Energy Levels of Light Nuclei
$A = 12$

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Abstract: An evaluation of $A = 5$–24 was published in *Nuclear Physics* 11 (1959), 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 TUNL/NNDC format.

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^{12}B

(Fig. 19)

GENERAL:

Theory: See (1956KU1A, 1958FR1C).

1. ^{12}B(β^-)^{12}C $\qquad Q_{\rm m} = 13.376$

The spectrum is complex: see ^{12}C. The transition to ^{12}C$_{\rm g.s.}$ is allowed; hence $J(^{12}{\rm B}) = 1^+$.

2. ^{6}Li(^{7}Li, p)^{12}B $\qquad Q_{\rm m} = 8.338$

Three groups of protons are reported, corresponding to the ground state and to the excited states at 0.95 and 1.67 MeV. At $E(^{7}{\rm Li}) = 2.0$ MeV, $\theta = 90°$ (lab), the relative intensities are 1 : 1.1 : 0.8 (1957NO14). See also (1957NO17).

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

See ^{14}C.

4. ^{9}Be(α, p)^{12}B $\qquad Q_{\rm m} = -6.884$

At $E_\alpha = 21.7$ MeV, proton groups are observed corresponding to ^{12}B*(0, 0.95, 1.65, 3.38, 3.82) (1951MC57, 1955RA41).

5. ^{9}Be(^{7}Li, α)^{12}B $\qquad Q_{\rm m} = 10.463$

See (1957NO17).

6. ^{10}B(t, p)^{12}B $\qquad Q_{\rm m} = 6.344$

Table 12.1: Energy levels of ^{12}B

E_x (MeV $\pm$ keV)	J^π	$\tau_{1/2}$ or Γ (keV)	Decay	Reactions
0	1^+	$\tau_{1/2} = 20.34 \pm 0.5$ msec	β^-	1, 2, 3, 4, 5, 10, 13, 15, 20, 22
0.947 ± 5	$\leq 3^+$	< 10	γ	2, 4, 6, 10
1.674 ± 11	1^-, 2^-	< 10	γ	2, 4, 6, 10
2.618 ± 11		< 10		6, 10
2.723 ± 11		< 10		10
3.383 ± 9	$\leq 3^+$	< 10		4, 6, 10
3.76 ± 10	2^+	40 ± 5	n	4, 6, 8, 10
4.54 ± 20	3^-	140 ± 20	n	6, 8, 10
5.00 ± 20	1	60 ± 20	n	8
5.61 ± 20	2	120 ± 40	n	8
5.73 ± 20	3	60 ± 20	n	8

At $E_t = 0.90$ MeV, proton groups are observed corresponding to ^{12}B*(0.94, 1.65, 2.61, 3.37, 3.75, 4.46) (1955BI26: $\pm \approx 0.1$ MeV).

7. ^{11}B(n, γ)^{12}B $\quad Q_m = 3.365$

$\sigma_{th} < 50$ mb (1958HU18). See also (1953WI1C).

8. ^{11}B(n, n)^{11}B $\quad E_b = 3.365$

The parameters of observed resonances at $E_n = 0.43$, 1.28, 1.78, 2.45 and 2.58 MeV are exhibited in Table 12.2. The rise of the cross section at low energies may indicate a broad level formed by s-wave neutrons (1951BO45). The angular distributions of elastically scattered neutrons have been studied for $E_n = 0.43$ to 1.50 MeV by (1955WI25). It is found that the 0.43-MeV resonance has $J = 2^+$, formed by p-waves, either all in channel spin 1 or all in channel spin 2. The 1.28 MeV resonance had $J = 3^-$, formed by d-waves, with the level width of channel spin 2 about 10 times that of channel spin 1. Potential scattering at $E_n = 1.5$ MeV is nearly all s-wave: $\delta_0 = -90^\circ$ (1955WI25).

The total cross section for natural boron shows no sharp discontinuities for $E_n = 4.4$ to 5.6 MeV ($\sigma \approx 1.6$ b) and for $E_n = 7.8$ to 8.6 MeV ($\sigma \approx 1.4$ b) (1956BE98). The total cross section has also been measured for $E_n = 6$ to 9.7 MeV (1954NE1A) and from $E_n = 14.1$ to 18.0

Table 12.2: Resonances in ^{11}B(n, n)^{11}B

E_n [a] (MeV)	$\sigma_{max} - \sigma_{tot}$ [b] b	Γ_n [a] (keV)	^{12}B* (MeV)	l [c]	θ_n^2 [b]	J^π
0.43 ± 0.01	2.9	40 ± 5	3.76	1	0.036	2^+
1.28 ± 0.02	2	140 ± 20	4.54	2	0.28	3
1.78 ± 0.02	0.4	60 ± 20	5.00	1	0.012	1
				2	0.056	
2.45 ± 0.02	0.5	120 ± 40	5.61	1	0.017	2
				2	0.053	
2.58 ± 0.02	0.6	60 ± 20	5.73	1	0.008	3
				2	0.025	

[a] (1951BO45, 1958HU18).
[b] (1951BO45): $R = 4.5 \times 10^{-13}$ cm.
[c] (1951BO45, 1955WI25, 1958HU18).

MeV by (1952CO41, 1954CO16); see (1955HU1B). See also (1955HI1C, 1956LA1C, 1957LA14, 1958HU18). At $E_n = 14.5$ MeV the non-elastic cross section for natural boron is 0.64 ± 0.04 b (1956FL1B).

9. (a) ^{11}B(n, d)^{10}Be $\quad Q_m = -9.010 \quad E_b = 3.365$
   (b) ^{11}B(n, t)^{9}Be $\quad Q_m = -9.564$
   (c) ^{11}B(n, α)^{8}Li $\quad Q_m = -6.636$
   (d) ^{11}B(n, p)^{11}Be $\quad Q_m = -10.69$

The cross section for reaction (c) decreases from 27 mb at $E_n = 12.6$ MeV to 16 mb at $E_n = 20.0$ MeV (1956AR21). At $E_n = 14.1$ MeV, the cross section for reaction (b) is 15 ± 5 mb (1958WY67). Reaction (a) has not been reported. See also (1954HE1B). For reaction (d) see ^{11}Be.

10. ^{11}B(d, p)^{12}B $\quad Q_m = 1.138$

Proton groups observed at $E_d = 4.0$ to 8.5 MeV are listed in Table 12.3. No other groups are observed for $E_x = 0$ to 3.15 MeV with an intensity greater than 4% of the ground-state

Table 12.3: ^{12}B levels from ^{11}B(d, p)^{12}B

^{12}B* (MeV) [a]	l_n	J^π	$\frac{\Lambda}{2J+1}$ [e]
0	1	1^+ [c]	3.4
0.947 ± 0.005	1	$3^+, 2^+, 1^+, (0^+)$	1.5, 2.1, 3.5, (10)
1.674 ± 0.011	0	$2^-, (1^-)$	3.5, (5.8)
2.618 ± 0.011			
2.723 ± 0.011			
3.383 ± 0.009	1	$3^+, 2^+, 1^+, (0^+)$	1.6, 2.2, 3.7, (11)
3.76 [b]			
4.53 [b]	2	3^- [d]	3.8

[a] (1950BU1A, 1953EL12).
[b] (1953HO48).
[c] From ^{12}B(β^-)^{12}C.
[d] From ^{11}B(n, n)^{11}B.
[e] Neutron capture probability; proportional to reduced width; values greater than 4 are regarded as improbable (1953HO48).

group, or from 3.15 to 3.5 MeV excitation with an intensity greater than 8% (1953EL12). See also (1954KH1A, 1955KH35). Angular distributions and absolute cross sections have been determined at $E_d = 8$ MeV. Analysis by stripping theory leads to the assignments indicated in Table 12.3. Neutron capture probabilities are compared with expected single-particle values to eliminate certain spin possibilities (1953HO48). At $E_d = 1.05$ MeV, γ-rays with energy 0.94 and 1.64 MeV are observed with an intensity ratio of 2 : 1 (1954TH1B). See also (1955RA41, 1956KA1A, 1956TA07, 1957CH25, 1957CO59).

11. ^{11}B(t, d)^{12}B $\qquad Q_m = -2.894$

Not reported.

12. ^{11}B(α, ^{3}He)^{12}B $\qquad Q_m = -17.213$

Not reported.

13. ^{12}C(n, p)^{12}B $\qquad Q_m = -12.593$

See (1948JE03).

14. ^{12}C(t, ^{3}He)^{12}B $Q_m = -13.358$

Not reported.

15. ^{13}C(γ, p)^{12}B $Q_m = -17.539$

See ^{13}C.

16. ^{13}C(d, ^{3}He)^{12}B $Q_m = -12.045$

Not reported.

17. ^{13}C(t, α)^{12}B $Q_m = 2.274$

Not reported.

18. ^{14}C(n, t)^{12}B $Q_m = -17.228$

Not reported.

19. ^{14}C(p, ^{3}He)^{12}B $Q_m = -17.993$

Not reported.

20. ^{14}C(d, α)^{12}B $Q_m = 0.358$
$Q_0 = 0.362 \pm 0.0015$ (1956DO41).

See also (1950HU72).

21. ^{14}N(n, ^{3}He)^{12}B $Q_{\rm m} = -17.365$

Not reported.

22. ^{15}N(n, α)^{12}B $Q_{\rm m} = -7.629$

See (1948JE03).

