Energy Levels of Light Nuclei

\( A = 16 \)

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Abstract: An evaluation of \( A = 16 \)–17 was published in Nuclear Physics A166 (1971), p. 1. This version of \( A = 16 \) differs from the published version in that we have corrected some errors discovered after the article went to press. Figures and introductory tables have been omitted from this manuscript. Reference key numbers have been changed to the NNDC/TUNL format.

(References closed November 30, 1970)

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E. Erratum to this Publication: PS or PDF
\( ^{16}\text{B} \)
(Fig. 5)

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

\( ^{16}\text{C} \)
(Figs. 1 and 5)

GENERAL:


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

See \((1968\text{CE1A}) \) and \((1960\text{GO1B}, 1961\text{BA1C})\).

1. \( ^{16}\text{C}(\beta^-)^{16}\text{N} \)

\[ Q_m = 8.010 \]

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

2. \( ^{14}\text{C}(\text{t}, \text{p})^{16}\text{C} \)

\[ Q_m = -3.014 \]
\[ Q_0 = -3.014 \pm 0.016 \ (1961\text{HI01}) \]

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

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

<table>
<thead>
<tr>
<th>( E_x ) (MeV ± keV)</th>
<th>( J^\pi; T )</th>
<th>( \tau_{1/2} ) (sec)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>( 0^+; 2 )</td>
<td>0.74 ± 0.03</td>
<td>( \beta^- )</td>
<td>1, 2</td>
</tr>
<tr>
<td>1.753 ± 12</td>
<td>( (2^+) )</td>
<td></td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>
\( ^{16}\text{N} \)
(Figs. 2 and 5)

GENERAL:


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

1. \(^{16}\text{N}(\beta^-)^{16}\text{O} \quad Q_m = 10.422\)

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

2. \(^7\text{Li}(^{14}\text{N}, ^{5}\text{Li})^{16}\text{N} \quad Q_m = 0.407\)

See (1958AL1D).

3. (a) \(^9\text{Be}(^{7}\text{Li}, \alpha)^{12}\text{B} \quad Q_m = 10.463 \quad E_b = 20.573\)
(b) \(^{9}\text{Be}(^{7}\text{Li}, ^{8}\text{Li})^{8}\text{Be} \quad Q_m = 0.367\)

The yields of \(\alpha_0\) and \(\alpha_2\) (reaction (a)) have been measured at \(E(^{7}\text{Li}) = 3.3\) MeV and 5.0 to 6.2 MeV (1969SN02). The cross section for reaction (b) rises monotonically for \(E(^{7}\text{Li}) = 1.1\) to 4 MeV (1957NO17, 1959NO40). At 4 MeV, the cross section is 70 mb (1960NO1A). See also (1960GE1B; theor.).

4. (a) \(^{10}\text{B}(^{7}\text{Li}, p)^{16}\text{N} \quad Q_m = 13.985\)
(b) \(^{11}\text{B}(^{6}\text{Li}, p)^{16}\text{N} \quad Q_m = 9.782\)
(c) \(^{11}\text{B}(^{7}\text{Li}, d)^{16}\text{N} \quad Q_m = 4.754\)

At \(E(\text{Li}) = 4.7\) to 5.2 MeV, proton and deuteron groups are observed to a number of known states of \(^{16}\text{N}\) with \(E_x < 9.5\) MeV, including states at \(E_x = 7.66, 8.10, 8.36, 8.83\) and 9.47 MeV (±50 keV). Angular distributions are also reported (1966MC05). See also (1963MO1B).
Table 16.2: Energy levels of $^{16}$N

