Energy Levels of Light Nuclei
$A = 16$

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Abstract: An evaluation of $A = 16$–17 was published in *Nuclear Physics A*166 (1971), p. 1. This version of $A = 16$ differs from the published version in that we have corrected some errors discovered after the article went to press. Figures and introductory tables have been omitted from this manuscript. Reference key numbers have been changed to the NNDC/TUNL format.

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^{16}B

(Fig. 5)

^{16}B is predicted to be unstable with respect to decay into ^{15}B+n by 1.0 ± 0.4 MeV (1966GA25).

^{16}C

(Figs. 1 and 5)

GENERAL:

See (1960ZE03, 1966LE1H, 1969SO08, 1969SO1E, 1970SU1B; theor.) and (1965DO13, 1967AU1B, 1967CA1J, 1968DO20, 1969AR13).

Mass of ^{16}C: From the Q-value of the ^{14}C(t, p)^{16}C reaction [$Q_0 = -3.014 \pm 0.016$ MeV (1961HI01)] and the (1965MA54) masses for ^{14}C, t and p, the mass excess of ^{16}C is 13.695 ± 0.016 MeV.

See (1968CE01) and (1960GO1B, 1961BA1C).

1. ^{16}C(β^-)^{16}N $\qquad Q_m = 8.010$

The half-life of ^{16}C is 0.74 ± 0.03 sec (1961HI01).

2. ^{14}C(t, p)^{16}C $\qquad Q_m = -3.014$

$Q_0 = -3.014 \pm 0.016$ (1961HI01).

Proton groups have been observed at $E_t = 12$ MeV to the ground state and to an excited state of ^{16}C at $E_x = 1.753 \pm 0.012$ MeV. The corresponding angular distributions show $L = 0$ for ^{16}C(0) and indicate $L = 2$ for ^{16}C*(1.75): J^π are then 0^+ and (2^+), respectively (1964MI05).

Table 16.1: Energy levels of ^{16}C

E_x (MeV $\pm$ keV)	$J^\pi; T$	$\tau_{1/2}$ (sec)	Decay	Reactions
0	$0^+; 2$	0.74 ± 0.03	β^-	1, 2
1.753 ± 12	(2^+)			2

^{16}N

(Figs. 2 and 5)

GENERAL:

Model calculations: (1957EL1B, 1957WI1E, 1959FA1C, 1960RA1A, 1960SH1A, 1960TA1C, 1961BA1F, 1962TA1E, 1964FE02, 1964LE20, 1964ST1B, 1965GI1B, 1966CO1G, 1966CO1H, 1966LE1H, 1966SL1A, 1966TO04, 1967DI1B, 1969BO37, 1969HO1U).

Reactions involving muons and pions: (1963CO1B, 1964AS1A, 1964BA1M, 1964BA1N, 1964CO1C, 1965DE1K, 1965GI1C, 1965JA1E, 1966KI1C, 1966OH1A, 1966WA1K, 1967DE1R, 1967DE1E, 1967RA02, 1967RH1A, 1967RH1B, 1967WA1K, 1969DE1T, 1969GR1E, 1969GR1G, 1969KE12, 1969MY01, 1970RA32).

Other topics: (1964LI1B, 1968AR1F, 1970BA1M).

1. ^{16}N(β^-)^{16}O $\qquad Q_{\rm m} = 10.422$

The half-life of ^{16}N is 7.13 ± 0.02 sec: see Table 16.3. From the character of the beta decay [see Table 16.24] it is concluded that ^{16}N(0) has $J^\pi = 2^-$. See ^{16}O.

2. ^{7}Li(^{14}N, ^{5}Li)^{16}N $\qquad Q_{\rm m} = 0.407$

See (1957AL78).

3. (a) ^{9}Be(^{7}Li, α)^{12}B $\qquad Q_{\rm m} = 10.463 \qquad E_{\rm b} = 20.573$

(b) ^{9}Be(^{7}Li, ^{8}Li)^{8}Be $\qquad Q_{\rm m} = 0.367$

The yields of α_0 and α_2 (reaction (a)) have been measured at $E(^7\rm Li) = 3.3$ MeV and 5.0 to 6.2 MeV (1969SN02). The cross section for reaction (b) rises monotonically for $E(^7\rm Li) = 1.1$ to 4 MeV (1957NO17, 1959NO40). At 4 MeV, the cross section is 70 mb (1960NO1A). See also (1960GE1B; theor.).

4. (a) ^{10}B(^{7}Li, p)^{16}N $\qquad Q_{\rm m} = 13.985$

(b) ^{11}B(^{6}Li, p)^{16}N $\qquad Q_{\rm m} = 9.782$

(c) ^{11}B(^{7}Li, d)^{16}N $\qquad Q_{\rm m} = 4.754$

At E(Li) $= 4.7$ to 5.2 MeV, proton and deuteron groups are observed to a number of known states of ^{16}N with $E_{\rm x} < 9.5$ MeV, including states at $E_{\rm x} = 7.66$, 8.10, 8.36, 8.83 and 9.47 MeV (± 50 keV). Angular distributions are also reported (1966MC05). See also (1963MO1B).

Table 16.2: Energy levels of ^{16}N

E_x (MeV $\pm$ keV)	$J^\pi; T$	τ or $\Gamma_{c.m.}$ (keV)	Decay	Reactions
0	$2^-; 1$	$\tau_{1/2} = 7.13 \pm 0.02$ sec	β^-	1, 6, 11, 12, 13, 14, 15, 18, 21, 22, 23, 24, 28, 29, 30
0.1206 ± 0.5	0^-	$\tau_m = 7.58 \pm 0.09$ μsec	γ	4, 11, 13, 18, 24, 28, 30
0.2970 ± 0.7	3^-	95 ± 20 psec	γ	4, 11, 12, 13, 18, 24, 28, 29, 30
0.3973 ± 0.7	1^-	42 ± 10 psec	γ	4, 11, 13, 18, 24, 28, 30
3.355 ± 5	1^+	$\Gamma = 20 \pm 5$ keV	n	4, 11, 13, 15, 18, 27, 28
3.520 ± 5	$0^{(-)}$	$\leq 7 \pm 4$	n	4, 11, 13, 15, 18, 28
3.961 ± 5	$(2, 3)^+$	$\leq 7 \pm 4$	n	4, 11, 12, 13, 15, 18, 28
4.318 ± 5	1^+	20 ± 5	n	4, 11, 13, 15, 18, 28
4.389 ± 6	1^-	68 ± 9	n	4, 11, 13, 15, 28
4.720 ± 7	1^-	260 ± 25		13, 18
4.776 ± 5	2^+	61 ± 5	n	4, 11, 13, 15, 18, 28
4.97 ± 100	2^-	1050 ± 200	n	14
5.049 ± 5	$(1, 2)^-$	20 ± 7	n	11, 13, 15, 18, 28
5.129 ± 7		$\leq 7 \pm 4$	(n)	11, 13, 15, 18, 28
5.150 ± 7		$\leq 7 \pm 4$	(n)	11, 13, 15, 18
5.232 ± 5		$\leq 7 \pm 4$		11, 13, 18, 28
5.306 ± 7	2^-	270 ± 30	n	13, 15, 18
5.523 ± 6		$\leq 7 \pm 4$		4, 13, 18, 28
5.736 ± 6	(5^+)	$\leq 7 \pm 4$	(n)	4, 12, 13, 15, 18, 28
6.005 ± 9	(3^-)	270 ± 30	(n)	13, 15, 28
6.168 ± 6		$\leq 7 \pm 4$		13, 18, 28
6.373 ± 7	2	30 ± 6	n	13, 15, 18, 28
6.426 ± 7	(2^-)	300 ± 30	n	13, 15, 18
6.511 ± 6	2	34 ± 6	n	13, 15, 18
6.613 ± 6		$\leq 7 \pm 4$		13, 18
6.851 ± 6		$\leq 7 \pm 4$	(n)	13, 15, 18
6.98 ± 20	1	22 ± 5	n	13, 15, 28
7.03 ± 10	(0)	28 ± 20	n	15, 18, 28
7.135 ± 6		$\leq 7 \pm 4$		13, 18
7.248 ± 6	3	17 ± 5	n	13, 15, 18
7.575 ± 7	≥ 4	$\leq 7 \pm 4$	n	13, 15, 18
7.639 ± 7	≥ 1	$\leq 7 \pm 4$	n	4, 13, 15, 18, 28

Table 16.2: Energy levels of ^{16}N (continued)

E_x (MeV $\pm$ keV)	$J^\pi; T$	τ or $\Gamma_{c.m.}$ (keV)	Decay	Reactions
7.678 ± 8		$\leq 7 \pm 4$	n	4, 13, 15, 18
7.857 ± 8	4, 5	100 ± 15	n	13, 15, 18, 28
8.038 ± 9	≥ 2	70 ± 20	n	4, 13, 15, 28
8.183 ± 10		28 ± 8		4, 13, 28
8.282 ± 8		24 ± 8		13, 28
8.365 ± 8		18 ± 8		4, 13, 28
8.49 ± 30		≤ 50		28
8.819 ± 15		≤ 50		4, 28
9.035 ± 15		≤ 50		28
(9.16 ± 30)		≤ 50		28
(9.34 ± 30)		≤ 50		28
9.459 ± 15		≤ 50		4, 28
(9.66 ± 40)		≤ 50		28
9.760 ± 10	$T = 1$	15 ± 8		11, 28
9.813 ± 10	$T = 1$			11
9.928 ± 7	$0^+; 2$	< 12		11, 27, 28
10.055 ± 15		≤ 50		28
(10.17 ± 30)		≤ 50		28
(10.26 ± 30)		≤ 50		28
11.61		220	n, d	7
11.701 ± 7	$1^-, 2^+; 2$	< 12		11
(11.91)		390	n, d	7
12.25		290	n, p, d	7, 9
12.60		180	n, p, d	7, 9
12.88		155	n, p, d	7, 9
(12.97)		175	n, d	7

In reaction (c), the τ_m for ^{14}N*(0.30, 0.40) are, respectively, > 0.7 and > 0.9 psec. The two transition energies are 297.6 ± 0.9 and 397.8 ± 1.0 keV. The $(0.40 \to 0.12)$ transition energy is 276.2 ± 0.8 keV (1969TH01). See also (1964HA09).

5. ^{13}C(α, p)^{16}N $\qquad Q_m = -7.425$

Not reported.

Table 16.3: The half-life of ^{16}N

$\tau_{\frac{1}{2}}$ (sec)	Refs. [a]
7.35 ± 0.05	(1947BL1A)
7.38 ± 0.05	(1954MA97)
7.352 ± 0.009	(1959EL41)
7.31 ± 0.04	(1962MA38)
7.14 ± 0.02	(1964BI02)
7.16 ± 0.04	(1965GR21)
7.10 ± 0.03	(1966SC05)
7.13 ± 0.04	(1970AL21)
7.13 ± 0.02	Weighted mean of last foue values

[a] See also (1961AL05, 1965CR01).

6. ^{14}C(d, γ)^{16}N $\qquad Q_m = 10.471$

The cross section has been measured for $1.2 < E_d < 2.6$ MeV. It shows some evidence of structure. Assuming compound nucleus formation at $E_d = 2.0$ MeV, and taking $\sigma = 5\ \mu$b, Γ_γ (total) ≈ 20 eV (1964NE09). See also (1959AJ76).

7. ^{14}C(d, n)^{15}N $\qquad Q_m = 7.984 \qquad E_b = 10.471$

Observed resonances in the yield of ground state neutrons are displayed in Table 16.4 (1961CH14, 1963IM01). The yield of neutrons to ^{15}N*(5.3, 6.32) has been measured by (1967LA11) for $2.9 < E_d < 3.1$ MeV. See also (1964NE09) and ^{15}N in (1970AJ04).

8. ^{14}C(d, p)^{15}C $\qquad Q_m = -1.007 \qquad E_b = 10.471$

The cross section of the γ-rays to ^{15}C*(0.75) rises monotonically for $2.7 < E_d < 3.4$ MeV. At $E_d = 3.4$ MeV it is ≈ 75 mb (1962CH14). Observed resonances are shown in Table 16.4 (1956DO37). See also (1959AJ76) and ^{15}C in (1970AJ04).

Table 16.4: Resonances in ^{14}C + d

E_d (MeV)	Resonant for	$\Gamma_{c.m.}$(keV)	E_x (MeV)	Refs.
1.30 [a]	n_0	220	11.61	(1961CH14, 1963IM01)
1.65	n_0	390	11.91	(1961CH14)
2.04 [a]	n_0, p	290	12.25	(1956DO37, 1961CH14, 1963IM01)
2.44 [a]	n_0, p	180	12.60	(1956DO37, 1961CH14)
2.75	n_0, p	155	12.88	(1956DO37, 1961CH14, 1963IM01)
2.86	n_0	175	12.97	(1961CH14)
(3.10)	n_0	(175)	(13.18)	(1961CH14)

[a] See also (1964NE09).

9. ^{14}C(d, α)^{12}B $\qquad$ $Q_m = 0.361$ $\qquad$ $E_b = 10.471$

See ^{12}B in (1968AJ02).

10. ^{14}C(t, n)^{16}N $\qquad$ $Q_m = 4.213$

Not reported.

11. ^{14}C(^{3}He, p)^{16}N $\qquad$ $Q_m = 4.977$

Thirteen proton groups have been observed corresponding to states of ^{16}N with $0 < E_x < 5.3$ MeV (1966GA08): see Table 16.5. At $E(^3\text{He}) = 12$ MeV, four proton groups are observed corresponding to two $T = 1$ states, and to two $T = 2$ states at $E_x = 9.93$ and 11.70 MeV with $J^\pi = 0^+$ and $(1^-, 2^+)$, respectively, corresponding to the first two states of ^{16}C (1968HE03). See also (1969BA1Z). Angular distributions of the protons to ^{16}N*(0, 3.36, 3.52, 3.96) have been measured at $E(^3\text{He}) = 1$ to 9 MeV; ^{16}N(0) has odd parity; the three excited states have even parity (1968DA1N, 1970LI1F). See also (1963WE15, 1964DU1A, 1966DU1B, 1966GO1J).

12. ^{14}C(α, d)^{16}N $\qquad$ $Q_m = -13.376$

At $E_\alpha = 46$ MeV, the angular distributions of five deuteron groups [see Table 16.5] have been determined: J^π of ^{16}N*(5.74) (the most strongly populated state) is (5^+) (1969LU07).

Table 16.5: Excited states in ^{16}N from ^{14}C(^{3}He, p)^{16}N and ^{14}C(α, d)^{16}N

E_x (MeV ± keV)			Γ (keV)	J^π; T
(1966GA08) [a]	(1968HE03) [a]	(1969LU07) [b]		
0.121 ± 6				
0.298 ± 6		0.307 ± 20		
0.396 ± 7				
3.348 ± 7				
3.517 ± 7				
3.958 ± 7		3.961 ± 20		
4.313 ± 9				
4.386 ± 9				
4.768 ± 11				
5.052 ± 9				
5.137 ± 9				
5.234 ± 9				
		5.745 ± 20		(5^+)
		7.599 ± 30		
	9.760 ± 10		15 ± 8	$T = 1$
	9.813 ± 10			$T = 1$
	9.928 ± 7		< 12	0^+; 2
	11.701 ± 7		< 12	1^-, 2^+; 2

[a] ^{14}C(^{3}He, p)^{16}N.
[b] ^{14}C(α, d)^{16}N.

13. ^{14}N(t, p)^{16}N $Q_m = 4.840$
$Q_0 = 4.853 \pm 0.010$ (1966HE10).

Proton groups observed at $E_t = 2.2$ to 2.6 MeV (1961SI04) and at 12 MeV (1966HE10) are displayed in Table 16.6. Angular distributions are reported at $E_t = 1.8$ MeV (1964SC09; $p_0 \to p_4$) and at 12 MeV (1966HE10). At the latter energy they have been analyzed by PWBA: see Table 16.6. See also (1961JA14).

Table 16.6: States in ^{16}N from ^{14}N(t, p)^{16}N

(1961SI04)		(1966HE10)		J^π
E_x (MeV ± keV)	Γ (keV)	E_x (MeV ± keV)	Γ (keV)	
0		0		2^-
0.121 ± 10		0.120 ± 10		0^-
0.297 ± 10		0.300 ± 10		3^-
0.396 ± 10		0.399 ± 10		1^-
3.340 ± 25	$\leq 25 \pm 17$	3.359 ± 10	15 ± 5	1^+
3.506 ± 25	$\leq 25 \pm 8$	3.519 ± 10	$\leq 7 \pm 4$	(0^-)
3.956 ± 25	$\leq 25 \pm 8$	3.957 ± 10	$\leq 7 \pm 4$	$(1, 2, 3)^+$
4.318 ± 25	$\leq 25 \pm 8$	4.318 ± 10	20 ± 5	1^+
4.392 ± 25	110 ± 31	4.391 ± 10	82 ± 20	
		4.725 ± 10	290 ± 30	1^-
4.773 ± 25	66 ± 7	4.774 ± 10	59 ± 8	$(1, 2, 3)^+$
5.059 ± 25	$\leq 25 \pm 8$	5.053 ± 10	19 ± 6	
		5.130 ± 10	$\leq 7 \pm 4$	
5.141 ± 25	38 ± 12			
		5.150 ± 10	$\leq 7 \pm 4$	
5.230 ± 25	$\leq 20 \pm 8$	5.226 ± 10	$\leq 7 \pm 4$	
		5.305 ± 10	260 ± 30	2^-
5.526 ± 25	$\leq 20 \pm 8$	5.520 ± 10	$\leq 7 \pm 4$	
		5.730 ± 10	$\leq 7 \pm 4$	
		6.009 ± 10	270 ± 30	(3^-)
		6.167 ± 10	$\leq 7 \pm 4$	
		6.371 ± 10	30 ± 6	
		6.422 ± 10	300 ± 30	(2^-)
		6.512 ± 10	34 ± 6	

Table 16.6: States in ^{16}N from ^{14}N(t, p)^{16}N (continued)

(1961SI04)		(1966HE10)		J^π
E_x (MeV ± keV)	Γ (keV)	E_x (MeV ± keV)	Γ (keV)	
		6.613 ± 10	$\leq 7 \pm 4$	
		6.854 ± 10	$\leq 7 \pm 4$	
		7.006 ± 10	22 ± 5	
		7.133 ± 10	$\leq 7 \pm 4$	
		7.250 ± 10	17 ± 5	
		7.573 ± 10	$\leq 7 \pm 4$	
		7.640 ± 10	$\leq 7 \pm 4$	
		7.675 ± 10	$\leq 7 \pm 4$	
		7.876 ± 10	100 ± 15	
		8.043 ± 10	85 ± 15	
		8.183 ± 10	28 ± 8	
		8.280 ± 10	24 ± 8	
		8.361 ± 10	18 ± 8	

14. ^{15}N(n, γ)^{16}N $Q_m = 2.487$

The thermal cross section is 24 ± 8 μb (1958HU18).

15. ^{15}N(n, n)^{15}N $E_b = 2.487$

The total cross section has been measured for $E_n = 0.4$ to 6.5 MeV: see (1959SC30, 1962SI05, 1964DO09, 1964DO1D, 1964FO07, 1966FO11). See also (1960SI03, 1960SI12). Observed resonances are displayed in Table 16.7. See also (1964ST25). Angular distributions of elastically scattered neutrons have been measured at a number of energies for $E_n = 0.4$ to 5 MeV (1962SI05, 1964DO09, 1964DO1D). See also (1963GO1J). See also (1964LE20, 1965BA1N, 1967EB02, 1967EB03, 1968AG1E, 1968HU1F, 1969AN1K, 1969DO05, 1970PO1B).

16. ^{15}N(n, p)^{15}C $Q_m = -8.990$ $E_b = 2.487$

Table 16.7: Resonances in ^{15}N(n, n)^{15}N

E_{res} [a] (MeV ± keV)	Γ_{lab} (keV)	E_x (MeV)	J^π	Refs.
0.93 ± 20	30 ± 10	3.36	1^+	(1964DO09, 1964FO07)
1.11 ± 20	20 ± 10	3.53	(0^+)	(1964FO07)
1.57 ± 20	≤ 10	3.96	(1^-)	(1964FO07)
1.94 ± 20	≤ 15	4.30	(1^+)	(1962SI05, 1964DO09, 1964FO07)
2.04 ± 20	65 ± 10	4.40	1^-	(1962SI05, 1964FO07)
2.45 ± 20	90 ± 15	4.78	$2^+(1^+)$	(1962SI05)
(2.55)	(1200)	(4.88)	(1^-)	(1962SI05)
2.65 ± 100	1100 ± 200	4.97	2^-	(1962SI05)
2.74 ± 30	50 ± 15	5.05	$(1, 2)^-$	(1962SI05)
2.82 ± 30	≤ 40	5.13	$(3^-, 4^-, 5^-)$	(1962SI05)
2.98 ± 30	200 ± 30	5.28	(2, 3)	(1956BA1A, 1959SC30, 1962SI05)
(3.48 ± 25)	(30)	(5.75)	(0)	(1964DO1D, 1966FO11)
3.73 ± 25	broad	5.98	(1, 2)	(1966FO11)
(4.00 ± 25)	(75)	(6.23)	(0)	(1964DO1D, 1966FO11)
4.14 ± 25	50 ± 20	6.37	2	(1964DO1D, 1966FO11)
(4.2 ± 25)	(broad)	(6.4)	(3)	(1966FO11)
4.27 ± 25	60 ± 20	6.49	2	(1964DO1D, 1966FO11)
(4.62 ± 25)		(6.81)		(1966FO11)
4.78 ± 25	30 ± 10	6.96	1	(1966FO11)
4.86 ± 25	30 ± 20	7.04	(0)	(1966FO11)
5.05 ± 25	25 ± 10	7.22	3	(1966FO11)
5.42 ± 25	≤ 20	7.56	≥ 4	(1966FO11)
5.50 ± 25	≤ 25	7.64	≥ 1	(1966FO11)
(5.55 ± 25)		(7.69)		(1966FO11)
5.72 ± 25	150 ± 50	7.85	4, 5	(1966FO11)
5.89 ± 25	40 ± 20	8.00	≥ 2	(1966FO11)
(6.25 ± 25)		(8.34)		(1966FO11)

[a] See also (1964ST25).

At $E_n = 14.8$ MeV, $\sigma = 16 \pm 4$ mb (1966PR14).

17. $^{15}N(n, \alpha)^{12}B$ $\qquad Q_m = -7.623 \qquad E_b = 2.487$

See (1948JE03, 1964GA1A).

18. $^{15}N(d, p)^{16}N$ $\qquad Q_m = 0.262$
$Q_0 = 0.270 \pm 0.010$ (1966HE10);
$Q_0 = 0.267 \pm 0.008$ (1963SP1B).

Levels derived from observed proton groups and γ-rays are listed in Table 16.8 (1957FR56, 1957WA01, 1957WI1B, 1963GI11, 1966HE10). Gamma transitions are shown in the inset of Fig. 2 (1963GI11).

The half-life of ^{16}N*(0.12) $= 6.7 \pm 0.5$ μsec (1957FR56), 5.43 ± 0.22 μsec (1959ZI18), 7.58 ± 0.09 μsec (1967BE14), together with the stripping results, leads to $J^\pi = 0^-$ for ^{16}N*(0.12): this is confirmed also by the measured α_K which is consistent with that for an E2 transition (1963GI11). The stripping pattern leads to $J^\pi = 0^-$ or 1^- for ^{16}N*(0.40). However, since it decays to both ^{16}N*(0, 0.12) [$J^\pi = 2^-, 0^-$, respectively], $J^\pi = 1^-$ is indicated: see (1956ZI1A, 1957WA01, 1957WI1B). The assignment $J^\pi = 3^-$ for ^{16}N*(0.30) is strongly favored by the (p-γ) angular correlation (1957FR56).

See also (1961AL05, 1961JA23, 1961LO10, 1961SE01, 1964MA57, 1967CH19, 1968BO1V).

19. $^{15}N(t, d)^{16}N$ $\qquad Q_m = -3.771$

Not reported.

20. $^{15}N(\alpha, {}^3He)^{16}N$ $\qquad Q_m = -18.091$

Not reported.

21. $^{15}N(^{11}B, {}^{10}B)^{16}N$ $\qquad Q_m = -8.969$

See (1969BR1D).

22. $^{16}C(\beta^-)^{16}N$ $\qquad Q_m = 8.010$

See ^{16}C.

