, 1964LO1E, 1965KR1A, 1965KR1B, 1967KA09, 1967LO1H). Similar studies at $E_{\text{p}} = 0.675$, 1.388 (1965KA1G), 2.0, 2.65, 3.25, 3.73, 4.00, 5.08, and 5.64 MeV (1964PH1A, 1965BR18, 1965PH1A) indicate that sequential decays through ^{8}Be*(0, 2.9) dominate; direct 3α decay is < 5%. The latter work shows evidence for "order-of-emission" interference in the shapes of α-groups: see also (1965DU1C, 1965SW1B). See also (1958FO1D, 1966AD1E, 1966SO1B, 1967LO1H, 1968CH1L).

The $E_{\text{p}} = 0.67$ MeV state (^{12}C* $= 16.58$ MeV) has a proton width $\Gamma_{\text{p}} \approx 150$ keV. Such a width indicates s-wave protons and therefore $J^{\pi} = 1^{-}$ or 2^{-}. These assignments are supported by the near isotropy of the two resonant exit channels, α_1 and γ_1. The size of the α_1 cross section indicates $2J + 1 \geq 5$; therefore $J^{\pi} = 2^{-}$. The reduced width $\theta^2(\alpha_1) \approx 0.05$ and the γ_1 E1 transition has $|M|^2 \approx 0.01$ Weisskopf units, suggesting $T = 1$ (1957DE11, 1965SE06). See also (1959AJ76). (1962BL10) report a γ-branch to the 12.71 MeV state, ≈ 6% of the intensity of the 4.4 MeV transition. Such a branch may also be present at ^{12}C*(17.23).

For the $E_{\text{p}} = 1.4$ MeV state (^{12}C* $= 17.23$ MeV), $(2J + 1)\ \Gamma_{\gamma_0} \geq 115$ 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); see also (1959AJ76). Two solutions for Γ_{p} are possible; the larger (chosen for Table 12.10) is favored by elastic scattering data (1965SE06). (1963SY01) find no evidence for resonance in α_0 or α_1 at this energy.

$J^{\pi} = 0^{+}$; $T = 1$ is consistent with all data for the $E_{\text{p}} = 2.0$ MeV resonance (^{12}C* $= 17.77$ MeV) which decays via the α_0 and α_1 channels (1965SE06). The resonance in the yield of α_0 requires natural parity, and 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 elastic anomaly than is observed (1965SE06: see also (1963SY01)).

At $E_{\text{p}} = 2.62$ MeV ($E_{\text{x}} = 18.36$ MeV), the resonance for α_0 again demands natural parity; the presence of a large P_4 term in the angular distribution requires $J \geq 2$ and $l_{\text{p}} \geq 2$. The assignment $J^{\pi} = 3^{-}$; $T = 0$ is consistent with the resonance data and with the angular distribution of α_0 at the $E_{\text{p}} = 1.98$ MeV resonance (1965SE06: see also (1955GO10, 1963SY01, 1967FL1F, 1968CH1L)).

The $E_{\text{p}} = 2.66$ MeV resonance, distinguished from that at $E_{\text{p}} = 2.62$ MeV by its width, is not seen here: see ^{11}B(p, p).

The $E_{\text{p}} = 3.01$ MeV resonance appears only in the angular distributions for α_0: the small α-widths suggest $T = 1$ (1965SE06).

At $E_{\text{p}} = 3.12$ MeV ($E_{\text{x}} = 18.82$ MeV), the angular distribution of γ_0 indicate 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 structure near $E_{\text{p}} = 3.5 - 3.7$ MeV ($E_{\text{x}} = 19.2$ and 19.4 MeV) 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).

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 ($E_x = 20.64$ MeV); the strength of γ_1 and absence of γ_0 favors $J^\pi = 3^-; T = 1$ (1963SY01).

In the range $4 < E_p < 14.5$ MeV, $\sigma(\gamma_0)$ is dominated by the giant dipole resonance at $E_p = 7.2$ MeV ($E_x = 22.6$ MeV), $\Gamma_{cm} = 3.2$ MeV: $\int \sigma dE = 630$ eV · b. $\sigma(\gamma_1)$ likewise shows a giant resonance centered at about 10.3 MeV ($E_x = 25.4$ MeV), $\Gamma_{cm} \approx 6.5$ MeV, $\int \sigma dE = 850$ eV · b. Both excitation functions show significant fine structure (Table 12.10): see (1964AL20, 1967FE04).

From $E_p = 4$ to 14 MeV the angular distributions of γ_0 are given by $W(\theta) = 1 + a_1 P_1(\cos\theta) + a_2 P_2(\cos\theta)$ with the coefficient a_2 almost constant at -0.6, in approximate agreement with the expectation from particle-hole calculations of $J^\pi = 1^-; T = 1$ states by (1962VI01). The a_1 term exhibits fluctuations for $E_p = 4$ to 5.5 MeV in the region of narrow resonances; from 5.5 to 14 MeV it rises smoothly from $+0.03$ to $+0.3$. A sharp resonance in $\sigma(\gamma_1)$ at $E_p = 10.15$ MeV, $\int \sigma dE = 4$ eV · b, may have $T = 2$ (1964AL20). See also (1959GE33, 1959GO89, 1961GO13, 1963BE18, 1964AL1J, 1964BL1D, 1964TA05, 1965TA1E, 1966HA1M, 1966ME1H, 1966UB01, 1967KA05, 1967KE1K, 1967MA11).

For $15 < E_p < 25$ MeV, a resonance is found at $E_x = 34.4 \pm 0.5$ MeV, $\Gamma \approx 4$ MeV, $\int \sigma(\gamma_0) dE = 38$ eV · b (1963RE09: see, however, (1968BR1M)). The resonance is ascribed to a component of the E1 giant resonance, but the cross section is an order of magnitude less than predicted (1963RE09). (1968BR1M) report no pronounced structure for $E_p = 13$ to 22 MeV.

See also (1961BL09, 1963FE03, 1963VA1C, 1966AR1D, 1966SU1F, 1967TA1D).

20. ^{11}B(p, n)^{11}C $Q_m = -2.763$ $E_b = 15.957$

Excitation functions are reported by (1955BA22: $E_p = 2$ to 5 MeV, long counter), (1959GI47: $E_p = 2.6$ to 5.5 MeV, 4π graphite sphere), (1964BA16: $E_p = 4$ to 14 MeV, 4π graphite sphere), (1961LE11: $E_p = 4.9$ to 11.4 MeV, ^{11}C activity), (1965SE06: $E_p = 3$ to 4 MeV, ^{11}C activity), and (1965OV01: $E_p = 4$ to 11.5 MeV: time-of-flight resolved groups).
The excitation functions are characterized by numerous peaks (see Table 12.11) whose positions appear to correspond with ^{11}B(p, α)^{12}C and with some of the (γ, n) and (γ, p) structure, suggesting that resonances, and not fluctuations, are involved. Angular distributions do not change as rapidly as might be expected from the pronounced structure 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 (1959GO89, 1960FU1A, 1961GO13).

Polarization measurements have been made for $E_p = 7$ to 11 MeV (1965WA04). See also (1962AL18, 1963VA1C, 1965VA23, 1966CA1J, 1966SK03, 1967CA1T) and (1959AJ76).

21. (a) ^{11}B(p, p)^{11}B $E_b = 15.957$
(b) ^{11}B(p, p′)^{11}B*

Table 12.11: Maxima in yields of $^{11}B(p, n)^{11}C$ and $^{11}B(p, p')^{11}B^*$

Peak number	(1955BA22, 1964BA16) [d]		(1959GI47) [d]	(1961LE11) [d]			(1965OV01) [c,d]	
	E_p (MeV)	Γ_{lab} (keV)	E_p (MeV)	E_p (MeV)	Γ_{lab} (keV)	σ (mb)	E_p (MeV)	res. in group(s)
1								
2								
3	3.17	100	3.18 [a]					
4	3.65	500	3.67 [a]					
5								
6	4.05	200					4.10	n_0
7								
8	4.70	150	4.70				4.62	n_0
9	5.10	150	5.10	5.065	210	335	5.07	n_0
10	5.5			5.48	300	308	5.50	n_0
11	6.05	500		6.03	610	430	6.01	n_0, n_1
12							6.4	n_0
13	7.30	300		7.28	420	365	7.3	n_0, n_1
14	7.75	60		7.73	70	322	7.73	n_0, n_1
15	8.26	350		8.25	410	363	8.25	n_0, n_1
16	(8.30)	(≤ 50)						
17	8.67 [b]	140		8.64	230	370	8.6	n_0, n_2
18	9.0							
19	9.26	80		9.24	140	320	9.25	n_0, n_2
20	9.7			9.79	1000	295	9.79	n_0, n_1
21	10.16 [b]	200		10.13	150	310	10.1	n_0, n_2
22	10.92 [b]	400		10.91	480	282	10.9	n_0
23	11.88 [b]	300						

Peak number	(1955BA22) [e]		(1963AN12) [f]		(1965SE06) [g]		
	E_p (MeV)	Γ_{lab} (keV)	E_p (MeV)	Γ_{lab} (keV)	E_p (MeV)	Γ_{lab} (keV)	E_x (MeV)
1			2.0		1.98 [f]		17.77
2	2.664	48	2.63	≈ 300	2.66 [e,f]	46	18.40
3	3.15	100	3.15	≈ 90	3.15 [e,f]	100	18.86
4	3.4	500			3.5 [e]	broad	19.3
5	3.78	50					19.42

Table 12.11: Maxima in yields of ^{11}B(p, n)^{11}C and ^{11}B(p, p′)^{11}B* (continued)

Peak number	(1955BA22) [e]		(1963AN12) [f]		(1965SE06) [g]		
	E_p (MeV)	Γ_{lab} (keV)	E_p (MeV)	Γ_{lab} (keV)	E_p (MeV)	Γ_{lab} (keV)	E_x (MeV)
6							19.69
7	4.28	100					19.88
8	4.68	200					20.24
9	5.13	200					20.60
10							20.99
11							21.49
12							21.8
13							22.64
14							23.04
15							23.52
16							(23.56)
17							23.89
18							24.2
19							24.44
20							24.93
21							25.26
22							25.96
23							26.84

[a] (1965SE06): $E_p = 3.12$ and ≈ 3.65 MeV.
[b] See also (1960FU1A).
[c] Widths ≈ 200 keV, except $E_p = 6.4$ and ≥ 9.25 which are wider.
[d] (p, n).
[e] (p, p′).
[f] (p, p).
[g] See also Table 12.10.

A pronounced anomaly in the elastic scattering is observed near $E_p = 0.67$ MeV at all angles; the level is therefore formed by s-waves. The 0.3 to 1.0 MeV results are well accounted for by two resonances: $E_p = 0.67$ MeV, s-wave, $J^\pi = 2^-$, $\Gamma = 0.33$ MeV. $\Gamma_p/\Gamma = 0.5$, and $E_p = 1.4$ MeV, $J^\pi = 1^-$ (1957DE11). Higher energy structure in the yields of reactions (a) and (b) are displayed in Table 12.11 (1955BA22, 1963AN12, 1965SE06). See also (1960SA28) and Table 12.10.

22. ^{11}B(p, d)^{10}B $Q_{\rm m} = -9.231$ $E_{\rm b} = 15.957$

See ^{10}B.

23. ^{11}B(d, n)^{12}C $Q_{\rm m} = 13.732$

Reported neutron groups are listed in Table 12.12. Angular distributions of the neutrons to many of the ^{12}C states up to $E_{\rm x} = 17.23$ MeV have been reported for energies in the range $E_{\rm d} = 0.5$ to 10 MeV: see (1957AM48, 1958AM13: 0.5 to 1.15 MeV), (1955WA30: 0.6 MeV), (1955IH1B: 0.69 MeV), (1954GR53: 0.85 MeV), (1957BI78: 0.92 MeV), (1962SA09: 1.0 to 2.0 MeV), (1963KI02: 1.6 to 2.7 MeV), (1961ZD02: 1.1 to 2.8 MeV), (1965SI12: 1.1 to 3.2 MeV), (1965CL02: 1.5 to 4.7 MeV), (1961GA04: 2.7 and 5.4 MeV), (1966HU1H, 1967WI1J: 3.0 to 5.5 MeV), (1965AL17: 2.4 to 9.7 MeV), (1964RO1F, 1966RO1X, 1966WE1B: 6.3 MeV), (1953GI05: 8.1 MeV), (1956MA83: 9 MeV), and (1958ZE01: 10 MeV). See also (1959AJ76) and (1960WA1G, 1961HO1D, 1962LE1A, 1963LA1E, 1964NA02, 1965SI13, 1967DI01).