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$J^\pi; T$</th>
<th>$\tau$ or $\Gamma_c.m.$ (keV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$2^-; 1$</td>
<td>$\tau_{1/2} = 7.13 \pm 0.02$ sec</td>
<td>$\beta^-$</td>
<td>1, 6, 11, 12, 13, 14, 15, 18, 21, 22, 23, 24, 28, 29, 30</td>
</tr>
<tr>
<td>0.1206 ± 0.5</td>
<td>$0^-$</td>
<td>$\tau_m = 7.58 \pm 0.09$ µsec</td>
<td>$\gamma$</td>
<td>4, 11, 13, 18, 24, 28, 30</td>
</tr>
<tr>
<td>0.2970 ± 0.7</td>
<td>$3^-$</td>
<td>$95 \pm 20$ psec</td>
<td>$\gamma$</td>
<td>4, 11, 12, 13, 18, 24, 28, 29, 30</td>
</tr>
<tr>
<td>0.3973 ± 0.7</td>
<td>$1^-$</td>
<td>$42 \pm 10$ psec</td>
<td>$\gamma$</td>
<td>4, 11, 13, 18, 24, 28, 30</td>
</tr>
<tr>
<td>3.355 ± 5</td>
<td>$1^+$</td>
<td>$\Gamma = 20 \pm 5$ keV</td>
<td>n</td>
<td>4, 11, 13, 15, 18, 27, 28</td>
</tr>
<tr>
<td>3.520 ± 5</td>
<td>$0^(-)$</td>
<td>$\leq 7 \pm 4$</td>
<td>n</td>
<td>4, 11, 13, 15, 18, 28</td>
</tr>
<tr>
<td>3.961 ± 5</td>
<td>$(2, 3)^+$</td>
<td>$\leq 7 \pm 4$</td>
<td>n</td>
<td>4, 11, 12, 13, 15, 18, 28</td>
</tr>
<tr>
<td>4.318 ± 5</td>
<td>$1^+$</td>
<td>$20 \pm 5$</td>
<td>n</td>
<td>4, 11, 13, 15, 18, 28</td>
</tr>
<tr>
<td>4.389 ± 6</td>
<td>$1^-$</td>
<td>$68 \pm 9$</td>
<td>n</td>
<td>4, 11, 13, 15, 28</td>
</tr>
<tr>
<td>4.720 ± 7</td>
<td>$1^-$</td>
<td>$260 \pm 25$</td>
<td>13, 18</td>
<td></td>
</tr>
<tr>
<td>4.776 ± 5</td>
<td>$2^+$</td>
<td>$61 \pm 5$</td>
<td>n</td>
<td>4, 11, 13, 15, 18, 28</td>
</tr>
<tr>
<td>4.97 ± 100</td>
<td>$2^-$</td>
<td>$1050 \pm 200$</td>
<td>n</td>
<td>14</td>
</tr>
<tr>
<td>5.049 ± 5</td>
<td>$(1, 2)^-$</td>
<td>$20 \pm 7$</td>
<td>n</td>
<td>11, 13, 15, 18, 28</td>
</tr>
<tr>
<td>5.129 ± 7</td>
<td></td>
<td>$\leq 7 \pm 4$</td>
<td>(n)</td>
<td>11, 13, 15, 18, 28</td>
</tr>
<tr>
<td>5.150 ± 7</td>
<td></td>
<td>$\leq 7 \pm 4$</td>
<td>(n)</td>
<td>11, 13, 15, 18</td>
</tr>
<tr>
<td>5.232 ± 5</td>
<td></td>
<td>$\leq 7 \pm 4$</td>
<td></td>
<td>11, 13, 18, 28</td>
</tr>
<tr>
<td>5.306 ± 7</td>
<td>$2^-$</td>
<td>$270 \pm 30$</td>
<td>n</td>
<td>13, 15, 18</td>
</tr>
<tr>
<td>5.523 ± 6</td>
<td></td>
<td>$\leq 7 \pm 4$</td>
<td></td>
<td>4, 13, 18, 28</td>
</tr>
<tr>
<td>5.736 ± 6</td>
<td>$(5^+)$</td>
<td>$\leq 7 \pm 4$</td>
<td>(n)</td>
<td>4, 12, 13, 15, 18, 28</td>
</tr>
<tr>
<td>6.005 ± 9</td>
<td>$(3^-)$</td>
<td>$270 \pm 30$</td>
<td>(n)</td>
<td>13, 15, 28</td>
</tr>
<tr>
<td>6.168 ± 6</td>
<td></td>
<td>$\leq 7 \pm 4$</td>
<td></td>
<td>13, 18, 28</td>
</tr>
<tr>
<td>6.373 ± 7</td>
<td>$2$</td>
<td>$30 \pm 6$</td>
<td>n</td>
<td>13, 15, 18, 28</td>
</tr>
<tr>
<td>6.426 ± 7</td>
<td>$(2^-)$</td>
<td>$300 \pm 30$</td>
<td>n</td>
<td>13, 15, 18</td>
</tr>
<tr>
<td>6.511 ± 6</td>
<td>$2$</td>
<td>$34 \pm 6$</td>
<td>n</td>
<td>13, 15, 18</td>
</tr>
<tr>
<td>6.613 ± 6</td>
<td></td>
<td>$\leq 7 \pm 4$</td>
<td>13, 18</td>
<td></td>
</tr>
<tr>
<td>6.851 ± 6</td>
<td></td>
<td>$\leq 7 \pm 4$</td>
<td>(n)</td>
<td>13, 15, 18</td>
</tr>
<tr>
<td>6.98 ± 20</td>
<td>$1$</td>
<td>$22 \pm 5$</td>
<td>n</td>
<td>13, 15, 28</td>
</tr>
<tr>
<td>7.03 ± 10</td>
<td>$(0)$</td>
<td>$28 \pm 20$</td>
<td>n</td>
<td>15, 18, 28</td>
</tr>
<tr>
<td>7.135 ± 6</td>
<td></td>
<td>$\leq 7 \pm 4$</td>
<td>13, 18</td>
<td></td>
</tr>
<tr>
<td>7.248 ± 6</td>
<td>$3$</td>
<td>$17 \pm 5$</td>
<td>n</td>
<td>13, 15, 18</td>
</tr>
<tr>
<td>7.575 ± 7</td>
<td>$\geq 4$</td>
<td>$\leq 7 \pm 4$</td>
<td>n</td>
<td>13, 15, 18</td>
</tr>
<tr>
<td>7.639 ± 7</td>
<td>$\geq 1$</td>
<td>$\leq 7 \pm 4$</td>
<td>n</td>
<td>4, 13, 15, 18, 28</td>
</tr>
</tbody>
</table>
Table 16.2: Energy levels of $^{16}$N (continued)