^{12}C
(Fig. 20)

GENERAL:

Theory : See (1955FE1A, 1955HE1E, 1956CA1F, 1956EL1C, 1956GL1B, 1956HA1C, 1956HA1D, 1956KU1A, 1956MO1D, 1956NA1A, 1956PE1A, 1956RE1C, 1956WI1F, 1957BA1H, 1957BI1C, 1957HE1B, 1957KU58, 1957PA1A, 1957RE1A, 1957SA1B, 1958CA1G, 1958FR1C).

1. ^{7}Li(^{6}Li, n)^{12}C $Q_{\rm m} = 20.931$

See (1957NO17).

2. (a) ^{9}Be(^{3}He, n)^{11}C $Q_{\rm m} = 7.565$ $E_{\rm b} = 26.286$
(b) ^{9}Be(^{3}He, p)^{11}B $Q_{\rm m} = 10.329$
(c) ^{9}Be(^{3}He, α)^{8}Be $Q_{\rm m} = 18.911$
(d) ^{9}Be(^{3}He, d)^{10}B $Q_{\rm m} = 1.093$

The yields and angular distributions of protons leading to the ground state and several excited states of ^{11}B have been investigated by (1956AL1E: $E(^{3}$He) up to 2.7 MeV), by (1955HO1D, 1956HL01: $E(^{3}$He) $= 2.0$ MeV), by ((1956WO1A, 1956WO1C, 1957JO1B) and E. Wolicki, private communication: 2 to 4.5 MeV) and by (D.R. Sweetman, private communication: 6.05 MeV). The yield rises rapidly to $E(^{3}$He) $= 1.8$ MeV and remains approximately constant to 4.5 MeV, with no indication of resonance. Angular distributions show fore and aft asymmetry and vary only slowly with energy. At $E(^{3}$He) $= 2$ MeV, it appears that both direct interaction and compound nucleus formation, involving interfering resonances with $l \leq 3$, may be taking place. At higher energies the forward peaking suggestive of direct interaction becomes more obvious. See also ^{11}B. For reactions (a), (c) and (d), see ^{11}C, ^{8}Be and ^{10}B.

Table 12.4: Energy levels of ^{12}C

E_x (MeV $\pm$ keV)	$J^\pi; T$	Γ (keV)	Decay	Reactions
0	0^+; 0	$-$ [a]	stable	1, 3, 10, 11, 16, 17, 19, 20, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 37, 39, 40, 41, 42
4.433 ± 5	2^+; 0	$0.01 - 0.02$ eV [b]	γ	3, 10, 16, 19, 20, 24, 25, 26, 27, 29, 30, 34, 39, 41
7.656 ± 7	0^+; 0	< 25	α, (γ)	3, 10, 16, 19, 24, 25, 26, 29, 30, 39
9.63 ± 14	(1^-); 0	30 ± 8 [a]	α	10, 16, 24, 25, 26, 27, 29, 39, 42
10.1 ± 200	0^+; 0	≈ 2000	α	19, 25, 42
10.84 ± 50				10, 16, 26
11.1 ± 100				16
11.81 ± 50				10, 16
12.73 ± 50	(1^+); 0		(α), γ	10, 16, 26, 29, 30
(13.21 ± 50)				16
13.30 ± 50				10, 16
14.05 ± 60				10, 16
15.11 ± 10	1^+; 1	0.069	(α), γ	3, 10, 16, 20, 23, 25, 26, 34, 39
15.62 ± 60				10, 16
16.11 ± 2	2^+; 1	6	α, p, γ	10, 12, 14, 16, 23
16.58 ± 15	2^-; (1)	295	α, p, γ	10, 12, 23
17.23	1^-; (1)	1160	α, p, γ	12, 14, 22, 23
17.77	(0^+)	140	α, p	12
18.37	(2^+)	280	α, p, γ	12, 23
18.40		46	p, p$'$	14
18.85		90	n, p, γ	12, 13, 14
19.26		450	n, p, γ	12, 13, 14, 21
19.42		45	p	14
19.67		180	n, p, (γ)	13, 21
19.88		90	p, p$'$	14
20.27		180	n, p, (γ)	13, 14, 21
20.49		180	(n), p, γ	12, 21
20.65		180	n, p, γ	12, 13, 14, 21, 22, 26
21.34			n, p, (γ)	12, 13, 21, 22

Table 12.4: Energy levels of ^{12}C (continued)

E_x (MeV ± keV)	$J^\pi; T$	Γ (keV)	Decay	Reactions
21.80			n, (α), p, (γ)	12, 13, 21, 22, 23
22.55 ± 100		≈ 4000	n, p, γ	12, 13, 20, 21, 22, 23
(22.8)			(n), (α), (p), (γ)	21, 22
(24.3)			n, (α), (γ)	13, 23
(25.4)			n, p, d	6, 13
(26.0)			n, α, (p), d, (γ)	5, 6, 8, 22
(26.4)			(α), p, d	6, 8
(26.8)			α, p, d	6, 8
(27.0)			p, d	6
(27.2)			p, d	6
(27.4)			p, d	6
(29.4)			(α), (γ)	23

[a] For reduced width, see ^{11}B(d, n)^{12}C and Table 12.8.

[b] See reactions 3, 20 and 24.

3. ^{9}Be(α, n)^{12}C $\qquad Q_m = 5.709$

Neutron groups corresponding to states of ^{12}C*(0, 4.4, 7.6) have been observed with E_α up to 5.3 MeV. At $E_\alpha = 5.3$ MeV the forward yield of the group leading to the 7.6 MeV state is about $\frac{1}{8}$ of that leading to the 4.4 MeV state: see (1952GU1A, 1955ST1C, 1956ME1B, 1957RI38); see also (1957DI1B).

The energy of the γ-ray from the first excited state is 4.425 ± 0.020 (1954MI68), 4.48 ± 0.06 MeV (1955BE1G) (both values corrected for Doppler shift). The internal pair conversion, coefficient indicates an E2 transition (1954MI68); the angular correlation of pairs admits M1 or E2, favoring the latter (1954HA07, 1956GO1K, 1956GO73, 1958AR1B). The angular distribution of γ-rays observed at several bombarding energies is consistent with $J = 2^+$ (1955TA28, 1956PR1A). The n-γ correlation at $E_\alpha = 5.3$ MeV (thick target) is isotropic within 6.5% (1956ST1E: see also (1958TA05)). The mean lifetime of the 4.4 MeV level is $(2.6 \pm 0.9) \times 10^{-14}$ sec, about one-eighth of the single-particle value for an E2 transition (1956DE22).

The 7.7 MeV state appears to decay predominantly into ^{8}Be + α (see ^{12}B(β^-)^{12}C and ^{12}C(α, α')^{12}C*). A gamma ray of energy 3.1 MeV has been reported by (1953BF01, 1954UE01, 1956ST1E, 1956ST1F, 1957ST1E), but (1955BE1G, 1957GO89, 1957KR1A) find no evidence of the 7.7 MeV nuclear pairs which should accompany the decay to the ground state. (1955BE1G) estimate that at least 96% of the decays proceed to ^{8}Be + α; (1957KR1A, 1958KR70) find $< 1.6 \times 10^{-5}$ 7 MeV pairs per 4.4 MeV γ-ray; assuming a population ratio of 1 : 8, this result yields $\Gamma_\pi/\Gamma < 1.3 \times 10^{-4}$. An upper limit of $\frac{1}{600}$ for the ratio of 7.6/4.4 MeV pairs is reported by (1957GO89). (1954DI1A) find no n-γ coincidences other than those associated with the 4.4 MeV level. See also (1957RO1E).

At $E_\alpha = 21.7$ and 175 MeV, γ-radiation from the 15 MeV, $J = 1^+$; $T = 1$ state (see ^{12}C(p, p′)^{12}C*) is reported (1954RA35, 1957WA04). At the higher energy, the ratio of 15 MeV to 4.4 MeV radiation is 1.2×10^{-2} (1957WA1F). See also (1954EL1B, 1955BR1A, 1955HA1E, 1956GO1N, 1957BR1J) and (1955MA1J; theor.).

4. ^{10}B(d, γ)^{12}C $\qquad Q_\mathrm{m} = 25.195$

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

5. ^{10}B(d, n)^{11}C $\qquad Q_\mathrm{m} = 6.473 \qquad E_\mathrm{b} = 25.195$

The thin-target excitation function in the forward direction in the range $E_\mathrm{d} = 0.3$ to 4.6 MeV shows some indication of a broad resonance near $E_\mathrm{d} = 0.9$ MeV. Above $E_\mathrm{d} = 2.4$ MeV, the cross section increases rapidly to 210 mb/sr at 3.8 MeV, and then remains constant to 4.6 MeV (1954BU06, 1955MA76). Angular distributions seem to be dominated by the stripping process: see ^{11}C. The yield of 6.5 MeV γ-rays has been measured at four bombarding energies between 0.8 and 2.2 MeV (1955SA1B). See also ^{11}C.

6. ^{10}B(d, p)^{11}B $\qquad Q_\mathrm{m} = 9.237 \qquad E_\mathrm{b} = 25.195$

Absolute yields and angular distributions are reported for various proton groups by (1952EN19, 1954BU06, 1954PA28, 1956MA69, 1956VA17) for $E_\mathrm{d} = 0.18$ to 3.1 MeV. Although the excitation functions show several broad peaks, no clear resonances can be identified, and it must be assumed that many overlapping resonances are involved (1956MA69). Angular distributions indicate both stripping and compound nucleus processes even at low bombarding energies (1954PA1D). However, the p_1 group, leading to ^{11}B*(2.1), shows no stripping even at $E_\mathrm{d} = 3$ MeV; it is suggested that an orbital angular momentum selection rule is operative here (1956MA69: see ^{11}B). Absolute cross sections reported by (1954BU06, 1954PA28, 1956MA69) differ rather greatly.