Table 16.8: Levels of ^{16}N from $^{15}N(d, p)^{16}N$ and $^{18}O(d, \alpha)^{16}N$

E_x (MeV ± keV)				J^{π} [c]
(1957WA01, 1963GI11) [a]	(1966HE10) [a]	(1966HE10) [b,f]	(1970BO08) [b]	
0	0	0		2^-
0.1201 ± 0.5 [d]	0.125 ± 10	0.119 ± 15		0^-
0.2962 ± 1.0 [d]	0.299 ± 10	0.301 ± 15		3^-
0.3973 ± 1.0 [d]	0.398 ± 10	0.400 ± 15		1^-
	3.365 ± 10	3.358 ± 15		(1^+)
(3.53 ± 30)	3.523 ± 10	3.524 ± 15	[g]	
3.98 ± 20	3.964 ± 10	3.964 ± 15		$(2, 3)^+$
	4.325 ± 10	4.324 ± 15		(1^+)
		4.383 ± 15		
	4.715 ± 10			
4.80 ± 50 [e]	4.780 ± 10	4.787 ± 15	[g]	
	(4.90 ± 10)			
(5.01 ± 50)				
	5.032 ± 10	5.065 ± 15		
	5.128 ± 10			
		5.139 ± 15		
	5.150 ± 10			
5.25 ± 50 [e]	5.231 ± 10	5.240 ± 15		
	5.310 ± 10			
	5.523 ± 10	5.528 ± 15	[g]	
	5.739 ± 10	5.740 ± 15	[g]	
			6.01 ± 15 [k]	
	6.170 ± 10	6.168 ± 15	[h]	
	(6.28 ± 10)			
	6.376 ± 10		6.37 ± 15 [k]	
	6.431 ± 10			
	6.514 ± 10	6.512 ± 15	[h]	
	6.609 ± 10	6.620 ± 15	[h]	
	(6.79 ± 10)			
	6.847 ± 10	6.852 ± 15	[h]	

Table 16.8: Levels of ^{15}N(d, p)^{16}N and ^{18}O(d, α)^{16}N (continued)

E_x (MeV ± keV)				J^{π} [c]
(1957WA01, 1963GI11) [a]	(1966HE10) [a]	(1966HE10) [b,f]	(1970BO08) [b]	
	7.034 ± 10		7.01 ± 15 [k]	
	7.135 ± 10	7.141 ± 15	[h]	
	7.250 ± 10	7.247 ± 15	[h]	
	7.577 ± 10	7.596 ± 15	[h]	
	7.638 ± 10		7.64 ± 15 [k]	
	7.676 ± 10	7.683 ± 15		
	7.840 ± 10		7.88 ± 15 [k]	
			8.06 ± 15 [k]	
			8.18 ± 15 [k]	
		8.286 ± 15	[h]	
		8.374 ± 15	[h]	
			8.49 ± 30 [i]	
			8.819 ± 15 [j]	
			9.035 ± 15	
			(9.16 ± 30)	
			(9.34 ± 30)	
			9.459 ± 15	
			(9.66 ± 40)	
			9.794 ± 15 [j]	
			9.90 ± 30	
			10.055 ± 15 [j]	
			(10.17 ± 30)	
			(10.26 ± 30)	

[a] ^{15}N(d, p)^{16}N.
[b] ^{18}O(d, α)^{16}N.
[c] J^{π} assignment from angular distribution analyses and gamma decay (1956ZI1A, 1957WA01, 1970BO08).
[d] From γ-decay studies (1963GI11). (1957FR56, 1957WI1B) found $E_{\rm x} = 120 \pm 1$, 294 ± 5 and 392 ± 3 keV.
[e] $\Gamma_{\rm c.m.} = 230 \pm 40$ and 290 ± 50 keV, respectively (1957WA01).
[f] See also (1970BO08).
[g] Angular distribution reported in ^{18}O(d, α)^{16}N at $E_{\rm d} = 10.0 - 11.2$ MeV but L not determined (1970BO08).
[h] Alpha group seen but $E_{\rm x}$ not determined.
[i] Γ for this level and the ones listed below $\leq 40 - 50$ keV (1970BO08).
[j] These levels appear to be correlated with thresholds for neutron emission to excited states of ^{15}N (1970BO08, 1970BO09).
[k] T.I. Bonner, private communication.

23. ^{16}O(n, p)^{16}N $\qquad Q_{\rm m} = -9.639$

At $E_{\rm n} = 14.4$ MeV, the angular distribution of the neutrons to the (unresolved) first four states of ^{16}N has been measured by (1964PA11). See also (1959PR73, 1961KA06, 1963AL18, 1964AL22, 1964BI02, 1965GR21, 1966SC05, 1966SC1G).

24. ^{16}O(t, ^{3}He)^{16}N $\qquad Q_{\rm m} = -10.403$

At $E_{\rm t} = 22$ MeV, ^{3}He groups have been observed to the first four states of ^{16}N: $E_{\rm x} = 0$, 0.121, 0.305 and 0.395 MeV (± 15 keV) (F. Ajzenberg-Selove and O. Hansen, private communication).

25. ^{17}O(d, ^{3}He)^{16}N $\qquad Q_{\rm m} = -8.288$

Not reported.

26. ^{18}O(n, t)^{16}N $\qquad Q_{\rm m} = -13.346$

Not reported.

27. ^{18}O(p, ^{3}He)^{16}N $\qquad Q_{\rm m} = -14.110$

At $E_{\rm p} = 43.7$ MeV, the angular distribution of the ^{3}He nuclei corresponding to a state at $E_{\rm x} = 9.9$ MeV fixes $L = 0$ and therefore $J^{\pi} = 0^{+}$ for ^{16}N*(9.9): it is presumably the $T = 2$ analog of the ground state of ^{16}C. Some lower-lying $T = 1$ states were also observed (1964CE05). See also (1969GA1P).

28. ^{18}O(d, α)^{16}N $\qquad Q_{\rm m} = 4.244$

$Q_{0} = 4.249 \pm 0.015$ (1966HE10);

$Q_{0} = 4.244 \pm 0.004$ (1967SP09).

Forty-three α-particle groups have been observed at $E_{\rm d} \leq 12$ MeV, corresponding to states of ^{16}N with $E_{\rm x} < 10.3$ MeV: see Table 16.8 (1966HE10, 1970BO08, 1970BO09). ^{16}N*(8.82, 9.8, 10.06) may be related to nearly bound virtual states of a 2s$_{1/2}$ neutron with ^{15}N*(6.32, 7.30, 7.57) (1970BO08, 1970BO09). $\tau_{\rm m}$ for ^{16}N*(0.4) $= 42 \pm 10$ psec; $|M|^2$ for the M1 transition to ^{16}N*(0.1) is 0.0350 W.u. (1969NI09). See also (1961LO10, 1964AM1A, 1964MA57) and ^{20}F in (1972AJ02).

29. ^{18}O(^{6}Li, ^{8}Be)^{16}N $\qquad Q_{\rm m} = 2.677$

$\tau_{\rm m}$ for ^{16}N*(0.3) $= 95 \pm 20$ psec; $|M|^2 = 0.0126$ W.u. (1969NI09).

30. ^{19}F(n, α)^{16}N $\qquad Q_{\rm m} = -1.524$

Angular distributions have been reported for $E_{\rm n} = 4.7$ to 14.4 MeV: see (1966BH05, 1966KN02, 1968AN1F, 1968RE07). See also (1959KO60, 1960BO1B, 1965HA1G), (1959AJ76) and ^{20}F in (1972AJ02).

^{16}O

(Figs. 3 and 5)

GENERAL: (See also (1959AJ76).)

Shell model: (1957WI1E, 1959BR1E, 1959FE1A, 1959PA1A, 1960TA1E, 1960TA1C, 1961BA1E, 1961TR1B, 1962BA1F, 1962GI02, 1962NA1A, 1962SA1A, 1962TA1E, 1962UL02, 1962VI02, 1963AB1A, 1963BR1B, 1963BU1C, 1963CO12, 1963KU1B, 1964BA1Q, 1964DI1B, 1964EI1A, 1964ER1A, 1964GA1D, 1964GI1B, 1964GI1C, 1964KA1C, 1964LE20, 1964MA1K, 1964MI1E, 1964RI1A, 1964VO1B, 1965BA08, 1965CH1D, 1965EI1A, 1965GI1B, 1965KE06, 1965NA1B, 1965SP1B, 1965VO1A, 1965WA1Q, 1965YO1C, 1965ZA1B, 1966AB1C, 1966BA2F, 1966BE1K, 1966BE1L, 1966BH1B, 1966BO10, 1966BO1P, 1966BR04, 1966BR1R, 1966BR1H, 1966CE06, 1966CO1G, 1966CO1H, 1966DA1F, 1966FE05, 1966GU06, 1966HA31, 1966JA1H, 1966KE1C, 1966KR02, 1966LE1L, 1966LE1M, 1966ME1J, 1966RI1F, 1966SE05, 1966SH1G, 1966SO05, 1966ST08, 1966SV1A, 1966WI1E, 1966WO02, 1966YO1B, 1967AM1G, 1967AR02, 1967BA1K, 1967BA31, 1967BA2D, 1967BE02, 1967BE1V, 1967BL1M, 1967BO1G, 1967BR1E, 1967BR1J, 1967EN01, 1967FE01, 1967FE1D, 1967GI1B, 1967KE1G, 1967KI1B, 1967KR1C, 1967LA1L, 1967MO1J, 1967MU02, 1967MU01, 1967PA10, 1967PA05, 1967PH02, 1967PI1B, 1967RI1B, 1967SA1G, 1967SH1H, 1967ST06, 1967ST1L, 1967SV1A, 1967VA1G, 1967WO1D, 1968AG1E, 1968BA1L, 1968BL01, 1968DE13, 1968GO01, 1968GU1C, 1968HA11, 1968HE1H, 1968KL1D, 1968LA1B, 1968MA01, 1968MA2B, 1968MU1E, 1968PA1T, 1968PE1D, 1968RO1G, 1968TA1R, 1968TA1G, 1968VA1L, 1968VA1N, 1968WA04, 1968WO1A, 1968WO1C, 1968YA1E, 1968ZU02, 1969AB05, 1969AB07, 1969AF02, 1969AG03, 1969BA2Q, 1969BU11, 1969DA1H, 1969DA1J, 1969DE1U, 1969EL05, 1969FU05, 1969GU1E, 1969HU1G, 1969JA10, 1969KA1A, 1969KE1B, 1969KL02, 1969LA1G, 1969LO06, 1969MA38, 1969PE06, 1969PE10, 1969PE1J, 1969PU04, 1969RE1C, 1969SA1F, 1969SA1A, 1969SE04, 1969SU1F, 1969SV1A, 1969UL02, 1969UL03, 1970AR21, 1970BE26, 1970DE24, 1970EL1G, 1970GI11, 1970GO26, 1970GU11, 1970KO04, 1970KR1D, 1970MA28, 1970MC1J, 1970ME1G, 1970NE13, 1970ON1A, 1970PE1A, 1970PE1C, 1970SV1A, 1970TA1A, 1970TE1A, 1970UL1A, 1970VA16, 1970WO12).

Collective model: (1961SA1C, 1962BA1H, 1963BR07, 1963DA1C, 1964BO29, 1964BR1H, 1964SC1G, 1965BO1J, 1965BR1J, 1965FU10, 1965KE06, 1965UB1A, 1965VO1A, 1966BR04, 1966BR1R, 1966BR1Q, 1966CE06, 1966HA1K, 1966LE1J, 1966ST08, 1967BR1E, 1967BR1J, 1967CE1A, 1967FE01, 1967GO23, 1967KR1E, 1967MA1H, 1967PA1M, 1968HO1G, 1968PE1D, 1969AB05, 1969AB07, 1969CU07, 1969DA1J, 1969KA05, 1969KL1E, 1969SE1C, 1969UL02, 1970DE24, 1970TU01).

Cluster and α-particle model: (1958DA1A, 1960RO1C, 1960SH1A, 1961HI09, 1962MA1H, 1962SA1A, 1963BU1C, 1963DA1C, 1963MA1D, 1963MA1E, 1964MA1L, 1964MA1G, 1965BE1H, 1965IN1A, 1965KU1E, 1965NE1C, 1965NE1B, 1966BR1W, 1966BR1U, 1966BR1H, 1966KA1A, 1967TA1C, 1968BE1W, 1968FO1D, 1968PI1A, 1969AB1B, 1969BA2E, 1969CH1K, 1969TA1F, 1970BA2B, 1970BR35, 1970MC1D, 1970NO1B, 1970ON1A, 1971NO03).

Astrophysical questions: (1959CA1B, 1966ST1G, 1969BA71).

Giant resonance (See also reactions 48 and 49.): (1960SA1F, 1961BR1B, 1961FA1A, 1961SA1C, 1962BA1E, 1962BA1H, 1963BA1H, 1964BI1E, 1964EI1A, 1964GA1D, 1964LE1B, 1964MI1E, 1964MI1G, 1964VI1A, 1965DA1D, 1965FU1C, 1965NE1C, 1965SP1B, 1965SP1C, 1965UB1A, 1965YO1C, 1966BA2F, 1966BL1D, 1966DI1D, 1966KL04, 1966LE1J, 1966ME1J, 1966RA1D, 1966WA1K, 1967BE02, 1967BE1V, 1967BU05, 1967GI1B, 1967HI1B, 1967ME1G, 1967MU1D, 1967UB1A, 1967YO04, 1967YO1F, 1968BA1J, 1968DA1M, 1968FR1E, 1968GI1F, 1968MA2B, 1969FU05, 1969KE12, 1969KL02, 1969PE06, 1969SA12, 1969SE1C, 1969SH1C, 1969UB01, 1970FR1E).

Electromagnetic transitions: (1959FA1B, 1959FA1C, 1962BE36, 1962BI12, 1962BI19, 1962MO1A, 1963BO1D, 1963MA1E, 1963PE04, 1964BR1H, 1965CH1D, 1965CO25, 1965EI1A, 1965FU10, 1965GR1H, 1965MA1E, 1965RO1L, 1965ST22, 1966BE1J, 1966GR1J, 1966HA31, 1966RO1P, 1967BA2A, 1967BL1M, 1967GO23, 1967KU1E, 1967YO03, 1968CA08, 1968JA10, 1968MU03, 1968YA1E, 1969AB05, 1969DA1J, 1969HA1F, 1969SE1C, 1969WA1C, 1969WI29, 1970GE12).

Special levels: (1959EG1C, 1960EV1A, 1961BA1F, 1961KA06, 1961TR1B, 1961YO1A, 1962BA1C, 1962BE36, 1962BI12, 1962BI19, 1962IK01, 1962NA1A, 1962VI02, 1963HA05, 1963VI1A, 1964BR1H, 1964CA1D, 1964GA1C, 1964MI16, 1964NA1A, 1964NA1B, 1964SC1G, 1965BO1J, 1965GR1G, 1965HU1C, 1965JO1B, 1965LE1C, 1965NA1B, 1966BA42, 1966BE1L, 1966BO1K, 1966BO1L, 1966CO04, 1966DE18, 1966HA1K, 1966HU13, 1966KA09, 1966LE04, 1966LE1H, 1966ME05, 1966SE05, 1966SO05, 1966TO04, 1966WA1J, 1967AM1G, 1967BO07, 1967DE1Q, 1967KU1J, 1967MA1J, 1968BL01, 1968BO1W, 1968HA06, 1968HA11, 1968JA10, 1968MU03, 1969BU11, 1969GA10, 1969GO1K, 1969HA1G, 1969HA1X, 1969HE12, 1969JA1Q, 1969KR01, 1969PE06, 1969PE10, 1969RO1P, 1969SO1G, 1969ST1J, 1970AR21, 1970DO1J, 1970GA1L, 1970GA1M, 1970ZA01).

Special reactions: (1960IN1B, 1961BA1D, LE63K, 1963SH1B, 1964CH1D, 1964CL1A, 1964ER1A, 1964MC1C, 1965SH11, 1966LE1M, 1967AU1B, 1967CR1F, 1967DE1R, 1967FO1D, 1967GO1A, 1967HI06, 1967PR1D, 1967RI1C, 1968GR1C, 1968WO1B, 1969DA14, 1969MY01, 1969RE1E, 1969TU01, 1970CO1H, 1970RA32).

Muon capture: (1963CO1B, 1964BA1M, 1964BA1N, 1964CO1C, 1964FO1C, 1965DE1K, 1965GI1C, 1965JA1E, 1965UB1A, 1966KI1C, 1966OH1A, 1966WA1K, 1967BA78, 1967BA1Y, 1967BA31, 1967BU1F, 1967DA1D, 1967DE1R, 1967DE1E, 1967FO1C, 1967HI1B, 1967MO1K, 1967RA02, 1967RH1A, 1967RH1B, 1967WA1K, 1968BA2G, 1968FR1E, 1968FU1B, 1968RH1A, 1968WA1L, 1969BU1H, 1969DE1T, 1969GR1E, 1969GR1G, 1969KA1R, 1969VA1A, 1969WU1A, 1970CA1H, 1970CA1J, 1970FR1E, 1970GR1H, 1970PL1A).

Pion capture and reactions: (1966LE1K, 1967DE1R, 1967FO1A, 1967KO1D, 1967ME1F, 1967MI1B, 1967MU1D, 1968BA2G, 1968BA1M, 1968BA48, 1968GU1H, 1968KA1F, 1968KO1C, 1968NO1A, 1968RH1A, 1968TA1C, 1968WI1B, 1968ZU1A, 1969BA1L, 1969BU1C, 1969CH1L, 1969CH1C, 1969ER1C, 1969FU1G, 1969GU1L, 1969KAZY, 1969KE12, 1969KO17, 1969MO1E, 1969MY01, 1969WE05, 1970BA2J, 1970BA44, 1970BE1J, 1970CA1J, 1970CH25, 1970CH1W, 1970EI1C, 1970EL1E, 1970HA46, 1970HO12, 1970KA1J, 1970KO1Q, 1970MA18, 1970TA1C, 1970WE1D).

Other topics: (1959ED1A, 1959GO84, 1960JA1F, 1961RO1D, 1961SW1A, 1962IN1A, 1962LA1D, 1962YU02, 1963BR1D, 1963EV01, 1963HO1E, 1963JO10, 1964BA1L, 1964BR1K, 1964FL1A, 1964LI1B, 1964NA1A, 1964RO1B, 1964VA1D, 1964VO1A, 1964ZU02, 1965HU1D, 1965MA1N, 1965MA36, 1965MA1M, 1965NI1A, 1965RO1K, 1965SI1C, 1966BR1P, 1966ED1B, 1966GI1A, 1966KA09, 1966KO1E, 1966KO1F, 1966MA1U, 1966MI1F, 1966RO1Q, 1966SI1D, 1966SU1D, 1966UL1A, 1966ZH1A, 1967AM1F, 1967BL1N, 1967BR1K, 1967DI1B, 1967EL1E, 1967GR1E, 1967GR1G, 1967HU1B, 1967KA1D, 1967KU13, 1967MA1B, 1967MC09, 1967NI1C, 1967RO1G, 1967RO1H, 1967SC1G, 1967SC16, 1967SH1B, 1968BE1W, 1968CH1F, 1968EL1E, 1968FA1B, 1968GR1J, 1968GU1C, 1968IR1A, 1968IS1A, 1968KO1M, 1968KO1N, 1968LE1F, 1968MC05, 1968MI1E, 1968MO1K, 1968NE1C, 1968PA1U, 1968PA1W, 1968SH08, 1968ST1Q, 1968SU1E, 1968TO1J, 1968WA1K, 1968WI1B, 1969AG03, 1969BA2N, 1969BE1Y, 1969BL1F, 1969FA06, 1969FI1A, 1969GI1B, 1969GR27, 1969GR1H, 1969HA1W, 1969HO1V, 1969IR1A, 1969KA1Q, 1969KH1B, 1969KO1Q, 1969KO14, 1969KO20, 1969LE1L, 1969MC07, 1969ME1H, 1969MI14, 1969NA1E, 1969OS01, 1969PA14, 1969RA21, 1969RU04, 1969SI1D, 1969SO08, 1969ST15, 1970BA2E, 1970BE1Q, 1970BE26, 1970BE1U, 1970BO2A, 1970BR02, 1970DA12, 1970DI1H, 1970DO1J, 1970GM02, 1970KA30, 1970KA1K, 1970KI1F, 1970MC1K, 1970ME1G, 1970MO18, 1970NE09, 1970SC1J, 1970SI02, 1970SP1C, 1970ST1D, 1970SU1B, 1970VO01).

Mass measurement: 15.994 9121 (±12) amu (1968MA45).

1. ^{6}Li(^{14}N, α)^{16}O $\quad Q_{\rm m} = 19.264$

The angular distribution of the α-particles corresponding to ^{16}O(0) has been measured at $E(^{14}\text{N}) = 27.6$ MeV (1964WA1B). See also reaction 37.

2. (a) ^{10}B(^{6}Li, p)^{15}N	$Q_{\rm m} = 18.751$	$E_{\rm b} = 30.877$
(b) ^{10}B(^{6}Li, d)^{14}N	$Q_{\rm m} = 10.141$	
(c) ^{10}B(^{6}Li, t)^{13}N	$Q_{\rm m} = 5.845$	
(d) ^{10}B(^{6}Li, ^{3}He)^{13}C	$Q_{\rm m} = 8.085$	
(e) ^{10}B(^{6}Li, α)^{12}C	$Q_{\rm m} = 23.716$	

At $E(^{6}\text{Li}) = 4.9$ MeV, the cross sections for reactions (a) to (e) leading to low-lying states in the residual nuclei are proportional to $(2J_{\rm f} + 1)$: this is interpreted as indicating that the reactions proceed via a statistical compound nucleus mechanism. For highly excited states, the cross section is higher than would be predicted by a $(2J_{\rm f} + 1)$ dependence (1966MC05). The yield curves for α_0 and α_1 (reaction (e)) measured at 0° for $E(^{6}\text{Li}) = 3.2$ to 13.6 MeV show broad structures. At 90°, for $E(^{6}\text{Li}) = 9.7$ to 13.0 MeV no structure is apparent, suggesting that the 0° yield is explainable in terms of Ericson fluctuations (1967SE08). See also (1963MO1B, 1964GA1E, 1967CA1D, 1970GI05).