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

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

5. $^{13}$C(α, p)$^{16}$N

$Q_m = -7.425$

Not reported.
Table 16.3: The half-life of $^{16}$N

<table>
<thead>
<tr>
<th>$\tau_{1/2}$ (sec)</th>
<th>Refs. $^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.35 ± 0.05</td>
<td>(1947BL1A)</td>
</tr>
<tr>
<td>7.38 ± 0.05</td>
<td>(1954MA1B)</td>
</tr>
<tr>
<td>7.352 ± 0.009</td>
<td>(1959EL41)</td>
</tr>
<tr>
<td>7.31 ± 0.04</td>
<td>(1962MA38)</td>
</tr>
<tr>
<td>7.14 ± 0.02</td>
<td>(1964BI02)</td>
</tr>
<tr>
<td>7.16 ± 0.04</td>
<td>(1965GR21)</td>
</tr>
<tr>
<td>7.10 ± 0.03</td>
<td>(1966SC05)</td>
</tr>
<tr>
<td>7.13 ± 0.04</td>
<td>(1970AL21)</td>
</tr>
<tr>
<td>7.13 ± 0.02</td>
<td>Weighted mean of last four values</td>
</tr>
</tbody>
</table>

$^a$ See also (1961AL05, 1965CR01).

6. $^{14}$C(d, $\gamma$)$^{16}$N  

$Q_m = 10.471$

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

7. $^{14}$C(d, n)$^{15}$N  

$Q_m = 7.984$  

$E_b = 10.471$

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

8. $^{14}$C(d, p)$^{15}$C  

$Q_m = -1.007$  

$E_b = 10.471$

The cross section of the $\gamma$-rays to $^{15}$C*(0.75) rises monotonically for $2.7 < E_d < 3.4$ MeV. At $E_d = 3.4$ MeV it is $\approx 75$ mb (1962CH14). Observed resonances are shown in Table 16.4 (1956DO37). See also (1959AJ76) and $^{15}$C in (1970AJ04).
Table 16.4: Resonances in $^{14}$C + d