For $E_{\rm d}$ less than 6 to 7 MeV, angular distributions of n_0 and n_1 are characterized by both forward and backward peaks, with broad minima near $90°$. Detailed shapes are strongly dependent on bombarding energy. The general behavior in the lower-energy range is ascribed to heavy-particle stripping by (1957OW03, 1958AN32, 1961ZD02), but others (1961GA04, 1965AL17, 1966ST1L, 1967WI1J), find reasonable agreement with DWBA, possibly also with compound nucleus effects (1963KI02, 1965CL02). For $E_{\rm d} > 7$ MeV, DWBA gives a quite satisfactory account of n_0 and n_1 distributions, except for a single example (n_1 at 8.8 MeV: (1965AL17)). See also (1968YA1G).

Angular correlations of neutrons and 4.4 MeV γ-rays have been studied by (1963HU05: 0.7 and 1 MeV), (1963RI03, 1964RI1D: 1 and 1.2 MeV), (1961ZD02: 1.1 MeV), (1961GA04: 2.65 and 5.35 MeV), (1966RO1X, 1966WE1B: 6.3 MeV). Angular correlations have also been determined for neutrons and 15.1 MeV γ-rays: see (1963KI14: 2.3 and 2.6 MeV), (1960FE01, 1960FE13: 5 and 8 MeV), (1964RO1F: $E_{\rm d} = 6.3$ MeV). The formation of the 15.11 MeV state involves $l_{\rm p} = 1$ with a 12 : 1 ratio between channel spins 2 and 1. The reduced proton width is approximately equal to the single-particle width (1960FE01, 1960FE13).

In the range $E_{\rm d} = 1.0$ to 5.5 MeV, two slow neutron thresholds are observed at 1.627 ± 0.004 MeV ($E_{\rm x} = 15.109 \pm 0.005$ MeV) and near 4.1 MeV (broad; $E_{\rm x} = 17.2$ MeV) (1955MA76). At the lower threshold, 15.1 MeV γ-rays are observed: $E_{\rm d} = 1.633 \pm 0.003$ MeV, width less than 2 keV (1958KA31) [$E_{\rm x} = 15.110 \pm 0.003$ MeV].

A study of the angular distributions and energy spectra of α-particles from the decay of ^{12}C states shows that the 12.71 and 11.83 MeV states decay sequentially via ^{8}Be; the former via ^{8}Be*(2.9), the latter 90% via ^{8}Be*(2.9) and 10% via ^{8}Be(0). There is some evidence that the 10.84 MeV state decays primarily to ^{8}Be(0). $J^{\pi} = 3^{-}$ for the 9.64 MeV state is favored on the basis of the angular distribution of the α-particles to ^{8}Be(0). 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).

Table 12.12: Neutron groups from ^{11}B(d,n)^{12}C

E_x (MeV ± keV) [a]	l_p	θ^2 [c]
0	1 [c]	0.11
4.38 ± 70	1 [c,d]	0.03
7.57 ± 110	[e]	
9.6 ± 100	2 [c,d,f]	0.02
10.8 ± 100	0 [f]	
11.1 ± 100		
11.74 ± 80	0 [f]	
12.76 ± 80	1 [f,g]	
13.21 ± 50 [b]		
13.36 ± 50 [b]		
(14.16 ± 50)		
15.09 ± 30 [i]	1 [h]	
(15.52 ± 30)		
16.07 ± 30	1 [h]	
17.23	> 1 [h]	

[a] (1952JO10, 1954GR53, 1957BI78, 1964RO1F).

[b] May represent a single level at 13.3 MeV (1952JO10).

[c] (1956MA83): $E_d = 9$ MeV.

[d] (1954GR53).

[e] Non-stripping distribution: see (1962SA09).

[f] (1962SA09).

[g] $J^\pi = 1^+$ (1965OL01).

[h] (1964RO1F).

[i] 15.110 ± 0.003 MeV.

Table 12.13: Deuteron groups from ^{11}B(^{3}He, d)^{12}C

^{12}C* [a] (MeV $\pm$ keV)	Γ [b] (keV)	l	J^π	$(2J+1)\theta_p^2$ [b]	$(2J+1)S_{rel}$ [e]
0		1 [c,e]	$0 \to 3^+$		1.00
4.44		1 [c,e]	$0 \to 3^+$		0.61
7.66		1 [c,e]	$0 \to 3^+$		0.035
9.629 ± 10 [d]		2 [b,c,e]	$0 \to 4^-$	0.048	0.30
(10.1)					
10.84 ± 20 [b]	320 ± 30	0 [b]	$1^-, 2^-$	0.040	
11.82 ± 20 [b]	300 ± 30	0 [b]	$1^-, 2^-$	0.073	
12.70 ± 10 [b]		1 [b,e]	$0 \to 3^+$	0.13	0.26
13.38 ± 20 [b]	700 ± 100				
14.71 ± 10 [b]	< 15				

[a] Levels listed without errors were observed by (1960FO01) or (1961HI08) but the level energies were not determined.
[b] (1961HI08); $E(^3\text{He}) = 9.84$ MeV.
[c] (1960FO01); $E(^3\text{He}) = 5.1$ MeV.
[d] Based on 7656 ± 7 keV for next lower level (1960FO01).
[e] (1967CR04); DWBA; $E(^3\text{He}) = 10$ MeV.

See also ^{13}C, (1959AJ76) and (1958ED1B, 1962KU02, 1962NA04, 1962RO1L, 1963RO1K, 1965MA1K, 1966ST1L).

24. ^{11}B(^{3}He, d)^{12}C $\quad Q_m = 10.463$
$Q_0 = 10.4697 \pm 0.0057$ (1967OD01).

Observed deuteron groups are displayed in Table 12.13 (1960FO01, 1961HI08). Excitation functions near 10 MeV show no structure; angular distributions exhibit characteristic direct interaction features (1967CR04). See also (1959HO01, 1959WO1B, 1961HO1F) and (1967AD1F).

25. ^{11}B(α, t)^{12}C $\quad Q_m = -3.858$

Differential cross sections have been obtained for the ground-state tritons and for the tritons to ^{12}C*(4.4), in the forward direction at $E_\alpha = 43$ MeV: single-proton transfer seems to be the dominant reaction mode (1967DE1K). The angular distributions appear to be affected by final state spin (1967SI1A).

26. ^{11}B(^{14}N, ^{13}C)^{12}C $\quad Q_{\rm m} = 8.407$

See (1962NE01).

27. ^{11}B(^{16}O, ^{15}N)^{12}C $\quad Q_{\rm m} = 3.831$

See (1965BO14, 1968KA1L).

28. ^{12}B(β^-)^{12}C $\quad Q_{\rm m} = 13.370$

The decay is mainly to the ground state of ^{12}C; branching ratios to other states are listed in Table 12.14. The half-life is 20.41 ± 0.06 msec (Table 12.2). Since transitions to ^{12}C(0^+) and (2^+) are allowed, J^π of ^{12}B is 1^+.

Since the decays of ^{12}B and ^{12}N are mirror transitions, comparison of the ft values has some interest. According to (1964KA08), ft(^{12}B) $= 11.800 \pm 70$ sec, ft(^{12}N) $= 13.060 \pm 90$ sec; the ratio ^{12}N/^{12}B is 1.11 ± 0.01: see also (1963FI05, 1963PE10, 1964FI02, 1964NA1C, 1964WU01, 1966BA1A). Possible explanations of the difference are discussed by (1963HU10, 1964EI1C, 1965BL1F, 1966MA2R, 1966OK1B).

Comparison of shape factors for the ground-state β-transitions for ^{12}B–^{12}N provides a test of the conserved vector current theory. The correction to the simple Fermi shape should have the form $1 + AE$ for ^{12}B and $1 - AE$ for ^{12}N where A is determined mainly by the (experimental) M1 width of the ^{12}C*(15.1) $T = 1$ level: A(theor.) $= 0.52 \pm 0.12$% MeV^{-1} (1958GE1C, 1959GE1D, 1963KI1D, 1964WU01): see also (1959FL41, 1959MO27, 1960WE1C, 1961MO1C, 1967HU10). The experimental values of (1964WU01) are $A = 0.55 \pm 0.10$ and 0.52 ± 0.06 for ^{12}B and ^{12}N, respectively: see also (1961MA16, 1962LI05, 1962MA22, 1962MC14, 1963GL04, 1963LE05, 1965WU1A).

Transitions to ^{12}C*(4.4), $J^\pi = 2^+$, are allowed. According to (1963PE10) the ratio ft(^{12}N)/ft(^{12}B) $= 0.92 \pm 0.06$. The level energy is 4438.91 ± 0.31 keV (1967CH19).

The level at $E_{\rm x} = 7.6$ MeV has special interest for helium burning processes in stars (1963SE17, 1963SE23, 1967FO1B). Observation of the α-spectrum yields Q(^{12}C*–^{8}Be–^{4}He) $= 278 \pm 4$ keV (1957CO59). With Q(^{8}Be–2^{4}He) $= 92.12 \pm 0.05$ keV (1966BE05), Q(^{12}C*–3^{4}He) $= 370 \pm 4$ keV. Using (1965MA54) masses for ^{8}Be and ^{4}He, ^{12}C* $= 7647.0 \pm 4.1$ keV. Although the level decays mainly by α-emission, both the gamma branch to ^{12}C*(4.4) and pair emission to ^{12}C$_{\rm g.s.}$ have been observed in various reactions. The relevant parameters are given in Table 12.8 (see (1963AL15, 1963SE23)). The fact that the β-decay is allowed indicates $J^\pi = 0^+$, 1^+ or 2^+ for

Table 12.14: Branching in ^{12}B(β^-)^{12}C

Decay to ^{12}C*	Branch (%)	log ft [a]	Ref.
g.s. [b]	97.1	4.075 ± 0.002	
4.43891 ± 0.00031 [c]	1.4 ± 0.4		(1958KA31)
	1.7 ± 0.4		(1956TA07)
	1.3 ± 0.1		(1963PE10)
	1.33 ± 0.09	5.10 ± 0.03	mean
7.647 ± 0.004	1.3 ± 0.4		(1957CO59)
	1.7 ± 0.5		(1963AL15)
	1.5 ± 0.3	4.14 ± 0.10	mean
10.3 ± 0.3 [d]	0.13 ± 0.04		(1958CO66)
	0.07 ± 0.02		(1963WI05)
	0.08 ± 0.02	4.2 ± 0.2	mean

[a] Based on $Q_{\rm m}$ and $\tau_{1/2} = 20.41$ msec: see (1966BA1A).
[b] E_{β^-}(max) $= 13.381 \pm 0.041$ (1962MA22).
[c] (1967CH19).
[d] $\Gamma = 3.0 \pm 0.7$ MeV, $\theta_\alpha^2 = 1.5$ (1966SC23).

Table 12.15: Parameters of the 15.1 MeV ^{12}C level from ^{12}C(γ, γ)^{12}C

	(1957HA13)	(1959GA09)	(1960HA1H)	(1961BU1E)	(1963SC21)	(1967KU11)
Γ(total) (eV)	79 ± 16	64.5 ± 10.4		60 ± 8	44.7 ± 10.3	39 ± 5
Γ_γ(15 $\rightarrow$ g.s.) (eV) [b]	54.5 ± 9.3	59.2 ± 9.7	50.5 ± 7.1 [a]	54 ± 6	40.2 ± 5.2	37 ± 5
Γ_γ(15 $\rightarrow$ 4.4) (eV)	< 5.5	3.2 ± 2.5		6.5 ± 3		
Γ_α (eV)	$(19 - 25) \pm 8$	2.1 ± 3.2				

[a] Measured $\Gamma_{\gamma_0}(\Gamma_{\gamma_0}/\Gamma)^{1/2} = 47.0 \pm 6.0$ eV.
[b] See also Tables 12.8 and 12.20.

^{12}C*(7.6); observation of the α particles eliminates $J^\pi = 1^+$, and the large Γ_α requires $J^\pi = 0^+$ (1957CO59).

The 10.3 MeV level is observed in both ^{12}B and ^{12}N decays. The excitation energy given by (1966SC23) is 10.3 ± 0.3 MeV, $\Gamma = 3.0 \pm 0.7$ MeV. The decay is to ^{8}Be$_{\rm g.s.}$. With $R = 5.2$ fm, $\theta^2_\alpha = 1.5$ and 7.5 for $J^\pi = 0^+$ and 2^+, respectively (1958CO66). It is suggested by (1966MO08) that this level is a highly deformed rotational state with $J^\pi = 2^+$, related to ^{12}C*(7.66). Some fraction of the observed α-spectrum is presumed to result from a "ghost" of the lower level (1962BA1C, 1963WI05, 1964BL12).