The yields of 6.8 and 7.3 MeV γ-rays have been measured at four bombarding energies between 0.8 and 2.2 MeV (1955SA1B). At $E_\mathrm{d} = 1.70$ MeV, θ(lab) $= 58°$, the cross section for protons leading to the 6.76 MeV state is 6.1 ($\pm$15%) mb/sr (1956KA1A).

7. ^{10}B(d, d)^{10}B $E_b = 25.195$

See ^{10}B.

8. ^{10}B(d, α)^{8}Be $Q_m = 17.819$ $E_b = 25.195$

Excitation curves for ground state α-particles have been measured for $E_d = 0.9$ to 2.6 MeV at $45°$, $90°$ and $150°$. Broad maxima are observed at 1.0, (1.4) and 2.0 MeV. At $E_d = 0.91$ MeV, the angular distribution of α_0 particles shows a peaking in the forward direction (1956MA69). See also ^{8}Be.

9. ^{10}B(t, n)^{12}C $Q_m = 18.937$

Not reported.

10. ^{10}B(^{3}He, p)^{12}C $Q_m = 19.702$

Proton groups reported by (1955BI26) and (1958MO99) are listed in Table 12.5. A careful search, at $E(^{3}\text{He}) = 1.25$ MeV, reveals no other level in the range $E_x = 4.4$ to 7.7 MeV (1958MO99: region at $E_x = 6.4$ MeV obscured). At $E(^{3}\text{He}) = 2.0$ MeV, the proton group leading to the 15.11 MeV level was found to be in coincidence with a 15.10 MeV γ-ray: Γ_γ/Γ for this level is 0.77 ± 0.20. The ratio of the width for γ-emission to the 4.4 MeV level to the ground state Γ_γ is ≈ 0.03. The 12.76 MeV level also emits γ-rays: $\Gamma_\gamma/\Gamma \approx 0.02$, suggested $J^\pi = 1^+$ ((1957GO1B) and H.E. Gove, private communication). Coincidence studies by (1958MO99) lead to $\Gamma_\gamma/\Gamma < 0.9$% for the 7.7 MeV level, $\Gamma_\gamma/\Gamma = 3 \pm 1$ % for the 12.76 MeV level, and 50 ± 25 % for the 15 MeV level. See also ^{11}B(d, n)^{12}C, (1958BR1D, 1958SW63) and ^{13}N.

11. ^{10}B(α, d)^{12}C $Q_m = 1.351$

$Q_0 = 1.341 \pm 0.002$ (1956DO41).

$Q_0 = 1.36 \pm 0.09$ (1956PI1A).

$Q_0 = 1.39 \pm 0.01$ (1953SH64).

See also ^{14}N.

12. (a) ^{11}B(p, γ)^{12}C $Q_m = 15.958$

(b) ^{11}B(p, α)^{8}Be $Q_m = 8.582$ $E_b = 15.958$

Table 12.5: ^{12}C states from ^{10}B(^{3}He, p)^{12}C

A		B	
E_x (MeV)	Γ_γ/Γ	E_x (MeV $\pm$ keV)	Γ_γ/Γ
4.43	1	4.43	1
7.77		7.65	< 0.009
9.61		9.61	
10.75		10.90 ± 60	
11.83		11.84 ± 60	
12.76	0.02	12.69 ± 60	0.03 ± 0.01
13.31		13.30 ± 60	
13.97		14.05 ± 60	
15.10	0.77 ± 0.20	14.97 ± 60	0.50 ± 0.25
		15.62 ± 60	
16.04		16.10	
16.57		16.57 ± 60	

A: (1955BI26, 1957GO1B): $E(^3\text{He}) = 0.9$ and 2.0 MeV, values ± 0.1 MeV.

B: (1958MO99): $E(^3\text{He}) = 1.25$ MeV.

In the range $E_p = 0$ to 3 MeV, five principal resonances occur, at $E_p = 0.16$, 0.67, 1.4, 2.0 and 2.6 MeV (see Table 12.6). All except the second and fourth exhibit resonance for α_0, α_1, γ_0 and γ_1 (to ^{8}Be*(0, 2.9) and ^{12}C*(0, 4.4)); at $E_p = 0.67$ MeV, only α_1, γ_1 are resonant. It follows from angular momentum selection rules that resonances for α_0 must have the character $J^\pi = 0^+$, 1^-, 2^+, 3^-...; $J = 0^+$ is excluded by observation of γ_0.

The $E_p = 0.16$ MeV resonance (^{12}C*(16.11)) is well established as $J = 2^+$; probably the $T = 1$ analogue of ^{12}B*(0.95). The angular distribution of α_0 particle is strongly anisotropic at resonance and shows a $(\cos\theta)$ term varying with energy near resonance. The assumption $J = 2^+$, $l_p = 1$, with interference from an s-wave state at higher energy gives a good account of the observed angular distributions from $E_p = 0.13$ to 0.3 MeV. The channel spin ratio $\chi = 0.42 \pm 0.02$; the relative amplitude of the interfering $J = 1^-$ state is 0.022 ± 0.002 (1952TH1B). The angular correlation of α_1 and the subsequent breakup of ^{8}Be*(2.9) also requires $J = 2^+$, with the ratio of reduced matrix elements for outgoing d to s-waves, $B = 0.80$, phase difference $\cos\beta = 0.60$ (1955GE1A). The angular distribution of γ_1 and of the following 4.4 MeV radiation is consistent with the scheme 2^+(M1)2^+(E2)0^+ with the channel spin ratio $\chi = 0.42$ (1954GR1C); (1956CR1C) obtain $\chi = 0.51 \pm 0.03$. Angular distributions of the 16 MeV radiation, γ_0, require $J = 2^+$, with interference from a $J = 1^-$ level at $E_p = 1.4$ MeV (1954GR1C, 1956CR1C). (γ_0 is not resonant at $E_p = 0.67$ MeV, so this state cannot be involved here.) The resonant energy is 163.1 ± 0.2 keV;

Table 12.6: Resonances in ^{11}B(p, γ)^{12}C and ^{11}B(p, α)^{8}Be

E_p (MeV)	Γ_{lab} (keV)	$\sigma(\gamma_{16})^a$ (μb)	$\sigma(\gamma_{12})^a$ (μb)	$\sigma(\alpha_0)^e$ (mb)	$\sigma(\alpha_1)^e$ (mb)	$\Gamma_{\gamma_{16}}{}^e$ (eV)	$\Gamma_{\gamma_{12}}{}^e$ (eV)	$\Gamma_{\alpha_0}{}^e$ (keV)	$\Gamma_{\alpha_1}{}^e$ (keV)	$\Gamma_p{}^e$ (keV)	^{12}C* (MeV)	$J^\pi; T$
0.163	7	5.5	152	0.2	10	$\lesssim 3$	70	0.1	5	0.005	16.11	$2^+; 1$
0.675 [b]	322	(< 2.3) [g]	48	(< 0.2) [g]	600	$\lesssim 0.5$	15	$\lesssim 0.05$	150	150	16.58	$2^-; (1)$
1.388 [b]	1270	35	18	6	150	40	20	7	200	1000 [h]	17.23	$1^-; (1)$
1.98 [c,d]	150	non-res.	non-res.	[8] [f]	[39] [f]						17.77	(0^+)
2.63 [c,d]	300	weak	res.	[16] [f]	[180] [f]						18.37	(2^+)
3.13 [d]	100	weak	res.								18.83	
3.55 [d]	500	res.	res.								19.21	
4.94 [d]	200	non-res.	res.								20.49	
5.12 [d]	200	non-res.	res.								20.65	

[a] (1953HU29); ratio $\sigma(\gamma_{16})/\sigma(\gamma_{12}) = 3.3 \pm 1$ % at $E_p = 0.16$ MeV (1956CR1C).
[b] (1953HU29).
[c] (1955HO48).
[d] (1955BA22).
[e] (1953BE61).
[f] (1953PA26): normalized at $E_p = 1.4$ MeV. See also (1955HO48).
[g] Non-resonant.
[h] According to (1957DE11), $\Gamma_p \approx 50$ keV: see ^{11}B(p, p)^{11}B. If this value is used, α-widths should be increased by a factor of 6, and γ-widths by a factor of 20.

$\Gamma_{lab} = 6.5 \pm 0.6$ keV (see (1955AJ61)). The very small α-width suggests $T = 1$ (1953BE61).

