

# Energy Levels of Light Nuclei $A = 16$

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**Abstract:** An evaluation of  $A = 16-17$  was published in *Nuclear Physics A281* (1977), 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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### $^{16}\text{Be}$

(Not illustrated)

This nucleus has not been observed. Its atomic mass excess is calculated to be 59.22 MeV. It is then unstable with respect to breakup into  $^{14}\text{Be} + 2n$  by 2.4 MeV (1974TH01). See also (1973TA30, 1975BE31; theor.).

### $^{16}\text{B}$

(Not illustrated)

This nucleus has not been observed in the 4.8 GeV proton bombardment of a uranium target: it is particle unstable (1974BO05). Its mass excess is predicted to be 37.97 MeV: it would then be unstable with respect to decay into  $^{15}\text{B} + n$  by 1.1 MeV, assuming the  $^{15}\text{B}$  mass excess is 28.8 MeV [both mass excesses calculated using the transverse form of the mass equation] (1974TH01, 1975JE02). See also (1973BO30), (1972TH13) and (1975BE31; theor.).

### $^{16}\text{C}$

(Figs. 1 and 5)

GENERAL: (See also (1971AJ02).):

*Experimental work:* (1971AR02, 1973KO1D).

*Reviews:* (1972CE1A, 1973TO16, 1974TH01).

*Theory:* (1972ST1C, 1973RE17, 1973WI15, 1975BE31, 1976BE1G).

1.  $^{16}\text{C}(\beta^-)^{16}\text{N}$   $Q_m = 8.011$

The half-life of  $^{16}\text{C}$  is  $0.747 \pm 0.008$  sec: it decays to  $^{16}\text{N}^*(3.36, 4.32)$  [both  $J^\pi = 1^+$ ] with branchings of 84% and 16% respectively [ $\log ft = 3.55, 3.83$ ]; see Table 16.2 (1976AL02). See also (1976FI03).

2.  $^{11}\text{B}(^7\text{Li}, 2p)^{16}\text{C}$   $Q_m = -4.695$

See (1976AL02).

Table 16.1: Energy levels of  $^{16}\text{C}$

$E_x$ (MeV $\pm$ keV)	$J^\pi; T$	$\tau_{1/2}$ (sec)	Decay	Reactions
0	$0^+; 2$	$0.747 \pm 0.008$	$\beta^-$	1, 2, 3, 4
$1.753 \pm 12$	$(2^+)$			3

Table 16.2: The  $\beta^-$  decay of  $^{16}\text{C}$  <sup>a</sup>

Decay to $^{16}\text{N}^*$ (MeV)	$J^\pi$	Branch (%)	$\log ft$
0.120	$0^-$	$< 0.5^b$	$> 6.85$
0.297	$3^-$	$< 0.5^b$	$> 6.83$
0.398	$1^-$	$< 0.7^b$	$> 6.64$
3.36	$1^+$	$84.4 \pm 1.7$	$3.551 \pm 0.012$
4.32	$1^+$	$15.6 \pm 1.7$	$3.83 \pm 0.05$

<sup>a</sup> (1976AL02).

<sup>b</sup> The combined branching to  $^{16}\text{N}^*(0.120, 0.297, 0.398)$  is  $< 1.2\%$  (1976AL02).

3.  $^{14}\text{C}(t, p)^{16}\text{C}$   $Q_m = -3.012$

At  $E_t = 12$  MeV proton groups have been observed to the ground state and to an excited state at  $1.753 \pm 0.012$  MeV:  $L = 0$  and 2 (1964MI05).

4.  $^{14}\text{C}(^{18}\text{O}, ^{16}\text{O})^{16}\text{C}$   $Q_m = -6.719$

See (1972EY01, 1976AL02).

$^{16}\text{N}$   
(Figs. 2 and 5)

GENERAL: (See also (1971AJ02).):

*Model calculations:* (1971AR1R, 1973RE17, 1973SI1G, 1975RA1T).

*Reactions involving muons:* (1971GR1U, 1971LA17, 1973JO17, 1973KA30, 1973NA28, 1975FU1F, 1975PA01).

Table 16.3: Energy levels of  $^{16}\text{N}$ 

$E_x$ (MeV $\pm$ keV)	$J^\pi; T$	$\tau$ or $\Gamma_{\text{c.m.}}$ (keV)	Decay	Reactions
0	$2^-; 1$	$\tau_{1/2} = 7.13 \pm 0.02$ sec	$\beta^-$	1, 15, 16, 17, 18, 22, 26, 28, 29, 31, 33
$0.1201 \pm 0.5$	$0^-$	$\tau_m = 7.58 \pm 0.09$ $\mu\text{sec}$	$\gamma, \beta^-$	1, 15, 17, 22, 28, 31, 33
$0.2970 \pm 0.7$	$3^-$	<sup>a</sup>	$\gamma$	5, 15, 16, 17, 22, 28, 29, 31, 33
$0.3975 \pm 0.7$	$1^-$	$\tau_m = 6.5 \pm 0.5$ psec $ g  = 1.83 \pm 0.13$	$\gamma$	5, 15, 17, 22, 28, 31, 33
$3.355 \pm 5$	$1^+$	$\Gamma = 15 \pm 5$	n	3, 15, 17, 19, 22, 31
$3.519 \pm 5$	$(2^+)$	3	n	3, 15, 17, 19, 22, 29, 31
$3.960 \pm 5$	$(3^+)$	$\leq 2$	n	3, 15, 16, 17, 19, 22, 31
$4.319 \pm 5$	$1^+$	$20 \pm 5$	n	3, 15, 17, 19, 22, 31
$4.387 \pm 6$	$1^-$	$82 \pm 20$	n	3, 15, 17, 19, 22, 31
$4.76 \pm 50$	$1^-$	$250 \pm 50$	n	17, 19, 22
$4.776 \pm 10$	$2^+$	$59 \pm 8$	n	15, 17, 19, 22, 31
$(4.90 \pm 10)$				22
$5.050 \pm 6$	$2^-$	$19 \pm 6$	n	15, 17, 19, 22, 31
$5.130 \pm 7$	$\geq 2$	$\leq 7 \pm 4$	n	15, 17, 19, 22, 29, 31
$5.150 \pm 7$	$(2, 3)^-$	$\leq 7 \pm 4$	n	15, 17, 19, 22, 29
$5.232 \pm 5$	$(2, 3)^+$	$\leq 4$	n	15, 17, 19, 22, 31
5.24	$1^+$	260	n	19
$5.25 \pm 70$	$2^-$	$320 \pm 80$	n	17, 19, 22
$5.518 \pm 6$	$(1, 2, 3)^+$	$\leq 7 \pm 4$	n	15, 17, 19, 22, 31
$5.730 \pm 6$	$(5^+)$	$\leq 7 \pm 4$	n	15, 16, 17, 19, 22, 29, 31
$6.009 \pm 10$	$1^-$	$270 \pm 30$	n	17, 19, 31
$6.168 \pm 4$	$(2, 3, 4)^-$	$\leq 7 \pm 4$	n	15, 17, 19, 22, 29, 31
$6.373 \pm 6$	$(3^-)$	$30 \pm 6$	n	17, 19, 22, 29, 31
$6.426 \pm 7$		$300 \pm 30$		17, 22
$6.513 \pm 6$	$(0, 1, 2)^+$	$34 \pm 6$	n	17, 19, 22, 31
$6.613 \pm 6$		$\leq 7 \pm 4$		17, 22, 31
$6.848 \pm 6$		$\leq 7 \pm 4$		15, 17, 22, 31
$(6.84)$	$\geq 2$	$> 140$	n	19
$7.02 \pm 20$	$\geq 1$	$22 \pm 5$	n	17, 19, 22, 31
$7.134 \pm 7$		$\leq 7 \pm 4$		15, 17, 22, 31
$7.250 \pm 7$	$\geq 2$	$17 \pm 5$	n	17, 19, 22, 31

Table 16.3: Energy levels of  $^{16}\text{N}$  (continued)

$E_x$ (MeV $\pm$ keV)	$J^\pi; T$	$\tau$ or $\Gamma_{\text{c.m.}}$ (keV)	Decay	Reactions
$7.573 \pm 6$	$\geq 3$	$\leq 7 \pm 4$	n	15, 16, 17, 19, 22, 31
$7.637 \pm 5$		$\leq 7 \pm 4$		15, 17, 22, 31
$7.675 \pm 5$		$\leq 7 \pm 4$	n	15, 17, 19, 22, 29, 31
$7.877 \pm 9$	$\geq 4$	$100 \pm 15$	n	17, 19, 22, 31
$8.048 \pm 9$		$85 \pm 15$	n	17, 19, 31
$8.182 \pm 9$		$28 \pm 8$		15, 17, 31
$8.282 \pm 8$		$24 \pm 8$		17, 31
$8.365 \pm 8$	$\geq 1$	$18 \pm 8$	n	17, 19, 31
$8.49 \pm 30$	$\geq 1$	$\leq 50$	n	19, 31
8.72	$\geq 1$	40	n	19
$8.819 \pm 15$		$\leq 50$	n	19, 31
$9.035 \pm 15$		$\leq 50$		31
$9.16 \pm 30$	$\geq 2$	100	n	19, 31
$9.34 \pm 30$		$\leq 50$	n	19, 31
$9.459 \pm 15$	$\geq 2$	100	n	19, 29, 31
$9.760 \pm 10$	$T = 1$	$15 \pm 8$		15, 31
$9.813 \pm 10$	$T = 1$			15, 31
$9.928 \pm 7$	$0^+; T = 2$	$< 12$		15, 30
$10.055 \pm 15$	$\geq 3$	30	n	19, 31
10.27	$\geq 2$	165	n	19, 31
10.71	$\geq 2$	120	n	19
11.49	$\geq 3$		n	19
11.62	$\geq 3$	220	n, d	9, 19
$11.701 \pm 7$	$1^-, 2^+; T = 2$	$< 12$		15
(11.92)		390	n, d	9
(12.09)			n	19
12.26		290	n, p, d	9, 10
(12.46)			n	19
12.61		180	n, p, d	9, 10
12.88		155	n, p, d	9, 10, 19
(12.97)		175	n, d	9
13.12			n	19
13.83			n	19

Table 16.3: Energy levels of  $^{16}\text{N}$  (continued)

$E_x$ (MeV $\pm$ keV)	$J^\pi; T$	$\tau$ or $\Gamma_{\text{c.m.}}$ (keV)	Decay	Reactions
$14.41 \pm 50$	$(3)^+$	180	d	11

<sup>a</sup> The previously reported  $\tau_m$  needs, in the opinion of the reviewer, to be remeasured: see (1971AJ02) for the previously reported value.

*Reactions involving pions:* (1970AL22, 1971EI01, 1971GU13, 1971SR03, 1973CA25, 1973KA1D, 1973LA1G, 1973LA1H, 1973RE10, 1973SR02, 1974LI15, 1974SZ04, 1975RA1R, 1976TR1A).

*Other topics:* (1971AR02, 1971SR03, 1972EV03, 1973KO1D, 1973RE17, 1973SI1G, 1973WI15, 1974MA1E, 1974SHYR, 1974VA24, 1975BE31, 1975FE1A, 1976NI1E).

*Mass of  $^{16}\text{N}$ :* the atomic mass excess of  $^{16}\text{N}$  is  $5681.7 \pm 2.3$  keV (A.H. Wapstra, private communication).

$$1. \ ^{16}\text{N}(\beta^-)^{16}\text{O} \quad Q_m = 10.418$$

The half-life of  $^{16}\text{N}$  is  $7.13 \pm 0.02$  sec: see Table 16.3 in (1971AJ02). See also (1975SA1D). From the character of the beta decay [see Table 16.23] it is concluded that  $^{16}\text{N}_{\text{g.s.}}$  has  $J^\pi = 2^-$ : see  $^{16}\text{O}$ . The beta decay of  $^{16}\text{N}^*(0.12)$  [ $J^\pi = 0^-$ ,  $\tau_{1/2} = 5.26 \pm 0.05$   $\mu\text{sec}$ ] to  $^{16}\text{O}_{\text{g.s.}}$  has been studied: the  $\beta$ -decay rate  $\lambda_\beta = 0.43 \pm 0.10$   $\text{sec}^{-1}$ . Comparison of this value with the rate of the inverse muon-capture reaction in  $^{16}\text{O}$  yields  $13 \leq g_p(q^2 \approx M_\mu^2) \leq 20$  for the induced-pseudoscalar form factor (1975PA01).

$$2. \text{ (a) } ^9\text{Be}(^7\text{Li}, t)^{13}\text{C} \quad Q_m = 8.181 \quad E_b = 20.575$$

$$\text{ (b) } ^9\text{Be}(^7\text{Li}, \alpha)^{12}\text{B} \quad Q_m = 10.462$$

$$\text{ (c) } ^9\text{Be}(^7\text{Li}, ^8\text{Li})^8\text{B} \quad Q_m = -17.613$$

The yields of  $t_0$  and of  $\alpha_0$ ,  $\alpha_1$  and  $\alpha_2$  have been measured for  $E(^7\text{Li}) = 4$  to  $14$  MeV at  $0^\circ$ : several broad peaks are observed (1971WY01). The yields of  $\alpha_0$  and  $\alpha_2$  have also been studied for  $E(^7\text{Li}) = 3.3$  and  $5.0$  to  $6.2$  MeV (1969SN02). The cross section for reaction (c) rises monotonically for  $E(^7\text{Li}) = 1.1$  to  $4$  MeV (1957NO17, 1959NO40).

$$3. \ ^{10}\text{B}(^7\text{Li}, p)^{16}\text{N} \quad Q_m = 13.990$$

Angular distributions have been obtained at  $E(^7\text{Li}) = 16$  MeV to  $^{16}\text{N}^*(3.36, 3.52, 3.96, 4.32, 4.39)$ . The  $\sigma_t$  for  $^{16}\text{N}^*(3.36, 3.96, 4.32, 4.39)$ , whose  $J^\pi$  are known, follow the  $2J_f + 1$  relation. From the  $\sigma_t$  for  $^{16}\text{N}^*(3.52)$  it follows then that  $J = 2$  if it is a single state or  $J = 0$  and 1 (with one of the two states having odd parity) if the group corresponds to two unresolved states (1975FO10). See also (1974KO1G), and see (1971AJ02) for a discussion of the earlier work of (1966MC05).

4.  $^{11}\text{B}(^6\text{Li}, \text{p})^{16}\text{N}$   $Q_m = 9.785$

See (1966MC05).

5.  $^{11}\text{B}(^7\text{Li}, \text{d})^{16}\text{N}$   $Q_m = 4.759$

See (1966MC05) and (1969TH01:  $E_x = 297.6 \pm 0.9$  and  $397.8 \pm 1.0$  keV).

6.  $^{13}\text{C}(\alpha, \text{p})^{16}\text{N}$   $Q_m = -7.421$

Not reported.

7.  $^{13}\text{C}(^7\text{Li}, \alpha)^{16}\text{N}$   $Q_m = 9.927$

Not reported.

8.  $^{14}\text{C}(\text{d}, \gamma)^{16}\text{N}$   $Q_m = 10.475$

The cross section has been measured for  $1.2 < E_d < 2.6$  MeV. It shows some evidence of structure (1964NE09). See also (1971AJ02).

9.  $^{14}\text{C}(\text{d}, \text{n})^{15}\text{N}$   $Q_m = 7.9827$   $E_b = 10.475$

Observed resonances in the yield of  $n_0$  are displayed in Table 16.4 (1961CH14, 1963IM01). The yields of  $n_{1+2}$ ,  $n_3$  have been measured by (1967LA11) for  $2.9 < E_d < 3.1$  MeV. Polarization measurements are reported for  $E_d = 1.28, 1.55$  and  $1.88$  MeV (1973NI01;  $n_0$ ) and  $2.00$  to  $3.30$  MeV (1974ME32;  $n_0, n_{1+2}, n_3$ ). See also  $^{15}\text{N}$  in (1976AJ04).



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

$E_d$ (MeV)	Resonant for	$\Gamma_{\text{c.m.}}$ (keV)	$E_x$ (MeV)	Refs.
1.30 <sup>a</sup>	$n_0$	220	11.61	(1961CH14, 1963IM01)
1.65	$n_0$	390	11.92	(1961CH14)
2.04 <sup>a</sup>	$n_0, p$	290	12.26	(1956DO37, 1961CH14, 1963IM01)
2.44 <sup>a</sup>	$n_0, p$	180	12.61	(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)
$4.50 \pm 0.05$	$d_0$	$180^b$	14.41	(1973CO31)

<sup>a</sup> See also (1964NE09).

<sup>b</sup>  $\Gamma_d = 45$  keV (1973CO31).

10.  $^{14}\text{C}(\text{d}, \text{p})^{15}\text{C}$

$$Q_m = -1.007$$

$$E_b = 10.475$$

The cross section of the  $\gamma$ -rays to  $^{15}\text{C}^*(0.74)$  rise monotonically for  $2.7 < E_d < 3.4$  MeV where it is  $\approx 75$  mb (1962CH14). Observed resonances are shown in Table 16.4 (1956DO37). See also  $^{15}\text{C}$  in (1976AJ04).

11.  $^{14}\text{C}(\text{d}, \text{d})^{14}\text{C}$

$$E_b = 10.475$$

Excitation functions for elastic scattering have been measured for  $E_d = 4$  to 10 MeV. A resonance is observed at  $E_d = 4.50 \pm 0.05$  MeV,  $\Gamma_{\text{cm}} = 180$  keV,  $l_d = 4$ ,  $J^\pi = 3^+$ , ( $4^+$ ,  $5^+$ ) (1973CO31). See also  $^{14}\text{C}$  in (1976AJ04).

12.  $^{14}\text{C}(\text{d}, \text{t})^{13}\text{C}$

$$Q_m = -1.9194$$

$$E_b = 10.475$$

See (1976WE01) and  $^{13}\text{C}$  in (1976AJ04).

13.  $^{14}\text{C}(\text{d}, \alpha)^{12}\text{B}$

$$Q_m = 0.361$$

$$E_b = 10.475$$

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

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

(1966GA08) <sup>a</sup>	(1968HE03, 1972FR05) <sup>a</sup> $E_x$ (MeV $\pm$ keV)	(1969LU07) <sup>b</sup>	$\Gamma$ (keV)	$J^\pi; T^c$
0.121 $\pm$ 6				0 <sup>-</sup>
0.298 $\pm$ 6		0.307 $\pm$ 20		3 <sup>-</sup>
0.396 $\pm$ 7				
3.348 $\pm$ 7				1 <sup>+</sup>
3.517 $\pm$ 7				2 <sup>+</sup> , (3) <sup>+</sup>
3.958 $\pm$ 7		3.961 $\pm$ 20		(2) <sup>+</sup> , 3 <sup>+</sup>
4.313 $\pm$ 9				1 <sup>+</sup>
4.386 $\pm$ 9				
4.768 $\pm$ 11				
5.052 $\pm$ 9				
5.137 $\pm$ 9				
5.234 $\pm$ 9				(1, 2, 3) <sup>+</sup>
	5.512 $\pm$ 5			(1, 2, 3) <sup>+</sup>
	5.724 $\pm$ 5	5.745 $\pm$ 20		5 <sup>+</sup>
	6.168 $\pm$ 5			
	6.843 $\pm$ 5			
	7.113 $\pm$ 5			
	7.570 $\pm$ 5	7.599 $\pm$ 30		
	7.636 $\pm$ 5			
	7.673 $\pm$ 5			
	8.205 $\pm$ 5			
	9.760 $\pm$ 10		15 $\pm$ 8	$T = 1$
	9.813 $\pm$ 10			$T = 1$
	9.928 $\pm$ 7		< 12	0 <sup>+</sup> ; 2
	11.701 $\pm$ 7		< 12	1 <sup>-</sup> , 2 <sup>+</sup> ; 2

<sup>a</sup>  $^{14}\text{C}(^3\text{He}, \text{p})^{16}\text{N}$ .

<sup>b</sup>  $^{14}\text{C}(\alpha, \text{d})^{16}\text{N}$ .

<sup>c</sup> From (1968HE03, 1972FR05).

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

(1961SI04)		(1966HE10)		$L^a$	$J^\pi^a$
$E_x$ (MeV $\pm$ keV)	$\Gamma$ (keV)	$E_x$ (MeV $\pm$ keV)	$\Gamma$ (keV)		
0		0		3	$2^-^b$
$0.121 \pm 10$		$0.120 \pm 10$		1	$0^-^b$
$0.297 \pm 10$		$0.300 \pm 10$		3	$3^-^b$
$0.396 \pm 10$		$0.399 \pm 10$		1	$1^-^b$
$3.340 \pm 25$	$\leq 25 \pm 17$	$3.359 \pm 10$	$15 \pm 5$	0	$1^+^b$
$3.506 \pm 25$	$\leq 25 \pm 8$	$3.519 \pm 10$	$\leq 7 \pm 4$	<sup>c</sup>	
$3.956 \pm 25$	$\leq 25 \pm 8$	$3.957 \pm 10$	$\leq 7 \pm 4$	2	$3^+^b$
$4.318 \pm 25$	$\leq 25 \pm 8$	$4.318 \pm 10$	$20 \pm 5$	0	$1^+^b$
$4.392 \pm 25$	$110 \pm 31$	$4.391 \pm 10$	$82 \pm 20$	1	$1^-^b$
		$4.725 \pm 10^d$	$290 \pm 30$	1	$1^-$
$4.773 \pm 25$	$66 \pm 7$	$4.774 \pm 10$	$59 \pm 8$	2	$2^-^b$
$5.059 \pm 25$	$\leq 25 \pm 8$	$5.053 \pm 10$	$19 \pm 6$	(1 + 3)	$2^-$
		$5.130 \pm 10$	$\leq 7 \pm 4$	<sup>c</sup>	
$5.141 \pm 25$	$38 \pm 12$				
		$5.150 \pm 10$	$\leq 7 \pm 4$		
$5.230 \pm 25$	$\leq 20 \pm 8$	$5.226 \pm 10$	$\leq 7 \pm 4$	2	(1, 2, 3) <sup>+</sup>
		$5.305 \pm 10^d$	$260 \pm 30$	<sup>c</sup>	
$5.526 \pm 25$	$\leq 20 \pm 8$	$5.520 \pm 10$	$\leq 7 \pm 4$	(1 + 3)	(2 <sup>-</sup> )
		$5.730 \pm 10$	$\leq 7 \pm 4$	4	$5^+^b$
		$6.009 \pm 10$	$270 \pm 30$	1	(1 <sup>-</sup> )
		$6.167 \pm 10$	$\leq 7 \pm 4$	3	(2, 3, 4) <sup>-</sup>
		$6.371 \pm 10$	$30 \pm 6$		
		$6.422 \pm 10$	$300 \pm 30$		
		$6.512 \pm 10$	$34 \pm 6$		
		$6.613 \pm 10$	$\leq 7 \pm 4$		
		$6.854 \pm 10$	$\leq 7 \pm 4$		
		$7.006 \pm 10$	$22 \pm 5$		
		$7.133 \pm 10$	$\leq 7 \pm 4$		
		$7.250 \pm 10$	$17 \pm 5$		
		$7.573 \pm 10$	$\leq 7 \pm 4$		

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

(1961SI04)		(1966HE10)		$L^a$	$J^\pi^a$
$E_x$ (MeV $\pm$ keV)	$\Gamma$ (keV)	$E_x$ (MeV $\pm$ keV)	$\Gamma$ (keV)		
		$7.640 \pm 10$	$\leq 7 \pm 4$		
		$7.675 \pm 10$	$\leq 7 \pm 4$		
		$7.876 \pm 10$	$100 \pm 15$		
		$8.043 \pm 10$	$85 \pm 15$		
		$8.183 \pm 10$	$28 \pm 8$		
		$8.280 \pm 10$	$24 \pm 8$		
		$8.361 \pm 10$	$18 \pm 8$		

<sup>a</sup> From reanalysis of data of (1966HE10): see (1975CR02).

<sup>b</sup> Identified with shell-model counterparts (1975CR02).

<sup>c</sup> Results are ambiguous (1975CR02).

<sup>d</sup> The errors listed here for the  $E_x$  to these two broad peaks are probably underestimates: I am indebted to Dr. H. Fuchs for his comments.

14.  $^{14}\text{C}(\text{t}, \text{n})^{16}\text{N}$   $Q_m = 4.217$

Not reported.

15.  $^{14}\text{C}(\text{}^3\text{He}, \text{p})^{16}\text{N}$   $Q_m = 4.981$

Proton groups have been observed to  $^{16}\text{N}$  states with  $E_x < 12$  MeV and angular distributions (with  $E(^3\text{He}) \leq 15$  MeV) lead to the  $J^\pi$  assignments shown in Table 16.5 (1966GA08, 1968HE03, 1972FR05). See also (1975FO06) and (1971AJ02).

16.  $^{14}\text{C}(\alpha, \text{d})^{16}\text{N}$   $Q_m = -13.373$

At  $E_\alpha = 46$  MeV the angular distributions of five deuteron groups [see Table 16.5] have been determined: the most strongly populated state is the  $5^+$  state,  $^{16}\text{N}^*(5.73)$  (1969LU07).

17.  $^{14}\text{N}(\text{t}, \text{p})^{16}\text{N}$   $Q_m = 4.843$

Table 16.7: Resonances in  $^{15}\text{N}(n, n)^{15}\text{N}$  <sup>a,b</sup>

$E_n$ (MeV $\pm$ keV)	$\Gamma_{\text{lab}}$ (keV)	$E_x$ (MeV)	$J^\pi$
0.921	14	3.355	1 <sup>+</sup> <sup>c</sup>
1.095	3	3.518	1
1.563	$\leq 2$	3.956	1
1.944	29	4.313	1 <sup>+</sup> <sup>d</sup>
2.038	56	4.401	1 <sup>-</sup> <sup>d</sup>
2.30 $\pm$ 70 <sup>e</sup>	410 $\pm$ 100 <sup>e</sup>	4.65	1 <sup>-</sup> <sup>d</sup>
2.399	107	4.739	2 <sup>+</sup> <sup>d</sup>
2.732	35	5.051	1 <sup>-</sup>
2.830	12	5.143	3 <sup>(-)</sup>
2.84 $\pm$ 70 <sup>f</sup>	70 $\pm$ 100 <sup>f</sup>	5.15	2 <sup>-</sup> <sup>d</sup>
2.915	$\leq 4$	5.223	$\geq 2$
2.93	260	5.24	1 <sup>+</sup>
3.225		5.513	
3.454	24	5.728	1 <sup>+</sup>
3.69	297	5.95	1 <sup>-</sup>
3.987	88	6.227	(1 <sup>+</sup> )
4.126	78	6.357	(3 <sup>-</sup> )
4.252	113	6.475	(2 <sup>+</sup> )
4.64	$> 150$	6.84	$\geq 2$
4.80	37	6.99	$\geq 1$
5.055	25	7.228	$\geq 2$
5.43	30	7.58	$\geq 3$
5.56		7.70	
5.73	165	7.86	$\geq 4$
5.90		8.02	
6.28		8.37	$\geq 1$
6.42		8.51	$\geq 1$
6.65	45	8.72	$\geq 1$
6.76		8.82	
7.10	110	9.14	$\geq 2$
7.31		9.34	

Table 16.7: Resonances in  $^{15}\text{N}(n, n)^{15}\text{N}$  <sup>a,b</sup> (continued)

$E_n$ (MeV $\pm$ keV)	$\Gamma_{\text{lab}}$ (keV)	$E_x$ (MeV)	$J^\pi$
7.44	105	9.46	$\geq 2$
7.71	150	9.71	$\geq 2$
8.07	30	10.05	$\geq 3$
8.30	175	10.27	$\geq 2$
8.77	130	10.71	$\geq 2$
9.61		11.49	$\geq 3$
9.77		11.64	$\geq 3$
10.25		12.09	
10.64		12.46	
11.09		12.88	
11.41		13.12	
12.10		13.83	

<sup>a</sup> (1971DO06, 1971ZE02). See Table 16.7 in (1971AJ02) for the earlier work.

<sup>b</sup> Below  $E_n = 4.5$  MeV, the multilevel  $R$ -matrix formalism was used to determine  $E_\lambda$ ,  $\Gamma_\lambda$  and whenever possible  $J^\pi$  by a  $\chi^2$  fitting and minimization technique. Above this energy the  $2J + 1$  dependence was used; the parity cannot be determined because no marked interference effects are observed between resonance and potential scattering. Above 5.65 MeV all  $J$ -values are lower limits because the inelastic channel is open. [A channel radius  $a = 4.69$  fm was used] (1971ZE02).

<sup>c</sup> Parity determined from angular distribution.

<sup>d</sup>  $J^\pi$  also obtained by phase-shift analysis.

<sup>e</sup> The phase-shift analysis indicates that the resonance is at  $E_n = 2.42 \pm 0.08$  MeV with  $\Gamma = 250 \pm 50$  keV. This is one of two ( $d_{3/2}p_{1/2}^{-1}$ ) single-particle resonances (1971ZE02).

<sup>f</sup> The phase-shift analysis finds  $E_\lambda = 2.94 \pm 0.1$  MeV,  $\Gamma = 320 \pm 80$  keV. This is the other ( $d_{3/2}p_{1/2}^{-1}$ ) single-particle resonance (1971ZE02).

Angular distributions are reported at  $E_t = 1.8$  MeV (1964SC09) and at 12 MeV (1966HE10, 1975CR02): see Table 16.6 for the observed proton groups. See also (1976AL16) and (1970EL17; theor.).

18.  $^{15}\text{N}(n, \gamma)^{16}\text{N}$

$Q_m = 2.492$

The thermal cross section is  $24 \pm 8 \mu\text{b}$  (1973MU14, 1974SH1E).

19.  $^{15}\text{N}(n, n)^{15}\text{N}$

$$E_b = 2.492$$

The scattering amplitude (bound)  $a = 6.5 \pm 0.2 \text{ fm}$  [recommended by (1973MU14)]. The total cross section has been measured for  $E_n = 0.4$  to 32 MeV: see (1971AJ02, 1976GAYV) and (1971ZE02). Observed resonances and parameters derived from  $R$ -matrix and phase-shift analyses of these data, angular distributions and polarization measurements are displayed in Table 16.7 (1971DO06, 1971ZE02). See (1971AJ02) for the earlier work, (1972LA1F) and (1971BA95, 1972AG02, 1972BA2C, 1972LI13, 1973BA74, 1973MO16, 1974AY01, 1974HO1L, 1975BA61, 1975MO10, 1975RO31; theor.).

20.  $^{15}\text{N}(n, p)^{15}\text{C}$

$$Q_m = -8.989$$

$$E_b = 2.492$$

See (1966PR1A, 1971PR09, 1976GAYV). See also (1972ED01, 1974BO1E).

21.  $^{15}\text{N}(n, \alpha)^{12}\text{B}$

$$Q_m = -7.622$$

$$E_b = 2.492$$

See (1971AJ02).

22.  $^{15}\text{N}(d, p)^{16}\text{N}$

$$Q_m = 0.267$$

Levels derived from observed proton groups and  $\gamma$ -rays are listed in Table 16.8. Gamma transitions are shown in the inset of Fig. 2: (1971PA28) report that the branchings of  $^{16}\text{N}^*(0.40)$  to  $^{16}\text{N}^*(0, 0.12, 0.30)$  are, respectively,  $(26.6 \pm 0.6)\%$ ,  $(73.4 \pm 1.6)\%$ , and  $\leq 2 \times 10^{-3}\%$  [(1963GI11) had reported a  $(5 \pm 2)\%$  branch for the latter transition]. The  $0.30 \rightarrow 0.12$  transition is  $\leq 10^{-2}\%$  (1971PA28).

The mean life of  $^{16}\text{N}^*(0.12)$  is  $7.58 \pm 0.09 \mu\text{sec}$  (1967BE14); together with the angular distribution analyses this leads to  $J^\pi = 0^-$  for the state. The very strong evidence for  $J^\pi = 2^-$ ,  $3^-$  and  $1^-$ , respectively, for  $^{16}\text{N}^*(0, 0.30, 0.40)$  is reviewed in (1971AJ02). See also (1972LI13, 1973BA74, 1973MO16, 1975BA61, 1975MO10; theor.) and reaction 1.

23.  $^{15}\text{N}(t, d)^{16}\text{N}$

$$Q_m = -3.766$$

Not reported.