Table 16.9: Energy Levels of ^{16}O [a]

E_x in ^{16}O (MeV ± keV)	$J^\pi; T$	$\Gamma_{\rm c.m.}$ (keV) or $\tau_{\rm m}$	Decay	Reactions
0	$0^+; 0$	–	stable	1, 3, 5, 11, 12, 13, 14, 15, 16, 17, 18, 24, 25, 26, 27, 28, 35, 36, 37, 38, 39, 43, 44, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81
6.0502 ± 1.0	$0^+; 0$	72 ± 7 psec	π	11, 12, 24, 27, 35, 36, 37, 44, 47, 55, 56, 58, 61, 66, 67, 70, 71, 79, 80
6.13066 ± 0.18	$3^-; 0$	24 ± 2 psec	γ	3, 4, 11, 12, 25, 27, 35, 36, 37, 43, 44, 47, 55, 56, 57, 58, 61, 64, 66, 67, 70, 71, 74, 79, 80
6.9188 ± 0.6	$2^+; 0$	6.8 ± 0.4 fsec	γ	11, 12, 25, 27, 35, 36, 37, 43, 44, 54, 55, 56, 57, 58, 61, 64, 66, 70, 71, 74, 79
7.11867 ± 0.35	$1^-; 0$	10.6 ± 0.9 fsec	γ	9, 11, 12, 25, 27, 35, 36, 37, 43, 44, 47, 54, 56, 57, 58, 61, 64, 66, 67, 70, 71, 74
8.8717 ± 0.5	$2^-; 0$	180 ± 16 fsec	γ	4, 11, 12, 25, 35, 36, 43, 44, 47, 56, 57, 61, 66, 67, 70, 74
9.597 ± 21	$1^-; 0$	$\Gamma = 510 \pm 60$	γ, α	5, 9, 11, 12, 35, 44, 47, 61
9.8469 ± 2.8	$2^+; 0$	1.1	γ, α	5, 9, 11, 12, 25, 35, 36, 43, 44, 47, 55, 57, 61, 70, 74, 79
10.353 ± 4	$4^+; 0$	27 ± 4	γ, α	5, 9, 11, 12, 25, 35, 36, 44, 57, 61, 67, 74
10.952 ± 3	$0^-; 0$	$\tau_{\rm m} = 8 \pm 5$ fsec	γ	35, 36, 43, 44
11.080 ± 3	$3^+; 0$	57 ± 19 fsec	γ	35, 36, 43, 44, 57, 74
11.096 ± 3	$4^+; 0$	$\Gamma = 0.3 \pm 0.1$	α	9, 11, 12, 25, 35, 36, 43, 44, 57, 74
11.26	$0^+; 0$	2500	α	9, 43, 44
(11.44)	$3^-; 0$	830	α	9
11.521 ± 4	$2^+; 0$	74 ± 4	γ, α	5, 11, 35, 36, 55, 61
11.63	$3^-; 0$	1200	α	9, 11
12.053 ± 3	$0^+; 0$	1.5 ± 0.5	α	9, 11, 35, 36, 55, 57, 61
12.441 ± 4	$1^-; 0$	97 ± 6	γ, p, α	5, 7, 9, 11, 35, 36, 39, 40, 42, 43, 44
12.528 ± 1	$2^-; 0$	≤ 0.5	γ, p, α	11, 35, 36, 39, 40, 42, 43, 44, 55, 57
12.795 ± 5	$0^-; 1$	38 ± 4	γ, p	35, 39, 40, 43, 44

Table 16.9: Energy Levels of ^{16}O [a] (continued)

E_x in ^{16}O (MeV $\pm$ keV)	$J^\pi; T$	$\Gamma_{c.m.}$ (keV) or τ_m	Decay	Reactions
12.9666 ± 0.9	$2^-; 1$	2.0 ± 0.2	γ, p, α	35, 39, 40, 42, 43, 44, 55
13.02 ± 10	2^+	150 ± 11	α	9, 55
13.093 ± 6	$1^-; 1$	127 ± 8	γ, p, α	5, 7, 9, 11, 34, 35, 39, 40, 42, 44, 55
13.129 ± 10	$3^-; 0$	128 ± 11	p, α	7, 9, 36, 44
13.14 ± 100	2^+	≈ 250	γ, p, α	5, 42
13.2582 ± 2.5	$3^-; 1$	21 ± 1	γ, p, α	5, 7, 9, 11, 35, 40, 42, 43, 44, 67
13.6634 ± 2.7	$1^+; 0$	64 ± 3	p, α	35, 36, 40, 42, 57
13.869 ± 10	4^+	85 ± 14	p, α	9, 11, 35, 42, 57
13.9782 ± 2.4	2^-	22 ± 2	p, α	35, 40, 42, 61
14.00 ± 50	0^+	170 ± 50	γ	55
14.0	0^+	4800	α	9
14.39 ± 25	$4^+; 0$	30 ± 30		11, 25, 35, 36
(14.53)				11
14.82 ± 30	$6^+; 0$	69 ± 30	α	9, 11, 25, 36
14.922 ± 6	4^+	51 ± 7	p, α	34, 35, 40, 42, 61
15.22 ± 35	2^-	70 ± 15	p, α	11, 40, 42, 57, 67
15.26 ± 50	$2^+; (0)$	660 ± 90	γ, p, α	11, 39, 40, 42, 55
15.42 ± 40	$(1^-, 3^-)$	95 ± 25	p, α	7, 9, 34, 40, 42, 67
15.792 ± 14	$(T = 0)$	≈ 60		11, 35, 36
16.218 ± 13	$1^+; 1$	19 ± 6	γ, n, p	35, 39, 40, 41, 48, 55, 57
16.23 ± 15	$6^+; 0$	125 ± 50	α	9, 11, 12, 34, 35, 36
16.30 ± 30	$0(^-)$	240 ± 30	n, p	41
16.407 ± 24	2^+	45	γ, n, p, α	5, 6, 7, 9, 55
16.80 ± 100	(3^+)	≤ 100	γ	55
16.94	2^+	≈ 280	α, ^{8}Be	10
17.142 ± 12	$1^-; 1$	33 ± 5	γ, n, p, α	6, 7, 9, 35, 36, 39, 40, 41, 44, 48, 55, 57
17.17	2^+	200	α, ^{8}Be	10, 44
17.30 ± 15	$1^-; 1$	90 ± 10	γ, n, p, α	6, 9, 39, 40, 41, 48, 55
17.55	(4^+)	165	(γ), n, α	6, 9, 48
17.63 ± 15	$\geq 1; 1$	59 ± 10	(γ), n, p, α	7, 9, 41, 55, 57
17.755 ± 15	$0^+, 2^+$	≈ 30	α, ^{8}Be	10, 35
17.82 ± 40	4^+	225	n, α, ^{8}Be	6, 9, 10, 35
17.86 ± 15	$\geq 1; 1$	101 ± 10	n, p	41
18.018 ± 15	$4^+; 0$	14	(n), p, α, ^{8}Be	7, 9, 10, 35, 41
18.05 ± 15	$(4^+); 1$	26 ± 5	γ, n, p, α	6, 9, 35, 39, 41

Table 16.9: Energy Levels of ^{16}O [a] (continued)

E_x in ^{16}O (MeV ± keV)	$J^\pi; T$	$\Gamma_{c.m.}$ (keV) or τ_m	Decay	Reactions
18.132 ± 24		220 ± 60	n, p, α	6, 41
18.18 ± 25	2^+	390 ± 80	n, α	6
18.46 ± 25		≈ 160	n, p	41
18.6	$(1^-, 5^-)$	140	α	9
18.71	$0^+, 2^+$	260 ± 30	n, p, α, ^{8}Be	10, 41
18.79	(4^+)	220	n, p, α, ^{8}Be	6, 7, 9, 10
(18.983 ± 15)		$\lesssim 25$		35
18.99 ± 30	$1^-; 1$	300 ± 100	γ, p	39, 55
19.04 ± 50	$2^-; 1$	400 ± 50	γ, α	9, 55
19.06 ± 60	$2^+; 1$	≈ 120	γ, p	39, 40, 48
19.12	$(2^+, 4^+)$	41	(n), α	6, 9
19.24 ± 25	$2^-; 1$	90 ± 10	γ, n, p	39, 41
19.25	(5^-)	23	(n), α	6, 9
19.34	6^+	50	α, ^{8}Be	10
(19.382 ± 15)	$\pi = +$	≈ 30	α	9, 35
19.48 ± 30	$1^-; 1$	300 ± 80	γ, n, p, α	9, 39, 41, 48, 55
19.62		240	n, α	6
19.80 ± 150			(α)	9, 57
19.90 ± 25	(2, 3; 1)	120 ± 40	γ, n, p, α	9, 35, 39, 41
20.087		310	n, α	6
20.3		≈ 1500	p, α	7
(20.348 ± 15)		≈ 30	γ, n	35, 48
20.36 ± 70	2^-	500 ± 100	γ	55
20.39 ± 25	≥ 2	150 ± 30	γ, n, p, α	6, 9, 39, 41
20.55 ± 25	≥ 1	140 ± 30	n, p, α	9, 41
20.8	(8^+)	≈ 600	γ	11, 12, 39
20.81		< 25	n, α	6
20.89 ± 25		≈ 250	γ, n, p	39, 41, 48, 49
(21.0)	(7^-)	750	(γ), α	9, 48
21.01 ± 20	$1^-; 1$	260 ± 60	γ, n, α	5, 48, 55
21.02 ± 20		55	(γ), n, α	6, 48
(21.1)	(5^-)	900	α	9
(21.2)	(6^+)	450	n, α	6, 9, 11
21.68		55	γ, n, α	6, 48
21.79		55	γ, n, p, d, α	6, 29, 39, 48
22.04		60	γ, n, d, α	6, 11, 29, 39
22.07		340	n, α	6, 11

Table 16.9: Energy Levels of ^{16}O [a] (continued)

E_x in ^{16}O (MeV $\pm$ keV)	$J^\pi; T$	$\Gamma_{c.m.}$ (keV) or τ_m	Decay	Reactions
22.13		< 150	γ, n, d, α	6, 11, 28, 29, 33, 48
22.26 ± 38	$1^-; 1$	≈ 650	γ, n, p, d, α	28, 29, 33, 39, 41, 48, 49, 55
22.52		375	n, d, α	6, 11, 33
22.720 ± 4	$0^+; T = 2$	15 ± 6	p, d, α	7, 9, 27, 30, 33, 70
22.75	$1^-; 1$	60	γ, n, d, α	6, 11, 28, 29, 31, 33, 55
23.11		≈ 20	d, α	9, 31, 33
23.15 ± 34		≈ 500	γ, n, (p), d, α	9, 33, 48, 49
23.40		< 40	n, d, α	6, 31, 33
23.54		300	n, p, d, α	9, 29, 30, 31, 33
23.75		120	n, α	6
23.89		≈ 25	α	9, 11
23.93		165	n, α	6
(24.05)		≈ 80	n, ^{3}He	19
24.05 ± 100		450	γ, n, ^{3}He	18, 48
24.4	$(T = 1)$	≈ 250	γ, n, p, d, ^{3}He, α	19, 28, 29, 30, 31, 33, 48, 49, 55
24.522 ± 11	$2^+; T = 2$	< 50		27, 55, 70
24.74	$T = 1$		(γ), p, d, ^{3}He, α	22, 30, 31, 33, 39
25.12 ± 50		650	γ, n, p, d, ^{3}He	18, 29, 30, 48, 49
25.55 ± 50	$(1^-; 1)$	1000	γ, n, p, ^{3}He, α	20, 22, 39, 48, 55
25.94	$(T = 1)$	600 ± 200	d, ^{3}He, α	22, 31, 33
(26.38 ± 180)			(γ, n, p)	39, 48, 49
26.7 ± 250	$(1^+; 1)$	600 ± 200	^{3}He, α	22, 33, 55
27.32 ± 92	$(2^+; 1)$	≈ 600	(γ, n), d, ^{3}He, α, ^{8}Be	22, 23, 31, 48
27.6 ± 100	$(3^-; 0)$	≈ 500	p, ^{3}He, α	20, 21, 22
(28.1 ± 100)	$(T = 1)$	600 ± 200	d, ^{3}He, α	22, 33
(28.3 ± 100)	$(T = 0)$		^{3}He, α	22
(28.9 ± 100)	$(T = 1)$	600 ± 200	^{3}He, α	22
29.7 ± 100	$(T = 1)$	600 ± 200	(γ, n), d, ^{3}He, α	22, 31, 48
(30.4 ± 100)	$(T = 1)$	600 ± 200	^{3}He, α	9, 22
31.2 ± 200	$(T = 1)$	600 ± 200	(γ, n, p), ^{3}He, α	22, 48, 49, 54
(33.0 ± 300)			(γ, n)	48
44.5	$(1^-; 1)$	$2000 - 3000$	γ	55
49	$(1^-; 1)$	$2000 - 3000$	γ	54, 55

[a] See also Tables 16.12, 16.19 and 16.26.

3. ^{10}B(^{14}N, ^{8}Be)^{16}O $\quad Q_{\rm m} = 14.708$

$\tau_{\rm m}$ for ^{16}O*(6.13) $= 21^{+1}_{-7}$ psec. The ground state E3 transition has a strength of 62 W.u. (1969NI09).

4. ^{11}B(^{7}Li, 2n)^{16}O $\quad Q_{\rm m} = 12.169$

$\tau_{\rm m}$ for ^{16}O*(8.88) $= 0.37 \pm 0.13$ psec. The transition energy for $8.88 \rightarrow 6.13$ is 2740.4 ± 1.0 keV (1969TH01).

5. ^{12}C(α, γ)^{16}O $\quad Q_{\rm m} = 7.161$

The yield of capture γ-rays has been studied for $E_\alpha < 23.5$ MeV: see Table 16.10. The cross section rises from $(1.1 \pm 0.4) \times 10^{-3}$ μb at $E_\alpha = 1.86$ MeV to $(29 \pm 4) \times 10^{-3}$ μb at $E_\alpha = 3.11$ MeV. At $E_\alpha = 1.6$ MeV, the capture cross section is $< 0.3 \times 10^{-3}$ μb (1970JA09). At higher energies resonances are observed. These are displayed in Table 16.11 (1960ME02, 1964LA16, 1965MI05, 1967SU02). Widths for γ-emission have been measured for several of the corresponding ^{16}O states: see Table 16.12 (1963GO31, 1964LA16, 1966GO18, 1967GO08, 1967SU02). See also (1969BR1L) and (1967GI1C, 1969GI1B; theor.). The asymmetries in the angular distributions in this reaction and in the inverse reaction ^{16}O(γ, α)^{12}C are the same within one standard deviation: there is no evidence for failure of time reversal invariance (1970VO13). The relevance of this reaction to the buildup of elements in stars is discussed by (1967ST1M, 1967WI1B, 1970TO1C, 1970WE1A, 1970WE1F) and in earlier papers listed in (1959AJ76).

6. ^{12}C(α, n)^{15}O $\quad Q_{\rm m} = -8.507 \quad E_{\rm b} = 7.161$

Cross section measurements have been made from threshold to $E_\alpha = 24.7$ MeV: see Table 16.10. Observed resonances are displayed in Table 16.11 (1963NE05, 1968BL08, 1970BE1T). See also (1962GO1J, 1963GO1J, 1965AL1J, 1965TS1A) and (1963KE1A; theor.). See also ^{15}O in (1970AJ04).

7. ^{12}C(α, p)^{15}N $\quad Q_{\rm m} = -4.965 \quad E_{\rm b} = 7.161$

The yield of protons corresponding to the ground state of ^{15}N has been studied for $E_\alpha =$ 7.7 to 23 MeV: see Table 16.10. Observed resonances are displayed in Table 16.11 (1960PR13, 1964AT02, 1964CA07, 1965MI05, 1968MO1H, 1970BE1T, 1970NE1H). See also (1963KE1A; theor.) and ^{15}N in (1970AJ04).

Table 16.10: Recent $^{12}C + \alpha$ yield curves [a]

E_α (MeV)	Yield of	Refs.
1.91 – 3.16	$\gamma_{capt.}$	(1968JA1K, JA69K)
2.60 – 3.25	$\gamma_{capt.}$	(1968AD1D)
2.8 – 8.3	$\gamma_{capt.}$	(1964LA16)
6.9 – 8.4	$\gamma_{capt.}$	(1964MI12, 1965MI05)
8.75 – 23.50	$\gamma_{capt.}$	(1967SU02)
thresh. – 19	$n(\sigma_t)$	(1963NE05)
thresh. – 22.7	$n(\sigma_t)$	(1968BL08)
13 – 16	n_0	(1970BE1T)
13.7 – 24.7	^{15}O	(1969SP1B)
15 – 19	$n(\sigma_t)$	(1962CA03)
7.7 – 8.4	p_0	(1965MI05)
9.6 – 17.6	p_0	(1964CA07)
12.4 – 16.0	p_0	(1967IV1B)
13 – 16	p_0	(1970BE1T)
13 – 23	p_0	(1968BL08)
15.8 – 19.0	p_0	(1960PR13)
15.9 – 26.3	p_0	(1965TE01)
19 – 23	$p_1 + p_2$	(1968BL08)
19.7 – 22.1	p_0	(1963YA1C)
20 – 23	p_0	(1964AT02)
2.5 – 4.8	α_0	(1962JO09)
2.8 – 6.6	α_0	(1968CL04)
4 – 13.3	α_0	(1969MA1U)
5.2 – 5.3	α_0	(1966LA09)
6 – 17	$\gamma_{4.4}$	(1964MI08)
6.5 – 6.6	α_0	(1966LA09)
6.6 – 8.5	α_0	(1968MO08)
7.3 – 8.4	$\gamma_{4.4}$	(1964MI12)
7.4 – 10.6	$\gamma_{4.4}$	(1964LA16)
7.7 – 8.3	α_1, $\gamma_{4.4}$	(1965MI05)
8.5 – 10.5	α_0, α_1	(1970OP01)

Table 16.10: Recent ^{12}C + α yield curves [a] (continued)

E_α (MeV)	Yield of	Refs.
9.5 – 19	α_1	(1964MI08)
9.8 – 19.1	α_0	(1964CA07)
10.7 – 11.8	α_0	(1967KR1D)
12.0 – 17.3	α_2	(1970MO22)
12.8 – 26.3	α_0, α_1	(1966IF01)
13.5 – 23.5	α_1	(1963LU08)
13.5 – 30.5	α_0	(1963LU08)
14.4 – 18.8	$\gamma_{4.4}$	(1962CA03)
14.5	α_0, α_1	(1968MO1H)
14.6 – 18.1	α_3	(1970MO22)
15 – 22.7	α_0	(1962JO14)
16.2 – 19.2	α_2	(1964MI08)
17.3 – 23.4	α_0, α_1	(1964JO14)
18.9 – 30.1	α_0, α_1	(1970MO06)
20 – 24	α_0	(1968AG03, 1969AG06)
20.2 – 22.8	α_1	(1964AT02)
27.0 – 35.5	α_0, α_1	(1961MI03)
11.9 – 19.4	^{8}Be	(1967CH21)

[a] See also (1959AJ76).

8. ^{12}C(α, d)^{14}N $\qquad Q_m = -13.575 \qquad E_b = 7.161$

See ^{14}N in (1970AJ04). See also (1968NO1C; theor.).

9. ^{12}C(α, α)^{12}C $\qquad E_b = 7.161$

The yield of α-particles corresponding to ^{12}C*(0, 4.4) and of 4.4 MeV γ-rays has been studied at many energies in the range $E_\alpha = 2.5$ to 35.5 MeV: see Table 16.10. Observed resonances are displayed in Table 16.11 (1953HI05, 1954BI96, 1955RA1B, 1961MI03, 1962JO09, 1962JO14, 1964CA07, 1964LA16, 1964MI08, 1964MI12, 1965MI05, 1966LA09, 1967LA1J, 1968AG03, 1968CL04, 1968MO08, 1968MO1H, 1969AG06, 1970HA15, 1970NE1H, 1970OP01). See also (1961FE02 and private communication, 1966BO28).

Table 16.11: Resonances in $^{12}C + \alpha$

E_α (MeV ± keV)	$\Gamma_{c.m.}$ (keV)	Outgoing particles [a] (x)	Γ_x (keV)	$^{16}O^*$ (MeV)	$J^\pi; T$	Refs.
3.322 ± 30	550	γ_0	$(2.2 \pm 0.5) \times 10^{-5}$	9.58	1^-	(1953HI05, 1962JO09, 1964LA16, 1968CL04)
		α_0				
3.575 ± 10	1.1	γ_0	$(5.9 \pm 0.6) \times 10^{-6}$	9.842	2^+	(1953HI05, 1960ME02, 1962JO09, 1964LA16)
		α_0				
4.241 ± 25	195	α_0		10.341	4^+	(1962JO09)
4.260 ± 15	27 ± 4	γ_0		10.355		(1964LA16)
5.245 ± 8	0.3 ± 0.1	α_0		11.094	4^+	(1966LA09)
5.47	2500	α_0		11.26	0^+	(1954BI96)
5.71	830	α_0		11.44	3^-	(1968CL04)
5.809 ± 18	73 ± 5	γ_0	$(0.66 \pm 0.09) \times 10^{-3}$	11.517		(1960ME02, 1964LA16)
5.96	1200	α_0		11.63	3^-	(1954BI96)
6.518 ± 10	1.5 ± 0.5	α_0		12.048	0^+	(1966LA09)
7.045 ± 5	99 ± 7	γ_0	$(7 \pm 1) \times 10^{-3}$	12.443	$1^-; 0$	(1954BI96, 1964LA16, 1964MI12, 1968MO08)
		p	1.1			
		α_0	98 ± 8			
		α_1	0.025			
7.82 ± 10	150 ± 11	α_0	150 ± 11	13.02	2^+	(1968MO08)
7.915 ± 10	113 ± 15	γ_0	8.8×10^{-2}	13.095	$1^-; 1$	(1964LA16, 1964MI12, 1965MI05, 1968MO08)
		p	100			
		α_0	45 ± 18			
		α_1	1			
7.960 ± 10	128 ± 11	p	1	13.129	$3^-; 0$	(1964LA16, 1964MI08, 1965MI05, 1967LA1J, 1968MO08)
		α_0	90 ± 14			
		α_1	≈ 20			
		$\gamma_{4.4}$				
7.98 ± 100	≈ 250	γ_0		13.14	2^+	(1964LA16, 1965MI05)

Table 16.11: Resonances in ^{12}C + α (continued)

E_α (MeV $\pm$ keV)	$\Gamma_{\mathrm{c.m.}}$ (keV)	Outgoing particles [a] (x)	Γ_{x} (keV)	^{16}O* (MeV)	$J^\pi; T$	Refs.
8.130 ± 15	26 ± 7	γ_0		13.257	$3^-; 1$	(1964LA16, 1964MI08, 1964MI12, 1965MI05, 1968MO08)
		p	4.5			
		α_0	9 ± 4			
		α_1	7.5			
		$\gamma_{4.4}$				
8.96	70	α_0, $\gamma_{4.4}$		13.88	4^+	(1964LA16, 1964MI08, 1970OP01)
9.1	4800	α_0		14.0	0^+	(1968CL04)
10.08	400	$\gamma_{4,4}$, (α_0)		14.72		(1964CA07, 1964LA16, 1964MI08)
10.18	40	α_0, α_1, $\gamma_{4,4}$		14.79	6^+	(1964CA07, 1964LA16, 1964MI08, 1970OP01)
10.25	55	p_0, α_0		14.85		(1964CA07)
11.02	≈ 100	p_0, α_0, α_1, $\gamma_{4.4}$		15.42	$(1^-, 3^-)$	(1964CA07, 1964MI08)
(11.08)	280	p_0, α_0		15.47		(1964CA07)
11.5	≈ 400	α_0, α_1, $\gamma_{4.4}$		15.8	3^-	(1964CA07, 1964MI08)
12.1	280	α_0		16.2	6^+	(1964CA07)
12.32 ± 25	45	γ_0, n, p_0, α_0, α_1, $\gamma_{4.4}$		16.40 [b]	2^+	(1964CA07, 1964MI08, 1967SU02, 1968BL08)
12.5	730	p_0, α_0		16.5		(1964CA07)
12.9	400	α_0		16.8	(4^+)	(1964CA07)
13.0	700	α_0		16.9	5^-	(1964CA07)
13.05	≈ 280	^{8}Be		16.94	2^+	(1967CH21)
13.26	110	n, (p_0), α_0, α_1, $\gamma_{4.4}$		17.10	$(1^-, 2^+, 0^+)$	(1964CA07, 1964MI08, 1968BL08)
13.35	200	^{8}Be		17.17	2^+	(1967CH21)
13.50	< 100	n		17.28		(1968BL08)
13.59	150	α_1, $\gamma_{4.4}$		17.35		(1964MI08)
13.86	165	n, α_0		17.55	(4^+)	(1964CA07, 1968BL08)
13.95	110	p_0, α_0		17.62		(1964CA07, 1970BE1T)
14.1		^{8}Be		17.7	$0^+, 2^+$	(1967CH21)
14.21	225	n, α_1, $\gamma_{4.4}$, ^{8}Be		17.81	4^+	(1964MI08, 1967CH21)

Table 16.11: Resonances in ^{12}C + α (continued)

E_α (MeV ± keV)	$\Gamma_{\rm c.m.}$ (keV)	Outgoing particles [a] (x)	$\Gamma_{\rm x}$ (keV)	^{16}O* (MeV)	$J^\pi; T$	Refs.
14.483 ± 15	14	p$_0$, α_0, α_1, ^{8}Be		18.018	4^+; 0	(1967CH21, 1968MO1H)
14.50	40	n, α_0, α_1, $\gamma_{4.4}$		18.03	(4^+)	(1964CA07, 1964MI08, 1968BL08)
14.59 ± 40	220 ± 60	n$_0$		18.10		(1963NE05, 1968BL08, 1970BE1T)
14.70 ± 25	390 ± 80	n		18.18	2^+	(1967SU02)
14.85	280	p$_0$, (α_0), α_1, $\gamma_{4.4}$		18.29		(1964CA07, 1964MI08)
15.0	510	α_0, (α_1, $\gamma_{4.4}$)		18.4	5^-	(1964CA07, 1964MI08)
15.2		^{8}Be		18.6	0^+, 2^+	(1967CH21)
15.2	140	α_0, (α_1, $\gamma_{4.4}$)		18.6	$(1^-, 5^-)$	(1964CA07, 1964MI08)
15.46	55	α_0		18.75	(1^-)	(1964CA07)
15.52	220	n, p$_0$, α_0, α_1, ^{8}Be		18.79	(4^+)	(1964CA07, 1964MI08, 1967CH21, 1968BL08)
15.88	broad	α_1, $\gamma_{4.4}$		19.06		(1964MI08)
15.96	41	(n), α_0		19.12	$(2^+, 4^+)$	(1964CA07, 1968BL08)
16.13	23	(n), α_0		19.25	(5^-)	(1964CA07, 1968BL08)
16.25	50	^{8}Be		19.34	6^+	(1967CH21)
16.30	23	α_0		19.38	$(4^+, 0^+)$	(1964CA07)
16.4	broad	α_1		19.5		(1964MI08)
16.62	240	n		19.62		(1968BL08)
16.73	17	α_0		19.70	even	(1964CA07)
(17.0)	825	α_0		(19.9)	(4^+)	(1964CA07)
17.10	140	α_0, α_1		19.98	$(2^+, 0^+, 1^-)$	(1964CA07, 1964MI08)
17.22	310	n		20.07		(1968BL08)
17.5	≈ 1500	p$_0$		20.3		(1960PR13)
17.66	< 150	n		20.40		(1968BL08)
(17.75)	110	α_0		(20.47)	(4^+)	(1964CA07)
17.90		α_1		20.58		(1964MI08)
18.21	< 25	n		20.81		(1968BL08)
18.4	750	α_0		21.01	7^-	(1964CA07)

Table 16.11: Resonances in ^{12}C + α (continued)

E_α (MeV ± keV)	$\Gamma_{c.m.}$ (keV)	Outgoing particles [a] (x)	Γ_x (keV)	^{16}O* (MeV)	$J^\pi; T$	Refs.
18.48	55	n		21.03		(1968BL08)
18.50 ± 25	240 ± 80	γ_0		21.0	1^-	(1967SU02)
18.5	900	α_0		21.1	(5^-)	(1962JO14, 1964CA07)
(18.6)	450	n, α_0, α_1		(21.2)	(6^+)	(1964CA07, 1964MI08, 1968BL08)
19.37	55	n		21.68		(1968BL08)
19.52	55	n		21.79		(1968BL08)
19.85	60	n		22.04		(1968BL08)
19.89	340	n		22.07		(1968BL08)
19.97	< 150	n		22.13		(1968BL08)
20.49	375	n		22.52		(1968BL08)
20.71	60	n		22.68		(1968BL08)
20.760 ± 5	15 ± 6	p_0, (α_0), α_2		22.721	$0^+; (T = 2)$	(1970NE1H)
(21.2)	680	α_0		(23.1)		(1968AG03, 1969AG06)
21.28	≈ 20	α_0, α_1		23.11		(1970HA15)
21.67	< 40	n		23.40		(1968BL08)
21.85	300	α_0, α_1		23.54		(1955RA1B, 1970HA15)
22.14	120	n		23.75		(1968BL08)
22.32	≈ 25	α_0, α_1		23.89		(1970HA15)
22.37	165	n		23.93		(1968BL08)
30	broad	α_0, α_1		30		(1961MI03)

[a] p_0, α_0, and α_1 correspond to groups to ^{15}N(0), ^{12}C(0) and ^{12}C*(4.4); $\gamma_{4.4}$ corresponds to the γ-decay of ^{12}C*(4.4); γ_0 corresponds to capture γ-rays.