For the $E_p = 1.4$ MeV state (^{12}C*(17.23)), the possible assignments are 1^- (s-wave), 2^+ (p-wave), 1^- or 3^- (d-wave); d-wave formation would seem to be excluded by the observed width. As indicated above, $J = 1^-$ appears to be required to account for the interference at lower energies in α_0 and γ_0; known higher resonances are probably too narrow to produce the observed effects. (1957DE11) find that the α_0-dsitributions for $E_p = 0.6$ to 1.4 MeV are well accounted for by the assumption of s-wave formation of $J = 1^-$ through channel spin $(\chi = 0)$ with a relative d-wave amplitude $A = 0.5$, and interference by the 2.6 MeV, $J = 2^+$, state, with relative amplitude $C = 0.25$. A qualitative fit to the behavior of α_1 can be obtained with the same assumptions (1957DE11). Angular distributions of γ_0 at $E_p = 1.4$ MeV admit either $J = 2^+$ or 1^-; for the latter, however, formation in channel spin 2 ($\chi = \infty$, d-waves) is required (1955GO10). The angular correlation of internal pairs indicates E1 for γ_0 (1956GO1K, 1956GO1N, 1958AR1B). The large E1 width suggests $T = 1$ for this state (1953BE61).

The $E_p = 0.67$ MeV state (^{12}C*(16.58)) may be formed by s- or p-waves; d-waves are excluded by the width (1953BE61). The angular distribution of α_1 at $E_p = 0.64$ and 0.93 MeV indicates s-wave formation: if $J = 2^-$ is assumed, the d-wave admixture is $< 10\%$. The correlation of α_1 with the subsequent ^{8}Be*(2.9) breakup is consistent with $J = 2^-$ and excludes

1^-; an appreciable f-wave admixture in outgoing α_1-particles is indicated (1957DE11). Correlation results at $E_p = 270$ keV can be accounted for by $J = 2^-$ with interference from the 1^-, $E_p = 1.4$ MeV state (1955GE1A, 1957DE11). The angular distribution of γ_1 is reported to require $J = 2^+$, with interference from the 1^-, $E_p = 1.4$ MeV state (1954GR1B): according to (1957DE11), however, the distributions observed by (1954GR1C, 1955GO10) can equally well be ascribed to $J = 2^-$, with interference from a broad, even parity state, possibly at $E_p = 2.0$ or 2.6 MeV (see, however, (1954GI1B)). The angular correlation of internal pairs indicates E1 for the γ_1 radiation (1956GO1K, 1956GO1N, AR57). The relatively large E1 width suggest $T = 1$ for this state (1953BE61).

The $E_p = 2.0$ MeV level is reported to be resonant for α_0 and α_1; the relative weakness of α_1 suggests $J = 0^+$ (1953PA26). These seems to be no clear indication of resonance for γ_0 or γ_1 at this energy (1955GO10: see also (1953HU29)). At $E_p = 2.65$ MeV, resonance occurs for α_0, α_1 (1953PA26) and, weakly, for γ_0, γ_1 (1955BA22, 1955GO10). A large P_2 coefficient in the angular distribution of γ_0 suggests $J = 2^+$ (1955GO10). (1955HO48) find $E_p = 1.98$ and 2.61 MeV for the resonant energies for α_0. Additional resonances for γ_0 and γ_1, reported by (1955BA22) are listed in Table 12.6. (1959GE33) have examined the excitation function for ground-state transitions from $E_p = 4$ to 7.7 MeV. The experiment locates the maximum of the ^{12}C giant resonance at $E_x = 22.55 \pm 0.1$ MeV but does not resolve individual levels. Two additional peaks, at $E_x = 21.4$ and 22.1 MeV are suggested. The maximum value of $\sigma(\gamma, p)$ is calculated to be 29 ± 5 mb.

An upper limit for the total cross section (average value, $E_p = 1.7$ to 4.0 MeV) for the production of nuclear pairs with $E_\pi = 6.5$ to 9.5 MeV is 0.03 μb (1955BE62). See also (1955AJ61, 1956MA1T), (1957SI1B; theor.) and ^{8}Be.

13. ^{11}B(p, n)^{11}C $\quad Q_m = -2.764 \quad E_b = 15.958$

Observed maxima in the (p, n) cross section are listed in Table 12.7 (1951BL1A, 1955BA22, 1957KA1C, 1959GI47). The region covered is characterized by considerable overlapping of resonances (1959GI47). See also (1956KO1D, 1958MA1F, 1958TA03).

14. (a) ^{11}B(p, p)^{11}B $\quad E_b = 15.958$
(b) ^{11}B(p, p$'$)^{11}B*

Absolute elastic scattering cross sections are reported for one angle for $E_p = 0.6$ to 2.0 MeV by (1956TA16), for four angles for $E_p = 0.3$ to 1.0 MeV by (1957DE11). A pronounced anomaly is observed near $E_p = 0.67$ MeV at all angles; the level is therefore formed by s-waves. The 0.3 to 1.0 MeV results are well accounted for by two resonances: $E_p = 0.67$ MeV, s-wave, $J = 2^-$, $\Gamma = 0.33$ MeV, $\Gamma_p/\Gamma = 0.5$, d-wave $< 10\%$, and $E_p = 1.4$ MeV, s-wave, $J = 1^-$, $\Gamma = 1.27$ MeV, $\Gamma_p/\Gamma = 0.05$ (1957DE11). (The reported Γ_p/Γ for the 1.4 MeV resonance appears to be inconsistent with

Table 12.7: Maxima in yields of ^{11}B(p, n)^{11}C and ^{11}B(p, p′)^{11}B*

A	B		C	D		E		^{12}C*
E_p (MeV)	E_p (MeV)	Γ (keV)	E_p (MeV)	E_p (MeV)	σ (mb)	E_p (MeV)	Γ (keV)	(MeV)
						2.664	48	18.40
	3.17	100		3.18	25	3.15	100	18.87
3.7	3.65	500		3.67	62	3.4	500	19.31
						3.78	50	19.42
	4.05	200						19.67
						4.28	100	19.88
	4.70	200	≈ 4.5	4.70	55	4.68	200	20.27
5.18				5.10	105	5.13	200	20.63
5.87								21.34
6.37								21.81
			6.6					22.0
			8.8					24.0
			10.1					25.3

A: (p, n) (1951BL1A): stacked foils.
B: (p, n) (1955BA22): $\theta = 0 - 15°$.
C: (p, n) (1957KA1C): stacked foils.
D: (p, n) (1959GI47): total cross section (estimated from curve).
E: (p, p′) (1955BA22).

the values 0.8 or 0.2 derived by (1953BE61) from (p, γ) and (p, α) cross sections.) (1956TA16) find no rapid variation in cross section near $E_p = 2.0$ MeV. The absence of a detectable anomaly near $E_p = 0.16$ MeV confirms the small value of Γ_p assumed for this resonance; $\Gamma_p < 200$ eV (J.C. Overley, private communication). See also (1956KI54).

Maxima in the yield of 2.1 MeV γ-radiation from ^{11}B*(2.1) are observed at $E_p = 2.664$ MeV, $\Gamma = 48$ keV: (1953HU29, 1955BA22) and at $E_p = 3.15$, 3.4, 3.78, 4.28, 4.68 and 5.13 MeV (1955BA22: see Table 12.7). (Judging form the width, the 2.66 MeV resonance is not that observed, e.g., in ^{11}B(p, γ)^{12}C.)

15. ^{11}B(p, d)^{10}B $\quad Q_m = -9.237 \quad E_b = 15.958$

See ^{10}B.

16. ^{11}B(d, n)^{12}C $Q_m = 13.731$

$Q_0 = 13.63 \pm 0.05$ (1957BI78).

Reported neutron groups are listed in Table 12.8. The group corresponding to the 7.6 MeV state is weak, relative to neighboring groups, at all bombarding energies investigated, and the stripping pattern is poorly developed. The relative weakness of the 7.6 MeV state in this reaction and in the ^{12}C(e, e′)^{12}C* and ^{12}C(p, p′)^{12}C* reactions is attributed to lack of parentage overlap with the ground state of ^{12}C (1955LA1C). At $E_d = 0.92$ MeV, there is no indication of a state in the range $E_x = 5.1 - 6.6$ MeV: the upper limit of the intensity of the corresponding neutron group is $\lesssim$ 1% of the intensity of the group corresponding to the 4.4 MeV state (1957BI78). For $E_d = 1.1$ to 2.0 MeV only the groups corresponding to ^{12}C*(4.4, 12.76) are accompanied by γ-radiation; an upper limit for (n, γ) coincidences from ^{12}C*(7.6) is 0.2% of ^{12}C*(4.4) (1958DA11, 1958NE38, 1959NE1A).

Angular distributions of the neutrons to the first four states of ^{12}C have been reported for a number of energies in the range $E_d = 0.5$ to 10 MeV. At the higher energies, the distributions are understood in terms of simple stripping theory (except for the 7.6 MeV state). At the lower energies, $E_d = 0.5$ to 5 MeV, a good account of the angular distributions of ground-state neutrons is obtained with the theory of (1957OW03) which includes not only stripping of the deuteron but also the possibility of stripping a neutron from ^{11}B, and the interference between the two processes. The relative probability of the exchange stripping increases with energy until the Coulomb barrier is surmounted. The exchange process seems to involve s-wave deuteron capture by a ^{10}B core with $J = 1^+$ (1956PR1B, 1957AM48, 1957OW03: see also (1959NE1A)). Angular distributions at $E_d = 9$ MeV indicate odd parity for the 9.6 MeV state (1956MA83: see also (1954GR53) and Table 12.8). For other work on angular distributions, see (1957AM48, 1958AM13: $E_d = 0.50$ to 1.15 MeV), (1955WA30: $E_d = 0.6$ MeV), (1955IH1B: $E_d = 0.69$ MeV), (1954GR53: $E_d = 0.85$ MeV), (1957BI78: $E_d = 0.92$ MeV), (1956PR1B: $E_d = 1.5$ to 5 MeV), (1953GI05: $E_d = 8.1$ MeV), and (1957ZE1A: $E_d = 10$ MeV). See also (1954BU06, 1956BO1F, 1956BO43, 1956KO1E, 1957RA1A) and (1955MA1J, 1958ED1C; theor.).