In ^{12}N, allowed transitions are observed to ^{12}C*(12.7) and (15.1) (1966SC23, 1967AL03: see also (1963GL04, 1963WI05)). The 12.7 MeV level decays primarily to ^{8}Be*(2.9; $J^\pi = 2^+$); the absence of decay to ^{8}Be$_{\rm g.s.}$ is in agreement with the assignment $J^\pi = 1^+$ (1966SC23). The ft values for both β-transitions (see Table 12.25) agree well with shell model calculations of (1965CO25). In particular, the agreement strongly suggests a close relation between ^{12}C*(12.71; $J^\pi = 1^+$; $T = 0$) and ^{12}C*(15.11; $J^\pi = 1^+$; $T = 1$). A search for the transition from ^{12}B to ^{12}C*(12.71) was unsuccessful (1967AL03). See also (1959JA1B, 1960FA02, 1964SH1J, 1966DU1E).

29. ^{12}C(γ, γ)^{12}C

The lifetime of the 4.4 MeV state has been determined by resonance scattering and absorption as $\tau_{\rm m} = 65 \pm 12$ fsec (1958RA14). See Table 12.8.

Resonance scattering and absorption by the 15.1 MeV level have been studied by (1957HA13, 1959GA09, 1960BU14, 1960HA1H, 1961BU1E, 1963SC21, 1967KU11): partial widths are displayed in Table 12.15. The scattering angular distribution is $W(\theta) = 1 + \cos^2\theta$, indicating dipole radiation (1959GA09); the azimuthal distribution of scattered polarized radiation indicates M1 (1960JA01) and the large Γ(M1) indicates $T = 1$.

The ground-state γ-width of ^{12}C*(16.11) is reported as $\Gamma_\gamma = 7.5 \pm 1.9$ eV (1959KE19: see, however, (1961SE10)). For ^{12}C*(17.22), the scattering cross section is 1.0 ± 1.0 μb, consistent with Γ_γ given by ^{11}B(p, γ) (1963SC21). See also (1960WE1C).

At higher energies, elastic scattering studies show the giant resonance peak at ≈ 24 MeV (see ^{12}C(γ, n)^{11}C), dσ/d$\Omega(135°) = 4$ μb/sr. A considerable tail is visible, extending to > 40 MeV (1959PE32). See also (1958WO53, 1961DE22, 1961WI1G, 1962SE02, 1967LO1B).

30. ^{12}C(γ, n)^{11}C $\qquad\qquad$ $Q_{\rm m} = -18.720$

Recent review papers dealing with this reaction are: (1963HA1E, 1965DA1D, 1965SH1G, 1966BA2Y, 1966FU1C, 1966ME1H).

The total absorption, mainly (γ, p) + (γ, n), in the range $E_\gamma = 13$ to 30 MeV is dominated by the giant resonance peak at 23.2 MeV, $\Gamma = 3.2$ MeV [$E_{\rm x} = 22.6$ MeV from ^{11}B(p, γ)^{12}C]. This

Table 12.16: Integrated cross sections, $^{12}C + \gamma$

Range in E_γ (MeV)	$\int \sigma dE$ (MeV · mb)	Reaction	Refs.
10 – 27	120	σ(tot)	(1959KO55)
11 – 32	200 ± 35	σ(tot)	(1960TA15)
0 – 30	130 ± 20	σ(tot)	(1960ZI01)
0 – 27	84 ± 10 [a]	σ(tot)	(1963BU1G)
0 – 35	144.0	σ(tot)	(1965WY02)
13 – 80	377 ± 60	σ(tot)	(1960WY1A) [b]
0 – 24	22	(γ, n)	(1961RO1C)
0 – 25	29	(γ, n)	(1953MO1B)
0 – 25	27 ± 5	(γ, n)	(1954NA02)
0 – 25	32 ± 3	(γ, n)	(1955BA63)
0 – 25	34	(γ, n)	(1957CO57)
0 – 26	29.4 ± 3	(γ, n)	(1966MI04)
0 – 28	39.2	(γ, n)	(1965MI03)
20 – 27	36	(γ, n)	(1966LO04)
20.5 – 26.5	40.5	(γ, n)	(1966CO09)
0 – 38	56 ± 3	(γ, n)	(1955BA63)
0 – 37	46.2 ± 4	(γ, n)	(1966FU02)
0 – 38	59 ± 5	(γ, n)	(1966CO09)
35 – 70	30 ± 5	(γ, n)	(1966FO06)
0 – 65	77 ± 6	(γ, n)	(1966CO09)
0 – 250	80 ± 10	(γ, n)	(1955BA63)
0 – 300	90 ± 22	(γ, n)	(1951ST89)
0 – 24	46 [c]	(γ, p)	(1956CO59)
20 – 26	43	(p, γ)	(1961GO13)
20 – 26	[58]	(p, γ)	(1964AL20)
20 – 29	50 ± 8	(γ, p)	(1962DO1A)
0 – 24	41 ± 9	(γ, p)	(1961VA10)
0 – 37	102	(γ, p)	(1964TA1G)
0 – 40	77 ± 18	(γ, p)	(1961VA10)
0 – 40	55 ± 13	(p, γ)	(1963RE09)
0 – 170	122 ± 5	(γ, p)	(1964TA1G)

[a] See, however, (1965WY02; p. 591).
[b] See also (1965WY02).
[c] As corrected by (1961VA10).

single peak accounts for 64% of the total strength below 27 MeV. The total integrated cross section to 35 MeV is 144 MeV · mb, about 80% of the classical sum rule, 60 NZ/A MeV · mb: see Table 12.16. Other resonant structure is reported at $E_\gamma = (16.5)$, 17.5, (19.1), 26 and 29 MeV: see Table 12.17 (1960ZI01, 1963BU1G, 1965WY02). See also (1958MO1F, 1958WO53, 1958ZI1B, 1959BU1H, 1959KO55, 1959KU84, 1959PE21, 1960CA09, 1960TA15, 1960WY1A, 1962DE03, 1962MI07, 1963BU18, 1963CO1D, 1965MA1N, 1967BR1P, 1967DR1E).

Shell-model calculations on the structure of the giant resonance ascribe the main effect to four $J^\pi = 1^-$; $T = 1$ levels formed from the particle-hole configurations $p_{\frac{3}{2}}^{-1}s_{\frac{1}{2}}$, $p_{\frac{3}{2}}^{-1}d_{\frac{5}{2}}$, $p_{\frac{3}{2}}^{-1}d_{\frac{3}{2}}$ and $s_{\frac{1}{2}}^{-1}p_{\frac{1}{2}}$, of which the second contributes most of the E1 strength. The computed energies are 19.6, 23.3, 25.0 and 35.8 MeV [the most probable identifications are $E_x = 19.2$, 22.6, 25.4 and 34.4 MeV (Table 12.7)] ((1964LE1D), and references therein). Calculations with a deformed potential suggest a somewhat more complicated structure (1962NI1D). See also (1961BA1D, 1962VI01, 1963BO21, 1963MI1B, 1964GI1C, 1964MI1E, 1965DA1D, 1966FU02, 1966LO04, 1966UB01, 1967LE1H, 1967MA1P).

Observations of $\sigma(\gamma$, n) show a giant resonance centered at about 22.5 MeV, σ(peak) ≈ 8 mb, $\Gamma \approx 3$ MeV, with a long tail slopping off to about 40 MeV. The integrated cross section to 40 MeV is about 60 MeV · mb; integrated to 250 MeV, it is about 80 MeV · mb (Table 12.16). In the giant resonance region, the angular distribution of ground-state neutrons is $W(\theta) = 1 + 1.5 \sin^2 \theta$, consistent with $l_n = 2$ ejection (1960EM02, 1964AL33, 1965VE03: see, however, (1967HA1P)). For $E_\gamma = 28$ to 145 MeV, comparison with (e, e′n) indicates mainly E1 processes, with $\lesssim$ 8% E2 (1958BA60: see also (1961RO1H)).

The giant resonance appears to have a fine structure (Table 12.18): at least two major components are identified at $E_x = 22.0$ and 23.5 MeV (1966FU02, 1966LO04: see also (1966CO09, 1967FI1E)). A satellite at $E_x = 25.5$ MeV is also well established: a large fraction of the decay of this level (6 MeV · mb) involves excited states of ^{11}B and ^{11}C (1966MA1T: see also (1966CO09, 1966FU02)). Up to 28 MeV, about 83% of the neutrons leave ^{11}C in the ground state (1966FU02). Several broad levels are indicated in the range $E_x = 27$ to 35 MeV (1966CO09, 1966FI1D, 1966FU02, 1967FI1E). A possible level near 52 MeV is reported by (1966FO06). See also (1962BO1H, 1966BI1B, 1966CO09). Considerable fine structure in the range $E_x = 19$ to 23 MeV is reported by (1959SA06, 1960GE06, 1961TH03, 1966CO09): see also (1959CO62, 1959VA1D, 1960EM02, 1962FU11, 1965MI03).

Polarization of neutrons has been studied by (1964BE1E, 1964HA1F, 1966RA1E, 1967HA1N, 1967HA1P).

See also (1959OC07, 1961BR28, 1961PR07, 1961RO1C, 1962MI07, 1963FU05, 1965BI1G, 1966KA1C, 1966ME1H, 1967AN11, 1967AU1F, 1967FE05, 1967GL1B, 1967SM1A).

31. ^{12}C(γ, p)^{11}B $\qquad Q_m = -15.957$

Table 12.17: Resonance structure in ^{12}C + γ (total absorption) [a]

E_x (MeV)	Γ (MeV)	σ (peak) (mb)	$\int \sigma \mathrm{d}E$ (MeV · mb)	Ref.
16.5	0.25		(3%)	(1963BU1G)
17.6	0.4		(6%)	(1963BU1G)
[17.5] [b]		[2]		(1965WY02)
19.1	0.65		(6.5%)	(1963BU1G)
23	4.6	[24]		(1959KO55)
22.5		18		(1960ZI01)
23.0	3.2	16 [c]	54 (64%)	(1963BU1G)
23.2		19.8		(1965WY02)
25.6	≈ 2	8	17 (20%)	(1963BU1G)
[26]		[11]		(1965WY02)
29		[12]		(1960ZI01)
[30]		[7]		(1965WY02)

[a] See also Table 12.18.

[b] Numbers read from graph.

[c] Corrected to 22 mb, see (1965WY02).

The photoproton cross section exhibits a single broad giant resonance peak centering at $E_\gamma = 22.5$ MeV, (Table 12.19). There appears to be a significant difference from $\sigma(\gamma$, n) both in shape and peak cross section (1963HA1E, 1966FU1C, 1966ME1H): such a difference could result from a comparatively small isospin mixing (1957BA1K). Some fine structure is suggested by the work of (1956CO59, 1962DO1A, 1963MU08, 1963WA18, 1964SH24, 1964TA1G): compare ^{11}B(p, γ)^{12}C. The angular distributions near the giant resonance are consistent with $W(\theta) = 1 + 1.5 \sin^2\theta$ expected on the IPM (1962DO1A). For higher energies, an appreciable $\cos\theta$ term makes its appearance (1959PE22, 1961VA10, 1963WA18). See also (1965DA1D, 1967FR1E). The azimuthal distribution observed with polarized γ-rays at $E_\gamma = 21.3 - 21.6$ MeV is not inconsistent with E1 (1966KE06). Evidence for involvement of excited states of ^{11}B for $E_\gamma > 30$ MeV is reported by (1959PE22). See also (1960BA1P, 1963BU1G, 1963FI1B, 1966MA1T, 1966RA1E, 1967LE1H).

At high energies, $E_\gamma \gtrsim 150$ MeV, the cross section for photoproton production remains relatively large (≈ 100 μb) and the angular distributions show forward peaking. The high internal momenta thus implies may be understood on a quasi-deuteron picture, in which the interaction involves neutron-proton pairs in close proximity within the target nucleus (1951LE1B). This picture is strongly supported by the observation that most, if not all, high energy photoprotons are accompanied by neutrons with the proper kinematical relation (1954MY1A, 1958BA1C, 1958WH35); see, however, (1965RE1B).