[b] $\Gamma_\gamma \Gamma_\alpha / \Gamma = 0.2$, 0.7 and 6 eV, respectively for ^{16}O*(16.40, 18.19, 21.04) (1967SU02).

Table 16.12: Radiative decays in ^{16}O [a]

E_i (MeV)	$J^\pi_i; T$	E_f (MeV)	$J^\pi_f; T$	Branch (%)	Γ_γ (eV)	Refs. [c]
6.05	$0^+; 0$	0	$0^+; 0$	100	3.66 ± 0.55 [b]	(1968ST31)
6.13	$3^-; 0$	0	$0^+; 0$	100	$(2.3 \pm 1.1) \times 10^{-5}$	(1968ST31)
6.92	$2^+; 0$	0	$0^+; 0$	> 99	$(80 \pm 7) \times 10^{-3}$	(1968EV03)
					$(93 \pm 10) \times 10^{-3}$	(1968ST04, 1968ST31)
					$(100 \pm 15) \times 10^{-3}$	(1967AR1A)
					$(110 \pm 5) \times 10^{-3}$	(1970SW03)
		6.05	$0^+; 0$	$(2.7 \pm 0.7) \times 10^{-2}$		(1965FU05)
				$(2.9 \pm 1.1) \times 10^{-2}$	$(1.6 \pm 0.6) \times 10^{-5}$	(1963GO31)
				$(2.3 \pm 0.5) \times 10^{-2}$	$(1.4 \pm 0.5) \times 10^{-5}$	(1966LO06)
				$(2.9 \pm 0.4) \times 10^{-2}$		(1967LO08)
				$(2.7 \pm 0.3) \times 10^{-2}$		mean
		6.13	$3^-; 0$	$< 4 \times 10^{-2}$	2.7×10^{-5}	(1963GO31)
				$\leq 4 \times 10^{-2}$		(1960PI04)
				$\leq 8 \times 10^{-3}$		(1968WI15)
7.12	$1^-; 0$	0	$0^+; 0$	> 99	$(47 \pm 6) \times 10^{-3}$	(1968EV03)
					$(62 \pm 5) \times 10^{-3}$	(1970SW03)
		6.05	$0^+; 0$	$\leq 3.5 \times 10^{-3}$	$\leq 3.0 \times 10^{-6}$	(1963GO31), B
				$< 6 \times 10^{-4}$		(1967LO08)
		6.13	$3^-; 0$	$(8 \pm 2) \times 10^{-2}$	$(5.3 \pm 2.1) \times 10^{-5}$	(1963GO31)
				$(7.0 \pm 1.4) \times 10^{-2}$		(1968WI15)
8.87 [d]	$2^-; 0$	0	$0^+; 0$	7 ± 2		(1957BE61)
				9 ± 4		(1957MC35)
				7.2 ± 0.8		(1968WI15)
					$(2.41 \pm 0.35) \times 10^{-4}$	(1967PI01)
		6.05	$0^+; 0$	0.112 ± 0.033	$(2.9 \pm 1.0) \times 10^{-6}$	(1963GO31, 1967PI01)
		6.13	$3^-; 0$	74		(1959BR68)
				76.0 ± 3.0		(1968WI15)
					$(1.70^{+0.35}_{-0.50}) \times 10^{-3}$ (E2)	(1967PI01)
					$(8.5^{+4.5}_{-2.5}) \times 10^{-4}$ (M1)	(1967PI01)
		6.92	$2^+; 0$	5		(1959BR68)
				4.2 ± 0.8		(1968WI15)
					$(1.72 \pm 0.25) \times 10^{-4}$	(1967PI01)
		7.12	$1^-; 0$	14		(1959BR68)
				12.6 ± 2.0	[e]	(1968WI15)
9.60	$1^-; 0$	0	$0^+; 0$	≈ 100	$(22 \pm 5) \times 10^{-3}$	(1964LA16)

Table 16.12: Radiative decays in ^{16}O [a] (continued)

E_i (MeV)	$J^\pi_i;T$	E_f (MeV)	$J^\pi_f;T$	Branch (%)	Γ_γ (eV)	Refs. [c]
					$(18 \pm 4) \times 10^{-3}$	A
		6.05	$0^+;0$	4.3 ± 1.4	$(1.2 \pm 0.4) \times 10^{-3}$	(1969BR1L), B
					$< 0.6 \times 10^{-3}$	A
		6.13	$3^-;0$	≤ 5	$\leq 1.4 \times 10^{-3}$	(1969BR1L), B
9.85	$2^+;0$	0	$0^+;0$	61 ± 4	$(10 \pm 4) \times 10^{-3}$	(1968ST04, 1968ST31), B
					$(6.3 \pm 0.6) \times 10^{-3}$	(1967GO08)
					$(20 \pm 10) \times 10^{-3}$	(1960ME02)
					$(5.9 \pm 0.6) \times 10^{-3}$	(1964LA16)
					$(6.1 \pm 0.5) \times 10^{-3}$	'best' value
		6.05	$0^+;0$	18 ± 4	$(1.89 \pm 0.42) \times 10^{-3}$	(1967GO08), B
		6.92	$2^+;0$	21 ± 4	$(2.2 \pm 0.4) \times 10^{-3}$	(1969BR1L), B
		7.12	$1^-;0$	≤ 4.2		B
10.35	$4^+;0$	6.13	$3^-;0$		$< 1.0 \times 10^{-3}$	(1963GO31)
		6.92	$2^+;0$	≈ 100	$(4.0 \pm 0.8) \times 10^{-2}$	(1963GO31), B
					$(4.6 \pm 0.6) \times 10^{-2}$	(1964LA16)
10.95	$0^-;0$	0	$0^+;0$	< 5		(1957BE61)
		6.05	$0^+;0$	< 1		(1957BE61)
		6.13	$3^-;0$	< 6		(1957BE61)
		6.92	$2^+;0$	< 20		(1957BE61)
		7.12 [f]	$1^-;0$	> 99		(1959BR68)
		8.87	$2^-;0$	< 40		(1957BE61)
11.08	$3^+;0$	0	$0^+;0$	< 1		(1959BR68)
		6.13	$3^-;0$	40		(1959BR68)
		6.92	$2^+;0$	44		(1959BR68)
		8.87	$2^-;0$	16		(1959BR68)
		9.85	$2^+;0$	6		(BE69W)
11.52	$2^+;0$	0	$0^+;0$	91.7	0.66 ± 0.09	(1964LA16), B
					0.55 ± 0.07	(1968ST04, 1968ST31)
					0.52 ± 0.13	(1967AR1A)
					0.9 ± 0.2	(1960ME02)
		6.05	$0^+;0$	4.2 ± 0.7	$(3.0 \pm 0.7) \times 10^{-2}$	(HO66C), B
		6.92	$2^+;0$	4.0 ± 1.0	$(29 \pm 7) \times 10^{-3}$	(1969BR1L), B
		7.12	$1^-;0$	≤ 0.8		B
12.44	$1^-;0$	0	$0^+;0$	≈ 100	12.8	(1960HE02), B
					7 ± 1	(1964LA16)

Table 16.12: Radiative decays in ^{16}O [a] (continued)

E_i (MeV)	$J^\pi_i; T$	E_f (MeV)	$J^\pi_f; T$	Branch (%)	Γ_γ (eV)	Refs. [c]
		6.05	$0^+; 0$	1.2 ± 0.4	$(87 \pm 29) \times 10^{-3}$	B
12.53 [g]	$2^-; 0$	0	$0^+; 0$		$(21 \pm 6) \times 10^{-3}$	(1968ST31)
		6.13	$3^-; 0$	60 ± 5.7	2.1 ± 0.2	(1968GO07), B
		6.92	$2^+; 0$	≤ 9.7	≤ 0.34	(1968GO07), B
		7.12	$1^-; 0$	15 ± 2.9	0.51 ± 0.10	(1968GO07), B
		8.87	$2^-; 0$	25 ± 2.9	0.86 ± 0.10	(1968GO07), B
12.80	$0^-; 1$	6.13	$3^-; 0$		≤ 0.1	(1968GO07)
		6.92	$2^+; 0$		≤ 0.1	(1968GO07)
		7.12	$1^-; 0$	≈ 100	2.5 ± 0.2	(1968GO07), B
		8.87	$2^-; 0$		≤ 0.06	(1968GO07)
		9.60	$1^-; 0$		$\leq 2 \times 10^{-4}$	(1969BR1L)
12.97	$2^-; 1$	0	$0^+; 0$		$(78 \pm 16) \times 10^{-3}$	(1968ST31)
					$(72 \pm 15) \times 10^{-3}$	B
		6.13	$3^-; 0$	63 ± 5.5	2.3 ± 0.2	(1968GO07), B
		6.92	$2^+; 0$	≤ 2.7	≤ 0.1	(1968GO07), B
		7.12	$1^-; 0$	12 ± 2.7	0.44 ± 0.10	(1968GO07), B
		8.87	$2^-; 0$	25 ± 2.7	0.90 ± 0.10	(1968GO07), B
		9.60	$1^-; 0$		$\leq 7.2 \times 10^{-3}$	(1969BR1L)
13.09	$1^-; 1$	0	$0^+; 0$	≈ 100		(1968WI15)
					88	(1960HE02)
					31 ± 8	(1966VA02, 1968ST31)
					44 ± 7	B, C
		6.05	$0^+; 0$	0.58 ± 0.12		(1968WI15)
				0.8 ± 0.2		(1963GO22)
					0.7 ± 0.2	(1963GO31)
		6.13	$3^-; 0$		≤ 0.2	(1966GO1H)
		6.92	$2^+; 0$		≤ 2.0	(1966GO1H)
		7.12	$1^-; 0$	3.1 ± 0.8	1.4 ± 0.4	(1969BR1L), B
					≤ 1.0	(1966GO1H)
		8.87	$2^-; 0$		≤ 0.1	(1966GO1H)
		9.60	$1^-; 0$		$\leq 2 \times 10^{-2}$	(1969BR1L)
13.25	$3^-; 1$	6.13	$3^-; 0$	> 85	9.2 ± 1.5	(1968GO07)
		6.92	$2^+; 0$		< 0.5	(1968GO07)
		7.12	$1^-; 0$		< 1.4	(1968GO07)
		8.87	$2^-; 0$		≤ 0.3	(1968GO07)
16.22	$1^+; 1$	0	$0^+; 0$	86.2	5.1 ± 0.8	(1970ST06)

Table 16.12: Radiative decays in ^{16}O [a] (continued)

E_i (MeV)	$J_i^\pi; T$	E_f (MeV)	$J_f^\pi; T$	Branch (%)	Γ_γ (eV)	Refs. [c]
		6.05	$0^+; 0$	13.8 ± 4.3		(1963GO22), B
17.14	$1^-; 1$	6.05	$0^+; 0$	13.8 ± 4.3		(1963GO22), B
17.30	$1^-; 1$	6.05	$0^+; 0$	≤ 1.3		(1963GO22)

A: J. Lowe, O. Karban and P.M. Rolph, private communication.

B: I am indebted to Dr. P. Chevallier for pointing out errors and omissions in this table.

C: D. Disdier, Thesis, Strasbourg, 1968.

[a] See also Tables 16.19, 16.21, and 16.26.

[b] Monopole matrix element in fm^2.

[c] See also (1962GO07, 1962GO15, 1963GO22, 1967GI07).

[d] $\Gamma_{\rm total} = 34 \times 10^{-4}$ eV (1967PI01). See also (1957WA1B).

[e] See also (1967PI01).

[f] 4.3×10^{-2} W.u. (BE69W).

[g] $\Gamma \leq 0.5$ keV (P. Chevallier, private communication; preliminary results).

In a study of the yield of α_0 and α_1 for $E_\alpha = 18.9$ to 30.1 MeV, (1970MO06) find that the cross section for the α_1 group is in general greater than that for the α_0 group [see also (1964MI08)]. Resent phase-shift analyses are reported by (1968CA11, 1969CL08, 1970MO06). The inclusion of the bound level of ^{16}O* at 7.12 MeV produces an improved fit to the low-energy p-wave phase shift data and leads to θ_α^2 for ^{16}O*(7.12) $= 0.71^{+0.37}_{-0.18}$ (1969CL08). The energy dependence of the α_1-$\gamma_{4.4}$ angular correlation has been studied for $E_\alpha = 18$ to 24 MeV by (1968KL07).

Astrophysical considerations are discussed by (1970MO22).

The non-elastic cross section at $E_\alpha = 40$ MeV has been measured by (1963IG01, 1963WI1D). Polarization measurements have been made at $E_\alpha = 22.5$ MeV by (1964EI01) and at $E_\alpha = 22.75$ MeV by (1970HA15). At the higher energy the cross section is free of resonance structure (1970HA15). Spallation studies are reported by (1968JA1J, 1968JU04, 1969JU03, 1970BA48, 1970JA1Q, 1970JU05, 1970RA30, 1970SC1F).

See also (1963DA1D, 1969BR1D), (1965BE16, 1966CE1E, 1967GR1F, 1968SH1G, 1969PI02; theor.), ^{12}C in (1968AJ02) and (1959AJ76).

10. ^{12}C(α, ^{8}Be)^{8}Be $\qquad Q_m = -7.464 \qquad E_b = 7.161$

The yield of ^{8}Be shows a number of resonances for $E_\alpha = 11.85$ to 19.4 MeV, some of which are attributed to rotational states of ^{16}O: see Table 16.11. J^π assignments were made from angular distribution studies (1967CH21). Levels seen in this reaction are attributed by (1967AB02, 1967AB04) to a rotational band generated by an axially symmetric 8p-8h state.

11. ^{12}C(^{6}Li, d)^{16}O $\qquad Q_{\rm m} = 5.689$

At $E(^{6}{\rm Li}) = 20$ and 29 MeV and at $E(^{12}{\rm C}) = 18$ to 24 MeV, deuteron groups are observed to many of the states with $E_{\rm x} \leq 16.2$ MeV (1967LO01, 1968ME10, 1970CO26). The spectrum at $E(^{6}{\rm Li}) = 20$ MeV is dominated by the groups corresponding to ^{16}O*(10.34, 14.8, 16.2) with $J^{\pi} = 4^{+}$, 6^{+} and 6^{+}, respectively (1967BE24, 1968ME10, 1970CO26). In addition, the excitation of a state at $E_{\rm x} \approx 20.8$ MeV ($\Gamma \approx 600$ keV) is reported by (1970CO26): it may be the 8^{+} member of the first even parity rotational band in ^{16}O, which is believed to have a predominantly 4p-4h character (1970CO26). See also (1969GO19). Measured angular distributions are listed in Table 16.13. (1967LO01) have analyzed their data to obtain θ^{2}_{α} for all ^{16}O states with $E_{\rm x} < 10.4$ MeV. See also (1960SH01, 1963OL1A, 1967CA1D, 1967DZ01, 1968OG1A, 1969CO1D, 1969GI1B, 1970OG1A), (1968RO1D, 1970DO07; theor.) and ^{18}F in (1972AJ02).

12. ^{12}C(^{7}Li, t)^{16}O $\qquad Q_{\rm m} = 4.694$

At $E(^{7}{\rm Li}) = 15$ to 31.5 MeV, triton groups are observed to many of the states with $E_{\rm x} \leq 16.2$ MeV (1969GI1B, 1969GO19, 1970CO26, 1970PU01). As in ^{12}C(^{6}Li, d)^{16}O, the spectra are dominated by groups corresponding to the 4^{+} and 6^{+} states at ^{16}O*(10.34, 14.8, 16.2) and by ^{16}O*(20.8). Table 16.13 lists the measured angular distributions. From these distributions and the weak excitation of ^{16}O*(8.87) it is concluded that the reaction proceeds predominantly by a direct α-transfer (1970PU01). See also (1963OL1A, 1967CH34, 1967OG1A, 1968DA20, 1968OG1A, 1970OG1A), (1969DA14, 1970DO07, 1970DU1E; theor.) and ^{19}F in (1972AJ02).

13. (a) ^{12}C(^{10}B, ^{6}Li)^{16}O $\qquad Q_{\rm m} = 2.700$
(b) ^{12}C(^{11}B, ^{7}Li)^{16}O $\qquad Q_{\rm m} = -1.503$
(c) ^{12}C(^{12}C, 2α)^{16}O $\qquad Q_{\rm m} = -0.113$

For reaction (a), see (1970JA1B, 1970VO1F). For reaction (b), see (1970JA1B). For reaction (c), see (1959AL1H, 1968JA1F, 1970JA1B) and ^{20}Ne in (1972AJ02).

14. ^{12}C(^{14}N, ^{10}B)^{16}O $\qquad Q_{\rm m} = -4.452$

See (1967BI1F, 1969BR1D).

15. (a) ^{12}C(^{16}O, ^{12}C)^{16}O
(b) ^{12}C(^{18}O, ^{14}C)^{16}O $\qquad Q_{\rm m} = 0.934$

Table 16.13: Angular distribution studies of $^{12}C(^{6}Li, d)^{16}O$ and $^{12}C(^{7}Li, t)^{16}O$

(a)

$E(^{6}Li)$ (MeV)	Distribution of deuteron groups	Refs.
3.0	d_0	(1963BA08)
3.4 – 4.0	d_0	(1962BL13)
4.5 – 5.5	d_0, d_{1+2}, d_3, d_4	(1966HE05)
5.6 – 6.6	d_0, d_{1+2}	(1970JO09)
9 – 14	d_0, d_{1+2}, d_{3+4}, d_5	(1970JO09)
18 – 24 [a]	d_0, d_1, d_2, d_3, d_4, d_5, d_6, d_7, d_8	(1967LO01)
18	d_1, d_3, d_8	(1970BE31)
20	d_0, d_{1+2}, d_3, d_4, d_7, d_8, d_{11+12}	(1968ME10)
25.8	d_0, d_{1+2}, d_{3+4}, d_8, and d to $^{16}O^*(16.2)$	(1969GO19)
29	d to $^{16}O^*(16.2, 20.8)$	(1970CO26)

(b)

$E(^{7}Li)$ (MeV)	Distribution of triton groups	Refs.
3.2 – 3.6	t_0	(1967MO23)
4 – 14	t_0	(1970CA1N)
15, 21.1, 24	$t_0 \rightarrow t_8$	(1970PU01)
17	t_1, t_3, t_8	(1970BE31)
21.2, 24	t to $^{16}O^*(11.10)$	(1970PU01)
28.2, 30.3	t_0, t_{1+2}, t_{3+4}, t_8, and t to $^{16}O^*(16.2)$	(1969GO19)
31.5	t to $^{16}O^*(16.2, 20.8)$	(1970CO26)

[a] $E(^{12}C) = 18$ to 24 MeV.

Table 16.14: ^{13}C + ^{3}He excitation functions

$E(^3\text{He})$ (MeV)	Particles	Refs.
1.0 – 3.5	γ_0	(1966PU01)
1.4 – 2.65	n_0, n_3	(1963DU12)
1.4 – 5.80	n_0	(1965DI07)
2.3 – 3.2	n_0	(1961JO24)
7.5 – 11	n_0	(1964DE1C)
2.0 – 6.0	$p_0 \rightarrow p_6$	(1970ST1M)
4.0 – 8.0	p_0, p_{1+2}	(1968WE15)
5.2 – 8.0	^{3}He	(1967WE06, 1968WE15)
1.3 – 2.0	α_0	(1960BA25)
1.5 – 5.7	$\gamma_{12.7}$, $\gamma_{15.1}$	(1968MO1J)
1.5 – 8.0	$\gamma_{15.1}$	(1968WE13)
2.1 – 4.9	$\gamma_{15.1}$	(1964KU09)
2.0 – 8.5	α_0, α_1	(1968WE13, 1968WE15)
2.6 – 12	$\gamma_{15.1}$	(1969TA09)
4.0 – 8.0	α_2	(1968WE15)
8 – 12	α_0	(1969TA09)
2 – 6	^{8}Be	(1968JA07)

For reaction (a) see (1968VO1A). See also (1967AB1D, 1970CL1E, 1970HE1E, 1970JA1B, 1970VO1F; theor.). For reaction (b) see (1969BR1D, 1969SU1E, 1970BA1J).

16. ^{12}C(^{19}F, ^{15}N)^{16}O $\qquad Q_m = 3.150$

See (1967BO1P, 1969VO1D, 1970VO1F).

17. ^{12}C(^{20}Ne, ^{16}O)^{16}O $\qquad Q_m = 2.432$

See (1970JA1B).