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

(1966HE10) <sup>a</sup> $E_x$ (MeV $\pm$ keV)	$l_n$ <sup>a,b</sup>	(1966HE10) <sup>c</sup>	(1970BO08) <sup>c</sup>	$J\pi$ <sup>d</sup>
0	k	0		$2^-$
$0.1201 \pm 0.5$ <sup>e</sup>	k	$0.119 \pm 15$		$0^-$
$0.2962 \pm 1.0$ <sup>e</sup>	k	$0.301 \pm 15$		$3^-$
$0.3973 \pm 1.0$ <sup>e</sup>	k	$0.400 \pm 15$		$1^-$
$3.365 \pm 10$		$3.358 \pm 15$		$(1^+)$
$3.523 \pm 10$	2 or 1 + 3	$3.524 \pm 15$	f	
$3.964 \pm 10$	3	$3.964 \pm 15$		$(2, 3)^+$
$4.325 \pm 10$	1	$4.324 \pm 15$		$(1)^+$
$4.40$ <sup>b</sup>	0	$4.383 \pm 15$		$(0, 1)^-$
$4.715 \pm 10$	1			$(1, 2, 3)^+$
$4.780 \pm 10$		$4.787 \pm 15$	f	
$(4.90 \pm 10)$				
$5.032 \pm 10$	2	$5.065 \pm 15$		$(1, 2)^-$
$5.128 \pm 10$	$\geq 2$			$\geq 2$
		$5.139 \pm 15$		
$5.150 \pm 10$	2			$(2, 3)^-$
$5.231 \pm 10$	3	$5.240 \pm 15$		$(2, 3, 4)^+$
$5.310 \pm 10$				
$5.523 \pm 10$	3	$5.528 \pm 15$	f	$(2, 3, 4)^+$
$5.739 \pm 10$	2	$5.740 \pm 15$	f	$(1, 2)^-$
			$6.01 \pm 15$ <sup>j</sup>	
$6.170 \pm 10$	$\geq 3$	$6.168 \pm 15$	g	$\geq 2$
$(6.28 \pm 10)$	1			$(0, 1, 2)^+$
$6.376 \pm 10$	2		$6.37 \pm 15$ <sup>j</sup>	$(1, 2, 3)^-$
$6.431 \pm 10$				
$6.514 \pm 10$	1	$6.512 \pm 15$	g	$(0, 1, 2)^+$
$6.609 \pm 10$		$6.620 \pm 15$	g	
$(6.79 \pm 10)$				
$6.847 \pm 10$		$6.852 \pm 15$	g	
$7.034 \pm 10$			$7.01 \pm 15$ <sup>j</sup>	



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

(1966HE10) <sup>a</sup> $E_x$ (MeV $\pm$ keV)	$l_n$ <sup>a,b</sup>	(1966HE10) <sup>c</sup>	(1970BO08) <sup>c</sup>	$J\pi$ <sup>d</sup>
7.135 $\pm$ 10		7.141 $\pm$ 15	g	
7.250 $\pm$ 10		7.247 $\pm$ 15	g	
7.577 $\pm$ 10		7.596 $\pm$ 15	g	
7.638 $\pm$ 10			7.64 $\pm$ 15 <sup>j</sup>	
7.676 $\pm$ 10		7.683 $\pm$ 15		
7.840 $\pm$ 10			7.88 $\pm$ 15 <sup>j</sup>	
			8.06 $\pm$ 15 <sup>j</sup>	
			8.18 $\pm$ 15 <sup>j</sup>	
		8.286 $\pm$ 15	g	
		8.374 $\pm$ 15	g	
			8.49 $\pm$ 30 <sup>h</sup>	
			8.819 $\pm$ 15 <sup>i</sup>	
			9.035 $\pm$ 15	
			(9.16 $\pm$ 30)	
			(9.34 $\pm$ 30)	
			9.459 $\pm$ 15	
			(9.66 $\pm$ 40)	
			9.794 $\pm$ 15 <sup>i</sup>	
			9.90 $\pm$ 30	
			10.055 $\pm$ 15 <sup>i</sup>	
			(10.17 $\pm$ 30)	
			(10.26 $\pm$ 30)	

<sup>a</sup>  $^{15}\text{N}(\text{d}, \text{p})^{16}\text{N}$ .

<sup>b</sup> (1971FU14, 1972FU16;  $E_{\text{d}} = 12$  MeV). I am very much indebted to Dr. H. Fuchs for his comments.

<sup>c</sup>  $^{18}\text{O}(\text{d}, \alpha)^{16}\text{N}$ .

<sup>d</sup>  $J^{\pi}$  assignment from angular distribution analyses and  $\gamma$ -decay (1956ZI1A, 1957WA01, 1970BO08, 1972FU16, 1973BO1G).

<sup>e</sup> From  $\gamma$ -decay studies (1963GI11). (1957FR56, 1957WI1B) found  $E_{\text{x}} = 120 \pm 1, 294 \pm 5$  and  $392 \pm 3$  keV.

<sup>f</sup> Angular distribution reported in  $^{18}\text{O}(\text{d}, \alpha)^{16}\text{N}$  at  $E_{\text{d}} = 10.0 - 11.2$  MeV but  $L$  not determined (1970BO08).

<sup>g</sup> Alpha group seen but  $E_{\text{x}}$  not determined.

<sup>h</sup>  $\Gamma$  for this level and the ones listed below  $\leq 40 - 50$  keV (1970BO08).

<sup>i</sup> These levels appear to be correlated with thresholds for neutron emission to excited states of  $^{15}\text{N}$  (1970BO08, 1970BO09).

<sup>j</sup> T.I. Bonner, private communication.

<sup>k</sup> Absolute spectroscopic factors for  $^{16}\text{N}^*(0, 0.12, 0.30, 0.40)$  are 0.55, 0.46, 0.54, 0.52 (1973BO1G: average values in the range  $E_{\text{d}} = 5$  to 6 MeV).

<sup>l</sup> (1975FO02) suggest  $J^{\pi} = 1^{-}$  or 2 on the basis of a study at  $E_{\text{d}} = 12$  MeV and comparison with the  $^{15}\text{N}(\text{n}, \text{n})$  results.

24.  $^{15}\text{N}(\alpha, ^3\text{He})^{16}\text{N}$   $Q_{\text{m}} = -18.087$

Not reported.

25.  $^{15}\text{N}(^{11}\text{B}, ^{10}\text{B})^{16}\text{N}$   $Q_{\text{m}} = -8.964$

See (1969BR1D).

26.  $^{16}\text{C}(\beta^{-})^{16}\text{N}$   $Q_{\text{m}} = 8.011$

See  $^{16}\text{C}$ .

27.  $^{16}\text{O}(\text{n}, \text{p})^{16}\text{N}$   $Q_{\text{m}} = -9.636$

See (1971AJ02) and (1976KI1D).

28.  $^{16}\text{O}(t, ^3\text{He})^{16}\text{N}$   $Q_m = -10.400$

At  $E_t = 23.5$  MeV  $^{16}\text{N}^*(0, 0.30)$  [ $J^\pi = 2^-, 3^-$ ] are strongly populated relative to  $^{16}\text{N}^*(0.12, 0.40)$  [ $0^-, 1^-$ ]. This suggests that the  $2^-$  and  $3^-$  states in  $^{16}\text{F}$  are those that are strongly populated in the  $^{16}\text{O}(^3\text{He}, t)^{16}\text{F}$  reaction [ $^{16}\text{F}^*(0.42, 0.72)$ ] and that the other two states in  $^{16}\text{F}$  [ $^{16}\text{F}^*(0, 0.20)$ ] are  $0^-$  and  $1^-$  [the ordering within the  $2^-$  and  $3^-$ , and the  $0^-$  and  $1^-$  states, in  $^{16}\text{F}$  is ambiguous] (1974FL06). See also  $^{16}\text{O}(^3\text{He}, t)$  in  $^{16}\text{F}$ .

29.  $^{17}\text{O}(d, ^3\text{He})^{16}\text{N}$   $Q_m = -8.288$

A comparison has been made at  $E_d = 52$  MeV of the population of states in this reaction and in the mirror (d, t) reaction in order to identify  $T = 1$  states in  $^{16}\text{O}$  and in order to study the mass dependence of the 1p spin-orbit splitting: see reaction  $^{17}\text{O}(d, t)$  in  $^{16}\text{O}$  (1974MA23). See also (1973WA1E) and (1976SC1H; theor.).

30.  $^{18}\text{O}(p, ^3\text{He})^{16}\text{N}$   $Q_m = -14.107$

At  $E_p = 43.7$  MeV, the angular distribution of the  $^3\text{He}$  nuclei corresponding to a state at  $E_x = 9.9$  MeV fixes  $L = 0$  and therefore  $J^\pi = 0^+$  for  $^{16}\text{N}^*(9.9)$ : it is presumably the  $T = 2$  analog of the ground state of  $^{16}\text{C}$ . Some lower-lying  $T = 1$  states were also observed (1964CE05). See also (1970OL1B, 1972OH1B).

31.  $^{18}\text{O}(d, \alpha)^{16}\text{N}$   $Q_m = 4.247$

Forty-three  $\alpha$ -particle groups have been observed at  $E_d \leq 12$  MeV, corresponding to states of  $^{16}\text{N}$  with  $E_x < 10.3$  MeV: see Table 16.8 (1966HE10, 1970BO08, 1970BO09).  $^{16}\text{N}^*(8.82, 9.8, 10.06)$  may be related to nearly bound virtual states of  $2s_{1/2}$  neutron with  $^{15}\text{N}^*(6.32, 7.30, 7.57)$  (1970BO08, 1970BO09). (1975AS02) find  $\tau_m = 6.5 \pm 0.5$  psec for  $^{16}\text{N}^*(0.40)$  and  $|g| = 1.83 \pm 0.13$ ;  $|M|^2$  for the M1 transition to  $^{16}\text{N}^*(0.12)$  is  $0.17 \pm 0.02$  W.u. See also (1969NI09) and  $^{20}\text{F}$  in (1978AJ03).

32.  $^{18}\text{O}(^6\text{Li}, ^8\text{Be})^{16}\text{N}$   $Q_m = 2.682$

See (1969NI09).

33.  $^{19}\text{F}(n, \alpha)^{16}\text{N}$   $Q_m = -1.521$

Angular distributions have been reported for  $E_n = 4.7$  to  $14.4$  MeV: see (1971AJ02) for the earlier references and see (1972FO21;  $E_n = 5.85$  MeV;  $\alpha_{0+1+2+3}$ ). See also  $^{20}\text{F}$  in (1978AJ03).

GENERAL: (See also (1971AJ02).):

*Shell model:* (1969BO1B, 1969FE1A, 1969IK1A, 1969WI1C, 1970BO33, 1970BO1J, 1970DE1F, 1970DO1A, 1970EI06, 1970EL14, 1970HA49, 1970IR01, 1970MA1Q, 1970NE15, 1970RE1G, 1970RU1A, 1970SV1B, 1970ZO1A, 1971AG02, 1971AN14, 1971AR1R, 1971BA1N, 1971BA67, 1971BE14, 1971BO29, 1971BR1E, 1971BR1J, 1971GO16, 1971HE15, 1971HS02, 1971HU15, 1971IR02, 1971IR03, 1971IR04, 1971IR05, 1971KH01, 1971LA13, 1971LE30, 1971MA60, 1971MO05, 1971RO03, 1971SU08, 1971VI08, 1971ZO03, 1971ZO01, 1971ZO1A, 1972AB12, 1972BO38, 1972BR1G, 1972CA23, 1972EH01, 1972EN03, 1972FR12, 1972GE05, 1972JA18, 1972JA24, 1972KA38, 1972LE1L, 1972MC1C, 1972NE13, 1972NI14, 1972PA21, 1972RA1C, 1972RE02, 1972RO06, 1972SA1B, 1972SH20, 1972VA09, 1972WA08, 1972WO04, 1972ZA1B, 1973EL04, 1973FE04, 1973HA05, 1973IC01, 1973KU03, 1973LA36, 1973LO1C, 1973MA55, 1973MU18, 1973RE17, 1973RO12, 1973SA05, 1973SH11, 1973TR08, 1973WA35, 1973YA1A, 1974BO31, 1974DA1J, 1974EL05, 1974FA1B, 1974KH01, 1974KU05, 1974MA21, 1974NA13, 1974NE1H, 1974NE1J, 1974SH1M, 1974TA19, 1974WO02, 1974ZA1E, 1975DI04, 1975DR01, 1975EN01, 1975FR06, 1975GI1C, 1975GR1N, 1975LO05, 1975MC1L, 1975MI1N, 1975MI12, 1975MP01, 1975SP08, 1975VE05, 1975ZA07, 1976BL03, 1976BO1Z, 1976DO04, 1976SA1R, 1976SC03, 1976SC05, 1976ZA07).

*Collective and rotational models:* (1969FE1A, 1970DA13, 1970FL1A, 1970PA1K, 1970SV1B, 1971AR1R, 1971BO29, 1971GO06, 1971IR05, 1971ON01, 1971OS03, 1971ZO01, 1972AB1C, 1972BO38, 1972HO56, 1972JA24, 1972LA12, 1972LE1L, 1972ZA1B, 1973CA16, 1973IC01, 1973KO1F, 1973LA36, 1973LA35, 1973RO12, 1973SH14, 1973SO07, 1973YA1A, 1974AR04, 1974MP01, 1975AB04, 1975DR01, 1975LE07, 1975LE14, 1975SO07, 1976BO2B, 1976GO17).

*Cluster and  $\alpha$ -particle models:* (1969BA1J, 1969IK1A, 1969TA1C, 1969WI1C, 1970EI06, 1970KO26, 1971AB1B, 1971AN14, 1971FR06, 1971KH06, 1971ME15, 1971NO03, 1971RI1D, 1972AB1C, 1972AB05, 1972AV02, 1972BA59, 1972FR1B, 1972GR42, 1972HO56, 1972IK1A, 1972LE1L, 1972LI1E, 1972NE1B, 1973BE1L, 1973CO13, 1973CO15, 1973DE26, 1973IC01, 1973KU03, 1973LA35, 1973YA1A, 1974DA1J, 1974DZ05, 1974GO12, 1974GO37, 1974KH02, 1974KH05, 1974ME08, 1974SU05, 1974SU1B, 1974TA19, 1974WA15, 1974WE08, 1975BA16, 1975BU03, 1975IK1A, 1975IN04, 1975KA1N, 1975KR1D, 1975KU1N, 1975PA11, 1975TA1K, 1975WA33, 1976BA1N, 1976GO1Q, 1976SA1P, 1976SU10).

*Astrophysical questions:* (1971LE33, 1972CL1A, 1972KO1A, 1973AR1H, 1973AU1D, 1973CA1B, 1973CO1J, 1973CO1B, 1973GR1G, 1973IB1B, 1973RA1D, 1973SA1J, 1973SM1A, 1973TA1E, 1973TR1C, 1973TR1B, 1973UL1B, 1973WO1B, 1974AR1G, 1974BE1R, 1974PA1E, 1974SC1F, 1974WI1F, 1975AU1D, 1975BA2D, 1975BE1R, 1975DA1G, 1975EN1A, 1975FA1H, 1975IB1A, 1975JA1F, 1975KE1A, 1975LA1E, 1975LE1L, 1975PE1E, 1975RA1M, 1975RY1A, 1975SC1R, 1975SC1H, 1975SC1W, 1975SU1B, 1975TA1G, 1975TR1A, 1975VL1A, 1976AU1F, 1976DW1A,

1976EP1A, 1976FIIE, 1976FU1D, 1976GI1C, 1976JA1Q, 1976ME1H, 1976OS1E, 1976RO1J).

*Giant resonance (See also reactions 56 and 57.):* (1970AL22, 1970KE1A, 1970MA1Q, 1970PA1K, 1971DU13, 1971IR05, 1971SE03, 1972GO20, 1973BA05, 1973CA25, 1973DE26, 1973DE53, 1973GE01, 1973GO23, 1973HA1Q, 1973KI08, 1973WA35, 1974FA1A, 1974KR24, 1974KR22, 1974KR1H, 1974SH1M, 1974WA12, 1974WA1J, 1974WO02, 1975AB04, 1975AU11, 1975CO1E, 1975DO10, 1975DU16, 1975GO22, 1975GR1N, 1975RA02, 1975SH07, 1975VE05, 1976BE45, 1976BR05, 1976FL09, 1976FO11, 1976HO12, 1976KN02, 1976LI14, 1976MA2F).

*Electromagnetic transitions:* (1969FE1A, 1970DO1A, 1970HA49, 1971IR03, 1971IR05, 1971KH01, 1971MIZQ, 1971RU12, 1972AB12, 1972AU03, 1972BE1E, 1972BE98, 1972BO38, 1972EC01, 1972EN03, 1972FA1D, 1972LO1D, 1972MI1E, 1972NA05, 1972YO1B, 1973BE1L, 1973CA16, 1973EL04, 1973HA1N, 1973HA1Q, 1973HO29, 1973IA1A, 1973JA11, 1973RE17, 1973SH14, 1973SO07, 1973WE14, 1974BU1E, 1974FE1E, 1974FI03, 1974HA1C, 1974KR22, 1974LA1F, 1974MC1F, 1975AR30, 1975BE2E, 1975BR1P, 1975BU03, 1975HO20, 1975HS01, 1975RA02, 1975SA1G, 1975VE05, 1975WE1C, 1975ZA07, 1976BL08, 1976HO12, 1976KI01, 1976KN02, 1976KR14, 1976VO1C).

*Special levels:* (1969FE1A, 1969WI1C, 1970BO33, 1970BO1J, 1970DA13, 1970HA51, 1970MA1Q, 1970NA16, 1970PA1K, 1970PE18, 1970RU1A, 1970VA1M, 1971AF02, 1971AG02, 1971AR1R, 1971BE2B, 1971BE2D, 1971ER08, 1971GO16, 1971GR49, 1971GR1V, 1971HE15, 1971HS02, 1971HU15, 1971IR03, 1971IR05, 1971KH01, 1971KO12, 1971MC15, 1971ME15, 1971OS03, 1971RO03, 1971RU12, 1971SC10, 1971SE03, 1971SE1C, 1971SU08, 1971WE03, 1971WE1F, 1971YA1B, 1972AV02, 1972DO02, 1972EN03, 1972FA1D, 1972GR1K, 1972HA1R, 1972HI17, 1972JA18, 1972JA24, 1972KA67, 1972LA12, 1972NI14, 1972NI15, 1972PA21, 1972SU04, 1972VA09, 1973BA1Z, 1973DO1B, 1973ER12, 1973FA1H, 1973FE04, 1973GA1H, 1973HO29, 1973IA1A, 1973JA11, 1973KI08, 1973KN1C, 1973KU04, 1973MA55, 1973MU18, 1973RO12, 1973SA05, 1973SH14, 1973SO07, 1973YA1A, 1974AR04, 1974DI1E, 1974EL05, 1974FE1E, 1974GA27, 1974GO12, 1974GO1P, 1974GO37, 1974HA1G, 1974IT1B, 1974KO1L, 1974KR1H, 1974LO11, 1974NA13, 1974NI1A, 1974SU05, 1974VA24, 1974ZA1E, 1975AR1J, 1975BA16, 1975BE2E, 1975BO1T, 1975BR1P, 1975BU03, 1975DI04, 1975GO19, 1975HA30, 1975HS01, 1975MA10, 1975MC1L, 1975MC1H, 1975MI03, 1975MI12, 1975NA21, 1975NG1A, 1975PE07, 1975RA02, 1975SA08, 1975TA1K, 1976BL03, 1976DO04, 1976FO11, 1976JA03, 1976KI01, 1976LI14, 1976SA1P, 1976SU10, 1976WE1P).

*Applications:* (1975BE1U, 1976EA1A, 1976EC1B, 1976GR1J, 1976RA1J, 1976SC1G).

*Special reactions:* (1970BE1D, 1971AR02, 1972PU1B, 1973KU03, 1973WI15, 1974KO1L, 1974WE08, 1975AL04, 1975AL1H, 1975AR17, 1975AR14, 1975DR01, 1975FA1D, 1975GR13, 1975KO1F, 1975KU01, 1975KU1K, 1975ME1F, 1975RE08, 1975RE17, 1975VO09, 1976BA08, 1976EG02, 1976HE1H, 1976HI05, 1976JA1R, 1976NA11).

*Muon and neutrino capture and reactions:* (1970BU1B, 1970EV1A, 1970KA1E, 1970PR1H, 1971ER01, 1971GR1U, 1971LA17, 1971MO1Q, 1971PA28, 1971PL01, 1971PL1F, 1971SAZK, 1972BA1X, 1972BL01, 1972BO11, 1972DO07, 1972DO17, 1972HI04, 1972LA1C, 1972VO12,

1972WA08, 1972WO1D, 1973BA68, 1973BE07, 1973DO04, 1973DO1H, 1973ER06, 1973FU11, 1973JO17, 1973KA30, 1973NA28, 1973SA1L, 1973WA1D, 1974DU02, 1974EN10, 1974GO1Q, 1974KO1M, 1974VO12, 1974WA1C, 1975BA40, 1975CH22, 1975DO1F, 1975DO10, 1975DO1D, 1975FU1F, 1975GE1E, 1975MC03, 1975PA01, 1976FO11, 1976LA1K, 1976SU03).

*Pion capture and reactions:* (1969BA70, 1969MA1C, 1970AL22, 1970BA1E, 1970CH1C, 1970GO1F, 1970HO1D, 1970HU18, 1970KE1A, 1970KO26, 1970WI21, 1971CA01, 1971CA1J, 1971CH41, 1971CH1U, 1971DE31, 1971DE1Y, 1971EI01, 1971FA09, 1971GU13, 1971KO10, 1971KO23, 1971LI1M, 1971MA1C, 1971MA1T, 1971MA2A, 1971MO1G, 1971SE02, 1971SR03, 1972BA2E, 1972BE57, 1972BI09, 1972EN07, 1972FA14, 1972FL1A, 1972HU1A, 1972KO27, 1972KO31, 1972MA1H, 1972RO02, 1972SA10, 1972SE1F, 1972SW1A, 1972YO1C, 1973AG05, 1973AG06, 1973AL1A, 1973AR1B, 1973BA2G, 1973BO49, 1973BR1J, 1973BU1B, 1973CA25, 1973DO1F, 1973EI01, 1973GA20, 1973GE11, 1973GR1F, 1973KA1D, 1973KO1G, 1973LA1G, 1973LA1H, 1973LE1F, 1973LE1G, 1973LE1H, 1973LE22, 1973MA10, 1973NY04, 1973PH01, 1973RE10, 1973RO1Q, 1973SE1E, 1973SR02, 1974AM01, 1974BL10, 1974BO2D, 1974CL04, 1974HU14, 1974LA12, 1974LI1H, 1974LI15, 1974LU1E, 1974LU1D, 1974NE18, 1974OH01, 1974PH1A, 1974PH1B, 1974PI02, 1974ST1G, 1974SZ04, 1974TA18, 1974UL02, 1974VI1B, 1974VO12, 1975AR02, 1975BA1L, 1975BU1A, 1975EN1D, 1975GI13, 1975HE06, 1975HU1D, 1975IA02, 1975KA1G, 1975KO1F, 1975KO25, 1975LI06, 1975MA1M, 1975MU06, 1975NA1K, 1975RA1R, 1975RO11, 1975TA1C, 1975VE05, 1975YA02, 1976AL1L, 1976AS1B, 1976BA1G, 1976BO2A, 1976CA1H, 1976CO13, 1976DO1D, 1976DY1B, 1976EN02, 1976GA1C, 1976GU01, 1976JA04, 1976JO1C, 1976KA02, 1976KI1E, 1976MA1U, 1976MI10, 1976MO1M, 1976MO1N, 1976OS03, 1976TR1A, 1976WA1R).

*K-mesons and other meson interactions:* (1971BA1N, 1971KO18, 1971MA1T, 1972BA09, 1972WA1F, 1973BA1Y, 1974CA1H, 1975BO1U, 1975OS1B, 1975PO1C, 1976BO2A, 1976EI1A, 1976GA1C, 1976KI1E, 1976NI1E).

*Antiproton interactions:* (1975TA1C).

*Other topics:* (1969EL1A, 1969GR1A, 1970AR1C, 1970BA1G, 1970BE1D, 1970BO1J, 1970DR07, 1970EL14, 1970GM1A, 1970GU13, 1970HA51, 1970KR10, 1970LO07, 1970NE15, 1970PE18, 1970RE1G, 1970RU1A, 1970TR1E, 1970VA1M, 1970VA1N, 1970ZA1B, 1970ZO1A, 1971AF02, 1971BA67, 1971BE1W, 1971BE2B, 1971BO1F, 1971BR1J, 1971DA03, 1971DA15, 1971ER08, 1971GA1M, 1971GO16, 1971GR13, 1971GR1L, 1971GR49, 1971GR1V, 1971HE01, 1971HE15, 1971IR02, 1971IR04, 1971IR05, 1971KA14, 1971KA40, 1971KO12, 1971KO18, 1971LA1D, 1971LA13, 1971MA63, 1971MA60, 1971MA2B, 1971MC15, 1971MU08, 1971OS01, 1971OS03, 1971RA01, 1971RU12, 1971RY1A, 1971SA1C, 1971SC01, 1971SE1C, 1971SR03, 1971NG01, 1971VI08, 1971WE03, 1971WE1E, 1971WI1D, 1971WO06, 1971YA1B, 1971ZO03, 1971ZO1A, 1972AB05, 1972AB12, 1972AR18, 1972AR13, 1972AU03, 1972BA29, 1972BR1G, 1972BR1H, 1972CA08, 1972CA23, 1972CU03, 1972DA18, 1972DO11, 1972EH01, 1972EL13, 1972FR1B, 1972FR12, 1972GR1G, 1972GR1H, 1972GR1L, 1972HA57, 1972HA53, 1972JA24, 1972JE01, 1972KA38, 1972KR11, 1972KR1D, 1972LA12, 1972LA21, 1972LE1L, 1972LE27, 1972LO13, 1972MA57, 1972MC1C, 1972MI01, 1972MI07, 1972MU08, 1972NE06, 1972NE13, 1972NI14,

1972NI15, 1972PA32, 1972PL1C, 1972RA1C, 1972RE02, 1972RO06, 1972SA1B, 1972SA1E, 1972SH20, 1972ST02, 1972ST1C, 1972SU04, 1972TR1C, 1972TR05, 1972VA09, 1972WO04, 1972ZH1A, 1973AN1G, 1973AV03, 1973BA1Y, 1973BA1Q, 1973BE1K, 1973BO18, 1973CI1A, 1973CL09, 1973DA07, 1973DI1D, 1973DO1B, 1973EL04, 1973EL1D, 1973ER1C, 1973FA02, 1973FA09, 1973FA1H, 1973FE04, 1973FO1F, 1973GA03, 1973GA1H, 1973GO1T, 1973GR11, 1973GR30, 1973GR1H, 1973HA05, 1973HO08, 1973HO36, 1973IA1A, 1973KI08, 1973KO26, 1973KR1B, 1973KU02, 1973KU04, 1973KU03, 1973KU1G, 1973LA29, 1973LA35, 1973LO1C, 1973MA20, 1973MA1R, 1973MA48, 1973MU21, 1973NE1D, 1973PA15, 1973PA1K, 1973PE05, 1973PO1D, 1973RA1E, 1973RE17, 1973RO1R, 1973RO1P, 1973SA05, 1973SA32, 1973SC1M, 1973SC32, 1973SC1Q, 1973SH11, 1973SH14, 1973SI21, 1973SI1G, 1973SI1H, 1973SP1A, 1973ST21, 1973TR08, 1973WA35, 1973WE14, 1973ZA03, 1974AR04, 1974CO30, 1974DA1J, 1974DZ03, 1974EL01, 1974EL05, 1974FA1A, 1974FA1B, 1974FE1E, 1974FI03, 1974FI13, 1974GA27, 1974GO12, 1974GO1P, 1974GR03, 1974HO1J, 1974MA21, 1974MA1Q, 1974MC1G, 1974ME08, 1974MI03, 1974MI1H, 1974MP01, 1974NA13, 1974NE1H, 1974NE1J, 1974PA1G, 1974RE03, 1974RO38, 1974SA05, 1974SE1B, 1974SH1J, 1974SH1K, 1974SH10, 1974TI04, 1974TR08, 1974VA24, 1974WA15, 1974WE09, 1974WE1N, 1974WO02, 1974YA11, 1974ZA01, 1974ZA07, 1974ZA1E, 1974ZU1A, 1975BE05, 1975BE2E, 1975BE48, 1975BO1U, 1975CA1N, 1975EN01, 1975FL02, 1975FR06, 1975GI1H, 1975GO1W, 1975HA1Y, 1975HE10, 1975KH01, 1975KH1C, 1975KO1C, 1975KR1H, 1975KR02, 1975KU01, 1975LO1B, 1975LO05, 1975MA10, 1975MA33, 1975MC1L, 1975MC1H, 1975MI02, 1975MI1N, 1975NE1D, 1975PA1L, 1975RO26, 1975SC1M, 1975SH21, 1975SO04, 1975SO07, 1975SP08, 1975WE1C, 1976BL03, 1976BO1Z, 1976BO2B, 1976BR05, 1976BR1V, 1976CU06, 1976DA1D, 1976FA08, 1976FL09, 1976GO1R, 1976HO1L, 1976KI01, 1976KR14, 1976MA04, 1976NA10, 1976NI1E, 1976OS1F, 1976PA03, 1976PA14, 1976QU1B, 1976SA16, 1976SC03, 1976SI14, 1976VA1K, 1976VA1C, 1976WE1P).

*Ground state:* (1969BO1B, 1970BA1G, 1971AF02, 1971BO29, 1971DA15, 1971GR1L, 1971IR05, 1971LA13, 1971MO05, 1971MU08, 1971NA19, 1971RU12, 1971RY1A, 1971SC29, 1971ZO03, 1972AB05, 1972AB12, 1972AU03, 1972BE1E, 1972BR1G, 1972CA23, 1972CU03, 1972DA18, 1972EH01, 1972FR12, 1972GE05, 1972GR1K, 1972GR1H, 1972GR42, 1972JA18, 1972KR11, 1972KR1D, 1972LE1L, 1972NI14, 1972RO06, 1972TR1C, 1972VA09, 1972YO1B, 1973AR1C, 1973AV03, 1973BO18, 1973CA16, 1973DA07, 1973DO1B, 1973ER1C, 1973ER12, 1973FA09, 1973FA1F, 1973FO1F, 1973HO29, 1973HO32, 1973KO26, 1973KU02, 1973LA29, 1973LO1C, 1973NE1D, 1973PE05, 1973RO1P, 1973SP1A, 1973ST21, 1973TR08, 1973VA1D, 1974AD1C, 1974AR04, 1974BA1Z, 1974BE15, 1974BO31, 1974CO30, 1974DA1J, 1974DE1E, 1974EL01, 1974EN10, 1974FA1B, 1974FI04, 1974GA27, 1974HO1K, 1974JA1F, 1974KH01, 1974MA21, 1974MA1Q, 1974MI03, 1974MP01, 1974PA11, 1974PA1G, 1974RE03, 1974RO38, 1974SHYR, 1974SI13, 1974SO1E, 1974WA15, 1974ZA01, 1975AL19, 1975BE05, 1975BE31, 1975BU03, 1975CA1N, 1975FL02, 1975FR06, 1975GI1H, 1975HA1Y, 1975KH1C, 1975KU1N, 1975LE05, 1975MA2D, 1975MA33, 1975MA50, 1975MI02, 1975MP01, 1975PE07, 1975RA1T, 1975SA08, 1975SH21, 1975SP08, 1975ZA07, 1976BE1G, 1976CH1W, 1976CU06, 1976DO04, 1976FA08, 1976FL09, 1976KR14, 1976NA10, 1976PA03, 1976PA14, 1976SA1R, 1976ZA1F, 1976ZA07).