Table 12.18: Resonance structure in $^{12}C(\gamma, n)^{11}C$ [a]

E_x [b] (MeV)	Γ (MeV)	σ (peak) (mb)	$\int \sigma dE$ (MeV · mb)	Refs.
[22] [c]				(1965VE03)
22.0	1.0	[8]	8.7	(1965BA2G, 1966BA34)
22.0	1.5	4.50	10.6	(1966FU02)
22.1				(1962FI1C, 1966FI1D) [d]
22.1				(1966CO09)
22.2		[7.7]		(1966LO04)
22.2				(1965MI03)
[22.2]		[6]		(1966MI04)
22.5		8.3		(1955BA63)
22.75				(1966CO09)
23.0		[7.7]		(1966LO04)
23.1				(1962FI1C, 1966FI1D)
23.2	2.0	5.75	18.1	(1966FU02)
[23.4]		[7.5]		(1966MI04)
23.5	0.8	[11]	10.9	(1965BA2G, 1966BA34)
[23.5]				(1965VE03)
23.5				(1965MI03)
23.6				(1966CO09)
23.7				(1966LO04)
23.8				(1962FI1C, 1966FI1D)
(24.0)				(1966FU02)
(24.9)				(1966LO04)
25.0	0.7	[9]	5.8	(1965BA2G, 1966BA34)
[25.1]				(1965VE03)
25.4				(1966CO09)
25.5	2.0	2.50	7.9	(1966FU02)
25.5				(1965MI03)
25.6		[5.7]		(1966LO04)
(26)				(1966MI04)
26.0				(1966CO09)

Table 12.18: Resonance structure in $^{12}C(\gamma, n)^{11}C$ [a] (continued)

E_x [b] (MeV)	Γ (MeV)	σ (peak) (mb)	$\int \sigma dE$ (MeV · mb)	Refs.
(26.0)				(1966LO04)
(26.5)				(1966LO04)
27.1	1.5	1.50	3.5	(1966FU02)
27.5				(1962FI1C, 1966FI1D)
27.6				(1966CO09)
28.3	1.5	1.50	3.5	(1966FU02)
29.5				(1966CO09)
30.0				(1962FI1C, 1966FI1D)
30.5	2.0	1.95	6.1	(1966FU02)
32.2				(1962FI1C, 1966FI1D)
32.7				(1966CO09)
35.2	≈ 3.5	≈ 1.0	≈ 5.5	(1966FU02)
36.4				(1966CO09)
35.0			5 ± 1	(1966FO06)
≈ 52				(1966FO06)

[a] See Table 12.16 for integrated cross section: see also (1957CO57).
[b] For structure in the range 19 to 22 MeV, see (1962FI1C, 1965BA2G, 1966BA34, 1966CO09, 1966FI1D, 1966FI1E, 1966LO04, 1966MI04).
[c] [ ] = read from figure.
[d] See also (1966FI1E).

Experimentally derived momentum distributions are reported by (1961CE1B, 1963KI03, 1963KI1C). See also (1958MA1A, 1959CH25, 1961MA36, 1961SH1C, 1962CH26, 1962PA08, 1964JI1A). Polarization of the photoprotons has been studied by (1962LI13).

See also (1959PE21, 1962FE12, 1963BO21, 1963FU1D, 1964MO02, 1964SE09, 1966RA1G, 1967MA1P), $^{11}B(p, \gamma)^{12}C$ and $^{12}C(e, ep)^{11}B$.

32. $^{12}C(\gamma, d)^{10}B$ $\qquad Q_m = -25.188$

For $E_{brems} = 90$ MeV, the ratio of yields of deuterons to protons is $\approx 2\%$, for particle energies 15 to 30 MeV. For higher particle energies, the ratio decreases. Angular distributions are similar for

Table 12.19: Giant resonance in $^{12}C(\gamma, p)^{11}B$ [a]

E_x (MeV)	Γ (MeV)	σ_{max} [b] (mb)	Refs.
22.1	3.6	8.1 ± 2.4	(1959PE22)
22.4		13.2 ± 1.6	(1964SH24)
22.4	3.1	9.6	(1962DO1A)
22.5		12.7 ± 2.5	(1961VA10)
22.5	3.1	12	(1961GO13) [f]
[22.5] [c]			(1962HE10)
22.55		19 ± 4 [d]	(1959GE33) [f]
22.6		14.7 [e]	(1956CO59)
22.6	3.2	[11]	(1964AL20) [f]

[a] Compare with $^{11}B(p, \gamma)^{12}C$.
[b] See Table 12.16 for integrated cross sections.
[c] [ ] = read from figure.
[d] As corrected by (1962DO1A).
[e] As corrected by (1961VA10).
[f] From $^{11}B(p, \gamma)^{12}C$.

(γ, d) and (γ, p), with strong forward peaking. These observations are consistent either with a quasi-deuteron mechanism or with a two-stage pickup process (1962CH26: see (1962MA1F, 1964SH1B)). According to (1964SH1B) the high apparent threshold for (γ, d) reflects the presence of continuum states of ^{10}B with a high parentage in ^{12}C. See also (1959CH25, 1960SH1D, 1963BA1K, 1964KI1D, 1965KI04, 1967SM1A).

33. $^{12}C(\gamma, t)^{9}B$ $\qquad Q_m = -27.369$

See (1968BU1D).

34. $^{12}C(\gamma, 3\alpha)$ $\qquad Q_m = -7.274$

The cross section exhibits broad peaks at about 18 MeV and ≈ 29 MeV; a pronounced minimum occurs at 20.5 MeV: to what extent the peaks have fine structure is not clear (1953GO13, 1955CA19, 1955GO59, 1955JO1C, 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). Integrated cross sections are 0.82 ± 0.03 MeV $\cdot$ mb (1964TO1A: to 20.5 MeV), 1.21 ± 0.16 MeV $\cdot$ mb (1953GO13: to 20.5 MeV), 2.8 ± 0.4 MeV $\cdot$ mb (1953GO13: 20.5 to 42 MeV) and < 0.2 MeV $\cdot$ mb (1953GO13: 42 to 60 MeV). Alpha energy distributions show surprisingly strong E1 contributions below $E_\gamma \approx 17$ MeV (1955GO59, 1964TO1A). See also (1958MA1A, 1960GA16, 1961SE13, 1964WA1J, 1965RO1J), and (1959YO1B, 1964LE1C, 1965DZ1A, 1965DZ1B).

35. (a) ^{12}C(γ, pα)^{7}Li $\quad Q_{\rm m} = -24.621$

(b) ^{12}C(γ, nα)^{7}Be $\quad Q_{\rm m} = -26.265$

Reported integrated cross sections for reaction (a) are for 25 to 40 MeV: 1.61 MeV $\cdot$ mb (1962MO16), 1.35 MeV $\cdot$ mb (1956LI05), 3.85 MeV $\cdot$ mb (1958MA1A); for 25 to 120 MeV: 1.9 ± 0.4 MeV $\cdot$ mb (1962MO16). For production of ^{7}Be (reaction (b)), the integrated cross section to 57 MeV is 6.0 ± 0.4 MeV $\cdot$ mb (1966AR01).

36. ^{12}C(e, e)^{12}C

Elastic scattering has been studied up to 800 MeV: momentum transfers $q^2 \leq 11.5$ fm^{-2} (1959ME24, 1964CR11, 1966CR07). The form factor is well accounted for by a harmonic-well model with R(r.m.s.) $= 2.40 \pm 0.02$ fm. Only one diffraction minimum is observed (1966CR07). $R = 2.42 \pm 0.04$ fm (1967EN1C), $R = 2.58$ fm (1967EL1B), $R = 2.35 \pm 0.1$ fm (1966AF1A: see also (1967AF02, 1967AF04, 1968AF1A)). See also (1960IN1A, 1963GO04, 1965MU1B, 1965RA1F, 1967BE1P, 1967BO1X, 1967EL1B, 1967FR1D, 1968BR1N).

Sharp inelastic peaks are reported corresponding to ^{12}C*(4.4, 7.7, 9.6, 15.1 and 16.1 MeV) (1956FR27, 1956HE83, 1959BA36, 1959EH1A, 1960BA47, 1961BO32, 1961DU09, 1962ED02, 1963BO36, 1963GO1P, 1964BR1N, 1964CR11, 1964GO14, 1965GU04, 1966CR07, 1967AR1A, 1967CR01, 1967PE07). Observed widths are reported in Table 12.20. Additional structure in the range $E_{\rm x} = 16.6$ to 25.5 MeV is reported by (1963BO36, 1966PR1C). The variation of the form factor $F(q^2)$ with momentum transfer yields unambiguous assignments of $J^\pi = 2^+$, 0^+ and 3^- for the first three levels (1960BA38, 1964CR11, 1967HA1U). There is some evidence of a diffraction structure in F(^{12}C*(4,4)) at high momentum transfer (1966CR07). Transverse and longitudinal scattering form factors from ^{12}C*(4,4) have been measured by (1967BE43).

The 15.1 MeV transition is a strong M1: $J^\pi = 1^+$; $T = 1$: the indicated Γ_γ is somewhat lower than the mean from ^{12}C(γ, γ) (1964GO15, 1964GU05, 1965FO1F). The theoretical value is sensitive to the spin-orbit coupling parameter, but a pure p$^4_{\frac{3}{2}}$ ground state seems to be excluded (1964BI1H, 1964KU1G). The 16.1 MeV level corresponds to that observed in ^{11}B(p, γ)^{12}C. $\Gamma_{\gamma_0} = 0.184 \pm 0.045$ eV is obtained from the electron data, and $T = 1$ is confirmed (1961DU09,

Table 12.20: Widths of ^{12}C states from ^{12}C(e, e)^{12}C [a]

^{12}C*	$J^\pi; T$	Γ_{γ_0} (eV)	Refs.
4.44	$2^+; 0$	$(12.5 \pm 2.5) \times 10^{-3}$	(1956HE83)
		$(11.2 \pm 1.2) \times 10^{-3}$	(1964CR11)
		$(10.6 \pm 1.1) \times 10^{-3}$	(1967CR01)
		$(12.2 \pm 0.8) \times 10^{-3}$	(1967AR1A)
7.65 [b]	$0^+; 0$	$(5.5 \pm 3) \times 10^{-5}$	(1956FR27) [d]
		$(6.5 \pm 0.7) \times 10^{-5}$	(1964CR11)
		$(7.3 \pm 1.3) \times 10^{-5}$	(1965GU04)
		$(6.2 \pm 0.6) \times 10^{-5}$	(1967CR01)
9.64	$3^-; 0$	$(3.6 \pm 0.4) \times 10^{-4}$	(1964CR11)
		$(3.1 \pm 0.4) \times 10^{-4}$	(1967CR01)
15.11 [c]	$1^+; 1$	40^{+8}_{-6}	(1959BA36, 1960BA47)
		39 ± 4	(1962ED02)
		34.4 ± 3	(1964GU05)
		36 ± 3	(1967PE07)
16.1	$2^+; 1$	$(184 \pm 45) \times 10^{-3}$	(1963BO36, 1965BI1B)
18.1			(1964GO14)
19.2	$(2^-; 1)$		(1963BO36, 1965DE1C, 1966BE1Q, 1967BI1K, 1967DR1C)
19.5	$(1^-; 1)$		(1963BO36, 1964GO14, 1967BI1K, 1967CR02)
≈ 24			(1964GO14)
≈ 34			(1964GO14)

[a] See also Tables 12.8 and 12.15.
[b] Partial width for g.s. decay via pairs.
[c] M1; see (1964GO15), Table 12.15.
[d] See (1967CR01).

1964BI1H, 1965BI1B, 1966PR1C). See also (1960IN1A, 1962KU1C, 1963BO36, 1964GI1A, 1965IN1A, 1965SE1D, 1967SH1L).

Inelastic excitation of the giant resonance has been studied by (1959BA36, 1960BA47, 1961BO32, 1963BO36, 1963GO1P, 1963LE1H, 1964GO14, 1966PR1C). There appears to be evidence for structure at 18.1 ± 0.05, 19.5 ± 0.05 ($\Gamma = 0.5 \pm 0.1$), ≈ 24 and ≈ 34 MeV (1964GO14: see also (1967CR02)). 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 $E_x = 19.6$, 23.3, 25.0 and 35.8 MeV (see also (1967CR02)). See also (1960FA1E, 1965LE1D, 1966FR1H, 1966UB01, 1967BI1K). Reported integrated cross sections are 75 MeV $\cdot$ mb (1960BA47), 50 MeV$\cdot$mb (1963GO1P). See also ^{12}C(γ, n)^{11}C. 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, 1966BE1Q, 1967BI1K, 1967CR02, 1967DR1C). A positive parity state with a large longitudinal matrix element may also be present (1967BI1K).

See (1962BA1D, 1964BA1R, 1966DE1K, 1966GO1C, 1967WA1E, 1967WA1F) for general discussions.

See also (1960DE1A, 1963PO1B, 1964ZI1A, 1966BO1N, 1966BO1P, 1966GI1A, 1966KA1C, 1966PE1E, 1966SI1E, 1967CZ1B, 1967IS1A).

