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Energy Levels of Light Nuclei
$A = 12$

F. Ajzenberg-Selove and C.L. Busch

University of Pennsylvania, Philadelphia, Pennsylvania 19104-6396

Abstract: An evaluation of $A = 11$–12 was published in *Nuclear Physics A*336 (1980), 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.

(References closed July 1, 1979)

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^{12}n

(Not illustrated)

^{12}n has not been observed in the interaction of 0.7 and 400 GeV protons with uranium: the cross section is $< 1.0 \times 10^{-5}$ μb (1977TU02) and 0.7 GeV and < 0.08 μb (1977TU03) at 400 GeV.

^{12}Li

(Not illustrated)

^{12}Li is not observed in the 4.8 GeV proton bombardment of a uranium target: it is particle unstable. Its atomic mass excess would then be > 49.0 MeV. (1974TH01) calculate the mass excess of ^{12}Li to be 52.92 MeV, while (1975JE02) calculate 52.94 MeV. Taking the average of these two values, ^{12}Li would then be unstable with respect to ^{11}Li + n, ^{10}Li + 2n and ^{9}Li + 3n by 3.92, 2.96 and 3.76 MeV, respectively. See also (1975AJ02) and (1975BE31, 1976IR1B; theor.).

^{12}Be

(Figs. 5 and 9)

GENERAL: (See also (1975AJ02).)

Special reactions: (1975VO09, 1977AR06, 1979NA1E).

General reviews: (1973TO16, 1974CE1A).

Theoretical papers: (1975BE31, 1976BA24, 1976BE1G, 1976IR1B, 1977SE1D).

Mass of ^{12}Be: The Q-value of the ^{10}Be(t, p) reaction (-4809 ± 15 keV) (1978AL29) leads to an atomic mass excess of 25078 ± 15 keV for ^{12}Be which we adopt. See also (1975AJ02, 1975JE02).

1. ^{12}Be(β^-)^{12}B $\qquad Q_{\rm m} = 11.708$

The half-life of ^{12}Be is 24.4 ± 3.0 msec (1978AL10): $\log ft = 3.84 \pm 0.06$ [†] assuming the decay is to ^{12}B$_{\rm g.s.}$. The upper limit to a branch involving delayed neutrons is 1% (1978AL10). See also (1975AJ02) and (1973TA30; theor.).

2. ^{7}Li(^{7}Li, 2p)^{12}Be $\qquad Q_{\rm m} = -9.840$

[†] M.J. Martin, Nuclear Data Project, ORNL.

Table 12.1: Energy levels of ^{12}Be

E_x (MeV ± keV)	$J^\pi; T$	$\tau_{1/2}$ or $\Gamma_{c.m.}$	Decay	Reactions
0	$0^+; 2$	$\tau_{1/2} = 24.4 \pm 3.0$ msec	β^-	1, 2, 3, 4, 5
2.102 ± 12	$2^+; 2$		γ	3, 4, 5
$((\approx 2.24))$ [a]				3
(2.712 ± 20)				3, 4
4.559 ± 25		[b]		3
5.703 ± 25		[b]		3

[a] The evidence for this state is very marginal: see (1978AL10).

[b] This state has an intrinsic width: see (1978AL10).

This reaction has been studied at $E(^7\text{Li}) = 25.0$ to 30.1 MeV (1971HO26).

3. ^{10}Be(t, p)^{12}Be $\qquad Q_m = -4.809$

$$Q_0 = -4809 \pm 15 \text{ keV (1978AL29)}.$$

At $E_t = 12$ MeV, ^{12}Be*(2.10) is populated and (p, γ) angular correlations lead to an assignment of $J = 2$ [it is not excluded that a 0^+ state might be unresolved; it would not, of course, γ-decay to $^{12}\text{Be}_{\text{g.s.}}$] (1978AL10). At $E_t = 17$ MeV proton groups are observed to the states shown in Table 12.1. Assignment of a possible group to a state at ≈ 2.24 MeV is very tentative. The energy of ^{12}Be*(2.10) is measured to be 2089 ± 20 keV. The two highest states have an intrinsic width. There is no evidence for a state at $E_x = 0.81$ MeV suggested in reaction 2. From the measured atomic mass excess of ^{12}Be, d, the cubic factor in the IMME, is calculated to be $+2.8 \pm 8.6$ keV and the first $T = 2$ state in ^{12}N should occur at $E_x = 12.27 \pm 0.04$ MeV (1978AL29): compare with ^{12}O. (1976BA24) suggests that first two $T = 2$ states do not belong exclusively to the lowest configuration ($1s^41p^8$), for which the first 2^+; $T = 2$ excited state is expected to have $E_x \approx 4.4$ MeV but is observed at 2.1 MeV. Model calculations suggest a 0^+ state at $E_x \approx 2.35$ MeV (1976BA24). See also ^{12}O.

4. ^{12}C(π^-, π^+)^{12}Be $\qquad Q_m = -25.078$

At $E_{\pi^-} = 164$ MeV, ^{12}Be*(0, 2.10 + 2.71 (?)) are populated (1978SE07).

5. ^{14}C(^{18}O, ^{20}Ne)^{12}Be $\qquad Q_m = -15.798$

At $E(^{18}\text{O}) = 88.7$ MeV, ^{12}Be*(0, 2.09 ± 0.05) are populated (1974BA15).

^{12}B

(Figs. 6 and 9)

GENERAL: (See also (1975AJ02).)

Model calculations: (1976BA24, 1977JA14).

Special states: (1974TA1E, 1976BA24, 1976IR1B, 1977JA14).

Electromagnetic transitions: (1974HA1C).

Special reactions: (1975HU14, 1976AB04, 1976BE1K, 1976BU16, 1976LE1F, 1976OS04, 1977AR06, 1977SU02, 1977TA1L, 1977UD1A, 1978AB08, 1978GE1C, 1978HE1C, 1978IS01, 1978ISZX, 1978KO01, 1978TA20, 1978UD01, 1979IS03).

Muon capture (See also reaction 17.): (1975KI2A, 1976HO1G, 1977BA1P, 1977DE1U, 1977LE1K, 1977PO1B, 1977PR1B, 1978DE15, 1978HW1A, 1978KO31, 1978MU04, 1978PA1F, 1978SE1B, 1978WU01, 1979OH1A, 1979PA1J, 1979PE1C, 1979PR1D, 1979RO03, 1979RO1H, 1979SH1N, 1979TR05, 1979WI1A).

Pion capture and pion reactions (See also reaction 16.): (1974CAZD, 1976AL1J, 1976TR1A, 1976TZ1A, 1977BA1Q, 1977BA2G, 1977DO06, 1977FU11, 1977RA1A, 1977SH14, 1978ER1C, 1978FU04, 1978FU09, 1978KO34, 1978SI1E, 1979BA1M, 1979NA1Q, 1979SOZY).

Astrophysical questions: (1977HA1L, 1978BU1B).

Applied topics: (1978MC1H).

Other topics: (1976IR1B, 1978DA1A, 1978GA1C, 1978PO1A).

Ground state: (1974SHYR, 1975AL19, 1975BE31, 1976FU06, 1977TA04, 1977YO1D, 1978ZA1D).

$\mu = +1.00306\ (15)$ nm (1978LEZA);

$Q = 1.71 \pm 0.16$ fm^2 (1971MI06, 1978LEZA);

$Q = 1.34 \pm 0.14$ fm^2 (1978MI19).

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

The half-life of ^{12}B is 20.20 ± 0.02 msec (1978AL01): see Table 12.2 of (1968AJ02) for a summary of earlier values. The decay is complex. ^{12}B decays to ^{12}C*(0, 4.4, 7.7, 10.3): see Table 12.15. The transitions to ^{12}C*(0, 4.4) are allowed: hence the J^π of ^{12}B$_{\rm g.s.}$ is 1^+.

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

At $E(^7Li) = 2$ MeV eleven groups of protons are reported to known states of ^{12}B (1959MO12). Angular distributions have been measured at $E(^6Li) = 3.5$ to 5.95 MeV. The distributions are generally featureless: see (1975AJ02).

Table 12.2: Energy levels of ^{12}B [a]

E_x in ^{12}B (MeV ± keV)	$J^\pi; T$	τ or $\Gamma_{c.m.}$ (keV)	Decay	Reactions
0	$1^+; T = 1$	$\tau_{1/2} = 20.20 \pm 0.20$ msec	β^-	1, 2, 3, 6, 7, 9, 10, 13, 16, 17, 18, 19, 21, 22, 23, 24, 25
0.95314 ± 0.60	2^+	$\tau_m = 260 \pm 40$ fsec	γ	2, 3, 7, 9, 13, 16, 17, 19, 20, 21, 22, 24
1.67365 ± 0.60	2^-	$\tau_m < 50$ fsec	γ	2, 3, 7, 9, 13, 16, 17, 19
2.6208 ± 1.2	1^-	$\tau_m < 70$ fsec	γ	2, 3, 7, 9, 13, 16, 17, 19
2.723 ± 11	0^+		γ	2, 3, 7, 9, 13, 19, 21
3.3889 ± 1.4	3^-	$\Gamma_{c.m.} = 3.1 \pm 0.6$ eV	γ, n	2, 7, 9, 10, 11, 13
3.759 ± 6	2^+	40 ± 4 keV	γ, n	7, 9, 10, 11, 13, 21
4.303 ± 7	1^-	9 ± 4	γ, n	7, 9, 10, 11, 18
4.37	2^-	broad	n	11
4.521 ± 7	4^-	110 ± 20	γ, n	7, 9, 10, 11, 13
5.00 ± 20	1^+	50 ± 15	γ, n	7, 9, 10, 11, 16, 21
5.612 ± 8	3^+	110 ± 40	n	7, 9, 11, 22
5.724 ± 8	3^-	50 ± 20	n	7, 9, 11
6.0	$(2)^-$	broad	n	11
6.6		140	n	11
6.9		broad	n	11
7.545 ± 20		≤ 14	n	7, 9, 11
7.836 ± 20		60 ± 40	n	7, 11
7.937 ± 20		27	n	7, 11
8.1 ± 100		900 ± 200		7
8.120 ± 20				7, 9
8.24 ± 30	3^-	65	n	7, 11
8.376 ± 20		40 ± 20	n	7, 9, 11
8.58 ± 30		75	n	7, 9, 11
8.707 ± 20	(1^+)		n	7, 11

Table 12.2: Energy levels of ^{12}B [a] (continued)

E_x in ^{12}B (MeV ± keV)	$J^\pi; T$	τ or $\Gamma_{c.m.}$ (keV)	Decay	Reactions
9.04 ± 20	(2^-)	95 ± 20	n	7, 9, 11
9.175 ± 20				7
9.43 ± 20		85 ± 30		7, 9
9.585 ± 5		34 ± 5		7, 9, 11
9.758 ± 20				7
(9.83)				7
10.00 ± 40		100	n	7, 11
10.11 ± 40				7
10.220 ± 20		< 25		7, 9
10.435 ± 20		75 ± 40		7
10.59 ± 20		< 30	n	7, 9, 11
10.90 ± 20		30 ± 10		7, 9
(11.08)				7
11.31 ± 30		130 ± 60		7
11.59 ± 20		75 ± 25		7
12.345 ± 25		100 ± 30	n	7, 9, 11
12.75 ± 50 [b]	$0^+; T = 2$	85 ± 40		7, 22
13.33 ± 30		50 ± 20		7
(13.4 ± 100)		broad		9
[c]				22
14.82 ± 100	$(2^+; T = 2)$	$\lesssim 200$		22
15.5				7

[a] See also Table 12.6.

[b] The state at $E_x = 12.77 \pm 0.05$ MeV reported in reaction 7, and the $T = 2$ state at 12.72 ± 0.07 MeV [$\Gamma \lesssim 200$ keV] may not be the same states.

[c] Thirteen resonances are reported in ^{9}Be(t, n)^{11}B with $13.6 < E_x < 14.7$ MeV: see Table 12.3 in (1975AJ02).

3. ^{7}Li(^{7}Li, d)^{12}B $\qquad Q_m = 3.311$

Angular distributions have been measured at $E(^7\text{Li}) = 2.10$ to 5.75 MeV (1969CA1A: d_0, d_1, d_2, d_{3+4}). The mean lifetimes of ^{12}B*(0.95, 2.62) are 295 ± 37 fsec and < 48 fsec, respectively

(1969TH01). For γ-decay results see (1975AJ02).

4. ^{9}Be(t, n)^{11}B $\quad Q_m = 9.5586 \quad E_b = 12.928$

Thirteen resonances have been reported corresponding to $13.6 < E_x < 14.7$ MeV: see Table 12.3 in (1975AJ02). See also (1977MA1N) and ^{11}B.

5. (a) ^{9}Be(t, p)^{11}Be $\quad Q_m = -1.167 \quad E_b = 12.928$
   (b) ^{9}Be(t, d)^{10}Be $\quad Q_m = 0.5545$
   (c) ^{9}Be(t, t)^{9}Be
   (d) ^{9}Be(t, α)^{8}Li $\quad Q_m = 2.926$
   (e) ^{9}Be(t, ^{6}He)^{6}Li $\quad Q_m = -5.383$

Yields of elastically scattered tritons have been measured for $E_t = 0.60$ to 2.1 MeV: see (1975AJ02). Differential cross sections and analyzing power for elastic tritons have been measured at $E_{\vec{t}} = 15$ and 17 MeV (1978SC02). The yield of α_0 and α_1 (reaction (d)) have been obtained for $E_t = 0.52$ to 1.70 MeV (1969NA04). There is no evidence of the resonance structure reported in reaction 4. The analyzing powers of the reactions leading to ^{6}He$_{\text{g.s.}}$ and ^{6}Li*(0, 3.56) have been measured at $E_{\vec{t}} = 17$ MeV (1979FL03). See also ^{6}He, ^{6}Li, ^{8}Li and ^{9}Be in (1979AJ01) and ^{11}Be here.

6. ^{9}Be(α, p)^{12}B $\quad Q_m = -6.886$

See (1968AJ02).

7. ^{9}Be(^{7}Li, α)^{12}B $\quad Q_m = 10.462$

Observed α-particle groups are displayed in Table 12.3. Angular distributions have been measured at $E(^{7}\text{Li}) = 3.3$ to 6.2 MeV, at 30.3 MeV [see (1975AJ02)] and at 20 MeV (1975AJ03). Angular distributions to the first seven states are rather featureless and have approximate symmetry about 90°. The integrated cross sections go as $2J_f + 1$ consistent with a compound nucleus mechanism for the transitions populating the low-lying states of ^{12}B. It is suggested that the sharp states of ^{12}B at high excitation energies correspond to states of high angular momenta with cluster configurations (1975AJ03).

Table 12.3: Levels of ^{12}B from ^{9}Be(^{7}Li, α)^{12}B [a]

E_x (MeV $\pm$ keV)	$\Gamma_{c.m.}$ (keV)	θ_n^2
0		
0.951 ± 15		
1.674 ± 15		
2.625 ± 15		
2.724 ± 15		
3.390 ± 15		
3.77 ± 20	40 ± 20	0.46 ± 0.06
4.305 ± 15	< 30	
[b]		
4.534 ± 15		
4.982 ± 15	40 ± 20	0.08 ± 0.03
5.57 ± 30		0.10 ± 0.02
5.728 ± 15	50 ± 20	
[b]		
7.545 ± 20	< 30	
7.836 ± 20	60 ± 40	
7.937 ± 20	< 40	
8.1 ± 100	900 ± 200	
8.120 ± 20		
8.24 ± 30		
8.376 ± 20	40 ± 20	
8.58 ± 30		
8.707 ± 20		
9.03 ± 20		
9.175 ± 20		
9.43 ± 20 [c]	85 ± 30 [c]	
9.585 ± 20	60 ± 30	
9.758 ± 20		
(9.83)		
10.00 ± 40		
10.11 ± 40		

Table 12.3: Levels of ^{12}B from ^{9}Be(^{7}Li, α)^{12}B [a] (continued)

E_x (MeV $\pm$ keV)	$\Gamma_{c.m.}$ (keV)	θ_n^2
10.21 ± 30	50 ± 20	
10.435 ± 20	75 ± 40	
10.58 ± 20	50 ± 30	
10.887 ± 20	40 ± 20	
(11.08)		
11.31 ± 30	130 ± 60	
11.59 ± 20	75 ± 25	
12.33 ± 30	100 ± 30	
12.77 ± 50	85 ± 40	
13.33 ± 30	50 ± 20	
15.5 [d]		

[a] (1975AJ03): $E(^{7}\mathrm{Li}) = 20$ MeV.
[b] There is evidence for at least one additional state in this region, but ^{12}B*(6.6) [$J^{\pi} = (1)^{+}$, $\Gamma_{c.m.} = 140$ keV], is not observed.
[c] Probably unresolved.
[d] (1969GL07): $E(^{7}\mathrm{Li}) = 30.3$ MeV.

8. (a) ^{10}Be(d, p)^{11}Be $\quad Q_m = -1.722 \quad E_b = 12.374$
   (b) ^{10}Be(d, α)^{8}Li $\quad Q_m = 2.372$

The cross sections for production of ^{8}Li (reaction (b)) and of ^{11}Be (reaction (a)) have been measured for $E_d = 0.67$ to 3.0 MeV and 2.3 to 12 MeV: the yields for both reactions vary smoothly with energy. No resonances are observed (1970GO11, 1973GO09).

9. ^{10}B(t, p)^{12}B $\quad Q_m = 6.343$

Observed excited states are displayed in Table 12.4. Angular distributions have been studied at $E_t = 10$ (1964MI04) and 23 MeV (1978AJ02). See also (1977ST1N) and (1975AJ02).

10. ^{11}B(n, γ)^{12}B $\quad Q_m = 3.370$

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

E_x in ^{12}B (MeV ± keV)		$\Gamma_{c.m.}$ (keV)	L	J^π
(1960JA17)	(1978AJ02)			
0	0		2 [d]	$(1, 2, 4, 5)^+$
0.955 ± 8	0.959 ± 20		2 [d]	$(1, 2, 4, 5)^+$
1.673 ± 8	1.690 ± 20		1 [d]	$(2, 3, 4)^-$
2.627 ± 8	$\equiv 2.62$		3 [d]	$(0, 1, 5, 6)^-$
2.73	$\equiv 2.72$		4 [d]	$(0, 6, 7)^+$
3.393 ± 8	$\equiv 3.39$			
3.754 ± 8	3.777 ± 20	42 ± 5 [c]	2 [d]	$(1, 2, 4, 5)^+$
4.297 ± 8	[a]	≤ 15 [c]		
4.514 ± 8	4.543 ± 20	95 ± 15 [c,d]		
5.00	[b]	130 ± 40 [c]		
5.612 ± 8	5.63 ± 30	120 ± 20 [c]		
5.724 ± 8	[a]	70 ± 20 [c]		
	7.55 [a]			
	8.16 ± 30			
	8.38 [a]			
	8.58 [a]			
	9.07 ± 30	95 ± 20 [d]		
	9.44 ± 30			
	9.626 ± 20	34 ± 10 [d]		
	10.227 ± 20	< 25 [d]		
	10.61 ± 30	< 30 [d]		
	10.91 ± 20	27 ± 10 [d]		
	12.36 ± 30			
	(13.4 ± 100)	broad		

[a] Observed but E_x not determined.
[b] Not observed.
[c] (1964MI04): $E_t = 10$ MeV.
[d] (1978AJ02): $E_t = 23$ MeV.

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

E_n (MeV ± keV)	$\Gamma_{c.m.}$ (keV)	^{12}B* (MeV)	l	J^π	Comments
0.0208 ± 0.5 [b]	$\ll 1.4$	3.3889	2	3^- [c]	$\Gamma_n = 3.1 \pm 0.6$ eV [b]
0.43 ± 10 [g,l]	37 ± 5	3.764	1	2^+ [c]	
1.027 ± 11 [h,l]	9 ± 4	4.311	0	1^- [c]	
1.09 [c]	broad	4.37	0, 2	2^- [c]	[i]
1.28 ± 20 [g,l]	130 ± 20	4.54	2	4^- [c]	
1.78 ± 20 [g,l]	60 ± 20	5.00	1	1^+ [c]	
2.45 ± 20 [g]	110 ± 40	5.61	1	3^+ [d]	
2.58 ± 20 [g]	55 ± 20	5.73	2	3^- [d]	
2.9 [d,j]	broad	6.0	0, 2	1^- [d,j]	
3.5 [e]	140	6.6	1	1^+ [j]	
3.8 [d]	broad	6.9	0, 2	1^- [j]	
4.55 [f]	≤ 14	7.54	> 3		
(4.68)	45	(7.66)	> 0		
4.80	90	7.77	> 0		
(5.01)	27	(7.96)	> 0		
5.31	65	8.23	2	3^- [j]	
5.49	110	8.40 [o]			
5.59	75	8.49	2	3^- [j]	
(5.85) [j]		(8.73) [j]	(1) [j]	(1^+) [j]	
6.18	120	9.03	0, 2	2^- [j,k]	
6.78 [m] [n]	34 ± 5	9.580 ± 0.005			
7.18	100	9.94	> 0		
7.82	65	10.53	> 2		
9.72	120	12.27	> 2		

[a] See also Table 12.5 in (1968AJ02).
[b] (1969MO10). Also observed in ^{11}B(n, γ): $\Gamma_\gamma = 25 \pm 8$ meV (1969MO10), $\Gamma_n = 1.9^{+0.8}_{-0.6}$ eV [reaction 13 in (1975AJ02)].
[c] (1970LA21).
[d] (1973NE19).
[e] (1961FO07).
[f] This reaction and all the higher energy ones have been observed by (1961FO07). See also (1977WHZZ, 1978WH1B).
[g] (1951BO45, 1968AJ02).
[h] (1962IM01).
[i] The low penetrability for $l = 2$ neutrons means that the observed width of this level is predominantly $l = 0$. The reduced width is probably $\approx 80\%$ $l = 2$ and 20% $l = 0$ (1970LA21).
[j] (1977WHZZ, 1978WH1B) and (R.O. Lane, private communication).
[k] ^{12}B*(9.0) may be due to unresolved resonances.
[l] Also observed in ^{11}B(n, γ) (1962IM01).
[m] (1979AU07).
[n] A broad resonance at $E_n = 7.0$ MeV [^{12}B*(9.8)] is observed in the even polynomial terms of the Legendre expansion coefficients (1977WHZZ, 1978WH1B). See also (1979AU07).
[o] May be due to interference of states at 5.3 and 5.6 MeV (R.O. Lane, private communication).

The thermal neutron capture section is 5 ± 3 mb (1962IM01) [(1973MU14) adopt 5.5 ± 3.3 mb]. The capture cross section shows a resonance at $E_n = 20.8 \pm 0.5$ keV (see also reaction 11) with $\Gamma_\gamma = 0.025 \pm 0.008$ eV (1969MO10). 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). See also (1976GAYV).

11. ^{11}B(n, n)^{11}B $\qquad E_b = 3.370$

The thermal (bound) scattering cross section is 3.9 ± 0.2 b. The scattering amplitude (bound) is $a = 6.1 \pm 0.1$ fm (1973MU14). Parameters of observed resonances in σ_{tot} are shown in Table 12.5.

Comparison of ^{11}B + n and of data from ^{11}B(d, p) shows that the $E_n = 20.8$ keV resonance is d-wave and that ^{12}B*(3.389) has $J^\pi = 3^-$. The neutron width [3.1 ± 0.6 eV] is about the Wigner limit. The 0.43 MeV resonance [^{12}B*(3.76)] is formed by $l = 1$; $\gamma^2_{S=1} = \gamma^2_{S=2}$; $J^\pi = 2^+$.

The polarization and differential cross sections have been measured for $0.075 \leq E_n \leq 2.2$ MeV by (1970LA21) as has σ_t for $0.3 \leq E_n \leq 2.05$ MeV. A two-channel R-matrix analysis fits both $\sigma(\theta)$ and $P(\theta)$ assuming broad 2^- ($l = 0$) and 4^- ($l = 2$) states at $E_x = 4.37$ and 4.54 MeV [$E_n = 1.09$ and 1.28 MeV] in addition to the sharp state ^{12}B*(4.31) fitted with $J^\pi = 1^-$. The analysis also confirms $J^\pi = 1^+$ for ^{12}B*(5.00) (1970LA21). Differential cross sections have also been measured for $2.2 < E_n < 4.5$ MeV by (1973NE19) and for 4.0 to 8.0 MeV by (1977WHZZ, 1978WH1B). See also (1976LA1C, 1977WH1A).

Recent additional measurements (1978WH1B) and R-matrix analysis for $2.6 < E_n < 4.0$ MeV confirm $J^\pi = 1^-$ ($l_n = 0$, 2) for the ^{12}B* state at $E_x = 5.8 - 6.0$ MeV, and give 1^- ($l_n = 0$, 2) for ^{12}B*(6.9) instead of 1^+ (1973NE19). In the region $7.5 < E_x < 8.5$ MeV 1^- and 2^- states of $l_n = 0$, 2 are present (1977WHZZ, 1978WH1B) and (R. Lane, private communication). Assignments of states at higher energies are displayed in Table 12.5 (1977WHZZ, 1978WH1B). See also (1975AJ02).

Total cross sections from $E_n = 3.4$ to 15.5 MeV (1961FO07) and from 1 to 14 MeV (1979AU07) have been studied: see Table 12.5. There is no evidence of sharp structure in the range $9.7 < E_x < 17.3$ MeV. Limitations of statistical accuracy exclude observation of $J = 0$ levels above $E_n = 4$ MeV, and of $J = 1$ levels above $E_n = 12$ MeV in this work (1961FO07). The σ_t for natural boron has been measured for $E_n = 2.5$ to 15 MeV (1971FO1P, 1971FO24). Other cross section measurements have been reported at $E_n = 7.55$ to 14.5 MeV [see (1975AJ02)] and 14.1 MeV (1974HY01). See also ^{11}B and (1976GAYV).

12. (a) ^{11}B(n, p)^{11}Be $\quad Q_m = -10.726 \quad E_b = 3.370$
(b) ^{11}B(n, d)^{10}Be $\quad Q_m = -9.0041$
(c) ^{11}B(n, t)^{9}Be $\quad Q_m = -9.5586$
(d) ^{11}B(n, α)^{8}Li $\quad Q_m = -6.633$

The cross section for reaction (a) has been measured for $E_n = 14.7$ to 16.9 MeV: see (1975AJ02). See also (1974BO1E). For reaction (b) see (1976SL2A). For reaction (c) see (1978QA01). See also (1973BI1B) and (1976SL2A). The cross section for reaction (d) has been measured in the range $E_n = 12.6$ to 20.0 MeV and at $E_n = 25$ and 38 MeV: see (1975AJ02). No resonances are observed. See also (1974BO1E, 1974CA1J, 1976SL2A) and (1976GAYV).

13. ^{11}B(d, p)^{12}B $\quad Q_m = 1.145$

Observed proton groups and γ-rays are displayed in Table 12.6. The J^π assignments for ^{12}B*(0.95, 1.67) are derived as follows [see (1968AJ02) for detailed listing of earlier references]: *0.95 MeV:* $l_n = 1$ leads to $J^\pi = 0^+$, 1^+, or 3^+. The γ-radiation is anisotropic and therefore $J \neq 0$ (1963WA20, 1968CO14). τ_m is too short for pure E2 and hence $J \neq 3$, which is confirmed by studies of the polarization of γ_1, most recently by (1968GO17: $E_d = 0.5$ to 5.5 MeV). The results are consistent with $J^\pi = 1^+$ or 2^+. The latter is fixed by γ-γ correlations in the cascade $1.67 \rightarrow 0.95 \rightarrow$ g.s. (1968CH05). The mixing ratio $\delta = -0.08 \pm 0.06$ (1968GO17). $\Gamma_\gamma = 2.2 \pm 0.25$ meV (1968OL01). See also (1968GO18, 1974KA29); *1.67 MeV:* $l_n = 0$ and therefore $J^\pi = 1^-$ or 2^-. The state decays primarily to ^{12}B$_{g.s.}$. Gamma-gamma correlations lead to $J^\pi = 2^-$ (1968CH05). An assignment of 1^- to ^{12}B*(2.62) is made in a similar manner.