18. ^{13}C(^{3}He, γ)^{16}O $\qquad Q_m = 22.793$

Table 16.15: Resonances in ^{13}C + ^{3}He

$E(^{3}\text{He})$ (MeV ± keV)	$\Gamma_{\text{c.m.}}$	Outgoing particles	^{16}O* (MeV)	$J^{\pi}; T$	Refs.
1.55	≈ 80	n_0, n_3	24.05		(1963DU12)
1.55 ± 100	450	γ_0	24.05		(1966PU01)
2.0	≈ 250	n_0	24.4		(1965DI07)
2.6 ± 100		$\alpha\gamma_{15.1}$	24.9	$(T = 1)$	(1964KU09, 1968MO1J, 1968WE13, 1969TA09)
2.87 ± 50	600	γ_0	25.12		(1966PU01)
(3.6)		p, $\alpha\gamma_{15.1}$	25.7		(1956SC01, 1957IL01, 1964KU09)
4.1 ± 100	[a]	$\alpha\gamma_{15.1}$	26.1	$(T = 1)$	(1964KU09, 1969TA09)
5.2 ± 100	[a]	$\alpha\gamma_{15.1}$	27.0	$(T = 1)$	(1968MO1J, 1968WE13, 1969TA09)
5.6 ± 100	≈ 600	$\alpha\gamma_{15.1}$, ^{8}Be	27.3	$(2^{+}; T = 1)$	(1968JA07, 1968WE13)
6.0 ± 100	≈ 500	p_0, p_{1+2}, ^{3}He, α_0, α_1, α_2	27.6	$(3^{-}; T = 0)$	(1968WE15)
6.5 ± 100	[a]	$\alpha\gamma_{15.1}$	28.1	$(T = 1)$	(1968WE13, 1969TA09)
6.8 ± 100		α_0, α_1, α_2	28.3	$(T = 0)$	(1968WE13)
7.5 ± 100	[a]	$\alpha\gamma_{15.1}$	28.9	$(T = 1)$	(1969TA09)
8.6 ± 100	[a]	$\alpha\gamma_{15.1}$	29.8	$(T = 1)$	(1969TA09)
9.4 ± 100	[a]	$\alpha\gamma_{15.1}$	30.4	$(T = 1)$	(1969TA09)
10.1 ± 100	[a]	$\alpha\gamma_{15.1}$	31.0	$(T = 1)$	(1969TA09)

[a] Widths (lab.) $0.5 - 1$ MeV (1969TA09).

The yield of ground state γ-rays for $E(^3\text{He}) = 1.0$ to 3.5 MeV shows two strong resonances corresponding to ^{16}O*(24.1, 25.1) [see Table 16.15] (1966PU01). See also (1970MO1A).

19. ^{13}C(^{3}He, n)^{15}O $\qquad Q_\text{m} = 7.125 \qquad E_\text{b} = 22.793$

The excitation functions (see Table 16.14) are marked at low energies by complex structures, and possibly by two resonances at $E(^3\text{He}) = 1.55$ and 2.0 MeV (see Table 16.15) (1963DE02, 1965DI07). For $E(^3\text{He}) = 7.5$ to 11 MeV, the n_0 curve is rather featureless (1964DE1C). Polarization measurements are reported by (1968ST19: 3.0 to 3.9 MeV; n_0) and by (1969DE1Q, 1969DE1R: 4.2 to 5.7 MeV; n_0). See also (1961JO07, 1964DI1C). See (1969BA1N) for a discussion of astrophysical implications. See also ^{15}O in (1970AJ04).

20. ^{13}C(^{3}He, p)^{15}N $\qquad Q_\text{m} = 10.667 \qquad E_\text{b} = 22.793$

The yield curves for p_0 and p_{1+2} (see Table 16.14) show a resonance corresponding to ^{16}O*(27.6) (1968WE15). See also (1970ST1M) and ^{15}N in (1970AJ04).

21. ^{13}C(^{3}He, ^{3}He)^{13}C $\qquad E_\text{b} = 22.793$

See (1967WE06, 1968WE15) and Tables 16.14 and 16.15.

22. ^{13}C(^{3}He, α)^{12}C $\qquad Q_\text{m} = 15.631 \qquad E_\text{b} = 22.793$

Yields of α_0, α_1, α_2 and γ-rays from the decay of ^{12}C*(12.71, 15.11) have been studied at many energies: see Table 16.14. Observed resonances are displayed in Table 16.15: those seen in the yield of 15.1 MeV γ-rays are assumed to correspond to ^{16}O states which have primarily a $T = 1$ character since ^{12}C*(15.11) has $T = 1$ (1964KU09, 1968MO1J, 1968WE15, 1968WE13, 1968WE1C, 1969TA09). See also (1968WE1F) and ^{12}C in (1968AJ02).

23. ^{13}C(^{3}He, ^{8}Be)^{8}Be $\qquad Q_\text{m} = 8.168 \qquad E_\text{b} = 22.793$

The excitation function for ^{8}Be$_{\text{g.s.}}$ has been studied for $E(^3\text{He}) = 2$ to 6 MeV. It shows a strong resonance at $E(^3\text{He}) = 5.6$ MeV corresponding to a state in ^{16}O at $E_\text{x} = 27.3$ MeV. J^π appears to be 2^+ from angular distribution measurements. ^{16}O*(27.3) does not belong to the rotational band studied by (1967CH21) in ^{12}C(α, ^{8}Be)^{8}Be: J^π for such a rotational state at $E_\text{x} = 27$ MeV would have to be 14^+. The off-resonance cross section is comparable to typical cross sections observed in the (^{3}He, α) process (1968JA07).

24. ^{13}C(α, n)^{16}O $\qquad Q_m = 2.215$

A threshold for ^{16}O*(6.05) is observed at $E_\alpha = 5.05$ MeV (1956BO61). The angular distributions of neutrons corresponding to the ground state have been measured for $E_\alpha = 12.8$ to 14.1 MeV (1962NI04), 17.4 to 22.5 MeV (1963DE27, 1965DE1F). See also (1961DE08, 1963WE1C), (1959CA1A, 1959MD1A, 1964KE1C, 1964MC1B; theor.) and ^{17}O.

25. ^{13}C(^{6}Li, t)^{16}O $\qquad Q_m = 7.000$

At $E(^6\text{Li}) = 20$ MeV, triton groups corresponding to ^{16}O states with $E_x < 16.9$ MeV have been observed. Angular distributions have been obtained for ^{16}O*(6.13, 6.92, 7.12, 8.87, 9.85, 10.34, 11.10). The triton groups corresponding to ^{16}O*(11.09) dominate the spectra; ^{16}O*(14.4, 14.8) were also strongly excited (1969BA50). See also (1969GI1B, 1970OG1A).

26. ^{13}C(^{12}C, ^{9}Be)^{16}O $\qquad Q_m = -3.489$

See (1969GI1B, 1970JA1B).

27. ^{14}C(^{3}He, n)^{16}O $\qquad Q_m = 14.616$

At $E(^3\text{He}) = 11$ to 16 MeV, neutron groups are observed to $T = 2$ states at $E_x = 22.717 \pm 0.008$ and 24.522 ± 0.011 MeV ($\Gamma < 30$ keV and < 50 keV, respectively). These two states are presumably the first two $T = 2$ states in ^{16}O, the analog states to ^{16}C*(0, 1.75). J^π for ^{16}O*(24.52) is found to be 2^+ from angular distribution measurements (1970AD01). Angular distributions are also reported at 2.1 to 3.4 MeV (1961JO24; n_0) and at 6 MeV (1970HO08; n_0, n_{1+2}, n_{3+4}). See also (1969BA1Z) and ^{17}O.

28. ^{14}N(d, γ)^{16}O $\qquad Q_m = 20.736$

The γ_0 yield has been studied for $E_d = 0.5$ to 5.5 MeV. The yield shows a resonance at $E_d = 2.2$ MeV corresponding to a state in ^{16}O at $E_x = 22.7$ MeV, formed with a cross section of ≈ 6 μb. The angular distribution of γ_0 at resonance is on the whole consistent with E1. Structure at $E_x = 22.2$ and 24.5 MeV is also reported (1966SU05, 1966SU1C). See also (1961SU17, 1963SU09). (1969GI1B) attributes the 2.2 MeV resonance to a 2p-2h 1^-; $T = 1$ state whose formation is possible because of polarization of the deuteron and isospin impurity. See also Tables 16.16 and 16.17 and (1967GI1C, 1969MA1N, 1969RA1F, 1969WE1H; theor.).

Table 16.16: Summary of recent ^{14}N + d yield and polarization measurements [a]

(a) *Yield measurements*

E_d (MeV)	Particles	Refs.
$0.5 - 5.5$	γ_0	(1966SU05, 1966SU1C)
$0.15 - 0.70$	n_0	(1963CS02)
$0.66 - 5.62$	n_0	(1960RE07)
$1.2 - 2.8$	n_0	(1960EL04)
$1.3 - 5.4$	n_0	(1965JA1F)
$1.53 - 2.90$	n_0	(1960MO18)
$0.5 - 5.5$	p_0	(1962GO21)
$0.55 - 0.85$	p_0, p_{1+2}	(1961SJ1B)
$1.0 - 2.2$	p_0, $p_3 \rightarrow p_7$	(1967BE09)
$1.05 - 3.15$	p_{1+2}, $p_3 \rightarrow p_7$	(1969GO14)
$1.4 - 3.2$	p_0, p_{1+2}	(1961KA05)
$2.0 - 3.7$	$p_0 \rightarrow p_7$	(1967BO37)
$0.65 - 2.0$	d_0	(1964SE14)
$1.1 - 3.3$	d_0	(1969GO14)
$1.8 - 5.5$	d_0	(1967FL10)
$2.0 - 3.7$	d_0	(1967BO37)
$5.5 - 10.2$	d_1	(1970DU04)
$5.9 - 12.2$	d_2	(1970DU04)
$0.55 - 0.85$	α_0	(1961SJ1B)
$1.0 - 2.2$	$\alpha_0 \rightarrow \alpha_3$	(1967LA16)
$1.05 - 3.3$	$\alpha_0 \rightarrow \alpha_3$	(1969GO14)
$1.1 - 2.5$	α_0, α_1	(1964MA53)
$1.1 - 3.1$	α_0, α_1	(1962IS02)
$1.3 - 2.2$	α_0	(1966EU01)
$1.4 - 2.4$	α_0, α_3	(1964MA53)
$1.5 - 3.0$	α_0	(1961IS03)
$2 - 4$	α_0, α_1	(1962AL09)
$2 - 12$	α_0, α_1, α_2	(1964CH1B, 1964CH1C)
$2.3 - 5.8$	α_0, α_1, α_2	(1967BO37)

Table 16.16: Summary of recent ^{14}N + d yield and polarization measurements [a] (continued)

2.8 – 12	$\gamma_{15.11}$	(1965BR08)
3.5 – 4.5	$\alpha_0 \rightarrow \alpha_3, \alpha_5 \rightarrow \alpha_7$	(1965SC12)
11.3, 12.6	α_0, α_1	(1966DR04)

(b) *Polarization measurements*

E_d (MeV)	Particles	Refs.
1.32	n_0	(1964EP01)
1.65 – 2.90	n_0	(1965BU1A)
3.1 – 3.7	n_0	(1967ME17)
3.7	n_0	(1965BA24, 1968BA52)
4.2 – 6	n_0	(1970BU15)
10, 12	p_0	(1970FI07)
13.6	p_0	(1963GO1L, 1967GO27)

[a] See also (1959AJ76).

29. ^{14}N(d, n)^{15}O $\qquad Q_m = 5.068 \qquad E_b = 20.736$

For $E_d = 0.66$ to 5.62 MeV, there is a great deal of resonance structure in the excitation curves with the anomalies appearing at different energies at different angles (1960RE07): see Table 16.16 for a summary of recent yield and polarization experiments. Angular distributions have been measured at many energies: see Table 15.27 in (1970AJ04). The more prominent structures in the yield curves are displayed in Table 16.17 (1960RE07, 1965BU1A, 1965JA1F). See also (1958WE1C, 1960EL04, 1960MO18), and (1959AJ76).

30. ^{14}N(d, p)^{15}N $\qquad Q_m = 8.610 \qquad E_b = 20.736$

Quite a lot of structure is observed in the yield curves of various proton groups for $E_p = 0.5$ to 5.5 MeV: see Table 16.16 for a summary of recent yield and polarization measurements, and (1961SJ1B, 1962GO21, 1967BO37, 1969GO14) for data showing the fluctuations. Angular distributions have been obtained at many energies: see Table 15.16 in (1970AJ04). Resonant structure reported by (1962GO21, 1970NE1H), is displayed in Table 16.17. See also (1961JO13) and (1959AJ76).

Table 16.17: Structure in $^{14}N + d$ [a]

E_d (MeV)	Resonant channel	$J^\pi; T$	E_x (MeV)	Refs.
1.4	n_0		21.9	(1960RE07)
1.7 ± 0.1	γ_0, n_0, α_0, α_1, α_2, α_3		22.2	(1962IS02, 1965JA1F, 1966SU05, 1967LA16)
1.85	n_0, α_0		22.35	(1961IS03, 1965BU1A)
2.0 ± 0.1	α_0, α_3		22.5	(1967LA16)
2.2	γ_0, n_0, d_0, α_0	$1^-; 1$	22.7	(1961IS03, 1965JA1F, 1966SU05, 1967FL10)
2.271 ± 0.005	p_0, p_{1+2}, (α_0), α_2	$0^+; (2)$	22.721	(1970NE1H)
2.5	α_0		22.9	(1961IS03)
2.6	(n_0, p_0), α_1		23.0	(1960RE07, 1962AL09, 1962GO21, 1962IS02, 1965JA1F)
2.8	(n_0, p_0), d_0, α_0		23.2	(1962AL09, 1962GO21, 1965JA1F, 1967FL10)
3.3	n_0, p_0, d_0, α_0		23.6	(1962AL09, 1962GO21, 1965JA1F, 1967FL10)
4.2	γ_0, n_0, p_0, d_0, $\gamma_{15.11}$		24.4	(1960RE07, 1962GO21, 1965BR08, 1965JA1F, 1966SU05, 1967FL10)
4.58	p_0, d_0, $\gamma_{15.11}$		24.74	(1965BR08, 1967FL10)
4.9	n_0, p_0		25.0	(1960RE07, 1962GO21)
5.95	d_1, $\gamma_{15.11}$		25.94	(1965BR08, 1970DU04)
7.1	$\gamma_{15.11}$		26.9	(1965BR08)
7.4	d_2		27.2	(1970DU04)
7.7	d_1		27.4	(1970DU04)
(8.5)	$(\gamma_{15.11})$		(28.2)	(1965BR08)
10.2	d_2		29.6	(1970DU04)

[a] See reactions 28, 29, 30, 31, 32, 33 and 34.

31. ^{14}N(d, d)^{14}N $E_b = 20.736$

The yield of elastically scattered deuterons has been studied for $E_d = 0.65$ to 5.5 MeV: see Table 16.16. Angular distributions for various deuteron groups have been measured at many energies: see Table 14.23 in (1970AJ04) and (1967FL10, 1970DU04). (1967FL10) report a number of resonances in the d_0 yield corresponding to states in ^{16}O with $22.6 \leq E_x \leq 25.2$ MeV. There is indication of broad structure at $E_d = 5.9$ MeV and of sharp structure at $E_d = 7.7$ MeV in the total cross section of the d_1 group to the $T = 1$ (isospin-forbidden), $J^\pi = 0^+$ state at $E_x = 2.31$ MeV in ^{14}N. The yield of deuterons (d_2) to ^{14}N*(3.95) [$J^\pi = 1^+$; $T = 0$] shows gross structures at $E_x = 7.4$ and 10.2 MeV (1970DU04). The d_1 resonance at $E_d = 5.9$ MeV is also reported in the (isospin-forbidden) yield of 15.11 MeV γ-rays to the 1^+; $T = 1$ state of ^{12}C: see reaction 33. For a display of the information on reported resonances, see Table 16.17. See also (1968NO1C; theor.).

32. ^{14}N(d, t)^{13}N $Q_m = -4.296$ $E_b = 20.736$

See ^{13}N in (1970AJ04).

33. ^{14}N(d, α)^{12}C $Q_m = 13.575$ $E_b = 20.736$

A great deal of structure is observed in the yields of various α-particle groups for $E_d = 0.5$ to 12 MeV. Recent measurements are summarized in Table 16.16. The more prominent structures in the yields of α_0, α_1, α_2 and α_3 are displayed in Table 16.17 (1961IS03, 1962AL09, 1962IS02, 1967LA16, 1970NE1H). See also (1964CH1B, 1964CH1C, 1964MA53, 1965SC12, 1967BO37, 1969GO14) for other fluctuation data. The yield of 15.11 MeV γ-rays [from the decay of ^{12}C*(15.11), $J^\pi = 1^+$; $T = 1$] which is isospin-forbidden has been studied for $E_d = 2.8$ to 12 MeV. Pronounced resonances are observed at $E_d = 4.2$, 4.58 and 5.95 MeV and broader peaks occur at $E_d = 7.1$ and, possibly, at 8.5 MeV (see Table 16.17). Above $E_d = 9.5$ MeV, the yield curve is quite featureless (1965BR08). Angular distributions have been measured at many energies between $E_d = 0.5$ and 28.5 MeV: see ^{12}C in (1968AJ02). See also (1959FI30, 1961JO13, 1965ST02).

34. (a) ^{14}N(t, n)^{16}O $Q_m = 14.479$
(b) ^{14}N(t, np)^{15}N $Q_m = 2.353$
(c) ^{14}N(t, nα)^{12}C $Q_m = 7.318$

At $E_t = 2.2$ to 2.6 MeV, the two-stage reaction (b) proceeds via ^{16}O*(14.94, 16.22) (1961JA14) while reaction (c) proceeds via ^{16}O*(13.10, 15.42) (1962SI04).

Table 16.18: ^{16}O states from ^{14}N(^{3}He, p)^{16}O [a,b]

E_x (MeV ± keV)	$\Gamma_{c.m.}$ (keV)	E_x (MeV ± keV)	$\Gamma_{c.m.}$ (keV)	L
0		12.964 ± 3	< 12	
6.052 ± 5	< 20	13.105 ± 15	160 ± 30	
6.131 ± 4	< 20	13.253 ± 5	25 ± 8	
6.916 ± 3	< 20	13.665 ± 6	65 ± 8	
7.115 ± 3	< 20	13.869 ± 10	85 ± 20	
8.870 ± 3	< 20	13.975 ± 4	24 ± 8	
9.614 ± 30	510 ± 60	14.922 ± 6	60 ± 10	
9.847 ± 3	< 20	15.787 ± 15	≈ 35	
10.353 ± 4	27 ± 8	16.219 ± 15	≈ 45	(0)
10.952 ± 3	< 12	17.144 ± 20	≈ 65	0
11.080 ± 3	< 12	17.755 ± 15	≈ 30	
11.096 ± 3	< 12	18.027 ± 15	< 25	(3)
11.521 ± 4	78 ± 8	18.983 ± 15	$\lesssim 25$	
12.053 ± 3	< 12	19.382 ± 15	≈ 30	2
12.437 ± 7	94 ± 15	19.913 ± 20	≈ 30	(0)
12.528 ± 3	< 12	20.348 ± 15	≈ 30	
12.798 ± 5	41 ± 10	≈ 21.05		

[a] (1964BR08): $E(^3\text{He}) = 3.74$ and 3.97 MeV; $E_x < 15$ MeV.
[b] (1968CO1R, 1968CO1T): $E(^3\text{He}) = 12.99$ MeV; $E_x > 15$ MeV.

35. (a) ^{14}N(^{3}He, p)^{16}O $\qquad Q_m = 15.243$
(b) ^{14}N(^{3}He, pα)^{12}C $\qquad Q_m = 8.081$

At $E(^3\text{He}) = 3.7$, 4.0 and 13.0 MeV, high-resolution spectral studies have led to E_x and Γ determinations for 33 excited states of ^{16}O with $E_x < 21.1$ MeV: see Table 16.18 (1964BR08, 1968CO1R, 1968CO1T). The separation of ^{16}O*(6.05, 6.13), is 81.0 ± 1.0 keV (C.P. Browne, private communication). The states with $E_x > 15$ MeV are believed to have $T = 1$ (1968CO1T). Angular distributions have been measured at $E(^3\text{He}) = 2.5$ to 5.5 MeV (1963GO09; p_0), 4.5 and 5.5 MeV (1963GO09; p_{1+2}, p_5), 8.0 to 10.6 MeV (1962BI01) and 13.0 MeV (1968CO1T: see Table 16.18).

The branching ratios of ^{16}O*(8.87, 10.95, 11.08) are listed in Table 16.12 (1959BR68, BE69W). These, as well as p-γ angular correlation measurements, lead to the assignments $J^\pi = 2^-$, 0^- and

3^+, respectively for ^{16}O*(8.87, 10.95, 11.08) (1959BR68, 1959KU78). The mean lifetimes for these states are displayed in Table 16.19 (1968HE1K, 1969FI02, 1970BE27, 1970FI06).

At $E(^3\text{He}) = 8$ MeV, a study of the protons in coincidence with 4.4 MeV γ-rays (reaction (b)) indicates that the reaction proceeds via ^{16}O states with $E_x = 12.51, 13.97, 14.39, 14.92, 15.82, 16.23, 17.16, 17.82, 18.04$ MeV (± 40 keV) (1969HO13).

See also (1962CL02, 1964GO1F, 1965BA1Q, 1966BA55, 1967BA1E).

36. (a) ^{14}N(α, d)^{16}O $\quad Q_m = -3.111$
(b) ^{14}N(α, dα)^{12}C $\quad Q_m = -10.272$

The excitation of a number of ^{16}O states with $E_x < 17.2$ MeV has been reported at $E_\alpha = 40$ to 48 MeV by (1962CE01, 1962HA40, 1966RI04, 1970ZI03). In particular strong deuteron groups are reported to states with $E_x = 14.40 \pm 0.03, 14.82 \pm 0.03, 15.80 \pm 0.04, 16.24 \pm 0.04$ and 17.17 ± 0.04 MeV, with $\Gamma_{\text{c.m.}} = 30 \pm 30, 69 \pm 30$, (60), 125 ± 50 and (70) keV, respectively (1970ZI03). Angular distributions of the deuteron groups corresponding to ^{16}O*(14.39, 14.82, 16.23) have been measured at $E_\alpha = 40$ and 42 MeV. A $T = 0$ state at $E_x \approx 13.1$ MeV is also reported (1966RI04); see, however, (1970ZI03). See also (1962CE01, 1962HA40). Angular distributions are also reported by (1959ZE1A: 43 MeV; d_0) and (1962CE01: 48 MeV; d_0, d_{1+2}, d_5).

An experiment to test time-reversal invariance by the principle of detailed balance in this reaction and in the reaction ^{16}O(d, α)^{14}N [see ^{14}N in (1970AJ04)] shows that detailed balance is satisfied to $\pm 0.5\%$ (1967TH1E, 1968TH1J).

The two-stage reaction (reaction (b)) at $E_\alpha = 22.9$ MeV appears to proceed via ^{16}O states at $E_x = 9.85 \pm 0.07, 10.37 \pm 0.07$ and 11.14 ± 0.07 MeV (1968KU1C, 1969BA17). See also (1969BR1D) and (1963GL1C, 1965GR1F; theor.).

37. ^{14}N(^{6}Li, α)^{16}O $\quad Q_m = 19.264$

Angular distributions of the α-particles to ^{16}O*(0, 6.05 + 6.13, 6.92 + 7.12) have been determined at $E(^6\text{Li}) = 5.3$ to 6.0 MeV (1968RI13). See also reaction 1.

38. ^{14}N(^{11}B, ^{9}Be)^{16}O $\quad Q_m = 4.918$

See (1966PO1E, 1967PO1E, 1967VO1A).

39. ^{15}N(p, γ)^{16}O $\quad Q_m = 12.126$

Table 16.19: Lifetime measurements of some ^{16}O states [c]

^{16}O* (MeV)	$\tau_{\rm m}$	Reaction	Refs.
6.05	72 ± 7 psec	^{19}F(p, α)	(1954DE36)
6.13	25 ± 2 psec	^{19}F(p, α)	(1965AL14)
	12 ± 6 psec	^{19}F(p, α)	(1958KO63)
	24 ± 2 psec		mean
6.92 [a]	12 ± 3 fsec	^{16}O(γ, γ)	(1957SW17)
	$9 < \tau < 25$ fsec	^{16}O(γ, γ)	(1958DU06)
	$6.4^{+1.9}_{-1.6}$ fsec	^{19}F(p, α)	(1970CO09)
	8.4 ± 1.6 fsec		mean
7.12 [a]	10 ± 3 fsec	^{16}O(γ, γ)	(1957SW17)
	$4 < \tau < 8$ fsec	^{16}O(γ, γ)	(1958DU06)
	7.2 ± 1.7 fsec		mean
8.87 [a]	240 ± 40 fsec	^{14}N(^{3}He, p)	(1970BE27)
	192 ± 80 fsec	^{14}N(^{3}He, p)	(1968HE1K)
	136^{+46}_{-36} fsec	^{14}N(^{3}He, p)	(1970FI06)
	150 ± 30 fsec	^{19}F(p, α)	(1970GA09)
	192 ± 29 fsec	^{19}F(p, α)	(1967PI01)
	180 ± 16 fsec		mean
10.95	8 ± 5 fsec	^{14}N(^{3}He, p)	(1970BE27)
	< 48 fsec	^{14}N(^{3}He, p)	(1968HE1K)
	58^{+120}_{-58} fsec	^{14}N(^{3}He, p)	(1970FI06) [b]
	8 ± 5 fsec		"best" value
11.08	57 ± 19 fsec	^{14}N(^{3}He, p)	(1970BE27)
	172 ± 60 fsec	^{14}N(^{3}He, p)	(1968HE1K)
	184^{+360}_{-146} fsec	^{14}N(^{3}He, p)	(1970FI06)
	57 ± 19 fsec		"best" value

[a] See also (1969NY1A, 1969TH01).