37. (a) ^{12}C(e, e′p)^{11}B $\quad Q_m = -15.957$

(b) ^{12}C(e, e′n)^{11}C $\quad Q_m = -18.720$

Electron spectra in the region of large energy loss show a broad peak which is ascribed to quasi-elastic processes involving ejection of single nucleons from bound shells: see (1961BO32, 1963CZ1A, 1966DE1K). A study of e′-p coincidences for incident energies around $550 - 600$ MeV reveals peaks corresponding to ejection of 1p and 1s protons: the results are consistent with observations in (p, 2p) (1961JA1L, 1964AM1C, 1967AM1E). Angular distributions for the two groups are analyzed by (1967AM03) in terms of proton momenta.

See also ^{12}C(γ, n)^{11}C, ^{12}C(γ, p)^{11}B and (1961GO1R, 1961RO1H, 1961VA10, 1962DO1A, 1962PA08, 1963BO36, 1964SU1B, 1966RA1C, 1967DE1P, 1968AM1A).

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

(b) ^{12}C(n, n′)^{12}C*

(c) ^{12}C(n, n′)^{4}He^{4}He^{4}He $\quad Q_m = -7.274$

Elastic and inelastic scattering have been studied at many energies up to 350 MeV. The data are summarized by (1963GO1M, 1964ST25); some later references are listed in Table 12.21. At $E_n = 14$ MeV, the elastic angular distribution shows a forward-peaked diffraction structure indicating direct interaction. Optical model fits in the forward hemisphere are satisfactory but fail at back angles (1963LU10, 1964CL05). A strong-coupling calculation has been made by (1965BL09).

Table 12.21: Summary of ^{12}C(n, n)^{12}C angular distribution studies [a]

E_n (MeV)	^{12}C states	Refs.
$0.05 - 2.30$	g.s.	(1961LA1A)
0.5, 0.8	g.s.	(1965KO1E)
$1.0 - 10$	g.s.	(1966FI1C)
6.0	g.s., 4.4	(1965WI17)
6.0, 7.5	4.4	(1966DR1E)
7.6	g.s., 4.4	(1967PE1E)
14	g.s.	(1966FR18)
14	4.4	(1960BE24, 1961BO28, 1964ST30)
14	g.s., 4.4, 7.7, 9.6	(1963BO15, 1963BO1M, 1964SZ1A)
14	g.s., 4.4, 9.6	(1964CL05)
14	4.4, 7.7, 9.6, 10.1	(1963RO1L)
14	4.4, 7.7, 9.6	(1963JO1G, 1964JO1E, 1966GR1L, 1966JO1B)
14.6	9.6, 10.8, 11.8	(1967TU02)
14.8	4.4, 7.6	(1962RE1B)
96	g.s.	(1960SA25)

[a] See also (1963GO1M, 1964ST25).

polarization studies at $E_n = 24$ MeV are in fair agreement with optical model predictions and yield a sign for the spin-orbit coupling in agreement with shell model predictions (1962WO08: see also (1960SA1E, 1965BR1E)). See also (1959GL57, 1959KE1A, 1959WI1C, 1960HO14, 1960RO24, 1964CR1B).

At 14 MeV the cross sections for n_0, n_1 (4.4) and n_2 (9.6) are about 800, 220 and 100 mb, respectively: see (1963BO15, 1964ST25, 1966GR1L, 1967GR1P). Angular distributions at $E_n = 14$ MeV of neutrons corresponding to ^{12}C*(4.4) show direct interaction, but DWBA optical model fits are unsatisfactory (1964CL05: see also (1959GL57, 1960PE02, 1960RO24)). (1967GR1P) find that coupled channel calculations, with ^{12}C*(0, 4.44, 9.64, 10.84) taken as collective states yield fair agreement with the experimental angular distributions at $E_n = 14$ MeV. See also (1962BA15, 1962BA25, 1962CO1E, 1963HO08, 1964JO1E). The angular correlation (n$'$, $\gamma_{4.4}$) has forward neutron angles the distributions are similar to (p, p$'\gamma$) while a strong difference is apparent at $\theta_n = 135°$ (1963BE31, 1966BE1R). See also (1961AS1B, 1963MO04, 1964MO1D, 1965LA1D). See also (1958AN32, 1958NA09, 1959GA1D, 1959HA06, 1959SI79, 1960DE10, 1960HE10, 1960PE1A, 1961BR08, 1961JA19, 1961ST22, BL62C, 1962BO06, 1962BR11, 1962ST18, 1962TE05, 1963ED1B, 1963GA1G, 1963KO1C, 1963MC1B, 1963OP1A, 1963SE1P, 1964AD1B, 1964EN1B,

Table 12.22: ^{12}C(p, p)^{12}C angular distribution and correlation studies [a]

(a) Angular distribution of protons

E_p (MeV)	Angular distribution of ^{12}C*	Refs.
2.4 – 13	g.s., 4.4, 7.7	(1966BA35, 1966SW04)
2.5 – 3.0	g.s.	(1965BE1L)
4.7 – 8.7	g.s. (and 4.4 at 8.7 MeV)	(1965MO15)
4.7 – 11.0	g.s., 4.4	(1960DE1C)
5 – 20	g.s., 4.4	(1962RO14)
6.5 – 16	g.s., 4.4	(1961NA02)
6.9	4.4	(1961GO13)
9.4 – 9.6	g.s.	(1953BU72, 1957GI14, 1957GR53, 1959GR1C)
9	g.s.	(1961HO09)
9.2, 10	4.4	(1961MC16)
12	4.4	(1957CO53)
13.6 – 19.6	g.s., 4.4, 7.7, 9.6	(1964DA03)
14 – 19.4	g.s., 4.4	(1957PE14)
14.5	g.s., 4.4	(1962ST11)
14.5, 20, 31.5	g.s.	(1955KI43, 1956KI54)
17	g.s.	(1956DA03)
17.5 – 20	12.7	(1962WA31)
19.5	15.1	(1962WA31)
17.8	g.s., 4.4	(1965BA54)
18.9	9.6	(1961BR08)
18 – 30	g.s., 4.4, 7.7, 9.6, 12.7	(1963DI04, 1963DI16)
29	g.s., 4.4	(1966CR14)
30.3	g.s.	(1964RI07)
30.6	g.s., 4.4, 9.6	(1952BR52)
31.1	g.s., 4.4, 7.7, 9.6, 12.7, 14.0, 15.1, 16.1	(1963DI04)
40	4.4, 7.7, 9.6	(1964ST15)
40	g.s., 4.4, 7.7, 9.6	(1963HW01, 1966BL19)
40	g.s.	(1967FR20)
40	4.4	(1959CH1B, 1966FR1G)
46	4.4, 7.7, 9.6, 10.8, 11.8, 12.7, 14.0, 15.1, 16.1	(1967PE05, 1967SA13)
48	g.s., 4.4, 7.7, 9.6, 18.4	(1965WI1H)
49	g.s., 4.4	(1966CR14)
49.5	g.s., 4.4, 7.7	(1967FA06)
57	g.s., 4.4	(1962NO08, 1962YA04)
68	g.s., 4.4	(1963PO06)
95, 135	4.4	(1957DI28)
96	g.s.	(1957GE08)

Table 12.22: ^{12}C(p, p)^{12}C angular distribution and correlation studies [a] (continued)

E_p (MeV)	Angular distribution of ^{12}C*	Refs.
96	g.s., 4.4, 9.6, 20.8	(1956ST65)
100	g.s., 4.4, 7.7, 9.6	(1966MA38)
142	g.s.	(1961TA06)
143	g.s.	(1964ST16)
145	g.s., 4.4, 9.6, 14, 18.5	(1966EM01, 1966JA03, 1966JA07)
150	15.1	(1961DE16)
155	g.s., 4.4, 7.7, 9.6, 15.1	(1957AL39, 1964JA03)
180	g.s.	(1961JO18)
185	4.4, 7.7, 9.6, 12.7, 15.1, 16.1, 18.2, 19.3	(1964HA34, 1965HA17)
185	13.9	(1967JO1F)
660	g.s.	(1963AZ01, 1963AZ1B, 1963AZ1C)
725	g.s.	(1965MC04)
1000	g.s., 4.4, $7.6 + 9.6$	(1967FR10, 1967PA25)

(b) Angular correlation of protons and gamma rays

E_p (MeV)	States involved	Refs.
6.5	4.4	(1960HA21, 1961AD04)
8.5	4.4	(1964BA14)
$9.9 - 14.6$	4.4	(1963NA1D)
$10 - 10.8$	4.4	(1959BR1J, 1964SC07)
$12 - 15$	4.4	(1966SC1L)
39	4.4	(1960AD1A, 1964AD1A)
147	4.4	(1964RO23)
150	4.4, 15.1	(1961DE16, 1962SA05)

[a] See also ^{13}N.

1964OL1B, 1964PE20, 1966BR1D, 1966CI1A, 1966FE1C, 1966JO1B, 1966KA1E, 1966KO1D, 1966LI1F, 1966MO1C, 1967BR23, 1967CH1R, 1967LE1G) and ^{13}C.

At $E_n = 14.2$ MeV, reaction (c) proceeds about 50% through ^{12}C states which then decay via ^{8}Be$_{g.s.}$ and ^{8}Be*(2.9). Most of the remainder of the observed events take place through ^{12}C(n, α)^{9}Be* $\rightarrow$ n + ^{8}Be* and ^{12}C(n, α)^{9}Be* (α) ^{5}He* (n) α. The reaction ^{12}C(n, ^{5}He*)^{8}Be* cannot be excluded. Four-body break-up is not necessary to explain the results. 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: see also (1966MO05)). See also (1959TS1A, 1960VA10, 1962BA15, 1962BA25, 1964SA1E, 1965GR1V, 1965GR1W, 1966CI1A, 1966FE1C, 1966GR1M).

39. (a) ^{12}C(p, p)^{12}C

(b) ^{12}C(p, pn)^{11}C $\qquad Q_{\rm m} = -18.720$

(c) ^{12}C(p, 2p)^{11}B $\qquad Q_{\rm m} = -15.957$

(d) ^{12}C(p, pd)^{10}B $\qquad Q_{\rm m} = -25.188$

(e) ^{12}C(p, pα)^{8}Be $\qquad Q_{\rm m} = -7.369$

Up to $E_{\rm p} \approx 12$ MeV, the elastic scattering exhibits resonance structure: see ^{13}N. References to elastic and inelastic studies at higher energies are listed in Table 12.22. Excitation functions for both (p, p) and (p, p_1(4.43)) exhibit pronounced resonance-like structure for $E_{\rm p} = 14$ to 20 MeV (1957PE14, 1961NA02, 1964DA03). An optical model analysis gives a good account of the data, but the parameters vary strongly with energy (1962NO03: see also (1962RO14)). Between 18 and 30 MeV the elastic scattering and polarization angular distributions show strong energy dependence, while those for inelastic groups are much smoother (1963DI04, 1963DI16, 1966CR04). An optical model analysis with resonances is discussed by (1964TA1E); see also (1965BA1M). At 40 MeV an 11-parameter optical model fit is satisfactory for elastic differential cross sections, but unsatisfactory for polarization data (1966BL19, 1967FR20: see also (1965BA54 , 1965FR17)). The same problem arises with the data at 46 MeV (1967SA13) and 49 MeV (1966CR14). For analysis of the 140 MeV small angle results, see (1966JA08). See also (1958BE1B, 1959WI1C, 1962RO1F, 1964CR1B, 1967BE1Q, 1967TA1B). At 1 MeV, the differential elastic scattering cross section exhibits diffraction-like structure associated with the multiple scattering of protons by nucleons inside the nucleus (1967PA25).

At $E_{\rm p} = 40$ MeV, angular distributions of inelastic protons corresponding to ^{12}C*(4.4, 7.7, 9.6) confirm the assigned parities even, even, odd, respectively. Comparison of deformation parameters for ^{12}C*(4.4) determined by (p, p′), (α, α') and (e, e′) show considerable differences (1964ST15): see, however, (1966BA2K, 1967SA13). Angular distribution measurements at $E_{\rm p} = 46$ MeV (1967PE05) have been analyzed by (1967SA13): a large quadrupole deformation was found ($\beta_2 \approx 0.6$); the inelastic scattering agrees best with deformation of both the real and imaginary parts of the optical potential; the angular distribution for ^{12}C*(7.6) is best described by double quadrupole excitation via ^{12}C*(4.4). ^{12}C*(14) is interpreted as the 4^+ rotational state. The similarities of distributions corresponding to ^{12}C*(10.8, 11.8) suggest that they have the same spin (1967SA13). Asymmetries observed with 40 MeV polarized protons on ^{12}C*(4.4) disagree with DWBA predictions (1966FR1G: see also (1967SA13)). See also (1960BA38, 1963DI16, 1964DA03, 1965FR17, 1966BL19, 1967FA06, 1967LE13, 1967LE1G, 1967PA1L, 1967SA1L, 1968GA1H, 1968TA1P).