(1971MO14) have analyzed existing ^{11}B(d, p)^{12}B and ^{11}B + p reactions and have listed the properties of the first seven $T = 1$ states in ^{12}B and ^{12}C: see Table 12.12. Neutron reduced widths

Table 12.6: ^{12}B states from ^{11}B(d, p)^{12}B [a]

^{12}B* (MeV ± keV)	l_n [f]	J^π [f]	S [h]	Gamma decay (%) [c]		τ_m (fsec)
0	1	1^+	0.69			
0.95314 ± 0.60 [b]	1	2^+	0.55	to g.s.		300 ± 33 [c]
						200 ± 40 [i]
1.67365 ± 0.60 [b]	0	2^-	0.57	(3.2 ± 0.4) [j]	$[\to 0.95]$	< 50 [c]
				(96.8 ± 0.4)	$[\to$ g.s.$]$	
2.6208 ± 1.2 [c]	0	1^-	0.75	(14 ± 3)	$[\to 1.67]$	< 70 [c]
				(80 ± 3)	$[\to 0.95]$	
				(6 ± 1)	$[\to$ g.s.$]$	
2.723 ± 11 [d]	1	0^+	0.21	(> 85)	$[\to$ g.s.$]$	
3.383 ± 9 [d]	2 [g]	3^-	0.58			
3.76 [e]	1	2^+				
4.52 [e]	2					

[a] See also Table 12.6 in (1968AJ02).
[b] (1966WI01).
[c] (1968OL01).
[d] (1950BU1A, 1953EL12).
[e] (1953HO48).
[f] See (1975AJ02) and (1971MO14).
[g] (1969FO10).
[h] DWBA analysis (1971MO14).
[i] (1969GA16, 1970GA09).
[j] (3.2 ± 0.5)% (1968OL01), (3.0 ± 0.6)% (1968CH05).

$\gamma^2_{\lambda_n}$ for the first six excited states in ^{12}B were calculated from spectroscopic factors and compared with $2\gamma^2_{\lambda_p}$ for the corresponding ^{12}C states. The agreement was quite good once new values for the partial widths of ^{12}C*(16.11) [see (1974AN19)] became available (1971MO14). For the polarization of ^{12}B$_{\rm g.s.}$ see (1977PO1B) and reaction 15.

The j mixing $A_{ls_{3/2}}/A_{ls_{1/2}} = -0.11 \pm 0.03$ or -0.90 ± 0.06 for ^{12}B$_{\rm g.s.}$ and $+0.12 \pm 0.02$ for ^{12}B*(0.95) (1976TA07). See also (1975HU1H, 1975MC1E, 1975MI1F, 1976MI1J, 1977KA1V), (1976HA1J), (1977SA25; theor.) and ^{13}C in (1981AJ01).

14. ^{11}B(α, ^{3}He)^{12}C $\qquad Q_m = -17.208$

See (1979CHZP).

15. ^{12}Be(β^-)^{12}B $\quad$ $Q_m = 11.708$

See ^{12}Be.

16. (a) ^{12}C(γ, π^+)^{12}B $\quad$ $Q_m = -152.936$
(b) ^{12}C(e, eπ^+)^{12}B $\quad$ $Q_m = -152.936$
(c) ^{12}C(π^-, γ)^{12}B $\quad$ $Q_m = 126.197$

π^+ electroproduction has been studied at $E_\pi \approx$ 17 and 29 MeV to ^{12}B*(0.95, 1.7, 2.6, 4.5) (1979PA06). See also (1979MI06) and reaction 39 in ^{12}C. At $E_e = 195$ MeV, angular distributions are reported for the π^+ to ^{12}B$_{g.s.}$ and to possibly unresolved excited states (1977SH14), including ^{12}B*(4.5) (1979SH1R). For reaction (c) see (1979AL1M). See also (1975HU1D, 1978FU04, 1978FU09; theor.).

17. ^{12}C(μ^-, ν)^{12}B $\quad$ $Q_m = 92.290$

Observations of γ-transitions have led to the determination of the capture rates to ^{12}B*(0, 0.95, 1.67, 2.62); those to ^{12}B*(0.95, 1.67) are consistent with zero (1972MI15). The polarization of ^{12}B$_{g.s.}$, $P_{av} = 0.452 \pm 0.042$ (1977PO1B). The longitudinal polarization, $P_L = -0.83 \pm 0.21$ (1979TR05). These two values lead to a neutrino polarization $h_\nu = -0.89 \pm 0.23$ [left-handed] (1979TR05). See also (1976SU03, 1978KO31; theor.).

18. ^{12}C(n, p)^{12}B $\quad$ $Q_m = -12.587$

At $E_n = 45$ to 64 MeV strong excitation of ^{12}B*(0, 4.3, 7.7) is reported (1977FI1B, 1977SU1C). See also (1975MC19, 1976KI1D), (1976SL2A) and ^{13}C in (1981AJ01).

19. ^{12}C(^{7}Li, ^{7}Be)^{12}B $\quad$ $Q_m = -14.231$

At $E(^7$Li$) = 52$ MeV the population of ^{12}B*(0, 0.95, 1.71, 2.70, 2.87) and ^{7}Be(0) [and in the case of ^{12}B(0), of ^{7}Be*(0.43)] is reported by (1973BA34).

20. ^{13}C(γ, p)^{12}B $\quad$ $Q_m = -17.533$

At $E_{\mathrm{bs}} = 15$ to 44 MeV the cross section for transitions to ^{12}B*(0.95) has been measured by (1975PA09). See also ^{13}C in (1981AJ01) and (1977MA06; theor.).

21. ^{13}C(d, ^{3}He)^{12}B $\quad Q_{\mathrm{m}} = -12.040$

Angular distributions have been measured for the transitions to ^{12}B*(0, 0.95) at $E_{\mathrm{d}} = 24.1$, 26.2 and 27.5 MeV (1977LI02), 28 MeV (1972BR27) and 52 MeV (1975MA41; also to ^{12}B*(2.72, 3.76, 5.00)) and at $E_{\mathrm{d}} = 29$ MeV (1979CO08). (1977LI02) find $S = 1.1 \pm 0.2$ and 2.0 ± 0.5 for the spectroscopic factors to ^{12}B*(0, 0.95). $C^2S = 1.09$ [assuming $1\mathrm{p}_{3/2}$], 2.17, 0.14, 0.07, 0.22 [assuming $1\mathrm{p}_{1/2}$] for ^{12}B*(0, 0.95, 2.72, 3.76, 5.00) (1975MA41). See also (1979CO08). For a discussion of analog states of ^{12}B and ^{12}C see reaction 73 in ^{12}C and (1977LI02, 1979CO08). See also (1977RI08) and (1979CO08) in ^{15}N (1981AJ01).

22. ^{14}C(p, ^{3}He)^{12}B $\quad Q_{\mathrm{m}} = -17.992$

At $E_{\mathrm{p}} = 54$ MeV, in addition to transitions to ^{12}B*(0, 0.95, 5.61), the population of $T = 2$ states at $E_{\mathrm{x}} = 12.72 \pm 0.07$ and 14.82 ± 0.10 MeV is reported. The angular distribution of ^{3}He ions to ^{12}B*(12.72) is fitted by $L = 0$; that to ^{12}B*(14.82) is rather featureless [its $T = 2$ character is assigned from the energies of the analog states]: both states have $\Gamma_{\mathrm{c.m.}} \lesssim 200$ keV (1976AS01). See also (1975AJ02), and reaction 80 in ^{12}C.

23. ^{14}C(d, α)^{12}B $\quad Q_{\mathrm{m}} = 0.361$

See (1968AJ02).

24. ^{14}N(^{12}C, ^{14}O)^{12}B $\quad Q_{\mathrm{m}} = -18.514$

At $E(^{14}\mathrm{N}) = 118$ MeV the excitation of ^{12}B*(0, 0.95) is reported (1974AN36). See also (1975NA11) in ^{14}O.

25. (a) ^{15}N(n, α)^{12}B $\quad Q_{\mathrm{m}} = -7.621$
(b) ^{18}O(^{11}B, ^{17}O)^{12}B $\quad Q_{\mathrm{m}} = -4.675$

See (1975AJ02).

^{12}C
(Figs. 7 and 9)

GENERAL: (See also (1975AJ02).)

Shell model: (1974BOZB, 1975BI05, 1975BO27, 1975FR06, 1975GI1C, 1975MU13, 1975WA30, 1976BA24, 1977CA02, 1977CA08, 1977GR02, 1977JA14, 1978FU13, 1978MU04, 1978SV01, 1979LO1F).

Collective and deformed models: (1974BOZB, 1975BO27, 1975KI21, 1975LE14, 1975MC15, 1975SO07, 1976GL1C, 1976PA25, 1977CA08, 1977TH03, 1977UE01, 1977VI03, 1979MA1J).

Cluster and alpha particle models: (1974AG06, 1975AB1E, 1975BA16, 1975HO1E, 1975IN04, 1975KA29, 1975KR1D, 1975KU1N, 1975NE1B, 1975RO1B, 1975WA30, 1976CA05, 1976FL1B, 1976FU1G, 1976HA09, 1976HO1F, 1976HO1A, 1976KA14, 1976KI16, 1976SA1F, 1976VA21, 1977AG03, 1977BA76, 1977BE49, 1977FU1E, 1977HO1E, 1977HO1F, 1977KA1U, 1977KA1Q, 1977KH02, 1977MY1A, 1977MY1B, 1977NA13, 1977SA19, 1977SA1C, 1977TA1J, 1977TA1K, 1977UE01, 1977UE1B, 1978AR1H, 1978DZ01, 1978HO1E, 1978HU09, 1978IS04, 1978MA1U, 1978OG1A, 1978OS01, 1978UE1B, 1979GO1P, 1979HE1G, 1979KA1P).

Special levels: (1974BOZB, 1975BA16, 1975HO1E, 1975IM02, 1975MC16, 1975NA21, 1975NG1A, 1976BA24, 1976FU1G, 1976GA16, 1976GL09, 1976GO1J, 1976HA09, 1976HO1A, 1976IR1B, 1976KI01, 1976VA21, 1977BA76, 1977CA08, 1977GR02, 1977GR24, 1977JA14, 1977KA1Q, 1977KN03, 1977MO1Q, 1977SA17, 1977TA1J, 1977UE01, 1977UE1B, 1978AR1H, 1978BA31, 1978BE56, 1978GO1K, 1978HO1E, 1978HU09, 1978LA1D, 1978MC04, 1978MI04, 1978RO17, 1978SH04, 1979DU1E, 1979HA1E, 1979PO03).

Electromagnetic transitions: (1974BOZB, 1974HA1C, 1975BE24, 1975BI05, 1975BO27, 1975DO1D, 1975KA29, 1975MC16, 1976KI01, 1976VO1C, 1977AG03, 1977BE49, 1977DE15, 1977DO06, 1977FU1E, 1977GR02, 1977GR24, 1977KA1Q, 1977MA1Y, 1977MY1B, 1977YO1D, 1978AR1H, 1978FU13, 1978GO1K, 1978KI08, 1978MU04, 1978MY1B, 1978UE1B, 1979MO07, 1979MO1U, 1979MO1X, 1979PO03).

Giant resonances: (1974HA1C, 1975CO1E, 1975DO10, 1975GE1K, 1975GO22, 1975MC15, 1976BE1P, 1976KO1G, 1976MS01, 1977DE15, 1977GO1F, 1977KN03, 1977MA2E, 1977SA1Q, 1979DE1T, 1979GO1Q).

Special reactions: (1975AB1D, 1975AL04, 1975AR14, 1975FA1D, 1975GR13, 1975HU14, 1975KO1F, 1975ME1F, 1975PE03, 1975RE08, 1976AB04, 1976BA08, 1976BE1K, 1976BO1N, 1976BU16, 1976CH28, 1976DA1G, 1976EG02, 1976FR05, 1976HE1H, 1976HI05, 1976HI01, 1976HO1D, 1976LE12, 1976LE1F, 1977AR06, 1977BU07, 1977CE1B, 1977FE1B, 1977GE08, 1977GO07, 1977HA18, 1977HO27, 1977JA1J, 1977KA1P, 1977KO1Y, 1977KU1D, 1977LI1J, 1977MA1U, 1977MA1W, 1977NA03, 1977PR05, 1977RE08, 1977SH1D, 1977ST1J, 1977ST1G, 1977TO1G, 1977UD1A, 1977VA02, 1977YA1B, 1978AB08, 1978BA24, 1978BH03, 1978BI03, 1978BI08, 1978DI04, 1978FU1H, 1978GE1F, 1978GE1C, 1978GO1N, 1978GR1F, 1978HE1J, 1978HE1C, 1978KO01, 1978LE15, 1978OB01, 1978TU06, 1978VO1D, 1978VO1A, 1978WE1D,

1978WI1G, 1979AL1H, 1979CH06, 1979DU1E, 1979DY01, 1979GA04, 1979GO11, 1979HA1E, 1979PO10, 1979SC08, 1979SI1A, 1979SI09, 1979WA1H, 1979WE06).

Table 12.7: Energy levels of ^{12}C [a]

E_x in ^{12}C (MeV ± keV)	$J^\pi; T$	$\Gamma_{c.m.}$ (keV)	Decay	Reactions
g.s.	$0^+; 0$	–	stable	4, 10, 11, 12, 13, 21, 22, 23, 24, 25, 26, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 113
4.43891 ± 0.31	$2^+; 0$	$(10.8 \pm 0.6) \times 10^{-6}$	γ	4, 10, 11, 12, 13, 21, 22, 23, 25, 26, 30, 31, 32, 35, 36, 37, 44, 46, 47, 48, 50, 52, 53, 54, 56, 57, 58, 59, 60, 65, 69, 70, 71, 72, 73, 74, 75, 84, 85, 86, 88, 90, 91, 92, 94, 95, 96, 97, 100, 102, 111, 112
7.6542 ± 0.15	$0^+; 0$	$(8.5 \pm 1.0) \times 10^{-3}$	γ, π, α	4, 10, 11, 12, 13, 21, 23, 31, 36, 44, 47, 48, 52, 53, 54, 57, 69, 73, 74, 75, 86, 91, 95, 96, 97
9.641 ± 5	$3^-; 0$	34 ± 5	γ, α	4, 10, 11, 12, 21, 23, 30, 31, 35, 44, 46, 47, 48, 50, 52, 53, 54, 57, 59, 74, 75, 83, 86, 95, 96, 97
10.3 ± 300	$(0^+); 0$	3000 ± 700	α	10, 36, 47, 69
10.844 ± 16	$1^-; 0$	315 ± 25	α	10, 11, 21, 30, 31, 47, 48, 50, 52, 53, 54, 83
(11.16 ± 50)	$(2^+); 0$	430 ± 80		30, 31

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

E_x in ^{12}C (MeV ± keV)	$J^\pi; T$	$\Gamma_{c.m.}$ (keV)	Decay	Reactions
11.828 ± 16	$2^-; 0$	260 ± 25	α	11, 21, 23, 30, 31, 47, 50, 52, 53, 54, 83
12.710 ± 6	$1^+; 0$	$(18.1 \pm 2.8) \times 10^{-3}$	γ, α	21, 22, 23, 30, 31, 44, 47, 48, 50, 52, 53, 54, 69, 72, 73, 74, 75, 85, 86
13.352 ± 17	$(2^-); 0$	375 ± 40	α	21, 30, 31, 54, 86
14.083 ± 15	$4^+; 0$	258 ± 15	α	21, 48, 52, 53, 54, 57, 60, 85, 86, 91, 95, 97
15.110 ± 3	$1^+; 1$	$(42.0 \pm 1.7) \times 10^{-3}$	γ, α	21, 22, 23, 30, 31, 37, 44, 46, 48, 50, 52, 69, 70, 72, 73, 74, 85, 86
(15.4 ± 100)		2000 ± 200		48, 52, 53
16.1067 ± 0.5	$2^+; 1$	$5.2^{+0.5}_{-0.3}$	γ, p, α	13, 21, 27, 30, 31, 37, 44, 52, 70, 72, 73, 74, 85, 91
16.58	$2^-; 1$	300	γ, p, α	21, 27, 29, 30, 44, 52
17.23	$1^-; 1$	1150	γ, p, α	27, 29, 30, 37
17.76 ± 20	$0^+; 1$	80 ± 20	p, α	13, 27, 29, 91
18.13	$(1^+; 0)$	600 ± 100	γ, p	27, 44
(18.27 ± 50)	$(4^-; 0)$	280 ± 50		31
18.35 ± 30	$3^-; (1)$	220 ± 50	γ, p, α	27, 31, 48
18.40 ± 60	$0^-; (1)$	43	p	29, 52
(18.6 ± 100)	(3^-)	300		44
18.71	$(T = 1)$	100	p, α	27
18.80 ± 40	$2^+; 1$	100 ± 10	γ, n, p	27, 28, 29
19.25	$(1^-; 1)$	1100	γ, n, p, α	27, 28, 29, 31, 44, 46
19.40	$(2^+; 0)$	≈ 800	γ, p, α	27, 29, 44, 46, 48, 86
19.56 ± 40	$(4^-; 1)$	400 ± 60		31, 48, 52
19.71	1^+	230 ± 35	n, p	28, 29
19.91		370	p	29
20.27 ± 50		140 ± 50	n, p	28, 29, 48
20.5 ± 100	$(3^+; 1)$	180	γ, p, α	21, 27, 44, 46, 86

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

E_x in ^{12}C (MeV ± keV)	$J^\pi; T$	$\Gamma_{c.m.}$ (keV)	Decay	Reactions
20.6 ± 100	$(3^-; 1)$	200 ± 40	γ, n, p, α	27, 28, 29, 31, 46, 48
20.98		270	n, p	28
21.60 ± 60	2^+	1200 ± 150	γ, n, p, α	27, 28, 29, 44, 48, 52, 53
21.95 ± 150	$1^-; 1$	800 ± 100		44, 48
22.40 ± 40	$1^-; 1$	275 ± 40	γ, n, p	31, 48, 53, 86
22.6	$1^-; 1$	3200	γ, n, p, α	27, 38, 39, 44, 48
23.05	$(2^-; 1)$	60	n, p	28
23.52 ± 30	$1^-; 1$	230 ± 80	γ, n, p, α	13, 27, 28, 48, 86
23.92 ± 80	$(1^-; 1)$	400 ± 100	n, p	28, 48
24.43		100	n, p	28, 29
24.92		920	n, p	28
(25.24)		165	n, p	28
25.3 ± 150	$(1^-; 1)$	510 ± 100	n, p	28, 48
25.4	$(1^-; 1)$	≈ 2000	γ, n, p	27, 38, 39, 44, 50, 52, 53
25.95		≈ 400	n, d, α	15, 17, 19, 28, 48
26.8		270	n, p, d, α	17, 19, 28
27.0 ± 300	$(1^-; 1)$	1400 ± 200	γ, p	27, 48, 50, 53
27.5950 ± 2.4	$0^+; 2$	≤ 30		13, 80
27.9		≈ 350	γ, n, p, ^{3}He	5, 27, 50
28.2	$1^-; 1$	1600	γ, ^{3}He	4
28.83 ± 40		1540 ± 90	γ, p, d, ^{3}He, α	4, 19, 27, 53
29.4 ± 300		1400 ± 200	γ, n, p, t, ^{3}He	8, 27, 48
29.63 ± 50	$T = 2$	$\lesssim 200$		80
30.29 ± 30		1960 ± 150	γ, ^{3}He	4
31.16 ± 30		2100 ± 150	γ, ^{3}He	4
32.29 ± 40		1320 ± 230	γ, ^{3}He	4
33.47 ± 210		1930 ± 50	γ, ^{3}He	4
35.7 ± 700			γ, p	39
[b]				

[a] See also Tables 12.8, 12.12 and 12.14.

[a] See also reaction 2.

Astrophysical questions: (1975AU1D, 1975BA2D, 1975BE1R, 1975BR1J, 1975DE1F, 1975DE1H, 1975EN1A, 1975EN1B, 1975FA1B, 1975IB1A, 1975JA1F, 1975KI1D, 1975LA1H, 1975LO1E, 1975PR1B, 1975RA1M, 1975RY1A, 1975SC1R, 1975SC1H, 1975SC1U, 1975SC1W, 1975SN1A, 1975ST1J, 1975ST1K, 1975SU1B, 1975TA1E, 1975TA1F, 1975TA1G, 1975TO1B, 1975TR1A, 1975UL1A, 1975VL1A, 1976AU1F, 1976BE1R, 1976BE1C, 1976BO1M, 1976DE1F, 1976DE1G, 1976DE1H, 1976DW1A, 1976EP1A, 1976FI1E, 1976FU1D, 1976FU1C, 1976GA1F, 1976GI1C, 1976HI1D, 1976MA1N, 1976ME1F, 1976NO1H, 1976NO1C, 1976QU1A, 1976RE1B, 1976RO1J, 1976SI1D, 1976TO1D, 1976VA1D, 1976VI1B, 1976WA1G, 1976WO1B, 1977AR1H, 1977AU1B, 1977AU1E, 1977AU1F, 1977AU1J, 1977BE2J, 1977BU1J, 1977CA1H, 1977CA1N, 1977CA1J, 1977CA1K, 1977CL1B, 1977CL1E, 1977CO1J, 1977DE1N, 1977DI1C, 1977EN1B, 1977FI1A, 1977FR1K, 1977FU1E, 1977FU1L, 1977GE1H, 1977HA1L, 1977HA1T, 1977IB1A, 1977IT1A, 1977IV1A, 1977JO1D, 1977LA1F, 1977LA1G, 1977MA1T, 1977PA1E, 1977PA1D, 1977PR1E, 1977SC1H, 1977SI1F, 1977SN1B, 1977ST1J, 1977ST1R, 1977ST1H, 1977TH1E, 1977TI1A, 1977VO1A, 1977WA1N, 1977WA1P, 1977WI1D, 1978AL1P, 1978BO1M, 1978BU1H, 1978BU1B, 1978BY1A, 1978CL1F, 1978DE1R, 1978DI04, 1978DO1B, 1978DW1B, 1978FE1E, 1978GL1E, 1978IB1B, 1978IB1C, 1978IB1A, 1978LA1K, 1978LU1C, 1978MC1G, 1978ME1D, 1978OR1A, 1978PE1H, 1978PE1J, 1978PO1B, 1978RO1D, 1978SN1A, 1978ST1C, 1978TO1C, 1978TR1D, 1978WA1F, 1978WA1E, 1979CH1T, 1979GL1J, 1979LA1H, 1979MA2D, 1979OL1B, 1979SA1M, 1979TU1A, 1979WE1F, 1979WI1H).

Applied topics: (1975BE1U, 1975GA1E, 1976EC1B, 1976LE1Q, 1976SC1G, 1977BE2F, 1977FI1A, 1977MO1B, AN78E, 1978HE1K, 1978KE1E, 1978LE1P, 1978NA21, 1978TR1E, 1979AN1L, 1979EN1D, 1979GR1E, 1981JA1H).

Muon and neutrino capture and reactions: (1974EN10, 1974KO1H, 1974WA1C, 1975BA40, 1975BA56, 1975CH22, 1975DO1F, 1975DO10, 1975DO1D, 1975FE1B, 1975GE1E, 1975IM02, 1975KI2A, 1976DA1H, 1976DO1J, 1976HO1G, 1976SU03, 1977BA1P, 1977BO2C, 1977BR1K, 1977CA1M, 1977DO06, 1977HW01, 1977LE1K, 1977MU1A, 1977PO1B, 1977PR1B, 1977WA1F, 1977WA1G, 1978BA1G, 1978BA57, 1978BR1C, 1978DE15, 1978GU05, 1978HW1A, 1978KO31, 1978MU04, 1978PA06, 1978PA1F, 1978SE1B, 1978WU01, 1979BE1N, 1979DE01, 1979DO1C, 1979FI1E, 1979PA1J, 1979PR1D, 1979RO03, 1979RO1H, 1979TR05, 1979VE1D).

Pion capture and pion reactions (See also reactions 39 and 46.): (1973BA1M, 1974AR1E, 1974AZ1B, 1974AZ1C, 1974BO1D, 1974BO1Y, 1974CAZD, 1974GR1K, 1974LU1D, 1974SP1A, 1974ST1K, 1975AB12, 1975AL1E, 1975AM03, 1975AN1L, 1975AZ1C, 1975AZ1D, 1975BA14, 1975BA1L, 1975BA54, 1975BA1G, 1975BA66, 1975BA1P, 1975BA57, 1975BA1W, 1975BH03, 1975BO1B, 1975BR1H, 1975BR1D, 1975BR1K, 1975BU1E, 1975BU1A, 1975BU1G, 1975CA17, 1975CA31, 1975CE03, 1975CO06, 1975CO1G, 1975DR02, 1975DU06, 1975DU1A, 1975EI1A, 1975EI1B, 1975ER08, 1975FU07, 1975GA08, 1975GI09, 1975GI13, 1975HE06, 1975HU1D, 1975HU13, 1975IN1B, 1975JU02, 1975KA03, 1975KA1G, 1975KI1E, 1975KO1F, 1975KO25, 1975KU02, 1975LO1F, 1975MA1M, 1975NA08, 1975NA16, 1975NI1B, 1975PA1D, 1975PE1C,

1975RA1N, 1975RO11, 1975RO1G, 1975SC1V, 1975SC1N, 1975SH1D, 1975SH17, 1975SI10, 1975SI18, 1975SI1E, 1975ST1G, 1975TA1C, 1975TO10, 1975VA1D, 1975VE05, 1975VO1D, 1975WA1H, 1975WA1J, 1976AL1J, 1976AL1K, 1976AS1B, 1976AZ1A, 1976BA1V, 1976BA1X, 1976BA47, 1976BAYQ, 1976BAYR, 1976BE39, 1976BE1K, 1976BO1P, 1976BO1K, 1976BR1M, 1976BR1N, 1976BU1F, 1976BU1D, 1976CA01, 1976CA23, 1976CA1H, 1976CH1H, 1976CHZW, 1976CO10, 1976CO13, 1976DO1D, 1976DO06, 1976DRZS, 1976DU1B, 1976DU1F, 1976ED1A, 1976EI1B, 1976EN02, 1976FR14, 1976FU1E, 1976GI1E, 1976GU17, 1976IV03, 1976KA02, 1976KI1E, 1976KI1H, 1976KI07, 1976LE02, 1976LE1P, 1976LI24, 1976LI26, 1976LO1C, 1976MA48, 1976MAYT, 1976MI14, 1976NA16, 1976NI02, 1976OS03, 1976PI1B, 1976PI12, 1976RO14, 1976SR1A, 1976TA1E, 1976TH09, 1976TR1A, 1976VA1F, 1976WA10, 1976WA07, 1977AB09, 1977AH04, 1977AL15, 1977AL1C, 1977AL1V, 1977AN1H, 1977AN1J, 1977AN1K, 1977AP1A, 1977AP1B, 1977AR1F, 1977AR1J, 1977AU1G, 1977AU1H, 1977BA60, 1977BA2H, 1977BA51, 1977BA1Q, 1977BA2G, 1977BA2Q, 1977BA2R, 1977BA73, 1977BA2V, 1977BE2K, 1977BE35, 1977BE69, 1977BEZY, 1977BO05, 1977BO1X, 1977BO1E, 1977BO1Y, 1976BR1L, 1977BU25, 1977BU1K, 1977BU1L, 1977CH1N, 1977CO1N, 1977DI03, 1977DI1B, 1977DO06, 1977DR1E, 1977DY02, 1977EI1A, 1977ER1A, 1977ER1B, 1977FR09, 1977FU11, 1977FY1A, 1977GE04, 1977GE1D, 1977GI06, 1977GI14, 1977GR1G, 1977HA1U, 1977HA1V, 1977HI1E, 1977HO1B, 1977JA1G, 1977KA1N, 1977KI1L, 1977KO25, 1977KU1G, 1977LE1H, 1977LE1G, 1977LI11, 1977MA1R, 1977MA1M, 1977MA2C, 1977MA35, 1977MC1E, 1977MO12, 1977NA02, 1977NA1K, 1977NA1L, 1977NA1M, 1977OH1B, 1977PI1D, 1977PI02, 1977PI1E, 1977PI09, 1977PR1G, 1977RA1A, 1977RO21, 1977RO25, 1977SC1F, 1977SE13, 1977SH14, 1977SI01, 1977SM06, 1977SP1B, 1977ST09, 1977ST1G, 1977TH1F, 1977VI1A, 1977WA1H, 1977WE1J, 1977WI1E, 1978AL1N, 1978AM01, 1978AN1E, 1978AN2B, 1978AN1F, 1978AN1G, 1978AN1H, 1978AR08, 1978AR18, 1978AZ1C, 1978AZ1D, 1978AZ02, 1978BA50, 1978BA1Y, 1978BA1T, 1978BE1N, 1978BE64, 1978BE1X, 1978BE27, 1978BH01, 1978BL1B, 1978BO01, 1978BO1P, 1978BO25, 1978BO26, 1978BR1J, 1978BR1K, 1978BU1J, 1978BU1L, 1978CH1V, 1978CO02, 1978CO16, 1978DO07, 1978DY01, 1978EI1A, 1978EP01, 1978EP02, 1978ER1C, 1978FU04, 1978FU09, 1978GA1D, 1978GA11, 1978GI01, 1978GI05, 1978GI14, 1978HA34, 1978HA1V, 1978HA37, 1978HI03, 1978JA09, 1978JA1G, 1978JO03, 1978JO09, 1978KI08, 1978KL06, 1978KO34, 1978KW1A, 1978LA1L, 1978LA08, 1978LI1E, 1978MA1T, 1978MA1J, 1978ME05, 1978ME1F, 1978MI02, 1978MO01, 1978MO25, 1978MO23, 1978NA1N, 1978PA14, 1978PE1D, 1978PE11, 1978PE12, 1978RO1J, 1978RO16, 1978RO1H, 1978SC1G, 1978SC1H, 1978SE07, 1978SI1E, 1978SI1D, 1978SP06, 1978TA1L, 1978TH1C, 1978TH1D, 1978VL1B, 1978WA1B, 1978WE1H, 1978WO11, 1978YO1D, 1978YO02, 1979AL1T, 1979AL1U, 1979AM1D, 1979AN1J, 1979AN1K, 1979AR1H, 1979AR1K, 1979BA04, 1979BA16, 1979BA2G, 1979BA1M, 1979BA2H, 1979BE1N, 1979BL1H, 1979BO1B, 1979BO1Y, 1979BO1U, 1979BO12, 1979BO23, 1979BO2D, 1979BO2E, 1979BOZW, 1979BR1F, 1979BU1K, 1979BU1D, 1979CE1A, 1979CH1P, 1979CH06, 1979CH05, 1979CH1U, 1979CH1V, 1979CH1W, 1979CO1L, 1979CO1M, 1979CO1H, 1979CO1N, 1979CR1E, 1979DA1J, 1979DA1L, 1979DE06, 1979DE1U, 1979DI1A, 1979DY02, 1979EI1A, 1979EL1E, 1979EN1E, 1979GA08, 1979GU01, 1979GY1A, 1979GY1B, 1979HA07, 1979HO1F, 1979HU02, 1979JA1K, 1979KL1D, 1979KL1E, 1979KL1F, 1979KL1G, 1979KN1E, 1979KU1J, 1979LA02, 1979LA1M, 1979LU1C, 1979MA07, 1979MA1P, 1979MA2H, 1979MA2J, 1979MI06, 1979MIZV, 1979MIZX,

1979MO1V, 1979MO1W, 1979NA1M, 1979NA1N, 1979NA1P, 1979NA1E, 1979OH1A, 1979OH1C, 1979PEZX, 1979PI1G, 1979PR1D, 1979RE1A, 1979SA1P, 1979SC02, 1979SC1J, 1979SH1M, 1979SH1N, 1979SH1P, 1979SH1Q, 1979SI1F, 1979SO1D, 1979ST02, 1979ST1N, 1979STZO, 1979TA1J, 1979WA1J, 1979WI1A, 1979WI1J, 1979WU07, 1979ZI1C).