The mass of  $^{16}\text{O}$  derived from the work of (1975SM02) is 15.994914616 (22) a.m.u. Using the

Table 16.9: Energy levels of  $^{16}\text{O}$  <sup>a</sup>

$E_x$ (MeV $\pm$ keV)	$J^\pi; T$	$K^\pi$	$\tau_m$ or $\Gamma_{c.m.}$ (keV)	Decay	Reactions
0	$0^+; 0$		stable		2, 3, 4, 5, 12, 13, 14, 16, 17, 18, 19, 20, 21, 29, 30, 32, 33, 34, 35, 42, 44, 45, 51, 52, 54, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92
$6.0494 \pm 1.0$	$0^+; 0$	$0^+$	$\tau_m = 96 \pm 7$ psec	$\pi$	2, 12, 13, 14, 15, 16, 19, 20, 29, 33, 42, 44, 45, 52, 61, 64, 65, 68, 71, 72, 75, 76, 79, 81, 82, 83, 85, 89, 90
$6.13043 \pm 0.05$	$3^-; 0$		$\tau_m = 26.6 \pm 0.7$ psec $ g  = 0.55 \pm 0.03$	$\gamma$	2, 12, 13, 14, 16, 19, 20, 30, 33, 42, 43, 44, 45, 51, 52, 61, 62, 63, 64, 65, 67, 68, 71, 72, 75, 76, 79, 80, 81, 82, 83, 85, 86, 89, 90
$6.9171 \pm 0.6$	$2^+; 0$	$0^+$	$\tau_m = 6.00 \pm 0.03$ fsec	$\gamma$	2, 12, 13, 14, 15, 16, 19, 20, 30, 31, 33, 42, 43, 44, 45, 51, 52, 61, 63, 64, 66, 67, 68, 71, 72
$7.11685 \pm 0.14$	$1^-; 0$		$\tau_m = 12.0 \pm 1.2$ fsec	$\gamma$	2, 12, 13, 14, 19, 20, 30, 33, 42, 43, 44, 45, 51, 52, 61, 63, 64, 65, 68, 71, 72, 75, 79, 81, 82, 83, 85, 86, 91
$8.8719 \pm 0.5$	$2^-; 0$		$\tau_m = 180 \pm 16$ fsec	$\gamma, \alpha$	2, 12, 13, 14, 20, 30, 31, 42, 43, 45, 51, 52, 55, 63, 64, 65, 67, 68, 72, 79, 80, 81, 82, 85, 86, 89
$9.632 \pm 21$	$1^-; 0$	$0^-$	$\Gamma_{c.m.} = 510 \pm 60$	$\gamma, \alpha$	5, 10, 12, 13, 42, 52, 55
$9.847 \pm 3$	$2^+; 0$		$0.9 \pm 0.3$	$\gamma, \alpha$	2, 5, 10, 12, 13, 14, 30, 42, 43, 45, 51, 52, 55, 61, 64, 65, 67, 68, 81, 82, 83, 85, 89



Table 16.9: Energy levels of  $^{16}\text{O}$  <sup>a</sup> (continued)

$E_x$ (MeV $\pm$ keV)	$J^\pi, T$	$K^\pi$	$\tau_m$ or $\Gamma_{\text{c.m.}}$ (keV)	Decay	Reactions
10.353 $\pm$ 4	4 <sup>+</sup> ; 0	0 <sup>+</sup>	27 $\pm$ 4	$\gamma, \alpha$	2, 5, 10, 12, 13, 14, 15, 16, 19, 20, 30, 31, 42, 43, 45, 52, 61, 64, 65, 67, 68, 71, 72, 79, 81, 82, 83, 85, 89
10.952 $\pm$ 3	0 <sup>-</sup> ; 0		$\tau_m = 8 \pm 5$ fsec	$\gamma$	42, 51, 52, 64, 65, 81
11.080 $\pm$ 3	3 <sup>+</sup> ; 0		$\Gamma_{\text{c.m.}} < 12$	$\gamma$	2, 42, 45, 51, 52, 81
11.095 $\pm$ 2	4 <sup>+</sup> ; 0		0.28 $\pm$ 0.05	$\gamma, \alpha$	2, 5, 10, 12, 13, 16, 20, 30, 31, 42, 43, 45, 64, 65, 67, 68, 72, 85
11.26 <sup>b</sup>	0 <sup>+</sup> ; 0		2500	$\alpha$	10, 52, 82
11.52 $\pm$ 4	2 <sup>+</sup> ; 0		74 $\pm$ 4	$\gamma, \alpha$	2, 5, 10, 42, 61, 64, 65, 67, 68
11.60 $\pm$ 20	3 <sup>-</sup> ; 0	0 <sup>-</sup>	800 $\pm$ 10	$\alpha$	10, 13
12.053 $\pm$ 3	0 <sup>+</sup> ; 0		1.5 $\pm$ 0.5	$\gamma, \alpha$	10, 42, 61, 64, 65, 67, 68, 82
12.442 $\pm$ 5	1 <sup>-</sup> ; 0		98 $\pm$ 7	$\gamma, p, \alpha$	5, 7, 10, 42, 46, 47, 50, 51, 52, 65, 68
12.530 $\pm$ 1	2 <sup>-</sup> ; 0		0.8	$\gamma, p, \alpha$	2, 42, 46, 47, 50, 51, 52, 61, 64, 65, 68
12.797 $\pm$ 5	0 <sup>-</sup> ; 1		38 $\pm$ 4	p	42, 47, 51, 52
12.9686 $\pm$ 0.6	2 <sup>-</sup> ; 1		1.9 $\pm$ 0.2	$\gamma, p, \alpha$	42, 46, 47, 50, 51, 52, 61, 79, 80, 81
13.02 $\pm$ 10	2 <sup>+</sup>		150 $\pm$ 11	$\gamma, p, \alpha$	2, 5, 10, 47, 50, 61, 64, 65, 67, 68
13.094 $\pm$ 7	1 <sup>-</sup> ; 1		130 $\pm$ 5	$\gamma, p, \alpha$	5, 7, 10, 41, 42, 46, 47, 50, 51, 52, 61, 81
13.129 $\pm$ 10	3 <sup>-</sup> ; 0		110 $\pm$ 30	$\gamma, p, \alpha$	2, 5, 7, 10, 41, 43, 51, 52, 68
13.254 $\pm$ 5	3 <sup>-</sup> ; 1		21 $\pm$ 1	$\gamma, p, \alpha$	5, 7, 10, 42, 47, 50, 51, 52, 64, 79, 80, 81, 83
13.664 $\pm$ 3	1 <sup>+</sup> ; 0		64 $\pm$ 3	$\gamma, p, \alpha$	42, 46, 47, 50, 65
13.875 $\pm$ 6	4 <sup>+</sup> ; 0		75 $\pm$ 7	$\alpha$	2, 10, 42, 50, 68
13.979 $\pm$ 3	2 <sup>-</sup>		22 $\pm$ 2	p, $\alpha$	2, 42, 43, 47, 50, 64, 67, 69
14.032 $\pm$ 15	0 <sup>+</sup>		185 $\pm$ 35	$\gamma, \alpha$	10, 61
14.1 $\pm$ 100	3 <sup>-</sup>		750 $\pm$ 200	$\alpha$	10
14.30 $\pm$ 20			< 30		13, 30, 43
14.400 $\pm$ 3	$\geq 5$		$\leq 30$		2, 13, 30, 42, 43
(14.52)					30

Table 16.9: Energy levels of  $^{16}\text{O}$  <sup>a</sup> (continued)

$E_x$ (MeV $\pm$ keV)	$J^\pi, T$	$K^\pi$	$\tau_m$ or $\Gamma_{c.m.}$ (keV)	Decay	Reactions
14.63 $\pm$ 40	4 <sup>+</sup>		500 $\pm$ 100	$\alpha$	10
14.67 $\pm$ 40	5 <sup>-</sup>	0 <sup>-</sup>	560 $\pm$ 75	$\alpha$	10, 12, 13, 16, 20, 30
14.815 $\pm$ 2	6 <sup>+</sup> ; 0		67 $\pm$ 8	$\alpha$	2, 10, 30, 31, 43, 68
14.922 $\pm$ 6	4 <sup>+</sup>		51 $\pm$ 7	p, $\alpha$	2, 41, 42, 47, 50, 67, 68
15.107 $\pm$ 50	0 <sup>+</sup>		190 $\pm$ 30	$\alpha$	10, 31, 43
15.22 $\pm$ 35	2 <sup>-</sup>		70 $\pm$ 14	p, $\alpha$	47, 50, 79
15.25 $\pm$ 50	2 <sup>+</sup> ; (0)		650 $\pm$ 100	$\gamma$ , p, $\alpha$	46, 47, 50, 61
15.405 $\pm$ 20	3 <sup>-</sup> ; 0		95 $\pm$ 15	p, $\alpha$	7, 10, 41, 43, 47, 50, 64, 68, 79
15.8	3 <sup>-</sup>		$\approx$ 400	$\alpha$	10
15.838 $\pm$ 15			$\leq$ 80		2, 42, 43
15.9	2 <sup>+</sup>		$\approx$ 600	$\gamma$ , $\alpha$	5
16.214 $\pm$ 15	(4 <sup>+</sup> )		96 $\pm$ 16		2, 43
16.22 $\pm$ 15	1 <sup>+</sup> ; 1		18 $\pm$ 3	$\gamma$ , n, p	46, 47, 48, 61
16.29 $\pm$ 15	6 <sup>+</sup>	0 <sup>+</sup>	370 $\pm$ 40	$\alpha$	10, 12, 13, 15, 16, 20, 31, 41, 42, 82, 83
16.42 $\pm$ 25	2 <sup>+</sup>		35 $\pm$ 5	$\gamma$ , n, p, $\alpha$	5, 6, 7, 10, 31, 61, 64, 67, 68
16.8 $\pm$ 100	(3 <sup>+</sup> )		$\leq$ 100	$\gamma$	61
16.9	5 <sup>-</sup>		700	$\alpha$	10
(16.94)	2 <sup>+</sup>		$\approx$ 280	$\alpha$ , $^8\text{Be}$	11
(17.0)	1 <sup>-</sup> ; 1		$\approx$ 1400	$\gamma$ , p	46
17.14 $\pm$ 15	1 <sup>-</sup> ; 1		36 $\pm$ 5	$\gamma$ , n, p, $\alpha$	6, 7, 10, 43, 46, 47, 48, 52, 61
17.200 $\pm$ 20	2 <sup>+</sup>		160 $\pm$ 60	$\alpha$ , $^8\text{Be}$	2, 11, 42, 43, 52, 64, 67, 68
17.29 $\pm$ 15	1 <sup>-</sup> ; 1		90 $\pm$ 10	$\gamma$ , n, p, $\alpha$	6, 10, 46, 47, 48
17.55	(4 <sup>+</sup> )		165	n, $\alpha$	6, 10
17.64 $\pm$ 15	(2 <sup>-</sup> ); 1		59 $\pm$ 10	$\gamma$ , n, p, $\alpha$	7, 10, 48, 61
(17.7)	0 <sup>+</sup> , 2 <sup>+</sup>			$\alpha$ , $^8\text{Be}$	11
17.85 $\pm$ 20	4 <sup>+</sup>		100 $\pm$ 10	n, p, $\alpha$ , $^8\text{Be}$	2, 6, 10, 11, 42, 48, 64
18.018 $\pm$ 15	4 <sup>+</sup> ; 0		14	( $\gamma$ ), p, $\alpha$ , $^8\text{Be}$	7, 10, 11, 42, 46, 48
18.06 $\pm$ 15	(2 <sup>+</sup> , 4 <sup>+</sup> ); 1		26 $\pm$ 5	( $\gamma$ ), n, p, $\alpha$	6, 10, 46, 47, 48
18.15 $\pm$ 30	(2 <sup>+</sup> ; 0)		260 $\pm$ 50	( $\gamma$ ), n, p	5, 6, 48, 64, 67, 68
18.29			280	$\gamma$ , p, $\alpha$	5, 7, 10
18.4	5 <sup>-</sup>		510	$\alpha$	10
18.48 $\pm$ 25	2 <sup>+</sup>		60 $\pm$ 9	$\gamma$ , n, p, $\alpha$ , $^8\text{Be}$	2, 11, 48, 61, 64, 67, 68

Table 16.9: Energy levels of  $^{16}\text{O}$  <sup>a</sup> (continued)

$E_x$ (MeV $\pm$ keV)	$J^\pi, T$	$K^\pi$	$\tau_m$ or $\Gamma_{c.m.}$ (keV)	Decay	Reactions
18.6	( $1^-, 5^-$ )		140	$\alpha$	10, 48
18.69 $\pm$ 30	$3^-; 0$		280 $\pm$ 80		48, 64, 68
(18.75)	( $1^-$ )		55	$\alpha$	10
18.80	( $4^+$ )		220	n, p, $\alpha$ , $^8\text{Be}$	6, 7, 10, 11
18.94 $\pm$ 30	2, 4		< 16	$\gamma, p$	2, 46, 81
18.99 $\pm$ 30	$3^-; 1$		240	$\gamma, p$	46, 68
19.09 $\pm$ 30	$2^+; (1)$		120	$\gamma, p$	46, 47, 67
19.10 $\pm$ 50	( $4^+; 1$ )		41	n, ( $\alpha$ )	6, 10, 64
19.24 $\pm$ 20	$2^-; 1$		90 $\pm$ 10	$\gamma, n, p, \alpha$	6, 10, 46, 48, 64
(19.34)	$6^+$		50	$^8\text{Be}$	11
(19.39)	( $4^+, 0^+$ )		23	$\alpha$	10
19.48 $\pm$ 25	$1^-; 1$		250 $\pm$ 60	$\gamma, n, p, \alpha$	10, 46, 47, 48, 61
19.55 $\pm$ 30	( $3^-; 0$ )		240	n, $\alpha$	2, 6, 10, 64, 68
19.89 $\pm$ 20	$3; 0$		100 $\pm$ 30	$\gamma, n, p$	2, 46, 48, 80
19.91 $\pm$ 20	( $4^+$ )		825	$\alpha$	10
19.98	( $2^+, 0^+, 1^-$ )		140	$\alpha$	10
20.15 $\pm$ 100	$2^+; 0$		350 $\pm$ 50	$\gamma, n, \alpha$	5, 6, 67, 68
20.3			$\approx$ 1500	p, $\alpha$	7
20.36 $\pm$ 70	$2^-; 1$		500 $\pm$ 100	$\gamma$	61
20.43 $\pm$ 20	$\geq 2$		150 $\pm$ 30	$\gamma, n, p, \alpha$	6, 46, 48
(20.47)	( $4^+$ )		110	$\alpha$	10
20.54 $\pm$ 15	$\geq 1$		140 $\pm$ 30	n, p, $\alpha$	2, 10, 47, 48, 64
20.81			< 25	n, $\alpha$	6
20.88 $\pm$ 60	$7^-$	$0^-$	650 $\pm$ 75	$\alpha$	7, 9, 10, 11, 13
20.9 $\pm$ 100	$2^+; 0$	350 $\pm$ 50			10, 12, 13, 16
20.945 $\pm$ 20	$1^-; 1$		300 $\pm$ 10	$\gamma, n, p$	47, 48, 61
21.0	( $5^-$ )		900	$\alpha$	10
(21.01)			55	n, $\alpha$	6
21.03 $\pm$ 25	$1^-$		255 $\pm$ 60	$\gamma, \alpha$	5, 64, 68
(21.1)	( $6^+$ )		450	n, $\alpha$	6, 10
21.175 $\pm$ 15					2
21.50	( $1 \rightarrow 4$ )		120	p	47
21.67	( $T = 0$ )		< 50	n, p, $\alpha$	6, 47, 50
21.82 $\pm$ 70	$2^+; 0$		400 $\pm$ 50		64, 68
21.84 $\pm$ 25	6		55	n, $\alpha$	2, 6, 12
22.04			60	n, d, $\alpha$	6, 36
(22.07)			340	n, $\alpha$	6

Table 16.9: Energy levels of  $^{16}\text{O}$  <sup>a</sup> (continued)

$E_x$ (MeV $\pm$ keV)	$J^\pi, T$	$K^\pi$	$\tau_m$ or $\Gamma_{c.m.}$ (keV)	Decay	Reactions
22.146 $\pm$ 20	$1^-; 1$		675 $\pm$ 10	$\gamma, n, p$	46, 47, 48
22.2 $\pm$ 100			< 150	$\gamma, n, d, \alpha, ^8\text{Be}$	6, 11, 35, 40
22.35				$n, d, \alpha$	36, 40
22.46 $\pm$ 70	$(2^+, 3^-); 0$		450 $\pm$ 50	$n, d, \alpha$	6, 40, 64, 68
22.65 $\pm$ 30			60	$n, \alpha, ^8\text{Be}$	2, 6, 11
22.721 $\pm$ 3	$0^+; T = 2$		12.5 $\pm$ 2.5	$n, p, d, \alpha$	6, 7, 10, 33, 37, 40, 82
22.87 $\pm$ 30	$1^-; 1$		300 $\pm$ 15	$\gamma, p, d$	35, 46, 47
23.1	$6^+$		$\lesssim 500$	$d, \alpha, ^8\text{Be}$	11, 38
23.11			$\approx 20$	$d, \alpha, ^8\text{Be}$	10, 11, 40
23.22 $\pm$ 70	$2^+; 0$		400 $\pm$ 50		64, 68
23.50 $\pm$ 150			1700 $\pm$ 300	$\alpha$	10, 68
23.51 $\pm$ 30			300	$p, d, \alpha$	2, 10, 37, 38
23.85 $\pm$ 100	$(2^+, 0^+); 0$		400 $\pm$ 50	$n, \alpha$	6, 68
23.879 $\pm$ 6	$6^+$		26 $\pm$ 4	$p, \alpha, ^8\text{Be}$	7, 10, 11
24.0 $\pm$ 100			1200 $\pm$ 300		64
24.065 $\pm$ 35	$1^-; 1$		550 $\pm$ 40	$\gamma, p, ^3\text{He}, \alpha, ^8\text{Be}$	11, 21, 46
24.4 $\pm$ 100	$(2^+, 3^-)$		400 $\pm$ 50	$\alpha$	10, 68
24.522 $\pm$ 11	$2^+; 2$		< 50		33, 82
24.77 $\pm$ 60	$(2^+, 4^+; 1)$		340 $\pm$ 60	$\gamma, n, p, d, ^3\text{He}, \alpha$	27, 36, 37, 46
25.12 $\pm$ 50	$1^-; 1$		2900 $\pm$ 300	$\gamma, p, ^3\text{He}, \alpha$	10, 21, 46, 60
25.50 $\pm$ 150	$1^-; 1$		1330 $\pm$ 300		64
25.6	$(3^-); 1$		$\approx 350$	$^3\text{He}, \alpha$	10, 27
26.1 $\pm$ 100	$T = 1$		450	$\gamma, d, ^3\text{He}, \alpha$	10, 21, 27, 38, 40
26.3	$2^+$		1200	$\alpha$	10
26.42 $\pm$ 80	$(2^+); 1$		530 $\pm$ 80	$\gamma, p, ^3\text{He}$	21, 46
27.0	$(T = 1)$		broad	$d, ^3\text{He}, \alpha$	27, 40
27.4 $\pm$ 100	$(2^+, 4^+; 1)$		825 $\pm$ 110	$\gamma, p, d, ^3\text{He}, \alpha, ^8\text{Be}$	27, 28, 38, 46
27.6	$(3^-; 0)$		$\approx 500$	$p, d, ^3\text{He}, \alpha$	23, 26, 27, 38
29.7			broad	$d, \alpha$	10, 38
31.8 $\pm$ 600				$\gamma$	60
$\approx 35$	$3^-$		$\approx 5000$		64

<sup>a</sup> See also Tables 16.15 and 16.21.<sup>b</sup> Calculated from  $E_x$  of  $^{16}\text{O}^*(6.13)$  and the  $\Delta E$  of  $81.0 \pm 1.0$  keV between  $^{16}\text{O}^*(6.05, 6.13)$  (C.P. Browne, private communication).

conversion factor 931.5016 (26) MeV/a.m.u., the mass excess of  $^{16}\text{O}$  would then be  $-4737.04 \pm 0.02$  keV. (1971WA1E) quotes  $-4736.68 \pm 0.19$  keV which we shall continue to assume. See also (1971SM01).

$$\langle r^2 \rangle^{1/2} = 2.71 \pm 0.02 \text{ fm (1974DU02),}$$

$$\langle r^2 \rangle^{1/2} = 2.718 \pm 0.021 \text{ fm (1973FE13, 1975SC18).}$$

$$|g| = 0.55 \pm 0.03 \text{ for } {}^{16}\text{O}^*(6.13) \text{ (1973BR31, 1973RA09). See also (1976KA1N).}$$

1. (a) ${}^{10}\text{B}({}^6\text{Li}, \text{p}){}^{15}\text{N}$	$Q_m = 18.749$	$E_b = 30.877$
(b) ${}^{10}\text{B}({}^6\text{Li}, \text{d}){}^{14}\text{N}$	$Q_m = 10.140$	
(c) ${}^{10}\text{B}({}^6\text{Li}, \text{t}){}^{13}\text{N}$	$Q_m = 5.844$	
(d) ${}^{10}\text{B}({}^6\text{Li}, {}^3\text{He}){}^{13}\text{C}$	$Q_m = 8.8083$	
(e) ${}^{10}\text{B}({}^6\text{Li}, \alpha){}^{12}\text{C}$	$Q_m = 23.715$	

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  $2J_f + 1$ : 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  $2J_f + 1$  dependence (1966MC05). The yield curves for  $\alpha_0$  and  $\alpha_1$  (reaction (e)) measured at  $0^\circ$  for  $E({}^6\text{Li}) = 3.2$  to  $13.6$  MeV show broad structures. At  $90^\circ$ , for  $E({}^6\text{Li}) = 9.7$  to  $13.0$  MeV no structure is apparent, suggesting that the  $0^\circ$  yield is explainable in terms of Ericson fluctuations (1967SE08).

2.  ${}^{10}\text{B}({}^{10}\text{B}, \alpha){}^{16}\text{O}$   $Q_m = 26.417$

States of  ${}^{16}\text{O}$  observed at  $E({}^{10}\text{B}) = 20$  MeV are displayed in Table 16.10. The reaction excites known  $T = 0$  states:  $\sigma_t$  follows  $2J_f + 1$  for 11 of 12 groups leading to states of known  $J$ . The angular distributions show little structure (1976AJ02).

3.  ${}^{10}\text{B}({}^{14}\text{N}, {}^8\text{Be}){}^{16}\text{O}$   $Q_m = 14.711$

See (1971AJ02).

4.  ${}^{11}\text{B}({}^7\text{Li}, 2\text{n}){}^{16}\text{O}$   $Q_m = 12.170$

See (1971AJ02).

Table 16.10: States in  $^{16}\text{O}$  from  $^{10}\text{B}(^{10}\text{B}, \alpha)^{16}\text{O}$  (1976AJ02)

$E_x$ (MeV $\pm$ keV)	Corresponds to $^{16}\text{O}^*[J^\pi]$	$\sigma_t^b$ (mb)	Predicted $\sigma_t^c$ (mb)
0	0[0 <sup>+</sup> ]	0.2	$\equiv$ 0.2
6.088 $\pm$ 15	6.05[0 <sup>+</sup> ] + 6.13[3 <sup>-</sup> ]	1.6	1.6
6.904 $\pm$ 20	6.92[2 <sup>+</sup> ]	1.1	1.0
7.115 $\pm$ 20	7.12[1 <sup>-</sup> ]	0.6	0.6
$\equiv$ 8.8719	8.87[2 <sup>-</sup> ]	1.0	1.0
9.850 $\pm$ 15	9.85[2 <sup>+</sup> ]	1.5	1.0
10.361 $\pm$ 20	10.35[4 <sup>+</sup> ]	1.8	1.8
11.106 $\pm$ 20	10.95[0 <sup>-</sup> ] + 11.08[3 <sup>+</sup> ] + 11.10[4 <sup>+</sup> ]	4.3	3.2
11.54 $\pm$ 30	11.52[2 <sup>+</sup> ]	1.0	1.0
12.554 $\pm$ 15	12.53[2 <sup>-</sup> ]	1.2	1.0
13.14 $\pm$ 30	13.13[3 <sup>-</sup> ]		
d	13.66[1 <sup>+</sup> ]		
13.910 $\pm$ 20	13.88[4 <sup>+</sup> ]		
13.98 $\pm$ 30	13.98[2 <sup>-</sup> ]		
14.412 $\pm$ 15	14.30[?] + 14.40[> 5]	4.1	> 2.2
14.86 $\pm$ 30	14.82[6 <sup>+</sup> ] + 14.92[4 <sup>+</sup> ]	3.9	4.4
15.838 $\pm$ 15	15.84[?]	1.4 $\pm$ 0.3	
16.276 $\pm$ 20	16.21[(4 <sup>+</sup> )]		
17.200 $\pm$ 20	17.20[2 <sup>+</sup> ]		
17.825 $\pm$ 25	17.85[4 <sup>+</sup> ]		
d	18.02[(4 <sup>+</sup> )]		
18.531 $\pm$ 25	18.48[2 <sup>+</sup> ] + 18.6[1 <sup>-</sup> , 5 <sup>-</sup> ]		
18.69 $\pm$ 30	18.69[3 <sup>-</sup> ]		
d	18.80[(4 <sup>+</sup> )]		
18.90 $\pm$ 35			
d	18.99[3 <sup>-</sup> ]		
19.55 $\pm$ 35	19.55[(3 <sup>-</sup> )]		
19.91 $\pm$ 20	19.91[(4 <sup>+</sup> )]		
20.538 $\pm$ 15	20.54[ $\geq$ 1]		
21.175 $\pm$ 15			
21.84 $\pm$ 25	21.84[6]		

Table 16.10: States in  $^{16}\text{O}$  from  $^{10}\text{B}(^{10}\text{B}, \alpha)^{16}\text{O}$  (1976AJ02) (continued)

$E_x$ (MeV $\pm$ keV)	Corresponds to $^{16}\text{O}^*[J^\pi]$	$\sigma_t$ <sup>b</sup> (mb)	Predicted $\sigma_t$ <sup>c</sup> (mb)
22.65 $\pm$ 30			
23.51 $\pm$ 30	23.51[?]		

<sup>a</sup> Very broad states in  $^{16}\text{O}$  are assumed not to contribute appreciably to the strength of the alpha group from which an appropriate smooth background has been subtracted.

<sup>b</sup> From integrating angular distribution over forward and back hemispheres, by folding the available data at  $\theta_{c.m.} = 90$ : estimated uncertainties  $\pm 20\%$ , except for  $^{16}\text{O}^*(15.84)$ .

<sup>c</sup> Predicted  $\sigma$  based on  $2J_f + 1$ , assuming that the states listed in col. 2 are involved and that  $\sigma_t$  for a  $J = 0$  state is 0.2 mb.

<sup>d</sup> Unresolved in this work.

5.  $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$   $Q_m = 7.1616$

The yield of capture  $\gamma$ -rays has been studied for  $E_\alpha < 27.5$  MeV: see Table 16.11. Observed resonances are displayed in Table 16.12.

This reaction plays an important role in astrophysical processes. (1974DY02) has determined  $\sigma_{E1}$  for  $E_\alpha = 1.88$  to 3.92 MeV. From these data  $S(E_\alpha(\text{lab}) = 400 \text{ keV}) = 0.08_{-0.04}^{+0.05} \text{ MeV} \cdot \text{b}$  (1974KO06) [used a hybrid  $R$ -matrix-optical model analysis ( $\alpha, \gamma$ ) and ( $\alpha, \alpha$ )],  $0.08_{-0.07}^{+0.14} \text{ MeV} \cdot \text{b}$  (1976HU1H) [used a two channel, two level approximation of a modified  $K$ -matrix]. See also (1971BA99, 1974WE14). (1974DY02) state that  $S$  depends quite strongly on  $\theta_\alpha^2(6.92)/\theta_\alpha^2(7.12)$ :  $S$  may have to be increased to allow for the tail of  $^{16}\text{O}^*(6.92)$ . For astrophysical considerations see (1974DY02) and (1971BA1A, 1971BI1H, 1973AR1E, 1973CL1E, 1973IB1B, 1974BA1X, 1975FO19, 1976AU1F, 1976SC1M), in addition to the references listed above and in (1971AJ02).

Upper limits of the parity forbidden  $\alpha$ -decay of  $^{16}\text{O}^*(10.95, 11.08)$  [ $J^\pi = 0^-$ ;  $T = 0$  and  $3^+$ ; 0, respectively] are  $< 6 \times 10^{-4} \text{ eV}$  and  $< 5 \times 10^{-4} \text{ eV}$ , respectively (1974BE32). See also (1974DA22) and (1973GA23; theor.).

At higher energies the E2 cross section shows resonances at  $E_x = 13.2, 15.9, 16.5, 18.3, 20.0$  and 26.5 MeV [see Table 16.12]. Some E2 strength is also observed for  $E_x = 14$  to 15.5 and 20.5 to 23 MeV. In the range  $E_\alpha = 7$  to 27.5 MeV the  $T = 0$  E2 strength is  $\approx 17\%$  of the sum rule. It appears from this and other experiments that the E2 centroid is at  $E_x \approx 15$  MeV, with a 15 MeV spread (1974SN02). See also (1969OM1A), (1973HA1Q, 1973HA1Y), (1975RA02; theor.) and (1971AJ02) for the earlier work.

6.  $^{12}\text{C}(\alpha, n)^{15}\text{O}$   $Q_m = -8.508$   $E_b = 7.1616$

Table 16.11: Recent  $^{12}\text{C} + \alpha$  yield measurements <sup>a</sup>

$E_\alpha$ (MeV)	Yield of	Refs.
1.88 $\rightarrow$ 3.92	$\gamma_0$	(1974DY02)
2.9 $\rightarrow$ 4.1	$\gamma_0$	(1970JA24)
7.0 $\rightarrow$ 27.5	$\gamma_0$	(1974SN02)
7.6 $\rightarrow$ 8.1	$\gamma_0$	(1971KE09)
2 $\rightarrow$ 9	n ( <sup>nat</sup> C)	(1973BA2D)
13 $\rightarrow$ 16	n <sub>0</sub>	(1971BE07)
8.5 $\rightarrow$ 10.5	p	(1971OP01)
11.3 $\rightarrow$ 17.9	p <sub>0</sub>	(1971ZE01)
13 $\rightarrow$ 16	p <sub>0</sub>	(1971BE07)
20.2 $\rightarrow$ 21.4	p <sub>0</sub>	(1973AD1B)
20.7 $\rightarrow$ 20.8	p <sub>0</sub> , p <sub>1+2</sub>	(1972NE10)
22.8 $\rightarrow$ 27	p $\gamma_{10.6}$	(1975SP04)
3 $\rightarrow$ 10	$\alpha_0$	(1974DA22, 1975DA1D)
4.0 $\rightarrow$ 13.3	$\alpha_0$	(1972MA01)
5.22 $\rightarrow$ 5.27	$\alpha_0$	(1975BR06)
8.5 $\rightarrow$ 10.5	$\alpha_0, \alpha_1, \alpha_1\gamma$	(1971OP01, 1973MA03)
10.0 $\rightarrow$ 10.3	$\alpha_0, \alpha_1$	(1971BE50, 1971RA24)
15.8 $\rightarrow$ 20.1	$\sigma_t$	(1973LA16)
16.1 $\rightarrow$ 17.2	$\alpha_2$	(1976GL1D)
18.0 $\rightarrow$ 26.6	$\alpha_0$	(1973KU18)
20 $\rightarrow$ 27	$\gamma_{12.71}$	(1975SP04)
20.7 $\rightarrow$ 20.8	$\alpha_0, \alpha_1, \alpha_2$	(1972NE10)
22 $\rightarrow$ 27	$\gamma_{15.11}$	(1975SP04)
$E(^{16}\text{O}) = 6.72$ to $6.98$	$\alpha_0$	(1976MC1K)
0.87 and 2.1 GeV/nucleon	$\sigma_t$	(1975JA1A)
15.0 $\rightarrow$ 19.0	$^8\text{Be}$	(1972MA53)
18.5 $\rightarrow$ 23.0	$^8\text{Be}$	(1974JA21)
19.0 $\rightarrow$ 26.5	$^8\text{Be}$	(1973BR1H)
17 $\rightarrow$ 33	$^8\text{Be}$	(1976BR07)
63 $\rightarrow$ 68	$^8\text{Be}$	(1974JE1A)

<sup>a</sup> For the earlier work see Table 16.10 in (1971AJ02).