In the range $E_d = 1.0$ to 5.5 MeV, two slow neutron thresholds are observed at 1.627 ± 0.004 MeV ($E_x = 15.11 \pm 0.01$ MeV) and near 4.1 MeV (broad; $E_x = 17.23$ MeV) (1955MA76). Gamma rays are observed with $E_\gamma = 4.44 \pm 0.05$ (1951RU1A) and 12.8 ± 0.3 MeV (1958KA31). If the latter γ-ray is properly attributed to decay of the 12.8 MeV level, it is not clear why the level should so decay in view of its instability with respect to ^{8}Be and ^{8}Be*(2.9) (1958KA31: see also ^{10}B(^{3}He, p)^{12}C). A 15.1 MeV γ-ray is observed with a threshold of $E_d = 1633 \pm 3$ keV, attributed to the first $T = 1$ state of ^{12}C at 15.11 MeV. The observed width is < 2 keV. A search for α-particles to ^{8}Be and ^{8}Be* gives $\Gamma_\alpha/\Gamma_\gamma < 1.5$. At $E_d = 2.96$ MeV the cross section for production of the 16.1 MeV $T = 1$ state is < 1 mb/sr (1958KA31). See also (1955AJ61) and (1957WA04).

17. ^{11}B(^{3}He, d)^{12}C $Q_m = 10.464$

Table 12.8: Energy levels of ^{12}C from ^{11}B(d, n)^{12}C

^{12}C* [a] (MeV)	l_p	$(2J+1)\gamma^2$ (10^{-13} MeV-cm)	$(2J+1)\theta^2$
0	1 [e]	1.6 [e]	0.11
4.38 ± 0.07	1 [c,e]	2.0 [e]	0.14
7.57 ± 0.11	[d]		
9.6 ± 0.1	2 [c,e]	1.9 [e]	0.13
10.8 ± 0.1			
11.1 ± 0.1			
11.74 ± 0.08			
12.76 ± 0.08			
13.21 ± 0.05 [b]			
13.36 ± 0.05 [b]			
(14.16 ± 0.05)			
15.09 ± 0.03			
(15.52 ± 0.03)			
16.07 ± 0.03			

[a] (1952JO10, 1954GR53, 1957BI78).
[b] May represent a single level at 13.3 MeV (1952JO10).
[c] (1954GR53).
[d] Angular distribution shows peaking forward and backward: (see (1954GR53, 1957BI78)).
[e] (1956MA83: $E_d = 9$ MeV).

At $E(^3\text{He}) = 4.5$ MeV, the ground state deuteron group is strongly peaked in the forward direction (1957HO61).

18. ^{11}B(α, t)^{12}C $\qquad Q_m = -3.855$

Not reported.

19. ^{12}B(β^-)^{12}C $\qquad Q_m = 13.376$

Table 12.9: Branching in ^{12}B(β^-)^{12}C (1958CO66)

^{12}C* (MeV)	J^π	Branching fraction (%)	log ft [a]
0	0^+	97	4.1 ± 0.1
4.43	2^+	1.5 ± 0.3 [b]	5.1 ± 0.2
7.653 ± 0.008	0^+	1.3 ± 0.4	4.2 ± 0.3
10.1 ± 0.2 [c]	0^+	0.13 ± 0.04	4.1 ± 0.4

[a] Based on $\tau_{1/2} = 20.6$ msec.

[b] (1958KA31): 1.4 ± 0.4 %. (1956TA07): 1.7 ± 0.4 %. (1958VE20): 6 ± 3 %.

[c] $\Gamma = 2.5$ MeV, $\theta^2_\alpha = 1.5$.

The half-life is 20.34 ± 0.5 msec (weighted mean of (1955AJ61, 1956NO1A, 1957CO57, 1958KR65, 1958VE20, 1959KR1B), excluding (1948JE03)). E_β(max) $= 13.40 \pm 0.05$ MeV (1958VE20). Branches are observed leading to ^{12}C*(0, 4.4, 7.65, 10.1): see Table 12.9. The fact that the transition to the 0^+ ground state is allowed establishes $J = 1^+$ for ^{12}B. This assignment is confirmed by the allowed character of the transition to ^{12}C*(4.4), $J = 2^+$. The 7.7 MeV level decays mainly by α-emission to ^{8}Be(0) with $Q = 278 \pm 4$ keV; $E_x = 7.653 \pm 0.008$ MeV (1957CO59). Gamma transitions with $E_\gamma > 6$ MeV accompany $< 10^{-4}$ of all β-decays (1956KA1A, 1958KA31); an upper limit of 3×10^{-5} is obtained in a search for β-γ (7.6) coincidences (1958KA14). Upper limits for $(3.2 + 4.4)$ MeV cascades are given as $(0.4 \pm 2) \times 10^{-3}$ and 10^{-5} of all decays by (1956TA07) and (1958KA14) respectively. It follows that the relative partial width of the 7.6 MeV level is $< 3 \times 10^{-3}$ for 7.6 MeV γ-rays and $< 10^{-3}$ for 3.2 MeV γ-rays (see also ^{9}Be(α, n)^{12}C). Since the β-transition is allowed, the 7.7 MeV state has $J = 0^+$, 1^+ or 2^+; $J = 1^+$ is ruled out by the α-decay. The preponderance of α-decay over γ-decay speaks for $J = 0^+$ (1957CO59).

The 10.1 MeV level decays mainly via α-emission to ^{8}Be(0); transitions to ^{8}Be*(2.9) amount to < 4%. The c.m. width is about 2.5 MeV (after removing the E^5_β factor): the best account of the observed α-spectrum is obtained with $J = 0^+$, $E_\lambda = 10.4$ MeV, $\theta^2_\alpha = 1.5$, $R = 5.21 \times 10^{-13}$ cm (1958CO66).

The β-spectrum has been reported by (1950HO01, 1958VE20). (1958GE1C) discusses a possible distortion of high-energy β-spectra in axial-vector coupling due to a "weak-magnetic" interaction.

See also (1957CH25), (1955JA1C, 1957FE1C, 1959SC1B; theor.).

20. ^{12}C(γ, γ')^{12}C*

Table 12.10: Parameters of the 15.1 MeV ^{12}C level from ^{12}C(γ, γ')^{12}C*

	(1957HA13)	(1959GA09)
peak absorption, σ_{n}^{0} (b)	22.2 ± 2.2	29.7 ± 1.1
integrated scattering, $\int \sigma_{\mathrm{s}} \mathrm{d}E$ (MeV · mb)	1.90 ± 0.27	2.33 ± 0.19
Γ(total) (eV)	79 ± 16	64.5 ± 10.4
$\Gamma_{\gamma}(15 \rightarrow$ g.s.) (eV)	54.5 ± 9.3	59.2 ± 9.7
$\Gamma_{\gamma}(15 \rightarrow 4.4)$ (eV)	< 5.5	3.2 ± 2.5
Γ_{α} (eV)	$18 - 25$ [a]	2.1 ± 3.2

[a] $\Gamma_{\alpha}/\Gamma < 1.5$ from ^{11}B(d, n)^{12}C (1958KA31).

The lifetime of the 4.4 MeV state has been determined by resonance scattering and resonant absorption (of γ-radiation from ^{15}N(p, α)^{12}C*) as $\tau_{\mathrm{mean}} = (6.5 \pm 1.2) \times 10^{-14}$ sec (1958RA14).

Excitation of the 15.1 MeV level by bremsstrahlung is reported by (GA57B, 1957HA13, 1959GA09). From measurement of the yield of resonance scattered radiation and of the self-absorption coefficient, the integrated scattering cross section $\int \sigma_{\mathrm{s}} \mathrm{d}E$, and the peak absorption cross section σ_{n}^{0} are deduced. The resulting values for partial widths are given in Table 12.10. It is noted the γ-ray width for the ground state transition is near the single-particle M1 value of 65 eV, and that the very small α-width strongly suggests $T = 1$ for this level (1957HA13). The scattering angular distribution indicates dipole radiation (1956LE1E, GA57B, 1959GA09). The strength of the M1 radiation also indicates $T = 1$: see (1958MO17). Inelastic scattering in the giant-resonance region has been studied by (1959GA09). See also (1957GO1F, 1958AX1A, 1958MC1D).

21. ^{12}C(γ, n)^{11}C $\qquad Q_{\mathrm{m}} = -18.722$

The cross section for production of ^{11}C exhibits a broad peak at $E_{\gamma} = 22.5$ MeV, $\Gamma \approx 4$ MeV, $\sigma_{\mathrm{max}} = 8.3$ mb (1955BA63). Other reported values for σ_{max} are summarized by (1957CO57: note a 10% correction in this work). See also (1957CA1D). AT high energies, the cross section exhibits a long tail, falling off approximately as E_{γ}^{-3}. The integrated cross section to $E_{\gamma} = 250$ MeV is 80 MeV-mb, accounting for about $\frac{1}{3}$ of the sum-rule limit for all absorption processes. It is noted that the relative prominence of the high-energy tail is not a general feature of (γ, n) reactions in heavy elements (1955BA63, 1957CO57). Comparison of (γ, n) and (e, n) cross section for 28 to 145 MeV are consistent with the assumption that the transitions are predominantly E1 (1958BA60). The angular distribution of photoneutrons at the giant resonance is $W(\theta) = 1 + (1.35 \pm 0.88) \sin^2 \theta$, indicating considerable emission of neutrons with $l > 0$ (1956FA30). See ^{12}C(γ, p)^{11}B and (1954TE1A, 1955MO1B, 1957BA1K; theor.).