Reactions involving antiprotons: (1977RO23, 1977WE1E, 1978YO02).

Kaon capture and reactions involving kaons and other mesons: (1974BO1Y, 1975DU1A, 1975PN1A, 1975PO1C, 1975TA1C, 1975VA1C, 1976AR1K, 1976BO1P, 1976BO1K, 1976BR1G, 1976DE1D, 1976EI1A, 1976KI1E, 1976KI1G, 1977BO2C, 1977CO04, 1977DO11, 1977JU1C, 1977PO1A, 1977TH1D, 1978AL04, 1978AT01, 1978BA1W, 1978BO1P, 1978BR1G, 1978DA1A, 1978EP02, 1978HE02, 1978KW1A, 1978PO1A, 1978SC1G, 1978TH1E, 1979BE2G, 1979BE2H, 1979BO12, 1979DA1K, 1979DO05, 1979GA1D, 1979KI1C, 1979MA2F, 1979MA2G, 1979PO1D, 1979WA1J).

Other topics: (1974BO1Y, 1974ZU1A, 1975BE48, 1975BL1E, 1975CA1N, 1975FA03, 1975FR06, 1975GA1G, 1975HO1E, 1975KO1C, 1975LE1E, 1975MU13, 1975PN1A, 1975PO1C, 1975SC1M, 1975SO04, 1975SO07, 1976BR1G, 1976DA1E, 1976ES1A, 1976GL09, 1976HA09, 1976IR1B, 1976KH04, 1976KI01, 1976KI16, 1976LO1D, 1976MA04, 1976SA16, 1976ST13, 1976VA1C, 1977BO2C, 1977CA02, 1977DE16, 1977JE04, 1977KI1K, 1977MO1Q, 1977NA13, 1977PO1A, 1977SA17, 1978BA31, 1978BI14, 1978DA1A, 1978HA1U, 1978KW1A, 1978LA1D, 1978LI1D, 1978MC04, 1978ON01, 1978OS01, 1978OS1B, 1978PO1A, 1978RO17, 1978SH04, 1978UL02, 1979CH06, 1979DA1K, 1979GA1D, 1979HE1F, 1979HE1G, 1979KI1C, 1979MA2F, 1979OS02, 1979QU1A).

Ground state of ^{12}*C:* (1974DE1E, 1974EN10, 1975BE31, 1975CA1N, 1975FR05, 1975FR06, 1975KA29, 1975KU1N, 1975LE05, 1975LE1E, 1975MA50, 1975MU13, 1976BE1G, 1976FU06, 1976GA16, 1976GI11, 1976KI16, 1976SR1A, 1977AN21, 1977BE49, 1977FI12, 1977GR08, 1977JE04, 1977MA35, 1977MA1Y, 1977MY1A, 1977NO07, 1977PA25, 1977SA17, 1977TH03, 1978AN07, 1978BE56, 1978BI14, 1978GO1K, 1978HE1D, 1978MU04, 1978NA07, 1978NE03, 1978ON01, 1978RO17, 1978SM02, 1978SV01, 1978TA09, 1978UE1B, 1978UL02, 1978ZA1D, 1979GO1P, 1979PO03, 1979TA1K).

$$R_{\rm rms} = 2.467 \pm 0.020 \text{ fm}$$ (1979FI1E; from muonic X-rays);

See also (1979BE1N) and reaction 44.

1. (a) ^{6}Li(^{6}Li, n)^{11}C	$Q_{\rm m} = 9.453$	$E_{\rm b} = 28.175$
(b) ^{6}Li(^{6}Li, p)^{11}B	$Q_{\rm m} = 12.218$	
(c) ^{6}Li(^{6}Li, d)^{10}B	$Q_{\rm m} = 2.987$	
(d) ^{6}Li(^{6}Li, α)^{8}Be	$Q_{\rm m} = 20.808$	
(e) ^{6}Li(^{6}Li, nα)^{7}Be	$Q_{\rm m} = 1.908$	

(f) ^{6}Li(^{6}Li, pα)^{7}Li $\quad Q_m = 3.552$

(g) ^{6}Li(^{6}Li, 2α)^{4}He $\quad Q_m = 20.900$

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) (reactions (e), (f) and (c)) 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). The α_0 yield shows a broad peak at $E(^6\text{Li}) \approx 10$ MeV (1970FR06: $E(^6\text{Li}) = 4$ to 24 MeV). The yield of $^6\text{Li} + {}^6\text{Li} \rightarrow 3\alpha$ (reaction (g)) for $E(^6\text{Li}) = 4$ to 20 MeV is dominated by a broad resonance ($\Gamma = 5$ MeV) at the Coulomb barrier which is consistent with the formation of a quasimolecular state ^{6}Li + ^{6}Li with $\tau \approx 10^{-21}$ sec (1970FR06). A multiparameter coincidence study of reaction (g) for $E(^6\text{Li}) = 2$ to 13 MeV shows the importance of direct interactions: the data were fitted assuming an (α + d) cluster structure for ^{6}Li and an interaction potential acting only between the two deuterons (1971GA21, 1972GA32). The cross section for reaction (g) rises rapidly for $E(^6\text{Li}) = 1.0$ to 5.5 MeV. Thermonuclear reaction rates have been calculated for kT values of 10 to 1000 keV (1978NO1E). Cross sections for reaction (e) are reported at $E(^6\text{Li}) = 1.6$, 3.5 and 5.0 MeV (1977RU06). See also (1975NO1C, 1976FI1F), ^{7}Li, ^{7}Be, ^{8}Be and ^{10}B in (1979AJ01), ^{11}B and ^{11}C here and (1975AJ02).

2. (a) ^{6}Li(^{6}Li, ^{6}He)^{6}Be $\quad Q_m = -7.795 \quad E_b = 28.175$

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

The elastic scattering (reaction (b)) follows the Mott formula at low energies [$\lesssim$ 4.0 MeV] (1966PI02: $E(^6\text{Li}) = 3.2$ to 7.0 MeV). A broad structure is observed in the excitation functions [$\theta_{\text{c.m.}} = 60°$ and $90°$] at $E(^6\text{Li}) \approx 13$ MeV (1973GR34) and ≈ 26 MeV [$\Gamma \approx 7$ MeV] (1971FO08: $\theta_{\text{c.m.}} = 90°$; $E(^6\text{Li})$ to 34 MeV). The elastic scattering appears to be dominated by absorption (1971FO08). Excitation functions for the transitions to $^6\text{Li}^*_{3.56} + {}^6\text{Li}^*_{3.56}$ have been measured for $E(^6\text{Li}) = 28.0$ to 33.0 MeV (1970NA02: $\theta_{\text{c.m.}} = 90°$) and 28.0 to 36.0 MeV (1973WH02, 1974WH01, 1974WH02; $\theta_{\text{c.m.}} = 88°$) [also ratio of $^6\text{Li}^*_{3.56} + {}^6\text{Li}^*_{3.56}$ to formation of $^6\text{He}_{\text{g.s.}} + {}^6\text{Be}_{\text{g.s.}}$ at $E(^6\text{Li}) = 28$, 32, 34 and 36 MeV]. The latter results have been compared with calculations using microscopic DWBA analysis. See also ^{6}He and ^{6}Li in (1979AJ01).

3. ^{6}Li(^{7}Li, n)^{12}C $\quad Q_m = 20.924$

See (1975AJ02).

4. ^{9}Be(^{3}He, γ)^{12}C $\quad Q_m = 26.2793$

Excitation functions and angular distribution studies have been carried out by (1972BL17: $E(^3\text{He})$ = 1.0 to 6.0 MeV; γ_0, γ_1, γ_2), (1972LI29: 1.5 to 11 MeV; γ_0, γ_1, γ_2, γ_3), (1964BL12: 2 to 4.5 MeV; γ_0, γ_1) and (1974SH01: 3 to 21 MeV (γ_2), to 24 MeV (γ_0), to 26 MeV (γ_1, γ_3)). Observed resonances are shown in Table 12.9.

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

E_x (MeV)	Width	References
4.44	$\Gamma_\gamma = 10.8 \pm 0.6$ meV	mean of values in Table 12.9
		(1975AJ02)
7.65	$\Gamma_\pi/\Gamma = (6.8 \pm 0.7) \times 10^{-6}$	(1977AL31, 1977RO05)
	$\Gamma_\pi = (60.5 \pm 3.9)$ μeV	See (1977RO05)
	Γ_{rad} [b] $/\Gamma = (4.13 \pm 0.11) \times 10^{-4}$	(1976MA46): see (1977AL31, 1977RO05) [c]
	$\Gamma = 8.9 \pm 1.2$ eV	from above values
	$= 6.9 \pm 1.9$ eV	(1979CR1D)
	$\Gamma_{\text{rad}} = 3.7 \pm 0.5$ meV	from above values
9.64	$\Gamma_{\text{rad}}/\Gamma < 4.1 \times 10^{-7}$	(1974CH32)
	$\Gamma_{\text{rad}} < 14$ meV [d]	(1974CH32)
	$\Gamma_{\gamma_0} = (3.1 \pm 0.4) \times 10^{-4}$ eV	(1967CR01)
12.71	$\Gamma_{\gamma_0}/\Gamma = (1.93 \pm 0.12) \times 10^{-2}$	(1977AD02)
	$\Gamma_{\gamma_1}/\Gamma_{\gamma_0} = 0.150 \pm 0.018$ [e]	(1977AD02)
	$\Gamma_{\gamma_0} = 0.35 \pm 0.05$ eV	(1974CE01)
	$\Gamma_{\gamma_1} = 0.053 \pm 0.010$ eV	(1974CE01, 1977AD02)
	$\Gamma = 18.1 \pm 2.8$ eV	(1977AD02)
	$\Gamma_\alpha = 17.7 \pm 2.8$ eV [f]	(1977AD02)
15.11 [g]	$\Gamma_{\gamma_0} = 37.0 \pm 1.1$ eV	(1973CH16)
	$\Gamma_{\gamma_1} = 0.92 \pm 0.36$ eV [h]	(1972AL03)
	$\Gamma_\gamma(15.11 \rightarrow 7.65) = 1.05 \pm 0.28$ eV [h]	(1972AL03)
	$\Gamma_\gamma(15.11 \rightarrow 12.71) = 0.56 \pm 0.16$ eV [h]	(1972AL03)
	$\Gamma_\gamma = 40.2 \pm 1.6$ eV [h]	(1972AL03)
	$\Gamma_\alpha/\Gamma = 0.041 \pm 0.009$ [h]	(1974BA42)
	$\Gamma_\alpha = 1.8 \pm 0.3$ eV	(1974BA42)
	$\Gamma = 42.0 \pm 1.7$ eV	from above
16.11 [i]	$\Gamma = 5.2^{+0.5}_{-0.3}$ keV	(1979DA03)
	$\Gamma_{\gamma_0}/\Gamma_{\gamma_1} = 4.6 \pm 0.7\%$	(1977AD02)
	$\Gamma_{\gamma_1}/\Gamma = (2.42 \pm 0.29) \times 10^{-3}$	(1977AD02)
	$\Gamma_\gamma(16.11 \rightarrow 9.64)/\Gamma_{\gamma_1} = 2.4 \pm 0.4\%$	(1977AD02)
	$\Gamma_\gamma(16.11 \rightarrow 12.71)/\Gamma_{\gamma_1} = 1.46 \pm 0.25\%$	(1977AD02)
	$\Gamma_{\gamma_0} = 0.58 \pm 0.12$ eV	from above
	$= 0.35 \pm 0.04$ eV	(1978FR03)
	$\Gamma_{\gamma_1} = 12.6 \pm 1.8$ eV	from above, (1977AD02)
	$\Gamma_\gamma(16.11 \rightarrow 9.64) = 0.30 \pm 0.07$ eV	from above, (1977AD02)

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

E_x (MeV)	Widths	References
	$\Gamma_\gamma(16.11 \to 12.71) = 0.19 \pm 0.04$ eV	from above, (1977AD02)

[a] See also Tables 12.9, 12.11 and 12.16.
[b] $\Gamma_{rad} \equiv \Gamma_\gamma + \Gamma_\pi$.
[c] Other values are $\Gamma_{rad}/\Gamma = (4.30 \pm 0.20) \times 10^{-4}$ (1975DA08), $\Gamma_\gamma/\Gamma = (4.02 \pm 0.28) \times 10^{-4}$ (1976OB03).
[d] Based on $\Gamma = 34 \pm 5$ keV: Table 12.7.
[e] The branching ratios for the $12.71 \to 4.44$ and $12.71 \to 0$ transitions are (13.0 ± 1.4)% and (87.0 ± 1.4)%, respectively (1977AD02). See also Table 12.9 in (1975AJ02).
[f] Assuming $\Gamma_\alpha + \Gamma_{\gamma_0} + \Gamma_{\gamma_1} = \Gamma$.
[g] See also Table 12.8 in (1968AJ02) and (1977AD02).
[h] Based on Γ_{γ_0} of (1973CH16) and on branching ratios of (1972AL03): ^{12}C*(15.11) $\to$ ^{12}C*(0, 4.4, 7.67, 12.71) are (92 ± 2), (2.3 ± 0.3), (2.6 ± 0.7) and (1.4 ± 0.4)%, respectively. In addition, an undetected branching of 1.6% to ^{12}C*(10.3) is indicated by the β-decay work (1972AL03). Other values for the transition $15.11 \to 4.4$ are 3.6 ± 0.7% (1970AH02), 3.6 ± 0.1% (1976ME25).
[i] We are grateful to E.G. Adelberger for his comments.

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

5. (a) ^{9}Be(^{3}He, n)^{11}C $Q_m = 7.558$ $E_b = 26.2793$
   (b) ^{9}Be(^{3}He, p)^{11}B $Q_m = 10.3224$
   (c) ^{9}Be(^{3}He, 2n)^{10}C $Q_m = -5.566$

Excitation functions for neutrons [and production cross sections for ^{11}C] have been measured for $E(^3\text{He}) = 1.2$ to 10 MeV for several neutron groups: see (1968AJ02, 1975AJ02) for a listing of the earlier references. 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). The total cross section for ^{11}C production shows a broad maximum, $\sigma = 113$ mb at $E(^3\text{He}) = 4.3$ MeV (1966HA21). Polarization measurements have been carried out for $E(^3\text{He}) = 2.1$ to 3.9 MeV (1971TH15: n_0, n_1, n_{2+3}): the shapes of the measured angular distributions for n_0 and n_1 show very gradual changes with energy. It is suggested that a significant direct interaction contribution is present (1971TH15). Excitation functions and angular distributions for protons (reaction (b)) have been measured for $E(^3\text{He}) = 1.0$ to 10.2 MeV for a number of proton groups: see (1968AJ02, 1975AJ02) for a listing of the earlier references and (1977LI1F: 3 to 6 MeV). No pronounced structures are reported. Polarization measurements have been carried out at $E(^3\text{He}) = 14$ MeV (1977IR01; p_0, p_1). For reaction (c) see (1974MO23; to $E(^3\text{He}) = 31$ MeV). See also (1974LO1B) and ^{11}B, ^{11}C.

6. (a) $^9\text{Be}(^3\text{He, d})^{10}\text{B}$ $\quad Q_m = 1.0918$ $\quad E_b = 26.2793$
(b) $^9\text{Be}(^3\text{He, t})^9\text{B}$ $\quad Q_m = -1.0860$

Analyzing powers have been measured at $E(^3\vec{\text{He}}) = 33.3$ MeV for nine proton groups (1976KA23). The cross section for ground state tritons (reaction (b)) increases monotonically for $E(^3\text{He}) = 2.5$ to 4.2 MeV (1969OR01: $\theta = 40°$) and then shows a broad maximum at $E(^3\text{He}) \approx 4.5$ MeV (1967EA01: $\theta = 20°$). See also (1976UE01) for continuum measurements. See also (1974LO1B) and ^{9}B, ^{10}B in (1979AJ01).

7. $^9\text{Be}(^3\text{He}, {}^3\text{He})^9\text{Be}$ $\quad E_b = 26.2793$

The elastic scattering excitation function decreases monotonically for $E(^3\text{He}) = 4.0$ to 9.0 MeV (1967EA01: $\theta = 45°$) and 15.0 to 21.0 MeV (1972MC01: $\theta_{\text{c.m.}} = 90°$). At $\theta_{\text{c.m.}} = 111°$ a slight rise is observed for $E(^3\text{He}) = 19$ to 21 MeV (1972MC01). Polarization measurements have been reported at $E(^3\text{He}) = 18$ (1972MC01), 31.4 (1971EN03) and 32.8 MeV (1975BU11; polarized ^{3}He). See also (1976RO1L) and ^{9}Be in (1979AJ01).

8. (a) $^9\text{Be}(^3\text{He}, \alpha)^8\text{Be}$ $\quad Q_m = 18.9126$ $\quad E_b = 26.2793$
(b) $^9\text{Be}(^3\text{He}, 2\alpha)^4\text{He}$ $\quad Q_m = 19.0045$

Excitation functions for the α_0 group for $E(^3\text{He}) = 2$ to 10 MeV show evidence of a complex structure at ≈ 4 MeV [$E_x \approx 29.3$ MeV] (1978BI15: see also for σ_t and α_0 in the range $2 \rightarrow 10$ MeV). Analyzing powers have been measured at $E(^3\vec{\text{He}}) = 33.3$ MeV for the groups to ^{8}Be*(16.9, 17.6, 19.2) (1976KA23). See also (1974SA1K: $1.3 \rightarrow 3.2$ MeV) and (1976RO1L). Reaction (b) has been studied for $E(^3\text{He}) = 2.9$ to 10 MeV (1975RO09, 1977GO16). See also (1979BA27), (1975AJ02) and ^{8}Be in (1979AJ01).

9. $^9\text{Be}(^3\text{He}, {}^6\text{Li})^6\text{Li}$ $\quad Q_m = -1.895$ $\quad E_b = 26.2793$

Excitation functions measured for $E(^3\text{He}) = 4$ to 10 MeV show some fluctuations: see (1975AJ02). Se also ^{6}Li in (1979AJ01).

Table 12.9: Resonances in ^{9}Be(^{3}He, γ)^{12}C

E(^{3}He) (MeV $\pm$ keV)	Res. in	E_x (MeV)	$\Gamma_{c.m.}$ (MeV)	J^π; T	References
2.55 [a]	γ_0, γ_2	28.2	1.6	1^-; 1	(1972BL17)
3.40 ± 40	γ_0, γ_2	28.83	1.54 ± 0.09		(1972LI29, 1974SH01)
5.35 ± 30	γ_1	30.29	1.96 ± 0.15		(1972LI29, 1974SH01)
6.51 ± 30	γ_0	31.16	2.10 ± 0.15		(1972LI29, 1974SH01)
8.02 ± 40	γ_1, γ_2	32.29	1.32 ± 0.23		(1974SH01)
9.60 ± 210	γ_1, γ_2	33.47	1.93 ± 0.05		(1974SH01)

[a] $\Gamma_\gamma \geq 11.8$ eV [γ_0], ≥ 4.6 eV [γ_1], ≥ 11.3 eV [γ_2], assuming $J = 1$, $\Gamma(^{3}\text{He}) = \Gamma$.

10. ^{9}Be(α, n)^{12}C $\qquad Q_m = 5.7015$

Neutron groups have been observed to ^{12}C*(0, 4.4, 7.7, 9.6, (10.1), (10.8)). Angular distributions of neutron groups have been measured at many energies in the range $E_\alpha = 1.75$ to 23 MeV: see (1968AJ02, 1975AJ02) for references.

The mean life of ^{12}C*(4.4) [$J^\pi = 2^+$] is 57^{+23}_{-17} fsec, $\Gamma_\gamma = 11.5^{+5}_{-3.2}$ meV (1966WA10). ^{12}C*(7.7) decays predominantly into ^{8}Be + α: $J^\pi = 0^+$. See also Table 12.8, (1978LO1C), (1974LO1B), (1978MC1F; applied work) and ^{13}C in (1981AJ01).

11. ^{9}Be(^{6}Li, t)^{12}C $\qquad Q_m = 10.485$

At $E(^{9}\text{Be}) = 26$ MeV, $\theta_{lab} = 10°$, the population of ^{12}C*(0, 4.4, 7.7, 9.6, 10.8, 11.8) is reported: the strongest transition is to ^{12}C*(9.6) (1975VE10). See also (1975AJ02).

12. ^{9}Be(^{9}Be, ^{6}He)^{12}C $\qquad Q_m = 5.102$

At $E(^{9}\text{Be}) = 26$ MeV, $\theta = 10°$, strong transitions are observed to ^{12}C*(4.4, 7.7, 9.6) (1975VE10).

13. ^{10}Be(^{3}He, n)^{12}C $\qquad Q_m = 19.467$

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

14. ^{10}B(d, γ)^{12}C $\qquad Q_m = 25.1875$

The (d, $\gamma\gamma$) excitation function [via the $J^\pi = 1^+$, $T = 1$ state at $E_x = 15.1$ MeV] has been measured for $E_d = 2.655$ to 2.91 MeV. The non-resonant yield of 15 MeV γ-rays is due to direct capture process or to a very broad resonance: no sharp resonances are observed corresponding to the $T = 2$ state reported in reaction 4 [$\Gamma_{d_0}\Gamma_\gamma/\Gamma \lesssim$ 0.2 eV] (1970BL09, 1974HA1G). See also (1975AJ02).

15. ^{10}B(d, n)^{11}C $\qquad Q_m = 6.466 \qquad E_b = 25.1875$

The thin-target excitation function in the forward direction in the range $E_d = 0.3$ to 4.6 MeV shows some indication of a broad resonance near $E_d = 0.9$ MeV. Above $E_d = 2.4$ MeV, the cross section increases rapidly to 210 mb/sr at 3.8 MeV, and then remains constant to 4.6 MeV (1954BU06, 1955MA76). Excitation functions have also been measured for $E_d = 3.2$ to 9.0 MeV: see (1975AJ02). The branching ratios at $90°$ for the transitions to the ground states of ^{11}C and ^{11}B[n_0/p_0] have been measured for $E_d = 1.0$ to 2.0 MeV by (1973BR24).

Polarization measurements have been carried out for $E_d = 1.20$ to 4.0 MeV: see (1975AJ02). See also (1969WO09), (1974LO1B), (1977YO1F; applied) and ^{11}C.

16. ^{10}B(d, p)^{11}B $\qquad Q_m = 9.2306 \qquad E_b = 25.1875$

Yields of protons have been measured for $E_d = 0.14$ to 12 MeV: see (1968AJ02, 1975AJ02). No clear resonance structure is observed. There is some indication that a broad resonance, corresponding to ^{12}C*(27.1) affects the p_1 and p_3 yields (1964BR1A). Upper limits for the partial widths ($p_0 \rightarrow p_3$) of the $T = 2$ state reported in reaction 4 are given by (1970BL09).

Polarization studies have been carried out for $E_d = 1.15$ to 21 MeV: see (1968AJ02, 1975AJ02). See also ^{11}B.

17. ^{10}B(d, d)^{10}B $\qquad E_b = 25.1875$

The yield of elastically scattered deuterons has been measured for $E_d = 1.0$ to 2.0 MeV: resonances at $E_d = 1.0$ and 1.9 MeV are suggested by (1969LO01). Excitation functions for the deuterons to ^{10}B*(1.74, 2.16) [J^π; $T = 0^+$; 1 and 1^+; 0, respectively] have been measured at several angles for $E_d = 4.2$ to 16 MeV: they are characterized by rather broad, slowly varying structures. The ratio $\sigma_{1.74}/\sigma_{2.15}$ varies from $0.69 \pm 0.04\%$ at $E_d = 6.5$ MeV to $0.16 \pm 0.04\%$ at $E_d = 12.0$ MeV corresponding, respectively, to isospin impurities of $\approx 2\%$ and $\approx 0.5\%$ (1974ST01). No resonance structure is observed in the elastic yield for $E_d = 14.0$ to 15.5 MeV (1974BU06). Polarization measurements are reported at $E_d = 12.5$ MeV (1975ZA08) and at 15 MeV (1974BU06). See also (1977IZ01; theor.) and ^{10}B in (1979AJ01).

18. (a) ^{10}B(d, t)^{9}B $\quad Q_m = -2.179 \quad E_b = 25.1875$

(b) ^{10}B(d, ^{3}He)^{9}Be $\quad Q_m = -1.0918$

For polarization measurements at $E_d = 15$ MeV involving ^{9}Be*(0, 2.43) and ^{9}B*(0, 2.36) see (1974LU06). See also ^{9}Be and ^{9}B in (1979AJ01).

19. (a) ^{10}B(d, α)^{8}Be $\quad Q_m = 17.8208 \quad E_b = 25.1875$

(b) ^{10}B(d, 2α)^{4}He $\quad Q_m = 17.9127$

Excitation functions have been measured for the α_0 and α_1 groups for $E_d = 0.4$ to 12 MeV [see (1968AJ02, 1975AJ02)] and for $E_d = 2.5$ to 4.5 MeV (1975VA04; α_0) and 0.8 to 9.0 MeV (1978BU04: α_0). Maxima in the α_0 yields are reported at $E_d = 1$, 2, 4.5 and (6) MeV. The first is attributed to an s-wave resonance corresponding to a state with $E_x \approx 26.0$ MeV, $\Gamma \approx 0.5$ MeV (1968FR07). The resonance structures at ≈ 2.0 and 4.5 MeV ($\Gamma \gtrsim 1$ MeV) may both involve the isoscalar giant resonance: $E_x \approx 28$ MeV, $\Gamma \approx 4$ MeV (1978BU04). No evidence for the $T = 2$ state was found in the α_0 and α_1 yield curves taken in 2 keV steps for $27.35 < E_x < 27.65$ MeV (1970BL09). For yields of the α particles to ^{8}Be*(17.6, 18.1) see (1970CA12) [also discussed in ^{8}Be (1959AJ76)]. Reaction (b) has been studied for $E_d = 2.7$ to 5.0 MeV: see (1975RO09, 1975VA04, 1977GO16) and at $E_d = 0.36$ MeV (1977NO10). The latter work suggests that a 3^- and a 4^+ state in ^{12}C contribute dominantly to the sequential decay. See also (1976GRZR) and (1979SE04; theor.).