<table>
<thead>
<tr>
<th>$E_d$ (MeV)</th>
<th>Resonant for</th>
<th>$\Gamma_{c.m.}$ (keV)</th>
<th>$E_x$ (MeV)</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.30 $^a$</td>
<td>$n_0$</td>
<td>220</td>
<td>11.61</td>
<td>(1961CH14, 1963IM01)</td>
</tr>
<tr>
<td>1.65</td>
<td>$n_0$</td>
<td>390</td>
<td>11.91</td>
<td>(1961CH14)</td>
</tr>
<tr>
<td>2.04 $^a$</td>
<td>$n_0$, $p$</td>
<td>290</td>
<td>12.25</td>
<td>(1956DO37, 1961CH14, 1963IM01)</td>
</tr>
<tr>
<td>2.44 $^a$</td>
<td>$n_0$, $p$</td>
<td>180</td>
<td>12.60</td>
<td>(1956DO37, 1961CH14)</td>
</tr>
<tr>
<td>2.75</td>
<td>$n_0$, $p$</td>
<td>155</td>
<td>12.88</td>
<td>(1956DO37, 1961CH14, 1963IM01)</td>
</tr>
<tr>
<td>2.86</td>
<td>$n_0$</td>
<td>175</td>
<td>12.97</td>
<td>(1961CH14)</td>
</tr>
<tr>
<td>(3.10)</td>
<td>$n_0$</td>
<td>(175)</td>
<td>(13.18)</td>
<td>(1961CH14)</td>
</tr>
</tbody>
</table>

$^a$ See also (1964NE09).

9. $^{14}$C(d, $\alpha$)$^{12}$B

$Q_m = 0.361 \quad E_b = 10.471$

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

10. $^{14}$C(t, n)$^{16}$N

$Q_m = 4.213$

Not reported.

11. $^{14}$C($^3$He, p)$^{16}$N

$Q_m = 4.977$

Thirteen proton groups have been observed corresponding to states of $^{16}$N with $0 < E_x < 5.3$ MeV (1966GA08); see Table 16.5. At $E(^3$He) = 12 MeV, four proton groups are observed corresponding to two $T = 1$ states, and to two $T = 2$ states at $E_x = 9.93$ and 11.70 MeV with $J^\pi = 0^+$ and $(1^-, 2^+)$, respectively, corresponding to the first two states of $^{16}$C (1968HE03). See also (1969BA1Z). Angular distributions of the protons to $^{16}$N*(0, 3.36, 3.52, 3.96) have been measured at $E(^3$He) = 1 to 9 MeV; $^{16}$N(0) has odd parity; the three excited states have even parity (1968DA1N, 1970LI1F). See also (1964DU1A, 1964WE1A, 1966DU1B, 1966GO1J).

12. $^{14}$C($\alpha$, d)$^{16}$N

$Q_m = -13.376$

At $E_\alpha = 46$ MeV, the angular distributions of five deuteron groups [see Table 16.5] have been determined: $J^\pi$ of $^{16}$N*(5.74) (the most strongly populated state) is $(5^+)$ (1969LU07).
Table 16.5: Excited states in $^{16}$N from $^{14}$C($^{3}$He, p)$^{16}$N and $^{14}$C(α, d)$^{16}$N

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$\Gamma$ (keV)</th>
<th>$J^\pi; T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{14}$C($^{3}$He, p)$^{16}$N</td>
<td>$^{14}$C(α, d)$^{16}$N</td>
<td>$^{14}$C($^{3}$He, p)$^{16}$N</td>
</tr>
<tr>
<td>0.121 ± 6</td>
<td>0.121 ± 6</td>
<td>0.307 ± 20</td>
</tr>
<tr>
<td>0.298 ± 6</td>
<td>0.298 ± 6</td>
<td>3.961 ± 20</td>
</tr>
<tr>
<td>0.396 ± 7</td>
<td>0.396 ± 7</td>
<td>5.745 ± 20</td>
</tr>
<tr>
<td>3.348 ± 7</td>
<td>3.348 ± 7</td>
<td>7.599 ± 30</td>
</tr>
<tr>
<td>3.517 ± 7</td>
<td>3.517 ± 7</td>
<td>5.745 ± 20</td>
</tr>
<tr>
<td>3.958 ± 7</td>
<td>3.958 ± 7</td>
<td>7.599 ± 30</td>
</tr>
<tr>
<td>4.313 ± 9</td>
<td>4.313 ± 9</td>
<td>15 ± 8</td>
</tr>
<tr>
<td>4.386 ± 9</td>
<td>4.386 ± 9</td>
<td>15 ± 8</td>
</tr>
<tr>
<td>4.768 ± 11</td>
<td>4.768 ± 11</td>
<td>&lt; 12</td>
</tr>
<tr>
<td>5.052 ± 9</td>
<td>5.052 ± 9</td>
<td>&lt; 12</td>
</tr>
<tr>
<td>5.137 ± 9</td>
<td>5.137 ± 9</td>
<td>&lt; 12</td>
</tr>
<tr>
<td>5.234 ± 9</td>
<td>5.234 ± 9</td>
<td>&lt; 12</td>
</tr>
</tbody>
</table>