Table 16.12: Resonances in  $^{12}\text{C} + \alpha$ 

$E_\alpha$ (MeV $\pm$ keV)	$\Gamma_{\text{c.m.}}$ (keV)	Outgoing particles <sup>a</sup> (x)	$\Gamma_x$	$\Gamma_{\alpha_0}/\Gamma$	$^{16}\text{O}^*$ (MeV)	$J^\pi; T$	Refs. <sup>b</sup>	
$3.322 \pm 30$	550	$\gamma_0$	$23 \pm 3$ meV	$\approx 1$	8.87 <sup>i</sup>	$1^-$	(1976MC1K) (1974KO06, 1975DA1D)	
		$\alpha_0$			9.65 <sup>c</sup>			
$3.575 \pm 10$	$0.9 \pm 0.3$	$\gamma_0$	$5.9 \pm 0.6$ meV		9.842	$2^+$	(1970BR14, 1976MC1K)	
		$\gamma_3$	$2.2 \pm 0.4$ meV					
		$\alpha_0$						
$4.256 \pm 11$	$27 \pm 4$	$\gamma_0$	$58 \pm 7$ meV	1	10.353	$4^+$	(1972MA01, 1975CH30)	
		$\gamma_3$						
		$\alpha_0$						
$5.245 \pm 8$	$0.28 \pm 0.05$	$\gamma_2$	$3.1 \pm 1.3$ meV		11.094	$4^+$	(1975BR06)	
		$\gamma_3$	$2.5 \pm 0.6$ meV					
		$\alpha_0$						
5.47	2500	$\alpha_0$			11.26	$0^+$	(but see 1972MA01)	
$5.809 \pm 18$	$73 \pm 5$	$\gamma_0$	$0.65 \pm 0.08$ eV		11.52	$2^+$	(1970BR14, 1972MA01)	
		$\gamma_3$	$29 \pm 7$ meV					
		$\alpha_0$		1				
$5.92 \pm 20$	$800 \pm 100$	$\alpha_0$		1	11.60	$3^-$	(1954BI1A, 1972MA01, 1974DA22)	
$6.518 \pm 10$	$1.5 \pm 0.5$	$\alpha_0$			12.049	$0^+$		
$7.045 \pm 5$	$99 \pm 7$	$\gamma_0$	$9.5 \pm 1.7$ eV <sup>d</sup>		12.444	$1^-; 0$	(1972MA01, 1973BR19, 1975DA1D)	
		$\gamma_1$	$0.12 \pm 0.06$ eV <sup>d</sup>					
		p	1.1 keV					
		$\alpha_0$	$92 \pm 8$ keV	1.0				
		$\alpha_1$	0.025 keV					
$7.82 \pm 10$	$150 \pm 11$	$\gamma_0$	<sup>e</sup>		13.02 <sup>k</sup>	$2^+$	(1971KE09, 1972MA01, 1974SN02)	
		$\alpha_0$	$150 \pm 11$ keV	0.8				
$7.915 \pm 10$	$130 \pm 5$	$\gamma_0$	$44 \pm 8$ eV <sup>f</sup>		13.096	$1^-; 1$	(1971KE09, 1972MA01, 1973BR19)	
		$\gamma_4$	$1.35 \pm 0.4$ eV					
		p	100 keV					

Table 16.12: Resonances in  $^{12}\text{C} + \alpha$  (continued)

$E_\alpha$ (MeV $\pm$ keV)	$\Gamma_{\text{c.m.}}$ (keV)	Outgoing particles <sup>a</sup> (x)	$\Gamma_x$	$\Gamma_{\alpha_0}/\Gamma$	$^{16}\text{O}^*$ (MeV)	$J^\pi; T$	Refs. <sup>b</sup>
7.960 $\pm$ 10	110 $\pm$ 30	$\alpha_0$	45 $\pm$ 18 keV	0.3	13.129	3 <sup>-</sup> ; 0	(1971KE09, 1972MA01)
		$\alpha_1$	1 keV				
		$\gamma_0$	> 0.01 eV				
8.130 $\pm$ 15	26 $\pm$ 7	p	1 keV	0.7	13.257	3 <sup>-</sup> ; 1	
		$\alpha_0$	90 $\pm$ 14 keV				
		$\alpha_1$	$\approx$ 20 keV				
		$\gamma$					
8.960 $\pm$ 10	75 $\pm$ 7	p	4.5 keV	0.65 $\pm$ 0.05	13.879 $\pm$ 8	4 <sup>+</sup>	(1971OP01, 1972MA01, 1973MA03, 1975DA1D)
		$\alpha_0$	9 $\pm$ 4 keV				
		$\alpha_1$	7.5 keV				
		$\gamma_{4.4}$					
9.1	4800	$\alpha_0$	23 keV		14.0	0 <sup>+</sup>	(1968CL04)
9.164 $\pm$ 15	200 $\pm$ 50	$\alpha_0$	$\approx$ 200 keV	> 0.9	14.032	0 <sup>+</sup>	(1971OP01, 1972MA01, 1973MA03)
9.3 $\pm$ 100	750 $\pm$ 200	$\alpha_0$		0.2 $\pm$ 0.1	14.1	3 <sup>-</sup>	(1973MA03)
9.96 $\pm$ 40	500 $\pm$ 100	$\alpha_1$		0.8 $\pm$ 0.1	14.63	4 <sup>+</sup>	(1972MA01, 1973MA03)
		$\alpha_0$					
10.02 $\pm$ 40 <sup>g</sup>	650 $\pm$ 100	$\alpha_1$		$\approx$ 0.95	14.67	5 <sup>-</sup>	(1973MA03)
10.195 $\pm$ 7 <sup>g</sup>	70 $\pm$ 8	$\alpha_0$	22 keV	0.45 $\pm$ 0.05	14.805	6 <sup>+</sup>	(1971BE50, 1971OP01, 1971RA24, 1972KE18, 1973MA03)
		$\alpha_1$	48 keV				
10.68 $\pm$ 50	190 $\pm$ 30	$\alpha_0$			15.17	0 <sup>+</sup>	(1972MA01)
11.05 $\pm$ 20	100 $\pm$ 20	p <sub>0</sub> , $\alpha_0$ , $\alpha_1$ , $\gamma_{4.4}$		0.6	15.45	3 <sup>-</sup>	(1972MA01)

Table 16.12: Resonances in  $^{12}\text{C} + \alpha$  (continued)

$E_\alpha$ (MeV $\pm$ keV)	$\Gamma_{\text{c.m.}}$ (keV)	Outgoing particles <sup>a</sup> (x)	$\Gamma_x$	$\Gamma_{\alpha_0}/\Gamma$	$^{16}\text{O}^*$ (MeV)	$J^\pi; T$	Refs. <sup>b</sup>
11.5	$\approx 400$	$\alpha_0, \alpha_1, \gamma_{4.4}$			15.8	$3^-$	
11.6	$\approx 600$	$\gamma_0$			15.9	$2^+$	(1974SN02)
		$\Gamma_\alpha \Gamma_\gamma / \Gamma \approx 0.4 \text{ eV}$					
$12.18 \pm 40$	$490 \pm 40$	$\alpha_0$			16.29	$6^+$	(1972MA01)
$12.32 \pm 25$	45	$\gamma_0, \text{n}, \text{p}_0, \alpha_0, \alpha_1, \gamma_{4.4}$			16.40 <sup>h</sup>	$2^+$	(1974SN02)
		$\Gamma_\alpha \Gamma_\gamma / \Gamma = 0.45 \text{ eV}$					
12.5	730	$\text{p}_0, \alpha_0$			16.5		
12.9	400	$\alpha_0$			16.8	$(4^+)$	
13.0	700	$\alpha_0$			16.9	$5^-$	
13.05	$\approx 280$	$^8\text{Be}$			16.94	$2^+$	
13.26	110	$\text{n}, (\text{p}_0), \alpha_0, \alpha_1, \gamma_{4.4}$			17.10	$(1^-, 2^+, 0^+)$	
13.35	200	$^8\text{Be}$			17.17	$2^+$	
13.50	$< 100$	$\text{n}$			17.28		
13.59	150	$\alpha_1, \gamma_{4.4}$			17.35		
13.86	165	$\text{n}, \alpha_0$			17.55	$(4^+)$	
13.95	120	$\text{p}_0, \alpha_0$			17.62		(1971BE07)
14.1		$^8\text{Be}$			17.7	$0^+, 2^+$	
14.21	225	$\text{n}, \alpha_1, \gamma_{4.4}, ^8\text{Be}$			17.81	$4^+$	
$14.483 \pm 15$	14	$\text{p}_0, \alpha_0, \alpha_1, ^8\text{Be}$			18.018	$4^+; 0$	
14.50	40	$\text{n}, \alpha_0, \alpha_1, \gamma_{4.4}$			18.03	$(4^+)$	
$14.6 \pm 100$	$220 \pm 60$	$(\gamma_0), \text{n}_0$			18.1 <sup>h</sup>	$(2^+; 0 + 1)$	(1971BE07)
14.85	280	$\gamma_0, \text{p}_0, (\alpha_0), \alpha_1, \gamma_{4.4}$			18.29 <sup>h</sup>		(1974SN02)
		$\Gamma_\alpha \Gamma_\gamma / \Gamma = 0.95 \text{ eV}$					
15.0	510	$\alpha_0, (\alpha_1, \gamma_{4.4})$			18.4	$5^-$	
15.2		$^8\text{Be}$			18.6	$0^+, 2^+$	
15.2	140	$\alpha_0, (\alpha_1, \gamma_{4.4})$			18.6	$(1^-, 5^-)$	
15.46	55	$\alpha_0$			18.75	$(1^-)$	

Table 16.12: Resonances in  $^{12}\text{C} + \alpha$  (continued)

$E_\alpha$ (MeV $\pm$ keV)	$\Gamma_{\text{c.m.}}$ (keV)	Outgoing particles <sup>a</sup> (x)	$\Gamma_x$	$\Gamma_{\alpha_0}/\Gamma$	$^{16}\text{O}^*$ (MeV)	$J^\pi; T$	Refs. <sup>b</sup>
15.52	220	n, p <sub>0</sub> , $\alpha_0$ , $\alpha_1$ , $^8\text{Be}$			18.80	(4 <sup>+</sup> )	
15.88	broad	$\alpha_1$ , $\gamma_{4.4}$			19.06		
15.96	41	(n), $\alpha_0$			19.12	(2 <sup>+</sup> , 4 <sup>+</sup> )	
16.13	23	(n), $\alpha_0$			19.25	(5 <sup>-</sup> )	
16.25	50	$^8\text{Be}$ , ( $\alpha_2$ )			19.34	6 <sup>+</sup>	(1976GL1D)
16.30	23	$\alpha_0$			19.39	(4 <sup>+</sup> , 0 <sup>+</sup> )	
16.4	broad	$\alpha_1$ , $\alpha_2$			19.5		(1976GL1D)
16.62	240	n			19.62		
16.73	17	$\alpha_0$			19.70	even	
17.0	825	$\alpha_0$ , $\alpha_2$			19.9	(4 <sup>+</sup> )	(1976GL1D)
17.10	140	$\alpha_0$ , $\alpha_1$			19.98	(2 <sup>+</sup> , 0 <sup>+</sup> , 1 <sup>-</sup> )	
17.22	310	$\gamma_0$ , n			20.07	2 <sup>+</sup>	(1974SN02)
17.5	$\approx 1500$	p <sub>0</sub>			20.3		
17.66	< 150	n			20.40		
(17.75)	110	$\alpha_0$			(20.47)	(4 <sup>+</sup> )	
17.90		$\alpha_1$			20.58		
18.21	< 25	n			20.81		
18.4	750	$\alpha_0$			21.0	7 <sup>-</sup>	
18.48	55	n			21.01		
18.50 $\pm$ 25	240 $\pm$ 80	$\gamma_0$			21.03 <sup>h</sup>	1 <sup>-</sup>	
18.5	900	$\alpha_0$			21.0	(5 <sup>-</sup> )	
(18.6)	450	n, $\alpha_0$ , $\alpha_1$			(21.1)	(6 <sup>+</sup> )	
19.37	55	n			21.68		
19.52	55	n			21.79		
19.85	60	n			22.04		
19.89	340	n			22.07		
19.95	< 150	n, $^8\text{Be}$			22.11		(1974JA21)

Table 16.12: Resonances in  $^{12}\text{C} + \alpha$  (continued)

$E_\alpha$ (MeV $\pm$ keV)	$\Gamma_{\text{c.m.}}$ (keV)	Outgoing particles <sup>a</sup> (x)	$\Gamma_x$	$\Gamma_{\alpha_0}/\Gamma$	$^{16}\text{O}^*$ (MeV)	$J^\pi; T$	Refs. <sup>b</sup>
20.49	375	n			22.52		
20.71	60	n, $^8\text{Be}$			22.68		(1974JA21)
20.760 $\pm$ 5	12.5 $\pm$ 2.5	$n_0, p_0, \alpha_0, \alpha_2$			22.721	$0^+; T = 2$	(1972NE10, 1973AD1B)
21.28	$\approx 20$	$\alpha_0, \alpha_1, ^8\text{Be}$			23.11		(1974JA21)
21.3	$\lesssim 500$	$^8\text{Be}$			23.1	$6^+$	(1974JA21)
21.67	$< 40$	n			23.40		
21.85	300	$\alpha_0, \alpha_1$			23.54		
22.0	1500	$\gamma_{12.71}$			23.6		(1975SP04)
22.14	120	n			23.75		
22.306 $\pm$ 6	26 $\pm$ 4	$p_0, \alpha_0, \alpha_1, \alpha_2, ^8\text{Be}$	j	0.06 $\pm$ 0.02	23.879	$6^+$	(1974JA21, 1976BR07)
22.37	165	n			23.93		
22.75	$\lesssim 500$	$^8\text{Be}$			24.21		(1974JA21)
23.2	750	$\gamma_{12.71}, \gamma_{15.11}$			24.5	$T = 1$	(1975SP04)
24.1	450	$\gamma_{15.11}$			25.2	$T = 1$	(1975SP04)
24.6	450	$\gamma_{15.11}$			25.6	$T = 1$	(1975SP04)
25.5	450	$\gamma_{15.11}$			26.3	$T = 1$	(1975SP04)
25.6	1200	$\alpha_0, \gamma_{12.71}$ $\Gamma_\alpha \Gamma_\gamma / \Gamma = 1.2 \text{ eV}$			26.3	$2^+$	(1974SN02, 1975SP04)
30	broad	$\alpha_0, \alpha_1$			30		

<sup>a</sup>  $p_0$  corresponds to  $^{15}\text{N}(0)$ .  $\alpha_0, \alpha_1$  correspond to  $^{12}\text{C}^*(0, 4.4)$  and  $\gamma_{4.4}$  corresponds to the  $\gamma$ -ray from the decay of  $^{12}\text{C}^*(4.4)$ ;  $\gamma_0, \gamma_1, \gamma_2, \gamma_3, \gamma_4$  correspond to the transitions to  $^{16}\text{O}^*(0, 6.05, 6.13, 6.92, 7.12)$ .

<sup>b</sup> See also Table 16.11 in (1971AJ02).

<sup>c</sup>  $\theta_\alpha^2(7.12)/\theta_\alpha^2(9.63) = 0.19_{-0.11}^{+0.16}$  (1974KO06).

<sup>d</sup> Branching ratios to  $^{16}\text{O}^*(0, 6.05) = 98.8\%$  and  $1.2\%$ .

<sup>e</sup>  $\Gamma_{\gamma_0} = 0.7 \pm 0.2$  eV (1971KE09), based on  $\Gamma_{\alpha_0}/\Gamma = 1.0$  (1968MO08) and  $\Gamma_{\text{c.m.}} = 190 \pm 40$  keV (1971KE09). See also (1974SN02).

<sup>f</sup>  $\Gamma_{\alpha_0}\Gamma_{\gamma_0}/\Gamma^2 = (1.49 \pm 0.17) \times 10^{-4}$  (1971KE09).

<sup>g</sup> See also (1972MA01).

<sup>h</sup>  $\Gamma_\gamma\Gamma_\alpha/\Gamma = 0.2, 0.7$  and  $6$  eV, respectively, for  $^{16}\text{O}^*(16.42, 18.18, 20.9)$  (1967SU02).

<sup>i</sup> An attempt is reported by (1976MC1K) to observe a  $0^+$  state in the vicinity of the known  $2^-$  state at  $8.87$  MeV: no such state exists with  $8.842 < E_x < 8.907$  MeV [this region was covered in  $0.5$  keV steps, with  $1.5$  to  $3\%$  statistics for the  $\alpha_0$  yield].

<sup>j</sup>  $\Gamma_{\text{sBe}}, \Gamma_{\alpha_0}$  and  $\Gamma_{\alpha_2} \approx 3.5, 1.5 \pm 0.5$  and  $\approx 6$  keV, respectively (1976BR07).

<sup>k</sup> The previously reported  $2^+$  state at  $13.14$  MeV (see 1971AJ02) appears to be identical to this level: a revised value for the width of that state is  $\Gamma_{\text{c.m.}} \approx 180$  keV (F.C. Barker, private communication).

Cross section measurements have been made from threshold to  $E_\alpha = 24.7$  MeV: see (1971AJ02) and Table 16.11. Observed resonances are displayed in Table 16.12. The resonance in  $n_0$  at  $E_\alpha = 14.6$  MeV ( $^{16}\text{O}^*(18.1)$ ) does not appear in the  $p_0$  yield: a large isospin mixing is suggested for that state (1971BE07). An anomaly is observed in the  $n_0$  yield corresponding to formation of the first  $T = 2$  state in  $^{16}\text{O}$  [ $^{16}\text{O}^*(22.7)$ ] (1973AD1B). See also  $^{15}\text{O}$  in (1976AJ04).

$$7. \text{}^{12}\text{C}(\alpha, \text{p})^{15}\text{N} \qquad Q_{\text{m}} = -4.9661 \qquad E_{\text{b}} = 7.1616$$

The yield of protons corresponding to  $^{15}\text{N}(0)$  has been studied for  $E_\alpha = 7.7$  to 23 MeV: see Table 16.10 in (1971AJ02) and Table 16.11 here. (1975SP04) have measured the yield of 10.6 MeV  $\gamma$ -rays [from  $^{15}\text{N}^*(10.45 \rightarrow 10.80)$ ] at  $E_\alpha = 22.8$  to 27 MeV. Observed resonances are displayed in Table 16.12. An anomaly is observed in the  $p_0$  yield corresponding to formation of the  $T = 2$  state  $^{16}\text{O}^*(22.7)$ : see (1973AD1B) and (1972WE03). See also  $^{15}\text{N}$  in (1976AJ04).

$$8. \text{}^{12}\text{C}(\alpha, \text{d})^{14}\text{N} \qquad Q_{\text{m}} = -13.5751 \qquad E_{\text{b}} = 7.1616$$

See  $^{14}\text{N}$  in (1976AJ04) and (1974BE41).

$$9. \text{(a) } ^{12}\text{C}(\alpha, \text{t})^{13}\text{N} \qquad Q_{\text{m}} = -17.871 \qquad E_{\text{b}} = 7.1616$$

$$\text{(b) } ^{12}\text{C}(\alpha, \text{}^3\text{He})^{13}\text{C} \qquad Q_{\text{m}} = -15.6321$$

See  $^{13}\text{N}$  and  $^{13}\text{C}$  in (1976AJ04) and (1974BE41).

$$10. \text{}^{12}\text{C}(\alpha, \alpha)^{12}\text{C} \qquad E_{\text{b}} = 7.1616$$

The yield of  $\alpha$ -particles corresponding to  $^{12}\text{C}^*(0, 4.4)$  and of 4.4, 12.7 and 15.1 MeV  $\gamma$ -rays has been studied at many energies in the range 2.5 to 35.5 MeV: see Table 16.11. Observed resonances are displayed in Table 16.12. The parameters of the first  $T = 2$  state of  $^{16}\text{O}$  at  $E_x = 22.7$  MeV observed as anomalies in the  $\alpha_0$  and  $\alpha_2$  yields are displayed in Table 16.12 (1972NE10). Astrophysical considerations are discussed in reaction 5. See also (1971LE33, 1974KO06, 1974WE14, 1975ME1E, 1975ST1K, 1976GL1D, 1976HU1H).

For angular correlation measurements see (1972BU09, 1972KE18). For differential cross section measurements at  $E_\alpha = 58$  MeV see (1974BE41). For polarization parameters see (1972BU09). For  $\pi^0$  emission at  $E_\alpha = 710$  MeV see (1976WA1P). For spallation measurements see (1971FO06, 1971LE33, 1972RU03, 1974GA1K, 1974RA11, 1975FU01, 1975RA12).

See also (1974JA1M, 1974SL01, 1974WI05), (1972HO56, 1973DU1B, 1973FA1G, 1973IC01, 1973SC1N, 1973TE02, 1974HO19, 1974KH05, 1974WA1D, 1975BA05, 1975CU1B, 1975HA30, 1975KU1K, 1975SU1F, 1976BO1Y, 1976HU07, 1976SA1N; theor.),  $^{12}\text{C}$  in (1975AJ02) and (1971AJ02).

11. (a) $^{12}\text{C}(\alpha, ^8\text{Be})^8\text{Be}$	$Q_m = -7.4587$	$E_b = 7.1616$
(b) $^{12}\text{C}(\alpha, 2\alpha)^8\text{Be}$	$Q_m = -7.3667$	
(c) $^{12}\text{C}(\alpha, 4\alpha)$	$Q_m = -7.2748$	

The yield of  $^8\text{Be}$  (reaction (a)) shows a number of resonances: see Table 16.12. There is no evidence below  $E_x \approx 24$  MeV for  $J^\pi = 8^+$  states although the existence of such states below this energy cannot be ruled out since it is possible that the  $L$  of the entrance channel inhibits the formation of such states. Above 26 MeV  $L = 8$  becomes dominant (1976BR07). See also (1972SU04; theor.) and (1971AJ02). For reaction (b) see (1975CO1C). For reaction (c) see (1970KL10, 1973RU09). See also  $^{12}\text{C}$  in (1975AJ02) and  $^8\text{Be}$  in (1974AJ01).

12. $^{12}\text{C}(^6\text{Li}, \text{d})^{16}\text{O}$	$Q_m = 5.6879$
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This reaction has been studied at many energies for  $E(^6\text{Li}) < 42$  MeV and  $E(^{12}\text{C}) = 18$  to 24 MeV: see Table 16.13 in (1971AJ02). Angular distributions are also reported at  $E(^6\text{Li}) = 32$  MeV [(1974DE16: to  $^{16}\text{O}^*(10.35, 11.10)$ ), (1972BA2B: to  $^{16}\text{O}^*(10.35)$ )], at 32.5 and 35.5 MeV (1975GO15: to  $^{16}\text{O}^*(10.35, 14.6, 16.3, 20.9)$ ) and at 42 MeV (1976JA1Q; to most states with  $E_x < 16$  MeV). At the higher energies the spectra are dominated by states with  $J \geq 4$  (and natural parity). Among these are states with  $E_x = 10.346 \pm 0.006$ ,  $16.304 \pm 0.020$  and  $20.88 \pm 0.06$  MeV [ $\Gamma_{\text{cm}} < 50$ ,  $360 \pm 40$  and  $720 \pm 100$  keV] and  $J^\pi = 4^+$ ,  $(6^+)$ ,  $(8^+)$  (1971BA31). Angular correlation (d,  $\alpha_0$ ) measurements agree with the  $6^+$  assignment for  $^{16}\text{O}^*(16.3)$  [ $\Gamma_{\text{cm}} = 370 \pm 50$  keV] (1971AR36, 1972AR1G) but show that  $^{16}\text{O}^*(20.9)$  [ $\Gamma_{\text{cm}} = 590 \pm 100$  keV] is a  $7^-$  state (1971AR36, 1972AR1G, 1975AV02). A state at  $E_x = 21.8$  MeV is reported by (1975AV02):  $J = 6$ . Angular correlations also suggest  $J^\pi = 5^-$  for a state with  $E_x = 14.6 \pm 0.1$  MeV,  $\Gamma_{\text{cm}} = 480 \pm 100$  keV (1971AR36, 1975AR1N): the branching ratios for the decay of  $^{16}\text{O}^*(14.6, 16.3, 20.9)$  to  $^{12}\text{C}_{\text{g.s.}}$  is  $85 \pm 10$ ,  $80 \pm 10$  and  $90 \pm 10$  %, respectively (1971AR36, 1972AR1G, 1975AR1N).

At  $E(^6\text{Li}) = 32$  MeV the  $\sigma(11.10)/\sigma(10.35) \approx 0.5$  even though the ratio of the reduced widths of these two  $4^+$  states to  $^{12}\text{C}_{\text{g.s.}}$   $S_\alpha(11.10)/S_\alpha(10.35) < 10^{-2}$ : a two step process via  $^{12}\text{C}^*(4.4)$  is suggested (1974DE16)<sup>†</sup>.  $\theta_\alpha^2$  for all  $^{16}\text{O}$  states with  $E_x < 10.4$  MeV are listed in (1967LO01). See also (1976JA1Q). Gamma-ray angular distribution measurements have been carried out at  $E(^6\text{Li}) = 4.5$  to 6.5 MeV (1972CA14, 1972ZA08). For angular correlation measurements, see (1973BA53, 1976BA2M) and  $^{18}\text{F}$  in (1978AJ03).

<sup>†</sup> However, compound nuclear effects may account for this ratio (F. Becchetti, private communication).



See also (1970JO1D), (1971BA2V, 1972GA1E, 1973FO1E, 1973FO1A, 1973OG1A) and (1970DO13, 1971DE1X, 1971OS02, 1972KU12, 1972OS01, 1972PA15, 1973CH17, 1973CH1H, 1973MC17, 1973TI04, 1974DO03, 1974NO03, 1975PA11, 1976NA05; theor.).

$$13. \text{}^{12}\text{C}(\text{}^7\text{Li}, \text{t})\text{}^{16}\text{O} \quad Q_{\text{m}} = 4.695$$

This reaction has been studied at many energies for  $E(\text{}^7\text{Li}) < 38$  MeV: see Table 16.13 in (1971AJ02) and (1971BA2Q, 1971BA2R:  $E(\text{}^7\text{Li}) = 32$  MeV) and (1976CO23:  $E(\text{}^7\text{Li}) = 38$  MeV). In the latter work the spectra at forward angles are dominated by members of the 4p-4h  $K^\pi = 0^+$  band [ $^{16}\text{O}^*(6.05, 6.92, 10.35, 16.3)$ :  $J^\pi = 0^+, 2^+, 4^+, 6^+$ ] and by those of the  $K^\pi = 0^-$  band [ $^{16}\text{O}^*(9.63, 11.60, 14.67, 20.9)$ :  $J^\pi = 1^-, 3^-, (5^-), 7^-$ ]. Hauser-Feshbach calculations have been made for many of the  $^{16}\text{O}$  states and, in particular, for a state at  $E_{\text{x}} = 14.363 \pm 15$  keV which is not resolved at forward angles. The width of this state is  $< 120$  keV and  $J > 5$ ,  $\pi = \text{natural}$  (1976CO23; M.E. Cobern, private communication). See also (1971LA1B, 1972CA1E), (1971BA2V, 1972GA1E, 1973FO1E, 1973FO1A, 1973OG1A, 1974ST1L, 1975GO15) and (1970DO13, 1972KU12, 1973IC01, 1974DO03, 1975PA11; theor.).

$$14. \text{}^{12}\text{C}(\text{}^{10}\text{B}, \text{}^6\text{Li})\text{}^{16}\text{O} \quad Q_{\text{m}} = 2.701$$

At  $E(\text{}^{10}\text{B}) = 18$  and 45 MeV angular distributions have been studied involving  $^{16}\text{O}^*(0, 6.1, 7.1, 8.9, 9.9, 10.4)$ : this reaction does not appear to select special states of  $^{16}\text{O}$  (1970HI08). See (1970JA1B, 1973YO1C). See also (1972GA1E) and (1973KU03, 1974NE18; theor.).

$$15. \text{}^{12}\text{C}(\text{}^{11}\text{B}, \text{}^7\text{Li})\text{}^{16}\text{O} \quad Q_{\text{m}} = -1.504$$

At  $E(\text{}^{11}\text{B}) = 110$  MeV, the population of  $^{16}\text{O}^*(6.05, 6.92, 10.35, 16.3)$  is particularly strong (1975PI1C). See also (1970RO23), (1973SC1J) and (1973ST1D; theor.).

$$16. \text{}^{12}\text{C}(\text{}^{12}\text{C}, \text{}^8\text{Be})\text{}^{16}\text{O} \quad Q_{\text{m}} = -0.205$$

Angular distributions have been measured at  $E(\text{}^{12}\text{C}) = 42$  MeV (1976AR02:  $^8\text{Be}_{\text{g.s.}} + ^{16}\text{O}^*(0, 6.1, 6.9, 10.4)$ ),  $60 \rightarrow 63$  MeV (1973CR1A, 1976MA12, 1976WE04:  $^8\text{Be}_{\text{g.s.}} + ^{16}\text{O}^*(0, 6.1, 6.9, 10.4, 11.1, 14.7, 16.3)$ ), and also for the ground state transitions at  $E(\text{}^{12}\text{C}) = 11.6$  to 13.4 MeV (1972CO1H), 18 to 40 MeV (1976FL05) and 37 MeV (1975EB03, 1976EB01). Angular correlations at  $E(\text{}^{12}\text{C}) = 78$  MeV confirm  $J^\pi = 4^+, 5^-, 6^+$  and  $7^-$  for  $^{16}\text{O}^*(10.35, 14.67, 16.29, 20.88)$  (1976SA1Q; and P.D. Parker, private communication:  $^8\text{Be}(0^\circ), \alpha_0$ ). At the latter energy

$l = 12$  seems dominant: for yield measurements see  $^{24}\text{Mg}$  in (1978EN06). See also (1972PA1G, 1972WO10, 1974HO30, 1975PI1C), (1972GA1E, 1973FO1E, 1973SC1J, 1974ST1L) and reaction 13 in (1971AJ02).

$$17. \text{}^{12}\text{C}(\text{}^{14}\text{N}, \text{}^{10}\text{B})\text{}^{16}\text{O} \quad Q_{\text{m}} = -4.452$$

See (1975ZE1C). See also (1975NA1L) and (1973SC1J).

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

For reaction (a) see reaction 72. For reaction (b) see (1974CH1Q, 1976WE05) [see  $^{30}\text{Si}$  in (1978EN06)], (1974GO1L), (1970AN1D, 1971AL1D, 1971RO1G, 1972RO35, 1975TA02, 1976KA04; theor.) and reaction 15 in (1971AJ02).

$$19. \text{}^{12}\text{C}(\text{}^{19}\text{F}, \text{}^{15}\text{N})\text{}^{16}\text{O} \quad Q_{\text{m}} = 3.149$$

Angular distributions have been measured at  $E(^{19}\text{F}) = 40, 60$  and  $68.8$  MeV involving different states in  $^{15}\text{N}$  and  $^{16}\text{O}^*(0, 6.1, 7.0, 10.4)$  (1972SC17). See also (1970VO1F, 1975PU02), (1972GA1E, 1972MO1E, 1973SC1J) and (1972BO21; theor.).

$$20. \text{}^{12}\text{C}(\text{}^{20}\text{Ne}, \text{}^{16}\text{O})\text{}^{16}\text{O} \quad Q_{\text{m}} = 2.4304$$

At  $E(^{20}\text{Ne}) = 108$  and  $147$  MeV the spectrum involves groups at  $E_{\text{x}} = 6.1$  (u),  $7.0$  (u),  $10.3$ ,  $11.1$ ,  $14.6$  (u) and  $16.2$  MeV [u = unresolved] (1974ME27, 1975PI1C). Angular distributions are reported at  $E(^{20}\text{Ne}) = 78$  MeV to  $E_{\text{x}} = 6.1$  (u),  $6.9$  (u),  $8.9$  and  $10.4$  MeV (1970RO23). See also  $^{32}\text{S}$  in (1978EN06) and (1975DO06). See also (1972GA1E).

$$21. \text{}^{13}\text{C}(\text{}^3\text{He}, \gamma)\text{}^{16}\text{O} \quad Q_{\text{m}} = 22.7937$$

The yield of  $\gamma_0$  has been studied for  $E(^3\text{He}) = 3$  to  $8$  MeV (1972VE1A; abstract) and  $3$  to  $16$  MeV (1974SH01). In the latter experiments the  $\gamma_{1+2+3+4}$  yield has also been measured as have many angular distributions: the  $90^\circ$   $\gamma_0$  yield is characterized by resonances at  $E(^3\text{He}) \approx 4$  and  $\approx 6$  MeV, the  $\gamma_{1+2+3+4}$  yield by a single broad structure at  $\approx 5.5$  MeV. The peak cross section for the

Table 16.13: Resonances in  $^{13}\text{C} + ^3\text{He}$ 

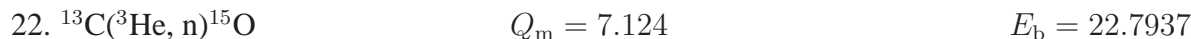
$E(^3\text{He})$ (MeV $\pm$ keV)	$\Gamma_{\text{c.m.}}$ (keV)	Outgoing particles	$^{16}\text{O}^*$ (MeV)	$J^\pi; T$	Refs. <sup>a</sup>
1.55	$\approx 80$	$n_0, n_3$	24.05		
$1.55 \pm 100$	450	$\gamma_0$	24.1		
2.0	$\approx 250$	$n_0$	24.4		
$2.6 \pm 100$		$\alpha\gamma_{15.1}$	24.9	( $T = 1$ )	
$2.87 \pm 50$	600	$\gamma_0$	25.12	( $1^-$ )	(1972VE1A)
$\approx 3.1$		$\alpha_0, \alpha_2$	$\approx 25.3$		(1971BO26)
$\approx 3.5$	$\approx 300$	$\alpha_0$	$\approx 25.6$	( $3^-$ )	(1971BO26)
$\approx 4$	$\approx 300$	$\alpha_0, \alpha_1, \alpha_2$	$\approx 26$	( $3^-$ )	(1971BO26)
$4.1 \pm 100$	<sup>b</sup>	$\gamma_0, \alpha\gamma_{15.1}$	26.1	( $T = 1$ )	(1972VE1A, 1974SH01)
4.5		$\gamma_1 + \gamma_2$	26.4		(1974CH37) <sup>c</sup>
$5.2 \pm 100$	<sup>b</sup>	$\alpha\gamma_{15.1}$	27.0	( $T = 1$ )	
$5.6 \pm 100$	$\approx 600$	$\alpha\gamma_{15.1}, ^8\text{Be}$	27.3	( $2^+; T = 1$ )	
$6.0 \pm 100$	$\approx 500$	$p_0, p_{1+2}, ^3\text{He}, \alpha_0, \alpha_1, \alpha_2$	27.7	( $3^-; T = 0$ )	
$\approx 6$		$\gamma_0$	28		(1972VE1A, 1974SH01)
$6.5 \pm 100$	<sup>b</sup>	$\alpha\gamma_{15.1}$	28.1	( $T = 1$ )	
$6.8 \pm 100$		$\alpha_0, \alpha_1, \alpha_2$	28.3	( $T = 0$ )	
$7.5 \pm 100$	<sup>b</sup>	$\alpha\gamma_{15.1}$	28.9	( $T = 1$ )	
$8.6 \pm 100$	<sup>b</sup>	$\alpha\gamma_{15.1}$	29.8	( $T = 1$ )	
$9.4 \pm 100$	<sup>b</sup>	$\alpha\gamma_{15.1}$	30.4	( $T = 1$ )	
$10.1 \pm 100$	<sup>b</sup>	$\alpha\gamma_{15.1}$	31.0	( $T = 1$ )	

<sup>a</sup> For a listing of the earlier references see Table 16.15 in (1971AJ02).