[b] See also (1969FI02).

[c] See also Table 16.12.

The yield of ground state radiation (γ_0) has been measured for $E_p = 0.17$ to 18 MeV: see Table 16.20 for a summary of the measurements and Table 16.21 for a display of the observed resonances. Angular distributions of the γ_0 radiation have been measured at many energies. The cross section shows a great deal of structure in quite good agreement with the results of high-resolution studies of ^{16}O(γ, n)^{15}O and ^{16}O(e, ep)^{15}N (see reactions 49 and 56). The excitation energies corresponding to the most pronounced resonances are in good agreement with the predictions of the shell model (1964TA06). Above $E_p = 8$ MeV, the angular distributions indicate the presence of a very broad 2^+ state ($E_x \approx 30$ MeV, $\Gamma \approx 5$ MeV), and imply the presence of a similarly broad 1^- state. In addition a number of weak 1^- states with $\Gamma \approx 0.5$ MeV appear to be present (1967EA02). The main part of the giant resonance at $E_x \approx 22.2$ MeV [$E_p = 10.7$ MeV] shows some structure (1967BL23). (1970BA33) suggest that ^{16}O*(19.90, 20.39), observed in the $(\gamma_1 + \gamma_2)$ yield, are 2^+ states from the coupling of the 1^- states at 12.44 and 13.10 MeV to the 3^- state at 6.13 MeV. Above $E_p = 14$ MeV, no pronounced structures are observed but there is some evidence for weak structures corresponding to $E_x \approx 25.5$ and 26.4 MeV (1967BL23).

Branching ratios and Γ_γ values for the low-energy resonances are listed in Table 16.12 (1963GO22, 1968GO07, 1968WI15, 1969BR1L). See also (1966GO1H). It appears that one needs to introduce 3p-3h admixtures into the $T = 0$ states and probably into those of $T = 1$ (1968WI15). An analysis of (p, γ) structure in terms of the theory of statistical fluctuations and a comparison with direct radiative capture calculations have been made by (1965TA1E). See also (1959TA1A, 1961WE01, 1962RI08), (1962WA1C, 1967TA1D) and (1965MA1H, 1966LE1M, 1967BU05, 1967KO1H, 1969SA12, 1969WE1H; theor.). See also (1959AJ76).

40. ^{15}N(p, p)^{15}N $\qquad E_b = 12.126$

Elastic scattering studies are reported for $E_p = 0.6$ to 11.7 MeV (see Table 16.20): observed anomalies are shown in Table 16.21 (see also (1962DE09)). The inelastic scattering of protons has also been studied for $E_p = 9$ to 11.7 MeV (p_{1+2}) and 10.3 to 11.5 MeV (p_3). In addition to other structures, a strong resonance in the (p_{1+2}) scattering occurs at $E_p \approx 10.0$ MeV (1969DR1C). See also (1966WA1L) and (1959AJ76).

41. ^{15}N(p, n)^{15}O $\qquad Q_m = -3.542 \qquad E_b = 12.126$

The absolute total cross section has been measured with excellent resolution and statistics for $E_p = 3.8$ to 12 MeV by (1968BA42): observed resonances are displayed in Table 16.22. (1968BA42) also discusses in detail the relationship of his results and the data reported in other experiments, including a comparison with analog states in ^{16}N [see Fig. 5]. Excitation functions have also been reported from threshold to 13.6 MeV: see Table 16.20. Angular distributions have been measured at many energies: see ^{15}O in (1970AJ04). Polarization measurements have been made for the n_0 group from $E_p = 7.9$ to 12.3 MeV (1964WA1G, 1965WA02). (1969BA1N) discuss the astrophysical implications of this reaction. See also (1961SA01) and (1966WA1L, 1967KA1E, 1968HA15, 1968KA1G, 1969HA1J, 1969PE1J; theor.).

Table 16.20: Summary of ^{15}N + p yield measurements [a]

E_p (MeV)	Particles	Refs.
0.17 – 0.63	γ_0	(1960HE02)
0.2 – 1.6	γ_0	(1952SC28)
0.4 – 1.9	γ_0	(1968GO07)
1 – 14	γ_0	(1967EA02)
4.1 – 12.8	γ_0, γ_{1+2}	(1970BA33)
1 – 14.4	γ_0	(1964TA05, 1964TA06)
10 – 15	γ_0	(1959CO1C, 1960CO01, 1961CO02)
10.5 – 18	γ_0	(1967BL23)
3.8 – 6.4	n_0	(1958JO28, 1958WE1C)
3.8 – 12	$n_0(\sigma_t)$	(1968BA42)
4.0 – 13.6	n_0	(1961WO03, 1963HA46)
0.6 – 1.8	p_0	(1957HA98)
1.0 – 3.6	p_0	(1959BA15)
2.7 – 11.7	p_0	(1962DE09)
9 – 11.7	p_{1+2}	(1969DR1C)
10.3 – 11.5	p_3	(1969DR1C)
0.2 – 1.6	α_0, $\gamma_{4.4}$	(1952SC28)
0.27 – 0.41	$\gamma_{4.4}$	(1960HE02)
0.4 – 1.9	$\gamma_{4.4}$	(1968GO07)
0.8 – 1.65	$\gamma_{4.4}$	(1969CL07)
0.9 – 2.9	α_0	(1957HG01)
1 – 3.6	α_0, $\gamma_{4.4}$	(1959BA15)
3.3 – 12.6	α_0, α_1	(1962RO04, 1963RO01)
3.4 – 3.7	α_0, α_1	(1968VA1M)
6.7 – 15.2	α_0	(1967NO02)
9.1 – 15.2	α_1	(1967NO02)

[a] See also (1959AJ76).

Table 16.21: Levels of ^{16}O from ^{15}N(p, γ)^{16}O, ^{15}N(p, p)^{15}N and ^{15}N(p, α)^{12}C

E_p (keV)	Γ_{γ_0} [a,f] (eV)	Γ_{γ_1} [a,f] (eV)	Γ_p [a] (keV)	Γ_{α_0} [a] (keV)	Γ_{α_1} [a] (keV)	Γ_{lab} (keV)	$J^\pi; T$	E_x (MeV)	Refs.
338	7 ± 1	0.12 ± 0.04	1.1	93	0.025	94	$1^-; 0$	12.443	(1952SC28, 1960HE02, 1966AD04, 1957HG01)
429 ± 1	$(21 \pm 6) \times 10^{-3}$	2.1 ± 0.2	0.020	n.r.	0.90	0.9	$2^-; 0$	12.528	(1952SC28, 1960HE02, 1968GO07)
710 ± 7			40	n.r.		40 ± 4	$0^-; 1$	12.791	(1957HA98)
897.37 ± 0.29	$(78 \pm 16) \times 10^{-3}$		1.2	n.r.	0.69 ± 0.07	2.0 ± 0.2	$2^-; 1$	12.9668	(1952SC28, 1964BO13, 1959VA04, 1969CL07, 1968GO07, 1957HA98)
1028 ± 10	31 ± 8		110	r.	r.	140 ± 10	$1^-; 1$	13.089 [b]	(1969CL07, 1957HA98, 1959BA15, 1952SC28, 1967EA02, 1957HG01, 1953WI1A, 1956WI1D)
1050 ± 150				$\Gamma_p\Gamma_{\alpha_0} = 500$ keV^2			2^+	13.1	(1966AD04)
1210 ± 3			4.1	r.	8.2 ± 1.1	22.5 ± 1	$3^-; 1$	13.260	(1969CL07, 1968GO07, 1952SC28, 1959BA15,

Table 16.21: Levels of ^{16}O from ^{15}N(p, γ)^{16}O, ^{15}N(p, p)^{15}N and ^{15}N(p, α)^{12}C (continued)

E_p (keV)	Γ_{γ_0} [a,f] (eV)	Γ_{γ_1} [a,f] (eV)	Γ_p [a] (keV)	Γ_{α_0} [a] (keV)	Γ_{α_1} [a] (keV)	Γ_{lab} (keV)	$J^\pi; T$	E_x (MeV)	Refs.
									1957HA98, 1957HG01)
1640 ± 3			10	n.r.	59 ± 6	68 ± 3	$1^+; 0$	13.663	(1969CL07, 1952SC28, 1959VA04, 1968GO07, 1957HG01, 1959BA15, 1957HA98)
1890 ± 20				r.	(r.)	90 ± 20		13.90	(1959BA15, 1957HG01)
1979 ± 3			0.5	n.r.	r.	23 ± 2	2^-	13.980	(1959BA15, 1957HG01)
3000 ± 30			r.	r.	r.	45 ± 10	4^+	14.94	(1959BA15, 1962DE09)
3300 ± 35			r.	n.r.	r.	75 ± 15	2^-	15.22	(1959BA15, 1962DE09)
3350 ± 50	≈ 0.6		≈ 125	r.	r.	750 ± 100	2^+; (0)	15.26	(1959BA15, 1967EA02)
3520 ± 40			r.	r.	r.	100 ± 25	$(1 \rightarrow 4)$	15.42	(1959BA15)
(4280 ± 20)		r. [g]						(16.14)	(1970BA33)
4380 ± 20	4.5 [f]		16 [c]			31	$1^{(+)}$; 1	16.23	(1962DE09, 1964TA06, 1967EA02, 1970BA33)
5200	r.					≈ 1500	1^-; 1	17.0	(1967EA02)
5350 ± 20	16		26 [d]			≈ 65	1^-; 1	17.14	(1962DE09,

Table 16.21: Levels of ^{16}O from ^{15}N(p, γ)^{16}O, ^{15}N(p, p)^{15}N and ^{15}N(p, α)^{12}C (continued)

E_p (keV)	Γ_{γ_0} [a,f] (eV)	Γ_{γ_1} [a,f] (eV)	Γ_p [a] (keV)	Γ_{α_0} [a] (keV)	Γ_{α_1} [a] (keV)	Γ_{lab} (keV)	$J^\pi; T$	E_x (MeV)	Refs.
									1964TA06, 1967EA02, 1970BA33)
5490 ± 20	67		45 [e]			≈ 110	$1^-; 1$	17.27	(1962DE09, 1964TA06, 1967EA02, 1970BA33)
6320 ± 20	n.r.	≤ 5 [g]	(r.)			≤ 60	(2, 3; 1)	18.05	(1970BA33)
7330 ± 30	38	≤ 3 [g]				260	$1^-; 1$	18.99	(1962DE09, 1967EA02, 1970BA33)
7420	r.		≈ 30			≈ 130	$2^+; (1)$	19.07	(1962DE09, 1967EA02)
7600 ± 30	n.r.	1.5 [g]				100	(2, 3; 1)	19.25	(1970BA33)
7840 ± 30	59		(r.)			350	$1^-; 1$	19.47	(1962DE09, 1967EA02, 1970BA33)
8300 ± 20	n.r.	8 [h,i]				75	(2, 3; 1)	19.90	(1970BA33)
8830 ± 20	n.r.	47 [h,i]				150	(2, 3; 1)	20.40	(1970BA33)
9300 ± 100	170					700	$(T = 1)$	20.8	(1970BA33)
10420	r.		(r.)					21.89	(1961CO02, 1962DE09, 1967BL23)
10590	r.							(22.05)	(1967BL23)
10700 ± 100	870					700	$(T = 1)$	22.2	(1967BL23, 1970BA33)
10770	r.		(r.)					(22.21)	(1962DE01,

Table 16.21: Levels of ^{16}O from ^{15}N(p, γ)^{16}O, ^{15}N(p, p)^{15}N and ^{15}N(p, α)^{12}C (continued)

E_p (keV)	Γ_{γ_0} [a,f] (eV)	Γ_{γ_1} [a,f] (eV)	Γ_p [a] (keV)	Γ_{α_0} [a] (keV)	Γ_{α_1} [a] (keV)	Γ_{lab} (keV)	$J^\pi; T$	E_x (MeV)	Refs.
									1967BL23)
11450 ± 50	120	27 [g]				350	$T = 1$	22.85	(1970BA33)
13400	r.							24.7	(1961CO02)
14300	r.							(25.5)	(1967BL23)
15200	r.							(26.4)	(1967BL23)

[a] n.r. = non resonant; r. = resonant.

[b] This state has a large p^{-1}d component (1967EA02).

[c] $\Gamma_n = 6$ keV (1964TA06).

[d] $\Gamma_n = 19$ keV (1964TA06).

[e] $\Gamma_n = 45$ keV (1964TA06).

[f] See Tables 16.12 and 16.26.

[g] These values are for $\gamma_1 + \gamma_2$.

[h] The decay is through ^{16}O*(6.13) (A.R. Barnett and J. Lowe, private communication).

[i] There is no indication ($< 10\%$) of decay to ^{16}O*(6.92, 7.13) (1970BA33).

42. (a) ^{15}N(p, α)^{12}C $\quad Q_m = 4.965 \quad E_b = 12.126$
(b) ^{15}N(p, t)^{13}N $\quad Q_m = -12.906$
(c) ^{15}N(p, ^{3}He)^{13}C $\quad Q_m = -10.667$

Excitation functions for α_0 and α_1 particles (corresponding to ^{12}C*(0, 4.43)) and of 4.43 MeV γ-rays have been measured for $E_p = 0.2$ to 15.2 MeV: see Table 16.20. Several resonances are reported for $E_p < 3.5$ MeV (1952SC28, 1957HG01, 1959BA15, 1959VA04, 1960HE02, 1964BO13, 1966AD04, 1968GO07, 1969CL07): see Table 16.21, and see also (1959AJ76). At higher energies, there is continuing structure in the yield curves, which is interpreted in terms of fluctuations: see (1962RO04, 1963RO01, 1967NO02) and (1964TE1D, 1964TE1E, 1964TE1F). Angular distributions have been obtained at many energies: see ^{12}C in (1968AJ02). Angular correlation measurements lead to $J^\pi = 2^-, 1^-, 3^-$, and 1^+, respectively for the resonances at $E_p = 0.898$, 1.08, 1.21, and 1.64 (1969CL07). For polarization measurements see (1966AD04). See also (1963MI1C, 1964EC03, 1969BR1L), (1963MI1H), Table 16.12 and (1965MA1H; theor.).

Polarization measurements of tritons and ^{3}He particles (reactions (b) and (c)) at $E_p = 43.8$ MeV are reported by (1970HA23): some of the transitions exhibit asymmetries at variance with DWBA predictions (1970HA23).

43. ^{15}N(d, n)^{16}O $\quad Q_m = 9.901$

Neutron groups corresponding to many of the ^{16}O states with $E_x < 13.3$ MeV have been observed: see Table 16.23. Angular distributions are reported at $E_d = 1.0$ MeV (1967CO1R; n_0, n_{1+2}, n_{3+4}, n_5), 1.1 to 5.2 MeV (1958WE31; n_0), 1.8 and 3.0 MeV (1967CO1R; n_0), 2.5 to 3.0 MeV (1963FE01, 1963FE1B; n_0, $n_2 \rightarrow n_5$), 5 and 6 MeV (1970MU1H: see Table 16.23), and 6 MeV (1967FU07; n_0, $n_2 \rightarrow n_5$); l-values are displayed in Table 16.23. The angular distribution of the n_3 group (to ^{16}O*(6.92)) does not show a stripping pattern.

Slow neutron thresholds have been observed at $E_d = 1.192$ and 1.335 MeV corresponding to ^{16}O* $= 10.952 \pm 0.010$ and 11.078 ± 0.015 MeV (1957WE1A, 1958WE1C). The 10.94 MeV state is observed to decay only to ^{16}O*(7.12), $J^\pi = 1^-$. This suggests $J^\pi = 0^-$ for ^{16}O*(10.94), an assignment strongly favored also by the γ-γ correlation (1957BE61): see also Table 16.12.

See also (1962LE1A; theor.) and ^{17}O.

44. ^{15}N(^{3}He, d)^{16}O $\quad Q_m = 6.632$

Angular distributions of the deuterons corresponding to a number of states of ^{16}O have been measured at $E(^3\text{He}) = 11$ MeV (1969BO13) and at $E(^3\text{He}) = 16.0$ and 24.9 MeV (1969FU08): l and S values derived from DWBA analyses are shown in Table 16.23. See also (1963PA01, 1965SE01, 1968SE1C, 1969FU1J).

Table 16.22: Resonances in $^{15}N(p, n)^{15}O$ (1968BA42) [a]

E_p (MeV ± keV)	$\Gamma_{c.m.}$ (keV)	$J^\pi; T$ [d]	E_x (MeV)
4.37 ± 15	19 ± 6	$1^{(+)}; 1$	16.22
4.45 ± 30	240 ± 30	$0^{(-)}$	16.30
5.35 ± 15	33 ± 5	$1^{(-)}; 1$	17.14
5.52 ± 15	90 ± 10	$1^-; 1$	17.30
5.88 ± 15	59 ± 10	$\geq 1; 1$	17.63
6.12 ± 15	101 ± 10	$\geq 1; 1$	17.86
6.23 ± 15 [b]	≤ 50	$T = 1$	17.96
6.33 ± 15	26 ± 5	$\geq 1; 1$	18.05
6.43 ± 30	≈ 300		18.15
6.76 ± 25	≈ 160		18.46
7.03 ± 30	260 ± 30		18.71
7.59 ± 25	90 ± 10	$2^-; 1$	19.24
7.86 ± 30	300 ± 80	1^- [c]	19.49
8.30 ± 25	120 ± 40		19.90
8.82 ± 25	150 ± 30	≥ 2	20.39
8.99 ± 25	140 ± 30	≥ 1	20.55
9.36 ± 25	≈ 300		20.89
10.7 ± 100	≈ 650	1	22.2

[a] See also (1958JO28, 1958WE1C, 1961WO03, 1963HA46).

[b] Probably a doublet: see (1968BA42).

[c] 1^- is from (p, γ); $J \geq 2$ is required from (p, n) yield.

[d] T-assignments by energy and width comparisons with states in ^{16}N.

Table 16.23: States in ^{16}O from ^{15}N(d, n)^{16}O and ^{15}N(^{3}He, d)^{16}O

^{16}O state at (MeV)	$J^\pi; T$	l [a,b]	l [c]	S [a]	S [b]	$S_{rel.}$ [d]
0	$0^+; 0$	1	1	2.60	3.52	3.5 ± 1.0
6.05	$0^+; 0$	1		0.09	0.16	
6.13	$3^-; 0$	2	2	0.72	0.63	$\equiv 1$
6.92	$2^+; 0$	$1 + 3$	not direct	0.02 [f]		< 0.18
7.12	$1^-; 0$	$0 + 2$	0	0.41 [g]	0.54	0.35 ± 0.10
8.87	$2^-; 0$	2	2	0.87	0.55	0.80 ± 0.10
9.60	$1^-; 0$	0		0.017		
9.85	$2^+; 0$	not direct	1			
10.34	$4^+; 0$	3		0.037		
10.95	$0^-; 0$	0	0	1.77	1.20	
11.08	$3^+; 0$	3	3	0.17		
11.26	$0^+; 0$	broad state				
12.44	$1^-; 0$	0	$0 + 2$	(0.75 ± 0.2)	0.25	
12.53	$2^-; 0$	2	2	(0.9 ± 0.2)	1.45	
12.80	$0^-; 1$	0	0	(2.8 ± 1)		
12.97	$2^-; 1$	2	2	(0.7 ± 0.2)	0.85	
13.10	$1^-; 1$	0		(0.7 ± 0.3)		
13.13 [e]	$3^-; 0$	2			0.96	
13.26	$3^-; 1$	2	2	(0.5 ± 0.2)		
17.14	$1^-; 1$				[b]	
17.17	2^+				[b]	

[a] (1969BO13): (^{3}He, d).
[b] (1969FU08): (^{3}He, d).
[c] (1967FU07, 1970MU1H): (d, n).
[d] (1967FU07); relative to $S(6.13) \equiv 1$.
[e] $\Gamma = 128$ keV.
[f] $l = 1$.
[g] $l = 0$.

45. ^{15}N(α, t)^{16}O $\qquad Q_{\rm m} = -7.688$

Not reported.

46. ^{15}N(^{11}B, ^{10}Be)^{16}O $\qquad Q_{\rm m} = 0.898$

See (1967PO13, 1969BR1D).

47. ^{16}N(β^-)^{16}O $\qquad Q_{\rm m} = 10.422$

^{16}N decays to seven states of ^{16}O: reported branching fractions are listed in Table 16.24. The ground state transition has the unique first-forbidden shape corresponding to $\Delta J = 2$, yes, fixing J^π of ^{16}N as 2^-. This assignment is also indicated by the fact that the transitions to ^{16}O*(6.13, 7.12) are both allowed (see (1959AJ76)).

A 1% allowed branch leads to ^{16}O*(8.88): J^π is then 1^-, 2^- or 3^-. The α-decay from this state has been reported: $\Gamma_\alpha = (1.8 \pm 0.8) \times 10^{-10}$ eV; $E_\alpha = 1278 \pm 10$ keV (1970HA42). The γ-branching and γ-γ correlation ($8.88 \rightarrow 6.13 \rightarrow$ g.s.) are consistent with the assignment $J^\pi = 2^-$ (1956WI1A). See also (1961KA06, 1961SE01, 1969HA42). The α-decays of ^{16}O*(9.59, 9.85) have been observed: see (1961KA06, 1961SE01, 1969HA42). See (1969GA10) for a discussion of parity-forbidden alpha decays of ^{16}O levels.

Recently reported transition energies derived from γ-ray measurements are: $E_{\rm x} = 6130.96 \pm 0.28$ and 7118.72 ± 0.49 keV [$E_\gamma = 6129.70 \pm 0.28$ and 7117.02 ± 0.49 keV] (1967CH19) and 6129.6 ± 0.4 keV (1968SP01). $E_\gamma = 6128.9 \pm 0.4$ keV (1966GR18). $\Delta E_{\rm x}$ for ^{16}O*(7.12, 6.13) $= 987 \pm 3$ keV (1965CR01). See also (1959PR73, 1963AL18, 1964AL22) and (1960ZI1B, 1963SO04, 1964NA1C, 1966CO1H, 1966LA1J, 1968JA10, 1969HE1R, 1969WA1C, 1970MC1J, 1971TO08).

48. (a) ^{16}O(γ, n)^{15}O $\qquad Q_{\rm m} = -15.668$

(b) ^{16}O(γ, 2n)^{14}O $\qquad Q_{\rm m} = -28.887$

Recent papers reviewing this reaction are (1963HA1E, 1964BI1E, 1966FU1C, 1966HA1M, 1966ME1H, 1966MI04, 1967DO1A, 1967FU1G, 1967MI15, 1967SH1E, 1968GI1F, 1968SC1B).

The absorption cross section and the (γ, n) cross section are marked by a number of resonances. The reported structure is displayed in Table 16.25 (1962BU23, 1962FI04, 1963BU18, 1963FU05, 1963GE13, 1964BR03, 1964TE04, 1965CA14, 1965DO05, 1966CO08, 1967DO1A, 1967MI15, 1970IV01). There are still conflicting reports on which structures are real [there are relatively few results obtained with monochromatic γ-rays] and on their widths, when these are given. For curves

Table 16.24: Beta decay of ^{16}N

Final state		Branch (%)	$\log ft$ [a]
^{16}O (MeV)	J^π		
0	0^+	26 ± 2 [e]	9.11 ± 0.04 [i]
6.05	0^+	$(1.2 \pm 0.4) \times 10^{-2}$ [f]	9.97 ± 0.15 [i]
6.13	3^-	68 ± 2 [e]	4.47 [j]
7.12	1^-	4.9 ± 0.4 [e]	5.09 [j]
8.87 [b]	2^-	1.0 ± 0.2 [e]	4.37 [j]
9.60 [c]	1^-	$(1.20 \pm 0.05) \times 10^{-3}$ [g]	6.21 [j]
9.85 [d]	2^+	$(6.5 \pm 2.0) \times 10^{-7}$ [h]	9.07 ± 0.13 [i]

[a] $\tau_{1/2} = 7.13 \pm 0.02$ sec: Table 16.3.
[b] See also (1961AL05, 1961KA06, 1961SE01, 1968BO1V).
[c] See also (1961AL05, 1961SE01).
[d] See also (1961SE01).
[e] (1956WI1A, 1958AL13, 1959AL06).
[f] (1968WA18).
[g] (1961KA06).
[h] (1969HA42).
[i] $\log f_1 t$ values: E.K. Warburton, private communication and (1968WA18).
[j] $\log f_0 t$ values: B. Zimmerman, private communication.

of the (γ, n) cross section obtained with monochromatic γ-rays, see, e.g., (1965CA14, 1966MI04). For other reports of cross section measurements see (1960CA09, 1961BR28, 1962BI09, 1962BR16, 1962DE03, 1962MI07, 1964DE1D, 1965HA19, 1965VE03, 1965WY02, 1968WU01, 1969BE92, 1969KH01, 1969NA1D, 1969NA23, 1970JU02).