$^a$ $^{14}$C($^{3}$He, p)$^{16}$N.

$^b$ $^{14}$C(α, d)$^{16}$N.
Proton groups observed at $E_t = 2.2$ to 2.6 MeV (1961SI04) and at 12 MeV (1966HE10) are displayed in Table 16.6. Angular distributions are reported at $E_t = 1.8$ MeV (1964SC09; $p_0 \rightarrow p_i$) and at 12 MeV (1966HE10). At the latter energy they have been analyzed by PWBA: see Table 16.6. See also (1961JA14).

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

<table>
<thead>
<tr>
<th>(1961SI04)</th>
<th>(1966HE10)</th>
<th>$J^\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_x$ (MeV ± keV)</td>
<td>$\Gamma$ (keV)</td>
<td>$E_x$ (MeV ± keV)</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0.120 ± 10</td>
</tr>
<tr>
<td>0.121 ± 10</td>
<td></td>
<td>0.120 ± 10</td>
</tr>
<tr>
<td>0.297 ± 10</td>
<td></td>
<td>0.300 ± 10</td>
</tr>
<tr>
<td>0.396 ± 10</td>
<td></td>
<td>0.399 ± 10</td>
</tr>
<tr>
<td>3.340 ± 25</td>
<td>$\leq 25 \pm 17$</td>
<td>3.359 ± 10</td>
</tr>
<tr>
<td>3.506 ± 25</td>
<td>$\leq 25 \pm 8$</td>
<td>3.519 ± 10</td>
</tr>
<tr>
<td>3.956 ± 25</td>
<td>$\leq 25 \pm 8$</td>
<td>3.957 ± 10</td>
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<tr>
<td>4.318 ± 25</td>
<td>$\leq 25 \pm 8$</td>
<td>4.318 ± 10</td>
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<tr>
<td>4.392 ± 25</td>
<td>110 ± 31</td>
<td>4.391 ± 10</td>
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<tr>
<td>4.725 ± 10</td>
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<tr>
<td>4.773 ± 25</td>
<td>66 ± 7</td>
<td>4.774 ± 10</td>
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<tr>
<td>5.059 ± 25</td>
<td>$\leq 25 \pm 8$</td>
<td>5.053 ± 10</td>
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<tr>
<td>5.130 ± 10</td>
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<td>5.130 ± 10</td>
</tr>
<tr>
<td>5.141 ± 25</td>
<td>38 ± 12</td>
<td>5.150 ± 10</td>
</tr>
<tr>
<td>5.230 ± 25</td>
<td>$\leq 20 \pm 8$</td>
<td>5.226 ± 10</td>
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<tr>
<td>5.305 ± 10</td>
<td></td>
<td>5.305 ± 10</td>
</tr>
<tr>
<td>5.526 ± 25</td>
<td>$\leq 20 \pm 8$</td>
<td>5.520 ± 10</td>
</tr>
<tr>
<td>5.730 ± 10</td>
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<td>6.009 ± 10</td>
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<td>6.009 ± 10</td>
</tr>
<tr>
<td>6.167 ± 10</td>
<td></td>
<td>6.167 ± 10</td>
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<tr>
<td>6.317 ± 10</td>
<td></td>
<td>6.317 ± 10</td>
</tr>
<tr>
<td>6.422 ± 10</td>
<td></td>
<td>6.422 ± 10</td>
</tr>
<tr>
<td>6.512 ± 10</td>
<td></td>
<td>6.512 ± 10</td>
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</table>
Table 16.6: States in $^{16}$N from $^{14}$N(t, p)$^{16}$N (continued)