20. ^{10}B(d, ^{6}Li)^{6}Li $\quad Q_m = -2.987 \quad E_b = 25.1875$

See (1975AJ02) and ^{6}Li in (1979AJ01).

21. (a) ^{10}B(^{3}He, p)^{12}C $\quad Q_m = 19.6940$

(b) ^{10}B(^{3}He, pα)^{8}Be $\quad Q_m = 12.3273$

(c) ^{10}B(^{3}He, 2p)^{11}B $\quad Q_m = 3.7371$

(d) ^{10}B(^{3}He, pn)^{11}C $\quad Q_m = 0.973$

Proton groups observed by (1958MO99, 1959AL96, 1962BR10) are displayed in Table 12.10. Angular distributions of many of these groups have been measured for $E(^{3}\text{He}) = 1.4$ to 14 MeV: see (1968AJ02).

From studies of ^{10}B(^{3}He, pα)^{8}Be it is determined that ^{12}C*(7.7, 9.6, 10.8, 14.1, 16.1) have natural parity $\pi = (-1)^J$, and that ^{12}C*(11.8, 12.7, 13.4), which decay only to ^{8}Be*(2.9) and not

Table 12.10: ^{12}C states from ^{10}B(^{3}He, p)^{12}C

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

[a] (1962BR10): excitation energies based on $Q_0 = 19.693$ MeV and P$_0$ $\alpha = 5.3056$ MeV.
[b] (1970BO39).
[c] (1962BR10).
[d] (1966WA16).
[e] See also Table 12.8.
[f] Branching ratios to ^{12}C*(0, 4.4) are 85 ± 4 and 15 ± 4%, respectively (1972AL03). See also Table 12.8.
[g] Proton-α correlations require $J \geq 2$ (1966WA16).
[h] (1965AL1B): $\Gamma_\alpha/\Gamma < 0.5$.
[i] Branching ratios to ^{12}C*(0, 4.4, 7.7, 12.7) are, respectively, (92 ± 2)%, (2.3 ± 0.9)%, (2.6 ± 0.7)%, (1.4 ± 0.4)% (1972AL03): see also Table 12.8.
[j] (1968KR02).
[k] (1965AL1B).
[l] (1977AD02): see, however, Table 12.8.

to the ground state, have unnatural parity: see Tables 12.8 and 12.10 and (1968AJ02). ^{12}C*(12.7) decays also by γ-emission. The charge dependent matrix element connecting ^{12}C*(12.7, 15.1) is 110 ± 30 keV (1976AD03, 1977AD02): see also reactions 22, 44, 50, 73, 74 and 86. ^{12}C*(16.11, 16.58) 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 $J^{\pi} = 2^{-}$ for the latter. 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). Table 12.8 summarizes the decay parameters of some of the excited states of ^{12}C.

Reactions (c) and (d) have been studied by (1970BO39). The latter, at $E(^{3}\text{He}) = 11$ MeV, appears to proceed via a state in ^{12}C at $E_{\text{x}} = 20.5 \pm 0.1$ MeV, which is suggested to be $J^{\pi} = 3^{+}$, $T = 1$. The relative intensities of the decays of ^{12}C states with $20 < E_{\text{x}} < 25$ MeV via channels (c) and (d) is estimated. The α_0 decay is very small, consistent with the expected population of $T = 1$ states (1970BO39). See also (1975NA1C), (1975MA21), (1976EP1A; astrophys.), ^{8}Be in (1979AJ01) and ^{13}N in (1981AJ01).

22. ^{10}B(α, d)^{12}C $\quad Q_{\text{m}} = 1.3408$

Angular distributions of d_0 and d_1 have been measured at $E_{\alpha} = 15.1$ to 25.2 MeV (1975VA19). The relative populations of ^{12}C*(12.71, 15.11) [both 1^{+}; the latter isospin forbidden] leads to values of $\lesssim 260$ keV (1975SP04), 285 ± 30 keV (1977LI02) for the charge dependent matrix element between these two states: see also reactions 21, 44, 50, 73, 74 and 86. See also (1976GU1B, 1976LE1K). (1978ZE03; theor.) and (1975AJ02).

23. ^{10}B(^{6}Li, α)^{12}C $\quad Q_{\text{m}} = 23.714$

At $E(^{6}\text{Li}) = 4.9$ MeV angular distributions have been obtained for the α-particles to ^{12}C*(0, 4.4, 7.7, 9.6). The population of ^{12}C*(11.8, 12.7) is also reported (1966MC05), as is that of ^{12}C*(15.11) [$T = 1$] (1964CA18: $E(^{6}\text{Li}) = 3.8$ MeV): the intensity ratio $\alpha_{15.1}/\alpha_{12.7} = 3 \pm 2\%$.

24. ^{10}B(^{13}C, ^{11}B)^{12}C $\quad Q_{\text{m}} = 6.5088$

See (1975SE03, 1975SE04) and ^{11}B.

25. ^{10}B(^{14}N, ^{12}C)^{12}C $\quad Q_{\text{m}} = 14.9151$

Angular distributions involving $^{12}\text{C}^{*}_{4.4} + {}^{12}\text{C}_{\text{g.s.}}$ and $^{12}\text{C}^{*}_{4.4} + {}^{12}\text{C}^{*}_{4.4}$ have been measured at $E(^{14}\text{N}) = 22.5$ and 30 MeV (1969IS01) and 73.9 and 93.6 MeV (1977MO1A). See also (1973ST1A).

26. ^{10}B(^{16}O, ^{14}N)^{12}C $\quad Q_m = 4.4512$

Angular distributions involving $^{14}N_{g.s.} + {}^{12}C_{g.s.}$ and $^{14}N_{g.s.} + {}^{12}C^*_{4.4}$ have been measured at $E(^{16}O) = 30$ and 32.5 MeV and also at 26 MeV for the double ground state transition (1969IS01).

27. (a) ^{11}B(p, γ)^{12}C $\quad Q_m = 15.9569$
(b) ^{11}B(p, α)^{8}Be $\quad Q_m = 8.5902$ $\quad E_b = 15.9569$
(c) ^{11}B(p, α)^{4}He^{4}He $\quad Q_m = 8.6821$

In view of the complexity of the available information on these three reactions, we will first summarize the recent experimental results and then review the evidence for the parameters of ^{12}C states observed as resonances.

(a) In the range 4 MeV $< E_p <$ 14.5 MeV $\sigma(\gamma_0)$ is dominated by the giant dipole resonance at $E_p = 7.2$ MeV ($E_x = 22.6$ MeV, $\Gamma_{c.m.} = 3.2$ MeV), while the giant resonance in γ_1 occurs at $E_p \approx 10.3$ MeV ($E_x = 25.4$ MeV, $\Gamma_{c.m.} \approx 6.5$ MeV): see (1964AL20). A study of the giant dipole resonance region with polarized protons ($E_p = 6$ to 14 MeV) sets new limits on the configuration mixing in the γ_0 giant resonance (1972GL01). The E2 strength is found to be centered near $E_p = 12$ MeV: it exhausts $\gtrsim 30\%$ of the isoscalar E2 sum rule (1976MAZG, 1976MAZL). The analysis of γ_1 is more complicated: the asymmetry results are consistent either with a single $J^\pi = 2^-$ state or with interference of pairs of states such as $(1^-, 3^-)$, $(2^-, 3^-)$ and $(1^-, 2^-)$ (1972GL01). See also (1979AR1G). Measurements of differential cross sections at 90° ($E_p = 13$ to 22 MeV), of angular distributions ($E_p = 7$ and 14 to 21 MeV), and of total cross sections ($E_p = 14$ to 21 MeV) have been reported by (1972BR26). The 90° yield of γ_0, γ_1, γ_2 and γ_3 [to ^{12}C*(0, 4.4, 7.7, 9.6)] has been studied by (1977SN01): the γ_2 yield shows a peak at $E_p \approx 14.3$ MeV with a cross section $\approx 2.3\%$ that of γ_0 [in γ_0 yield, $E_{res} = 15.0$ MeV (1977SN01), 14.8 MeV (1969KE02)] and perhaps as well a low intensity structure at $E_p = 11.8$ MeV. The γ_3 yield exhibits two asymmetric peaks at $E_p = 12.5$ and 13.8 MeV ($\Gamma \approx 0.7$ and 2.5 MeV) and a weaker structure at ≈ 9.8 MeV (1977SN01). The (p$\gamma\gamma$) process [via ^{12}C*(15.1)] has been studied in the vicinity of the first two $T = 2$ states; only a non-resonant yield is observed: $(2J + 1)\Gamma_\gamma\Gamma_p/\Gamma < 0.25$ eV and < 1.5 eV, respectively for ^{12}C*(27.4, 28.6) (1977NA1F). At $E_p = 40$, 60 and 80 MeV, radiative capture is observed to a state, or a narrow group of states, at $E_x = 19.2 \pm 0.6$ MeV (1979KO05). Work on other resonances is reported below.

(b) Excitation functions have been measured for $E_p = 3.0$ to 8.0 MeV (1975BO1H), 6.53 to 7.32 MeV (1977OH1A; α_0, α_1) and 6.0 to 18.0 MeV (1977BU07; α_0). A wide resonance-like structure centered at $E_p = 13$ MeV [^{12}C*(28)] with $\Gamma \approx 6$ MeV is reported by (1977BU07): the angular distributions of α_0 show prominent back peaking. See also (1978BU1D). Polarization measurements are reported for $E_p = 2.62$ to 2.66 MeV (1975MA49: α_0).

(c) This reaction has been studied for $E_p = 35.4$ keV to 10.5 MeV. The total cross section has been measured for $E_p = 35.4$ to 1500 keV: it shows the 163 keV resonance and a broad peak centered at about 600 keV ($\sigma_{max} \approx 0.9$ b; read from Fig. 3). The 163 keV resonance has $\sigma_R = 54 \pm 6$ mb and $\Gamma^R_{c.m.} = 5.2^{+0.5}_{-0.3}$ keV, E_{res}(c.m.) $= 149.8 \pm 0.2$ keV [$E_x = 16.1067\,(5)$]. The astrophysical

Table 12.11: Resonances in ^{11}B(p, γ)^{12}C and ^{11}B(p, α)^{8}Be

Peak no.	E_p (MeV)	$\Gamma_{c.m.}$ (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)	Γ_{α_0} (keV)	Γ_{α_1} (keV)	Γ_p (keV)	^{12}C* (MeV)	$J^\pi; T$	Refs. [†]
1	0.163 [a]	$5.2^{+0.5}_{-0.3}$	5.5	152	res.	res.	(0.65)	(21.0 ± 3.3) [b]	0.290 ± 0.045	(6.3 ± 0.5)	0.0217 ± 0.0018	16.1067 ± 0.5 keV	$2^+; 1$	(1974AN19, 1979DA03)
2	0.675	300	non-res.	48 [f]	non-res.	600 [f]	< 0.4	8.0	< 0.27	150	150	16.58	$2^-; 1$	(1965SE06)
3	1.388 [l]	1150	[27] [c]	3	3.3	≈ 180	44	5	10	140	1000	17.23	$1^-; 1$	(1965SE06, 1963SY01)
4	1.98	100	non-res.	non-res.	9.0	(25)	< 0.5	< 0.5	4.6	11.4	76	17.77	$0^+; 1$	(1965SE06, 1963SY01)
5	2.37	600 ± 100		0.77 [h]								18.13	$(1^+; 0)$	(1972SU08)
6	2.62	310	weak?	res.	32.4 ± 4.8	270 ± 40	< 1.5	3.2	65	177	68	18.36	$(3^-; 1)$	(1965SE06, 1963SY01)
7	2.66	43	non-res.	non-res.	non-res.	non-res.	< 0.5	< 0.5	< 1	< 5	33	18.39	0^-	(1965SE06)
8	3.01	100	non-res.	non-res.	3.4						< 10	18.71	n.π. [g]; (1)	(1965SE06)
9	3.12	100	weak	[20] [c]	non- res.	non-res.	(0.4)	2.0	< 0.2	< 1.5	97	18.81	$2^+; 1$	(1965SE06, 1975BO1H)
10	3.5	1100	[20] [c]	res.	5.2	res.	25	10	50	200	300	19.2	$(1^-; 1)$	(1965SE06, 1975BO1H)
11	3.75	(1100) [o]	non-res.	res.	7.4 ± 1.1	300 ± 40	< 3	3	20	450	450	19.39	$(2^+; 0)$	(1965SE06, 1963SY01, 1975BO1H)
12	4.93	180	non-res.	res.	res. [p]	170 ± 40						20.47		(1963SY01, 1964AL20, 1975BO1H)
13	5.11	275	non-res.	[35] [c]	6.0 ± 0.9	non-res.						20.64	$(3^-; 1)$	(1963SY01, 1964AL20)
14	5.85	300			res.							(21.32)		(1975BO1H)
15	6.0		res.	non-res.	res.							21.5		(1964AL20, 1975BO1H)
16	6.7	500	res.	[35] [c]	res.							22.1		(1964AL20, 1975BO1H)
17	7.27 [m]	3200	120	non-res.	[q]	res.	≥ 2500 [e]					22.6	$(1^-; 1)$	(1964AL20)
18	8.3		res.	res.	res.							23.6		(1964AL20)
19	10.3	≈ 6500	[60] [c]	83								25.4	[i]	(1964AL20, 1972GL01)
20	11.76 [j]		non-res.	45 [d]	res.							26.73	(1^-) [k]	(1964AL20, 1977SN01)
21	12.5 [n]	≈ 700	21 [d]	non-res.								27.4		(1967FE04, 1977SN01)
22	13.0	≈ 6000			res.							27.9		(1977SN01)
23	13.09		19 [d]	38 [d]								27.94		(1964AL20, 1967FE04)
24	13.8 [n]	≈ 2500	non-res.	25 [d]								28.6		(1967FE04, 1977SN01)
25	14.3 [j]		16 [d]	non-res.								29.0		(1967FE04, 1977SN01)
26	14.8	broad	res.									29.5		(1969KE02, 1977SN01)

[†] See also other references in Table 12.12 (1975AJ02).

[a] $E_{\rm res}$(c.m.) $= 149.8 \pm 0.2$ keV, $\Gamma_{\rm c.m.} = 5.2^{+0.5}_{-0.3}$ keV (1979DA03).

[b] 97% of the value of Γ_γ reported by (1974AN19) [21.7 ± 3.3 eV] to take into account the branching ratios; see however, Table 12.8.

[c] Estimated from graph (1964AL20).

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

[e] Assuming a single resonance (1961GO13).

[f] (1953BE61, 1953HU29).

[g] n.$\pi.$ = natural parity.

[h] Resonance in yield of 15.1 MeV γ-rays; $(2J+1)\Gamma_\gamma \geq 2.8 \pm 0.6$ eV (1972SU08).

[i] See text (1972GL01).

[j] Resonant in γ_2 (1977SN01).

[k] See (1970KO27).

[l] (1975KR1E) suggest 2^- for ^{12}C*(17.23).

[m] (1977OH1A): $J^\pi = (3^-)$. See also (1974KA1J, 1977FU09).

[n] Resonant in γ_3 (1977SN01).

[o] $\Gamma = 780$ keV (1975BO1H: prelim.).

[p] (1975BO1H).

[q] (1975BO1H; prelim.) report resonances in α_0 at $E_{\rm p} = 7.0$, 7.2 and 7.5 MeV, the latter with $\Gamma = 0.2$ MeV.

S-factor and the reaction rate $\langle \sigma\nu \rangle$ have been calculated. The values of $\langle \sigma\nu \rangle$ obtained in this work suggest that the ^{11}B(p, 3α) reaction may be a poorer candidate for CTR than previously thought (1979DA03). At higher energy the reaction proceeds predominantly by sequential two-body decays via ^{8}Be*(0, 2.9): see ^{8}Be in (1979AJ01), ^{12}C [reaction 25] in (1975AJ02) and (1974KA1J, 1975KR1E, 1975VA04, 1977FU09, 1977GR10, 1977OH1A). Contributions from ^{12}C*(23.0, 23.6, 25.4) are also reported (1975VA04).

See also (1976BO08, 1977AV01: spallation), (1977MC1C, 1977TR1E, 1978ZI1A: applications), (1974LO1B, 1976GL1E, 1979BL1J, 1979SN1A) and (1976GA1K, 1977GA1H, 1978GA13, 1979RAZW; theor.).

The parameters of the observed resonances are displayed in Table 12.11. The following summarizes the information on the low-lying resonances: for a full list of references see (1968AJ02).

$E_{\rm p} = 0.16$ *MeV:* [^{12}C*(16.11)]. This is the $J^{\pi} = 2^{+}$; $T = 1$ analog of the first excited states of ^{12}B and ^{12}N. The γ-decay is to ^{12}C*(0, 4.4, 9.6), and also ^{12}C*(12.71) [see Table 12.8]: the angular distribution of γ_3, together with the known α-decay of ^{12}C*(9.6), fix $J^{\pi} = 3^{-}$ for the latter (1961CA13). A new measurement of the (p, γ) and (p, α) resonant cross sections yields 125 ± 16 μb and 38.5 ± 3.2 mb, respectively, based on $\Gamma_{\rm c.m.} = 6.7$ keV. Γ_{γ} and $\Gamma_{\rm p}$ for ^{12}C*(16.11) are then 21.7 ± 3.3 eV and 21.7 ± 1.8 eV, respectively (1974AN19). (1977AD02) report $\Gamma_{\gamma_0} = 0.75$, $\Gamma_{\gamma_1} = 16.2$, and $\Gamma_{\gamma_7} = 0.24$ eV: see, however, Table 12.8.

$E_{\rm p} = 0.67$ *MeV:* [^{12}C*(16.58)]. The proton width [$\Gamma_{\rm p} \approx 150$ keV] indicates s-wave protons and therefore $J^{\pi} = 1^{-}$ or 2^{-}. This is supported by the near isotropy of the two resonant exit channels, α_1 and γ_1. The α_1 cross section indicates $2J + 1 \geq 5$: therefore $J^{\pi} = 2^{-}$. [This is consistent with the results of an $\alpha - \alpha$ correlation study via ^{8}Be*(2.9) (1972TR07).] The γ_1 E1 transition has $|M|^2 \approx 0.1$ W.u., suggesting $T = 1$ (1957DE11, 1965SE06).

$E_{\rm p} = 1.4$ *MeV:* [^{12}C*(17.23)]. $(2J + 1)\Gamma_{\gamma_0} \geq 115$ eV. This indicates $J^{\pi} = 1^{-}$, with $T = 1$ most probable (1965SE06). $J^{\pi} = 1^{-}$ is also required to account for the interference at lower energies in α_0 and γ_0 [see (1957DE11)] and is consistent with the $\alpha - \alpha$ correlation results of (1972TR07). Two solutions for $\Gamma_{\rm p}$ are possible; the larger (chosen for Table 12.11) is favored by elastic scattering data (1965SE06). See, however, (1975KR1E).

$E_{\rm p} = 2.0$ *MeV:* [^{12}C*(17.8)]. The resonance in the yield of α_0 requires natural parity, the small α-widths suggest $T = 1$. For $J^{\pi} = 1^{-}$ or 3^{-} the small γ-widths would be surprising; $J^{\pi} = 2^{+}$ would lead to a larger anomaly than is observed. J^{π} is then 0^{+}, $T = 1$ (1965SE06).

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

$E_{\rm p} = 2.62$ *MeV:* [^{12}C*(18.35)]. The resonance for α_0 requires natural parity; the presence of a large P_4 term in the angular distribution requires $J \geq 2$ and $l_{\rm p} \geq 2$. The assignment $J^{\pi} = 3^{-}$ is consistent with the data (1965SE06, 1972CH35, 1972VO01, 1974GO21).

$E_{\rm p} = 2.66$ *MeV:* [^{12}C*(18.40)] is not seen here: see ^{11}B(p, p).

$E_{\rm p} = 3.12$ *MeV:* [^{12}C*(18.80)]. The angular distribution of γ_0 indicates E2 radiation, $J^{\pi} = 2^{+}$. This assignment is supported by the angular correlation in the cascade γ_1 and by the behavior of $\sigma(\alpha_0)$; $T = 1$ is suggested by the small Γ_{α} (1965SE06).

Table 12.12: Reduced widths of certain states in ^{12}B and ^{12}C [a]

$E_x(^{12}B)$	$E_x(^{12}C)$	J^π	S(d, p) [b]	$S(^3$He, d) [c]	S(p, d) [d]	$\frac{\gamma^2_{\lambda_n}}{2\gamma^2_{\lambda_p}}$
	0	0^+		6.09	0.70	
	4.44	2^+		1.41	0.99	
	12.71	1^+		0.86	0.61	
0 [e]	15.11 [e]	1^+	0.69	0.76	1.71	
0.95	16.11	2^+	0.55	0.56	3.18	
1.67	16.58	2^-	0.57			0.68
2.62	17.23	1^-	0.75			0.70
2.72	17.76	0^+	0.21			0.93
3.39	18.35	3^-	0.58			0.99
3.76	18.80	2^+				0.93 [f]

[a] See also Table 12.13 in (1975AJ02) and p. $494-495$ of (1977AD02).
[b] (1971MO14).
[c] ^{11}B(^{3}He, d)^{12}C: (1969MI15); $E(^3\text{He}) = 12$ and 18 MeV. See (1977AD02).
[d] ^{13}C(p, d)^{12}C: (1970SC02; $E_p = 50$ MeV) and (1968TA08; $E_p = 54.9$ MeV). See (1977AD02).
[e] This state and the states listed below have $T = 1$.
[f] See discussion on p. 2196 of (1971MO14).

The structure near $E_p = 3.5 - 3.7$ MeV [^{12}C*(19.2, 19.4)] seems to require at least two levels. The large Γ_{γ_0} requires that one be $J^\pi = 1^-$, $T = 1$ and interference terms in $\sigma(\alpha_0)$ require the other to have even spin and even parity: $J^\pi = 2^+$; $T = 0$ is favored (1963SY01, 1965SE06). Resonances at $E_p = 4.93$ and 5.11 MeV, seen in $\sigma(\gamma_1)$ (1955BA22) also appear in $\sigma(\alpha_1)$, but not in $\sigma(\alpha_0)$. Angular distributions suggest $J^\pi = 2^+$ or 3^- for the latter [^{12}C*(20.64)]; the strength of γ_1 and absence of γ_0 favors $J^\pi = 3^-$, $T = 1$ (1963SY01).

The first seven $T = 1$ states in ^{12}B and ^{12}C have been identified by comparing reduced proton widths obtained for this reaction and reduced widths obtained from the (d, p) and (d, n) reactions: see Table 12.12 (1971MO14, 1974AN19). See also (1977AD02).

28. ^{11}B(p, n)^{11}C $\qquad Q_m = -2.764 \qquad E_b = 15.9569$

Excitation functions have been reported for $E_p = 2.6$ to 11.5 MeV. They are characterized by numerous peaks: see Table 12.13. The positions of these appear to correspond with ^{11}B(p, α)^{8}Be 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

Table 12.13: Anomalies and maxima in yields of ^{11}B(p, n)^{11}C and ^{11}B(p, p)^{11}B

Peak number	A		(1965OV01) [a,b]		(1955BA22) [c]		(1965SE06) [e]		B			J^π	E_x (MeV)
	E_p (MeV)	Γ_{lab} (keV)	E_p (MeV)	Res. in group(s)	E_p (MeV)	Γ_{lab} (keV)	E_p (MeV)	Γ_{lab} (keV)	E_p (MeV)	Γ_{lab} (keV)	Res. in group(s)		
1									0.67	330	p_0	2^-	16.57
2									1.4		p_0	1^-	17.23
3							1.98 [d]		2.08 ± 0.02 [g]	86 ± 20	p_0	0^+	17.77
4					2.664	48	2.66 [c,d]	46	2.6 [h]		p_0	[h]	18.40
5	3.16	100	3.16 [f]		3.15	100	3.15 [c,d]	100	3.12 [k]	110 ± 10	p_0		18.84
6	3.66	500	3.58 [f]		3.4	500	3.5 [c]	broad	[j]		p_0	2^-	19.3
7					3.78	50			3.85	400 ± 55	p_0	2^-	19.48
8	4.05	200	4.10	n_0					4.10 [k]	250 ± 35	p_0	1^+	19.71
9					4.28	100			4.35	400	p_1		19.91
10	4.70	150	4.68 [f]	n_0	4.68	200			4.7 [l]	(350)	p_0, p_1		20.24
11	5.065	180	5.07	n_0	5.13	200			5.08	365	p_0, p_1		20.60
12	5.48	300	5.50	n_0									20.98
13	6.04	560	6.01	n_0, n_1					6.05	600	p_0, p_1	≥ 4	21.48
14			6.4	n_0									21.8
15	7.29	360	7.3	n_0, n_1					7.5	200	p_0, p_3		22.63
16	7.74	65	7.73	n_0, n_1					7.8 [m]	650	$p_0 \rightarrow p_3$		23.05
17	8.25	380	8.25	n_0, n_1									(23.51)
18	(8.30)	(≤ 50)											(23.56)
19	8.65	180	8.6	n_0, n_2									23.88
20	9.0 [i]												24.2
21	9.25	110	9.25	n_0, n_2					[m]		p_0, p_1		24.43
22	9.79	1000	9.79	n_0, n_1									24.92
23	10.14	180	10.1	n_0, n_2									25.24

Table 12.13: Anomalies and maxima in yields of ^{11}B(p, n)^{11}C and ^{11}B(p, p)^{11}B (continued)

Peak number	A		(1965OV01) [a,b]		(1955BA22) [c]		(1965SE06) [e]		B				
	$E_{\rm p}$ (MeV)	$\Gamma_{\rm lab}$ (keV)	$E_{\rm p}$ (MeV)	Res. in group(s)	$E_{\rm p}$ (MeV)	$\Gamma_{\rm lab}$ (keV)	$E_{\rm p}$ (MeV)	$\Gamma_{\rm lab}$ (keV)	$E_{\rm p}$ (MeV)	$\Gamma_{\rm lab}$ (keV)	Res. in group(s)	J^π	$E_{\rm x}$ (MeV)
24	10.91	440	10.9	n_0									25.95
25	11.88	300											26.84

A: See (1968AJ02).

B: (1957DE11, 1975BO1H [prelim.], 1977MA37, 1977RI01).

[a] Widths ≈ 200 keV, except $E_{\rm p} = 6.4$ and ≥ 9.25 MeV which are wider.

[b] (p, n).

[c] (p, p′).

[d] (p, p).

[e] See also Table 12.11.

[f] (p, n) (1978VA12).

[g] (1977MA37) [polarized protons]: a broad 0^+ resonance at $E_{\rm p} = 2.39$ MeV is also suggested.

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

[i] Also resonance in $K_{\rm y}^{\rm y}(0°)$ (1976LI08).

[j] (1977RI01) suggest two resonances at $E_{\rm p} = 3.30$ and 3.50 MeV with $\Gamma_{\rm c.m.} = 700 \pm 200$ and 750 ± 200 keV and $J^\pi = 4^-$ and 1^- respectively. See also (1975BO1H).

[k] See also (1975BO1H).

[l] (1975BO1H; prelim.) also report structures in p_0 at $E_{\rm p} = 4.95$ and 5.85 MeV, both $\Gamma = 0.3$ MeV, in p_0, p_2 and p_3 at $E_{\rm p} = 6.7$ MeV, $\Gamma = 0.5$ MeV and in p_2 and p_3 at 7.0 MeV.

[m] See (1975VA04).

structure in the excitation function (1965OV01).

Polarization transfer coefficients for $\bar{n}_0$ have been measured for $E_{\bar{p}} = 7.3$ to 14.8 MeV (1976LI08) and 16.3, 21.3 and 26.5 MeV (1976HI11). The lower energy work shows a strong peak at $E_{\bar{p}} = 9$ MeV (1976LI08). (1976HI11) find that the results are not in agreement with direct reaction theory calculations using a charge-exchange effective interaction which includes both central and tensor forces. See also (1974MA07; theor.) and (1975AJ02). See also ^{11}C, (1977ME1C), (1977YO1G, 1979OV1A; applications), (1976WA1B) and (1977GA1H, 1978DE37; theor.).

29. (a) ^{11}B(p, p)^{11}B $E_b = 15.9569$

(b) ^{11}B(p, p′)^{11}B*

(c) ^{11}B(p, 2p)^{10}Be $Q_m = -11.2287$

(d) ^{11}B(p, d)^{10}B $Q_m = -9.2306$

Anomalies and maxima observed in the excitation functions of p_0 and p_1 are displayed in Table 12.13. Recent studies are reported at $E_p = 1.8$ to 3.1 MeV (1975MA49, 1976MA64; p_0), $E_{\bar{p}} = 1.9$ to 3.0 MeV (1977MA37; p_0), $E_p = 3.0$ to 5.2 MeV (1977RI01; p_0), 3 to 8 MeV (1975BO1H: prelim.; $p_0 \rightarrow p_3$), 7.5 to 10.5 MeV (1975VA04; p_0, p_1) and 19.2 to 47.4 MeV (1978NA03; σ_t).