A number of inelastic groups have been studied at $E_{\rm p} = 155$ to 185 MeV: see Table 12.23. When treated in the impulse approximation, the cross sections and angular distributions are closely related to the electric transition moments. Comparison of (p, p′) and (e, e′) form factors yield the transition multipolarities indicated in Table 12.23 (1964JA03: see also (1960NI02, 1961BR08, 1961PI04, 1962BR11, 1962RO1F, 1962SA1G, 1963HO1D, 1963NI02, 1964HA1L, 1965HA17, 1965HA28, 1966HA51, 1967HA1U, 1967JO1F). The broad levels reported in the range $E_{\rm x} = 20$ to 24 MeV are associated with the giant E1 resonance (1961SA1E, 1962SA1G, 1963DE35, 1965HA17).

Table 12.23: ^{12}C levels from ^{12}C(p, p′)^{12}C*

^{12}C* [a,b] (MeV ± keV)	Multipolarity [c]	Γ [a] (keV)
4.43 ± 100 [d,e]	E2	
7.65 ± 100		
9.7 ± 150	E3	
10.6 ± 400		
11.1 ± 400		
12.7 ± 200	(M1)	[h]
13.9 ± 100 [f]		
15.15 ± 100	M1	[h]
16.1 ± 200		
18.2 ± 300		$500 - 800$
19.3 ± 200	M2 [g]	$500 - 800$
(20.4 ± 400)		$500 - 800$
21.4 ± 300		$500 - 800$
22.1 ± 300	E1	$500 - 800$
23.4 ± 400		$500 - 800$

[a] (1965HA17: 185 MeV).

[b] (1963DE35, 1964ST15). See also (1956ST65, 1959AJ76, 1960GA10, 1960LA03, 1962NO08, 1963ME04, 1966EM01).

[c] (1964JA03).

[d] $E_x = 4437 \pm 7$ keV (1962BR10).

[e] $E_x = 4440.0 \pm 0.5$ keV (1967KO14).

[f] (1967JO1F): $J^\pi = (4^+)$.

[g] See also (1960RI1C).

[h] (1962WA31): $\Gamma_\gamma/\Gamma = 0.027 \pm 0.007$ for ^{12}C*(12.7), 1.15 ± 0.3 for ^{12}C*(15.1).

The energy of the first excited state is 4440.0 ± 0.5 keV, from the γ-ray. The character of the Doppler broadening indicates rather little spin-flip contribution to the inelastic scattering (1967KO14: $E_p = 23$ MeV). Proton γ-angular correlations provide a sensitive measure of the spin-flip: for $E_p = 10$ to 15 MeV a considerable contribution is observed (1964SC07, 1966SC1L: see also (1961AD04, 1961CL1D, 1961GI1C, 1961GO13, 1962NO04, 1964BA14, 1964RO23, 1967GI1D, 1967KO1N) and Table 12.21).

The following is a list of other recent theoretical and review papers dealing with this reaction: (1959GL57, 1959HO95, 1959MC63, 1959PU1A, 1960BE31, 1960LU1B, 1960MA43, 1960MI1C, 1960SA1C, 1960SA1E, 1960SA1G, 1961DO1C, 1961GI1D, 1961MC1C, 1961SA1B, 1962KA1E, 1962MA1P, 1962NI1C, 1963BU1E, 1963LO1A, 1963VI1A, 1964DA07, 1964HO1C, 1964SA1L, 1965CL1E, 1966BO1P, 1966GI1A, 1966LI1F, 1966SA1D, 1967CH1R, 1967VA1K) and (1959AJ76).

See also (1960WA15, 1961CL09, 1961RA1B, 1964SC1F, 1965DE14, 1965JA1A, 1966YA04).

Reaction (b) is widely used to monitor high-energy proton beams: see (1963CU05, 1963CU1B). For studies of recoil spectra, see (1962SI09, 1965BE1U). Possible emission of singlet deuterons is discussed by (1966NO1A). See also (1967HO1M).

In the summed proton spectrum of reaction (c), peaks are observed corresponding to the ejection of p- and s-shell protons: see ^{11}B. Absolute cross sections are reported by (1965GI1F). See also (1962AU1A, 1962ST1F, 1964LI1D, 1964LI1E, 1965MC1F, 1965RI1A, 1966BE1B, 1966KO1F, 1966JA1A, 1967CO1V, 1967EL1C, 1967GO01, 1967JA1C, 1967RI08, 1968JA1G, 1968YU1B). At $E_p = 57$ MeV the reaction involves an excited state at 20.3 MeV (1967EP1B, 1968RO1L).

For reaction (d) see (1963SH1A, 1965BA11, 1967SU1C, FR68A). See also (1962AU1A, 1964BA1P).

Reaction (e) has been studied up to $E_p = 660$ MeV. Various states in ^{12}C appear to be involved. At $E_p = 57$ MeV, the sequential process dominates; α-decay to ^{8}Be$_{\text{g.s.}}$ is observed via ^{12}C*(21.1, 22.2, 26); comparison with other reactions suggests $(J^\pi;\, T) = (1^+,\, 3^+;\, 0)$, $(1^-;\, 0+1)$; ($\pi =$ natural; significant $T = 0$ component) (1967EP1B). See also (1966RO1D, 1968RO1L). See also (1959VA15, 1960VA10, 1961VA17, 1962VA1A, 1962ZH1B, 1963JA07, 1963VA04, 1963ZH1A, 1964BA29, 1964KE1F, 1964SY02, 1964YU1A, 1965IS05, 1965KU14, 1965SA1K, 1965YU1C, 1965ZH1A, 1966JA1B, 1966ZE1A, 1967GA01) and (1959AJ76).

Total proton reaction cross sections are reported by (1959BU97, 1959GO90, 1964GI05, 1964GR1M, 1967CA1K).

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

(b) ^{12}C(d, pn)^{12}C $\qquad Q_m = -2.224$

The angular distribution of elastically scattered deuterons has been studied at a number of energies from $E_d = 2.8$ to 650 MeV: see (1954FR24, 1960BU25, 1960CA24, 1961IG02, 1961IS02, 1961LO01, 1962SL02, 1963BU24, 1963CA1E, 1963FR1F, 1963VA23, 1965DI1C, 1965DU01, 1966CO24, 1966DO1B, 1966DU08, 1966GA09, 1966GE03, 1966NG01, 1967AU05, 1967DU1E,

1967FI07, 1967NE09 , 1967PL1B, 1967WA1M). Inelastic groups corresponding to levels at 4.4 and 9.6 MeV are reported by (1961JA02, 1962SL02, 1966NG01: see also (1951KE02, 1954FR24, 1956GR37, 1956HA90)). The angular distributions of inelastically scattered deuterons to these two states and to ^{12}C*(7.7) have been measured at $E_{\rm d} = 25.9$ MeV (1963VA23). A systematic optical model analysis yields a set of smoothly varying parameters which give a good account of the elastic angular distributions from $E_{\rm d} = 3$ to 34 MeV. For the inelastic scattering, $Q = -4.4$, deformation of the potential corresponding to $\beta = 0.4 - 0.6$ was required (1966SA1C). See also (1961CI08, GO61I, 1963CA1J, 1963SA1G, 1968HI1H), (1958MA52, 1960EL09, 1960FA05, 1960LU1B, 1961RO1G, 1962SA1J, 1963ST1A, 1963ZA1B, 1964HE1H, 1964HO1C, 1964RU1A, 1964SA1K, 1965CA1F, 1965TJ1A, 1966BA2W, 1966JA1J, 1966MA2Q, 1967RE1E, 1967RU1A; theor.) and (1959AJ76).

For reaction (b), see (1963PH1A, 1965LA08, 1965LA1F, 1967MA1N, 1967NO1A) and ^{13}N.

41. ^{12}C(d, ^{6}Li)^{8}Be $\quad\quad$ $Q_{\rm m} = -5.897$

Differential cross sections measured for $E_{\rm d} = 14.7$ MeV are analyzed by DWBA to yield S_α, a measure of the composition ^{8}Be + α in the wave function of ^{12}C$_{\rm g.s.}$. Subject to an uncertain normalization, S_α is found to be close to unity (1964DA1B, 1966DA1C, 1966DE09).

42. ^{12}C(t, t)^{12}C

Angular distributions of elastically scattered tritons have been determined at $E_{\rm t} = 1.0$ to 1.75 MeV (1962GU01: see also (1968HE1N)), at 6.4, 6.8 and 7.2 MeV (1964PU01) and at 12 MeV (1965GL04: optical model analysis; see also (1966GL1B)).

43. (a) ^{12}C(^{3}He, ^{3}He)^{12}C
(b) ^{12}C(^{3}He, pd)^{12}C $\quad\quad$ $Q_{\rm m} = -5.494$

Angular distributions of elastically scattered ^{3}He particles have been determined for $E(^{3}{\rm He}) =$ 2 to 6 MeV (1966SC12), 5.5 MeV (1961PA04), 8.5 and 10 MeV (1966SC22), 12 MeV (1965YO1B), 12.0 to 18.6 MeV (1967FO1F), 20.1 MeV (1967MA1G: also ^{12}C*(4.4)), 24.5, 25.3 and 26.8 MeV (1964SE05), 25.7 MeV (1966DA1H: also ^{12}C*(4.4, 7.7)), 26.1 to 32.6 MeV (1963PA15: also ^{12}C*(4.4)) and $29 - 30$ MeV (1961AG1A, 1961CA18, 1962AG01, 1962CA29, 1962GA17, 1965BU1H, 1967BA2P, 1967BR1N). See also (1961FO02, 1962WE1C, 1967AR17, 1967AS1B) and (1961HO1J, 1964GO1J, 1965FR1E, 1967GR1N, 1967PA1U; theor.). For reaction (b) see (1965DO1H).

44. (a) ^{12}C(α, α)^{12}C
(b) ^{12}C(α, αn)^{11}C $\qquad Q_{\rm m} = -18.720$
(c) ^{12}C(α, 4α) $\qquad Q_{\rm m} = -7.274$

Angular distributions of elastic and inelastic α-particles and of 4.43 MeV γ-rays have been measured at a number of energies: see Table 12.24. DWBA fits to differential cross sections observed at 40.5 MeV for $Q = -4.4$ yield B(E2)↓ $= 13\ e^2 \cdot$ fm^4; for $Q = -9.6$, B(E3)↓ $=$ $50 - 70\ e^2 \cdot$ fm^6 (1966HA19). Except for the broad 10.1 MeV state all known levels of ^{12}C with $E_{\rm x} < 14$ MeV have been observed by (1966HA19). Angular distributions of α-particles and 4.4 MeV γ-rays have been studied at $E_\alpha = 22.5$ (1964EI01) and at 43 MeV (1959SH62, 1962MC11). The studies of (1962MC11, 1964EI01) yield information on the polarization of the ^{12}C*(4.4) as produced in inelastic scattering. The derived polarizations show strong dependence on scattering angle and are not explained by simple PWBA or adiabatic reaction mechanisms: DWBA gives qualitative agreement. Similar studies involving ^{12}C*(9.6) confirm that $J^\pi = 3^-$ (1963LA07). See also (1959CA14, 1962BR14, 1964BU1F, 1964LA07, 1967VE1C) and (1959BL31, 1959GL57, 1960RO1E, 1961EI1A, 1962RE1C, 1963DA1B, 1963HO1J, 1964DA1D, 1964GR1L, 1965JA1D, 1966JO1A, 1967BO1W, 1967JA1G, 1967LA1K; theor.) and (1959AJ76). The 9.6 MeV state decays predominantly through ^{8}Be$_{\rm g.s.}$ (1966BO28).

The angular distribution of alphas corresponding to ^{12}C*(12.7; $J^\pi = 1^+$) at $E_\alpha = 28.5$ MeV is not accounted for in DWBA. A spin-orbit interaction leading to spin flip appears to be involved (1967NA06).

For reaction (b) see (1953LI28). Angular correlations in ^{12}C(α, 2α) (reaction (c)) observed at $E_\alpha = 915$ MeV give evidence for strong α-clustering in ^{12}C (1961GO1T). See also (1961VA38, 1962BR14, 1962VA25, 1965YA02).

45. (a) ^{12}C(^{6}Li, ^{6}Li)^{12}C
(b) ^{12}C(^{7}Li, ^{7}Li)^{12}C

See (1964OL1A); see also (1963BE1R, 1966DE09, 1967SI1C).

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

See (1964OL1A). See also (1963SH1E) for reaction (a) and (1963SA1E) for reaction (b).