Discontinuities in the yield function are reported to indicate levels at 19.3, 19.8, 20.1, 20.5, 20.7, 21.1, 21.6, 22.4, and 22.8 MeV (1954GO39, 1954KA1A). The first two are given as $19.09 \pm$

0.05 and 19.55 ± 0.05 MeV by (1955SP1A). Eighteen discontinuities observed between $E_\gamma = 18.90$ and 22.88 MeV are tabulated by (1958KA1D). A search for resonance absorption near $E_\gamma = 22.8$ MeV indicates a width $\Gamma > 580$ keV, in apparent contradiction of the activation results (1956TZ1A). (1958WO1B), using monochromatic gamma rays, find no evidence of fine structure in the total cross section from $E_\gamma = 20.3$ to 20.8 MeV. The upper limit is, however, not in conflict with the recent report of (1958KA1D). See also (1955JO1B, 1955SA1F, 1958BA1K, 1958SM1A).

22. ^{12}C(γ, p)^{11}B $\qquad Q_\mathrm{m} = -15.958$

The cross section exhibits a giant resonance at $E_\gamma = 21.5 \pm 0.5$ MeV, $\Gamma = 1.7 \pm 0.5$ MeV (1951HA1C). The peak cross section is 22 mb, and the integrated cross section to 24 MeV is 56 MeV-mb (1956CO59): compare ^{11}B(p, γ)^{12}C (1959GE33). The photoproton spectrum shows the general features of the inverse reaction, ^{11}B(p, γ)^{12}C, and suggests resonances at $E_\gamma = 17.3$, (20.8), 22.6, and (23.1) MeV (1956CO59: see, however, (1958WO1B)). (1957LI1A) finds indications of peaks at $E_\gamma = 21.8$, 22.6, 23.3 and 25.8 MeV. An absolute measurement, based on σ(^{12}C*(γ, 3α)) for $E_\gamma = 17.6$ MeV yields $\sigma(\gamma, \mathrm{p}) = 1.19 \pm 0.21$ mb, in good agreement with the value 1.09 ± 0.16 mb calculated from the inverse reaction (1956MA1T). See also (1956GO1G, 1958CH31, 1958PE1A, 1958WH35).

Angular distributions of photoprotons show a pronounced $90°$ peaking, somewhat skewed in the forward direction (1952HA1B, 1953HE1B, 1955JO1B, 1956KL19, 1957DO1A, 1957LI1A, 1957MI1A). Such distributions are inconsistent with s-wave proton emission from $J = 1^-$; ^{12}C compound states formed by E1 absorption and suggest a direct interaction involving independent-particle states: L-S coupling seems to be favored (1955MA1H). The angular distributions of ^{12}C(γ, n) and (γ, p) are evidently quite similar, as expected on the assumption of charge independence; the difference of about a factor of 2 in total cross section is ascribed to a 1% $T = 0$ admixture in the intermediate state (1957BA1K). See also (1953HE1B, 1957CH24, 1958BA1M, 1958BA30, 1958PA1B, 1958PE1B, 1958SM1A) and (1955MO1B, 1957SI1B; theor.).

23. ^{12}C(γ, 3α) $\qquad Q_\mathrm{m} = -7.281$

Maxima in the yield of 3-prong stars are reported at $E_\gamma = 17.3$, 18.3, 21.9, 24.3 and 29.4 MeV; some evidence of fine structure is also found. The integrated cross section is 1.21 ± 0.16 MeV-mb for $E_\gamma < 20.5$ MeV, 2.8 ± 0.4 MeV-mb for $20.5 \leq E_\gamma < 42$ MeV, and < 0.2 MeV-mb for $42 \leq E_\gamma < 60$ MeV (1953GO13, 1955GO59). (1955CA19) summarize cross section measurements for the ^{7}Li(p, γ) radiation and find evidence for a resonance near $E_\gamma = 12.3$ MeV and possibly others at 15 and 16 MeV. According to (1955JO1C), peaks occur at $E_\gamma = 14.7$, 15.8, 16.6, 18.3, 24.3, and > 29 MeV, in fair agreement with (1953GO13). Absolute cross sections are reported for $E_\gamma = 13$ to 30 MeV, and integrated cross sections agree well with (1953GO13, 1955JO1C).

See also (1953DA1A, 1953GU1A, 1953MI31, 1955HA1D). According to (1955GO59), the three-body reaction is not involved for $E_\gamma < 40$ MeV (see, however, (1953MI31, 1954CH1B)). The reaction ^{12}C(γ, α)^{8}Be*(p)^{7}Li is reported by (1956LI05).

Studies of angular distributions indicate that for $E_\gamma = 12$ to 15.6 MeV, the reaction involves mainly E2 absorption (^{12}C*: $J = 2^+$; $T = 0$); from 15.6 to 20 MeV both E1 ($J = 1^-$; $T = 1$) and E2 ($J = 2^+$; $T = 1$), and for $E_\gamma > 20$ MeV, mainly E1 ($J = 1^-$; $T = 1$). Significant E2 absorption ($J = 2^+$; $T = 0$) also occurs for $E_\gamma = 20$ to 25 MeV (1955GO59: see, however, (1951TE1A, 1953GE1B)). See also (1953LI1C, 1954GR1B, 1955RA1E, 1955SO1B, 1955TI1A, 1956MA1T, 1957MU1C).

24. ^{12}C(e, e′)^{12}C

Both elastic and inelastic scattering angular distributions have been studied at $E_e = 80$, 150 and 187 MeV by (1955FR1G, 1956FR27) and at 420 MeV by (1958EH1B). The elastic data are well accounted for by a modified Gaussian charge distribution of r.m.s. radius 2.50×10^{-13} cm, derived from a harmonic well with a characteristic length parameter of 1.68×10^{-13} cm (1956FR27, 1958EH1B). See also (1953HO79, 1956FE1B, 1956HO93, 1957HO1E, 1958EH1A, 1958RA43).

Inelastic peaks corresponding to ^{12}C*(4.4, 7.7, 9.6) are observed, in addition to some unresolved structure near 11 MeV. There is no indication of the 15.1 MeV level. The observed angular distributions agree well with shell-model calculations of (1955RA1D, 1956MO1E, 1956TA1C, 1957TA1B) with a harmonic well of r.m.s. radius 2.40×10^{-13} cm. Predicted absolute cross sections are low by a factor of 2 in L-S coupling, 6 in j-j coupling; it is presumed that some collective modes of excitation are involved.

Excitation of the 4.4 MeV level is electric; a width of $(12.5 \pm 2.5) \times 10^{-3}$ eV, $\tau_m = (0.53 \pm 0.11) \times 10^{-13}$ sec, is obtained (1956HE83). The 7.7 and 9.6 MeV levels are also electrically excited; the angular distributions indicate either monopole or quadrupole transitions, $J = 0^+$, 2^+. The matrix element for the 7.7 MeV E0 transition is 50 mb, in good agreement with that observed for the ^{16}O monopole transition (1955SC1B, 1956FR27). A shell model calculation in intermediate coupling indicates that configuration mixing is required to give a non-zero matrix element for the 0^+-0^+ transition and suggests that a semi-collective model is indicated (1955SC1B, 1956SH1F, 1957TA1B: see also (1955LA1C)). According to (1956EL1C), satisfactory agreement is obtained with a 50% admixture of 1s^{3}1p^{8}2s and 1s^{4}1p^{7}2p. (1956RE1C) also finds reasonable agreement using the 1s^{-1}2s configuration and suggests that such a “core” excitation might appear quite generally in the light nuclei (see ^{16}O, ^{14}C and (1954CH1A)). Calculations using an independent-particle approach to a collective description give a good account of the form factors for both the 4.4 and 7.7 MeV excitations. The form factor for the 9.6 MeV level is consistent with $J = 1^-$ (1956FE1B: see also (1957PA1B)). See also (1958EL48; theor.).

Neutron production with $E_e = 35$ to 150 MeV has been studied by (1956GE1B). Comparison of σ(γ, n) and σ(e, e′n) for $E_e = 24$ to 145 MeV indicates that the transitions are largely E1 (1958BA60).

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

(b) ^{12}C(n, n′)^{12}C*

(c) ^{12}C(n, n′)^{4}He^{4}He^{4}He $\qquad Q_{\rm m} = -7.281$

For $E_{\rm n} \gtrsim$ 14 MeV, elastic scattering angular distributions show pronounced optical-model effects: see (1956BU95, 1956CU1A, 1958NA09) and ^{13}C.

A gamma ray of energy 4.42 ± 0.03 MeV is observed at $E_{\rm n} = 6.58$ MeV (1956DA23: see also (1954TH42, 1955BA95, 1955BE1H)). Production of 15.1 MeV γ-rays is observed at $E_{\rm n} = 90$ MeV (1957WA04, 1957WA1F). At $E_{\rm n} = 14$ MeV, inelastic neutron groups corresponding to ^{12}C*(4.4, 9.6) are reported by (1956WO1B: see also (1953WH1A, 1956BE1F, 1956CA1E, 1958AN32)). The angular distributions for neutrons corresponding to ^{12}C*(4.4) agree well with (p, p′) distributions and with direct interaction theory (1958AN32: $E_{\rm n} = 14$ MeV).