Polarization measurements have been carried out at a number of energies for $E_p = 1.9$ to 155 MeV: see (1975AJ02). (1977MO09) have observed polarization transfer in order to study the spin-flip process at $E_{\bar{p}} = 32$ MeV: the cross section is lower than that predicted by DWBA. See also (1975MA1H, 1976PH01, 1977PH02; theor.). For reactions (c) and (d) see ^{10}Be, ^{10}B in (1979AJ01).

30. ^{11}B(d, n)^{12}C $Q_m = 13.7323$

Reported neutron groups are displayed in Table 12.14. Angular distributions have been studied in the range $0.5 < E_d < 11.8$ MeV: see (1968AJ02, 1975AJ02) for a listing of the references. See (1971MU18) for a discussion of the problems involved in comparing spectroscopic factors obtained in this reaction and in the (^{3}He, d) reaction [reaction 31]. Angular correlation studies involving ^{12}C*(4.4, 15.1) have been carried out at many energies in the range $0.7 < E_d < 6.3$ MeV.

In the range $E_d = 1.0$ to 5.5 MeV, two slow neutron thresholds are observed at 1.627 ± 0.004 MeV ($E_x = 15.109 \pm 0.005$ MeV) and near 4.1 MeV (broad; $E_x = 17.2$ MeV) (1955MA76). At the lower threshold, 15.1 MeV γ-rays are observed: $E_d = 1.633 \pm 0.003$ MeV, $\Gamma < 2$ keV (1958KA31) [$E_x = 15.110 \pm 0.003$ 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

Table 12.14: States in ^{12}C from ^{11}B(d, n) and ^{11}B(^{3}He, d)

Peak number	E_x (MeV ± keV)	$J^\pi; T$	Γ_{lab} [a] (keV)	l_p [b]	l [c]	S_{rel} [d]	S_{rel} [e]	S_{rel} [f]	S_{rel} [g]	S_{rel} [h]	S_{rel} [i]	S_{rel} [j]	S_{rel} [k]
1	g.s.	$0^+; 0$		1	1	8.0 ± 2.6	3.30	5.4		5.8 ± 0.6	7.1 ± 1.5		
2	4.44	$2^+; 0$		1	1	3.1 ± 0.7	1.53	0.78	1.23 ± 0.20	2.2 ± 0.3	1.64 ± 0.17		
3	7.65	$0^+; 0$			1	< 0.5		0.078	0.08 ± 0.02				
4	9.629 ± 10 [l]	$3^-; 0$		2	2	0.73 ± 0.09	0.29	0.28	0.45 ± 0.08	0.35 ± 0.1	0.35	0.155 ± 0.01	0.191 ± 0.01
5	10.84 ± 20 [m]	$1^-; 0$	330 ± 30	0	0	0.13 ± 0.08		1.1	0.13 ± 0.02	0.17 ± 0.02	0.22 ± 0.10	0.038 ± 0.01	0.047 ± 0.01
				2		0.5 ± 0.2			$\leq 0.14 \pm 0.10$				
6	11.16 ± 50 [n]	$(2^+); 0$	550 ± 100		(1)			0.14					
7	11.82 ± 20 [m]	$2^-; 0$	300 ± 30	0	2	0.13 ± 0.03		0.17	0.11 ± 0.02	0.11 ± 0.04	0.20 ± 0.1	0.11 ± 0.01	0.073 ± 0.03
				2		0.5 ± 0.2			$\leq 0.28 \pm 0.10$				
8	12.70 ± 10 [m]	$1^+; 0$		1	1	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$	$\equiv 1$ [s]	$\equiv 1$	$\equiv 1$	$\equiv 1$
9	13.38 ± 20 [m]	$(2^-); 0$	500 ± 80		((0))								
10	(14.71 ± 10) [m,o]		< 15		0 [g,o]				0.02 ± 0.01 [o,r]				
11	15.11	$1^+; 1$		1	1	0.63 ± 0.04 [p]	1.58	0.92	1.50 ± 0.20	[s]		0.87 ± 0.05	0.89 ± 0.05
12	16.11	$2^+; 1$		1	1	0.27 ± 0.05 [p] [q]		1.1	1.55 ± 0.50			0.58 ± 0.04	0.65 ± 0.04
13	16.58	$2^-; 1$											
14	17.23	$1^-; 1$		> 1									
15	18.27 ± 50 [n]	$(4^-; 0)$	350 ± 50		(2)								
16	18.36	$(3^-; 1)$	270 ± 50		(2)								
17	19.25	$(1^-; 1)$			(2)								
18	19.56 ± 50 [n]	$(4^-; 1)$	500 ± 80		(2)								
19	20.6	$(3^-; 0)$	250 ± 50		(2)								
20	22.40 ± 80 [n]	$(1^-; 1)$	350 ± 50		(2)								

[a] (1961HI08, 1971RE03).
[b] (d, n): see Table 12.12 in (1968AJ02).
[c] (^{3}He, d): see Table 12.13 in (1968AJ02) and (1971RE03).
[d] All S_{rel} are relative to ^{12}C*(12.71); $E_d = 6$ MeV (1967FU07). See, however, (1977AD02).
[e] $E_d = 11.8$ MeV (1971MU18). See, however, (1977AD02).
[f] $E(^3\text{He}) = 44$ MeV (1971RE03): values recomputed so that they are relative to ^{12}C*(12.71). See, however, (1977AD02).
[g] $E(^3\text{He}) = 11.8$ MeV (1968BO26). Values shown are average when r (cutoff) is varied between 0 and 4 fm.
[h] $E(^3\text{He}) = 10 - 12$ MeV: deep potential, zero range, no cutoff (1969MI15).
[i] $E(^3\text{He}) = 10 - 12$ MeV: deep potential, finite range, no cutoff (1969MI15).
[j] $E(^3\text{He}) = 18$ MeV: deep potential, zero range, no cutoff (1969MI15).
[k] $E(^3\text{He}) = 18$ MeV: deep potential, finite range, no cutoff (1969MI15).
[l] Based on 7656 ± 7 keV for next lower level (1960FO01).
[m] (1961HI08).
[n] (1971RE03): (^{3}He, d).
[o] This state, reported by (1961HI08), is not seen by (1971RE03). At $E(^3\text{He}) = 44$ MeV, $\theta = 12.5°$, its yield is $< 2\%$ that of ^{12}C*(15.11). (1968BO26) report an angular distribution for ^{12}C*(14.71) but their paper does not give enough information to determine whether the group was a clearly resolved one.
[p] See also Table 12.12 (1974AN19).
[q] See (1974AN19).
[r] Assuming $J^\pi = (1)^-$.
[s] See also (1977KA1R).

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 $E_x = 9$ to 13 MeV, nor does ^{12}C*(10.3) appear to participate in this reaction (1965OL01). See also (1978GR07) and ^{13}C in (1981AJ01).

31. (a) ^{11}B(^{3}He, d)^{12}C $\qquad Q_m = 10.4634$
(b) ^{11}B(^{3}He, np)^{12}C $\qquad Q_m = 8.2388$

Observed deuteron groups are displayed in Table 12.14. Angular distributions have been measured at $E(^3\text{He}) = 5.1$ to 44 MeV [see (1975AJ02)] and at $E(^3\text{He}) = 23.2$ MeV (1977KA1R: d to ^{12}C*(12.71, 15.11)). ^{13}N*(15.1) [$T = \frac{3}{2}$] has been observed to decay to ^{12}C*(9.6, 10.8) with branching ratios of $(9.6 \pm 1.4)\%$ and $(16.4 \pm 3.6)\%$ respectively (1979AD01). See also ^{13}N in (1981AJ01).

32. ^{11}B(α, t)^{12}C $\qquad Q_m = -3.8571$

Angular distributions have been measured at five energies in the range $E_\alpha = 15.1$ to 46 MeV [see (1975AJ02)], at $E_\alpha = 25.1$ MeV (1974DM01: t_0, t_1) and at 120 MeV (1979CHZP). The (t_1, γ) angular correlations have been measured for $E_\alpha = 21.2$ to 25.0 MeV (1972EL09). See also (1976GU1B, 1976LE1K) and (1978ZE03; theor.).

33. ^{11}B(^{7}Li, ^{6}He)^{12}C $\qquad Q_m = 5.982$

See (1968ST12).

34. ^{11}B(^{14}N, ^{13}C)^{12}C $\qquad Q_m = 8.4063$

Angular distributions have been measured for the ground state transition at $E(^{14}\text{N}) = 41$, 77 and 113 MeV: they show damping of the oscillations with increasing energy (1971LI11).

35. ^{11}B(^{16}O, ^{15}N)^{12}C $\qquad Q_m = 3.8294$

Angular distributions have been measured at $E(^{16}\text{O}) = 27$, 30, 32.5, 35 and 60 MeV for the transitions $^{15}\text{N}_{\text{g.s.}} + {}^{12}\text{C}_{\text{g.s.}}$, $^{15}\text{N}^*_{6.3} + {}^{12}\text{C}_{\text{g.s.}}$, $^{15}\text{N}_{\text{g.s.}} + {}^{12}\text{C}^*_{4.4}$ and $^{15}\text{N}_{\text{g.s.}} + {}^{12}\text{C}^*_{9.6}$ (the latter at $E = 60$ MeV only) (1972SC03): at the highest energy the ratio $\theta^2/\theta^2_{\text{g.s.}}$ for the transition $^{11}\text{B}_{\text{g.s.}} + \text{p} \rightarrow {}^{12}\text{C}$ is 0.12 and 0.05, respectively for ^{12}C*(4.4, 9.6). See also (1975SC35) and (1974FL1A, 1975OS01, 1976DE08, 1977GO1D, 1977WE1H; theor.).

Table 12.15: Branching in $^{12}B(\beta^-)^{12}C$

Decay to $^{12}C^*$ (MeV)	Branch (%)	Log ft	Refs.
g.s.	97.14 ± 0.30	4.067 ± 0.002	(1978AL01) [a]
4.43891 ± 0.00031 [b]	1.276 ± 0.05		(1978AL01)
	1.283 ± 0.04	5.110 ± 0.014	Mean: see (1978AL01)
7.6544 ± 0.0021 [c]	1.5 ± 0.3 [d]	4.14 ± 0.10 [e]	
10.3 ± 0.3 [f]	0.08 ± 0.02 [g]	4.2 ± 0.2 [e]	

[a] See also (1974MC11).

[b] (1967CH19).

[c] Based on (1977WA08) for the atomic mass excess of ^{4}He and the decay energy for the breakup of this state into 3α measured by (1973BA73) [$Q = 379.6 \pm 2.0$ keV].

[d] Mean of values obtained by (1957CO59, 1963AL15).

[e] See (1966BA1A).

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

[g] Mean of values obtained by (1958CO66, 1963WI05).

36. $^{12}B(\beta^-)^{12}C$ $\qquad Q_m = 13.370$

The decay is mainly to $^{12}C_{g.s.}$; branching ratios to $^{12}C^*$(0, 4.4, 7.7, 10.3) are displayed in Table 12.15. All the observed transitions are allowed. The half-life is 20.20 ± 0.02 msec (1978AL01). See also Table 12.2 of (1968AJ02).

$^{12}C^*(7.7)$ is of particular interest for helium burning processes in stars [see (1968AJ02)]. The fact that the β-decay is allowed indicates $J^\pi = 0^+$, 1^+ or 2^+; it decays primarily by α-emission eliminating $J^\pi = 1^+$, and requiring 0^+. (1973BA73) have measured the Q of the α-decay of $^{12}C^*(7.7)$ to be 379.6 ± 2.0 keV. When this result is combined with the Q determined from accurate measurements of the E_x of $^{12}C^*(7.7)$, the "best" value is $Q = 380.1 \pm 1.1$ keV. This value, together with previously measured values of Γ_π, Γ_π/Γ and Γ_{rad}/Γ lead to $\Gamma_{rad} = 3.41 \pm 1.12$ meV and to a mean lifetime for the destruction of helium by the $[\alpha\alpha\alpha]$ process of $2.59 \times 10^{-8}\rho^2 T_9^{-3}\exp(-4.411/T^9)$ sec^{-1} (1973BA73). See, however, Table 12.8. A search for transitions to $^{12}C^*(12.7)$ has been unsuccessful (1967AL03).

(1978LE02) have measured the alignment correlation term which leads to $\alpha_-(E_0) = -(1 \pm 2)$%/MeV; (1978BR01) find $\alpha_- = +(0.24 \pm 0.44)$%/MeV. The shapes of the β-spectra of ^{12}B and ^{12}N have both been analyzed [see reaction 69]. The values for $\alpha_- - \alpha_+$ are all now in agreement with the predictions of CVC and with the absence of second class currents: see, e.g., (1977KA24, 1977SU1F, 1977WU01, 1978MO02, 1979KO12).

See also (1975MI1F, 1975ST1H, 1975SU01, 1976SU1C), (1973MIYZ, 1974AD1B, 1976BE1E, 1977GA1E, 1977RI08, 1977TE1B, 1978CA1H, 1978WE1J, 1979DO1A) and (1975BE24, 1975DO10, 1975DO1D, 1975IM02, 1975KU20, 1975MO1F, 1975RH1A, 1975WI1E, 1976CA29, 1976KH05, 1976MO1G, 1976SU09, 1976YO1D, 1977AZ02, 1977BE2A, 1977CA1M, 1977HW01, 1977KU1E,

1977MA2D, 1977OK1A, 1977WA1F, 1977YA1D, 1977YO1D, 1978BE1V, 1978BE58, 1978KU1A, 1978MO02, 1978PA06, 1978SE1B, 1978SZ07, 1979DE15, 1979PR1D, 1979SZ02; theor.).

37. ^{12}C(γ, γ)^{12}C

Resonance scattering and absorption by ^{12}C*(15.11) have been studied by many groups: see Table 12.15 in (1968AJ02) and (1970AH02, 1976ME25). The partial widths are displayed in Table 12.8. Elastic scattering to ^{12}C*(4.4, 16.1, 17.2) has also been observed. The E_x of ^{12}C*(4.4) is 4439.4 ± 1.6 keV (1977WE1C). Rayleigh scattering has been studied at $\theta = 1.02°$ for $E_\gamma = 0.4$ to 3 MeV by (1978KA1P) and nuclear Thomson scattering for $E_\gamma = 5.5$ to 7.2 MeV (1977BE32: $\theta = 140°$). At higher energies elastic scattering studies show the giant resonance peak at ≈ 24 MeV. A considerable tail is visible, extending to > 40 MeV (1959PE32). See also (1975RO1N, 1976VE06, 1977CR1C, 1977HA1W, 1979KA1Q), (1975BR1F), (1975AJ02) and reaction 38.

38. (a) ^{12}C(γ, n)^{11}C $\qquad Q_m = -18.721$
(b) ^{12}C(γ, 2n)^{10}C $\qquad Q_m = -31.846$

The total absorption, mainly (γ, n) + (γ, p), is dominated by the giant resonance peak at 23.2 MeV, $\Gamma = 3.2$ MeV [$\sigma_{\max} = 21$ mb (1975AH06)] and by a smaller structure at 25.6 MeV, $\Gamma \approx 2$ MeV [$\sigma_{\max} \approx 13$ mb (1975AH06)]: see (1968AJ02, 1975AJ02) for a detailed listing of the earlier references and results. The attenuation coefficient of 6.42 MeV γ-rays has been measured by (1975MO27).

The (γ, n) cross section shows a giant resonance centered at about 22.5 MeV, $\Gamma \approx 3$ MeV ($\sigma_{\max} \approx 8$ mb), a secondary maximum at 25.5 MeV, $\Gamma \approx 2$ MeV, and a long tail: see (1966FU02, 1966LO04, 1975KN10), (1975BE1F, 1976BE1H) and (1968AJ02). The (γ, n_0) cross section has been measured at 90° for $21 < E_x < 40$ MeV and compared with the (γ, p_0) cross section (1968WU01): the isospin mixing averages about 2% in intensity and shows structure at the giant resonance. Angular distributions of n_0 measured over the giant resonance region indicate that the main excitation mechanism is of a $1p_{3/2} \rightarrow 1d_{5/2}$ E1 single particle character. No significant E2 strength is observed (1968RA21). See also (1975AJ02), ^{11}C and (1975SC05). The production cross section of ^{11}C by 30 MeV electrons is 11.92 ± 0.15 μb: this corresponds to an electric dipole (γ, n) integrated cross section to 30 MeV of 41.0 ± 0.6 MeV · mb (1978KL03). Pair production by 6.6 MeV γ-rays in carbon has been studied by (1976RO1N).

The cross section for reaction (b) has been measured for $E_\gamma = 35$ to 130 MeV. The (γ, 2n) cross section is very much smaller than that for (γ, n): the highest value is 0.15% of the maximum value for reaction (a) in the energy range $E_\gamma = 20$ to 140 MeV (1970KA37). The ^{10}C production cross section has been measured for $E_{bs} = 100$ to 800 MeV (1977JO02). See also (1975NO10, 1975WO04, 1977BA3D, 1977HI12), (1974BU1A, 1975BE60, 1977DA1B, 1979BO1U), (1976WA1J; applications) and (1975WO07, 1976HE12, 1977GR08, 1977WU02, 1978KA1Q; theor.).

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

(b) ^{12}C(γ, π^+)^{12}B $\qquad Q_m = -152.936$

(c) ^{12}C(γ, π^-)^{12}N $\qquad Q_m = -156.905$

The photoproton cross section exhibits two broad peaks, the giant resonance peak at 22.5 MeV, $\Gamma = 3.2$ MeV, $\sigma_{max} = 13.1 \pm 0.8$ mb and a 2 MeV broad peak at 25.2 MeV, $\sigma_{max} = 5.6 \pm 0.3$ mb: see (1976CA21) and Table 12.19 in (1968AJ02). While the E1 component dominates in the GDR, a 2% E2 contribution may possibly be present (1976CA21). In contrast with the giant resonance peak in the (γ, n) cross section, the (γ, p) cross section shows a strong peak in the center of the broad giant resonance peak. Above 24.5 MeV the ground state (γ, p) and (γ, n) excitation functions have the same shape up to at least 36 MeV (E.G. Fuller, private communication). There is agreement between the (γ, p) results and those from the inverse reaction ^{11}B(p, γ_0)^{12}C [see reaction 27] when the population of ^{11}B*(4.4, 5.0) is taken into account. See also (1975AJ02). The fraction of transitions to the ground and excited states of ^{11}B have been determined at several energies in the range $E_{bs} = 24.5$ to 42 MeV: most of the transitions are to ^{11}B$_{g.s.}$ and the excited state transitions appear to originate from localized E_x regions (1970ME17). The cross sections for (γ, p$_0$) and (γ, p$_0$ + p$_1$) have been measured at $E_\gamma = 60$, 80 and 100 MeV (1976MA34). See also ^{11}B and (1978KI03).

(1978BA50) have studied the momentum distribution of π^+ and π^- for $E_\gamma = 300$ to 850 MeV and (1978AR08) have measured the cross section for π^- production in the range 510 to 750 MeV. The cross section for π^+ production, summed over ^{12}B states, has been measured for E_{bs} to 175 MeV (1979MI06). See also the "*Pion capture and pion reactions*" section here, (1976BE39, 1979BOZW, 1979PA06, 1979SH1N) and (1975AJ02). See also (1975TO10, 1976KU1C, 1977AL33, 1977AL1P, 1977KI1J, 1979AL1T), (1976GA02) and (1975AN1H, 1975BI05, 1975FU07, 1976HE12, 1977FI12, 1977NE2A, 1978FI10, 1978FU09, 1978WO11; theor.).

40. (a) ^{12}C(γ, d)^{10}B $\qquad Q_m = -25.1875$

(b) ^{12}C(γ, pn)^{10}B $\qquad Q_m = -27.4122$

Cross sections and angular distributions of the deuterons corresponding to transitions to ^{10}B$_{g.s.}$ and/or low excited states have been measured at $E_\gamma \approx 40$ MeV: the results are consistent with E2. There is some evidence also for the excitation of higher states of ^{10}B via non-E2 transitions (1972SK08). For $E_{bs} = 90$ 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 (1962CH26). For reaction (b) see (1975AJ02).

41. (a) ^{12}C(γ, t)^{9}B $\qquad Q_m = -27.366$

(b) ^{12}C(γ, ^{3}He)^{9}Be $\quad Q_m = -26.2793$

The yield of tritons has been measured for $E_\gamma = 35$ to 50 MeV by (1967KR05). For reaction (b) see (1969TA11).

42. ^{12}C(γ, α)^{8}Be $\quad Q_m = -7.3667$

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: see (1964TO1A) and (1968AJ02). 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). Alpha energy distributions show surprisingly strong E1 contributions below $E_\gamma \approx 17$ MeV (1955GO59, 1964TO1A). See also (1976TU05, 1979FL1G) and (1978DZ01, 1978MY1B; theor.).

43. (a) ^{12}C(γ, pα)^{7}Li $\quad Q_m = -24.6222$
(b) ^{12}C(γ, nα)^{7}Be $\quad Q_m = -26.2665$

The yield of 0.48 MeV γ-rays from the decay of ^{7}Be, formed in reaction (b), shows a resonance at $E_\gamma \approx 29.5$ MeV, $\sigma = 0.9 \pm 0.2$ mb (1969OW01). For work on the γ-induced spallation of ^{12}C see (1968AJ02, 1975AJ02) and (1976TU05).

44. ^{12}C(e, e)^{12}C

The nuclear charge radius of ^{12}C, $R_{\rm rms} = 2.472 \pm 0.002$ fm (1979CA1G). Other values include $R_{\rm rms} = 2.445 \pm 0.015$ fm (Fermi model), 2.453 ± 0.008 fm (shell model) (1972JA10), 2.462 ± 0.022 fm (1973FE13), 2.45 ± 0.04 fm (1979DO1M). See also (1975AJ02). Elastic scattering has been studied up to 4 GeV: see (1968AJ02, 1975AJ02).

^{12}C states observed in inelastic scattering are displayed in Table 12.16. The variation of the form factor $F(q^2)$ with momentum transfer yields unambiguous assignments of $J^\pi = 2^+$, 0^+ and 3^- for ^{12}C*(4.4, 7.7, 9.6): see (1975AJ02) and (1978CR1A, 1979CR1D, 1979FL1F). The isospin mixing between the 1^+ states ^{12}C*(12.7, 15.1) has been measured by (1974CE01): $\beta = 0.19 \pm 0.01$ or 0.05 ± 0.01. See also reactions 21, 22, 50, 73, 74 and 86. A study at $E_e = 57$ to 215 MeV ($\theta = 180°$) of the transverse form factors squared of the 2^+ states ^{12}C*(4.4, 16.1) indicates appreciable contributions of nuclear convection currents to the $T = 0$ state at low momentum transfer and spin magnetization contributions to the $T = 1$

Table 12.16: States of ^{12}C(e, e′)^{12}C [a]

E_x (MeV)	$J^\pi; T$	Γ_{γ_0} (eV)	Refs.
4.44	$2^+; 0$	$(10.6 \pm 1.1) \times 10^{-3}$	(1967CR01)
		$(11.0 \pm 1.0) \times 10^{-3}$	(1970ST10)
7.66 [b]	$0^+; 0$	$(6.2 \pm 0.6) \times 10^{-5}$	(1967CR01)
		$(5.9 \pm 0.5) \times 10^{-5}$	(1970ST10)
9.64	$3^-; 0$	$(3.1 \pm 0.4) \times 10^{-4}$	(1967CR01)
10.84	$1^-; 0$		(1969TO01, 1971NA14)
12.71 [c]	$1^+; 0$	0.35 ± 0.05 (M1)	(1974CE01)
14.08 [d]	$4^+; 0$		(1971NA14)
15.11	$1^+; 1$	37.0 ± 1.1	(1973CH16)
16.11	$2^+; 1$	0.83 ± 0.06	(1969GU05)
		0.35 ± 0.04	(1978FR03)
16.58	2^- [g]		(1970AN1C, 1971YA03)
17.6 ± 0.2	[g]		(1969GU05)
18.1	(1^-)		A, (1978SH14)
18.6 ± 0.1	(3^-) [g]		A
19.3	2^- [g]		A
19.6 ± 0.1	(4^-)		A
20.0 ± 0.1	(2^+)		A
20.6 ± 0.1	(3^+)		A
21.6 ± 0.1	(3^-)		A
22.0 ± 0.1	(1^-) [g]		A
22.7 ± 0.1 [e,f]	(1^-)		A
23.8 ± 0.1	(1^-) [g]		A
24.9 ± 0.2			A
25.5	(1^-)		A
25.5	(3^-)		(1971YA03)
26.4 ± 0.3			(1969GU05)
27.8 ± 0.2			(1969GU05)
30.2 ± 0.4			(1969GU05)
32.3 ± 0.3			(1969GU05)

A: References for this state listed in Table 12.18 (1975AJ02).

[a] See also Table 12.20 and reaction 36 in (1968AJ02), Table 12.18 in (1975AJ02) and Table 12.8 here. See also (1975FA1A).

[b] The matrix element is 5.48 ± 0.22 fm^2 (1968ST20), 4.38 ± 0.2 fm^2 (1979CR1D) for the E0 decay by π emission to $^{12}C_{g.s.}$.

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

[d] $\Gamma \approx 0.3$ MeV (1971NA14).

[e] The giant dipole resonance has an average $E_x = 23.0 \pm 0.7$ MeV and $\Gamma = 5.7 \pm 0.7$ MeV (1969GU05).

[f] May involve fine structure at $E_x = 22.2$, 22.8, 23.4 and 23.8 MeV.

[g] See (1972AN03). Widths for these states have also been calculated.

state at higher q (1978FL09). Longitudinal and transverse form factors of ^{12}C*(16.1) have been studied by (1978FR03) at $E_e = 32.8$ to 62.2 MeV. The ground state branching ratio for ^{12}C*(17.76) is $< 10^{-9}$ (1979CR1D).

Inelastic scattering of the giant resonance has been studied by many groups: see (1968AJ02) and Table 12.16. The longitudinal form factors show ^{12}C*(16.1, 18.6, 20.0, 21.6, 22.0, 23.8, 25.5) while the transverse form factors show ^{12}C*(15.1, 16.1, 16.6, 18.1, 19.3, 19.6, 20.6, 22.7, (25.5)) (1970AN1C, 1970TO13, 1971YA03, 1972AN03). ^{12}C*(19.3) may be the expected giant magnetic quadrupole state, $J^\pi = 2^-$: see (1975AJ02). See also (1978FA1F, 1979FL1F).

See also (1975BE1T, 1975LA23, 1975LU1B, 1976BU1H, 1976VL01, 1977HA1W, 1978DE32, 1979FLZZ), (1974DE1E, 1975FA1A, 1975HU1D, 1977RI1H, 1979LI06, 1979BE2E) and (1974UBZY, 1974WA1C, 1975AB1E, 1975BE12, 1975BO27, 1975DO10, 1975DO1D, 1975FR05, 1975IN04, 1975KI21, 1975LA1G, 1975LE14, 1975OK1A, 1975WA30, 1975WE1A, 1976BU1B, 1976BU1G, 1976BH1B, 1976GU11, 1976KA07, 1976RA28, 1976TA1F, 1977AG03, 1977AH04, 1977BR37, 1977DE16, 1977FU1M, 1977FU1E, 1977GR02, 1977GR24, 1977GU1D, 1977RI1H, 1977VI03, 1977WA1F, 1977WA1G, 1978AL04, 1978BU1K, 1978DO1D, 1978DU12, 1978FU13, 1978GU13, 1978HO1E, 1978KO32, 1978MA1U, 1978MU04, 1978RI1C, 1978SE1B, 1978UE1B, 1979AM02, 1979CA1H, 1979FR1C, 1979GO1Q, 1979IN06, 1979KA1P, 1979KN1E, 1979PEZX, 1979PO03, 1979SA20, 1979SE06; theor.).