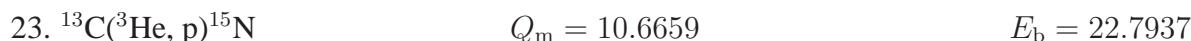
<sup>b</sup> Lab widths 0.5 – 1 MeV (1969TA09).

<sup>c</sup> And J. Lowe, private communication.

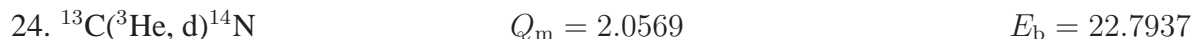
latter yield is an order of magnitude greater than the cross sections for the peaks observed in the  $\gamma_0$  yield (1974SH01). The yield of  $(\gamma_1 + \gamma_2)$  [ $E(^3\text{He}) = 3.9$  to  $12$  MeV] shows one resonance at  $E(^3\text{He}) = 4.5$  MeV (1974CH37): see Table 16.13 [also measured the  $(\gamma_3 + \gamma_4)$  yield in the range  $3.9$  to  $8.7$  MeV]. For the earlier work see (1966PU01). See also (1973SU1E) and reaction 46.



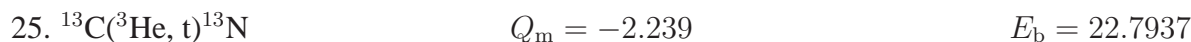
The excitation functions to  $E(^3\text{He}) = 11$  MeV [see Table 16.14 of (1971AJ02) and (1972ET01:  $E(^3\text{He}) = 4.0 \rightarrow 5.8$  MeV for n to  $^{15}\text{O}^*(0, 6.18, 7.28, 7.56)$ )] are marked at low energies by complex structures and possibly by two resonances at  $E(^3\text{He}) = 1.55$  and  $2.0$  MeV: see Table 16.13. Polarization measurements for the  $n_0$  group have been reported at  $E(^3\text{He}) = 3.0$  to  $5.7$  MeV [see (1971AJ02)] and at  $E(^3\text{He}) = 12, 16$  and  $20$  MeV (1973RH1A; abstract). See also  $^{15}\text{O}$  in (1976AJ04).



The yield curves for  $p_0$  and  $p_{1+2}$  for  $E(^3\text{He}) = 4.0$  to  $8.0$  MeV show a resonance at  $6$  MeV (1968WE15, 1968WE1C): see Table 16.13. (1972ST22) have measured excitation functions for  $E(^3\text{He}) = 3.5$  to  $6$  MeV for the  $p_0, p_{1+2}, p_3 \rightarrow p_6$  groups: some uncorrelated structures are observed. See also  $^{15}\text{N}$  in (1976AJ04).



See  $^{14}\text{N}$  in (1976AJ04).



The excitation function for formation of  $^{13}\text{N}_{g.s.}$  has been studied for  $E(^3\text{He}) = 11$  to  $17$  MeV (1970NU02). See also  $^{13}\text{N}$  in (1976AJ04).



See (1967WE06, 1968WE15, 1968WE1C) and Table 16.13.

27.  $^{13}\text{C}(^3\text{He}, \alpha)^{12}\text{C}$

$Q_m = 15.6321$

$E_b = 22.7937$

Yields of  $\alpha_0$ ,  $\alpha_1$ ,  $\alpha_2$  and  $\gamma$ -rays from decay of  $^{12}\text{C}^*(12.71, 15.11)$  have been studied up to  $E(^3\text{He}) = 12$  MeV: see Table 16.14 in (1971AJ02) and (1971BO26:  $E(^3\text{He}) = 1.2$  to 5.4 MeV;  $\alpha_0$ ,  $\alpha_1$ ,  $\alpha_2$ ). Observed resonances are displayed in Table 16.13. Those seen in the yield of  $\gamma_{15.1}$  are assumed to correspond to  $^{16}\text{O}$  states which have primarily a  $T = 1$  character. See (1971AJ02) for a summary of the earlier references and  $^{12}\text{C}$  in (1975AJ02).

28.  $^{13}\text{C}(^3\text{He}, ^8\text{Be})^8\text{Be}$

$Q_m = 8.173$

$E_b = 22.7937$

The excitation function for  $^8\text{Be}_{\text{g.s.}}$  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  $^{16}\text{O}$  at  $E_x = 27.3$  MeV.  $J^\pi$  appears to be  $2^+$  from angular distribution measurements (1968JA07).

29.  $^{13}\text{C}(\alpha, n)^{16}\text{O}$

$Q_m = 2.2152$

Angular distributions for the  $n_0$  group have been measured for  $E_\alpha = 12.8$  to 22.5 MeV: see (1971AJ02).  $^{16}\text{O}^*(6.05)$  has been observed as a neutron threshold (1956BO61). See also  $^{17}\text{O}$ , (1970CL1C, 1973CL1E, 1973TR1B; astrophys. considerations) and (1971TE10; theor.).

30.  $^{13}\text{C}(^6\text{Li}, t)^{16}\text{O}$

$Q_m = 6.999$

Angular distributions have been studied at  $E(^6\text{Li}) = 20$  and 28 MeV to  $^{16}\text{O}^*(0$  [at 28 MeV], 6.13, 7.0, 8.87, 9.85, 10.35, 11.09). At these energies the spectra are dominated by the triton groups to  $^{16}\text{O}^*(11.09, 14.30, 14.39, 14.82)$ . At  $E(^6\text{Li}) = 25$  MeV the excitation of  $^{16}\text{O}^*(14.52, 14.66)$  is also reported (1969BA50, 1971BA2Q, 1971BA2R, 1971DE1X, 1972BA2B). See also (1971BA2V).

31.  $^{13}\text{C}(^{12}\text{C}, ^9\text{Be})^{16}\text{O}$

$Q_m = -3.486$

At  $E(^{12}\text{C}) = 87$  MeV, angular distributions are reported for transitions to  $^{16}\text{O}^*(6.9, 8.9, 10.4, 11.1, 13.5, 14.8, 15.1, 16.1, 16.5)$  (1970RO23). The ground state angular distribution has also been studied at  $E(^{13}\text{C}) = 36$  MeV (1976WE21).

32.  $^{13}\text{C}(^{17}\text{O}, ^{14}\text{C})^{16}\text{O}$

$Q_m = 4.032$

Table 16.14: Structure in  $^{14}\text{N} + \text{d}$ 

$E_d$ (MeV)	Resonant channel	$\Gamma_{\text{cm}}$ (keV)	$J^\pi; T$	$E_x$ (MeV)	Refs.
1.4	$n_0$			22.0	(1960RE07)
$1.7 \pm 0.1$	$\gamma_0, \alpha_0 \rightarrow \alpha_3$			22.2	(1962IS02, 1966SU05, 1967LA16)
1.85	$n_0, \alpha_0$			22.35	(1961IS03, 1965BU1A)
$2.0 \pm 0.1$	$\alpha_0, \alpha_3$			22.5	(1967LA16)
$2.272 \pm 0.05^a$	$p_0, p_{1+2}, p_3, \alpha_0, \alpha_2$	$12 \pm 3$	$0^+; 2$	22.723	(1972NE10)
$2.40 \pm 0.005^b$	$\gamma_0$	600	$1^-; 1$	22.83	(1966SU05, 1972WE04)
2.5	$\alpha_0$			22.9	(1961IS03)
2.6	$(n_0, p_0), \alpha_1$			23.0	(1960RE07, 1962GO21, 1962IS02)
2.8	$(n_0, p_0), d_0$			23.2	(1962GO21, 1967FL10)
3.3	$p_0, d_0$			23.6	(1962GO21, 1967FL10)
4.2	$\gamma_0, p_0, d_0, \gamma_{15.1}$			24.4	(1960RE07, 1962GO21, 1965BR08, 1966SU05, 1967FL10)
4.58	$p_0, d_0, \gamma_{15.1}$			24.74	(1965BR08, 1967FL10)
4.9	$n_0, p_0$			25.0	(1960RE07, 1962GO21)
5.95	$d_1, \gamma_{15.1}$			25.9	(1965BR08, 1970DU04)
7.1	$\gamma_{15.1}$			26.9	(1965BR08)
7.4	$d_2$			27.2	(1970DU04)
7.7	$d_1$			27.5	(1970DU04)
(8.5)	$(\gamma_{15.1})$			(28.2)	(1965BR08)
10.2	$d_2$			29.7	(1970DU04)

<sup>a</sup>  $(\Gamma_{d_0}\Gamma_i/\Gamma^2) \times 10^{-3}$  are greater than  $1.6 \pm 0.4$ ,  $0.27 \pm 0.13$ ,  $0.41 \pm 0.15$  and  $0.07 \pm 0.05$  for the  $\alpha_2$ ,  $p_0$ ,  $p_{1+2}$  and  $p_3$  groups.

<sup>b</sup> If this resonance is fitted with a single-level Breit-Wigner shape, penetrability effects could lower the resonance energy by as much as 50 keV, assuming  $l = 1$  (1972WE04). See also (1971AJ02).

See (1974CH1Q).

$$33. \text{}^{14}\text{C}(\text{}^3\text{He}, \text{n})\text{}^{16}\text{O} \quad Q_{\text{m}} = 14.6167$$

At  $E(^3\text{He}) = 11$  to  $16$  MeV, neutron groups are observed to  $T = 2$  states at  $E_{\text{x}} = 22.717 \pm 0.008$  and  $24.522 \pm 0.011$  MeV ( $\Gamma < 30$  keV and  $< 50$  keV, respectively). These two states are presumably the first two  $T = 2$  states in  $^{16}\text{O}$ , the analog states to  $^{16}\text{C}^*(0, 1.75)$ .  $J^{\pi}$  for  $^{16}\text{O}^*(24.52)$  is found to be  $2^+$  from angular distribution measurements (1970AD01). Angular distributions are also reported at  $E(^3\text{He}) = 2.1$  to  $3.4$  MeV and at  $6$  MeV: see (1971AJ02). See also (1974MA1M, 1975CE1D).

$$34. \text{}^{14}\text{C}(\text{}^{18}\text{O}, \text{}^{16}\text{C})\text{}^{16}\text{O} \quad Q_{\text{m}} = -6.719$$

See  $^{16}\text{C}$ , reaction 4.

$$35. \text{}^{14}\text{N}(\text{d}, \gamma)\text{}^{16}\text{O} \quad Q_{\text{m}} = 20.7368$$

The  $\gamma_0$  yield has been studied for  $E_{\text{d}} = 0.5$  to  $5.5$  MeV (1966SU05, 1966SU1C) and  $2.1$  to  $2.9$  MeV (1972WE04). The yield shows a resonance at  $E_{\text{d}} = 2.40 \pm 0.05$  MeV,  $\Gamma_{\text{cm}} \approx 0.6$  MeV (1972WE04, 1974DA30). The angular distribution of  $\gamma_0$  at resonance is consistent with  $E1$ :  $J^{\pi} = 1^-$ ;  $T = 1$ : it may be the Gillet 2p-2h quasibound state: see, however, reaction 46. Structures at  $E_{\text{x}} = 22.2$  and  $24.5$  MeV are also reported (1966SU05): see Table 16.14. See also (1971AJ02), (1973SU1E) and (1973JA1E; theor.).

$$36. \text{}^{14}\text{N}(\text{d}, \text{n})\text{}^{15}\text{O} \quad Q_{\text{m}} = 5.067 \quad E_{\text{b}} = 20.7368$$

For  $E_{\text{d}} = 0.66$  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: the more prominent structures in the yield curves are displayed in Table 16.14 (1960RE07, 1965BU1A). Yield measurements are also reported for  $E_{\text{d}} = 2.9$  to  $5.0$  MeV (1970RI01:  $n_2, n_3, n_4, n_6, n_7$ ). For polarization measurements see Table 16.16 in (1971AJ02) and (1976LI1R:  $4.5$  to  $15$  MeV:  $n_{1+2}$ ), (1972FO07:  $5.16$  MeV;  $n_0, n_{1+2}, n_3, n_{4+5}, n_6, n_7$ ) and (1971HI09:  $10.0$  and  $11.8$  MeV;  $n_0$ ). See also (1969WO09, 1971WA1D, 1974LO1B), (1970ME25; theor.) and  $^{15}\text{O}$  in (1976AJ04).

$$37. \text{}^{14}\text{N}(\text{d}, \text{p})\text{}^{15}\text{N} \quad Q_{\text{m}} = 8.6090 \quad E_{\text{b}} = 20.7368$$

The yield curves of various proton groups show a great deal of structure: see reaction 30 and Table 16.16 in (1971AJ02) for a summary of the earlier work. Resonant structure reported by (1962GO21, 1972NE10) is displayed in Table 16.14. For polarization measurements see Table 16.16 in (1971AJ02), (1976PA1K; 11.8 MeV,  $p_0$ ) and (1971EG01; 13.8 MeV;  $p_0$ ). See also (1974DA13), (1974LO1B), (1972KO30; theor.) and  $^{15}\text{N}$  in (1976AJ04).

38.  $^{14}\text{N}(\text{d}, \text{d})^{14}\text{N}$

$$E_b = 20.7368$$

The yield of elastically scattered deuterons has been studied for  $E_d = 0.65$  to 5.5 MeV [see Table 16.16 in (1971AJ02)] and for 14.0 to 15.52 MeV (1974BU06). (1967FL10) report a number of resonances in the  $d_0$  yield corresponding to states in  $^{16}\text{O}$  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  $^{14}\text{N}$ . The yield of deuterons ( $d_2$ ) to  $^{14}\text{N}^*(3.95)$  [ $J^\pi = 1^+$ ;  $T = 0$ ] shows gross structures at  $E_d = 7.4$  and 10.2 MeV (1970DU04): see Table 16.14. Polarization measurements involving the elastic group are reported at  $E_d = 11.6$  MeV (1973BR15) and 15 MeV (1973DA26, 1974BU06). See also  $^{14}\text{N}$  in (1976AJ04) and (1970ME25, 1974FA1A; theor.).

39. (a)  $^{14}\text{N}(\text{d}, \text{t})^{13}\text{N}$

$$Q_m = -4.296$$

$$E_b = 20.7368$$

(b)  $^{14}\text{N}(\text{d}, ^3\text{He})^{13}\text{C}$

$$Q_m = -2.0569$$

Polarization measurements have been carried out at  $E_d = 15$  MeV for the groups to  $^{13}\text{C}_{\text{g.s.}}$  and  $^{13}\text{N}_{\text{g.s.}}$  (1973DA26, 1974LU06). See also  $^{13}\text{C}$  and  $^{13}\text{N}$  in (1976AJ04).

40.  $^{14}\text{N}(\text{d}, \alpha)^{12}\text{C}$

$$Q_m = 13.5751$$

$$E_b = 20.7368$$

There is a great deal of structure in the yields of various  $\alpha$ -particle groups for  $E_d = 0.5$  to 12 MeV: see Table 16.16 in (1971AJ02) for the earlier work. The more prominent structures are shown in Table 16.14 (1961IS03, 1962IS02, 1967LA16, 1972NE10). The yield of 15.11 MeV  $\gamma$ -rays [from the decay of  $^{12}\text{C}^*(15.11)$ ,  $J^\pi = 1^+$ ;  $T = 1$ ] 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 16.14). Above  $E_d = 9.5$  MeV, the yield curve is quite featureless (1965BR08). See also  $^{12}\text{C}$  in (1975AJ02). Polarization measurements have been carried out at  $E_d = 15$  MeV (1976LU1A;  $\alpha_0, \alpha_1, (\alpha_2)$ ).

41. (a)  $^{14}\text{N}(\text{t}, \text{n})^{16}\text{O}$

$$Q_m = 14.4792$$

(b)  $^{14}\text{N}(\text{t}, \text{np})^{15}\text{N}$

$$Q_m = 2.351$$

(c)  $^{14}\text{N}(\text{t}, \text{n}\alpha)^{12}\text{C}$

$$Q_m = 7.318$$



Table 16.15: Radiative decays in  $^{16}\text{O}$  <sup>a</sup>

$E_i$ (MeV)	$J_i^\pi; T$	$E_f$ (MeV)	$J_f^\pi; T$	Branch (%)	$\Gamma_{\text{rad}}$ (eV)	Refs.
6.05	$0^+; 0$	0	$0^+; 0$	100	$3.55 \pm 0.21$ <sup>b</sup>	(1975MI08)
6.13	$3^-; 0$	0	$0^+; 0$	100	$(2.60 \pm 0.13) \times 10^{-5}$	(1975MI08)
6.92	$2^+; 0$	0	$0^+; 0$	$> 99$	$0.130 \pm 0.009$	(1973BE49)
					$0.100 \pm 0.004$	(1975MI08)
		6.05	$0^+; 0$	$(2.7 \pm 0.3) \times 10^{-2}$	$(3.0 \pm 0.5) \times 10^{-5}$	mean <sup>a,d</sup>
		6.13	$3^-; 0$	$\leq 8 \times 10^{-3}$		(1968WI15)
7.12	$1^-; 0$	0	$0^+; 0$	$> 99$	$(55 \pm 5) \times 10^{-3}$	best <sup>a</sup>
		6.05	$0^+; 0$	$< 6 \times 10^{-4}$		(1967LO08)
		6.13	$3^-; 0$	$(7.0 \pm 1.4) \times 10^{-2}$		(1968WI15)
8.87	$2^-; 0$	0	$0^+; 0$	$7.2 \pm 0.8$	$(2.4 \pm 0.4) \times 10^{-4}$	(1967PI01, 1968WI15)
		6.05	$0^+; 0$	$0.122 \pm 0.033$	$(2.9 \pm 1.0) \times 10^{-6}$	(1963GO31, 1967PI01)
		6.13	$3^-; 0$	$76.0 \pm 3.0$		(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	$2^+; 0$	$4.2 \pm 0.8$	$(1.72 \pm 0.25) \times 10^{-4}$	(1967PI01, 1968WI15)
		7.12	$1^-; 0$	$12.6 \pm 2.0$		(1968WI15)
9.63	$1^-; 0$	0	$0^+; 0$	$\approx 100$	$(23 \pm 3) \times 10^{-3}$	Table 16.12
9.85	$2^+; 0$	0	$0^+; 0$	$61 \pm 4$	$(6.1 \pm 0.5) \times 10^{-3}$	best <sup>a</sup>
					$(5.9 \pm 0.6) \times 10^{-3}$	Table 16.12
		6.05	$0^+; 0$	$18 \pm 4$	$(1.9 \pm 0.4) \times 10^{-3}$	(1967GO08)
		6.92	$2^+; 0$	$21 \pm 4$	$(2.2 \pm 0.4) \times 10^{-3}$	Table 16.12
10.35	$4^+; 0$	0	$0^+; 0$		$(5.6 \pm 2.0) \times 10^{-8}$	(1973BE49)
		6.13	$3^-; 0$		$< 1.0 \times 10^{-3}$	(1963GO31)
		6.92	$2^+; 0$	$\approx 100$	$(5.8 \pm 0.7) \times 10^{-3}$	Table 16.12
10.95	$0^-; 0$	7.12	$1^-; 0$	$> 99$	$(0.08 \pm 0.05) \times 10^{-2}$	(1959BR68; Table 16.12)
11.095 <sup>a</sup>	$4^+; 0$	6.13	$3^-; 0$	<sup>a</sup>	$(3.1 \pm 1.3) \times 10^{-3}$	Table 16.12
		6.92	$2^+; 0$	<sup>a</sup>	$(2.5 \pm 0.6) \times 10^{-3}$	Table 16.12
11.52	$2^+; 0$	0	$0^+; 0$	91.7	$0.61 \pm 0.02$	(1973BE50)
					$0.65 \pm 0.08$	Table 16.12
		6.05	$0^+; 0$	$4.2 \pm 0.7$	<sup>a</sup>	
		6.92	$2^+; 0$	$4.0 \pm 1.0$	$(29 \pm 7) \times 10^{-3}$	Table 16.12
		7.12	$1^-; 0$	$\leq 0.8$		
12.05	$0^+; 0$	0	$0^+; 0$		$4.03 \pm 0.09$ <sup>b</sup>	(1973BE50)
12.44	$1^-; 0$	0	$0^+; 0$	$\approx 100$	$9.5 \pm 1.7$	(1973BR19)
					$12 \pm 2$	(1974RO37)
		6.05	$0^+; 0$	$1.2 \pm 0.4$ <sup>a</sup>	$0.12 \pm 0.06$	Table 16.12
					$0.12 \pm 0.04$	Table 16.19

Table 16.15: Radiative decays in  $^{16}\text{O}$  <sup>a</sup> (continued)

$E_i$ (MeV)	$J_i^\pi; T$	$E_f$ (MeV)	$J_f^\pi; T$	Branch (%)	$\Gamma_{\text{rad}}$ (eV)	Refs.
12.53	$2^-; 0$	0	$0^+; 0$		$(21 \pm 6) \times 10^{-3}$	(1968ST31)
					$(108 \pm 15) \times 10^{-3}$	(1970KI02)
		6.13	$3^-; 0$	$60 \pm 6$	$2.1 \pm 0.2$	(1968GO07)
		6.92	$2^+; 0$	$< 10$	$\leq 0.34$	(1968GO07)
		7.12	$1^-; 0$	$15 \pm 3$	$0.5 \pm 0.1$	(1968GO07)
12.80 <sup>a</sup>	$0^-; 1$	8.87	$2^-; 0$	$25 \pm 3$	$0.9 \pm 0.1$	(1968GO07)
		7.12	$1^-; 0$	$\approx 100$	$2.5 \pm 0.2$	(1968GO07)
		12.97 <sup>a</sup>	$2^-; 1$	0	$0^+; 0$	$(71 \pm 2) \times 10^{-3}$
13.09 <sup>a</sup>	$1^-; 1$	6.13	$3^-; 0$	$63 \pm 6$	$2.3 \pm 0.2$	(1968GO07)
		7.12	$1^-; 0$	$12 \pm 3$	$0.44 \pm 0.10$	(1968GO07)
		8.87	$2^-; 0$	$25 \pm 3$	$0.90 \pm 0.10$	(1968GO07)
		0	$0^+; 0$	$\approx 100$	$32 \pm 5$	(1974RO37)
13.26 <sup>a</sup> <sub>c</sub>	$3^-; 1$				$44 \pm 8$	(1973BR19)
		6.05	$0^+; 0$	$0.58 \pm 0.12$		(1968WI15)
		7.12	$1^-; 0$	$3.1 \pm 0.8$	$1.4 \pm 0.4$	(1973BR19)
		6.13	$3^-; 0$	$> 85$	$9.2 \pm 1.5$	(1968GO07)

<sup>a</sup> See Table 16.12 in (1971AJ02) for the earlier work.

<sup>b</sup> Monopole matrix element in  $\text{fm}^2$ .

<sup>c</sup> For the radiative decays of higher states see Tables 16.12, 16.19 and 16.24.

<sup>d</sup> Mean for branch.  $\Gamma_\gamma$  for this state based on  $\Gamma_\gamma = 0.11 \pm 0.01$  for  $6.92 \rightarrow 0$  transition.

 Table 16.16:  $^{16}\text{O}$  states from  $^{14}\text{N}(^3\text{He}, p)^{16}\text{O}$  <sup>a</sup>

$E_x$ (MeV $\pm$ keV)	$\Gamma_{\text{c.m.}}$ (keV)	$L$ <sup>c</sup>
0		0 + 2
$6.052 \pm 5$	$< 20$	
$6.131 \pm 4$	$< 20$	1 + 3
$6.916 \pm 3$	$< 20$	0 + 2 + 4
$7.115 \pm 3$	$< 20$	1 + 3
$8.870 \pm 3$	$< 20$	1 + 3
$9.614 \pm 30$	$510 \pm 60$	
$9.847 \pm 3$	$< 20$	0 + 2 + 4
$10.353 \pm 4$	$27 \pm 8$	2 + 4

Table 16.16:  $^{16}\text{O}$  states from  $^{14}\text{N}(^3\text{He}, \text{p})^{16}\text{O}$  <sup>a</sup> (continued)

$E_x$ (MeV $\pm$ keV) <sup>a,b</sup>	$\Gamma_{\text{c.m.}}$ <sup>a,b</sup> (keV)	$L$ <sup>c</sup>
10.952 $\pm$ 3	< 12	1
11.080 $\pm$ 3	< 12	
11.096 $\pm$ 3	< 12	
11.521 $\pm$ 4	78 $\pm$ 8	0 + 2 + 4
12.053 $\pm$ 3	< 12	0 + 2
12.437 $\pm$ 7	94 $\pm$ 5	1 + 3
12.528 $\pm$ 3	< 12	1 + 3
12.798 $\pm$ 5	41 $\pm$ 10	
12.964 $\pm$ 3	< 12	
13.105 $\pm$ 15	160 $\pm$ 30	
13.253 $\pm$ 5	25 $\pm$ 8	
13.665 $\pm$ 6	65 $\pm$ 8	0 + 2
13.869 $\pm$ 10	85 $\pm$ 20	
13.975 $\pm$ 4	24 $\pm$ 8	
14.922 $\pm$ 6	60 $\pm$ 10	
b		

<sup>a</sup> (1964BR08):  $E(^3\text{He}) = 3.74$  and  $3.97$  MeV.

<sup>b</sup> Higher states reported in Table 16.18 in (1971AJ02) have not been published.

<sup>c</sup> (1971WE16:  $E(^3\text{He}) = 18$  MeV).

At  $E_t = 2.2$  to  $2.6$  MeV, the two-stage reaction (b) proceeds via  $^{16}\text{O}^*(14.92, 16.22)$  (1961JA14) while reaction (c) proceeds via  $^{16}\text{O}^*(13.10, 15.45)$  (1962SI04).

$$42. \text{ (a) } ^{14}\text{N}(^3\text{He}, \text{p})^{16}\text{O} \quad Q_m = 15.2430$$

$$\text{ (b) } ^{14}\text{N}(^3\text{He}, \text{p}\alpha)^{12}\text{C} \quad Q_m = 8.0814$$

Observed proton groups are displayed in Table 16.16 (1964BR08). Angular distributions have been measured at  $E(^3\text{He}) = 2.5$  to  $18$  MeV: see (1971AJ02), (1972BI01:  $E(^3\text{He}) = 7.96 \rightarrow 18.0$  MeV), (1971GU22:  $E(^3\text{He}) = 9$  MeV) and (1971WE16:  $18$  MeV). Analysis by DWBA is satisfactory for  $^{16}\text{O}^*(6.13, 7.12, 8.87, 10.95)$ .  $^{16}\text{O}^*(6.05, 6.92, 10.35)$  are very weakly populated in accord with their presumed 4p-4h character. It is suggested that the 2p-2h strength lies mainly

above  $E_x = 14$  MeV (1971WE16). Branching ratios (shown in Table 16.15) and  $p\gamma$  correlation measurements lead to  $J^\pi = 2^-, 0^-$  and  $3^+$  for  $^{16}\text{O}^*(8.87, 10.95, 11.08)$  (1959BR68, 1959KU78);  $\tau_m$  are shown in Table 16.21.

At  $E(^3\text{He}) = 8$  MeV a study of the protons in coincidence with 4.4 MeV  $\gamma$ -rays (reaction (b)) indicates that the reaction proceeds via  $^{16}\text{O}^*(12.51, 13.97, 14.39, 14.92, 15.82, 16.23, 17.16, 17.82, 18.04)$  [ $\pm 40$  keV] (1969HO13). See also (1970ME1N, 1975OT01), (1972BR1J) and (1972AL27; theor.). For the decay of  $T = \frac{3}{2}$  states of  $^{17}\text{F}$ , see reaction 9 in  $^{17}\text{F}$  and (1973AD02).

$$43. \text{ (a) } ^{14}\text{N}(\alpha, \text{d})^{16}\text{O} \quad Q_m = -3.1108$$

$$\text{ (b) } ^{14}\text{N}(\alpha, \text{d}\alpha)^{12}\text{C} \quad Q_m = -10.2725$$

Deuteron angular distributions to states of  $^{16}\text{O}$  have been reported at many energies up to  $E_\alpha = 48$  MeV: see (1971AJ02) for the earlier references and (1975TU02:  $E_\alpha = 21$  MeV) and (1972LO08:  $E_\alpha = 29.98$  MeV; see Table 16.17). The results of (1972LO08) are consistent with  $J^\pi = 5^+, 6^+$  and  $4^+$  for  $^{16}\text{O}^*(14.40, 14.82, 16.29)$  [2p-2h] and with  $6^+$  for  $^{16}\text{O}^*(16.30)$  [4p-4h].

An experiment to test time-reversal invariance by the principle of detailed balance in this reaction and in  $^{16}\text{O}(\text{d}, \alpha)^{14}\text{N}$  leads to an upper limit of 0.2% for the time-reversal non-invariant part of the reaction amplitudes (1971TH03).

The two-stage reaction (reaction (b)) at  $E_\alpha = 22.9$  MeV appears to proceed via  $^{16}\text{O}$  states at  $E_x = 9.85 \pm 0.07, 10.37 \pm 0.07$  and  $11.14 \pm 0.07$  MeV (1969BA17). See also (1971BA2Q, 1971BA2V, 1973OG1A, 1976LE1K) and (1971BU1K, 1971TE10; theor.).

$$44. ^{14}\text{N}(^6\text{Li}, \alpha)^{16}\text{O} \quad Q_m = 19.2631$$

Angular distributions have been measured at  $E(^6\text{Li}) = 5.3$  to  $6.0$  MeV (1968RI13;  $\alpha_0, \alpha_{1+2}, \alpha_{3+4}$ ) and  $E(^{14}\text{N}) = 27.6$  MeV (1964WA1B;  $\alpha_0$ ).

$$45. ^{14}\text{N}(^{11}\text{B}, ^9\text{Be})^{16}\text{O} \quad Q_m = 4.920$$

At  $E(^{14}\text{N}) = 50$  MeV angular distributions have been measured to  $^{16}\text{O}^*(0, 6.1 \text{ (u)}, 7.0 \text{ (u)}, 8.9, 9.9, 10.3, 11.0 \text{ (u)})$  [u = unresolved] (1975KL1A). See also (1975PO10:  $E(^{11}\text{B}) = 113$  MeV) and (1971AJ02).

$$46. ^{15}\text{N}(\text{p}, \gamma)^{16}\text{O} \quad Q_m = 12.1277$$

The yield of ground state radiation ( $\gamma_0$ ) has been measured for  $E_p = 0.15$  to  $27.4$  MeV: see

Table 16.17: Excited states of  $^{16}\text{O}$  from  $^{14}\text{N}(\alpha, d)$

$E_x^a$ (MeV $\pm$ keV)	$\Gamma_{\text{cm}}^a$ (keV)
6.13	
6.92	
7.12	
8.87	
9.85	
10.35	
11.094 $\pm$ 3	
13.98 $\pm$ 50	$\leq 80$
14.32 $\pm$ 20	$< 30$
14.400 $\pm$ 3	$\leq 30$
14.815 $\pm$ 2	60 $\pm$ 12
15.17 $\pm$ 50	$\leq 80$
15.44 $\pm$ 50	$\leq 80$
15.78 $\pm$ 50	$\leq 80$
16.214 $\pm$ 15	96 $\pm$ 16
17.18 $\pm$ 50	$\leq 80$

<sup>a</sup> (1972LO08:  $E_\alpha = 29.98$  MeV); angular distributions are reported to the states below, except  $^{16}\text{O}^*(13.98, 14.32, 15.17, 15.44, 15.78, 17.18)$  which are weakly excited and  $^{16}\text{O}^*(6.13, 8.87)$  which are not seen at all angles. See also (1970ZI03).

Table 16.18 for a listing of the measurements and Table 16.19 for a display of the parameters of the observed resonances.

Below  $E_p = 0.4$  MeV capture to the ground state is dominant:  $S(0) = 64 \pm 6$  keV  $\cdot$  b, a value which makes the oxygen side cycle in CNO burning more important than previously thought. Study of the direct radiative capture process leads to a single particle spectriscopic factor  $C^2S = 1.8 \pm 0.4$  for  $^{16}\text{O}_{\text{g.s.}}$  (1974RO37). The cross section shows a great deal of structure up to  $E_p = 17$  MeV. Above that energy the  $\gamma_0$  yield decreases monotonically to 27.4 MeV. In the same energy region the  $\gamma$ -yield to  $^{16}\text{O}$  states at 6–7 MeV and  $\approx 12.9$  MeV is large and it also decreases with increasing energy (1973OC1A; prelim. results.).