The splitting of the giant resonance peak is ascribed by (1967GI1B) to the existence of a 2p-2h coherent quasi-bound state lying in the dip of the photoabsorption cross section.

Branching ratios for the decays of ^{16}O in the giant resonance region to various excited states in ^{15}O have been reported by many groups: see reaction 22 in ^{15}O (1970AJ04). The cross section is reported to display a maximum at 23.5 MeV for emission of neutrons to ^{15}O*(6.18) [$J^\pi = \frac{3}{2}^-$] (1966MA1T). See (1970HO21). See also (1964TA1C, 1965WI03, 1967CA1C, 1967CA1P, 1967FU1G, 1969MU07).

Polarization measurements are reported by (1964HA1F, 1967HA1N, 1967HA1P, 1968WU01, 1969CO15). See also (1959CA1C, 1959MI89, 1959MI95, 1959PE21, 1959PE24, 1959PE32, 1959SA08, 1960SA01, 1960WY1A, 1960ZI01, 1961FI04, 1961KE02, 1961RO1C, 1962BO1D, 1962FU11, 1962GO1E, 1962GO27, 1963AN02, 1963CA12, 1963GR1F, 1963GR35, 1964BE1E, 1964YE02, 1965GR1K, 1965MA45, 1966BA56, 1966FI1C, 1966KA1C, 1966MA1T, 1967FI1E,

1967FO1D, 1967GL1B, 1968BA2L, 1968CO1Q, 1968KA38, 1969HO1T, 1970CO1Q, 1970HE19, 1970ST1E; exp.), (1962RE1A, 1963FE1C, 1963GR1D, 1964EI1A, 1964FU1B, 1965WE06, 1966GI1B, 1966ME1J, 1966RA1E, 1967BA2C, 1967BU05, 1967DU1C, 1967FU02, 1967GI1C, 1967KA1E, 1967LE1H, 1967RA1D, 1968ER1B, 1968KA1G, 1969ER1A, 1969FU05, 1969MA35, 1969PE06, 1969PE1J, 1969RA1F, 1969SA12, 1969SE1C, 1969UB01, 1969UN05, 1969VA1A, 1969WA1G, 1969WE1H, 1970MU1D; theor.), (1959AJ76) and "*Giant resonance*" in the "GENERAL" section here. For reaction (b), see (1962BR16, 1968ME23).

Table 16.25: Resonance structure in ^{16}O + γ [a]

E_γ (MeV ± keV) [b]								Γ	Γ_γ
A	B	C	D	E	F	G	H	(keV)	(eV)
		16.23					16.2	32 [c]	14 [c]
	17.10	17.14	17.1					45 [c]	16 [c]
(17.3)	17.3	17.30	17.3	17.30 ± 30		17.2	17.21	300 [d]	145 [d]
								90 [c]	86 [c]
		17.55						< 400 [c]	
	18.25								
							18.44		
	18.70	18.68						50 [c]	9 [c]
	19.1	19.08	19.1	19.06 ± 60	19.1	19.0		300 [d]	250 [d]
								200 [c]	63 [c]
(19.4)	19.6	19.47	19.6	19.56 ± 100	19.6	19.4	19.53	600 [d]	375 [d]
								300 [c]	146 [c]
	19.9								
	20.2	20.45		20.20 ± 150				40 [c]	18 [c]
		20.88						200 [c]	138 [c]
(21.2)	21.02 ± 40 [e]	21.10	21.0	21.0 ± 30	21.0	20.9	20.75	700 [d]	650 [d]
								25 [c]	56 [c]
		21.35						25 [c]	52 [c]
	21.7	21.59		21.7 ± 30			21.72	25 [c]	39 [c]
		21.89						250 [c]	210 [c]
	22.1	22.15	22.2					40 [c]	95 [c]
22.3	22.4	22.47		22.26 ± 38	22.2	22.3		1000 [d]	2500 [d]
								600 [c]	1457 [c]
23.05	23.0		23.0	23.15 ± 34	23.0	23.1		300 [d]	530 [d]

Table 16.25: Resonance structure in ^{16}O + γ [a] (continued)

E_γ (MeV ± keV) [b]								Γ	Γ_γ
A	B	C	D	E	F	G	H	(keV)	(eV)
	24.1			24.1 ± 170				700 [d]	1200 [d]
24.3	24.4		24.3		24.3	24.3			
25.15	25.0		25.2	24.9 ± 210		25.2		700 [d]	1260 [d]
25.8	25.4			25.55 ± 50		25.8		1000 [d]	1000 [d]
			26.3	26.38 ± 180					
			27.4	27.45 ± 230					
				28.55 ± 195					
				29.6 ± 230					
				31.4 ± 140					
				33.0 ± 300 [f]					

A: (1962BU23, 1963BU18): γ-absorption. The structures are each several hundred keV wide.
B: (1964TE04): γ-absorption [monochromatic γ-rays]; (1962FI04, 1963FU05, 1964FI03): (γ, n).
C: (1963GE13): (γ, n). See also (1964DE1D).
D: (1965CA14): (γ, n), and S.C. Fultz, private communication. See also (1964BR03).
E: (1966CO08): (γ, n).
F: (1967MI15): (γ, n).
G: (1965DO05, 1967DO1A): γ-absorption.
H: (1970IV01): (γ, n).
[a] See also (1959AJ76).
[b] See also study of "breaks" by (1959KI89, 1960GE06).
[c] (1963GE13).
[d] (1967DO1A).
[e] There is some indication that this broad peak is composed of two narrower structures at E_γ = 20.86 and 21.05 MeV. There is also some indication of structure at E_γ = 20.62 MeV (1964TE04). See also (1962FI04).
[f] Six additional structures to E_γ = 60.2 MeV are reported by (1966CO08).
[g] Several additional structures are also reported for $E_x = 16.4 - 17.0$ MeV. Γ_p and Γ_n are also listed (1963GE13). (Note: This footnote is not labeled in the tabular.)

49. ^{16}O(γ, p)^{15}N $\qquad Q_m = -12.126$

Resonances in the yield of ground state protons have been observed at 20.89, 22.20, 23.03, 24.23, 24.99, (25.42), 26.37 and 31.15 MeV using bremsstrahlung radiation (1969BA39, 1969FR20).

See also (1963FI1B, 1968ST11). Angular distribution coefficients show strong correlation with the structure in the cross section. It is predominantly d-wave protons from the 1^- states of ^{16}O which are emitted, although some s-wave emission is required by the data (1969FR20). (1969BA39) report that, in the region between 20 and 30 MeV, there is interference from the E2, p-wave proton channel, and possibly also from an M1 absorption channel. The peak interfering amplitude is $> 10\%$ of the corresponding E1 amplitude (1969BA39). $\int_{21}^{30} \sigma \mathrm{d}E = 37$ MeV · mb (1969BA39). See also (1967TH04).

Branching ratios for the decays of ^{16}O states in the giant resonance region to various excited states in ^{15}N have been reported by many groups: see reaction 55 in ^{15}N (1970AJ04) and (1970HO21).

For a calculation of the (γ, p) cross section from the ^{15}N(p, γ)^{16}O cross section (reaction 39) using the principle of detailed balance, see (1967BL23).

Recent papers reviewing the evidence on this reaction are (1963HA1E, 1966FU1C, 1966HA1M, 1966ME1H, 1967FU1G, 1967SH1E, 1968SC1B).

See also (1957JO20, 1959BR69, 1959PE32, 1961DO08, 1961HE06, 1961SH18, 1962GO1E, 1962GO27, 1965DE24, 1965MA45, 1965MO13, 1965ST1C, 1966KO1G, 1966MA1T, 1967CA1C, 1967CA1P, 1967FU1G, 1967MO1L, 1967TU04, 1968BA2L, 1968DE07, 1969HO1T, 1969MU07, 1969SH02, 1969ST11; exp.), (1964FU1B, 1966RA1E, 1966WA1L, 1967BA2C, 1967BU05, 1967KA1E, 1967RA1D, 1968ER1B, 1968KA1G, 1969MA35, 1969PE06, 1969PE1J, 1969SA12, 1969UB01, 1969UN05, 1969VA1A, 1970MU1D; theor.) and (1959AJ76).

50. (a) ^{16}O(γ, d)^{14}N $\quad Q_\mathrm{m} = -20.736$
(b) ^{16}O(γ, pn)^{14}N $\quad Q_\mathrm{m} = -22.961$
(c) ^{16}O(γ, dn)^{13}N $\quad Q_\mathrm{m} = -31.289$
(d) ^{16}O(γ, dp)^{13}C $\quad Q_\mathrm{m} = -28.286$

For reactions (a) see (1966FU1C) and (1962MA1F, 1963BA1K, 1965OS1A; theor.). For reaction (b) see (1962MI07, 1965GA1E) and (1963KO1B; theor.). For reactions (c) and (d), see (1962KO19).

51. ^{16}O(γ, α)^{12}C $\quad Q_\mathrm{m} = -7.161$

The cross section for production of ^{12}C exhibits a maximum near 17.5 MeV ($\Gamma \approx 5$ MeV), σ(max) $\approx 50\,\mu$b (1953MI31). See also reaction 5 (1970VO13), (1959AJ76), (1957JO20, 1962GO1E, 1964GR08, 1964TO1B, 1965RO05, 1965RO1J, 1967CA1C) and (1968ER1B, 1969MA1N; theor.).

52. ^{16}O(γ, 4α) $\quad Q_\mathrm{m} = -14.436$

See (1959AJ76) and (1958MA1A, 1962GO1E, 1964GR08, 1964TO1B, 1965RO1J).

Table 16.26: Excited states observed in ^{16}O(e, e$'$)^{16}O*

E_x [a] (MeV ± keV)	$J^\pi; T$	Mult.	Γ (keV)	Γ_{γ_0} (eV)	Refs.
6.05	0^+	E0		3.66 ± 0.55 [b]	(1968ST31)
6.13	3^-	E3		$(2.3 \pm 1.1) \times 10^{-5}$	(1968ST31)
6.92	2^+	E2		0.093 ± 0.010	(1968ST04, 1968ST31)
				0.100 ± 0.015	(1967AR1A)
9.85	2^+	E2		0.010 ± 0.004	(1968ST04, 1968ST31)
11.0 ± 250	2^+	E2		< 0.1	(1966ST13)
				2.7	(1966VA02)
11.52	2^+	E2		0.55 ± 0.07	(1968ST04, 1968ST31)
				0.52 ± 0.13	(1967AR1A)
				0.85 ± 0.09	(1970KI02)
12.0 ± 250	2^+	E2		1.0 ± 0.3	(1966VA02)
12.05	0^+	E0		4.40 ± 0.44 [b]	(1968ST04, 1968ST31, 1970KI02)
12.53	2^-	M2		0.021 ± 0.006	(1968ST31)
				0.108 ± 0.015	(1970KI02)
12.97	2^-	M2		0.078 ± 0.016	(1968ST31)
				0.071 ± 0.002	(1970KI02)
13.0	2^+	E2		≈ 0.13	(1968ST04, 1968ST31)
				0.89	(1970KI02)
13.10 ± 250	$1^-; 1$	E1		31 ± 8	(1966VA02, 1968ST31)
				48.5 ± 12.8	(1970KI02)
14.00 ± 50	0^+	E0	170 ± 50	3.3 ± 0.7 [a]	(1969ST06, 1970ST06)
15.15 ± 150	2^+	E2	500 ± 200	1.0 ± 0.5	(1970ST06)
16.21 ± 30	1^+	M1		5.1 ± 0.8	(1970ST06)
16.46 ± 70	2^+	E2	≤ 100	0.5 ± 0.2	(1970ST06)
16.80 ± 100	(3^+)		≤ 100	$(1.7 \pm 1.9) \times 10^{-3}$	(1970ST06)
17.20 [c]	$1^-; 1$	E1		62 ± 12	(1966VA02, 1970ST06)
17.60 ± 100	(2^-)		≤ 100	0.07 ± 0.04	(1970ST06)
18.50 ± 100	(2)				(1970ST06)
19.00 ± 100	$1^-; 1$	E1	300 ± 100	41 ± 20	(1965VA09, 1970ST06)
19.04 ± 50	$2^-; 1$ [d]	M2	400 ± 50	1.5 ± 0.3	(1970GO03, 1970ST06)
			850 ± 150		(1967DR05, 1968DR01)
19.50 ± 100	$1^-; 1$	E1	200 ± 70	40 ± 20	(1970ST06)
20.36 ± 70	2^-	M2	500 ± 100	2.9 ± 1.0	(1965VA09, 1968DR01, 1969SI10, 1970GO03, 1970ST06)
20.95 ± 50	$1^-; 1$	E1	270 ± 70	180 ± 50	(1970ST06)
21.34 ± 250	(2^-)	(M2)			(1965DE1C, 1965VA09)
22.0 ± 250	1^+	M1			(1965VA09)

Table 16.26: Excited states observed in ^{16}O(e, e′)^{16}O* (continued)

E_x [a] (MeV ± keV)	$J^\pi; T$	Mult.	Γ (keV)	Γ_{γ_0} (eV)	Refs.
22.8 ± 250	$1^-; 1$	E1			(1963IS02, 1965VA09)
23.7 ± 250	$(2^-; 1)$				(1965VA09, 1970GO03)
24.4 ± 250	2^+	E2			(1963IS02, 1965VA09, 1970GO03)
25.5 ± 250	$1^-; 1$	E1			(1963IS02, 1965VA09)
26.7 ± 250	1^+	M1			(1965VA09)
44.5	$(1^-; 1)$		$2000 - 3000$	5300	(1961IS06, 1962BI19)
49	$(1^-; 1)$		$2000 - 3000$	19000	(1961IS06, 1962BI19)

[a] See also (1962ED02, 1963BA19, 1963BI23, 1964BI08, 1964GO14, 1965BI1D, 1966CR07, 1966ST13, 1970MA1C).

[b] Monopole matrix element in fm^2.

[c] Unresolved doublet.

[d] See, however, (1969SI10).

53. (a) ^{16}O(γ, t)^{13}N $\qquad Q_m = -25.032$

(b) ^{16}O(γ, breakup)

For reaction (a) see (1962BI09, 1965BU1F, 1966GO1F, 1967KR05). For reaction (b), resulting in multi-particle breakup, see (1958MA1A, 1962BI09, 1962GO1E, 1962MO16, 1963CO1D, 1965SA1F, 1966AR01, 1967FE05, 1967KR05).

54. ^{16}O(γ, γ')^{16}O*

The differential scattering cross section has been measured for $E_\gamma = 18.5$ to 33 MeV: the main giant resonance peaks are located at ≈ 22 and ≈ 25 MeV (1967LO1B). (1970AH02) report resonances at $E_\gamma = 22.5 \pm 0.3$, 25.2 ± 0.3, 31.8 ± 0.6 and 50 ± 3 MeV: the dipole sum up to 80 MeV exceeds the classical value $60\ NZ/A$ MeV · mb by a factor 1.4. See also (1959PE32, 1960RE05, 1962SE02). For lifetime measurements of ^{16}O*(6.9, 7.1), see Table 16.19 (1957SW17, 1958DU06); for widths, see Table 16.12 (1970SW03). The separation between the (7.12) and (6.92) γ-lines is 199.8 ± 0.5 keV (1970SW03). Based on 7118.67 ± 0.35 keV (Table 16.9), E_x for the lower state is 6918.9 ± 0.6 keV. See also (1962BA58, 1968SI1A; theor.).

55. (a) ^{16}O(e, e′)^{16}O*

(b) ^{16}O(e, ep)^{15}N $\qquad Q_m = -12.126$

The ^{16}O charge radius, $r_{\rm rms} = 2.65 \pm 0.04$ fm (1966CR07), 2.674 ± 0.022 (using a distorted wave approximation), 2.712 ± 0.022 fm (using a Born approximation) (1970SI02), 2.666 ± 0.033 fm (1969BE21). See also (1959EH1A, 1959ME24).

Form factors for transitions to the ground state and to excited states of ^{16}O have been reported by (1961LA09, 1963GO04, 1964BI08, 1967BI12, 1969SI10, 1969TO01, 1970BE03) as well as in some of the papers which follow.

Table 16.26 lists the excited states observed from spectra of inelastically scattered electrons (1961IS06, 1962BI19, 1963IS02, 1965DE1C, 1965VA09, 1966VA02, 1967AR1A, 1967DR05, 1968DR01, 1968ST04, 1968ST31, 1969ST06, 1970GO03, 1970KI02, 1970ST06).

Discussions of this reaction are presented in (1959ME24, 1962BA1D, 1966GO1C, 1966KA1C, 1967IS1A). See also (1960IS04, 1964BA1R, 1964BI1D, 1968GO1J, 1969MC1D) and (1960DE1A, 1960IN1A, 1963BI05, 1963WI09, 1964GI1A, 1965DE1K, 1965IN1A, 1965LE1D, 1965SE1D, 1966BO1N, 1966GR1K, 1966LE1J, 1966RA1F, 1966SI1E, 1967CZ1B, 1967CZ1C, 1967EL1B, 1967HI1B, 1967RH1B, 1967WA1E, 1967WA1F, 1968FR1E, 1968HO1B, 1968KA1H, 1968MA1N, 1969CI1A, 1969DE14, 1969DO1D, 1969FU1F, 1969GE08, 1969KA05, 1969KU1C, 1969TU01, 1969UB01, 1969VI02, 1970BO2A, 1970CI1B, 1970DE1R, 1970FR1E, 1970GE12, 1970GO1U, 1970JA08, 1970KA20, 1970LI18, 1970LO1G, 1970MC1D, 1970MC1L, 1970ON1B, 1970SA1B). See also (1959AJ76).

Reaction (b) studied at $E_{\rm e} = 30$ MeV shows resonances (assuming ground state transitions) at $E_{\rm x} = 17.27$, 18.07, 18.99, 19.57, 20.65, 22.30, 23.10 and 24.35 MeV. The states corresponding to the three highest resonances have $\Gamma = 620$, 170 and 790 keV, respectively (1962DO1A). See also (1967AM1E) and (1966RA1C, 1967DE1P, 1968MA1M).

56. ^{16}O(n, n$'$)^{16}O*

Angular distributions have been measured at several energies: see Table 16.27 (1962MA05, 1963BA46, 1966LI03, 1966MC01, 1967BE75, 1969ME15). Gamma rays have been observed corresponding to the ground state decay of ^{16}O states at $E_{\rm x} = 6129.1 \pm 1.2$ keV [$E_\gamma = 6127.8 \pm 1.2$ keV] (1966BE1A), 6906 ± 15, 7112 ± 10 and 8865 ± 3 keV (1969NY1A). See also (1970DI1C). Measured lifetimes are shown in Table 16.19 (1969NY1A). See also (1961AS1B, 1963HO08, 1963MO04, 1963OP1A, 1964EN1B, 1964MO1D, 1964PE20, 1966KO1D, 1966MO1C, 1970DR11, 1970MA1J), (1960PE1A, 1962PA1A, 1963KO1C, 1967HO1H, 1967LA1K, 1967LE1G, 1968CA1A, 1969OW1B, 1969SC1L; theor.), ^{17}O and (1959AJ76).

57. (a) ^{16}O(p, p$'$)^{16}O*

(b) ^{16}O(p, 2p)^{15}N $\quad Q_{\rm m} = -12.126$

(c) ^{16}O(p, pd)^{14}N $\quad Q_{\rm m} = -20.736$

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

Angular distributions of elastic and inelastic proton groups have been measured at many energies: see Table 16.27 (1959HU17, 1960KO09, 1961TA06, 1964DA02, 1964DA07, 1964KI06, 1964RI07, 1965HA17, 1967FA06, 1967FR10, 1967IG1B, 1967PA1L, 1967PA25, 1968AN13, 1968AN27, 1968AU1C, 1968CA30, 1969BA23, 1969SN03, 1969SU03, 1970AU1C, 1970HO07). Observed proton groups are displayed in Table 16.28 (1955HO68, 1969SU03). See also (1965HA17).

Table 16.27: Recent ^{16}O(n, n), (p, p), (d, d), (t, t), (^{3}He, ^{3}He), (α, α) angular distribution studies

$E_{\rm n}$ (MeV)	Angular distribution of groups	Refs.
1.51 – 2.25	n_0	(1962MA05)
3.07 – 4.67	n_0	(1966LI03)
14.0	n_0	(1967BE75)
14	n_0, $n_{1+2+3+4}$	(1963BA46)
14.1	n_0, n_{1+2}, n_{3+4}	(1969ME15)
14.1	n_0, n_{1+2}, n_{3+4}, n_5	(1966MC01)
$E_{\rm p}$ (MeV)	Angular distribution of groups	Refs.
1.47 – 2.98	p_0	(1965GO08)
5.91	p_0	(1968AN13, 1968AN27)
6.9 – 15.6	p_0	(1960KO09)
7.2 – 10.5	p_0, p_1, p_2, p_3, p_4	(1964DA02)
7.3 – 13.3	p_0	(1959HU17)
12.9 – 15.6	p_{1+2}	(1960KO09)
13.8 – 18.2	p_0	(1964KE01)
13.9 – 15.6	p_{3+4}	(1960KO09)
14.8 – 19.2	p_0, p_{1+2}, p_{3+4}, p_5	(1964DA07)
19.8 – 30.5	p_0	(1969KA14)
20.9	p_0	(1969BA23)
23.4 – 46.1	p_0	(1968CA30)
23.4 – 46.1	p_{1+2}, p_5	(1968AU1C, 1970AU1C)
25.5 – 45.1	p_0	(1969SN03)
30.3	p_0	(1964RI07)
31	p_0	(1964KI06)
49.5	p_0	(1967FA06)
100	p_0	(1970HO07)
142	p_0	(1961TA06)
185	p to ^{16}O*(11.5, 13.1, 15.3, 18.7, 20.2)	(1965HA17)
185	p_2, p_3, p_4	(1969SU03)

Table 16.27: Recent ^{16}O(n, n), (p, p), (d, d), (t, t), (^{3}He, ^{3}He), (α, α) angular distribution studies (continued)

1000	p_0, $p_{1+2+3+4}$	(1967FR10, 1967IG1B, 1967PA1L, 1967PA25)
E_d (MeV)	Angular distribution of groups	Refs.
1.95 – 3.63	d_0	(1968DI06)
4.0	d_0	(1966GA09)
4.0 – 6.0	d_0	(1970DA14)
8.0 – 10.5	d_0	(1963CA17, 1963CA1E, 1963CA1F, 1963GA1D)
10.95	d_0	(1960TA08)
11.8	d_0	(1967FI07)
12	d_0	(1967AL06)
13.6	d_0	(1963NE1C, 1964NE1D)
14.25	d_0, d_1, d_2, d_3, d_4	(1966NG01)
15.8	d_0	(1966CO24)
26.3	d_0	(1962MA25, 1964TE1C)
28	d_0	(1968GA13)
34.4	d_0	(1967NE09)
52	d_0	(1966DU08, 1968HI14)
E_t (MeV)	Angular distribution of groups	Refs.
6.4, 6.8, 7.2	t_0	(1964PU01)
12	t_0	(1965GL04, 1966GL1B)
$E(^3$He) (MeV)	Angular distribution of groups to ^{16}O	Refs.
1.94, 2.37	g.s.	(1961SI09)
2.7 – 4.0	g.s.	(1965JI1A)
8.5, 9.4	g.s.	(1965AL05)
9.80 – 11.74	g.s.	(1969BR07, 1969NU02)
12	g.s.	(1965YO1B)
15	g.s.	(1969ZU02)
16.6, 25.8, 36.6	g.s.	(1965AR1E)
17.3	g.s.	(1967HA1F)
18	g.s.	(1970MC1F)
28.9	g.s.	(1962SE13)
29	g.s.	(1963AG1A)
E_α (MeV)	Angular distribution of groups	Refs.
5.0 – 12.5	α_0	(1969JO18)

Table 16.27: Recent ^{16}O(n, n), (p, p), (d, d), (t, t), (^{3}He, ^{3}He), (α, α) angular distribution studies (continued)

8.64, 9.31, 10.15	α_0	(1967BR39)
18.3	α_0, α_{1+2}, α_{3+4}, α_5	(1959CO70)
20.0 – 23.2	α_0	(1969AG06, 1969FE10)
20.1, 21.5	α_{1+2}, α_{3+4}	(1970FE07)
20.2 – 23.4	α_0	(1968CE1B)
21.2 – 22.7	α_0	(1962JO14)
22.5	α_0, α_{1+2}, α_{3+4}, α_5	(1963CR04, 1965BL03)
23.05	α_0	(1968TA1Q)
24.7	α_0	(1964BU1C)
25.4 – 32.2	α_0	(1970CO13)
27.3	α_0, α_{1+2}, α_{3+4}, α_5, α_{6+7}, α_8	(1965KO1A)
28.5	α_0, α_{1+2}, α_{3+4}, α_5, α_{6+7}, α_9	(1964KO02, 1965KO07)
31.8, 39.5	α_0, α_{1+2}, α_{3+4}, α_5	(1964BO1E, 1965PR1E)
38.1	α_0, α_{1+2}, α_{3+4}	(1960AG01)
40	α_0, α_{1+2}, α_{3+4}	(1959YA01)
40.5	α_0, α_2, α_3, α_4, α_5	(1966HA19)
40.6	α_{1+2}	(1965BU05)
41.9, 49.7	α_0	(1965VA11)
56	α_0	(1968GA1C)
50, 80.7	α_0, α_2, α_{3+4}, α_5	(1968RE1F)
65	α_0 (and see Table 16.29)	(1964HA16)
104	α_0	(1968HA1D, 1969HA14)

See also (1968PA1J), (1960LA03, 1960MA43, 1960WA15, 1962FO03, 1962RO25, 1964BA04, 1964SC1F, 1966YA04, 1968GA1H) and (1959EG20, 1959EG21, 1959GL57, 1959HO95, 1959PU1A, 1960SA1C, 1960SA1E, 1961SA1B, 1963DU1B, 1963HO1D, 1964HO1C, 1966GI1A, 1967LE13, 1968BA1K, 1968CH35, 1968CZ1A, 1968GL1A, 1968LE1D, 1968RE03, 1969KO1H, 1969KU1D, 1969LE03, 1969OW1B, 1969RE10, 1969VA18, 1969WA11, 1970KU1C, 1970SA06, 1970SH14, 1970VA1A; theor.). See also (1959AJ76).