45. (a) ^{12}C(e, ep)^{11}B $\qquad Q_m = -15.9569$
(b) ^{12}C(e, en)^{11}C $\qquad Q_m = -18.721$
(c) ^{12}C(e, eπ^+)^{12}B $\qquad Q_m = -152.936$
(d) ^{12}C(e, eπ^-)^{12}N $\qquad Q_m = -156.905$

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 (1968AJ02). Studies of $e' - p$ coincidences for $E_e = 497$ to 700 MeV reveal peaks corresponding to ejection of 1p and 1s protons: the energy of the two peaks [$\Gamma = 6.9 \pm 0.1$ and 19.8 ± 0.5 MeV] are 15.5 ± 0.1

and 36.9 ± 0.3 MeV (1976NA17: 700 MeV; DWIA). By studying the missing energy spectrum at $E_e = 497$ MeV (1976MO17) the population of ^{11}B*(2.14, 5.0) [as well as of $^{11}B_{g.s.}$ (1974BE12)] is reported. See also (1975AJ02) and (1977ZI1B). The deep inelastic response function has been studied by (1978MO19: $E_e = 160$ to 520 MeV, $\theta = 60°$ and 130°): a pronounced transverse strength is found in the region between the quasielastic and the N peaks.

For reaction (b) see (1975WO04) and (1975AJ02). For reaction (c) see (1977SH14) and ^{12}B. For reaction (d) see (1976HE13). For both see also the "*Pion capture and pion reactions*" section here.

See also (1977KN04, 1979FI1D, 1979FR1B, 1979PA1G, 1979PA1K, 1979SC1E, 1979SH1N, 1979ZI1D) and (1974JA1N, 1975AN1K, 1975DI1G, 1975DZ04, 1975GO33, 1975KA40, 1975RO18, 1975WO07, 1976BE60, 1976GO08, 1976NA03, 1976TA1G, 1977BE67, 1977FI12, 1977HA23, 1977KA1T, 1977MC1F, 1977NE2A, 1978FU04, 1978HA36, 1978KE1F, 1978NA20, 1978TA1D, 1979BE2F, 1979BO07, 1979FIZW, 1979KL1C; theor.).

46. (a) ^{12}C(π^-, π^-)^{12}C
(b) ^{12}C(π^+, π^+)^{12}C
(c) ^{12}C(π^-, $\pi^+\pi^-\pi^-$)^{12}C

Angular distributions of the scattering (primarily elastic at forward angles) have been measured at $E_\pi = 29$ MeV (1978JO09; π^-), 29.2 and 49.5 MeV (1979GY1B; π^-), 50 MeV (1977DY02, 1978MO25, 1979DY02; π^+), 120 to 280 MeV (1970BI1A; π^-), 125 MeV (1979NA04; π^+), 162 MeV (1978MO23; π^+) and 150, 162, 226 MeV (1977PI02, 1977PI09, 1979CH05; π^+ and π^-). Inelastic distributions to ^{12}C*(4.4, 9.6) are reported by (1977DY02; $E_{\pi^+} = 50$ MeV), (1970BI1A; $E_{\pi^-} = 120$ to 280 MeV; also to ^{12}C*(15.0)), (1979CH05; also to 7.7; $E_{\pi^+} = E_{\pi^-} = 162$ MeV), (1978TH1C; $E_{\pi^-} = 162$ MeV) and (1978MO23; $E_{\pi^+} = 162$ MeV; also to 19.3). Observation of 4.4 MeV γ-rays at $E_\pi = 73$ MeV leads to a cross section ratio (π^-/π^+) of 1.23 ± 0.22. The cross section is 14.5 ± 3.0 mb for π^+ (1970HI10). At $E_{\pi^+} = 148$ MeV, ^{12}C*(7.6, 15.1) are also populated (1978PE11). See also (1977GR1G, 1979MOZW). ‡ The absorption cross section at $E_{\pi^+} = 125$ MeV is 161 ± 28 mb (1979NA04). The emission of 2 photons in the capture of stopped pions, i.e. (π^-, $\gamma\gamma$), occurs at a rate of $\approx (1.3 \pm 0.3) \times 10^{-5}$/capture (1979DE06). See also (1977RO21, 1979MA2J). For the (π^+, π^+p) reaction see (1978CO02). For reaction (c) see (1973AS1A). See also the "*Pion capture and pion reactions*" section here.

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

‡ Comparison of π^+ and π^- inelastic scattering at $E_\pi = 180$ MeV shows structures at $E_x \approx 19.2 - 19.7$ MeV which may be due in part to an isospin-mixed 4^- doublet (1979CO1N). Angular distributions have been reported at $E_{\pi^+} = 100$ to 300 MeV for ^{12}C*(4.4, 7.7, 9.6, 19.3) (1979AL1U). Preliminary values for the isospin mixing of ^{12}C*(12.71, 15.11) and ^{12}C*(18.4, 19.4) are 125 ± 35 and 250 ± 50 keV, respectively (1979BO2D, 1979MO1W; prelim.; $E_\pi = 116$, 180 MeV). See also (1979CO1L).

(b) ^{12}C(n, n)^{4}He^{4}He^{4}He $\qquad Q_m = -7.2748$

(c) ^{12}C(n, nd)^{10}B $\qquad Q_m = -25.1875$

Table 12.17: Summary of recent ^{12}C(p, p), ^{12}C(d, d), ^{12}C(^{3}He, ^{3}He) and ^{12}C(α, α) angular distributions [a]

(a) ^{12}*C(p, p) measurements*

E_p (MeV)	Angular distributions to ^{12}C	Refs.
$1.5 \rightarrow 4.0$	g.s.	(1976CU08, 1978CU04)
$5.55 \rightarrow 6.15$	g.s.	(1974AL31)
5.65, 8.6	g.s.	(1976KO36)
6	g.s., 4.4	(1975DE26, 1977SA1B)
$18.5 \rightarrow 35.3$	g.s., 4.4	(1975DE32)
$19 \rightarrow 23$	g.s., 4.4, 7.7, 9.6, 12.7	(1976GA1L, 1977GA1G)
$E_{\bar{p}} = 22.3, 26.7, 30.5$	12.71	(1974AM05)
$22.5 \rightarrow 45$	g.s., 4.4, 12.7, 15.1	(1975GE15, 1975SP07, 1976KN1E)
$E_{\bar{p}} = 30.4$	g.s., 4.4, 7.7, 9.6	(1972GR02)
35.2	g.s.	(1977CO1L)
$E_{\bar{p}} = 36.2$	g.s. (small θ)	(1978BE49)
40	g.s.	(1979BO03)
45	see Table 12.18	(1977BU19)
$E_{\bar{p}} = 50, 65$	12.7, 15.1	(1978HO11)
61.9	12.7, 15.1	(1974AM05)
$E_{\bar{p}} = 65$	4.4, 15.4, 16.1	(1978HO11)
122	12.7, 15.1	(1977CO1T)
155	see Table 12.18	(1977BU19)
185	g.s., 4.4, 9.6	(1979IN01)
0.8 GeV	g.s., 4.4, 7.7, 9.6, 14.1, 15.1	(1977BL09, 1978BL02, 1979MO1E)
$E_{\bar{p}} = 0.8$ GeV	g.s., 4.4, 12.7, 15.1	(1978HO05, 1978RA08, 1978RA17, 1979GL1C, 1979LI03)
1 GeV	g.s.	(1976AL1G)

Table 12.17: Summary of recent ^{12}C(p, p), ^{12}C(d, d), ^{12}C(^{3}He, ^{3}He) and ^{12}C(α, α) angular distributions [a] (continued)

(b) ^{12}*C(d, d) measurements*

E_d (MeV)	^{12}C states	Refs.
$2.61 \rightarrow 2.82$	g.s.	(1974DA06)
$E_d = 15$	g.s.	(1974BU06)
$24.1 \rightarrow 28.8$	4.4, 12.7, 15.1, 16.1	(1977LI02)
26	9.6	(1979HE06)
28	g.s.	(1970BU08)
$E_d = 29.5$	g.s.	(1977PE07)
57	g.s., 4.4, 7.7, 9.6, 12.7	(1977TOZY)
60.6, 77.3, 90	g.s., 4.4, 7.7, 9.6, 14.1	(1975AS06)
70	g.s., 4.4, 9.6, 18.4	(1975CH1K, 1975CH1L, 1977CH1L)

(c) ^{12}*C(^{3}He, ^{3}He) measurements*

$E(^3$He) (MeV)	^{12}C states	Refs.
18, 20, 22, 24.5	g.s., 4.4	(1976MA26, 1978AD01)
$E(^3\vec{\mathrm{He}}) = 20.5, 26.6, 31.7$	g.s.	(1977KA25)
$E(^3\vec{\mathrm{He}}) = 32.6$	g.s., 4.4	(1975BU11)
39.7	g.s.	(1977BA05)
44	17.76	(1976CE02)
44.04	g.s.	(1979GO07)
70	g.s.	(1976DI05) [b]
82.1	g.s., 4.4, 7.7, 9.6	(1976KO36, 1976TA12)
130	See Table 12.19	(1977BU03)
132	g.s.	(1978CH1P)

(d) ^{12}*C(α, α) measurements*

E_α (MeV)	^{12}C states	Refs.
$3.0 \rightarrow 10.0$	g.s.	(1975DA10)
$4.0 \rightarrow 13.3$	g.s.	(1972MA01)
$8.3 \rightarrow 10.5$	g.s., 4.4	(1971OP01, 1973MA03)
$10.4 \rightarrow 19.7$	g.s., 4.4, 7.7	(1978AM1B, 1979AMZU)
$15.77 \rightarrow 20.14$	g.s.	(1973LA16)

Table 12.17: Summary of recent ^{12}C(p, p), ^{12}C(d, d), ^{12}C(^{3}He, ^{3}He) and ^{12}C(α, α) angular distributions [a] (continued)

16.95	7.7	(1976GL1D)
20.2 → 23.3	g.s.	(1977EN01)
24	g.s., 4.4, 7.7, 9.6	(1974FE08)
25.3	4.4	(1978AL20)
33.4, 39, 50.5	g.s., 4.4	(1976PA05)
60	g.s., 4.4, 9.6, 14.1, 15.5	(1977BU19)
65 [c]	g.s., 4.4, 9.6	(1976JA17)
100	4.4, 27	(1975RO1L)
145, 172.5	g.s.	(1976KIZP)
150	4.4, 21.3, 26.2	(1976KN05)
1.37 GeV	g.s., 4.4, 7.7, 9.6	(1976CH15)

[a] See also Tables 12.22 in (1968AJ02) and 12.20 and 12.22 in (1975AJ02).
[b] No results shown.
[c] Detected α-particles to ^{4}He*(20.1) [0^+].

Elastic and inelastic scattering to ^{12}C*(4.4, 7.7, 9.6, 10.3, 10.8, 11.8) have been studied at many energies up to 350 MeV: see (1968AJ02) and Table 12.19 in (1975AJ02). Recent angular distribution measurements have been reported at $E_n = 1.5$ to 4.0 MeV (1975HO1G, 1978SM1D; n_0, *natural* C), 8.0 to 14.5 MeV (1978HA1P; n_0, n_1), 8.97 to 14.93 MeV (1976GL11; n_0, n_1), 14.2 MeV (1978ME12; n_0, n_1), 14.2 MeV (1978DR03; $n_1\gamma$) and 14.6 MeV (1975KO27; n_0). Angular correlations (n_1, $\gamma_{4.4}$) have been studied at $E_n = 13.9$ to 15 MeV: see (1975AJ02). For a brief discussion of studies of the spin-flip probability for the transition to ^{12}C*(4.4) see (1975AJ02). See also ^{13}C in (1976AJ04, 1981AJ01).

At $E_n = 14.4$ MeV reaction (b) involves ^{12}C*(9.6, 10.8, 11.8, 12.7): see (1975AJ02, 1976CO1N). For reaction (c) see (1978RI02). See also (1975AN1J, 1975AN1G, 1975HO1F, 1975JE01, 1975PO08, 1976HA1N, 1977WHZZ), (1976MC1E, 1976WA1B, 1978FU1G) and (1976CA13, 1976TH10, 1977NO07, 1978AD1A; theor.).

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

Angular distributions of elastically and inelastically scattered protons have been measured at many energies up to $E_p = 1040$ MeV: see Tables 12.22 in (1968AJ02), 12.20 in (1975AJ02) and 12.17 here.

Table 12.18 displays the information on excited states of ^{12}C. The newly reported value of $E_x = 7654.00 \pm 0.20$ keV leads to a Q-value for the decay of this state into 3α of 379.31 ± 0.21 keV ((1976NO02) and J. Nolen, private communication): this implies an increase of 9%, at a stellar temperature of $10^{8\circ}$ K, in the 3α reaction rate calculated by (1975FO19). A summary of the information on the decays of this and other excited states of ^{12}C is shown in Table 12.8.

The spin-flip probability (SFP) for the transition to ^{12}C*(4.4) has been measured for $E_p = 15.9$ to 37.6 MeV: two bumps appear at ≈ 20 and ≈ 29 MeV. It is suggested that the lower one is due to a substructure of the E1 giant dipole resonance while the upper one results from the E2 giant quadrupole resonance (1975DE32). See also the studies listed in (1975AJ02). SFP has also been measured for ^{12}C*(12.71) at $E_p = 42$ MeV (1977MO18) and for ^{12}C*(12.7, 15.1) for $E_p = 23.5$ to 27 MeV (1978HOZJ). The relative population of ^{12}C*(12.7, 15.1) has been measured at $E_p = 800$ MeV, $\theta = 5.8°$: it is roughly $1 : 2$ (1978BO1Q).

The angular distributions of the proton groups to ^{12}C*(4.4, 12.7, 15.1) for $E_p = 22.5$ to 45 MeV have been analyzed by (1975GE15) to obtain the structures of the giant resonances. It is suggested that the E2 strength is fragmented, with the major concentration, corresponding to the isoscalar E2 resonance, near 28 MeV, and subsidiary strength near 32 and 42 MeV, the latter possibly a part of the isovector quadrupole resonance. See also the structures reported by (1977BU19) and displayed in Table 12.18.

For polarization measurements see ^{13}N in (1976AJ04, 1981AJ01). See also (1975KA2D, 1976FR05, 1977BR33, 1977DY1C, 1977SP1D, 1979BLZY, 1979BU1D), (1975IG1A, 1976SL2A, 1977AL1U, 1977SP1B, 1978AL1G, 1978ER1C, 1978IG1B, 1979LI06), (1976CR1D; astrophys.), (1978GO1E; applied) and (1974SA1G, 1974SC1E, 1975AH1C, 1975AH03, 1975AH1E, 1975BR14, 1975CL1D, 1975DU1A, 1975FR13, 1975GU11, 1975MA23, 1975NA07, 1975SC1T, 1975ST1M, 1975VI09, 1976AB05, 1976BU01, 1976HO1E, 1976KO1G, 1977AH04, 1977AL15, 1977AL19, 1977GU1D, 1977GU1E, 1977KH02, 1977KO1T, 1977NE06, 1977PH02, 1977SU1E, 1977VI03, 1977WE1K, 1978BE64, 1978BE1Y, 1978BE66, 1978CO1J, 1978FA04, 1978GU12, 1978KO32, 1978LE06, 1978MA34, 1978RA20, 1979AB01, 1979AM02, 1979BO03, 1979DY1E, 1979JA1L, 1979PEZX; theor.).

49. (a) ^{12}C(p, 2p)^{11}B — $Q_m = -15.9569$
(b) ^{12}C(p, pn)^{11}C — $Q_m = -18.721$
(c) ^{12}C(p, pd)^{10}B — $Q_m = -25.1875$
(d) ^{12}C(p, pt)^{9}B — $Q_m = -27.366$
(e) ^{12}C(p, p^{3}He)^{9}Be — $Q_m = -26.2793$
(f) ^{12}C(p, pα)^{8}Be — $Q_m = -7.3667$
(g) ^{12}C(p, d^{3}He)^{8}Be — $Q_m = -25.7199$

The (p, 2p) reaction has been studied at energies up to 1 GeV: see (1975AJ02) for the earlier work, ^{11}B and (1976BH02, 1977KO08, 1977NA16, 1977NA29, 1978KO30). See also (1978CH1K,

Table 12.18: ^{12}C levels from ^{12}C(p, p′)^{12}C* [a]

E_x (MeV ± keV)	Γ (MeV)	$J^\pi; T$	Refs.
4.4390 ± 1.1 [b]	[c]	$2^+; 0$	(1974JO14)
7.65400 ± 0.13 [d]	[e]	$0^+; 0$	(1976NO02)
9.63 ± 40	[e]	$3^-; 0$	(1969SU03, 1965HA17)
10.78 ± 100		$1^-; 0$	(1969SU03, 1965HA17)
12.70 ± 80	[e]		(1969SU03, 1965HA17)
14.05 ± 100		$4^+; 0$	(1969SU03, 1965HA17)
15.11 ± 50	[e]	$1^+; 1$	(1969SU03, 1965HA17)
15.3 ± 200 [f]	2.0 ± 0.2	$2^+; 0$	A
18.35 ± 30	0.35 ± 0.1	$2^+, 3^-$	A
19.4 ± 50	0.53 ± 0.1	$2^-; 1$	A
19.65 ± 50	0.44 ± 0.1	$4^+; 0$	A
20.27 ± 50 [g]	0.14 ± 0.05		A
20.57 ± 50	0.35 ± 0.1	$3^-; 1$	A
21.65 ± 100	1.20 ± 0.15	$3^-; 0$	A
21.95 ± 150	0.8 ± 0.1	$1^-; 1$	A
22.36 ± 50 [g]	0.3 ± 0.05		A
22.6 ± 100	0.9 ± 0.1	$1^-; 1$	A
23.50 ± 50	0.23 ± 0.1	$1^-; 1$	A
23.92 ± 80	0.4 ± 0.1	$1^-; 1$	A
25.3 ± 150	0.51 ± 0.1	$1^-; 1$	A
(25.8 ± 300)	0.75 ± 0.15	$(1^-; 1)$	A
27.0 ± 300	1.4 ± 0.2	$1^-; 1$	A
29.4 ± 300 [h]		$(2^+; 1)$	A

A: (1977BU19): $E_p = 45$ and 155 MeV. See also (1975BU1F).

[a] See also Tables 12.23 in (1968AJ02) and 12.21 in (1975AJ02).

[b] 4442.2 ± 1.5 keV (1971ST22), 4439.2 ± 0.5 keV (1974NO07).

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

[d] The Q for the decay of this state into 3α is 379.31 ± 0.21 keV (1976NO02). See also (1975AJ02).

[e] See Table 12.8.

[f] This state is also reported in (α, α') at $E_\alpha = 60$ MeV (1977BU19).

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

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

1979KRZX). For reaction (b) see (1975AJ02), (1976HO19) and ^{13}C in (1981AJ01). For reaction (c) see ^{10}B in (1979AJ01), (1977GR04) and ^{13}N in (1981AJ01). See also (1978AZ1B). For reactions (d, e) see (1976GR1H, 1977GR04).

At $E_p = 56.5$ MeV reaction (f) proceeds primarily by sequential α-decay: initially ^{12}C*(19.7 ± 0.5, 21.1 ± 0.3, 22.2 ± 0.5, 26.3 ± 0.5) are formed. These states, which must therefore have natural parity and a significant $T = 0$ admixture, subsequently decay to ^{8}Be$_{g.s.}$ [^{12}C*(22.2, 26.0)] or ^{8}Be*(2.9) [^{12}C*(19.7, 21.1, 26.3)] (1969EP01). At $E_p = 100$ MeV reactions (f) and (g) to ^{8}Be$_{g.s.}$ have been studied by (1977CO07, 1977RO02): $\langle S_\alpha \rangle = 0.59 \pm 0.05$ and 0.56 ± 0.12, respectively. For reaction (f) see also ^{8}Be and (1978CH1H, 1978DE1J, 1978LA11). For pion production see (1978PE12).

See also (1977BA85, 1977WA05, 1978AZ02), (1975RO1B, 1977MC1F, 1977RO1E, 1975SC1V, 1978CH1C) and (1974JA1N, 1975BA1H, 1975EI1B, 1975FR06, 1975SA01, 1976BI11, 1976KO08, 1976LE02, 1977JA1F, 1977KO1P, 1978BA1C, 1978GO1L, 1978HA35, 1978TA1H, 1978WO1A, 1978WR01, 1979CH06, 1979FA1B, 1979FU1J, 1979GU1F, 1979LA02, 1979MA20; theor.).

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

(b) ^{12}C(d, pn)^{12}C $\quad Q_m = -2.2246$

(c) ^{12}C(d, dα)^{8}Be $\quad Q_m = -7.3667$

The angular distribution of elastically and inelastically scattered deuterons has been studied at many energies up to $E_d = 650$ MeV: see (1968AJ02), Table 12.22 in (1975AJ02) and Table 12.17 here. E_x of ^{12}C*(4.4) is 4440.5 ± 1.1 keV (1974JO14). The isospin mixing of ^{12}C*(12.7, 15.1) [$J^\pi = 1^+$; $T = 0$ and $T = 1$] gives a mean charge dependent matrix element of 324 ± 33 keV (1977LI02: $E_d = 24.1$ to 28.8 MeV). See also (1976COYZ), (1975AJ02) and reactions 21, 22, 44, 73, 74 and 86. The quadrupole deformation parameter is calculated to be $\beta_2 = -0.48 \pm 0.02$ independent of incident energy [$E_d = 60.6$, 77.3, 90.0 MeV] (1975AS06; coupled channels analysis). (1971DU09) report $\beta_2 = 0.47 \pm 0.05$ and $\beta_3 = 0.35 \pm 0.06$ for ^{12}C*(4.4, 9.6) [$E_d = 80$ MeV].

In addition to the well-known states of ^{12}C, (1975AS06) report the population of states with $E_x = 18.3 \pm 0.3$, 20.6 ± 0.3 and 21.9 ± 0.3 MeV [broad], of a broad maximum at ≈ 27 MeV, and possibly also of states at $E_x = 10.8 \pm 0.2$ and 11.8 ± 0.2 MeV. (1977CH1L) report two structures at $E_x = 26 \pm 1$ and 29 ± 1 MeV, with $\Gamma = 2 \pm 1$ and 4 ± 1 MeV, and determine $L = 3$ in the excitation of ^{12}C*(18.4).

Reaction (b) has been studied in a kinematically complete experiment at $E_d = 5.00$ to 5.50, 9.20 and 9.85 MeV by (1973SA03) and also at $E_d = 5.1$ to 6.5 MeV [see the discussion in (1975AJ02)]. See also ^{13}C and ^{13}N in (1976AJ04). For pion production see (1977BR33, 1978PE12). See also ^{14}N in (1976AJ04, 1981AJ01). See also (1975KI1G, 1979AZ1B), (1974AD1B, 1975SC1V) and (1974CH58, 1975GU10, 1975MA23, 1976CH03, 1977DM1A, 1977KU07, 1977VA03, 1978GH03, 1978HA1Q, 1978MA34, 1978NI1A, 1978ZE03, 1979CH06, 1979LA02; theor.). For reaction (c) see (1979HE06).

51. ^{12}C(t, t)^{12}C

Angular distributions of elastically scattered tritons have been determined at $E_t = 1.0$ to 20.04 MeV: see (1975AJ02).

Table 12.19: States of ^{12}C from ^{12}C(^{3}He, ^{3}He), ^{12}C(α, α) and ^{14}N(d, α) [a]

E_x [b,c,d] (MeV ± keV)	Γ [d] MeV	L [c,d] (MeV)	E_x [b,g] (MeV ± keV)	Γ (MeV)	$J^\pi; T$ [u]
0		0	0		$0^+; 0$
4.4422 ± 1.5 [e]		2	4.44 [h]		$2^+; 0$
7.67			7.67 [h]		$0^+; 0$
9.64		3	9.642 ± 14 [h,i]	0.030 ± 0.008 [i]	$3^-; 0$
10.84		[j]	10.84 [j]		$1^-; 0$ [v]
11.83		[j]	11.83 [j]		$2^-; 0$
12.71		0	12.7 ± 70 [j,k]		$1^+; 0$
			13.29 [l]	0.355 ± 0.050 [l]	
14.08			14.08 ± 30 [m]		4^+ [n,v]; 0
15.11 [f]		0			$1^+; 1$
15.2 ± 300	1.8 ± 0.3	2	15.5 ± 100 [o,q]	2.1 ± 0.3 [o]	$(2^+; 0)$ [o]
16.11 [f]		2			$2^+; 1$
16.58 [f]					$2^-; 1$
18.40 ± 60 [f]	0.4 ± 0.1	2	18.5 ± 150 [j,o,q]		(2^+) [d]
18.9 ± 150 [f]	0.7 ± 0.15	2			(2^+) [d]
			19.50 ± 100 [o,r]	≈ 0.25 [r]	$(1, 2, 3)^+$ [r]
19.58 ± 60 [f]					
			20.55 ± 100 [r]	≈ 0.2 [r]	$(2, 3)^+$ [r]
21.3 ± 150 [s]	1.4 ± 0.2	2	21.65 ± 100 [j,o,p,q]	0.43 ± 0.08 [g]	2^+ [d,v]
			22.4 ± 100 [o,r]	≈ 0.25	2^+ [d,r]
23.5 ± 200	0.6 ± 0.2	2	23.9 ± 100 [j,r,t]	≈ 0.4	
25.9 ± 300	2.2 ± 0.3	2	[q]		(2^+) [d]
			27 [p]	3.8 [p]	(2^+) [v]
28.8 ± 400	2.7 ± 0.4	2			(2^+) [d]

[a] See also Table 12.23 in (1975AJ02).
[b] When no errors are shown, values are from Table 12.8.
[c] $E(^3\text{He}) = 49.8$ MeV (1969BA06).
[d] $E(^3\text{He}) = 130$ MeV (1977BU03).
[e] (1971ST22).
[f] $T = 1$ (1969BA06).
[g] (1972FA07): $E_\alpha = 90$ MeV and $E_\text{d} = 52$ MeV; except where other footnotes are shown.
[h] See Table 12.8.
[i] (1956DO41): ^{14}N(d, α)^{12}C.
[j] Angular distribution not obtained.
[k] (1965PE17): ^{14}N(d, α)^{12}C.
[l] (1965SC12): ^{14}N(d, α)^{12}C.
[m] (1972FA07) suggests $J^\pi = 3^-$ for ^{12}C*(14.08) and 4^+ for ^{12}C*(15.6).
[n] (1977MC07): the decay is $(9 \pm 3)\%$ to $^8\text{Be}_{\text{g.s.}}$ [this branching ratio is somewhat uncertain because there may be an appreciable effect due to continuum breakup].
[o] (1975BU1F, 1977BU19): $E_\alpha = 60$ MeV.
[p] (1975RO1L): $E_\alpha = 100$ MeV; preliminary results.
[q] (1976KN05): $E_\alpha = 150$ MeV.
[r] (1976VA07): $E_\text{d} = 40$ MeV.
[s] Possibly unresolved.
[t] Weakly populated.
[u] Best values: see Table 12.7 when other footnotes are not given.
[v] (1978RI03): $E_\alpha = 104$ MeV.

52. ^{12}C(^{3}He, ^{3}He)^{12}C

Angular distributions of ^{3}He ions have been measured in the range $E(^3\text{He}) = 2$ to 217 MeV: see (1968AJ02), Table 12.22 in (1975AJ02) and Table 12.17 here. Parameters of observed ^{3}He groups are displayed in Table 12.19.

Angular distributions of the ^{3}He groups to ^{12}C*(15.11, 16.11, 16.58, 19.56) have been compared with those for the tritons to ^{12}N*(0, 0.96, 1.19, 4.25) in the analog (^{3}He, t) reaction: the correspondence is excellent and suggests strongly that these are $T = 1$ isobaric analog states (1969BA06: $E(^3\text{He}) = 49.8$ MeV). See also Tables 12.12 and 12.19. The states reported by (1977BU03) at $E(^3\text{He}) = 130$ MeV [see Table 12.19]: ^{12}C*(4.4, 15.2, 18.4, 18.9, 21.3, 23.5, 25.9, 28.8) are all stated to correspond to E2 transitions: their strengths add up to 46% of the EWSR (energy-weighted sum rule). The quadrupole deformation parameter $\beta_2 = 0.30$ can account for both the elastic and inelastic data providing that the ratio of the s.o. and central deformation $\beta_{\text{s.o.}}/\beta_{\text{cent}}$ is energy dependent ($E(^3\text{He}) = 20.5 - 33$ MeV) (1977KA25). See also (1975AJ02). For pion production see (1976WA10).

See also ^{15}O in (1976AJ04, 1981AJ01), (1975AU01), (1976RO1L, 1978BE1H) and (1974CH58, 1974KU15, 1975MA23, 1977DM1A, 1977GE1E, 1977KU07, 1978ZE03; theor.).