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

Table 12.24: Summary of ^{12}C(α, α)^{12}C angular distribution data

E_α (MeV)	^{12}C states	Refs.
2.5 – 4.8	g.s.	(1962JO09)
7.9 – 8.1	4.4	(1964MI12)
7.9 – 19	4.4	(1964MI08)
8.8 – 10.1	g.s.	(1967BR1F)
11 – 19	g.s.	(1964CA07)
14	g.s., 4.4	(1963JO1F)
18	g.s., 4.4, 7.7, 9.6	(1959CO70)
18.5	7.7	(1964MI08)
18.7	g.s.	(1962WO02)
20	g.s., 4.4, 7.7, 9.6	(1959FU62)
20.3, 21.9	g.s., 4.4, 7.7, 9.6	(1964JO14)
21.2 – 22.7	g.s.	(1962JO14)
22	g.s., 4.4	(1959HU14)
22.5	g.s., 4.4	(1964EI01)
24	g.s.	(1967AG1A)
24.7	g.s.	(1964BU1E)
25	9.6	(1966BO28)
27.2	g.s.	(1966NE1D, 1967NE1F)
27 – 36	g.s., 4.4, 7.7, 9.6, 12.7	(1960MI03, 1960MI10)
28.5	g.s.	(1962AG01)
28.5	g.s., 4.4, 7.7, 9.6, 11.8, 12.7, 14.1	(1967NA06)
31.5	g.s., 4.4, 7.7	(1956WA29)
33.4	g.s., 4.4	(1967AR17)
38 [a]	g.s., 4.4, 7.7, 9.6	(1960AG01, 1960VA03)
40	g.s., 4.4, 7.7, 9.6	(1956IG02, 1957IG03, 1959YA01)
40.5	g.s., 4.4, 7.7, 9.6	(1966HA19)
42	g.s., 4.4	(1959EC13, 1962MC11)
51	g.s.	(1966VI1A)
56	g.s.	(1967SY1A)

[a] (1960VA03) report $E_x = 4.38 \pm 0.04, 7.59 \pm 0.04, 9.67 \pm 0.06$ MeV.

At $E(^{12}C) = 126$ MeV, strong inelastic peaks corresponding to ^{12}C*(0, 4.4, 14.0 ± 0.5) have been observed. Groups with $Q = -9$ and -19 MeV are also seen. Their interpretation is less clear. Angular distributions suggest that the 14 MeV state has $J^\pi = 4^+$; the large intensity indicates close association with $^{12}C_{g.s.}$ (1962WA24, 1963GA05, 1966BA2K); deformation parameters are listed by (1966BA2K); see also (1962GA02, 1962WI09). The elastic scattering has also been studied for $E_{c.m.} = 3$ to 13.4 MeV (1961BR15) and at $E_{c.m.} = 56.7$ MeV (1962SM02). See also (1965GR1F), (1959AL1H, 1962BE43, 1962SE1G, 1963WI1G) and (1962BU1B, 1963BA1Y).

48. $^{12}C(^{14}N, ^{14}N)^{12}C$

Differential cross sections have been determined for the $^{12}C_{g.s.}$ transition at $E(^{14}N) = 21.5$ to 27.3 MeV (1960HA16) and at $E_{c.m.}(^{14}N) = 62.5$ MeV (1962SM02); those to the 4.4 MeV state have been measured at $E(^{14}N) = 27.3$ MeV (1961HA04). See also (1961KU1D, 1961NE04, 1962WI09) and (1963KU1L).

49. $^{12}C(^{16}O, ^{16}O)^{12}C$

Differential cross sections have been determined for the $^{12}C_{g.s.}$ transition at $E_{c.m.}(^{16}O) = 8$ to 13.7 MeV (1963KU12) and at $E(^{16}O) = 35$ (1967GO1A, 1968VO1D), 42 (1964NE01), 67 (1959MC1D) and 168 MeV (1964HI09): those to the 4.4 MeV state have been measured at $E(^{16}O) = 42$ and 168 MeV (1964HI09, 1964NE01).

A DWBA analysis of the 168 MeV data is given by (1966BA2K). See also (1963KU1L, 1967AB1D).

50. (a) $^{12}C(^{17}O, ^{17}O)^{12}C$
(b) $^{12}C(^{18}O, ^{18}O)^{12}C$

The elastic scattering angular distributions in both (a) and (b) have been measured at $E = 35$ MeV (1967GO1A).

51. $^{12}N(\beta^+)^{12}C$ $\qquad Q_m = 17.342$

The decay is mainly to the ground state via an allowed transition. Branching fractions to other states of ^{12}C are listed in Table 12.25. The half-life is 10.97 ± 0.04 msec; see Table 12.28. Since transitions to $^{12}C_{g.s.}$ and ^{12}C*(4.4) are allowed, $J^\pi(^{12}N) = 1^+$. See discussion of $^{12}B(\beta^-)$ and (1965WU1A). See also (1962PO02, 1966DU1E, 1967HU10).

Table 12.25: Branching in ^{12}N(β^+)^{12}C

Decay to ^{12}C*	Branch (%)	$\log ft$ [f]	Refs.
g.s. [a]	94.25	4.117 ± 0.002	
4.44	2.4 ± 0.2		(1963PE10)
	2.2 ± 0.25 [b]		(1963WI05)
	2.3 ± 0.2	5.06 ± 0.04	mean
7.65 [c]	2.2 ± 0.6		(1963GL04)
	3.0 ± 0.5		(1962MA22)
	2.7 ± 0.4	4.34 ± 0.06	mean
10.3 [d]	0.85 ± 0.6		(1963GL04)
	0.44 ± 0.15		(1963WI05)
	0.46 ± 0.15	4.36 ± 0.17	mean
12.71 [e]	0.29 ± 0.13	3.55 ± 0.16	(1967AL03)
15.11	$(4.4 \pm 1.5) \times 10^{-3}$	3.30 ± 0.13	(1967AL03)

[a] E_β(max) $= 16.384 \pm 0.015$ MeV (1963GL04, 1963PE10).
[b] 1.72 times ^{12}B value.
[c] See also (1963WI05).
[d] (1966SC23).
[e] See also (1963GL04, 1963WI05, 1966SC23).
[f] Based on $\tau_{1/2} = 10.97 \pm 0.04$ msec and on $Q_{\rm m}$: see (1966BA1A).

52. ^{13}C(γ, n)^{12}C $\qquad Q_{\rm m} = -4.947$

See ^{13}C.

53. ^{13}C(p, d)^{12}C $\qquad Q_{\rm m} = -2.722$

Angular distributions of deuterons to ^{12}C*(0, 4.4) have been measured by (1966GL01: 8 and 12 MeV) and by (1961BE12: 17 MeV). For the ground state, $\theta^2 = 0.036$ at $E_{\rm p} = 8$ MeV and 0.058 at 12 MeV; for the 4.4 MeV state $\theta^2 = 0.051$ at 12 MeV (1966GL01: PWBA). See also (1960NE1C, 1964TE1G). At $E_{\rm p} = 54.9$ MeV, strong deuteron groups are observed to ^{12}C*(0, 4.4, 12.7, 15.1, 16.1) and partial angular distributions of these groups have been observed. Spectroscopic factors (from DWBA) indicate that the summed transition strengths to the four excited states are approximately equal to the $P_{\frac{3}{2}}$ neutron pickup strength in ^{12}C(p, d) (1968TA1V).

54. ^{13}C(d, t)^{12}C $\quad Q_m = 1.311$

$Q_0 = 1.311 \pm 0.006$ (1961TE02, 1964MA57);

$Q_0 = 1.3109 \pm 0.0007$ (1967OD01).

Angular distributions of tritons have been obtained by (1954HO48: 2.2 and 3.3 MeV; t_0), (1966GL01: 8 and 12 MeV; t_0 and t_1), (1960MA10: 14.8 MeV; t_0, t_1, t_2). The relative θ^2 for the ground and first two excited states are 1 : 0.76 : 0.039 (1960MA10, 1966GL01: PWBA). Assuming $\theta^2 = 0.031$ for $^{12}C_{g.s.}$, $\theta^2 = 0.024$ for ^{12}C*(4.4) and 0.0012 for ^{12}C*(7.7) (1960MA32). See also (1959KU1C, 1963OG1A, 1965DE26, 1967DE1J).

55. ^{13}C(^{3}He, α)^{12}C $\quad Q_m = 15.631$

Angular distributions have been determined at many energies: see (1962CH02: 1.6 to 3.3 MeV; α_0, α_1, α_2), (1968MI1H: 1.66 to 3.12 MeV; α_0, α_1, α_2), (1957HO63: 2 MeV; α_0, α_1), (1960BA25: 1.8 MeV; α_0), (1957HO62: 4.5 MeV; α_0, α_1), (1964DE1E, 1965DE26: 8.8, 9.4, 10.3 MeV; α_0, α_1; DWBA), (1966KE08: 12, 15, 18 MeV; α_0, α_1, α_2, α_3, α_5, α_6, α_7, α_8; DWBA), (1967BA2G: $40-45$ MeV). (1966KE08) find $l = 1$ or 0 for all the groups except α_3 (to ^{12}C*(9.6)) for which $l = 2$. Angular correlations of α-particles and 4.4 MeV γ-rays have been studied at $E(^3\text{He}) = 4.5$ MeV (1962HO13). See also (1968NO1E). The 15.1 MeV γ-ray has been observed: see (1957BR18, 1959AL96, 1959BR79). See also (1959OW1A, 1961HO1F, 1964EL1B, 1965NE1B, 1967BH1B).

56. ^{14}C(p, t)^{12}C $\quad Q_m = -4.641$

At $E_p = 18.5$ MeV, the angular distribution of the tritons to the ground state has been determined: $l = 0$ (1961LE1A, 1963LE03).

57. ^{14}N(γ, d)^{12}C $\quad Q_m = -10.272$

Not reported.

58. ^{14}N(n, t)^{12}C $\quad Q_m = -4.015$

At $E_n = 14 - 15$ MeV, the angular distribution of the tritons to the ground state has been fitted with $L = 2$ (1967AN08, 1967FE06, 1967LI06, 1967RE01). See also (1959GA14, 1967BA1E, 1967MO21).

59. ^{14}N(p, pd)^{12}C $\qquad Q_m = -10.272$

See (1964BA1C, 1967FU1A).

60. ^{14}N(p, ^{3}He)^{12}C $\qquad Q_m = -4.779$

At $E_p = 40$ MeV, angular distributions of the ^{3}He to ^{12}C*(0, 4.4) have been determined. They show strong forward peaking (1966BR1X, 1966HO1F). See also (1961CL09, 1962MA1L, 1967HO1N).

61. ^{14}N(d, α)^{12}C $\qquad Q_m = 13.575$

$Q_0 = 13.579 \pm 0.006$ (1964MA57: see also (1962TE02)).

Alpha groups have been observed corresponding to all ^{12}C states up to ^{12}C*(16.11), with the exception of ^{12}C*(10.3) and ^{12}C*(14.7) (see (1965BR08)). See Table 12.26 for a listing of energy parameters measurements. Angular distributions have been obtained at many energies: see (1966EU01: 0.5 to 2.2 MeV; α_0), (1961SJ1B: 0.6 to 0.8 MeV; α_0), (1965WI11; 0.8 to 1.9 MeV; α_0, α_1), (1965ST02: 0.9 to 1.2 MeV; α_0, α_1), (1960KA1H: 1.4 to 2.9 MeV; α_0), (1961IS03: 1.5 to 3 MeV; α_0), (1965SC12: 4 MeV; α_0, α_1, α_2, α_3, α_5, α_6, α_7; 7.2 MeV; α_7, α_8, α_9, α_{11}), (1965BR08: 5.9 and 7.2 MeV; α_7, α_{11}, α_{12}), (1964CH1C: 4, 6, 8 and 10 MeV; α_0, α_1, α_2), (1962WI05: 10 MeV; α_0, α_1), (1960HU10: 10.3 to 11.4 MeV: α_0, α_1), (1966DR04: 11.3 and 12.6 MeV; α_0, α_1), (1961YA08: 14.7 MeV; α_0, α_1), (1959BO40, 1959HE1C: 20.0 MeV; α_0), (1959FI30: 20.9 MeV; α_0, α_1, α_3), (1965PE17: 24 MeV; α_0, α_1, α_2, α_3), (1966VI1A: 28.5 MeV; α_1). Integrated cross sections for eight alpha groups have been obtained at $E_d = 11.8$ MeV (1966JA05). At $E_d = 24$ MeV, α_1 is strongly favored over α_0, and α_3 is favored over α_4. For α_0, α_1 $L = 2$ is preferred (1965PE17). Angular distributions at $E_d = 4$ MeV are nearly symmetric about $90°$, suggesting a compound nucleus process involving many overlapping levels (1965SC12).