Inelastic excitation leading to α-particle states has been studied by (1955FR35); levels of ^{12}C at 7.7 and 9.6 MeV are involved. (1953JA1C) find that for $E_{\rm n} < 20$ MeV, most events proceed through a level at 10 ± 0.8 MeV, $\Gamma_{\rm obs} = 1.6$ MeV, to ^{8}Be(0) (See (1955FR35) and ^{12}B(β^-)^{12}C). See also ^{13}C, (1953LI1C) and (1956LA1D; theor.).

26. (a) ^{12}C(p, p′)^{12}C*

(b) ^{12}C(p, p′)^{4}He^{4}He^{4}He $\qquad Q_{\rm m} = -7.281$

Elastic scattering differential cross sections have been determined by (1953BU72, 1957GI14, 1957GR53: $E_{\rm p} = 9.4$ to 9.6 MeV), (1954FI1B: $E_{\rm p} = 10$ MeV), (1956SH1C: $E_{\rm p} = 12$ MeV), (1957PE14: $E_{\rm p} = 14$ to 19.4 MeV), (1956DA03: $E_{\rm p} = 17.0$ MeV, c.m.), (1955KI43, 1956KI54: $E_{\rm p} = 14.5$, 20 and 31.5 MeV), (1952BR52, 1953WRZZ: $E_{\rm p} = 30.6$ MeV), (1957HI1C: $E_{\rm p} = 40$ MeV) and (1957GE08: $E_{\rm p} = 96$ MeV). Calculations based on the diffuse-surface optical model give a good account of the data at higher energies (1957GL58, 1957ME21, 1958GL11). At $E_{\rm p} = 9.5$ MeV, some evidence for compound elastic scattering is seen in the marked energy variation at back angles (1957GI14). See also ^{13}N. Polarization of elastic and inelastic protons has been studied by (1958BR24) for $E_{\rm p} = 16$ to 18 MeV. Polarization of elastic protons for $E_{\rm p} = 5 - 7$ MeV is reported by (1958WA1D, 1958WA1E). See also (1957LE1G, 1958KO03, 1958SQ53; theor.). Polarization studies at high energies are discussed by (1956ER1A, 1956NI1B, 1957AL79, 1957HE51, 1957HI98, 1957TY1B, 1958NI1B, 1958NI26).

Excitation of the 4.4 MeV level is commonly observed for all energies above $E_{\rm p} \approx 5$ MeV: see (1955AJ61) and (1956RE39: $E_{\rm p} = 5$ to 6 MeV), (1957GI14, 1957HO1H: $E_{\rm p} = 9.5$ MeV), (1957CO53: $E_{\rm p} = 12$ MeV), (1957PE14: $E_{\rm p} = 14$ to 19 MeV), (1952BR52: $E_{\rm p} = 31.5$ MeV), (1958CH26: $E_{\rm p} = 40$ MeV), (1956ST65: $E_{\rm p} = 96$ MeV), (1957DI28: $E_{\rm p} = 95$ and 135 MeV) and (1957AL39, 1957TY36, 1957TY37, 1958MA1B, 1958TY49: $E_{\rm p} = 182$ MeV). $E_{\rm x} = 4431 \pm 8$ keV (1957BU36). The 7.7 and 9.6 MeV levels are reported by (1957CO53, 1957HO1H, 1957PE14, 1957TY37, 1958CH26). Levels at 12.6, 15.0, and ≈ 20 MeV are also reported by (1957TY36, 1957TY37); the last appears strongly in the work of (1956ST65) ($E_{\rm x} = 20.8$ MeV) and is there associated with the giant resonance seen in ^{12}C(γ, n) and ^{12}C(γ, p).

For $E_p \lesssim 30$ MeV, the angular distribution of the proton group corresponding to the 4.4 MeV level exhibits a minimum near $90° - 100°$ (c.m.) and a definite fore-and-aft asymmetry. Neither the compound nucleus model nor the direct interaction theory appears to give a satisfactory account of these distributions (1957CO53, 1957GI14, 1957PE14). A direct interaction calculation, using distorted waves, does reproduce the general features of the distributions and also fits the observed (p′-γ) correlation of (1956SH1E) and (1958LE06). See also (1956BE1G, 1957BA1L, 1957BU52, 1957MA58, 1958BR83, 1958CH26, 1958MO98).

The angular distribution of protons corresponding to the 7.7 MeV state depends strongly on energy in the range $E_p = 14$ to 19 MeV, but consistently shows a strong forward peak, indicative of $l = 0$ and hence $J = 0^+$ (1957PE14). See also (1955LA1C). An attempt to observe γ-decay of this level yields an upper limit of 3% for $\Gamma_\gamma/\Gamma_\alpha$ (1956HO1D). The angular distribution of protons leading to the 9.6 MeV level is consistent with $l = 1$, $J = 0^-$, 1^-, 2^- (1957PE14).

The angular distribution of pick-up deuterons at $E_p = 95$ MeV indicates significant contributions of high momentum components in the bound, 1p neutron wave function, suggesting strong interactions, (≈ 200 MeV), for close distances, $R \approx 1 \times 10^{-13}$ cm (1955SE1C, 1956SE1A). See also (1956GR1E).

Emission of (15.1 ± 0.2) MeV γ-radiation, ascribed to the first $T = 1$ level, has been studied in the range $E_p = 15$ to 340 MeV by (1957WA04, 1957WA1F). The general shape of the excitation function indicates direct nucleon-nucleon interaction for the higher energies; near threshold, emission of s-wave protons is indicated. Estimates of the α-particle width, and comparison with isobaric spin forbidden reactions (e.g. ^{12}C(α, α')^{12}C*, ^{12}C(d, d′)^{12}C*) indicate a $T = 0$ admixture $a^2 \approx 10^{-3}$. At 31 MeV, $\theta_{lab} = 80°$, γ-rays of energy 15.1, 12.8 and 10.7 MeV are observed, with relative intensities $1/0.090 \pm 0.015/0.095 \pm 0.014$. The 12.8 MeV radiation is ascribed to excitation of a ^{12}C level of that energy, while the 10.7 MeV radiation represents a cascade from ^{12}C*(15.1) to ^{12}C*(4.4) (1957WA1F: see also ^{10}B(^{3}He, p)^{12}C).

A study of reaction (c) at an energy of 29 MeV shows no indication of direct 4-body decay of ^{13}N*; $\frac{1}{4}$ of the events proceed via ^{8}Be(0), and $> \frac{1}{2}$ via ^{8}Be*(2.9). Evidence is found for the participation of ^{12}C*(9.6, $\approx$ 12, 16, 20, 25) (1955NE18). See also (1955RE16), (1957JA1B) and (1955CU1C, 1956SA1C, 1956SA1D).

See also (1956ST30, 1957AL39, 1957GO1D) and (1957KA1D, 1958EL48; theor.).

27. ^{12}C(d, d′)^{12}C*

The angular distribution of elastic scattering has been studied at $E_d = 19$ MeV by (1954FR24); several diffraction peaks appear. See also (1958WA07).

Inelastic groups corresponding to ^{12}C*(4.4, 9.6) are reported by (1951KE02, 1954FR24, 1956GR37, 1956HA90: see also (1956CA65)). The 7.7 MeV level has not been observed. The angular distribution of the $Q = -4.4$ MeV group at $E_d = 15$ MeV has been analyzed in terms of direct nuclear interaction theory and in terms of electric interaction theory by (1956HA90); neither appears to give a satisfactory account of the observations.

A search for 15 MeV γ-radiation at $E_{\rm d} = 85$ MeV yielded a negative result; a $T = 0$ admixture of $< 4 \times 10^{-2}$ is indicated (1957WA04, 1957WA1F).

See also (1955KH31, 1955KH35).

28. ^{12}C(^{3}He, ^{3}He′)^{12}C*

See (1958WE1E).

29. (a) ^{12}C(α, α')^{12}C*

(b) ^{12}C(α, αn)^{11}C $\qquad Q_{\rm m} = -18.722$

Elastic scattering has been studied at $E_\alpha = 19$ MeV by (1958PR65), at 31.5 MeV by (1956WA29), at 40 MeV by (1956IG02, 1956WE1C, 1957IG03) and at 48 MeV by (1955VA1A). The angular distributions show strong diffraction effects indicative of a direct interaction. Inelastic groups corresponding to levels at 4.4, 7.64 ± 0.07, 9.6 and possibly, 12.7 MeV are observed. ^{12}C recoils corresponding to the ground and 4.4 MeV states are also reported; the absence of recoils corresponding to the 7.7 MeV state is taken to indicate that this state disintegrates primarily (> 80%) by α-emission (1955RA1B: see ^{11}B(d, n)^{12}C). From a similar experiment, (1958EC12) find that the chance is less than 0.1 for $\Gamma_\gamma/\Gamma > 10^{-3}$.

Angular distribution of the $Q = -4.4$ MeV inelastic group at $E_\alpha = 31.5$ MeV are consistent with the direct surface interaction theory of (1953AU1A). A similar analysis of the $Q = -7.7$ MeV group gives good agreement for $J = 0^+$ (1956WA29). At $E_\alpha = 42$ MeV, the angular distribution of this group is well matched by the $j_0^2(kr)$ or $j_2^2(kr)$ functions, indicating $J^\pi = 0^+$ or 2^+. The former is preferred in view of the small γ-width (1958EC12). See also (1956WE1C, 1957FI1C, 1958PR65, 1958SH65).