Table 16.18: Summary of  $^{15}\text{N} + \text{p}$  yield measurements <sup>a</sup>

$E_p$ (MeV)	Particles	Refs.
0.15 – 2.50	$\gamma_0$	(1974RO37)
0.25 – 1.30	$\gamma_0$	(1973BR19)
6.0 – 19.6	$\gamma_{1+2}$	(1974CH37)
7.4 – 16	$\gamma_0^b$	(1972HA52, 1974HA01)
8.5 – 18	$\gamma_0$	(1973OC1B)
10 – 18	$\gamma_0^b$	(1976BU1M) <sup>c</sup>
17.3 – 25	$\gamma_0$	(1972SN1A) <sup>c</sup>
17.50 – 27.37	$\gamma_0$	(1973OC1A) <sup>c</sup>
8.4 – 10.5	$p_0$	(1975FI1E)
8.5 – 11.6	$p_0 \rightarrow p_3$	(1971DR06)
9.2 – 11.6	$p_4 \rightarrow p_6$	(1971DR06)
24.0 – 43.5	$t_0 \rightarrow t_2, {}^3\text{He}_1, {}^3\text{He}_2$	(1974PI05, 1975MI01)
0.093 – 0.418	$\alpha_0$	(1975PA1M)
0.15 – 2.50	$\alpha_1\gamma$	(1974RO37)
0.25 – 1.10	$\alpha_0$	(1973BR19)
0.34 – 1.21	$\alpha_0^b$	(1976PE1H)
8.5 – 11.5	$\alpha_0, \alpha_1$	(1971DR06)
19 – 45	$\alpha_0, \alpha_1$	(1971GU23, 1974PI05)

<sup>a</sup> See also Table 16.20 in (1971AJ02) for a listing of the earlier measurements.

<sup>b</sup> Polarized protons.

<sup>c</sup> Preliminary results.

Measurements with polarized protons have been made over the giant dipole resonance at  $E_x = 22.2$  MeV (1972HA52) and over a broad E2 giant resonance at  $E_x \approx 24$  MeV (1974HA01). See also (1976BU1M). The giant M2 resonance is robustly centered at  $E_x = 20.4$  MeV (1974CH37).

Branching ratios and  $\Gamma_\gamma$  values for the low energy resonances are listed in Table 16.15 (1968GO07, 1968WI15, 1973BR19). See also (1971AJ02).

See also (1972CA1H, 1973JA1D), (1972HA1Y, 1973GL1B, 1973GL1C, 1973HA1X, 1973HA1Q, 1973SU1E, 1974HA1N, 1974HA1C, 1975CA1T, 1976GL1E), (1972BA2D, 1973BA05, 1973GO23, 1973HO36, 1974DA30, 1975MA2A, 1975RA01, 1975RA02, 1975SN1B, 1975SN1C, 1976LO01, 1976MA2G; theor.) and (1971BA1A, 1973CL1E, 1973TR1E; astrophys. considerations).

Table 16.19: Levels of  $^{16}\text{O}$  from  $^{15}\text{N}(p, \gamma)^{16}\text{O}$ ,  $^{15}\text{N}(p, p)^{15}\text{N}$  and  $^{15}\text{N}(p, \alpha)^{12}\text{C}$ 

$E_p$ (keV) (keV)	$\Gamma_{\gamma_0}$ <sup>a</sup> (eV) (eV)	$\Gamma_{\gamma_1}$ <sup>a</sup> (eV) (eV)	$\Gamma_p$ <sup>a</sup> (keV) (keV)	$\Gamma_{\alpha_0}$ <sup>a</sup> (keV) (keV)	$\Gamma_{\alpha_1}$ <sup>a</sup> (keV) (keV)	$\Gamma_{\text{lab}}$ (keV) (keV)	$J^\pi; T$	$E_x$ (MeV $\pm$ keV) (MeV $\pm$ keV)	Refs. <sup>b</sup>
338	$12 \pm 2$	$0.12 \pm 0.04$	1.2	$95^c$	0.025	96	$1^-; 0$	12.444	(1974RO37, 1973BR19)
$429 \pm 1$	$(21 \pm 6) \times 10^{-3}$	$2.1 \pm 0.2^p$	0.020	nr	0.90	0.9	$2^-; 0$	12.530	(1974RO37)
$710 \pm 7$			40	nr		$40 \pm 4$	$0^-; 1$	12.793	
$897.37 \pm 0.29$	$(78 \pm 16) \times 10^{-3}$		1.2	nr	$0.69 \pm 0.07$	$2.0 \pm 0.2$	$2^-; 1$	12.9686	(1974RO37)
$1028 \pm 10$	$32 \pm 5$		100	40	r	$140 \pm 10$	$1^-; 1$	13.091	(1974RO37, 1973BR19)
$1050 \pm 150$				$\Gamma_p \Gamma_{\alpha_0} = 500 \text{ keV}^2$			$2^+$	13.1	
$1210 \pm 3$			4.1	r	$8.2 \pm 1.1$	$22.5 \pm 1$	$3^-; 1$	13.261	(1974RO37)
$1640 \pm 3$	$\approx 8.5$		10	nr	$59 \pm 6$	$68 \pm 3$	$1^+; 0$	13.664	(1974RO37)
$1890 \pm 20$				r	(r)	$90 \pm 20$		13.90	
$1979 \pm 3$			0.5	nr	r	$23 \pm 2$	$2^-$	13.982	
$3000 \pm 30$			r	r	r	$45 \pm 10$	$4^+$	14.94	
$3300 \pm 35$			r	nr	r	$75 \pm 15$	$2^-$	15.22	
$3350 \pm 50$	$\approx 0.6$		$\approx 125$	r	r	$750 \pm 100$	$2^+; (0)$	15.27	
$3520 \pm 40$			r	r	r	$100 \pm 25$	$(1 \rightarrow 4)$	15.43	
(4280 $\pm$ 20)		$r^d$						(16.14)	
$4380 \pm 20$	4.5		$16^e$			31	$1^{(+)}; 1$	16.23	
5200	r					$\approx 1500$	$1^-; 1$	17.0	
$5350 \pm 20$	16		$26^e$			$\approx 65$	$1^-; 1$	17.14	
$5490 \pm 20$	67		$45^e$			$\approx 110$	$1^-; 1$	17.27	
$6290 \pm 20$	nr	$5 \pm 2^f$	(r)			$< 40$	3	18.02	(1970BA33, 1974CH37) <sup>p</sup>
$7310 \pm 20$		$1 \text{ or } 2^f$				$< 40$	2, 4	18.97	(1974CH37) <sup>p</sup>
$7330 \pm 30$	38					260		18.99	(1970BA33) <sup>p</sup>
7420	r		$\approx 30$			$\approx 130$	$2^+; (1)$	19.08	
$7600 \pm 30$	nr	$1.5^d$				100	(2, 3; 1)	19.25	(1970BA33)
$7840 \pm 30$	59		(r)			350	$1^-; 1$	19.47	(1970BA33)
$8290 \pm 20$	nr	$13 \text{ or } 26^f$				$80 \pm 30$	3	19.89	(1970BA33, 1971BA04, 1974CH37) <sup>p</sup>
$8860 \pm 20^g$	nr	$137 \pm 50$				200	$(2^-); 1$	20.43 <sup>h</sup>	(1970BA33, 1971BA04, 1974CH37) <sup>p</sup>
8990 <sup>i</sup>			j			160		20.55	(1971DR06)
9410 <sup>i</sup>	170		k			$320 \pm 10^l$	$1^-; 1$	$20.945 \pm 20$	(1970BA33,

Table 16.19: Levels of  $^{16}\text{O}$  from  $^{15}\text{N}(p, \gamma)^{16}\text{O}$ ,  $^{15}\text{N}(p, p)^{15}\text{N}$  and  $^{15}\text{N}(p, \alpha)^{12}\text{C}$  (continued)

$E_p$ (keV)	$\Gamma_{\gamma_0}$ <sup>a</sup> (eV)	$\Gamma_{\gamma_1}$ <sup>a</sup> (eV)	$\Gamma_p$ <sup>a</sup> (keV)	$\Gamma_{\alpha_0}$ <sup>a</sup> (keV)	$\Gamma_{\alpha_1}$ <sup>a</sup> (keV)	$\Gamma_{\text{lab}}$ (keV)	$J^\pi; T$	$E_x$ (MeV $\pm$ keV)	Refs. <sup>b</sup>
10000 <sup>i</sup>			m			130	$4 \geq J \geq 1$	21.50	<a href="#">1971DR06</a> , <a href="#">1973OC1B</a>
10180 <sup>i</sup>			n	r		< 45	$T = 0$	21.66	<a href="#">(1971DR06)</a>
10700 <sup>i</sup>	r		m			$725 \pm 10$ <sup>1</sup>	$1^-; 1$	$22.146 \pm 20$	<a href="#">(1970BA33</a> , <a href="#">1971DR06</a> , <a href="#">1973OC1B)</a>
11490 <sup>i</sup>	120	27 <sup>d</sup>	m			$320 \pm 15$ <sup>1</sup>	$1^-; 1$	$22.888 \pm 30$	<a href="#">(1970BA33</a> , <a href="#">1971DR06</a> , <a href="#">1973OC1B)</a>
12740 <sup>i</sup>	r					$590 \pm 40$ <sup>1</sup>	$1^-; 1$	$24.065 \pm 35$	<a href="#">(1973OC1B)</a>
$13490 \pm 60$		$260 \pm 100$ or $140 \pm 50$ <sup>f</sup>				$360 \pm 60$	$(2^+, 4^+); 1$	24.77 <sup>o</sup>	<a href="#">(1974CH37)</a> <sup>p</sup>
13870 <sup>i</sup>	r					$3150 \pm 320$ <sup>1</sup>	$1^-; 1$	$25.12 \pm 65$	<a href="#">(1973OC1B)</a>
$15250 \pm 80$		$450 \pm 160$ <sup>f</sup>				$565 \pm 90$	$(2^+); 1$	26.42 <sup>o</sup>	<a href="#">(1974CH37)</a> <sup>p</sup>
$16250 \pm 100$		$1190 \pm 430$ or $660 \pm 240$ <sup>f</sup>				$880 \pm 120$	$(2^+, 4^+); 1$	27.36	<a href="#">(1974CH37)</a> <sup>p</sup>

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<sup>a</sup> nr = non-resonant; r = resonant.

<sup>b</sup> For earlier references see Table 16.21 in [\(1971AJ02\)](#).

<sup>c</sup>  $\Gamma_{\alpha_0}\Gamma_{\gamma_0}/\Gamma = (0.97 \pm 0.18) \times 10^{-4}$  [\(1973BR19\)](#).

<sup>d</sup>  $\gamma_1 + \gamma_2$ .

<sup>e</sup>  $\Gamma_n = 6, 19$  and  $45$  keV, respectively, for  $^{16}\text{O}^*(16.23, 17.14, 17.27)$  [\(1964TA06\)](#).

<sup>f</sup> Decay is via  $^{16}\text{O}^*(6.13)$  [ $\Gamma_{\gamma_2}$ ] [\(1970BA33, 1971BA04, 1974CH37\)](#).

<sup>g</sup> This state is attributed to the giant M2 resonance [\(1974CH37\)](#).

<sup>h</sup> [\(1971DR06\)](#) suggest two states at  $E_x = 20.37$  and  $20.42$  MeV [ $\Gamma_{c.m.} = 120$  and  $180$  keV;  $J^\pi \geq 1$  and  $(2, 3, 4)^+$ , respectively]. The first corresponds to a structure in the  $p_1$  yield, the second to structures in the  $n, p_0$  and  $(p_2)$  yields.

<sup>i</sup> Nominal  $E_p$ , calculated from  $E_x$ .

<sup>j</sup> Resonant in  $n, p_2$  [\(1971DR06\)](#).

<sup>k</sup> Resonant in  $p_2$  [\(1971DR06\)](#).

<sup>1</sup>  $(\Gamma_{p;l=0} + \Gamma_{p;l=2})\Gamma_\gamma\Gamma = 21.0 \pm 1.0, 488 \pm 20, 69 \pm 5, 130 \pm 13, 650 \pm 50$  eV for  $^{16}\text{O}^*(20.95, 22.15, 22.89, 24.07, 25.12)$ , respectively [\(1973OC1B\)](#).

<sup>m</sup> Resonant in  $p_1$  [\(1971DR06\)](#).



<sup>n</sup> Resonant in  $p_0, p_1, p_6$  (1971DR06).

<sup>o</sup> These three states are attributed to the configuration  $(1p_{1/2}^{-1}1f_{7/2})_{4^+;T=1}$ .  $J = 2$  and  $3$  are not excluded (1974CH37).

<sup>p</sup> S.H. Chew and J. Lowe, private communication.

Table 16.20: Resonances in  $^{15}\text{N}(\text{p}, \text{n})^{15}\text{O}$  (1968BA42) <sup>a</sup>

$E_p$ (MeV $\pm$ keV)	$\Gamma_{\text{c.m.}}$ (keV)	$J^\pi; T^d$	$E_x$ (MeV)
4.37 $\pm$ 15	19 $\pm$ 6	1 <sup>(+)</sup> ; 1	16.22
4.45 $\pm$ 30	240 $\pm$ 30	0 <sup>(-)</sup>	16.30
5.35 $\pm$ 15	33 $\pm$ 5	1 <sup>(-)</sup> ; 1	17.14
5.52 $\pm$ 15	90 $\pm$ 10	1 <sup>-</sup> ; 1	17.30
5.88 $\pm$ 15	59 $\pm$ 10	$\geq 1$ ; 1	17.64
6.12 $\pm$ 15	101 $\pm$ 10	$\geq 1$ ; 1	17.86
6.23 $\pm$ 15 <sup>b</sup>	$\leq 50$	$T = 1$	17.96
6.33 $\pm$ 15	26 $\pm$ 5	$\geq 1$ ; 1	18.06
6.43 $\pm$ 30	$\approx 300$		18.15
6.76 $\pm$ 25	$\approx 160$		18.46
7.03 $\pm$ 30	260 $\pm$ 30		18.71
7.59 $\pm$ 25	90 $\pm$ 10	2 <sup>-</sup> ; 1	19.24
7.86 $\pm$ 30	300 $\pm$ 80	1 <sup>-</sup> <sup>c</sup>	19.49
8.30 $\pm$ 25	120 $\pm$ 40		19.90
8.82 $\pm$ 25	150 $\pm$ 30	$\geq 2$	20.39
8.89 $\pm$ 25	140 $\pm$ 30	$\geq 1$	20.55
9.36 $\pm$ 25	$\approx 300$		20.90
10.7 $\pm$ 100	$\approx 650$	1	22.2

<sup>a</sup> See also (1971AJ02).

<sup>b</sup> Probably a doublet: see (1968BA42).

<sup>c</sup> 1<sup>-</sup> is from (p,  $\gamma$ );  $J \geq 2$  is required from (p, n) yield.

<sup>d</sup>  $T$ -assignments by energy and width comparisons with states in  $^{16}\text{N}$ .

Elastic scattering studies are reported for  $E_p = 0.6$  to 11.7 MeV: see Table 16.20 in (1971AJ02) and Table 16.18 here. Observed anomalies are displayed in Table 16.19 (1971DR06). Inelastic scattering has been studied for  $E_p = 8.5$  to 11.6 MeV: the  $p_1$  yield is dominated by a structure at  $E_p = 10.6$  MeV,  $\Gamma_{\text{cm}} \approx 650$  keV (1971DR06). A study of the elastic yield and the polarization ( $E_p = 8.4$  to 10.5 MeV) shows that a narrow  $s$ -wave resonance does not exist at the deuteron threshold ( $E_x = 20.74$  MeV) (1975FI1E). See also (1973HO36; theor.).

$$48. \ ^{15}\text{N}(\text{p}, \text{n})^{15}\text{O}$$

$$Q_m = -3.542$$

$$E_b = 12.1277$$

Table 16.21: Lifetime measurements of some  $^{16}\text{O}$  states

$^{16}\text{O}^*$ (MeV)	$\tau_m$ <sup>a</sup>	Reaction	Refs.
6.05	$96 \pm 7$ psec	$^{19}\text{F}(\text{p}, \alpha)$	(1973BI17)
6.13	$26.6 \pm 0.7$ psec	$^{19}\text{F}(\text{p}, \alpha)$	(1973BR31)
6.92	$8.4 \pm 1.6$ fsec		b
	$6.00 \pm 0.03$ fsec	Table 16.15	“best” value
7.12	$7.2 \pm 1.7$ fsec		b
	$12.0 \pm 1.2$ fsec	Table 16.15	“best” value
8.87	$180 \pm 16$ fsec		b
10.95	$8 \pm 5$ fsec		b

<sup>a</sup> See also Table 16.15.

<sup>b</sup> “Mean” or “best” value from Table 16.19 of (1971AJ02).

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 16.20 (1968BA42) also discusses in detail the relationship of his results and the data reported in other experiments, including a comparison with analog states in  $^{16}\text{N}$  [see Fig. 5]. Excitation functions have also been reported from threshold to 13.6 MeV: see Table 16.20 in (1971AJ02). Polarization measurements for  $n_0$  have been carried out at  $E_p = 7.9$  to 12.3 MeV (1965WA02) and at 10.3 and 11.3 MeV (1976BY1A, 1976BY1B). See also (1974LO1B) and (1972DU1D, 1973BA05, 1973HO36, 1973VO1J, 1974HO1L, 1974MA07, 1975RO31, 1976AR1F; theor.).

$$49. \text{ (a) } ^{15}\text{N}(\text{p}, \text{t})^{13}\text{N} \quad Q_m = -12.905 \quad E_b = 12.1277$$

$$\text{ (b) } ^{15}\text{N}(\text{p}, ^3\text{He})^{13}\text{C} \quad Q_m = -10.6659$$

The yields of the first three triton and  $^3\text{He}$  groups have been measured for  $E_p = 24.0$  to 43.5 MeV (1974PI05, 1975MI01). Polarized protons with  $E_p = 43.8$  MeV have been used to study the transitions to  $^{13}\text{C}^*(0, 3.68, 7.55, 15.11)$  and  $^{13}\text{N}^*(0, 3.51, 7.38, 15.07)$  (1974MA12). See also (1970HA23, 1972HA1X).

$$50. ^{15}\text{N}(\text{p}, \alpha)^{12}\text{C} \quad Q_m = 4.9661 \quad E_b = 12.1277$$

Excitation functions for  $\alpha_0$  and  $\alpha_1$  particles [corresponding to  $^{12}\text{C}^*(0, 4.43)$ ] and of 4.43 MeV  $\gamma$ -rays have been measured for  $E_p = 0.093$  to 45 MeV: see Table 16.20 in (1971AJ02) and Table

16.18 here. Observed resonances are shown in Table 16.19. Angular correlation measurements lead to  $J^\pi = 2^-, 1^-, 3^-$  and  $1^+$  for  $^{16}\text{O}^*(12.97, 13.09, 13.26, 13.66)$  (1969CL07). For  $E_p > 3.5$  MeV there is continuing structure in the yield curves which is interpreted in terms of fluctuations: see (1971AJ02). For polarization measurements see (1976PE03, 1976PE1H: 0.34 to 1.21 MeV).

A study of  $\alpha_1\gamma$  for  $E_p = 0.15$  to 2.50 MeV leads to  $S(0) \approx 0.1$  keV · b and shows that this reaction makes a negligible contribution to hydrogen burning at stellar energies compared to the (p,  $\gamma_0$ ) and (p,  $\alpha_0$ ) processes (1974RO37). See also (1973JA1D), (1974CL1F, 1975LA1J, 1976LA1J; applications), (1971BA1A; astrophys. considerations) and (1972MA1K, 1976GA1K; theor.).

$$51. \ ^{15}\text{N}(\text{d}, \text{n})^{16}\text{O} \quad Q_m = 9.9031$$

Observed neutron groups are displayed in Table 16.22. Angular distributions have been reported for  $E_d$  to 6 MeV: see (1971AJ02) and (1971MU09, 1972FO17:  $E_d = 4.83$  and 5.84 MeV) and (1973BA2C:  $E_d = 5.0, 5.5$  and 6.0 MeV):  $l$ -values and spectroscopic factors are also shown in Table 16.22.

Slow neutron thresholds have been observed to  $^{16}\text{O}^*(10.954 \pm 0.010, 11.080 \pm 0.015)$  (1957WE1A).  $^{16}\text{O}^*(10.95)$   $\gamma$ -decays only to  $^{16}\text{O}^*(7.12)$ ,  $J^\pi = 1^-$ . This suggests  $J^\pi = 0^-$  for  $^{16}\text{O}^*(10.95)$ , an assignment also strongly favored by the  $\gamma - \gamma$  correlation (1957BE61). See also  $^{17}\text{O}$ .

$$52. \ ^{15}\text{N}(\text{}^3\text{He}, \text{d})^{16}\text{O} \quad Q_m = 6.6340$$

Angular distributions have been measured at  $E(^3\text{He}) = 11$  MeV (1969BO13, 1971BO02) and at  $E(^3\text{He}) = 16.0$  and 24.9 MeV (1969FU08):  $l$ - and  $S$ -values are shown in Table 16.22. See also (1973FR1E), (1973OG1A), (1970CO30, 1972EN03, 1975HS01; theor.).

$$53. \ ^{15}\text{N}(\alpha, \text{t})^{16}\text{O} \quad Q_m = -7.6869$$

Not reported.

$$54. \ ^{15}\text{N}(\text{}^{11}\text{B}, \text{}^{10}\text{Be})^{16}\text{O} \quad Q_m = 0.898$$

See (1975SC2C) and (1971AJ02).

$$55. \ ^{16}\text{N}(\beta^-)^{16}\text{O} \quad Q_m = 10.418$$

Table 16.22: States in  $^{16}\text{O}$  from  $^{15}\text{N}(\text{d}, \text{n})^{16}\text{O}$ ,  $^{15}\text{N}({}^3\text{He}, \text{d})^{16}\text{O}$  and  $^{17}\text{O}({}^3\text{He}, \alpha)^{16}\text{O}$ 

$^{16}\text{O}$ state at (MeV)	$J^\pi; T$	$l^a$	$l^b$	$S^c$	$S^d$	$S^e$	“Best” $S^f$	$S^g$	$S^h$	$S^p$	$l^p$
0	$0^+; 0$	1	1			2.5	3.1	1.33	3.52	0.88	2
6.05	$0^+; 0$		1					0.05	0.16	0.009	2
6.13	$3^-; 0$	2	2	0.72	0.75	0.80		0.40	0.63	0.37	1
6.92	$2^+; 0$	not direct	1 + 3					0.04 <sup>n</sup>		0.022	(2 + 0)
7.12	$1^-; 0$	0	0 + 2	0.33	0.75 <sup>j</sup>	0.32		0.20 <sup>o</sup>	0.54	0.007 <sup>q</sup>	(3 + 1)
8.87	$2^-; 0$	2	2	0.33	0.55	0.44	0.72	0.36	0.55	0.26	1
9.63	$1^-; 0$		0					0.008			
9.85	$2^+; 0$	1	not direct	0.02	< 0.05					0.025	2
10.35	$4^+; 0$		3					0.02		0.025	2
10.95	$0^-; 0$	0	0	0.48	1.25	0.76	0.76	0.50	1.20	0.008	(3 + 1)
11.08	$3^+; 0$	3	3	0.30	0.30	0.30	0.18	0.09		0.044 or 0.086	2
11.26	$0^+; 0$		broad state								
12.44	$1^-; 0$	0	0	(0.16)	0.64 <sup>k</sup>	0.40	0.40	$0.25 \pm 0.1$	0.25		
12.53	$2^-; 0$	2	2	(0.52)	0.50 <sup>l</sup>	0.72 <sup>m</sup>	0.72	$0.45 \pm 0.1$	1.45		
12.80	$0^-; 1$	0	0	(0.40)	1.20	0.44	0.44	$0.40 \pm 0.1$			
12.97	$2^-; 1$	2	2	(0.63)		0.40	0.40	$0.35 \pm 0.1$	0.85	0.38	1
13.10	$1^-; 1$	(0)		(0.63)		0.58	0.58	$\leq 0.4 \pm 0.2$		0.10	1
			2(+0)								
13.13 <sup>i</sup>	$3^-; 0$	(2)				0.32	0.32	$0.12 \pm 0.05$	0.96		
13.26	$3^-; 1$	2	2	(0.60)		0.46	0.46	$0.27 \pm 0.1$	0.96	0.34	1
17.14 <sup>b</sup>	$1^-; 1$										
17.20 <sup>b</sup>	$2^+$										

- <sup>a</sup> (1967FU07, 1971MU09, 1973BO1G): (d, n);  $E_d = 4.8 \rightarrow 6$  MeV.
- <sup>b</sup> (1969BO13, 1969FU08, 1971BO02): ( $^3\text{He}$ , d),  $E(^3\text{He}) = 11, 16.0$  and  $24.9$  MeV.
- <sup>c</sup> (1971MU09): (d, n).
- <sup>d</sup> (1972FO17): (d,  $\bar{n}$ ).
- <sup>e</sup> (1973BO1G): (d, n),  $E_d = 5 - 6$  MeV.
- <sup>f</sup> “Best” values as discussed by (1973BO1G) [from (d, n) and ( $^3\text{He}$ , d) data]. See also (1975HS01).
- <sup>g</sup> (1969BO13, 1971BO02): ( $^3\text{He}$ , d);  $E(^3\text{He}) = 11$  MeV.
- <sup>h</sup> (1969FU08): ( $^3\text{He}$ , d);  $E(^3\text{He}) = 16.0$  and  $24.9$  MeV.
- <sup>i</sup>  $\Gamma = 128$  keV.
- <sup>j</sup> For  $2s_{1/2}$ , 0.18 for  $1d_{3/2}$ .
- <sup>k</sup> For  $2s_{1/2}$ , 0.17 for  $1d_{3/2}$ .
- <sup>l</sup> For  $1d_{3/2}$ , 0.05 for  $1d_{5/2}$ .
- <sup>m</sup> For  $1d_{3/2}$ , 0.62 for  $1d_{5/2}$ .
- <sup>n</sup> For  $1f_{5/2}$ , 0.01 for  $1p_{3/2}$ .
- <sup>o</sup> For  $1s_{1/2}$ .
- <sup>p</sup> (1971BO02): ( $^3\text{He}$ ,  $\alpha$ );  $E(^3\text{He}) = 11$  MeV.
- <sup>q</sup>  $1d_{3/2}$  (1971BO02).

The ground state of  $^{16}\text{N}$  decays to seven states of  $^{16}\text{O}$ : reported branching ratios are listed in Table 16.23. The ground state transition has the unique first-forbidden shape corresponding to  $\Delta J = 2$ , yes, fixing  $J^\pi$  of  $^{16}\text{N}$  as  $2^-$ : see (1959AJ76). For the  $\beta$ -decay of  $^{16}\text{N}^*(0.12)$  see reaction 1 in  $^{16}\text{N}$  (1975PA01).

The  $\alpha$ -decay of  $^{16}\text{O}^*(8.87, 9.63, 9.85)$  has been observed: see (1971AJ02). The parity-forbidden  $\alpha$ -decay from the  $2^-$  state  $^{16}\text{O}^*(8.87)$  has been reported:  $\Gamma_\alpha = (1.03 \pm 0.28) \times 10^{-10}$  eV [ $E_\alpha = 1282 \pm 5$  keV] (1970HA42, 1974NE10). (1971WE14) suggests that the  $\alpha$ -width of  $^{16}\text{O}^*(7.12)$  is an order of magnitude smaller than that for  $^{16}\text{O}^*(9.58)$ . See also (1970SP1D).

Recently reported transition energies derived from  $\gamma$ -ray measurements are:  $E_x = 6130.43 \pm 0.05$  keV [ $E_\gamma = 6129.170 \pm 0.043$  keV (1975SH18)] and  $7116.85 \pm 0.14$  keV [ $E_\gamma = 7115.15 \pm 0.14$  keV (1976AL16)]. See also (1967CH19, 1974AL11) and (1973DO1H, 1974WI1N, 1975BO1V, 1975DO10, 1976LO01; theor.).

Table 16.23: Beta decay of the ground state of  $^{16}\text{N}$  <sup>a</sup>

Final state		Branch (%)	$\log ft$ <sup>b</sup>
$^{16}\text{O}^*$ (MeV)	$J^\pi$		
0	$0^+$	$26 \pm 2$ <sup>c</sup>	$9.10 \pm 0.04$ <sup>g</sup>
6.05	$0^+$	$(1.2 \pm 0.4) \times 10^{-2}$ <sup>d</sup>	$9.96 \pm 0.15$ <sup>g</sup>
6.13	$3^-$	$68 \pm 2$ <sup>c</sup>	$4.47$ <sup>h</sup>
7.12	$1^-$	$4.9 \pm 0.4$ <sup>c</sup>	$5.09$ <sup>h</sup>
8.87	$2^-$	$1.0 \pm 0.2$ <sup>c</sup>	$4.37$ <sup>h</sup>
9.63	$1^-$	$(1.20 \pm 0.05) \times 10^{-3}$ <sup>e</sup>	$6.21$ <sup>h</sup>
9.85	$2^+$	$(6.5 \pm 2.0) \times 10^{-7}$ <sup>f</sup>	$9.07 \pm 0.13$ <sup>i</sup>

<sup>a</sup> See also reaction 1 in  $^{16}\text{N}$ .

<sup>b</sup>  $\tau_{1/2} = 7.13 \pm 0.02$  sec: see Table 16.3 in (1971AJ02).

<sup>c</sup> (1956WI1A, 1958AL13, 1959AL06).

<sup>d</sup> (1968WA18).

<sup>e</sup> (1961KA06). See also (1974NE10).

<sup>f</sup> (1969HA42).

<sup>g</sup> (1971TO08):  $\log f_1 t$ .

<sup>h</sup> B. Zimmerman, private communication:  $\log f_0 t$ .

<sup>i</sup> E.K. Warburton, private communication:  $\log f_1 t$ .

56. (a)  $^{16}\text{O}(\gamma, n)^{15}\text{O}$   $Q_m = -15.669$   
 (b)  $^{16}\text{O}(\gamma, 2n)^{14}\text{O}$   $Q_m = -28.8886$

Recent papers reviewing this reaction are (1973DI1C, 1975BE60).

The absorption cross section and the  $(\gamma, n)$  cross section are marked by a number of resonances. Some of the reported structure is displayed in Table 16.25 of (1971AJ02). In view of the availability of experiments using monoenergetic photons and good resolution and statistics we suggest, on the basis of the work of (1974VE06, 1975BE60, 1975BE1F, 1965CA1B) that excited states of  $^{16}\text{O}$  are observed at  $E_x = 17.3$  [u], 19.3 [u] and 21.0 MeV [u = unresolved], followed by the giant resonance whose principal structures are at  $\approx 22.2$  and 24.1 MeV, with additional structures at 23 and 25 MeV. See also (1972WA13; theor.). The best resolution achieved so far appears to be that of (1974VE06) who measured the  $(\gamma, n + \gamma, pn)$ ,  $(\gamma, pn)$  and  $(\gamma, 2n)$  cross sections separately to  $E_\gamma = 37$  MeV. Besides the monoenergetic photon work, there are still a number of reports of bremsstrahlung studies: the most convincing of these is by (1975JO04) and (1970JU02). These time-of-flight data confirm the structure indicated above. See also (1971BA2W, 1971IS1A, 1972TH12, 1973SY1A). The yield of reaction (a) has been measured for  $E_{bs} = 100$  to 800 MeV (1971AD05, 1971FR11; also 6.18  $\gamma$ ). The absorption cross section has been measured from  $E_{bs} = 10$  MeV to above the meson threshold (1975AH06). The cross section for reaction (b) has been measured between threshold and  $E_\gamma = 120$  MeV: it is usually small compared to the  $(\gamma, n)$  cross section at corresponding energies (1970FI15). Polarization measurements for the  $n_0$  group have been carried out at  $E_{bs} = 20$  to 30 MeV and at 64 MeV (1970CO1G, 1971CO1E, 1973NA1F).

Branching ratios for the decay of  $^{16}\text{O}$  in the giant resonance region to various excited states in  $^{15}\text{O}$  are discussed in  $^{15}\text{O}$  (1976AJ04).

See also (1971KA70, 1975SC05), (1970FI1D, 1970HA1F, 1972BU1J, 1973GL1B, 1973GL1C, 1973HA1Q, 1974BU1A, 1975BR1F), (1976AL1L; applied work) and (1970HU18, 1970MU20, 1970VA1M, 1971AN08, 1971PE02, 1971SH05, 1971WE04, 1972AG02, 1972DU1D, 1972FI09, 1973BA05, 1973BA2H, 1973CI1A, 1973DE26, 1973GO36, 1973HO36, 1973IS1A, 1973MA1T, 1973ROYN, 1973SR1B, 1973WA03, 1974DO13, 1974FA1B, 1974FI03, 1974KR24, 1974MU1E, 1974WA12, 1975DU16, 1975MA2A, 1975RO31, 1976HE12, 1976KA09, 1976KA1Q, 1976NI1D; theor.).