In a test of isospin conservation, (1965BR08) find, at $E_d = 7.2$ MeV, the cross section for excitation of ^{12}C*(15.11, $J^\pi = 1^+$; $T = 1$) = 31% of that for ^{12}C*(12.71, $J^\pi = 1^+$; $T = 0$); σ(16.11)/σ(12.71) $= 4$%. Violation of this order can be understood as being due to coulomb mixing in the compound nucleus.

Comparison of angular distributions of ^{14}N(d, α)^{12}C at $E_d = 20$ MeV and ^{12}C(α, d)^{14}N at $E_d = 41.7$ MeV suggest an upper limit of 3% for the time reversal non-conserving fraction of the Hamiltonian (1959BO40, 1959HE1C, 1965PE17). See also (1962AL09, 1966ME1E).

At $E_d = 1.8$ MeV, the alpha particles to the 7.65 MeV state were observed in coincidence with recoiling ^{12}C$_{\rm g.s.}$ nuclei. If $\Gamma_{\rm rad} \equiv (\Gamma_\gamma + \Gamma_\pi)$, the ratio $\Gamma_{\rm rad}/\Gamma = (2.8 \pm 0.3) \times 10^{-4}$: see ^{12}B($\beta^-$)^{12}C (1963SE23). See also (1967UI01).

Table 12.26: Alpha groups from ^{14}N(d, α)^{12}C

E_x (MeV ± keV)	Γ (keV)	Ref.
4.438 ± 6 [a]		(1951MA08)
4.430 ± 30		(1965PE17)
4.447 ± 10		(1961JA23)
7.665 ± 15		(1955PA50)
7.663 ± 13		(1956AH32)
7.669 ± 10		(1961JA23)
7.66 ± 50		(1965PE17)
9.642 ± 14	30 ± 8	(1956DO41)
9.616 ± 15		(1961JA23)
9.620 ± 3 [b]		(1951MA08)
9.64 ± 50		(1965PE17)
10.85 [c]		(1965SC12)
11 [c]		(1965SC12)
12.7 ± 70		(1965PE17)
13.29 [c]	355 ± 50	(1965SC12)
14.08 [c]		(1965SC12)
15.11		(1965BR08)
16.11		(1965BR08)

[a] Based on Q_{m}.

[b] (1956DO41) suggest that a systematic error exists in (1951MA08)'s value for this state.

[c] Nominal value; E_x not determined in this experiment.

62. ^{14}N(^{3}He, pα)^{12}C $\qquad Q_m = 8.081$

See (1962BL1E) and ^{16}O.

63. ^{14}N(α, ^{6}Li)^{12}C $\qquad Q_m = -8.800$

At $E_\alpha = 42$ MeV, angular distributions of ^{6}Li ions corresponding to the ground and first excited states of ^{12}C have been measured (1964ZA1A). See also (1964BR1L).

64. ^{14}N(^{10}B, 3α)^{12}C $\qquad Q_m = 7.642$

See (1965SH1A).

65. ^{15}N(p, α)^{12}C $\qquad Q_m = 4.965$
$Q_0 = 4.954 \pm 0.008$ (1961LO10).

Searches for double dipole de-excitation of the 4.4 MeV state have been unsuccessful $\Gamma_{\rm E1E1}/\Gamma_{\rm E2} \leq 0.5 \times 10^{-4}$ (1964AL18), $\leq 1.7 \times 10^{-4}$ (1960MC03). A theoretical estimate of 10^{-8} is cited by (1960MC03).

Angular distributions of α-particles leading to the ground and 4.4 MeV states have been determined for E_p up to 18.6 MeV: (see (1963MI1H, 1963RO01, 1964EC03, 1965WA1N, 1967NO02)). At the higher energies the ground-state alpha particles show marked backward peaking, in agreement with the inverse reaction ^{12}C(α, p)^{15}N (1964EC03). See also (1963NA1C, 1964HO1D, 1966EV1B).

66. ^{15}N(α, ^{7}Li)^{12}C $\qquad Q_m = -12.382$

Angular distributions of the ^{7}Li ions to the ground and 4.4 MeV states have been determined at $E_\alpha = 42$ MeV (1966MI1M).

67. (a) ^{16}O(γ, α)^{12}C $\qquad Q_m = -7.161$
(b) ^{16}O(γ, 4α) $\qquad Q_m = -14.436$

There is evidence for the involvement of many ^{12}C states: see (1965RO05, 1967CA1C).

68. (a) ^{16}O(n, nα)^{12}C $\quad Q_{\rm m} = -7.161$

(b) ^{16}O(p, pα)^{12}C $\quad Q_{\rm m} = -7.161$

(c) ^{16}O(α, 2α)^{12}C $\quad Q_{\rm m} = -7.161$

For reaction (a), see (1963MO04, 1964MO1D). In reaction (b), 4.4 MeV γ-rays are observed at $E_{\rm p} = 146$ (1962FO03) and 150 MeV (1962RO25). See also (1957CH1A, 1964BA1C, 1965ZH1A, 1967CH04, 1967FU1A). In reaction (c), the angular distributions 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. The angular distributions and integrated cross sections vary strongly with energy (1965BR13). See also (1962DO1B, 1962ZU01, 1965KU1B, 1965ZE1B, 1967PA1T, 1967TA1C, 1968YA1C).

69. ^{16}O(d, ^{6}Li)^{12}C $\quad Q_{\rm m} = -5.689$

At $E_{\rm d} = 14.6$ MeV, the ground state angular distribution suggests that direct interaction predominates (1964DA1B). Qualitative agreement with DWBA is reported (1966DA1C). See also (1963DR1B, 1964BL1C, 1965SL1C).

70. ^{16}O(^{3}He, ^{7}Be)^{12}C $\quad Q_{\rm m} = -5.574$

See (1967ZA1B).

71. ^{16}O(^{10}B, ^{14}N)^{4}He^{4}He^{4}He $\quad Q_{\rm m} = -2.822$

See (1965SH10, 1966SH1B).

72. ^{16}O(^{14}N, ^{18}F)^{12}C $\quad Q_{\rm m} = -2.745$

See (1966GA10).

73. ^{17}O(d, ^{7}Li)^{12}C $\quad Q_{\rm m} = -2.579$

See (1967DE03).

74. ^{18}O(d, ^{8}Li)^{12}C $Q_{\rm m} = -8.593$

See (1963DE02).

75. ^{19}F(p, 2α)^{12}C $Q_{\rm m} = 0.953$

See (1962FO03).

76. ^{19}F(d, ^{9}Be)^{12}C $Q_{\rm m} = 0.299$

Ground-state angular distributions have been measured at $E_{\rm d} = 9$ to 14.5 MeV (1964DA1B, 1967DE03, 1967DE14).

77. ^{19}F(^{3}He, ^{10}B)^{12}C $Q_{\rm m} = 1.393$

See (1967DE14).

78. ^{20}Ne(α, ^{12}C)^{12}C $Q_{\rm m} = -4.617$

The α-induced fission of ^{20}Ne has been studied by (1962LA03, 1962LA05, 1962LA15). See also (1963HO1H, 1963TA1B).

^{12}N
(Figs. 7 and 8)

GENERAL: See (1964NA1G, 1964SH1J, 1964ST1B, 1966KE16, 1967KE1L).

Mass of ^{12}N: From a weighted average of the Q_0 values for ^{10}B(^{3}He, n)^{12}N and ^{12}C(p, n)^{12}N (see reactions 2 and 3), $M - A$ for ^{12}N $= 17.342 \pm 0.005$ MeV.

1. ^{12}N(β^+)^{12}C $\qquad Q_m = 17.342$

Measured values of the half-life are displayed in Table 12.28. The decay is complex; ^{12}N decays to the ground state of ^{12}C and to several excited states: see ^{12}C.

2. ^{10}B(^{3}He, n)^{12}N $\qquad Q_m = 1.570$

$Q_0 = 1.561 \pm 0.009$ (1964KA08);
$Q_0 = 1.568 \pm 0.020$ (1966ZA01);
$Q_0 = 1.570 \pm 0.025$ (1964FI02);
$Q_0 = 1.574 \pm 0.007$ (1967AD1E);
$Q_0 = 1.569 \pm 0.005$ (mean).

Observed neutron groups are displayed in Table 12.29 (1957AJ71, 1964KA08, 1966ZA01, 1967AD1E). Angular distributions have been studied at $E(^3\text{He}) = 2.5$ and 3.6 MeV (1957AJ71) at $E(^3\text{He}) = 2.4$, 2.75 and 2.94 MeV (1967AD1E), and at $E(^3\text{He}) = 4.0$ and 5.8 MeV (1966ZA01). See also (1964BR13, 1966SC23, 1967AL03) and (1965SH1E, 1966SH1F; theor.).

3. ^{12}C(p, n)^{12}N $\qquad Q_m = -18.124$

$Q_0 = -18.122 \pm 0.009$ (1966BR17).

At $E_p = 138$ MeV, $\theta = 3°$, neutron structure corresponding to the ground state (and possibly to the unresolved first two energy levels of ^{12}N) is observed in addition to structure corresponding to ^{12}N*($E_x \approx 6$ MeV). At large angles (to $\theta = 16°$), the latter structure becomes relatively more prominent. It is suggested that it corresponds to the ^{12}N equivalent of the $T = 1$ giant dipole state at $E_x \approx 20$ MeV in ^{12}C (1963LA1F; see also (1962BO33)). See also (1949AL05, 1960TA1K, 1963BA1X, 1963EL1C).

Table 12.27: Energy levels of ^{12}N

E_x (MeV ± keV)	$J^\pi; T$	$\tau_{1/2}$ or Γ (keV)	Decay	Reactions
g.s.	$1^+; 1$	$\tau_{1/2} = 10.97 \pm 0.04$ msec	β^+	1, 2, 3, 4
0.969 ± 7		< 50		2, 4, 6
1.198 ± 9		140 ± 40		2
1.65 ± 80				2
(2.0 ± 100)				2
2.35 ± 80				2
3.15 ± 80		280 ± 80		2
3.55 ± 80		270 ± 80		2
(≈ 6)	$(1^-; 1)$			3

Table 12.28: Half-life of ^{12}N

$\tau_{1/2}$ (msec)	Ref.
12.5 ± 1	(1949AL05) [a]
11.2 ± 0.4	(1959FA03)
11.1 ± 0.2	(1962PO02)
10.95 ± 0.05	(1963FI05)
11.0 ± 0.1	(1963PE10)
10.97 ± 0.04	Weighted mean

[a] This value is excluded from the weighted average.

Table 12.29: Neutron groups from $^{10}B(^3He, n)^{12}N$

E_x (MeV ± keV)				Γ_{cm} (keV)
(1957AJ71)	(1964KA08)	(1966ZA01)	(1967AD1E)	(1966ZA01)
g.s.	g.s.	g.s.	g.s.	sharp
	0.994 ± 20	0.959 ± 20	0.969 ± 10	< 50
1.06 ± 80				
	1.22 ± 30	1.24 ± 30	1.191 ± 10	140 ± 40
1.56 ± 80		[a]		[c]
(1.97 ± 100)		[b]		
2.35 ± 80		2.4 ± 100		[c]
3.18 ± 150		3.14 ± 80		280 ± 80
3.46 ± 150		3.57 ± 80		270 ± 80

[a] There is some evidence for $^{12}N^*$ at 1.72 ± 0.08 MeV.
[b] The evidence on this state is inconclusive.
[c] These groups are very weak at $E(^3He) = 5.8$ MeV, typically two orders of magnitude less than the first two excited states.

4. $^{12}C(^3He, t)^{12}N$ $\quad Q_m = -17.361$

At $E(^3He) = 44.6$ MeV, triton groups are observed to the ground state of ^{12}N and to the first excited state: $E_x = 0.957 \pm 0.020$ MeV (1969BA06). See also (1965RI1C).

5. $^{14}N(\gamma, 2n)^{12}N$ $\quad Q_m = -30.621$

See ^{14}N.

6. $^{14}N(p, t)^{12}N$ $\quad Q_m = -22.139$

At $E_p = 43.7$ MeV, triton groups are observed to $^{12}N(0)$ and to the first excited state: $E_x = 0.963 \pm 0.030$ MeV (1967CE1B).

^{12}O
(Not illustrated)

See (1960GO1B, 1965GO1D, 1966GO1B, 1966KE16).

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(Closed 15 December 1967)

References are arranged and designated by the year of publication followed by the first two letters of the first-mentioned author's name and then by two additional characters. Most of the references appear in the National Nuclear Data Center files (Nuclear Science References Database) and have NNDC key numbers. Otherwise, TUNL key numbers were assigned with the last two characters of the form 1A, 1B, etc. In response to many requests for more informative citations, we have, when possible, included up to ten authors per paper and added the authors' initials.

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