53. (a) ^{12}C(α, α)^{12}C

(b) ^{12}C(α, 2α)^{8}Be $\quad Q_m = -7.3667$

(c) ^{12}C(α, ^{8}Be)^{8}Be $\quad Q_m = -7.4586$

Angular distributions have been measured at many energies up to 1.37 GeV: see Tables 12.24 in (1968AJ02), 12.22 in (1975AJ02) and 12.17 here. Parameters of observed states of ^{12}C are displayed in Table 12.19. J^π assignments have also been suggested for ^{12}C states with $9.6 \leq E_x \leq 39.3$ MeV on the basis of their decay into 3α-particles: see (1973JA02; $E_\alpha = 90$ MeV). The quadrupole deformation, β_2, is -0.29 ± 0.02 (1971SP08), -0.30 ± 0.02 (1976PA05), 0.4 (1977BU19), 0.46 (1973SM03); $\beta_3 = 0.24$ (1973SM03), 0.23 (1977BU19).

Angular correlation measurements ($\alpha_1\gamma_{4.4}$) have been carried out for $E_\alpha = 10.2$ to 104 MeV: see (1975AJ02, 1978AL20, 1978RI03). See also (1976AL23, 1976GU1B). The relative population of magnetic substates has been studied by (1970HA15, 1972BU09). Alpha-alpha correlations from ^{12}C*(14.1) to ^{8}Be$_{g.s.}$ lead to an assignment of $J^\pi = 4^+$ for that state (1977MC07). See also (1978RI03).

At $E_\alpha = 104$ MeV, the sum of the E2 strength in the dominant decay channels $[\alpha_0+\alpha_1+p_0]$ for $20 < E_x < 30$ MeV exhausts less than 15% of the EWSR (energy-weighted sum rule) (1978RI03). At $E_\alpha = 150$ MeV, the observed isoscalar E2 strength is $(6 \pm 2)\%$ of EWSR (1976KN05). See also (1976KIZN). The yields of the 12.71 and 15.11 γ-rays have been measured for $E_\alpha = 22$ to 27 MeV: strong structures are observed [see ^{16}O]. The yield of $\gamma_{15.1}$ is 1 to 20% of that for $\gamma_{12.7}$ (1975SP04). Measurements of the radiative widths for ^{12}C*(7.7, 9.6) are reported in Table 12.8 (1974CH32, 1976MA46).

Reaction (b) has been studied for E_α up to 700 MeV: see (1975AJ02). See also (1977YA1A, 1979DO04). For pion production see (1976WA10, 1977BR33, 1978PE12). For reaction (c) see (1976WO11).

See also (1974YOZO, 1976YU01, 1978FR1L, 1978SH1H, 1979AR05), (1975GR41, 1975SC1V, 1976OG1A, 1976SI1E, 1977HA1P, 1977MA2E, 1977ST1G, 1978BE1H, 1978MO29) and (1974CH58, 1974KU15, 1975CO1H, 1975GO02, 1975MA23, 1975RU10, 1975ST10, 1976AV05, 1976BA1N, 1976CU07, 1976HU07, 1976ME20, 1976PA25, 1976SAZC, 1977AL01, 1977BA12, 1977CL1D, 1977DM1A, 1977GE1E, 1977HO1H, 1977SA1P, 1977SA19, 1977TU1E, 1977VI06, 1977VI1C, 1977ZE01, 1977ZE1C, 1977ZE1D, 1978AH03, 1978FR1F, 1978FR1H, 1978SU01, 1978SU1G, 1978YO1F, 1978ZE03, 1979CH06, 1979DY1F, 1979LA02, 1979MO07; theor.).

54. (a) ^{12}C(^{6}Li, ^{6}Li)^{12}C

(b) ^{12}C(^{7}Li, ^{7}Li)^{12}C

The elastic scattering in reaction (a) has been studied at $E(^6\text{Li}) = 4.5$ to 40 MeV [see (1975AJ02)], at 4.5 to 13 MeV (1976PO02), 50.6 MeV (1976CH27) and 59.8 MeV (1975BI06; also to ^{12}C*(4.4, 7.7)), and at $E(^6\vec{\text{Li}}) = 20$ and 22.8 MeV (1976WE10). See also (1977SC1B: $E(^6\text{Li}) = 100$ MeV) and (1976WE10, 1978DR07, 1978MA13) in 18F (1978AJ03, 1983AJ01). (1974BI04: $E(^6\text{Li}) = 36.4$ and 40 MeV) have measured the inelastic angular distributions to ^{12}C*(4.4, 7.7, 9.6, 10.8, 11.8, 12.7, 13.4, 14.1) and have calculated deformation parameters under various assumptions. For the α-decay of ^{16}O states see (1977CU1B).

The elastic scattering in reaction (b) has been studied at $E(^7\text{Li}) = 4.5$ to 36 MeV [see (1975AJ02)], at 4.5 to 13 MeV (1976PO02), 36 MeV (1976CO23) and at 89 MeV (1979BR04; also to ^{12}C*(4.4); $\beta_2^2 = 0.51 \pm 0.02$). See also (1978DR07) in ^{19}F (1983AJ01). See also (1971SC21, 1975GR41, 1976OG1A, 1978FI1E) and (1975TH1C, 1976AM01, 1976ST22, 1977KU07, 1978MA1B, 1978ME14, 1978NO08, 1978PE1C, 1979BE59; theor.).

55. ^{12}C(^{9}Be, ^{9}Be)^{12}C

Elastic scattering angular distributions have been obtained at $E(^9\text{Be}) = 14$, 20 and 26 MeV (1979JA04, 1979UN01), 39.7 and 43.8 MeV (1979MA21; also to ^{12}C*(4.4)) and at $E(^{12}\text{C}) = 12$, 15, 18 and 21 MeV (1970BA49). For excitation function measurements see (1978MA44); for fusion cross sections see (1978CH02). See also (1976ECZZ, 1977IG1D, 1977PE1B), (1976OG1A, 1978TA1B) and (1978PA1B; theor.).

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

Elastic angular distributions for reaction (a) have been measured at $E(^{10}\text{B}) = 18$ MeV (1968VO1A, 1969VO10) and 100 MeV (1975NA15, 1977TO02; also to ^{12}C*(4.4, 9.6)). Elastic angular distributions in reaction (b) have been studied at $E(^{12}\text{C}) = 15$, 17, 20 and 24 MeV (1974BO15), 16, 18, 22 and 24 MeV (1975DU11) and 87 MeV (1971LI11) and at $E(^{11}\text{B}) = 28$ MeV (1968VO1A, 1969VO07, 1969VO10; also to ^{12}C*(4.4) as well as to several ^{11}B states). See (1978FR20) for differential cross section measurements in the range $E(^{11}\text{B}) = 18.8$ to 34.1 MeV and (1976ST12, 1977HI01) for fusion cross section measurements. See also (1973BR1C, 1975AJ02), (1976AR1H, 1978RO1D; astrophys.) and (1975RE04, 1978AV1A, 1978VA1A; theor.).

57. ^{12}C(^{12}C, ^{12}C)^{12}C

Angular distributions have been measured at $E(^{12}\text{C}) = 10$ to 20 MeV (1977HI1D, 1977KO1Q, 1977KO1W, 1978ER1D: g.s.), 10 to 37.6 MeV (1973EM03, 1975EM01: g.s. + g.s., g.s. + 4.4,

$4.4+4.4$), 17.6 to 27.5 MeV (1977CI01: g.s.), 40 to 60 MeV (1973WI09: g.s. + g.s., g.s. + 4.4), 30 to 50 MeV (1978CO20: g.s.), 70 MeV (1971KO11, 1975KO1E: g.s., 4.4, $4.4 + 4.4$, 9.6), 70.7 to 126.7 MeV (1976WI14, 1977ST1Q, 1979ST10: g.s., 4.4, $((4.4+4.4)+9.6)$), 87 MeV (1971LI11: g.s.), 98.2 MeV (1977ST1Q: 7.65, 9.64, 14.07), and 114 and 174 MeV (1973AN22: g.s., 4.4, 7.7, 9.6, 14.1, 19.6).

The relative population of elastic and inelastic channels is very energy dependent: see, e.g., (1975AJ02) and (1975EM01, 1977BR18, 1977CI01, 1977CO05, 1977CO1P, 1977KO1Q, 1977KO1V, 1977KO1X, 1978CA1K, 1978CO20, 1978ER1D, 1978JA1D, 1979CL06). Total cross sections at 1.55 and 2.89 GeV/c/A are reported by (1978JA16). See also (1976SP07, 1978CO1L, 1978KO1L, 1978SA05, 1979COZS, 1979HA1P, 1979HEZX, 1979NA02) and (1974FO1F, 1978RO1D, 1978RO1L; astrophys.) and (1974VE05, 1975FR13, 1976AR14, 1976CU03, 1976CU07, 1976MA45, 1976ZI01, 1977AB1B, 1977BA3E, 1977CH11, 1977CI1C, 1977CL1D, 1977FI1C, 1977FR1H, 1977FR12, 1977FR1L, 1977KI1L, 1977LO1H, 1977PA28, 1977PA1H, 1977RO1K, 1977SA09, 1977SA10, 1977WA1Q, 1978AB1C, 1978AR1H, 1978AV1A, 1978BE1R, 1978BI1G, 1978CH10, 1978DA1G, 1978FI1G, 1978FR1F, 1978FR1H, 1978FR1N, 1978KO14, 1978SC1G, 1978SC1E, 1978TA13, 1978TA1P, 1978TA1B, 1978TA19, 1978TA1T, 1978TO12, 1978VA1G, 1978VA1A, 1978WI05, 1979AB02, 1979CH06, 1979CO06, 1979GO1P, 1979HA07, 1979HE1H, 1979KO11, 1979LAZY, 1979MO1J, 1979NA03, 1979PH01, 1979PI03, 1979TA02, 1979TA1K; theor.).

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

Angular distributions for reaction (a) have been studied at $E(^{12}\mathrm{C}) = 15,\ 19,\ 20 \rightarrow 36$ and 87 MeV [see (1975AJ02)] and at $E(^{12}\mathrm{C}) = 20.0$ to 35.5 MeV (1978CH29: g.s. and 4.4 – the latter from 30 MeV) and $E(^{13}\mathrm{C}) = 12$ MeV (1976WE28, 1977GU07: g.s.) and 36 MeV (1976WE21: g.s.). Elastic angular distributions in reaction (b) are reported at $E(^{12}\mathrm{C}) = 12$ to 20 MeV (1972BO68). For yield measurements see (1975AJ02) and (1976ST12, 1976WE28, 1977GE1G, 1978CH29, 1978LE1N). See also (1974GO1L, 1975VO1B, 1977WI1C), (1978RO1D; astrophys.) and (1975DE09, 1977IM1A, 1977TR1A, 1978AV1A, 1978CH30, 1978IM1A, 1978PA1B, 1978TA1B; theor.).

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

Angular distributions have been measured at $E(^{14}\mathrm{N}) = 21$ to 88 MeV [see (1975AJ02)], 37 to 58.3 MeV (1978CO20: g.s.) and at 53 MeV (1976ZE04: g.s.), 65, 84 and 88 MeV (1971KO11, 1975KO1E: g.s., 4.4, 9.6) and 155 MeV (1975NA11, 1975NA15, 1977TO02: g.s., 4.4, 9.6). See also (1977MO1A) and ^{14}N in (1976AJ04). For fusion cross sections see (1976ST12, 1977KO1V, 1977SW02, 1978CO20, 1979GO09, 1979GO11). Reaction (b) has been studied for $E(^{15}\mathrm{N}) = 31.5$ to 47 MeV (1978CO20). See also (1977PH1C). See also (1978DA1E), (1975VO1B, 1976LE1F, 1978TS04), (1978RO1D; astrophys.) and (1975DE09, 1975MO23, 1975RA33, 1976AM01, 1977BA3E, 1977MA11, 1978AV1A, 1978CU1C, 1978CU1E, 1978CU06, 1978FR1N, 1978HO13, 1978KA14, 1978VA1A, 1979NA03; theor.).

60. (a) ^{12}C(^{16}O, ^{16}O)^{12}C
(b) ^{12}C(^{16}O, α)^{12}C^{12}C $\quad$ $Q_{\rm m} = -7.1620$

Angular distributions have been measured at $E(^{16}{\rm O})$ = 20 to 168 MeV [see (1971AJ02, 1975AJ02, 1977AJ02)] and at $E(^{16}{\rm O})$ = 17.29 to 23.14 MeV (1976CH13), 30.8 to 33.9 MeV (1978SC06), 31.7 to 52.7 MeV (1978JA1H; also ^{12}C*(4.4) from 46 MeV), 46 MeV (1976SP01; also involves various states in ^{16}O), 52.0 MeV (1977SH16; also excited ^{16}O states), 55.3, 56.7, 65.8 MeV (1978KA13; also excited ^{16}O states), 59.6 to 61.2 MeV (1978SH01; not g.s.: ^{12}C*(4.4)). 65 and 80 MeV (1973GU12; also ^{12}C*(4.4) and excited ^{16}O states), 84 MeV (1978BO11; only ^{12}C*(4.4)). 80 to 122 MeV (1977CO20), and at 315 MeV (1979DO01; not g.s.: ^{12}C*(4.4, 14.1, $25.3-26.7$)), and at $E(^{12}{\rm C}) = 65$ MeV (1978BO11; also ^{12}C*(4.4)) and 76.8 MeV (1977MO1A, 1977MO1H). See also (1978MA1R) and ^{16}O in (1977AJ02, 1982AJ01).

(1979DO01) present evidence for the excitation of giant resonances in a number of nuclei including ^{12}C: ^{12}C*($25.3-26.7$) ($\Gamma \approx 4$ MeV) contain 25^{+15}_{-10}% of the E2 strength. (1978BO11) have measured the m-state populations in the transition to ^{12}C*(4.4) at $E(^{12}{\rm C}) = 65$ MeV and $E(^{16}{\rm O}) = 84$ MeV. See also (1977DE1P). For reaction (b) see (1974WI05, 1979FU02, 1979SC10). See also (1975AJ02).

For fusion cross section measurements see (1976CU04, 1976EY01, 1976FR20, 1976SP03, 1977BR38, 1977KO1V, 1977NA23, 1978CH15, 1978FE04, 1978TA11, 1979KO03). For other yield measurements see (1975SH24, 1976CH13, 1976SP01, 1977CO20, 1977TA03, 1978JA04, 1978KA13, 1978MA22, 1978MA32, 1978SC06, 1978SH01, 1979FRZX, 1979FU02, 1979JAZY, 1979TA05). See also (1978MA1R). A number of resonances are observed. See also ^{28}Si in (1978EN06).

See also (1977QU1A, 1978CI06, 1978CL1E, 1978KA1L, 1978LAZZ, 1979GAZV), (1976CU04, 1978RO1D; astrophys.), (1973BR1C, 1975GR41, 1975VO1B, 1978KO1L, 1978LE1T, 1978TS04, 1979CH07) and (1974SA1M, 1974VE05, 1975CH08, 1975VE12, 1976BA52, 1976CH1M, 1976YO01, 1977BA28, 1977BA3E, 1977CH11, 1977CL1D, 1977FR12, 1977JA1E, 1977MA1V, 1977MA1X, 1977MO1J, 1977PA1G, 1977RO1N, 1978AB1C, 1978AV1A, 1978BA53, 1978BI1G, 1978FR1N, 1978GO07, 1978MA28, 1978MA22, 1978MA50, 1978TA16, 1978TA1B, 1978VA1A, 1979KR07, 1979NA03, 1979STZU, 1979TA07, 1979TA1K, 1979TA12; theor.)

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

The elastic scattering angular distributions have been measured at $E(^{17}{\rm O}) = 30.5$ and 33.8 MeV (1978CH03) and 35 MeV (1967GO1A) and at $E(^{18}{\rm O}) = 32.3$ and 35 MeV (1978CH03), 35 MeV (1967GO1A) and 47.5, 55 and 57.5 MeV (1976WE05). Fusion cross sections have been measured for $E(^{17}O) = 16.9$ to 33.8 MeV (1976EY01) and 34 to 80 MeV (1978HE18) and for $E(^{18}O) = 17.5$ to 35.0 MeV (1976EY01), 50 MeV (1978HE18) and 100 MeV (1978CO07). See also (1976SP07, 1978CH03, 1978FR05, 1979CH07, 1979GAZV: yield measurements), (1974GO1L, 1978LE1T, 1978TS04) and (1977BA3E, 1978BI1G, 1978PA1B, 1978VA1A, 1979KR07, 1979NA03, 1979PAZY; theor.).

62. $^{12}C(^{19}F, ^{19}F)^{12}C$

Elastic scattering angular distributions have been measured at $E(^{19}F) = 40$, 60 and 68.8 MeV (1968VO1A, 1969VO10, 1972SC03). See also (1976SP07, 1977KO38: fusion cross section at $E(^{19}F) = 92$ MeV), (1973BR1C, 1975GR41, 1975VO1B) and (1977BA3E, 1978BI1G, 1978HO13, 1978VA1A, 1979NA03; theor.).

63. (a) $^{12}C(^{20}Ne, ^{20}Ne)^{12}C$
(b) $^{12}C(^{22}Ne, ^{22}Ne)^{12}C$

Elastic angular distributions for reaction (a) have been measured at $E(^{12}C) = 37$ MeV (1974VA18) and $E(^{20}Ne) = 65.7$ MeV (1975DO06, 1978DO01). For yield measurements see (1977CO1Q, 1977PR1F, 1978DO01, 1979FOZY). See also (1977SC1G), (1978RO1L; astrophys.) and (1976VA12, 1977OS02, 1978VO06; theor.).

64. (a) $^{12}C(^{24}Mg, ^{24}Mg)^{12}C$
(b) $^{12}C(^{26}Mg, ^{26}Mg)^{12}C$

See (1978CL1E, 1979DAZT). See also (1978TA1B, 1979TA1K; theor.).

65. $^{12}C(^{27}Al, ^{27}Al)^{12}C$

The angular distribution of the transition to $^{12}C^*(4.4)$ has been measured at $E(^{12}C) = 82$ MeV (1977BE42). See also (1977SC1G) and (1978VA1A; theor.).

66. $^{12}C(^{28}Si, ^{28}Si)^{12}C$

Elastic angular distributions have been studied at $E(^{12}\mathrm{C}) = 19$ to 36 MeV (1977CH25), 24, 27 and 30 MeV (1977EC04), 40.2 MeV (1975RA33), 49.3, 70 and 83.5 MeV (1971KO11) and 186.4 MeV (1977DE23) and at $E(^{28}\mathrm{Si}) = 58.3$ to 116.7 MeV (1978CL02, 1979OS01). For yield measurements see (1978BA02, 1978CL02, 1979KUZX). See also (1978TA1B) and (1977ZI1C, 1979TA1K; theor.).

67. ^{12}C(^{32}S, ^{32}S)^{12}C

Elastic angular distributions are reported at $E(^{12}\mathrm{C}) = 35.8$ MeV (1978GE14) and $E(^{32}\mathrm{S}) = 73.3$ to 128.3 MeV (1979OS01: back angles).

68. (a) ^{12}C(^{40}Ca, ^{40}Ca)^{12}C
(b) ^{12}C(^{41}Ca, ^{41}Ca)^{12}C
(c) ^{12}C(^{42}Ca, ^{42}Ca)^{12}C
(d) ^{12}C(^{48}Ca, ^{48}Ca)^{12}C

The elastic scattering in reactions (a), (c) and (d) has been studied at $E(^{12}\mathrm{C}) = 51.0$, 49.9 and 49.9 MeV, respectively (1979RE03). See also (1979OS01). For reaction (b) see (1978BA26; theor.). For yield measurements see (1978RE06, 1979KU02, 1979RE03).

69. ^{12}N(β^+)^{12}C $\qquad Q_\mathrm{m} = 17.338$

The decay is mainly to the ground state via an allowed transition. Branching ratios to other states of ^{12}C are displayed in Table 12.20. The half-life of ^{12}N is 11.000 ± 0.016 msec (1978AL01). See also the earlier values in Table 12.28 of (1968AJ02). Since transitions to ^{12}C*(0, 4.4) are allowed $J^\pi(^{12}\mathrm{N}) = 1^+$.

A recent measurement of the ratio of the branching ratios ^{12}N/^{12}B for the decays to ^{12}C*(4.4) is $R = 1.56 \pm 0.05$ (1978AL01). This leads to the following values for the mirror asymmetries of ^{12}B and ^{12}N for decay to ^{12}C*(0, 4.4): $\delta_{4.4} = +0.044 \pm 0.034$, $\delta_\mathrm{g.s.} = +0.129 \pm 0.008$ (1978AL01). See also (1975AJ02) for earlier measurements. These values in turn lead to second class current (SCC) contributions $\delta_0^\mathrm{SCC} = -0.006 \pm 0.038$ and $\delta_1^\mathrm{SCC} = -0.047 \pm 0.037$, which are consistent with zero (1978AL01).

The shapes of the β-spectra of ^{12}B and ^{12}N have been analyzed to give the following values for $\alpha_- - \alpha_+$: $(+0.98 \pm 0.09)$%/MeV (1977KA24), $(+0.86 \pm 0.24)$%/MeV (1977WU01) and $(+0.302 \pm 0.062)$%/MeV (1977SU1F). (1978BR18) find $\alpha_+ = -0.273 \pm 0.039$%/MeV in agreement with the results of (1977SU1F: -0.277 ± 0.052%/MeV), These measurements are in agreement with CVC and with the absence of second class induced tensor currents. See also (1976CA29, 1978MO02,

Table 12.20: Branching in $^{12}N(\beta^+)^{12}C$

Decay to $^{12}C^*$	Branch (%)	Log ft [a]	Refs.
g.s.	94.55 ± 0.60	4.120 ± 0.003	(1978AL01)
4.44	2.00 ± 0.10	5.128 ± 0.023	(1978AL01)
	2.02 ± 0.09 [d,A]		mean [b]
7.65	2.7 ± 0.4	4.34 ± 0.06	mean [c]
10.3	0.46 ± 0.15	4.36 ± 0.17	mean [c]
12.71	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] = adopted.

[a] Based on $\tau_{1/2} = 11.000 \pm 0.016$ msec and Q_m. See also (1976CA29, 1978RA2A).

[b] Of values quoted in (1975AJ02) and (1978AL01).

[c] Of values quoted in (1975AJ02).

[d] See also ref. 7 in (1977KA24).

1979KO12; theor.). See also (1975SU01, 1976SU1C, 1977DE11), (1973MIYZ, 1974AD1B, 1976BE1E, 1977GA1E, 1977RI08, 1977TE1B, 1978CA1H, 1978LE02, 1978RA2A, 1978WE1J, 1979DO1A) and (1975BE24, 1975DO10, 1975DO1D, 1975KU20, 1975MO1F, 1975RH1A, 1975WI1E, 1976KH05, 1976MO1G, 1976SU09, 1976YO1D, 1977BE2A, 1977HW01, 1977KU1E, 1977OK1A, 1977WA1F, 1977YA1D, 1978BE1V, 1978BE58, 1978KU1A, 1978MO02, 1978SE1B, 1978SZ07, 1979DE15, 1979SZ02; theor.).

70. $^{13}C(\gamma, n)^{12}C$ $\qquad Q_m = -4.9464$

The decay of the giant resonance in ^{13}C takes place predominantly to ^{12}C*(15.1, 16.1) [and their analogues in ^{12}B]. Below $E_\gamma = 21$ MeV transitions to ^{12}C*(0, 4.4) are dominant (1975PA09). See also (1976CR1C, 1977WO04), (1977MA06; theor.), (1975AJ02) and ^{13}C in (1981AJ01).

71. $^{13}C(\pi^+, p)^{12}C$ $\qquad Q_m = 135.403$

At $E_{\pi^+} = 34$ MeV the population of ^{12}C*(4.4) is more than 10 times that of $^{12}C_{g.s.}$ (1978DO1F). See also (1975HU1D; theor.).

72. (a) $^{13}C(p, d)^{12}C$ $\qquad Q_m = -2.7218$

(b) $^{13}C(p, pn)^{12}C$ $\qquad Q_m = -4.9464$

Angular distributions of the d_0 and d_1 groups to ^{12}C*(0, 4.4) have been measured at $E_p = 8$, 12, 17, 50 and 54.9 MeV [see (1975AJ02)], 16.7 and 17.7 MeV (1977GU14) and 200 to 500 MeV (1979KA1R). See also (1978BA1R, 1978IG1A; prelim.: 650 and 800 MeV) and (1979CA1A). Angular distributions have also been measured for the groups to ^{12}C*(12.7, 15.1, 16.1) at $E_p = 50$ MeV (1970SC02) and 54.9 MeV (1968TA08). ^{12}C*(14.1) is not excited, consistent with $J^\pi = 4^+$ (1970SC02, 1974PA01). At $E_p = 62$ MeV, (1974PA01) report the excitation of states with $E_x = 15112 \pm 5, 16110 \pm 5$ [< 20], 17760 ± 20 [80 ± 20], 18800 ± 40 [80 ± 30], 21500 ± 100 [< 200] and 22550 ± 50 [< 200] keV [the numbers shown in brackets are $\Gamma_{c.m.}$, in keV]: $l_n = 1$ for all states except ^{12}C*(21.5) and (22.55) for which $l_p = (1)$ and $\neq 1$, respectively. Spectroscopic factors are derived by (1968TA08, 1970SC02, 1974PA01): see (1977AD02).

In a kinematically complete experiment at $E_p = 7.9$ to 12.5 MeV, it is found that sequential decay via states in ^{13}C and ^{13}N is strongly involved in reaction (b). Near $E_p = 12.5$ MeV there is some indication of sequential decay via singlet deuteron formation (1971OT02). See also (1975AJ02), ^{13}C, ^{13}N, ^{14}N in (1981AJ01) and (1978MA34; theor.).

73. ^{13}C(d, t)^{12}C $\qquad Q_m = 1.3109$

Angular distributions have been studied at $E_d = 0.41$ to 28 MeV [see (1975AJ02)] and at $E_{\vec{d}} = 13$ MeV (1978DA17: t_0, t_1, t_2), $E_d = 24.1$, 26.2 and 27.5 MeV (1977LI02: t to ^{12}C*(12.71, 15.11, 16.11) and $E_{\vec{d}} = 29$ MeV (1979CO08: t to ^{12}C*(0, 4.4, 12.71, 15.11, 16.11); see also ^{13}C(d, ^{3}He) in ^{12}B). (1977LI02) find an isospin mixing parameter, β, of 0.07 ± 0.03 for the two 1^+ states ^{12}C*(12.71, 15.11) and a charge-dependent matrix element of 180 ± 80 keV (1977LI02), 120 ± 30 keV (1979CO08); both are lower than the value previously obtained in this reaction, 250 ± 50 keV (1972BR27). If the $j = \frac{1}{2}$ component is excluded, which appears to be unwarranted, the charge dependent matrix element is 140 ± 40 keV (1979CO08). See also reactions 21, 22, 44, 50, 74 and 86. See also ^{15}N in (1981AJ01) and (1975ZA06, 1977AD02).

74. (a) ^{13}C(^{3}He, α)^{12}C $\qquad Q_m = 15.6314$
(b) ^{13}C(^{3}He, 2α)^{8}Be $\qquad Q_m = 8.2647$

Angular distributions have been measured at many energies up to $E(^3\text{He}) = 45$ MeV [see (1968AJ02, 1975AJ02)] and at 18 and 20 MeV (1977AD07; α_0, α_1) and 29.2 MeV (1976FU1F; α_1). Angular correlations of α-particles and 4.4 MeV γ-rays have been studied at $E(^3\text{He}) = 4.5$ MeV (1962HO13) and 29.2 MeV (1976FU1F) and for $\alpha\gamma_{15.1}$ at 9.4 and 11.2 MeV (1969TA09).

A study of reaction (b) leads to Γ_α/Γ for ^{12}C*(15.11) $= 4.1 \pm 0.9\%$; together with the other parameters for the decay of the state (see Table 12.8) this leads to $\Gamma_\alpha = 1.8 \pm 0.3$ eV. If this isospin forbidden α-width is the result of the mixing between the 1^+ states ^{12}C*(12.71, 15.11) [$T = 0$ and 1, respectively] via a charge dependent interaction, the matrix element is 340 ± 60 keV

(1974BA42). See also reactions 21, 22, 44, 50, 73 and 86. For the decay of ^{12}C*(12.7, 15.1) see Table 12.8 (1970RE09). See also (1976STYX, 1978SM1B) and (1977TA06; theor.).

75. (a) ^{13}C(^{6}Li, ^{7}Li)^{12}C $\quad Q_{\rm m} = 2.3041$
(b) ^{13}C(^{7}Li, ^{8}Li)^{12}C $\quad Q_{\rm m} = -2.9137$

At $E(^{7}$Li) = 34 MeV angular distributions have been observed for the reactions to ^{12}C*(0, 4.4) + ^{7}Li*(g.s., 0.48) and ^{8}Li*(0, 0.95) in all combinations. While ^{12}C*(0, 4.4) are dominant in the two spectra, ^{12}C*(7.7, 9.6) and, in reaction (a) at $E(^{6}$Li) = 36 MeV, ^{12}C*(12.7) are also populated (1973SC26).