57.  $^{16}\text{O}(\gamma, p)^{15}\text{N}$

$$Q_m = -12.1277$$

The  $(\gamma, p_0)$  cross section derived from the inverse capture reaction (reaction 46) confirms the giant resonance structure indicated above as do also the direct  $(\gamma, p_0)$  measurements. The total  $(\gamma, p)$  cross section is given by (1968DE07). For yields at higher energies see (1973MA1U:  $E_{bs} = 50 \rightarrow 80$  MeV) and (1971AD05: 100  $\rightarrow$  800 MeV; 6.32  $\gamma$ -ray). Branching ratios for the decays of  $^{16}\text{O}$  states in the giant resonance region to various excited states in  $^{15}\text{N}$  are discussed in  $^{15}\text{N}$  in (1976AJ04) and in (1973DI1C, 1975BE1F). For a comparison with results from the  $^{15}\text{N}(p, \gamma)^{16}\text{O}$  reaction see (1974HA01).

See also (1973DO13, 1976MA2E), (1970FI1D, 1970HA1F, 1972BU1J, 1973CO1N, 1973HA1Q, 1974HA1C) and (1969GR1A, 1970HU18, 1970MU20, 1970WE1H, 1971DE1G, 1971WE04, 1972FI09,



1972WA13, 1973BA05, 1973BL1D, 1973CI1A, 1973DE26, 1973HO36, 1973MA1T, 1974FA1B, 1974KR24, 1975RA02, 1976FI06, 1976HE12, 1976KA1Q, 1976NI1D; theor.).

58. (a)  $^{16}\text{O}(\gamma, d)^{14}\text{N}$   $Q_m = -20.7368$   
 (b)  $^{16}\text{O}(\gamma, pn)^{14}\text{N}$   $Q_m = -22.9614$   
 (c)  $^{16}\text{O}(\gamma, pp)^{14}\text{C}$   $Q_m = -22.3350$   
 (d)  $^{16}\text{O}(\gamma, pd)^{13}\text{C}$   $Q_m = -28.2874$

For reactions (b), (c) and (d) see (1973HA2B). For reaction (b) see reaction 56, (1972BU1J) and (1970WE1G, 1973KO1H, 1976HE12; theor.). For the previous work on all these reactions see (1971AJ02).

59. (a)  $^{16}\text{O}(\gamma, t)^{13}\text{N}$   $Q_m = -25.033$   
 (b)  $^{16}\text{O}(\gamma, \alpha)^{12}\text{C}$   $Q_m = -7.1616$   
 (c)  $^{16}\text{O}(\gamma, 4\alpha)$   $Q_m = -14.4364$

For reactions (a) and (c) see (1971AJ02). A study of the  $^{16}\text{O}(\gamma, \alpha_0)$  reaction at  $\theta = 45^\circ$  and  $90^\circ$  shows a  $2^+$  resonance at  $E_x = 18.2$  MeV with an E2 strength which is spread out over a wide energy interval. A strong resonance corresponding to an isospin forbidden  $1^-$  state at  $E_x \approx 21.1$  is also observed (1975SK06). See also (1973HA1Q, 1976MA62, 1976MA1D) and (1971AJ02).

60.  $^{16}\text{O}(\gamma, \gamma)^{16}\text{O}$

The differential scattering cross section has been measured for  $E_\gamma = 18.5$  to 33 MeV: the main giant resonance peaks are located at  $\approx 22$  and  $\approx 25$  MeV (1967LO1B). (1970AH02) report resonances at  $E_\gamma = 22.5 \pm 0.3$ ,  $25.2 \pm 0.3$ ,  $31.8 \pm 0.6$  and  $50 \pm 3$  MeV: the dipole sum up to 80 MeV exceeds the classical value  $60 NZ/A$  MeV · mb by a factor 1.4. For lifetime measurements of  $^{16}\text{O}^*(6.9, 7.1)$ , see Table 16.19 in (1971AJ02); for widths, see Table 16.12 in (1971AJ02). The separation between the (7.12) and (6.92)  $\gamma$ -lines is  $199.8 \pm 0.5$  keV (1970SW03). Based on  $7116.85 \pm 0.14$  keV (Table 16.9),  $E_x$  for the lower state is  $6917.1 \pm 0.6$  keV.

61. (a)  $^{16}\text{O}(e, e)^{16}\text{O}$   
 (b)  $^{16}\text{O}(e, ep)^{15}\text{N}$   $Q_m = -12.1277$

The  $^{16}\text{O}$  charge radius =  $2.718 \pm 0.021$  fm (1973FE13, 1975SC18). See also (1971BE25) and

Table 16.24: Excited states observed in  $^{16}\text{O}(e, e')^{16}\text{O}^a$ 

$E_x$ (MeV $\pm$ keV)	$J^\pi; T$	Mult.	$\Gamma$ (keV)	$\Gamma_{\gamma_0}$ (eV)	Refs.
6.05	$0^+$	E0		$3.55 \pm 0.21^b$	(1975MI08)
6.13	$3^-$	E3		$(2.60 \pm 0.13) \times 10^{-5}$	(1975MI08)
6.92	$2^+$	E2		$0.130 \pm 0.009$	(1973BE49)
				$0.100 \pm 0.004$	(1975MI08)
7.12	$1^-$	E1		$(4.6 \pm 2.3) \times 10^{-2}$	(1975MI08) <sup>c</sup>
9.85	$2^+$	E2		$(8.8 \pm 1.7) \times 10^{-3}$	(1973BE49)
10.35	$4^+$	E4		$(5.6 \pm 2.0) \times 10^{-8}$	(1973BE49)
11.52	$2^+$	E2		$0.61 \pm 0.02$	(1973BE50)
12.05	$0^+$	E0		$4.03 \pm 0.09^b$	(1973BE50)
12.53	$2^-$	M2		$0.021 \pm 0.006$	(1968ST31)
				$0.108 \pm 0.015$	(1970KI02)
12.97	$2^-$	M2		$0.071 \pm 0.002$	(1970KI02)
13.0	$2^+$	E2		0.89	(1970KI02) <sup>d</sup>
$13.10 \pm 250$	$1^-; 1$	E1		$\leq 49 \pm 13$	(1970KI02) <sup>d</sup>
$14.00 \pm 50$	$0^+$	E0	$170 \pm 50$	$3.3 \pm 0.7^b$	(1969ST06, 1970ST06)
$15.15 \pm 150$	$2^+$	E2	$500 \pm 200$	$1.0 \pm 0.5$	(1970ST06)
$16.21 \pm 30$	$1^+$	M1	$18 \pm 3$	$5.1 \pm 0.8$	(1970ST06, 1975MI08)
$16.46 \pm 70$	$2^+$	E2	$35 \pm 5$	$0.5 \pm 0.2$	(1970ST06, 1975MI08)
$16.80 \pm 100$	$(3^+)$		$\leq 100$	$(1.7 \pm 1.9) \times 10^{-3}$	(1970ST06)
17.14	$1^-; 1$	E1	$40 \pm 6$	$62 \pm 12$	(1970ST06, 1975MI08)
$17.60 \pm 100$	$(2^-)$		$\leq 100$	$0.07 \pm 0.04$	(1970ST06)
$18.50 \pm 100$	$2^+$	E2	$60 \pm 9$		(1970ST06, 1974HO20, 1975MI08)
$19.00 \pm 100$	$1^-; 1$	E1	$300 \pm 100$	$41 \pm 20$	(1965VA1D, 1970GO40, 1970ST06)
$19.04 \pm 50$	$2^-; 1$	M2	$400 \pm 50$	$1.5 \pm 0.3$	(1970GO03, 1970GO40, 1970ST06)
			$850 \pm 150$		(1967DR05, 1968DR01)
$19.50 \pm 100$	$1^-; 1$	E1	$200 \pm 70$	$40 \pm 20$	(1970GO40, 1970ST06)
$20.36 \pm 70$	$2^-$	M2	$500 \pm 100$	$2.9 \pm 1.0$	(1965VA1D, 1968DR01, 1969SI10, 1970GO03, 1970GO40, 1970ST06)
$20.95 \pm 50$	$1^-; 1$	E1	$270 \pm 70$	$180 \pm 50$	(1970GO40, 1970ST06)
$21.34 \pm 250$	$(2^-)$	(M2)			(1965DE1C, 1965VA1D)
22.3					(1970GO40)
23.0					(1970GO40)
$23.7 \pm 250$	$(2^-; 1)$				(1965VA1D, 1970GO03)
24.2					(1963IS02, 1965VA1D, 1970GO03, 1970GO40)
$25.5 \pm 250$	$1^-; 1$	E1			(1963IS02, 1965VA1D)
$26.7 \pm 250$	$1^+$	M1			(1965VA1D)
44.5	$(1^-; 1)$		2000–3000	5300	(1961IS06, 1962BI19)
49	$(1^-; 1)$		2000–3000	19000	(1961IS06, 1962BI19)

<sup>a</sup> See also Table 16.26 in (1971AJ02).

<sup>b</sup> Monopole matrix element in fm<sup>2</sup>.

<sup>c</sup> See also text and (1975MI13).

<sup>d</sup> See also (1968ST31).

(1971AJ02). Form factors for transitions to the ground and to excited states of <sup>16</sup>O have been reported in many studies: see (1971AJ02) and (1970SI08, 1973BE49, 1973BE50). Table 16.24 lists the excited states observed from spectra of inelastically scattered electrons. The isospin-forbidden (E1) excitation of <sup>16</sup>O\*(7.12) has been reported by (1975MI08, 1975MI13): the isovector contribution interferes destructively with the isoscalar part and has strength  $\approx 1\%$  of the  $T = 0$  amplitude (1975MI08; and H.H. Miska, private communication).

The  $0^+$  states <sup>16</sup>O\*(6.05, 12.05, 14.00) saturate  $\approx 19\%$  of an isoscalar monopole sum rule (1973BE50). As for the E2 strength it is distributed over a wide energy region: see Table 16.24 and (1974HO20).

See also (1970SI1K, 1971BI1H, 1975HI1C), (1970BR1C, 1972THZF, 1973TH1B, 1974DE1E, 1975BE1T, 1975BE1G, 1975SI1H) and (1970DO1A, 1970FU1A, 1971BO05, 1971BR42, 1971DU06, 1971EI01, 1971ER08, 1971FR13, 1971KH02, 1971LE31, 1971MA1N, 1972CA23, 1972DO02, 1972DO17, 1972FI10, 1972FR06, 1972GA26, 1972GU14, 1972WE14, 1973BL1C, 1973BO1Q, 1973DO1H, 1973EL1C, 1973ER12, 1973FA1F, 1973GA19, 1973GO1P, 1973HO23, 1973HO29, 1973MA07, 1973SP1A, 1973WA1D, 1974BA1Z, 1974BO2D, 1974CI02, 1974DZ06, 1974DZ05, 1974FA1B, 1974FR12, 1974SO13, 1974TR08, 1975AB04, 1975AR30, 1975DE1L, 1975DO10, 1975DO1D, 1975DZ04, 1975IN04, 1975LA1G, 1975LE14, 1975RA02, 1975RO23, 1975WA33, 1976BU1B, 1976CU06, 1976FA08, 1976RA1M; theor.).

62. (a) <sup>16</sup>O( $\pi^+$ ,  $\pi^+$ )<sup>16</sup>O

(b) <sup>16</sup>O( $\pi^-$ ,  $\pi^-$ )<sup>16</sup>O

The small angle scattering of  $\pi^+$  and  $\pi^-$  has been studied at  $E_\pi = 155, 185$  and  $213$  MeV (1975MU06). At  $E_{\pi^-} = 230$  MeV, the excitation of <sup>16</sup>O\*(6.13) is reported (1974LI15). See also the “General” section here.

63. <sup>16</sup>O(n, n)<sup>16</sup>O

Angular distributions have been measured at energies to  $E_n = 14.1$  MeV: see Table 16.27 in (1971AJ02) and Table 16.25 here. Gamma rays have been observed corresponding to the ground state decay of <sup>16</sup>O states at  $E_x = 6129.1 \pm 1.2$  keV [ $E_\gamma = 6127.8 \pm 1.2$  keV] (1966BE1A),  $6906 \pm 15$ ,  $7112 \pm 10$  and  $8865 \pm 3$  keV (1971NY03). See also (1974HO1E, 1975PO08, 1976NO1F) and (1972JE01, 1973DA1H, 1973SC1L; theor.).

Table 16.25: Recent  $^{16}\text{O}(\text{n}, \text{n})$ ,  $^{16}\text{O}(\text{p}, \text{p})$ ,  $^{16}\text{O}(\text{d}, \text{d})$ ,  $^{16}\text{O}(\text{t}, \text{t})$ ,  $^{16}\text{O}(\text{}^3\text{He}, \text{}^3\text{He})$ ,  $^{16}\text{O}(\alpha, \alpha)$ ,  $^{16}\text{O}(\text{}^6\text{Li}, \text{}^6\text{Li})$ ,  $^{16}\text{O}(\text{}^7\text{Li}, \text{}^7\text{Li})$ ,  $^{16}\text{O}(\text{}^{12}\text{C}, \text{}^{12}\text{C})$ ,  $^{16}\text{O}(\text{}^{16}\text{O}, \text{}^{16}\text{O})$  <sup>a</sup> angular distribution studies

$E_n$ (MeV)	Angular distribution of group	Refs.
4.34 $\rightarrow$ 8.56	$n_0$	(1972KI1D)
6.87, 7.82	$\gamma_2$	(1970LU16)
7.54, 8.04, 8.56	$n_{1+2}$	(1972KI1D)
14.1	$n_0$	(1972BO52)
$E_p$ (MeV)	Angular distribution of group	Refs.
9.0 $\rightarrow$ 20.35	$p_0$	(1974SK02)
12.703, 13.600, 16.160, 19.425	$p_0$	(1974JA25)
21.5 $\rightarrow$ 30.8	$p_0, p_2$	(1971BU05)
23.4 $\rightarrow$ 46.1	$p_1, p_2, p_5$	(1971AU04)
27.2	$p_1$	(1976CE1F)
30.3 <sup>b</sup>	$p_0$	(1976DE12)
30.4 <sup>b</sup>	$p_0, p_5$	(1972GR02)
31.7 $\rightarrow$ 39.9 <sup>b</sup>	$p_5$	(1976LE16)
45	see Table 16.26	(1975BU1F, 1976BU15)
49.5	$p_0$ (back angles)	(1970CL10)
65.8	$p_0$	(1973LE07)
$E_d$ (MeV)	Angular distribution of group	Refs.
1.0 $\rightarrow$ 2.0	$d_0$	(1972CO15)
8	$d_0$	quoted in (1971KO21)
9.3, 13.3	$d_0$	(1973CA30)
10.000, 12.052	$d_0$ <sup>c</sup>	(1974JA25)
13.6	$d_0$	(1970VE06, 1972MA47)
15	$d_0$	(1974BU06)
25.4, 36.0, 63.2	$d_0$	(1974CO04)
81.6	see Table 16.26	(1974DU06)
$E_t$ (MeV)	Angular distribution of group	Refs.
1.85 $\rightarrow$ 3.70	$t_0$	(1973WE11)
20.010	$t_0$ <sup>c</sup>	(1974JA25)

Table 16.25: Recent  $^{16}\text{O}(\text{n}, \text{n})$ ,  $^{16}\text{O}(\text{p}, \text{p})$ ,  $^{16}\text{O}(\text{d}, \text{d})$ ,  $^{16}\text{O}(\text{t}, \text{t})$ ,  $^{16}\text{O}(^3\text{He}, ^3\text{He})$ ,  $^{16}\text{O}(\alpha, \alpha)$ ,  $^{16}\text{O}(^6\text{Li}, ^6\text{Li})$ ,  $^{16}\text{O}(^7\text{Li}, ^7\text{Li})$ ,  $^{16}\text{O}(^{12}\text{C}, ^{12}\text{C})$ ,  $^{16}\text{O}(^{16}\text{O}, ^{16}\text{O})$  <sup>a</sup> angular distribution studies (continued)

$E(^3\text{He})$ (MeV)	Angular distribution of group	Refs.
11	g.s.	(1970BO25)
71	see Table 16.26	(1974MO26)
$E_\alpha$ (MeV)	Angular distribution of group	Refs.
14.0 → 18.1	$\alpha_0, \alpha_{1+2}, \alpha_3, \alpha_4$	(1975BI1H)
18.9 → 23.0	$\alpha_0$	(1971BE17)
20.1	$\alpha_0$	(1972CA45)
20.40 → 24.28	$\alpha_0$	(1971TA05)
22, 24, 28, 29	$\alpha_0$	(1972OE01, 1973OE01)
26.6	$\alpha_0$	(1972KU19)
60	Table 16.26	(1975BU1F, 1976BU15)
104	$\alpha_0$	(1970HA1G)
104	see Table 16.26	(1976HA19, 1976HA27)
146	$^{16}\text{O}^*(0, 6.13, 6.92, 11.52, 18.4)$ [Table 16.26]	(1975KN05)
$E(^6\text{Li})$ (MeV)	Angular distribution of group	Refs.
4.5, 5.8, 9.0, 13.0	g.s.	(1976PO02)
20	g.s.	(1969BE90)
22.8 <sup>b</sup>	g.s.	(1976WE10)
29.8	g.s.	(1972BA52)
30	g.s.	(1971CH1P, 1971DA33)
$E(^{16}\text{O}) = 36$	g.s.	(1971OR02)
36	g.s.	(1973SC26)
51	g.s.	(1975CH1Q)
$E(^7\text{Li})$ (MeV)	Angular distribution of group	Refs.
9.0, 13.0	g.s.	(1976PO02)
20	g.s.	(1969BE90)
$E(^{16}\text{O}) = 36$	g.s.	(1971OR02)
36	g.s.	(1973SC26)

Table 16.25: Recent  $^{16}\text{O}(n, n)$ ,  $^{16}\text{O}(p, p)$ ,  $^{16}\text{O}(d, d)$ ,  $^{16}\text{O}(t, t)$ ,  $^{16}\text{O}(^3\text{He}, ^3\text{He})$ ,  $^{16}\text{O}(\alpha, \alpha)$ ,  $^{16}\text{O}(^6\text{Li}, ^6\text{Li})$ ,  $^{16}\text{O}(^7\text{Li}, ^7\text{Li})$ ,  $^{16}\text{O}(^{12}\text{C}, ^{12}\text{C})$ ,  $^{16}\text{O}(^{16}\text{O}, ^{16}\text{O})$  <sup>a</sup> angular distribution studies (continued)

$E(^{16}\text{O})$ [reaction 72] <sup>d</sup> (MeV)	Angular distribution of group	Refs.
24, 42, 65, 80	g.s.	(1973GU12)
36	g.s.	(1971OR02)
40.3 $\rightarrow$ 53.2	g.s.	(1976CH13)
45.3, 46.0, 47.1	g.s.	(1972MA29)
46	$^{16}\text{O}^*(6.05, 6.13, 6.92, 7.12)$	(1976SP01)
65, 80	$^{16}\text{O}^*(6.1, 6.9, 8.9, 10.3)$ <sup>e</sup>	(1973GU12)
$E(^{16}\text{O})$ [reaction 76] (MeV)	Angular distribution of group	Refs.
25 to 63	g.s.	(1969MA40, 1970MA1P)
46.6	g.s.	(1974VA18)
51.5	g.s., 6.1 + 6.9	(1974RO04)

<sup>a</sup> The earlier work is displayed in Table 16.27 of (1971AJ02).

<sup>b</sup> Polarized.

<sup>c</sup> Very accurate differential cross sections at several angles.

<sup>d</sup> See also reaction 64 in (1971AJ02).

<sup>e</sup> And  $^{12}\text{C}^*(0, 4.4)$ .

64. (a)  $^{16}\text{O}(p, p)^{16}\text{O}$

(b)  $^{16}\text{O}(p, 2p)^{15}\text{N}$   $Q_m = -12.1277$

(c)  $^{16}\text{O}(p, pd)^{14}\text{N}$   $Q_m = -20.7368$

(d)  $^{16}\text{O}(p, p\alpha)^{12}\text{C}$   $Q_m = -7.1616$

Angular distributions of elastically and inelastically scattered protons have been measured at many energies up to  $E_p = 1000$  MeV: see Table 16.27 in (1971AJ02) and Table 16.25 here. Parameters of the observed groups are displayed in Table 16.26. Evidence, based on a study of the angular distribution and polarization involving  $^{16}\text{O}^*(8.87)$  [ $J^\pi = 2^-$ ], has been obtained by (1976LE16) for an octupole (E3) giant resonance of predominantly isoscalar nature centered near  $E_x \approx 35$  MeV,  $\Gamma \approx 5$  MeV.

For reaction (b) see (1971EI06, 1971HA61) and  $^{15}\text{N}$  in (1976AJ04). For reaction (c) see (1971AJ02) and (1976GO1E). At  $E_p = 46.8$  MeV reaction (d) proceeds predominantly via  $^{16}\text{O}^*(11.0)$  (1971EP03). See also (1973BO1D) and (1971AJ02), (1969BU1B, 1970QU1C, 1971BA1K,

Table 16.26: States of  $^{16}\text{O}$  from  $^{16}\text{O}(\text{p}, \text{p}')$ ,  $(\text{d}, \text{d}')$ ,  $(^3\text{He}, ^3\text{He}')$  and  $(\alpha, \alpha')$  <sup>a</sup>

$E_x^{\text{b}}$ (MeV $\pm$ keV)	$L^{\text{b}}$	$E_x^{\text{d}}$ (MeV)	$E_x^{\text{f}}$ (MeV $\pm$ keV)	$E_x^{\text{g}}$ (MeV $\pm$ keV)	$E_x^{\text{k}}$ (MeV $\pm$ keV)	$L^{\text{g}}$	$\Gamma^{\text{b}}$ (keV)	$J^\pi; T^{\text{h}}$	$\beta^2^{\text{k}}$ ( $\times 10^{-3}$ )
		6.05							
$6.13 \pm 40^{\text{c}}$		6.13	$6.13^{\text{e,f}}$	$6.14 \pm 50^{\text{j}}$	6.13	$3^{\text{j,k}}$		$3^-; 0$	<sup>1</sup>
$6.92^{\text{c}}$		6.92	$6.92^{\text{c,f}}$	$6.90 \pm 50^{\text{j}}$	6.92	$2^{\text{j,k}}$		$2^+; 0^{\text{f}}$	$36^{\text{l}}$
$7.12^{\text{c}}$		7.12		$6.97 \pm 50^{\text{j}}$	7.12	$1^{\text{j,k}}$		$1^-; 0$	
$8.75 \pm 150^{\text{c}}$		8.87	$8.87 \pm 30^{\text{f}}$	$8.876^{\text{j}}$		$3^{\text{j}}$			
$9.70 \pm 150^{\text{c}}$		9.85	$9.84 \pm 30$	$9.80 \pm 50^{\text{j}}$	9.85	$2^{\text{k}}$		$2^+; 0^{\text{f}}$	1.8
$10.35 \pm 20$	4	10.34	$10.35 \pm 30$	$10.35 \pm 30$	10.35	$4^{\text{k}}$		$4^+; 0$	
$10.95 \pm 30$	1	10.95						$T = 0$	
$11.10 \pm 20$	4	$11.1^{\text{e}}$	$11.09 \pm 30^{\text{e}}$	$11.10 \pm 30$	11.10	$4^{\text{k}}$		$4^+; 0$	
$11.52 \pm 20$	2	11.52	$11.52 \pm 30^{\text{f}}$	$11.52 \pm 30$	11.52	$2^{\text{k}}$	$74 \pm 4^{\text{k}}$	$2^+; 0$	$19^{\text{l}}$
$12.05 \pm 20$		12.05	$12.04 \pm 30$	$12.05 \pm 30$	12.05	$(0)^{\text{k}}$		$0^+; 0$	
		12.44			12.44	$1^{\text{k}}$		$1^-; 0$	
$12.53 \pm 20$	1	12.53		$12.51 \pm 30$					
$13.02 \pm 20$	2	$13.1^{\text{e}}$	$13.11 \pm 30$	$13.07 \pm 20$	$13.02 \pm 13.13^{\text{e}}$	$2^{\text{e,k}}$		$2^+; 0$	$4.4^{\text{l}}$
$13.26 \pm 30$	3							$3^-; 1$	
		13.66							
$13.95 \pm 50$	$(0 + 4)$		$13.97 \pm 30$	$13.95 \pm 50$	13.88	$4^{\text{e,k}}$	<sup>e</sup>	$4^+; 0$	
			$14.94 \pm 30$	$14.87 \pm 100$	14.82	$6^{\text{k}}$		$6^+$	
$15.26 \pm 50$	$(3)$		15.4						
$15.50 \pm 30$	3			$15.50 \pm 50^{\text{k}}$	15.45	$3^{\text{k}}$	$200 \pm 60$	$3^-; 0$	
$16.52 \pm 50$	2		$16.46 \pm 30$	$16.40 \pm 100$			$< 100$	$2^+^{\text{f}}$	
$16.93 \pm 50$	$(3)$								

Table 16.26: States of  $^{16}\text{O}$  from  $^{16}\text{O}(\text{p}, \text{p}')$ ,  $(\text{d}, \text{d}')$ ,  $(^3\text{He}, ^3\text{He}')$  and  $(\alpha, \alpha')$  <sup>a</sup> (continued)

$E_x^{\text{b}}$ (MeV $\pm$ keV)	$L^{\text{b}}$	$E_x^{\text{d}}$ (MeV)	$E_x^{\text{f}}$ (MeV $\pm$ keV)	$E_x^{\text{g}}$ (MeV $\pm$ keV)	$E_x^{\text{k}}$ (MeV $\pm$ keV)	$L^{\text{g}}$	$\Gamma^{\text{b}}$ (keV)	$J\pi; T^{\text{h}}$	$\beta^2^{\text{k}}$ ( $\times 10^{-3}$ )
17.25 $\pm$ 50			17.19 $\pm$ 30	17.25 $\pm$ 80		(2)	160 $\pm$ 60	2 <sup>+</sup> <sup>f</sup>	
17.88 $\pm$ 50	3			17.83 $\pm$ 100			150 $\pm$ 60		
18.15 $\pm$ 50	(2)		17.8		18.0 $\pm$ 100	2 <sup>k</sup>	300 $\pm$ 50	(2 <sup>+</sup> ); 0	3.4
18.40 $\pm$ 100	2		18.52 $\pm$ 30	18.35 $\pm$ 100	18.5 $\pm$ 100	2 <sup>k</sup>		2 <sup>+</sup> ; 0	7.7
18.60 $\pm$ 100				18.70 $\pm$ 100	19.0 $\pm$ 100	(3)	280 $\pm$ 80 <sup>e</sup>	3 <sup>-</sup> ; 0	
19.10 $\pm$ 50	(4)						< 100	4 <sup>+</sup> ; 1	
			19.09 $\pm$ 30					2 <sup>+</sup> <sup>f</sup>	
19.35 $\pm$ 80	(1)								
19.56 $\pm$ 50	3			19.50 $\pm$ 100	19.5 $\pm$ 100	(3)		3 <sup>-</sup> ; 0	2.9
			20.0		20.15 $\pm$ 100	2 <sup>k</sup>	350 $\pm$ 50 <sup>k</sup>	2 <sup>+</sup> ; 0 <sup>f</sup>	3.6
19.95 $\pm$ 50	3						< 100	3 <sup>-</sup> ; 1	
20.56 $\pm$ 80	(1, 2)						370 $\pm$ 100		
21.05 $\pm$ 50	1			21.1 $\pm$ 100	20.9 $\pm$ 100	2 <sup>k</sup>	270 $\pm$ 80	(2 <sup>+</sup> ; 0)	4.7
							350 $\pm$ 50 <sup>k</sup>		
21.80 $\pm$ 80	1						370 $\pm$ 100	1 <sup>-</sup> ; 1	
					21.85 $\pm$ 100	2 <sup>k</sup>	400 $\pm$ 50 <sup>k</sup>	2 <sup>+</sup> ; 0	5.7
22.40 $\pm$ 80	(1, 2)						420 $\pm$ 100	1 <sup>-</sup> ; 1	
					22.5 $\pm$ 100		400 $\pm$ 50 <sup>k</sup>	(2 <sup>+</sup> , 3 <sup>-</sup> ); 0	5.0
23.20 $\pm$ 80	1						600 $\pm$ 200	1 <sup>-</sup> ; 1	
				23.50 $\pm$ 150 <sup>i</sup>	23.25 $\pm$ 100	2	400 $\pm$ 50 <sup>k</sup>	2 <sup>+</sup> ; 0	5.6
					23.85 $\pm$ 100	(0) <sup>k</sup>	400 $\pm$ 50 <sup>k</sup>	(2 <sup>+</sup> , 0 <sup>+</sup> ); 0	4.4



Table 16.26: States of  $^{16}\text{O}$  from  $^{16}\text{O}(\text{p}, \text{p}')$ ,  $(\text{d}, \text{d}')$ ,  $(^3\text{He}, ^3\text{He}')$  and  $(\alpha, \alpha')$  <sup>a</sup> (continued)

$E_x$ <sup>b</sup> (MeV $\pm$ keV)	$L$ <sup>b</sup>	$E_x$ <sup>d</sup> (MeV)	$E_x$ <sup>f</sup> (MeV $\pm$ keV)	$E_x$ <sup>g</sup> (MeV $\pm$ keV)	$E_x$ <sup>k</sup> (MeV $\pm$ keV)	$L$ <sup>g</sup>	$\Gamma$ <sup>b</sup> (keV)	$J^\pi; T$ <sup>h</sup>	$\beta^2$ <sup>k</sup> ( $\times 10^{-3}$ )
$24.00 \pm 100$	(1, 2)						$1200 \pm 300$	$1^-; 1$	
					$24.4 \pm 100$		$400 \pm 50$ <sup>k</sup>	$(2^+, 3^-); 0$	4.3
$25.50 \pm 150$	(1)						$1330 \pm 300$	$1^-; 1$	

<sup>a</sup> See also Tables 16.28 and 16.29 in (1971AJ02).

<sup>b</sup> (p, p'): (1975BU1F, 1976BU15),  $E_p = 45$  MeV, except for the  $\Gamma$  labeled <sup>k</sup>.

<sup>c</sup> (p, p'): (1969SU03),  $E_p = 185$  MeV.

<sup>d</sup> (d, d'): (1974DU06),  $E_d = 81.6$  MeV; energies are nominal ( $\pm 100$  to  $\pm 260$  keV); angular distributions reported to all but last state.

<sup>e</sup> Unresolved states.

<sup>f</sup> ( $^3\text{He}, ^3\text{He}'$ ): (1974MO26),  $E(^3\text{He}) = 71$  MeV; angular distributions are reported to states labeled by <sup>f</sup>.

<sup>g</sup> ( $\alpha, \alpha'$ ): (1975BU1F, 1976BU15),  $E_\alpha = 60$  MeV, except for states labeled by <sup>j</sup> and <sup>k</sup> where see these references for additional evidence.

<sup>h</sup> Proposed by (1975BU1F, 1976HA19, 1976HA27).

<sup>i</sup>  $\Gamma = 1.70 \pm 0.3$  MeV (1976BU15).

<sup>j</sup> (1964HA16, 1966HA19).

<sup>k</sup> Angular distribution at  $E_\alpha = 104$  MeV (1976HA19, 1976HA27). The strong excitation of  $^{16}\text{O}^*(7.12)$  is consistent with a DWBA calculation using a microscopic form factor obtained from a 1p-1h model with  $1\hbar\omega$  excitation (1976HA19).

<sup>l</sup> ( $\alpha, \alpha'$ ): see also (1975KN05).

1972LO1F, 1973GO27, 1974AL1G, 1975HI02, 1976NO02), (1971GA1J, 1972PA1A, 1973TH1A, 1975IG1A, 1975KA2D), (1970BA1F, 1970CZ1A, 1971FE10, 1971HE25, 1971RA36, 1972AU1A, 1972BO08, 1972BO39, 1972GE07, 1972GE16, 1972JA1C, 1972JO1A, 1972KE10, 1972LE27, 1972LE28, 1972LE1G, 1972PE04, 1972ST29, 1972WI16, 1973BL02, 1973GE01, 1973GE07, 1973GU1A, 1973JA13, 1973MI19, 1973RU07, 1973SC1L, 1973VA18, 1974BE22, 1974CI02, 1974GO1G, 1974GU21, 1974MA40, 1974PE1D, 1974SC1K, 1974SC1E, 1974SI13, 1974ZE04, 1975AN1N, 1975BA1H, 1975CL1D, 1975DU1A, 1975FR06, 1975GE05, 1975MA18, 1975MA50, 1975SC1T, 1975SM01, 1975TH03, 1976DA1Q, 1976GO1E, 1976JA03, 1976YA08; theor.) and  $^{17}\text{F}$ .