A search for γ-radiation from the de-excitation of the 15 MeV, $T = 1$ level at $E_\alpha = 48$ and 175 MeV gives an upper limit of $\approx 10^{-3}$ for the $T = 0$ admixture (1957WA04, 1957WA1F).

See also (1954JU1B). For reaction (b), see (1953LI28).

30. ^{12}N(β^+)^{12}C $\qquad Q_{\rm m} = 17.46$

The decay is mainly to the ground state via an allowed transition. Transitions to ^{12}C*(4.4, 7.65) also are allowed. Branching ratios are 100/15/3; $\log ft = 4.17$, 4.4 and 4.4, respectively (1958VE20). Delayed α-particles with a total energy of ≈ 4 MeV are also observed, suggesting that a state of ^{12}C in the region 11 to 12 MeV is involved (1950AL57). See ^{12}N.

31. ^{13}C(γ, n)^{12}C $\qquad Q_{\rm m} = -4.946$

See ^{13}C.

32. ^{13}C(p, d)^{12}C $Q_{\rm m} = -2.719$
$Q_0 = -2.720 \pm 0.007$ (1957BU36).

See (1955NE18) and (1957BE49).

33. ^{13}C(d, t)^{12}C $Q_{\rm m} = 1.313$

Angular distributions of the ground state tritons have been measured at $E_{\rm d} = 2.2$ and 3.3 MeV (1954HO48).

34. ^{13}C(^{3}He, α)^{12}C $Q_{\rm m} = 15.632$

Angular distributions of the α-particle groups to the ground and 4.4 MeV states have been obtained at $E(^3{\rm He}) = 2$ MeV (1957HO63) and 4.5 MeV (1957HO62). Some direct interaction appears to be involved at both energies. At $E(^3{\rm He}) = 2$ MeV, a 15.1 MeV γ-ray is observed (1957BR18, 1957GO1B, 1958BR1D).

35. ^{14}C(p, t)^{12}C $Q_{\rm m} = -4.635$

Not observed.

36. ^{14}N(γ, d)^{12}C $Q_{\rm m} = -10.265$

Not observed.

37. ^{14}N(n, t)^{12}C $Q_{\rm m} = -4.007$

See ^{15}N and (1952LI24).

38. ^{14}N(p, ^{3}He)^{12}C $Q_{\rm m} = -4.772$

Table 12.11: ^{12}C states from ^{14}N(d, α)^{12}C

A		B	C	D	E	F	G
Q (MeV $\pm$ keV)	σ (mb)	Q (MeV $\pm$ keV)	Q (MeV $\pm$ keV)	Q (MeV $\pm$ keV)	Q (MeV $\pm$ keV)	Q (MeV $\pm$ keV)	^{12}C* (MeV)
13.39 ± 80	1	13.575 ± 12					0
9.02 ± 70	3	9.137 ± 6					4.442
5.77 ± 70	0.3		5.89 ± 30	5.910 ± 15	5.912 ± 13		7.664
		3.955 ± 3				3.933 ± 14	9.63

A: $E_\alpha = 1.01$ MeV, $\theta = 90°$ (1940HO1A).
B: (1951MA08).
C: Based on $Q_1 = 9.137$ for the second group (1953DU23). At $E_\alpha = 0.62$ MeV, $\theta = 90°$, this group has 6% the intensity of the first.
D: (1955PA50).
E: (1956AH32).
F: (1956DO41): it is suggested that a systematic error exists in (1951MA08)'s value for this state.
G: Based on $Q_0 = 13.579$.

Not observed.

39. ^{14}N(d, α)^{12}C $\quad Q_m = 13.579$

For α-groups have been observed corresponding to ^{12}C*(0, 4.4, 7.7, 9.6): see Table 12.11 and (1957HO1H). Alpha-gamma correlations give $J = 2^+$ for the 4.4 MeV state (1954ST1C) while γ-γ correlations give $J = 0$ or > 2 for the 7.7 MeV state (1955SE03: see, however, ^{12}B(β^-)^{12}C). The width of the 7.7 MeV state is < 25 keV (1953DU23, 1956AH32) and that of the 9.6 MeV state is 30 ± 8 keV (c.m.). The J^π values for the 9.6 MeV state are limited to 0^+, 1^-, 2^+, 3^-, 4^+ (1956DO41). Angular distributions of the α-particles to the ground, 4.4 and 9.6 MeV states have been measured at $E_d = 20.9$ MeV (1957FI1C). See also (1952GI01, 1958BO18, 1958BO71). A small yield of 15 MeV γ-radiation is observed at $E_d = 10.8$ MeV, presumably due to excitation of the 15.1 MeV, $T = 1$ state (1954RA35). See also (1956GR37, 1958RA13) and ^{16}O.

40. ^{14}N(^{3}He, pα)^{12}C $\quad Q_m = 8.086$

See ^{16}O.

41. ^{15}N(p, α)^{12}C $\quad Q_{\rm m} = 4.964$

Alpha particles have been observed to a state of ^{12}C at 4.432 ± 0.010 MeV (1952SC28). The γ-ray energy after Doppler correction of 20 keV is 4.443 ± 0.020 MeV. The necessity for the correction implies a lifetime $< 3 \times 10^{-13}$ sec (1952TH24); see ^{12}C(γ, γ')^{12}C*. The angular distributions of short-range alpha particles and 4.4 MeV γ-radiation indicate that the 4.4 MeV state has $J = 2^+$ or > 4 (1953KR1B: see also (1957GO1E)). See also ^{16}O and (1958RA14).

42. (a) ^{16}O(γ, α)^{12}C $\quad Q_{\rm m} = -7.148$

(b) ^{16}O(γ, 4α) $\quad Q_{\rm m} = -14.429$

There is evidence for the involvement of ^{12}C states at 9.6 and ≈ 11 MeV which decay to the ground state of ^{8}Be, a state at $12 - 13$ MeV, decaying mainly to the 2.9 MeV state of ^{8}Be, and $T = 1$ state at ≈ 16 and $18 - 19$ MeV, again leading mainly to the 2.9 MeV ^{8}Be state. The 4.4 and 7.7 MeV states of ^{12}C seem to occur rarely, if at all (see ^{16}O).

43. ^{19}F(p, 2$\alpha\gamma$)^{12}C $\quad Q_{\rm m} = 0.971$

See (1957ZA1A).

^{12}N
(Fig. 21)

GENERAL:

Mass of ^{12}N: From the Q of the ^{10}B(^{3}He, n)^{12}N reaction, 1.46 ± 0.06 MeV, and the Wapstra (1955WA1A) atomic masses for ^{10}B, ^{3}He and n, the mass excess of ^{12}N is 21.00 ± 0.06 MeV.

1. ^{12}N(β^+)^{12}C $\quad Q_{\rm m} = 17.46$

The half life is 12.5 ± 1 msec; $E_\beta(\max) = 16.6 \pm 0.2$ MeV (1949AL05), $\tau_{1/2} = 11.43 \pm 0.05$ msec; $E_\beta(\max) = 16.37 \pm 0.06$ MeV (1958VE20). The decay is complex; ^{12}N decays to the ground state of ^{12}C and to ^{12}C*(4.4, 7.6): see ^{12}C. Log $ft = 4.17$ for the ground state transition (1958VE20). See also (1959SC1B; theor.).

Table 12.12: Energy levels of ^{12}N

E_x (MeV)	J^π	$\tau_{1/2}$	Decay	Reactions
0	1^+	$(11.43 \pm 0.05) \times 10^{-3}$ sec	β^+	1, 2, 3, 5
1.06 ± 0.08				2
1.56 ± 0.08				2
(1.97 ± 0.10)				(2)
2.35 ± 0.08				2
3.18 ± 0.15				2
3.46 ± 0.15				2

2. ^{10}B(^{3}He, n)^{12}N $\qquad$ $Q_m = 1.46$

$Q_0 = 1.46 \pm 0.06$ (1957AJ71).

The neutron spectrum has been studied at $E(^3\text{He}) = 2.54$ and 3.60 MeV. Seven neutron groups are observed, corresponding to the ground state and to excited states at 1.06 ± 0.08, 1.56 ± 0.08, (1.97 ± 0.10), 2.35 ± 0.08, 3.18 ± 0.15 and 3.46 ± 0.15 MeV, in good agreement with the levels of the mirror nucleus, ^{12}B. At the lower energy, the (c.m.) angular distribution of the ground state neutrons is isotropic within ≈ 15 % statistics; at the higher energy, the distribution is peaked forward (1957AJ71).

3. ^{12}C(p, n)^{12}N $\qquad$ $Q_m = -18.24$

$E_{\text{thresh}} = 20.0 \pm 0.1$ MeV (1949AL05). See also (1957CA1E, 1957GR1F) and ^{13}N.

4. ^{12}C(^{3}He, t)^{12}N $\qquad$ $Q_m = -17.48$

Not reported.

5. ^{14}N(γ, 2n)^{12}N $\qquad$ $Q_m = -30.73$

See ^{14}N.

6. ^{14}N(p, t)^{12}N $\qquad$ $Q_m = -22.25$

Not reported.

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(Closed 1 December 1958)

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