76. ^{13}C(^{13}C, ^{14}C)^{12}C $\quad Q_{\rm m} = 3.2302$

See (1979KOZZ).

77. ^{13}C(^{14}N, ^{15}N)^{12}C $\quad Q_{\rm m} = 5.8870$

See (1975SE03, 1975SE04).

78. (a) ^{13}C(^{16}O, ^{17}O)^{12}C $\quad Q_{\rm m} = -0.8021$
(b) ^{13}C(^{17}O, ^{18}O)^{12}C $\quad Q_{\rm m} = 3.0982$
(c) ^{13}C(^{18}O, ^{19}O)^{12}C $\quad Q_{\rm m} = -0.9894$

Angular distributions for reaction (a) have been measured at $E(^{16}$O) = 13 and 14 MeV (1976DU04), 14, 17 and 20 MeV (1968KN1A, 1971BA68) and 41.7 and 46.0 MeV (1973DE21). See also (1975SE03). Angular distributions for reaction (b) are reported at $E(^{17}$O) = 29.8 and 32.3 MeV (1977CH22, 1978CH16) while reaction (c) has been studied at $E(^{18}$O) = 15, 20 and 24 MeV (1971BA68, 1971KN05) and 31.0 MeV (1978CH16). In all cases the ^{12}C$_{\rm g.s.}$ is involved as well as various states in the residual nucleus: see ^{13}C in (1981AJ01), ^{17}O in (1982AJ01) and ^{18}O and ^{19}O in (1978AJ03, 1983AJ01). See also (1978PA1D, 1978SC1E; theor.).

79. ^{13}C(^{19}F, ^{20}F)^{12}C $\quad Q_{\rm m} = 1.6548$

See (1975SE03, 1975SE04).

80. ^{14}C(p, t)^{12}C $\qquad Q_m = -4.6410$

Angular distributions have been measured at $E_p = 14.5$, 18.5 and 39.8 MeV: see (1975AJ02). At $E_p = 54$ MeV angular distributions are reported to two states at $E_x = 27.57 \pm 0.03$ and 29.63 ± 0.05 MeV [$\Gamma_{c.m.} \lesssim$ 200 keV]: their identification as the first $T = 2$ states is supported by the similar angular distributions to the first two $T = 2$ states in ^{12}B, reached in the (p, ^{3}He) reaction [see reaction 20 in ^{12}B]. The lower $T = 2$ state is well fitted by $L = 0$; the angular distribution to ^{12}C*(29.63) is rather featureless. It is suggested that its shape is somewhat more consistent with $L = 0$ than with $L = 2$ (1976AS01). [(1976BA24) has suggested that the second $T = 2$ state in $A = 12$ may have $J^\pi = 0^+$.] It is not excluded that the group to ^{12}C*(29.63) may be due to unresolved states (1976AS01). (1976AS01) report $\Gamma_p/\Gamma \approx 0.3 \pm 0.1$ and $\Gamma_{\alpha_1}/\Gamma < 0.1$ for the first $T = 2$ state and $\Gamma_p/\Gamma = 0.8 \pm 0.2$, $\Gamma_{p_0}/\Gamma \approx 0.4$ and $\Gamma_\alpha/\Gamma \approx 0.2$ for ^{12}C*(29.63). (1978RO08) report $E_x = 27595.0 \pm 2.4$ keV, $\Gamma \leq 30$ keV for the first $T = 2$ state and calculate the decay properties for two values of total width, 0 and 30 keV. Branching ratios for the decays to ^{8}Be(0) + α; ^{11}B*(0, 2.12, 4.45, 5.02, 6.74 + 6.79) + p; and ^{10}B(0) + d are, respectively, 10.5 ± 3.0, 3.0 ± 2.2, 8.0 ± 2.3, 0 ± 3.3, 8.4 ± 3.2, 8 ± 5, and 2.8 ± 2.0% (1979FR04).

81. (a) ^{14}C(^{16}O, ^{18}O)^{12}C $\qquad Q_m = -0.9341$
(b) ^{14}C(^{18}O, ^{20}O)^{12}C $\qquad Q_m = -1.562$

Angular distributions leading to the ground states in reaction (a) have been measured at $E(^{16}\mathrm{O}) =$ 20, 25 and 30 MeV (1973SC24, 1975SC35) and 32 MeV (1968GO01: see (1975SC35)). For reaction (b) see (1972EY01). See also (1978KA23; theor.).

82. ^{14}N(γ, np)^{12}C $\qquad Q_m = -12.4970$

See ^{13}C, ^{14}N in (1976AJ04) and (1979ME1E; theor.).

83. (a) ^{14}N(n, t)^{12}C $\qquad Q_m = -4.0151$
(b) ^{14}N(n, t)^{4}He^{4}He^{4}He $\qquad Q_m = -11.2899$

Angular distributions of the t_0 group have been measured at $E_n = 14-15$ MeV: see (1968AJ02). At $E_n = 18.2$ MeV reaction (b) takes place predominantly via sequential decay processes involving ^{12}C*(9.6, 10.8, 11.8) (1976TU04). See also ^{15}N in (1981AJ01).

84. ^{14}N(p, pd)^{12}C $\qquad Q_m = -10.2724$

See (1971WE05). See also (1976DO12; theor.).

85. $^{14}N(p, ^{3}He)^{12}C$ $Q_m = -4.7788$

Angular distributions have been studied at $E_p = 7.53$ to 44.6 MeV [see (1975AJ02)], at 50 MeV (1970SC02: to g.s., 4.4, 12.7, 14.1, 15.1, 16.1) and at 51.9 MeV (1976YO03: to 15.1, 16.1). The results of (1970SC02) strongly indicate $J^\pi = 4^+$ for ^{12}C*(14.1). At the highest energy (1976YO03) have measured the angular distributions to the first two $T = 1$ states in ^{12}C and to the analog states in ^{12}N, in the (p, t) reaction. See also ^{15}O in (1981AJ01).

86. (a) $^{14}N(d, \alpha)^{12}C$ $Q_m = 13.5743$
(b) $^{14}N(d, 2\alpha)^{8}Be$ $Q_m = 6.2076$

Observed α-particle groups are shown in Table 12.19. Angular distributions have been measured at energies up to 28.5 MeV [see (1968AJ02, 1975AJ02)] and at $E_d = 2.70$ to 2.76 MeV (1977KO33: α_0, α_1, α_2), 15 MeV (1976LU1A: α_0, α_1, α_2) and 40 MeV (1976VA07: α_0, α_1 and α to ^{12}C*(12.71, 14.08, 19.5, 20.6, 22.5)). Analysis of the angular distributions with a one-step, ZRDWBA, leads to $J^\pi = (1, 2, 3)^+$, $(2, 3)^+$ and $(2, 3)^+$, respectively for ^{12}C*(19.5, 20.6, 22.5) (1976VA07: spectroscopic factors calculated for all observed transitions). For a comparison of the relative strengths of ^{12}C*(12.7, 15.1) at $E_d = 40$ MeV see (1974VA15). See also reactions 21, 22, 44, 50, 73 and 74. For reaction (b) see (1972FA07). See also ^{16}O in (1977AJ02), (1975OL1A; applications) and (1978BE1H).

87. $^{14}N(^{3}He, p\alpha)^{12}C$ $Q_m = 8.0808$

See ^{16}O in (1977AJ02).

88. (a) $^{14}N(\alpha, ^{6}Li)^{12}C$ $Q_m = -8.7989$
(b) $^{14}N(\alpha, \alpha d)^{12}C$ $Q_m = -10.2724$

At $E_\alpha = 42$ MeV angular distributions of ^{6}Li ions corresponding to transitions to ^{12}C*(0, 4.4) have been measured by (1964ZA1A). For reaction (b) see ^{16}O in (1977AJ02).

89. $^{14}N(^{10}B, 3\alpha)^{12}C$ $Q_m = 7.6403$

See (1965SH1A).

90. ^{15}N(γ, t)^{12}C $\qquad Q_m = -14.8484$

See (1976PA22). See also (1977SP06) and ^{15}N in (1981AJ01).

91. ^{15}N(p, α)^{12}C $\qquad Q_m = 4.9656$

Angular distributions of α_0 and α_1 have been measured for E_p up to 18 MeV [see (1968AJ02)], at $E_p = 2.99$ to 5.14 MeV (1977JA11) and at six energies in the range $E_p = 19.85$ to 43.35 MeV (1971GU23). At $E_p = 43.7$ MeV the angular distributions to the 0^+ states ^{12}C*(0, 7.65, 17.76) are fitted by $L = 1$, and $L = 3$ is consistent with the distributions to ^{12}C*(14.1, 16.1) [$J^\pi = 4^+$ and 2^+, respectively] (1972MA21). The lifetime of ^{12}C*(4.4) $\tau_m = 65 \pm 9$ fsec (1970CO09). The energy of the second excited state of ^{12}C is 7654.2 ± 1.6 keV. The weighted average of this and previous values leads to $E_x = 7654.6 \pm 1.1$ keV, a value which leads to a sharply reduced rate for the ($\alpha\alpha\alpha$) process (1973MC01). See also (1966YO1A), (1977RO1H; astrophys.), (1975KU1L; theor.) and (1979ZY02) in ^{16}O in (1982AJ01).

92. ^{15}N(α, ^{7}Li)^{12}C $\qquad Q_m = -12.3817$

At $E_\alpha = 42$ MeV angular distributions have been obtained for all four of the transitions: $^{12}C_{g.s.} + {}^7$Li*(g.s., 0.48) and $^{12}C^*_{4.4} + {}^7$Li*(g.s., 0.48) (1968MI05).

93. (a) ^{16}O(γ, α)^{12}C $\qquad Q_m = -7.1620$
(b) ^{16}O(γ, 3α)^{4}He $\qquad Q_m = -14.4368$

See (1975AJ02) and (1975SK06) in ^{16}O (1977AJ02).

94. (a) ^{16}O(n, nα)^{12}C $\qquad Q_m = -7.1620$
(b) ^{16}O(p, pα)^{12}C $\qquad Q_m = -7.1620$

For reaction (a) see (1968AJ02). Reaction (b) appears to proceed primarily via excited states of ^{13}N and ^{16}O to ^{12}C*(4.4): see (1971EP03: $E_p = 46.8$ MeV) and (1972BO71: $E_p = 50$ MeV). See also (1975AJ02) for unpublished measurements and (1976GO1E; theor.).

95. ^{16}O(d, ^{6}Li)^{12}C $Q_m = -5.6885$

Angular distributions have been measured at $E_d = 12.7$, 13.6 and 14.6 MeV (1974GA30, 1975GO09; g.s.), $E_{\bar{d}} = 16$ MeV (1976JA1G; g.s.), $E_d = 35$ MeV (1975BE01, 1976NA19; g.s., 4.4), 50, 65 and 80 MeV (1978BE1T: g.s., 4.4, 14.1: ZRDWBA) and 80 MeV (1978OE02; to g.s., 4.4, 7.7, 9.6, 14.1, and broad (or unresolved) structures at 14.1 ± 2.6, 19.5 ± 1.5 MeV: ZRDWBA and FRDWBA). (1978BE1T, 1978OE02) report relative S_α. The relative S_α are strongly influenced by the choice of bound state parameters: see (1978BE1T), and compare with (1978OE02). Earlier studies at $E_d = 14.6$, 19.5, 28 and 55 MeV are listed in (1975AJ02). See also (1973FO1A, 1978BE1H), (1977KU1H, 1978TA1F; theor.) and ^{18}F in (1978AJ03).

96. ^{16}O(^{3}He, ^{7}Be)^{12}C $Q_m = -5.5758$

Angular distributions have been studied at $E(^3\text{He}) = 25.5$ MeV (D. Pisano, Yale Ph.D. thesis [P.D. Parker, private communication]: ^{12}C*(0, 4.4) + ^{7}Be*(0, 0.4)), 30 MeV (1970DE12: (^{12}C*(0, 4.4, 9.6) + ^{7}Be*(0, 0.4), ^{12}C*(7.7) + ^{7}Be$_{\text{g.s.}}$) and at 70 MeV (1976ST11: ^{12}C*(0, 4.4) and ^{7}Be*(0, 4.4); S_α are calculated). In the latter experiment ^{12}C*(7.7, 9.6) are observed but they are weakly populated (1976ST11). (1975AU01) report the extraction of S_α, the α-particle pickup spectroscopic factor, using a FRDWBA analysis [$E(^3\text{He}) = 26$ MeV]. See also (1975AJ02).

97. (a) ^{16}O(α, 2α)^{12}C $Q_m = -7.1620$
(b) ^{16}O(α, ^{8}Be)^{12}C $Q_m = -7.2538$

At $E_\alpha = 90$ MeV angular distributions involving ^{12}C*(0, 4.4) (reaction (a)) have been analyzed by PWIA and DWBA by (1976SH02): $S_\alpha = 2.9 \pm 0.5$ and 0.70 ± 0.23, respectively. At $E_\alpha = 65$ MeV angular distributions involving ^{8}Be$_{\text{g.s.}}$ (reaction (b)) and ^{12}C*(0, 4.4, 7.7, 9.6, 14.1) have been measured by (1974WO1C, 1976WO11) [the ground state distributions have also been studied for $E_\alpha = 55$ to 72.5 MeV]: $S_\alpha = 0.25$, 1.07, 0.05, 1.40 for ^{12}C*(0, 4.4, 7.7, 14.1). See also (1975AJ02) for earlier work, (1975HA1P, 1975IG1A, 1979BEZV) and (1977CH02; theor.).

98. ^{16}O(^{13}C, ^{17}O)^{12}C $Q_m = -0.8021$

See (1975SE03) and ^{17}O in (1977AJ02). See also (1973BR1C).

99. ^{16}O(^{14}N, ^{18}F)^{12}C $Q_m = -2.7461$

See (1966GA10, 1977VO08).

100. (a) ^{16}O(^{16}O, ^{20}Ne)^{12}C $\qquad Q_{\rm m} = -2.4310$
(b) ^{16}O(^{17}O, ^{21}Ne)^{12}C $\qquad Q_{\rm m} = 0.186$
(c) ^{16}O(^{18}O, ^{22}Ne)^{12}C $\qquad Q_{\rm m} = 2.5061$

Angular distributions have been measured at $E(^{16}\text{O}) = 23.9$ MeV (1974SP06: g.s. + g.s.) and 51.5 MeV (1974RO04: ^{12}C*(0, 4.4) and various ^{20}Ne states). At $E_{\rm c.m.} = 17.5$ MeV (reaction (a)) and 17 MeV (reactions (b) and (c)) angular distributions involving ^{12}C$_{\rm g.s.}$ (reaction (a)), ^{12}C$_{\rm g.s.}$ and ^{12}C*(0, 4.4) (reactions (b) and (c)) as well as a number of states in ^{20}Ne, ^{21}Ne and ^{22}Ne have been studied by (1977KA26). See reaction 25 in ^{20}Ne (1978AJ03) for additional work. See also (1978BO1R; theor.).

101. ^{17}O(d, ^{7}Li)^{12}C $\qquad Q_{\rm m} = -2.582$

See (1967DE03).

102. ^{18}O(p, tα)^{12}C $\qquad Q_{\rm m} = -10.8689$

The decay of the lowest $T = 2$ state of ^{16}O to ^{12}C*(0, 4.4) has been studied by (1973KO02). See also ^{16}O in (1977AJ02).

103. ^{18}O(d, ^{8}Li)^{12}C $\qquad Q_{\rm m} = -8.594$

See (1975AJ02).

104. ^{19}F(p, ^{8}Be)^{12}C $\qquad Q_{\rm m} = 0.8599$

See reaction 38 in ^{20}Ne (1978AJ03).

105. ^{19}F(d, ^{9}Be)^{12}C $\qquad Q_{\rm m} = 0.3005$

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

106. ^{19}F(^{3}He, ^{10}B)^{12}C $Q_{\rm m} = 1.3922$

See (1967DE14).

107. ^{19}F(^{13}C, ^{20}F)^{12}C $Q_{\rm m} = 1.6548$

See ^{20}F in (1978AJ03).

108. ^{19}F(^{15}N, ^{22}Ne)^{12}C $Q_{\rm m} = 6.6402$

See (1973GA14).

109. ^{20}Ne(α, ^{12}C)^{12}C $Q_{\rm m} = -4.6181$

See (1975AJ02) and (1978DA1F).

110. ^{24}Mg(α, ^{16}O)^{12}C $Q_{\rm m} = -6.7686$

Angular distributions have been reported at $E_{\alpha} = 22.8$ to 25.4 MeV (1978SO10) and 90 MeV (1977BE2G, 1978BE1U, 1979BEZV). See also ^{16}O in (1982AJ01).

111. (a) ^{24}Mg(e, e$'^{12}$C)^{12}C $Q_{\rm m} = -13.9306$
(b) ^{28}Si(e, e$'^{16}$O)^{12}C $Q_{\rm m} = -16.7542$

See (1978SA04, 1978SA1F).

112. ^{24}Mg(^{16}O, ^{28}Si)^{12}C $Q_{\rm m} = 2.824$

See (1972MA36: $E(^{16}{\rm O}) = 42$ MeV). See also (1975AJ02).

113. (a) ^{24}Mg(α, ^{18}O)^{12}C $Q_{\rm m} = -13.004$
(b) ^{28}Si(α, ^{20}Ne)^{12}C $Q_{\rm m} = -12.0233$

See (1979BEZV).

^{12}N
(Figs. 8 and 9)

GENERAL: (See also (1975AJ02).)

Model calculations: (1976IR1B).

Pion reactions (See also reaction 2.): (1975NA16, 1976NA16, 1978BU1J, 1978EP01, 1978NA1N, 1979BO23, 1979BOZW, 1979DI1A, 1979EP1B, 1979NA1Q, 1979WI1A).

Other topics: (1975HU14, 1976AB04, 1976BE1K, 1976IR1B, 1977SI1D, 1978SE1B, 1979WI1A).

Ground state of ^{12}N: (1974SHYR, 1975BE31, 1977YO1D, 1978LEZA).

$$\mu = +(0.4571 \pm 0.005)\ \text{nm (1968SU05)}.$$

The value of $|eqQ/h|$ for ^{12}N in Hg is 59.3 ± 3.3 kHz (1977TA04).

1. ^{12}N(β^+)^{12}C $\qquad Q_{\rm m} = 17.338$

The half-life of ^{12}N is 11.000 ± 0.016 msec (1978AL01): ^{12}N decays to ^{12}C*(0, 4.44, 7.65, 10.3, 12.71, 15.11): see Table 12.20.

2. ^{10}B(^{3}He, n)^{12}N $\qquad Q_{\rm m} = 1.574$

Observed neutron groups are displayed in Table 12.22. Angular distributions have been studied at $E(^3\text{He}) = 2.5$ to 13 MeV: see (1975AJ02).

3. ^{12}C(γ, π^-)^{12}N $\qquad Q_{\rm m} = -156.905$

π^- electroproduction has been studied at 90° for $E_\pi \approx 17$ and 29 MeV (1979PA06)[§] . See also (1976BE39, 1979BO1Y, 1979BOZW) and the "GENERAL" section here.

4. ^{12}C(p, n)^{12}N $\qquad Q_{\rm m} = -18.120$

[§] The total cross section (measured from threshold to $E_\gamma = 360$ MeV) peaks at $E_{\pi^-} \approx 40$ MeV [$\sigma \approx 8\ \mu$b] and then gradually decreases (1979BO23).

Table 12.21: Energy levels of ^{12}N

E_x (MeV ± keV)	$J^\pi; T$	$\tau_{1/2}$ or $\Gamma_{c.m.}$ (keV)	Decay	Reactions
0	$1^+; 1$	$\tau_{1/2} = 11.000 \pm 0.016$ msec	β^+	1, 2, 3, 4, 5, 6, 7
0.960 ± 12	2^+	$\Gamma < 20$ keV		2, 4, 5, 7
1.189 ± 12	$(2)^-$	100 ± 25	(p)	2, 4, 5
2.415 ± 20	(0^+)	45 ± 15	(p)	2, 5, 7
3.118 ± 14	$(2)^+$	210 ± 30	(p)	2, 5
3.534 ± 15	$\pi = +$	150 ± 40	(p)	2, 4, 5
4.25 ± 30 [a]		≈ 400	(p)	2, 4, 5
5.320 ± 12 [a]		≈ 250	(p)	2, 4, 5
6.10 ± 80 [a]		300 ± 100	(p)	5
7.13 ± 100 [a]		500 ± 100	(p)	5
7.629 ± 20 [a]		200 ± 40	(p)	2, 4, 5
8.446 ± 17 [a]		90 ± 30		2
(8.86 ± 100)		≈ 100		5
9.035 ± 12		< 35		2
9.42 ± 100		≈ 200		5
9.90 ± 100		100 ± 50		5

[a] Probably corresponds to unresolved states. See discussions in reaction 5 and Table 12.23.

$$E_{\text{thresh.}} = 19651.2 \pm 0.0061 \text{ (1969OV01, 1976FR13).}$$

At $E_p = 50$ MeV neutron groups are reported to ^{12}N*(0, 1.0, 3.7, 4.2, 5.3, 7.5) (1970CL01). Angular distributions have been reported at $E_p = 30.5$ and 49.5 (1970CL01), 61.9 (1977GOZY) and 144 MeV (1977MO1M, 1979MOZY). At $E_p = 62$ and 135 MeV, the M1 strength appears to be concentrated in the ground state group (1977BA2X). At $E_p = 647$ and 800 MeV, the spectra show a narrow high energy peak and a broad bump at lower energies associated with pion production (1976CA17). See also (1976ANZQ), (1976NO1E, 1976SL2A) and (1978GO1E; applications).

5. ^{12}C(^{3}He, t)^{12}N $\qquad Q_m = -17.357$

Triton groups observed at $E(^3\text{He}) = 44$ to 49.8 MeV are displayed in Table 12.23. Angular distributions of inelastically scattered ^{3}He to ^{12}C*(15.11, 16.11, 16.58, 19.57) have been compared with those of tritons to ^{12}N*(0, 0.96, 1.19, 4.25). When the ^{3}He cross sections are corrected for phase-space and isospin factors, the angular distributions are closely similar (to within 10%) to

Table 12.22: Neutron groups from ^{10}B(^{3}He, n)^{12}N [a]

E_x (MeV ± keV)		L	$\Gamma_{c.m.}$ (keV)	
(1966ZA01)	(1974FU11)	(1974FU11)	(1966ZA01)	(1974FU11) [d]
g.s.	g.s.	2	sharp	20 ± 20
0.959 ± 20	0.960 ± 12	2	< 50	16 ± 20
1.24 ± 30	1.189 ± 12	1	140 ± 40	140 ± 30
(1.72 ± 0.08)				
2.4 ± 100	(2.40 ± 60)			
3.14 ± 80	3.114 ± 15	2	280 ± 80	180 ± 40
3.57 ± 80	3.533 ± 15	2	270 ± 80	120 ± 40
	4.250 ± 30 [b]			290 ± 70 [b]
	5.320 ± 12	(0)		180 ± 20
	[c]			
	7.629 ± 20			200 ± 40
	8.446 ± 17			90 ± 30
	9.035 ± 12			16 ± 20

[a] See also Tables 12.29 in (1968AJ02) and 12.28 in (1975AJ02).

[b] May be due to unresolved states.

[c] States at $E_x = 6.4$, 6.9, 7.7 and 9.2 MeV are reported to be involved in the sequential decay at $E(^3\text{He}) = 11$ MeV (1970BO39). See also Table 12.23.

[d] T.G. Masterson, private communication.

those for the triton groups, strongly suggesting isobaric analogs (1969BA06). At $E(^3\text{He}) = 44$ MeV the distributions to ^{12}N*(2.42) and to ^{12}C*(17.77) are found to be similar. This, coupled with the strength of the group to ^{12}N*(2.42) in the ^{14}N(p, t) reaction, suggests that ^{12}N*(2.42) and ^{12}C*(17.77) are analog states and therefore that ^{12}N*(2.42) has $J^\pi = 0^+$ (1976CE02). See also (1976MA15). Angular distributions have also been studied at $E(^3\text{He}) = 217$ MeV (1974WI16, 1976WI05).

At $E(^3\text{He}) = 49.3$ MeV (1976MA15) report no evidence for a state at $E_x = 1.72$ MeV. A 1^- state exists in ^{12}B at $E_x = 2.62$ MeV. The missing analog state in ^{12}N would have a width > 1 MeV. ^{12}N*(4.15, 5.23), observed in this reaction, occur at lower energies and are broader than ^{12}N*(4.25, 5.32) reported in ^{10}B(^{3}He, n); and ^{12}N*(6.10, 7.13) observed here are not reported in ^{10}B(^{3}He, n). It is suggested that the selectivity is greater in the latter reaction and that the triton groups go to

Table 12.23: States of ^{12}N from ^{12}C(^{3}He, t)^{12}N [a]

E_x (MeV ± keV)	$\Gamma_{c.m.}$ (keV)	J^{π} [b]
0	–	
$\equiv 0.964$	< 20	2^+
1.190 ± 20	80 ± 30	(2^-)
2.415 ± 20	45 ± 15	(0^+) [f]
3.136 ± 30	240 ± 40	
3.55 ± 50	150 ± 100	
4.15 ± 80 [c]	650 ± 100	
5.23 ± 80 [c]	400 ± 80	
6.10 ± 80 [c]	300 ± 100	
7.13 ± 100 [c]	500 ± 100	
7.48 ± 100 [c]	180 ± 80	
(8.86 ± 100) [d]	≈ 100	
9.42 ± 100	≈ 200	
9.90 ± 100	100 ± 50	
[e]		

[a] (1976MA15): $E(^3\text{He}) = 49.3$ MeV. See also (1969BA06).
[b] (1969BA06): $E(^3\text{He}) = 49.8$ MeV.
[c] May be due to unresolved states: see text.
[d] Observed at only one angle.
[e] No other states observed with $E_x < 13$ MeV.
[f] (1976CE02): $E(^3\text{He}) = 44$ MeV.

unresolved states. At higher E_x it should be pointed out that many more states are observed in ^{12}B than in ^{12}N: with the possible exception of the relatively narrow states ^{12}N*(9.42, 9.90), the other reported groups with $E_x > 6$ MeV may thus be due to unresolved groups (1976MA15). See also (1975GO1L, 1978TA1M).

6. ^{12}C(^{14}N, ^{14}C)^{12}N $\qquad Q_m = -17.494$

See (1975NA11).

7. ^{14}N(p, t)^{12}N $\qquad Q_m = -22.135$

At $E_p = 51.9$ MeV angular distributions of the tritons to ^{12}N*(0, 0.96) and of the ^{3}He ions to the analog $T = 1$ states [^{12}C*(15.11, 16.11)] have been measured (1976YO03). At $E_p = 52.5$ MeV the angular distribution to ^{12}N*(2.42) has been studied: see reaction 5 (1976CE02). The atomic mass excess of ^{12}N derived from this reaction is 17338 ± 1 keV (1976NO1J): it is adopted by (1977WA08).

^{12}O

(Fig. 9)

^{12}O has been observed in the ^{16}O(α, ^{8}He) reaction at $E_\alpha = 117.4$ MeV. At $\theta_{\text{lab}} = 8°$, the differential cross section (lab) $= 2 \pm 1$ nb/sr: $Q_0 = -66.02 \pm 0.12$ MeV. The width of the ground state is $\approx 400 \pm 250$ keV. There is some indication of an excited state of ^{12}O at $E_x = 1.0 \pm 0.1$ MeV, which would imply an appreciable downward shift from the position of the analog first excited state in ^{12}Be. This would be surprising if the latter is indeed a 2^+ state (1978KE06), as it appears to be: see ^{12}Be. Q_0 leads to a mass excess of 32.10 ± 0.12 MeV for ^{12}O: it is thus unstable to decay into ^{10}C + 2p by 1.83 MeV and into ^{11}N* + p by 0.41 [note that ^{11}N* is probably not the ground state of ^{11}N and that it is very broad: see ^{11}N]. The diproton branching ratio of ^{12}O$_{\text{g.s.}}$ is estimated to be $60 \pm 30\%$. The d-coefficient in the IMME for $A = 12$ is calculated to be 0 ± 11 keV. Based on this the first $T = 2$ state in ^{12}N should occur at $E_x = 12.29 \pm 0.02$ MeV (1978KE06). See also (1979NA1E), (1975AJ02, 1977CE05, 1978GU10) and (1975BE31, 1975HU14, 1976IR1B; theor.).

^{12}F

(Not illustrated)

This nucleus has not been observed: see (1975BE31, 1976IR1B; theor.).

^{12}Ne

(Not illustrated)

This nucleus has not been observed: see (1975BE31; theor.).

References

(Closed 01 July 1979)

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