65. (a)  $^{16}\text{O}(\text{d}, \text{d})^{16}\text{O}$

(b)  $^{16}\text{O}(\text{d}, \text{pn})^{16}\text{O} \quad Q_{\text{m}} = -2.2246$

Angular distribution studies have been carried out for  $E_{\text{d}}$  up to 81.6 MeV: see Table 16.27 in (1971AJ02) and Table 16.25 here. Observed deuteron groups are displayed in Table 16.26 (1974DU06). For reaction (b) see (1971NE07). See also (1972PA1A), (1969VE09, 1970EL16, 1970OH1C, 1971DO1A, 1971SI24, 1972DM01, 1972GA16, 1974CH58, 1975BO1P, 1975CO12, 1976CO01, 1976LE1U: theor.) and  $^{18}\text{F}$  in (1978AJ03).

66.  $^{16}\text{O}(\text{t}, \text{t})^{16}\text{O}$

Angular distributions are reported for  $E_{\text{t}}$  to 20.01 MeV: see Table 16.27 in (1971AJ02) and Table 16.25 here. See also (1976LE19; theor.) and  $^{19}\text{F}$  in (1978AJ03).

67.  $^{16}\text{O}({}^3\text{He}, {}^3\text{He})^{16}\text{O}$

Angular distributions have been measured to  $E({}^3\text{He}) = 71$  MeV: see Table 16.27 in (1971AJ02) and Table 16.25 here. Inelastic groups are shown in Table 16.26 (1974MO26). See also (1970KA1D, 1975GO1L), (1974HA1C) and (1974CH58, 1975KU1K, 1975SI09, 1976LE19; theor.).

68. (a)  $^{16}\text{O}(\alpha, \alpha)^{16}\text{O}$

(b)  $^{16}\text{O}(\alpha, 2\alpha)^{12}\text{C} \quad Q_{\text{m}} = -7.1616$

Angular distributions of  $\alpha$ -particles have been measured up to  $E_{\alpha} = 146$  MeV: see Table 16.27 in (1971AJ02) and Table 16.25 here. The fraction of the isoscalar quadrupole ( $T = 0$ , E2) energy weighted sum rule (EWSR) exhausted between  $E_{\text{x}} = 17$  and 25 MeV is  $40_{-10}^{+20}\%$

(1976HA27). See also (1975KN05, 1975MO04, 1976BU15, 1976YO02). The forward angular behavior of the giant resonance structure for  $E_x = 23\text{--}24$  MeV is consistent with  $l = 0$  transfer while  $l \geq 3$  contributions cannot be excluded above  $E_x = 20$  MeV. For low-lying states coupled channel calculations are required to describe the angular distributions to the  $2^+$  and  $4^+$  states at 9.85 and 10.35 MeV while the  $1^-$ ,  $T = 0$  states require a microscopic wave function analysis (1976HA27).

Reaction (b) proceeds via excited states of  $^{16}\text{O}$ : see (1971GU15, 1975SH1K). (1976CH12) find  $N_{\text{eff}} = 0.34_{-0.05}^{+0.09}$  at  $E_\alpha = 850$  MeV [square well]. (1975SH1K) report that the principal parent of  $^{16}\text{O}$  in an  $\alpha$ -cluster model is  $^{12}\text{C}_{\text{g.s.}}$ , and not  $^{14}\text{C}^*(4.4)$ .

See also (1969PI1B, 1973EC1A, 1973LI1F, 1974DO1G), (1971GA1J, 1974HA1C, 1975GR41, 1975RO1B), (1970AG08, 1970BU1C, 1970MI12, 1971BE20, 1971LO24, 1971MC03, 1971MU1H, 1971NO03, 1971TA30, 1971TE10, 1972AV04, 1972BO13, 1972CA44, 1972DM01, 1972LO16, 1972MI05, 1972SH10, 1972SU10, 1973CE01, 1973CO15, 1973RU07, 1973SU1A, 1974BA40, 1974CA31, 1974CH58, 1974PI11, 1974KA1P, 1974MO24, 1974WA02, 1975AN1F, 1975FL1B, 1975KO28, 1975KU1K, 1975SI09, 1975SU1C, 1976CO27, 1976LE20, 1976PA1J, 1976RE04; theor.) and  $^{20}\text{Ne}$  in (1978AJ03).

69. (a)  $^{16}\text{O}(^6\text{Li}, ^6\text{Li})^{16}\text{O}$   
 (b)  $^{16}\text{O}(^7\text{Li}, ^7\text{Li})^{16}\text{O}$   
 (c)  $^{16}\text{O}(^7\text{Li}, t\alpha)^{16}\text{O}$   $Q_m = -2.4668$

For studies of the elastic scattering see Table 16.25. See also (1974MI1F), (1973FO1A, 1975GR41, 1976FI1F) and (1970SC31, 1972WA31, 1976OH03; theor.). For a study of d- $\alpha$  angular correlations see  $^{20}\text{Ne}$  in (1978AJ03) and (1975AR20). For reaction (c) see (1974PA16) and  $^{20}\text{Ne}$  in (1978AJ03).

70.  $^{16}\text{O}(^9\text{Be}, ^9\text{Be})^{16}\text{O}$

The elastic scattering has been studied for  $E(^{16}\text{O}) = 25.7$  to  $29.5$  MeV (1975FU05). See also (1974TA1C).

71. (a)  $^{16}\text{O}(^{10}\text{B}, ^{10}\text{B})^{16}\text{O}$   
 (b)  $^{16}\text{O}(^{11}\text{B}, ^{11}\text{B})^{16}\text{O}$

The elastic scattering angular distributions have been studied at  $E(^{10}\text{B}) = 100$  MeV (1975NA15) and, in reaction (b), at  $E(^{16}\text{O}) = 27, 30, 32.5, 35$  and  $60$  MeV (1972SC03). At  $E(^{16}\text{O}) = 60$  MeV, angular distributions involving states of  $^{11}\text{B}$  and  $^{16}\text{O}^*(0, 6.1, 7.0, 10.34)$  have been measured by (1972SC17). See also (1974DE17, 1974KO1P; theor.).

72.  $^{16}\text{O}(^{12}\text{C}, ^{12}\text{C})^{16}\text{O}$

The elastic scattering has been studied at  $E(^{16}\text{O})$  up to 168 MeV: see reaction 64 in (1971AJ02) and Table 16.25 here. The scattering to  $^{16}\text{O}^*(6.05, 6.13, 6.92, 7.12, 8.9, 10.3)$  has also been studied [see Table 16.25] (1973GU12, 1976SP01) and the populations of  $^{16}\text{O}^*(11.1)$  (1975SH24) and  $^{16}\text{O}^*(15)$  (1973GU12) have been reported. See also (1970RO23). Most of the studies of this reaction have involved yield measurements as they apply to compound structures in  $^{28}\text{Si}$ : see (1978EN06) and (1972MA29, 1972ST09, 1973MA1N, 1974MA1L, 1975MA2C, 1975SH24, 1976CH13, 1976CH1Y, 1976EY01, 1976SP03). For spallation experiments see (1974WI05).

See also (1972MA1P, 1975HA1X, 1975PI1C), (1969HE06, 1972GA1E, 1973BR1C, 1973PA1J, 1973PE1D, 1973ST1F, 1973ST1A, 1975GR41, 1975VO1B), (1973AR1E, 1973CL1E, 1974CO1L, 1976CU04; astrophys.), (1970AN1D, 1971DA30, 1972BA73, 1972CH1E, 1972GO1G, 1972NA14, 1972RI03, 1973DE40, 1973FE1G, 1973LO02, 1973SA1K, 1974GA1L, 1974SA1M, 1974VE05, 1974WA02, 1975CH08, 1975KI01, 1975PE03, 1975SW1A, 1975VE12, 1976CH1X, 1976YO01; theor.) and (1971AJ02).

73. (a)  $^{16}\text{O}(^{13}\text{C}, ^{13}\text{C})^{16}\text{O}$   
 (b)  $^{16}\text{O}(^{14}\text{C}, ^{14}\text{C})^{16}\text{O}$

The elastic scattering has been studied at  $E(^{13}\text{C}) = 36$  MeV (1976WE21). See also (1974BE1J, 1975RA33; theor.). The elastic scattering in (b) has been studied at  $E(^{16}\text{O}) = 20, 25$  and  $30$  MeV (1975SC35).

74. (a)  $^{16}\text{O}(^{14}\text{N}, ^{14}\text{N})^{16}\text{O}$   
 (b)  $^{16}\text{O}(^{15}\text{N}, ^{15}\text{N})^{16}\text{O}$

The elastic scattering angular distributions have been studied at  $E(^{14}\text{N})$  and  $E(^{15}\text{N}) = 25$  MeV (1971BO1U), at  $E(^{14}\text{N}) = 79$  MeV (1976MO03) and at  $E(^{14}\text{N}) = 155$  MeV (1975NA15). For yield measurements see (1973GO01, 1974ST1N, 1976ST12) and  $^{30}\text{P}$  and  $^{31}\text{P}$  in (1978EN06). See also (1975VO1B) and (1973KA46, 1974BA40, 1975MO23; theor.).

75.  $^{16}\text{O}(^{16}\text{O}, ^{16}\text{O})^{16}\text{O}$

The angular distributions of elastically scattered  $^{16}\text{O}$  ions have been measured with  $E(^{16}\text{O})$  up to 140.4 MeV: see reaction 66 in (1971AJ02) and Table 16.25 here. See (1973GO01) for a general study of the elastic scattering. The angular distributions corresponding to the excitation of the first four excited states of  $^{16}\text{O}$  have been studied at  $E(^{16}\text{O}) = 51.5$  MeV (1974RO04) and at 140.4 MeV

(1962WI09). The astrophysical import of the cross section for elastic scattering (and of the total reaction cross section) has been studied by (1974SP06). For other yield measurements see  $^{32}\text{S}$  in (1978EN06) and (1974HA44, 1974RO04, 1974VA18). See also (1973RE13).

See also (1971PU1B), (1969HE06, 1973BR1C, 1973PE1D, 1973ST1A, 1974ST1L, 1975VO1B), (1971WO1E, 1973AR1E, 1973CL1E, 1974AR1G, 1974CO1L, 1976AR1H; astrophys. questions) and (1970AN1D, 1970MO35, 1971EC01, 1971FL08, 1971GR1W, 1971HE16, 1971MC03, 1971NE1C, 1971RA1C, 1971RA1G, 1971RE21, 1971TO11, 1971TO09, 1972AL46, 1972AR11, 1972FL11, 1972MO22, 1972PE12, 1972RE14, 1972SE01, 1972TA30, 1972YU01, 1972YU02, 1973BO06, 1973FI07, 1973FU14, 1973LO02, 1973PA20, 1973SC1K, 1973VO1H, 1974FL1C, 1974FR06, 1974GA1L, 1974GL05, 1974KN06, 1974KO1N, 1974MO1E, 1974SC1J, 1974TA16, 1974VE05, 1974WA02, 1974YA11, 1975AN1F, 1975BR13, 1975CU1B, 1975DE02, 1975FU10, 1975KU09, 1975MA2B, 1975PH02, 1975SW1A, 1975TO1D, 1975TO1E, 1976BA07, 1976CH1X, 1976CU01, 1976FE1G, 1976GO12, 1976JA1F, 1976KO09, 1976SA1N, 1976SA1E, 1976ZI01; theor.).

76. (a)  $^{16}\text{O}(^{17}\text{O}, ^{17}\text{O})^{16}\text{O}$   
 (b)  $^{16}\text{O}(^{18}\text{O}, ^{18}\text{O})^{16}\text{O}$

Angular distributions of elastically scattered ions have been studied at  $E(^{16}\text{O}) = 24, 28$  and  $32$  MeV (1973GE04) and  $E(^{17}\text{O}) = 53.0, 57.1, 61.5$  and  $66$  MeV (1975KA24) [reaction (a)] and at  $E(^{16}\text{O}) = 24, 28$  and  $32$  MeV (1972GE18),  $31.5$  and  $42.0$  MeV (1975RE15),  $39.9, 44.8, 49.9$  and  $54.8$  MeV (1972SI16) and  $41.8$  and  $51.9$  MeV (1974VA22: also  $^{16}\text{O}^*(6.1)$ ), and at  $E(^{18}\text{O}) = 53.1, 57.4, 61.6, 76.5$  and  $89.3$  MeV (1975KA24). See also  $^{17}\text{O}$ , and  $^{18}\text{O}$  in (1978AJ03).

See also (1973FI1C, 1974GO1L, 1975VO1B) and (1973BA2F, 1974BA46, 1974BE1J, 1974BO13, 1974YU01, 1975IM04, 1975WO1E; theor.) [reaction (a)] and (1973FI1C, 1973VO1E, 1975VO1B) and (1973BO1H, 1973MC1D, 1974GE02, 1974KU1E, 1975GR41, 1976GL08, 1976IM01, 1976OH03; theor.) [reaction (b)].

77.  $^{16}\text{O}(^{19}\text{F}, ^{19}\text{F})^{16}\text{O}$

Angular distributions of elastically scattered ions have been studied at  $E(^{16}\text{O}) = 21.4$  and  $25.8$  MeV (1975MO31) and at  $E(^{19}\text{F}) = 33$  and  $36$  MeV (1973GA14). See also  $^{19}\text{F}$  in (1978AJ03), (1973VO1E, 1975VO1B) and (1976OH03; theor.).

78.  $^{16}\text{O}(^{20}\text{Ne}, ^{20}\text{Ne})^{16}\text{O}$

Elastic scattering angular distributions have been measured at  $E(^{16}\text{O}) = 40.7, 51.1$  and  $59.4$  MeV (1975ZI1C).

79.  $^{17}\text{O}(\text{p}, \text{d})^{16}\text{O}$

$$Q_{\text{m}} = -1.918$$

Angular distributions for the ground state deuteron group have been studied at  $E_{\text{p}} = 8.62, 9.56, 10.5, 11.16$  and  $11.44$  MeV (1975CR05). At  $E_{\text{p}} = 31$  MeV, angular distributions are reported for the deuterons corresponding to  $^{16}\text{O}^*(0, 6.05 + 6.13, 7.12, 8.87, 10.35, 12.97, 13.26)$ . States at  $E_{\text{x}} = 15.22$  and  $15.42$  MeV were also observed. Spectroscopic factors were obtained from a DWBA analysis (1970ME01).

80.  $^{17}\text{O}(\text{d}, \text{t})^{16}\text{O}$

$$Q_{\text{m}} = 2.115$$

At  $E_{\text{d}} = 52$  MeV the spectrum at  $10^\circ$  is dominated by  $^{16}\text{O}^*(0, 6.13, 8.87, 12.97, 13.26, 18.97, 19.79)$ .  $^{16}\text{O}^*(18.97, 19.79)$  are assigned  $J^\pi = (4)^-; T = 1$  and  $(4); 0$ , respectively. Spectroscopic factors are given for various of the  $^{16}\text{O}$  states (1974MA23). See also reaction 29 in  $^{16}\text{N}$ , (1973WA1E) and (1975HS01, 1976SC1H; theor.).

81.  $^{17}\text{O}(^3\text{He}, \alpha)^{16}\text{O}$

$$Q_{\text{m}} = 16.436$$

Angular distributions to many states of  $^{16}\text{O}$  have been observed at  $E(^3\text{He}) = 11$  MeV: see Table 16.22 for  $l$ - and  $S$ -values (1971BO02). At  $E(^3\text{He}) = 36$  MeV the widths of  $^{16}\text{O}^*(18.97, 19.79)$  are  $< 16$  and  $< 37$  keV, respectively (1974DO1J). See also (1976WA1Q) and (1971AJ02).

82. (a)  $^{18}\text{O}(\text{p}, \text{t})^{16}\text{O}$

$$Q_{\text{m}} = -3.7070$$

(b)  $^{18}\text{O}(\text{p}, \text{pt})^{15}\text{N}$

$$Q_{\text{m}} = -15.8347$$

(c)  $^{18}\text{O}(\text{p}, \text{t}\alpha)^{12}\text{C}$

$$Q_{\text{m}} = -6.2274$$

Angular distributions of tritons (reaction (a)) have been measured for  $E_{\text{p}}$  to  $43.7$  MeV: see (1971AJ02) for the earlier work and (1974FL09:  $E_{\text{p}} = 20$  MeV;  $\text{t}_0 \rightarrow \text{t}_5, \text{t}_7$ ), (1974PI05:  $E_{\text{p}} = 20.0, 24.4, 29.8, 37.5, 43.6$  MeV;  $\text{t}_{1+2}, \text{t}_{3+4}, \text{t}_5, \text{t}_8$ ), (1973PI09:  $E_{\text{p}} = 24.4$  MeV (polarized protons);  $\text{t}_0, \text{t}_{1+2}, \text{t}_3 \rightarrow \text{t}_5, \text{t}_7, \text{t}_8$ ) and (1972AD10:  $E_{\text{p}} = 41.7$  MeV;  $\text{t}_0, \text{t}_{1+2}$  and  $\text{t}$  to  $^{16}\text{O}^*(11.26, 12.05, 16.33, 22.72)$ ). See also (1970OL1B). Most of the states are more strongly populated than expected on the basis of simple calculations: it is suggested that complete coupled channels calculations may be necessary [see (1972AD10, 1974FL09)]. The population of  $^{16}\text{O}^*(22.7, 24.5)$  is consistent with  $L = 0$  and  $2$ , respectively, and with assignments of  $T = 2, J^\pi = 0^+$  and  $2^+$  (1964CE05). A study, at  $E_{\text{p}} = 43$  MeV, of decay of the first  $T = 2$  state at  $E_{\text{x}} = 22.72$  MeV shows that it decays via proton emission [reaction (b)] with branchings of  $(25 \pm 6)\%$ ,  $(22 \pm 5)\%$  and  $(15 \pm 5)\%$  to  $^{15}\text{N}^*(0, 5.27 + 5.30, 6.32)$ . The  $\alpha$ -decay [reaction (c)] is not observed: the branchings to  $^{12}\text{C}^*(0, 4.4)$  are  $(1.1 \pm 4.0)\%$  and  $(0.0 \pm 3.4)\%$ . The remaining decay modes have not been determined

(1973KO02). See also (1973SO07, 1974MC1F, 1975CH18, 1975HO06, 1975IB01, 1975SE09; theor.) and  $^{19}\text{F}$  in (1978AJ03).

$$83. \text{}^{18}\text{O}(\alpha, \text{}^6\text{He})\text{}^{16}\text{O} \quad Q_{\text{m}} = -11.218$$

Angular distributions have been measured at  $E_{\alpha} = 58$  MeV to  $^{16}\text{O}^*(0, 6.1, 6.92, 7.12)$ . Groups at  $E_{\text{x}} = 10.4, 13.3 \pm 0.1$  and  $16.3 \pm 0.1$  MeV were also observed. The cross sections are about a factor of 20 smaller than in the  $^{18}\text{O}(\text{p}, \text{t})$  reaction but the angular distributions are consistent with a direct transfer mechanism (1975VA01). See also (1975VA1F).

$$84. \text{}^{18}\text{O}(\text{}^{18}\text{O}, \text{}^{20}\text{O})\text{}^{16}\text{O} \quad Q_{\text{m}} = -0.628$$

See (1972EY01, 1976KU1F) and  $^{20}\text{O}$  in (1978AJ03).

$$85. \text{(a) } \text{}^{19}\text{F}(\text{p}, \alpha)\text{}^{16}\text{O} \quad Q_{\text{m}} = 8.1148$$

$$\text{(b) } \text{}^{19}\text{F}(\text{p}, 2\text{d})\text{}^{16}\text{O} \quad Q_{\text{m}} = -15.733$$

Angular distributions have been reported at many energies to  $E_{\text{p}} = 44.5$  MeV: see Table 16.30 in (1971AJ02) and (1964BR12:  $E_{\text{p}} = 2.06$  to  $3.30$  MeV;  $\alpha_0$ ) and (1975BU1B:  $E_{\text{p}} = 13.5$  to  $18.0$  MeV;  $\alpha_0$ ). Observed states of  $^{16}\text{O}$  are displayed in Table 16.31 in (1971AJ02).

Very accurate  $\gamma$ -ray measurements are reported by (1967CH19) [see reaction 55] and (1970GA09) [the  $E_{\gamma}$  of the  $8.87 \rightarrow 6.13$  transition is  $2741.5 \pm 0.5$  keV]. The E0 transition ( $6.05 \rightarrow 0; 0^+ \rightarrow 0^+$ ) has been investigated in some detail: the internal conversion to pair production ratio  $(4.00 \pm 0.46) \times 10^{-5}$  (1963LE06). The ratio of double  $\gamma$ -emission to pair production  $\Gamma_{\text{E1E1}}/\Gamma_{\text{E0}(\pi)} \leq 1.1 \times 10^{-4}$  (1964AL18),  $(2.5 \pm 1.1) \times 10^{-4}$  (1975WA20). The  $\tau_{\text{m}}$  for  $^{16}\text{O}^*(6.05) = 96 \pm 7$  psec (1973BI17). An attempt to observe a scalar boson produced in the decay of  $^{16}\text{O}^*(6.05)$  was unsuccessful; together with other results it demonstrates that the mass of such a boson cannot be  $1.030 \leq m \leq 18.2$  MeV (1974KO1Q).

$^{16}\text{O}^*(6.13)$  has also been studied extensively:  $|g| = 0.55 \pm 0.04$ ,  $\tau_{\text{m}} = 26.6 \pm 0.7$  psec (1973BR31). A search for double positron-electron pair creation by the  $6.13$  MeV  $\gamma$ -ray was unsuccessful: the ratio of the cross section for production of such a double pair to the cross section for formation of a single pair is  $-(2 \pm 5) \times 10^{-5}$  (1972WI09). See also (1971BE60, 1972VA1H, 1976KA1N). For  $\gamma$ -ray branching ratios and  $\Gamma_{\gamma}$  for these and other transitions see Table 16.15. See also (1971AJ02) and  $^{20}\text{Ne}$  in (1978AJ03).

See also (1973LI1F, 1974KR1D), (1971ST06, 1973GO1M, 1973GO1N, 1974LO1B) and (1974LE1H, 1975BU1H, 1975GO1T, 1975SW1B; applications). For reaction (b) see (1971DE1F).

86.  $^{19}\text{F}(^3\text{He}, ^6\text{Li})^{16}\text{O}$   $Q_m = 4.095$

Angular distributions have been measured at  $E(^3\text{He}) = 22.4, 30$  and  $40.7$  MeV (1972OH01; g.s.),  $28$  MeV (1970KL09; g.s. of  $^{16}\text{O}$  and various  $^6\text{Li}$  states) and  $40.7$  MeV (1971DE14; to  $^{16}\text{O}^*(6.13, 6.92, 7.12, 8.87, 11.0, 12.5, 13)$ ). See also (1972YO02).

87.  $^{19}\text{F}(\alpha, ^7\text{Li})^{16}\text{O}$   $Q_m = -9.233$

The ground state angular distribution has been measured at  $E_\alpha = 42$  MeV (1968MI05).

88. (a)  $^{20}\text{Ne}(\gamma, \alpha)^{16}\text{O}$   $Q_m = -4.7313$

(b)  $^{20}\text{Ne}(p, p\alpha)^{16}\text{O}$   $Q_m = -4.7313$

For reaction (a) see (1975SK06) and  $^{20}\text{Ne}$  in (1978AJ03). See also (1973CL1E; astrophys.). For reaction (b) see (1967CH04).

89.  $^{20}\text{Ne}(d, ^6\text{Li})^{16}\text{O}$   $Q_m = -3.2576$

Angular distributions have been studied at  $E_d = 40$  MeV (1973KI1C, 1974EP1B; to  $^{16}\text{O}^*(0, 8.87)$ ). See also (1975BE01: quote data at  $36$  MeV). At  $E_d = 55$  MeV,  $\theta = 16^\circ$ , the spectrum is dominated by  $^{16}\text{O}^*(0, 6.1, 6.9, 9.85)$ .  $^{16}\text{O}^*(8.87, 10.35)$  are also observed (1971MC04). See also (1975CO1N).

90.  $^{20}\text{Ne}(^3\text{He}, ^7\text{Be})^{16}\text{O}$   $Q_m = -3.145$

At  $E(^3\text{He}) = 30$  MeV angular distributions involving  $^{16}\text{O}^*(0, 6.1)$  and the first two states of  $^7\text{Be}$  are reported by (1970DO1H). See also (1971DE37:  $E(^3\text{He}) = 41$  MeV), (1975AU01) and (1973KL1B; theor.).

91.  $^{20}\text{Ne}(\alpha, 2\alpha)^{16}\text{O}$   $Q_m = -4.7313$

At  $E_\alpha = 78.6$  MeV the reaction goes predominantly to  $^{16}\text{O}_{\text{g.s.}}$  with a small yield to  $^{16}\text{O}^*(7.1)$ . Quasifree  $\alpha - \alpha$  scattering plays an important role in the reaction (1974EP01).

92.  $^{28}\text{Si}(\alpha, ^{16}\text{O})^{16}\text{O}$   $Q_m = -9.5928$

See (1967VA18).



**<sup>16</sup>F**  
(Figs. 4 and 5)

GENERAL: (See also (1971AJ02).):

See (1972JA14, 1973LA1G, 1973LA1H, 1973RO1R, 1974VA24, 1975BE31).

1. (a)  $^{14}\text{N}(^3\text{He}, \text{n})^{16}\text{F}$   $Q_{\text{m}} = -0.969$   
(b)  $^{14}\text{N}(^3\text{He}, \text{np})^{15}\text{O}$   $Q_{\text{m}} = -0.421$

Observed neutron groups and  $L$ -values derived from angular distribution measurements are displayed in Table 16.28 [(1973BO50);  $E(^3\text{He}) = 13$  MeV]. See (1971AJ02) for the earlier work. See also (1971ADZZ, 1975OT01). For reaction (b) see (1976OT02) [Table 16.28], (1973AD02) and  $^{17}\text{F}$ .

2.  $^{16}\text{O}(\text{p}, \text{n})^{16}\text{F}$   $Q_{\text{m}} = -16.212$

Observed neutron groups are listed in Table 16.28 (1971MO34). See also (1971BE46, 1971TH1D), (1974MO06; theor.) and (1971AJ02).

3.  $^{16}\text{O}(^3\text{He}, \text{t})^{16}\text{F}$   $Q_{\text{m}} = -15.448$

Observed triton groups are displayed in Table 16.28 (1965PE04). Comparisons of relative populations of the first four states in this reaction and in the analog reaction ( $^{16}\text{O}(\text{t}, ^3\text{He})^{16}\text{N}$ ) to known states in  $^{16}\text{N}$  [see reaction 28 in  $^{16}\text{N}$  (1974FL06)] suggest that  $^{16}\text{F}^*(0, 0.20)$  are  $0^-$  and  $1^-$  and that  $^{16}\text{F}^*(0.42, 0.72)$  are  $2^-$  and  $3^-$  (the relative ordering of the  $J^\pi$  is ambiguous). (1965PE04) suggest, on the basis of angular distributions, that the ordering is  $J^\pi = 0^-, 1^-, 2^-, 3^-$  for the first four states of  $^{16}\text{N}$ . At  $E(^3\text{He}) = 73$  MeV the spectrum is dominated by a very large peak at  $E_x \approx 7$  MeV (1975GO1L; abstract). See also (1976CE1G, 1976MO1P).

4.  $^{19}\text{F}(^3\text{He}, ^6\text{He})^{16}\text{F}$   $Q_{\text{m}} = -14.845$

This reaction has been studied at  $E(^3\text{He}) = 70$  MeV (1976MO1P).

Table 16.27: Energy levels of  $^{16}\text{F}$

$E_x$ (MeV $\pm$ keV)	$J^\pi; T$	$\Gamma_{\text{c.m.}}$ (keV)	Decay	Reactions
0	$(1)^-; 1$	$40 \pm 20$	p	1, 2, 3
$0.194 \pm 9$	$(0)^-$	$< 40$	p	1, 2, 3
$0.424 \pm 5$	$(2)^-$	$40 \pm 30$	p	1, 2, 3
$0.720 \pm 6$	$(3)^-$	$< 15$	p	1, 2, 3
$3.763 \pm 8$	$1^+$	$< 40$	p	1, 3
$3.870 \pm 7$	$(2)^+$	$< 20$	p	1
$4.372 \pm 7$		$50 \pm 20$	p	1
$4.653 \pm 7$	$1^+$	$60 \pm 20$	p	1
$4.973 \pm 10$	$\pi = +$			1
$5.264 \pm 20$				1
$5.390 \pm 20$	$\pi = +$			1
$5.448 \pm 20$				1, 3
$5.528 \pm 20$	$\pi = +$			1
$5.840 \pm 40$				1, 3
$6.230 \pm 50$				1
$6.371 \pm 20$				1, 3
$6.678 \pm 10$				1
$7.110 \pm 20$				1, (3)
$7.730 \pm 40$				1

Table 16.28:  $^{16}\text{F}$  levels from  $^{14}\text{N}(^3\text{He}, \text{n})^{16}\text{F}$ ,  $^{16}\text{O}(\text{p}, \text{n})^{16}\text{F}$  and  $^{16}\text{O}(^3\text{He}, \text{t})^{16}\text{F}$  <sup>a</sup>

$^{16}\text{F}^* \text{ }^{\text{b}}$ (MeV $\pm$ keV)	$L \text{ }^{\text{b}}$	$^{16}\text{F}^* \text{ }^{\text{c}}$ (MeV $\pm$ keV)	$J\pi \text{ }^{\text{d}}$	$^{16}\text{F}^* \text{ }^{\text{e}}$ (MeV $\pm$ keV)	$^{16}\text{F}^* \text{ }^{\text{f}}$ (MeV $\pm$ keV)	$\Gamma_{\text{c.m.}} \text{ }^{\text{g}}$ (keV)	$J\pi \text{ }^{\text{h}}$
0	1	0	(1 <sup>-</sup> )	0	0	40 $\pm$ 20	(1) <sup>-</sup>
0.192 $\pm$ 15	1	0.190 $\pm$ 20	(0 <sup>-</sup> )	0.197 $\pm$ 12	i	40	(0) <sup>-</sup>
0.425 $\pm$ 15	3	0.425 $\pm$ 10	( $\geq$ 2)	0.424 $\pm$ 5	i	40 $\pm$ 30	(2) <sup>-</sup>
0.722 $\pm$ 10	(3)	0.725 $\pm$ 10	( $\geq$ 2)	0.720 $\pm$ 6	i	< 15	(3) <sup>-</sup>
3.751 $\pm$ 10	0	3.775 $\pm$ 10	(1)		i	< 40	1 <sup>+</sup>
3.861 $\pm$ 10	2	3.880 $\pm$ 10				< 20	(2) <sup>+</sup>
4.370 $\pm$ 10		4.375 $\pm$ 10	( $\geq$ 2)		4.25 $\pm$ 50	50 $\pm$ 20	
4.646 $\pm$ 10	0	4.661 $\pm$ 10				60 $\pm$ 20	1 <sup>+</sup>
4.973 $\pm$ 10	2						$\pi = +$
5.264 $\pm$ 20							
5.390 $\pm$ 20	2				5.45 $\pm$ 50		$\pi = +$
5.448 $\pm$ 20							
5.528 $\pm$ 20	2						$\pi = +$
5.840 $\pm$ 40					5.9 $\pm$ 50		
6.230 $\pm$ 50							
6.371 $\pm$ 20					6.4 $\pm$ 50		
6.678 $\pm$ 10							
7.110 $\pm$ 20							
7.730 $\pm$ 40							

<sup>a</sup> See also Table 16.33 in (1971AJ02).

<sup>b</sup>  $^{14}\text{N}(^3\text{He}, \text{n})^{16}\text{F}$  (1973BO50;  $E(^3\text{He}) = 13$  MeV).

<sup>c</sup>  $^{14}\text{N}(^3\text{He}, \text{np})^{15}\text{O}$  (1976OT02;  $E(^3\text{He}) = 6.5 - 7.8$  MeV).

<sup>d</sup> From angular correlation studies (1976OT02).

<sup>e</sup>  $^{16}\text{O}(\text{p}, \text{n})^{16}\text{F}$  (1971MO34;  $E = 23.9$  MeV).

<sup>f</sup>  $^{16}\text{O}(^3\text{He}, \text{t})$  (1965PE04;  $E(^3\text{He}) = 40.2$ ).

<sup>g</sup>  $^{14}\text{N}(^3\text{He}, \text{n})^{16}\text{F}$  (1965ZA01, 1976OT02).

<sup>h</sup> See (1965PE04, 1973BO50, 1974FL06, 1976OT02).

<sup>i</sup> These states were observed but  $E_x$  was not determined.

**$^{16}\text{Ne}$**   
(Fig. 5)

$^{16}\text{Ne}$  has not been observed. The isobaric multiplet mass equation predicts  $M - A = 25.15 \pm 0.6$  MeV (1968CE1A);  $^{16}\text{Ne}$  is then unbound with respect to breakup into  $^{14}\text{O} + 2\text{p}$  by 2.6 MeV: see (1971AJ02) for the earlier work. See also (1972WA07) and (1975BE31; theor.).

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(Closed 01 November 1976)

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