For polarization measurements see reaction 7 in ^{17}F and see also (1960KA1E, 1961SA1B, 1963DU1B, 1963HO1D, 1965BA1M, 1965HA28; theor.).

For reaction (b), see the reviews by (1965RI1A, 1967RI1C) and ^{15}N. See also (1966TY01, 1968PE1A) and (1965BE1E, 1966JA1A, 1967JA1E, 1968HE1J, 1969KO1J; theor.).

For reaction (c) see (1967SU1C, 1968FR1J) and (1963SH1A, 1964BA1P, 1968KO1P, 1968RO1F; theor.). For reaction (d) see (1961KO02, 1962FO03, 1962RO25, 1962VA1A, 1965ZH1A, 1967CH04, 1970GO12). For spallation studies, see reaction 7 in ^{17}F.

Table 16.28: Energy levels of ^{16}O from ^{16}O(p, p′)^{16}O*

E_x (MeV ± keV)	
(1955HO68) [a]	(1969SU03) [b]
6.14 ± 30	6.13 ± 40
	6.92
7.02 ± 30	
	7.12
8.87 ± 30	8.75 ± 150
9.85 ± 30	9.70 ± 150
10.34 ± 30	10.25 ± 150
11.08 ± 30	
	11.35 ± 100
11.51 ± 30	
12.02 ± 30	
12.53 ± 30	
13.06 ± 30	12.93 ± 100
(13.39 ± 30)	
	13.80 ± 150
	15.15 ± 150
	16.30 ± 150
	17.10 ± 150
	17.70 ± 150
	18.80 ± 150
	19.80 ± 150
	20.35 ± 150
	(22.1 ± 150)

[a] $E_p = 19$ MeV.
[b] $E_p = 185$ MeV.

58. ^{16}O(d, d′)^{16}O*

Angular distribution studies have been carried out for $E_d = 2.0$ to 52 MeV: see Table 16.27 (1960TA08, 1962MA25, 1963CA17, 1963CA1E, 1963CA1F, 1963GA1D, 1963NE1C, 1964NE1D, 1964TE1C, 1966CO24, 1966DU08, 1966GA09, 1966NG01, 1967AL06, 1967FI07, 1967NE09, 1968DI06, 1968GA13, 1968HI14, 1970DA14). See also (1961LO01, 1963DO1B, 1965DI1C) and (1968ME1E, 1969HA1V, 1969IC02; theor.). For polarization studies, see (1969CO12, 1970CO1P) and ^{18}F in (1972AJ02).

59. ^{16}O(t, t)^{16}O

Angular distributions are reported for $E_t = 6.4$ to 12 MeV: see Table 16.27 (1964PU01, 1965GL04, 1966GL1B). See also (1968HO1C).

60. ^{16}O(^{3}He, ^{3}He)^{16}O

Angular distributions have been measured for $E(^3\text{He}) = 1.9$ to 29 MeV: see Table 16.27 (1961SI09, 1962SE13, 1963AG1A, 1965AL05, 1965AR1E, 1965JI1A, 1965YO1B, 1967HA1F, 1969BR07, 1969NU02, 1969ZU02, 1970MC1F). See also (1966AG1B), (1968HO1C, 1969HO27, 1969RA1B; theor.) and ^{19}Ne in (1972AJ02).

61. (a) ^{16}O(α, α')^{16}O*
(b) ^{16}O(α, 2α)^{12}C $\quad Q_m = -7.161$

Inelastic α-groups observed by (1964HA16, 1966HA19) are tabulated in Table 16.29. Angular distributions have been measured for $E_\alpha = 5$ to 104 MeV: see Table 16.27 (1959CO70, 1959YA01, 1960AG01, 1962JO14, 1963CR04, 1964BO1E, 1964BU1C, 1964HA16, 1964KO02, 1965BL03, 1965BU05, 1965KO07, 1965KO1A, 1965PR1E, 1965VA11, 1966HA19, 1967BR39, 1968CE1B, 1968GA1C, 1968HA1D, 1968RE1F, 1968TA1Q, 1969AG06, 1969FE10, 1969HA14, 1969JO18, 1970CO13, 1970FE07). See also (1968FA1A). Angular correlation measurements involving ^{16}O*(6.13) [$J^\pi = 3^-$] are reported by (1965BL03).

See also (1959FU62, 1963CR01, 1963MI1C, 1963NO1C, 1967JA1G, 1967RE1B), (1959BL31, 1964HO1C, 1965FA1D, 1965JA1D, 1966CE1F, 1966MC20, 1968HI08, 1968RA1C, 1968SH1E, 1969PI02, 1971NO03; theor.) and ^{20}Ne in (1972AJ02).

Reaction (b) proceeds via excited states of ^{16}O: see (1962VA25, 1964DO1C, 1968PA12) and (1970PI1D). See also (1968BA1H; theor.).

Table 16.29: Energy levels of ^{16}O from ^{16}O(α, α')^{16}O* (1964HA16, 1966HA19)

E_x [a] (MeV)	L	λ	$B(\lambda)\downarrow/e^2$
6.137 [b]	3	E3	90 fm^6
6.903	2	E2	7.7 fm^4
6.973	1		
8.876 [b]	3 [c]		
9.797			
10.308	[e]		
11.069			
11.480	[e]		
11.997	[e]		
12.492 [d]	[e]		
12.989 [d]	[e]		
13.966	[e]		
14.975	[e]		

[a] ±50 keV (1964HA16).
[b] Used to set energy scale.
[c] Weakly excited.
[d] Unresolved groups.
[e] Angular distribution measured but L-value not assigned.

62. (a) ^{16}O(^{6}Li, ^{6}Li)^{16}O
(b) ^{16}O(^{7}Li, ^{7}Li)^{16}O

The elastic scattering has been studied for $E(^6\text{Li})$ and $E(^7\text{Li}) = 20$ MeV by (1969BE90).

63. (a) ^{16}O(^{9}Be, ^{9}Be)^{16}O
(b) ^{16}O(^{10}B, ^{10}B)^{16}O
(c) ^{16}O(^{11}B, ^{11}B)^{16}O

For reaction (a), see (1969KR03). For reaction (b), see (1968OK06, 1969KR03). For reaction (c), see (1968OK06, 1969VO10, 1970SC1G).

64. ^{16}O(^{12}C, ^{12}C)^{16}O

The elastic scattering has been observed at $E(^{16}\mathrm{O}) = 20$ to 42 MeV (1969VO10), 26.0 to 32.5 MeV (1969KR03), 35 MeV (1967GO1A), 110.9 MeV (1962WI09) and 168 MeV (1964HI09). The excitation of ^{16}O*(6.13, 6.92, 7.12) is also reported: see (1962WI09, 1963GO27, 1964HI09, 1964NE01). See also (1969BR1D), (1965GR09, 1968MA1J) and (1964KU1D, 1964MC1C, 1966BA2K, 1969KA1G, 1969RO1G; theor.).

65. ^{16}O(^{14}N, ^{14}N)^{16}O

See (1969JA15, 1970MA1A).

66. ^{16}O(^{16}O, ^{16}O)^{16}O

The angular distributions of elastically scattered ^{16}O ions have been measured at $E(^{16}\mathrm{O}) = 14$ to 30 MeV (1961BR15), 25 to 63 MeV (1969MA40), and at 140.4 MeV (1962WI09). At the highest energy the angular distribution corresponding to the excitation of ^{16}O to the first four excited states (unresolved) has also been measured (1962WI09). See also (1962RO15). Excitation curves are reported by (1961BR15, 1965CA02, 1967SI18, 1968PA1V, 1969MA40, 1970SP1E). Very striking structure is observed in the elastic scattering for $E(^{16}\mathrm{O}) = 34$ to 72 MeV: see (1969MA40).

See also (1968BR1D, 1969BR1D, 1969BR1G, 1969GO1L, 1969VO1E, 1970BR1G), and (1967BL1K, 1968BR1K, 1968EL1D, 1968MU1D, 1968SC1F, 1969CH11, 1969RI1B, 1969SC1M, 1970BL1E, 1970CH1V, 1970EC1A, 1970GR1J, 1970PR12, 1970SC1K). For astrophysical considerations, see (1969TR1E).

67. ^{17}O(p, d)^{16}O $\qquad Q_{\mathrm{m}} = -1.918$

At $E_{\mathrm{p}} = 31$ MeV, angular distributions are reported for the deuterons corresponding to ^{16}O*(0, $6.05 + 6.13$, 7.12, 8.87, 10.34, 12.97, 13.26). States at $E_{\mathrm{x}} = 15.22$ and 15.42 MeV were also observed. Spectroscopic factors were obtained from a DWBA analysis (1970ME01). The strength of the group to ^{16}O*(10.34) is ≈ 20 times less than predicted by the shell-model wave functions of (1968ZU02) and (1970ME01).

68. ^{17}O(d, t)^{16}O $\qquad Q_{\mathrm{m}} = 2.115$

Not reported.

69. ^{17}O(^{3}He, α)^{16}O $\qquad Q_{\mathrm{m}} = 16.435$

Angular distributions of ground state α-particles have been measured for $E(^{3}\mathrm{He}) = 2.7$ to 6.5 MeV (1965WA1D).

70. ^{18}O(p, t)^{16}O $\qquad Q_{\mathrm{m}} = -3.707$

Angular distributions of tritons have been measured at $E_{\mathrm{p}} = 17.6$ MeV (1961LE1A, 1963LE03; t_0), 18.2 MeV (1967LU05; t_0, t_{1+2}, t_3, t_4, t_5) and at 43.7 MeV (1964CE05, 1966CE05). At the higher energy, angular distributions are reported for the tritons corresponding to ^{16}O states at $E_{\mathrm{x}} = 0$, 9.85, 22.9 and 24.7 MeV, with $L = 0$, 2, 0 and 2, respectively. The $E_{\mathrm{x}} = 22.9$ and 24.7 MeV states are presumably the 0^{+}; $T = 2$ and 2^{+}; $T = 2$ analogs of ^{16}O*(0, 1.75), respectively (1964CE05). See also (1965RE1A, 1968BL1G), (1969GA1P) and (1967DO1B, 1969JA1P; theor.).

71. ^{18}O(α, ^{6}He)^{16}O $\qquad Q_{\mathrm{m}} = -11.219$

At $E_{\alpha} = 42$ MeV, angular distributions of the ^{6}He particles corresponding to the ground state of ^{16}O and to the (unresolved) states at 6.1 and at 7.0 MeV have been measured (1970AR1H).

72. ^{18}O(^{7}Li, ^{9}Li)^{16}O $\qquad Q_{\mathrm{m}} = -6.104$

See (1969TO1D).

73. ^{18}O(^{12}C, ^{14}C)^{16}O $\qquad Q_{\mathrm{m}} = 0.934$

See (1968GO1Q).

74. ^{19}F(p, α)^{16}O $\qquad Q_{\mathrm{m}} = 8.115$

$Q_0 = 8.122 \pm 0.009$ (1967SP09).

Table 16.30: Angular distributions of α-particles in ^{19}F(p, α)^{16}O

E_p (MeV)	Alpha-particle group(s)	Refs.
$0.49 - 0.72$	α_0	(1959BR67)
$2.64 - 3.35$	α_0	(1966MO25)
$4.26 - 12.00$	α_0	(1963WA12)
$4.1 - 6.5$	α_0	(1960TE03)
$6.0 - 7.4$	α_0	(1961YA09)
$8.0 - 14.2$	α_0	(1959OG15)
18.5	α_0	(1956LI37)
22.8	α_0, α_{1+2}, α_{3+4}	(1963HO24)
26.7	α_0	(1970GU06)
30.5	α_0	(1967CO05)
38	α_0	(1969GA03)
44.5	α_0	(1966CR05, 1967CR05)

Angular distributions of various α-particle groups have been obtained at many energies: see Table 16.30. Observed excited states are displayed in Table 16.31 (1956SQ1A, 1957YO04, 1965BE1J, 1967CH19, 1967DO1C). In addition to the very accurate γ-ray energies listed in Table 16.31, (1970GA09) report $E_\gamma = 2741.5 \pm 0.5$ keV for the ($8.87 \rightarrow 6.13$) transition. The E0 transition ($6.05 \rightarrow 0$; $0^+ \rightarrow 0^+$) has been investigated in some detail: $E = 6051 \pm 5$ keV (1962NE02), 6052 ± 4 keV (1963LE06). The internal conversion to pair production ratio is $(4.00 \pm 0.46) \times 10^{-5}$ (1963LE06). See also (1962NE02, 1963GO18). The ratio of double γ-emission to pair production, $\Gamma_{\mathrm{E1E1}}/\Gamma_{\mathrm{E0}(\pi)} \leq 1.1 \times 10^{-4}$ (1964AL18). Gamma-ray branching ratios and widths for γ-emission have been obtained for many transitions: see Table 16.12 (1960PI04, 1962GO07, 1962GO15, 1963GO31, 1965FU05, 1966LO06, 1967GI07, 1967LO08, 1967PI01, 1968EV03, 1968WI15). For lifetime measurements see Table 16.19 (1954DE36, 1958KO63, 1965AL14, 1967PI01, 1970CO09, 1970GA09).

See also (1959FA1A, 1966MA60), (1959TR1A, 1960GO20, 1960NE15, 1960RI05, 1961BE1E, 1961GO10, 1961GO30, 1961KN02, 1962CO17, 1962FO03, 1962GO08, 1962GO10, 1963BE1J, 1963GO34, 1963ME17 (and Thesis, Univ. of Strasbourg), 1963SC33 (and Thesis, Univ. of Strasbourg), 1963SU12 (and Thesis, Univ. of Strasbourg), 1965BU1E, 1966EV1B, 1966SW01, 1970WI13), and (1961KR1A, 1962TE1B, 1963ED1A, 1965NE1D, 1965OK1A, 1965WA08, 1968HI08, 1969SM1C; theor.). See (1969BA71) for astrophysical considerations. See also (1959AJ76) and ^{20}Ne in (1972AJ02).

75. ^{19}F(d, nα)^{16}O $\qquad Q_m = 5.890$

Table 16.31: ^{16}O levels from ^{19}F(p, α)^{16}O

E_x (MeV ± keV)			Γ [a] (keV)
(1956SQ1A)	(1957YO04)	(1967CH19) [b]	
0	0		< 20
6.051 ± 10	6.058 ± 17		< 20
6.131 ± 10	6.138 ± 11	6.13096 ± 0.28	< 20
6.920 ± 10	6.926 ± 11		< 20
7.120 ± 10	7.122 ± 11	7.11872 ± 0.49	< 20
8.874 ± 12	8.882 ± 11		< 20
9.852 ± 12			< 20
10.363 ± 14			$\approx 25 - 30$
11.085 ± 14			$\approx 25 - 30$

[a] (1956SQ1A).
[b] From γ-ray measurements: $E_\gamma = 6129.70 \pm 0.28$ and 7117.02 ± 0.49 keV (1967CH19). (1965BE1J) report $E_\gamma = 6127.8 \pm 1.2$ keV (1967DO1C) $E_\gamma = 6129 \pm 2$ keV.

See (1965PE01).

76. ^{19}F(^{3}He, ^{6}Li)^{16}O $\quad Q_m = 4.094$

Angular distributions of the ^{6}Li ions corresponding to the transition to the ground state of ^{16}O have been measured for $E(^3\mathrm{He}) = 5$ MeV (1968ME13) and at 40.7 MeV (1969OH1B, 1970DE1T).

77. ^{19}F(α, ^{7}Li)^{16}O $\quad Q_m = -9.232$

The angular distribution of the ^{7}Li ions corresponding to ^{16}O(0) has been measured at $E_\alpha = 42$ MeV (1968MI05).

78. (a) ^{20}Ne(p, pα)^{16}O $\quad Q_m = -4.730$
(b) ^{20}Ne(α, 2α)^{16}O $\quad Q_m = -4.730$

For reaction (a) see (1967CH04, 1969EP1C). For reaction (b) see (1968YA1C).

79. ^{20}Ne(d, ^{6}Li)^{16}O $\quad Q_{\rm m} = -3.257$

At $E_{\rm d} = 50$ MeV, strong transitions are reported to ^{16}O*(0, $6.05 + 6.13$, 6.92, 9.85). The 4^+ state at $E_{\rm x} = 10.34$ MeV is very weakly excited (1970DU1E, 1970MC1G).

80. ^{20}Ne(^{3}He, ^{7}Be)^{16}O $\quad Q_{\rm m} = -3.143$

At $E(^{3}{\rm He}) = 30$ MeV, angular distributions of ^{7}Be ions [^{7}Be(0) and (1)] associated with the transitions to ^{16}O*(0, $6.05 + 6.13$) (1970DE12) are reported. See also (1970DU1E).

81. ^{28}Si(α, ^{16}O)^{16}O $\quad Q_{\rm m} = -9.592$

See (1967VA18).

^{16}F

(Figs. 4 and 5)

GENERAL: See (1966LE1H, 1967DI1B).

Mass of ^{16}*F:* From the Q-value of the ^{14}N(^{3}He, n)^{16}F reaction [$Q_0 = -969{\pm}14$ keV (1965ZA01, 1968AD03)] and the (1965MA54) masses for ^{14}N, ^{3}He and n, the mass excess of ^{16}F is 10.693 ± 0.014 MeV. ^{16}F is then unstable with respect to proton emission by 0.544 MeV. The binding energies of a deuteron, a ^{3}He particle and an α-particle in ^{16}F are, respectively, 10.451, 9.584 and 9.074 MeV. (1966KE16) predict $M - A = 11.204$ from the isobaric multiplet mass equation [the difference between this value and the experimentally observed mass excess is due to a Thomas-Ehrman shift of the unbound ^{16}F ground state]. See also the general discussion in (1969GA1G) and (1964GA1C, 1966GA25).

1. ^{14}N(^{3}He, n)^{16}F $\quad Q_m = -0.969$

$Q_0 = -0.970 \pm 0.015$ (1968AD03);

$Q_0 = -0.963 \pm 0.040$ (1965ZA01).

Observed neutron groups are displayed in Table 16.33 (1965ZA01, 1968AD03). Angular distributions of the neutrons corresponding to ^{16}F*(0, 0.43, 0.72) have been measured at E(^{3}He) $=$ 3.5 MeV. The widths of the first four states of ^{16}F (see Table 16.33) [and comparison with the analog states in ^{16}N, ^{16}O] suggest that J^{π} for ^{16}F*(0, 0.24, 0.43, 0.71) are (0^-, 2^-, 1^- and 3^-, respectively) [see, however, reaction 3] (1965ZA01). See also (1960BO1B, 1964BR13).

2. ^{16}O(p, n)^{16}F $\quad Q_m = -16.212$

$Q_0 = -16.4 \pm 0.2$ (1965GR15).

At $E_p = 30$ and 50 MeV, neutron groups are reported to eight excited states of ^{16}F with $E_x \lesssim$ 19.5 MeV, including two states at $E_x = 4.20 \pm 0.05$ and 6.16 ± 0.05 MeV (1965GR15). See also (1970WI1B).

3. ^{16}O(^{3}He, t)^{16}F $\quad Q_m = -15.448$

Triton groups observed at E(^{3}He) $= 40.2$ MeV are displayed in Table 16.33. The angular distributions of the tritons to ^{16}F*(0, 0.24) are similar, as are those of the tritons to ^{16}F*(0.43, 0.71): comparison with analog states in ^{16}N, ^{16}O then suggests $J^{\pi} = 0^-, 1^-, 2^-$ and 3^-, respectively, for these states (1965PE04). See also (1966TO04; theor.) and (1965RI1C, 1967HA1Q).

Table 16.32: Energy levels of ^{16}F

E_x (MeV ± keV)	$J^\pi; T$	Γ (keV)	Decay	Reactions
0	$(0^-); 1$	50 ± 30	p	1, 2, 3
0.236 ± 29		< 40		1, 3
0.425 ± 14		40 ± 30	p	1, 3
0.714 ± 14	(3^-)	< 15		1, 3
3.78 ± 60		< 40		1, 3
4.25 ± 50				2, 3
5.45 ± 50				3
5.9 ± 50				2, 3
6.4 ± 50				2, 3

Table 16.33: ^{16}F levels from ^{14}N(^{3}He, n)^{16}F and ^{16}O(^{3}He, t)^{16}F

^{16}F* [a] (MeV ± keV)	^{16}F* [b] (MeV ± keV)	Γ [b] (keV)	^{16}F* [c] (MeV ± keV)
0	0	50 ± 30	0
0.253 ± 35	0.20 ± 50	< 40	[d]
0.422 ± 15	0.436 ± 30	40 ± 30	[d]
0.711 ± 15	0.736 ± 40	< 15	[d]
	3.78 ± 60	< 40	[d]
			4.25 ± 50
			5.45 ± 50
			5.9 ± 50
			6.4 ± 50

[a] ^{14}N(^{3}He, n)^{16}F: (1968AD03).
[b] ^{14}N(^{3}He, n)^{16}F: (1965ZA01).
[c] ^{16}O(^{3}He, t)^{16}F: (1965PE04).
[d] These states were observed but E_x was not determined.

^{16}Ne

(Fig. 5)

^{16}Ne has not been observed. The isobaric multiplet mass equation predicts $M - A = 25.15 \pm 0.6$ MeV (1968CE01): ^{16}Ne is then unbound with respect to breakup into ^{14}O + 2p by 2.6 MeV. See also (1960GO1B, 1960GO1D, 1961BA1C, 1961GO1D, 1962GO28, 1962GO31, 1964GA1C, 1965JA1C, 1966KE16). A search has been made for the two-proton decay of ^{16}Ne in the bombardment of nickel by 150 MeV ^{20}Ne ions: the cross section is either ≤ 1.8 μb (if $E_{pp} > 1$ MeV and τ(^{16}Ne) $\geq 10^{-8}$ sec), or else τ(^{16}Ne) $< 10^{-8}$ sec (1964KA28). See also (1965GO1D, 1966GO1B, 1966LE1H, 1970WA1G).

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(Closed 30 November 1970)

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