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$\Gamma$ (keV)</th>
<th>$E_x$ (MeV ± keV)</th>
<th>$\Gamma$ (keV)</th>
<th>$J^p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.613 ± 10</td>
<td>≤ 7 ± 4</td>
<td>6.613 ± 10</td>
<td>≤ 7 ± 4</td>
<td></td>
</tr>
<tr>
<td>6.854 ± 10</td>
<td>≤ 7 ± 4</td>
<td>6.854 ± 10</td>
<td>≤ 7 ± 4</td>
<td></td>
</tr>
<tr>
<td>7.006 ± 10</td>
<td>22 ± 5</td>
<td>7.006 ± 10</td>
<td>22 ± 5</td>
<td></td>
</tr>
<tr>
<td>7.133 ± 10</td>
<td>≤ 7 ± 4</td>
<td>7.133 ± 10</td>
<td>≤ 7 ± 4</td>
<td></td>
</tr>
<tr>
<td>7.250 ± 10</td>
<td>17 ± 5</td>
<td>7.250 ± 10</td>
<td>17 ± 5</td>
<td></td>
</tr>
<tr>
<td>7.573 ± 10</td>
<td>≤ 7 ± 4</td>
<td>7.573 ± 10</td>
<td>≤ 7 ± 4</td>
<td></td>
</tr>
<tr>
<td>7.640 ± 10</td>
<td>≤ 7 ± 4</td>
<td>7.640 ± 10</td>
<td>≤ 7 ± 4</td>
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<tr>
<td>7.675 ± 10</td>
<td>≤ 7 ± 4</td>
<td>7.675 ± 10</td>
<td>≤ 7 ± 4</td>
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</tr>
<tr>
<td>7.876 ± 10</td>
<td>100 ± 15</td>
<td>7.876 ± 10</td>
<td>100 ± 15</td>
<td></td>
</tr>
<tr>
<td>8.043 ± 10</td>
<td>85 ± 15</td>
<td>8.043 ± 10</td>
<td>85 ± 15</td>
<td></td>
</tr>
<tr>
<td>8.183 ± 10</td>
<td>28 ± 8</td>
<td>8.280 ± 10</td>
<td>24 ± 8</td>
<td></td>
</tr>
<tr>
<td>8.361 ± 10</td>
<td>18 ± 8</td>
<td>8.361 ± 10</td>
<td>18 ± 8</td>
<td></td>
</tr>
</tbody>
</table>

14. $^{15}$N(n, $\gamma$)$^{16}$N

$Q_m = 2.487$

The thermal cross section is $24 \pm 8 \mu b$ (1958HU18).

15. $^{15}$N(n, n)$^{15}$N

$E_b = 2.487$

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

16. $^{15}$N(n, p)$^{15}$C

$Q_m = -8.990$

$E_b = 2.487$
Table 16.7: Resonances in $^{15}$N(n, n)$^{15}$N

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

a See also (1964ST25).
At $E_n = 14.8$ MeV, $\sigma = 16 \pm 4 \text{ mb}$ (1966PR1A).

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

   See (1948JE03, 1964GA1A).

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

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

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


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

   Not reported.

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

   Not reported.

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

   See (1969BR1D).

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

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

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>(1957WA01, 1963GI11) $^a$</th>
<th>(1966HE10) $^a$</th>
<th>(1966HE10) $^{b, f}$</th>
<th>(1970BO08) $^b$</th>
<th>$J^\pi$ $^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td>2$^-$</td>
</tr>
<tr>
<td>0.1201 ± 0.5 $^d$</td>
<td>0.125 ± 10</td>
<td>0.119 ± 15</td>
<td></td>
<td></td>
<td>0$^-$</td>
</tr>
<tr>
<td>0.2962 ± 1.0 $^d$</td>
<td>0.299 ± 10</td>
<td>0.301 ± 15</td>
<td></td>
<td></td>
<td>3$^-$</td>
</tr>
<tr>
<td>0.3973 ± 1.0 $^d$</td>
<td>0.398 ± 10</td>
<td>0.400 ± 15</td>
<td></td>
<td></td>
<td>1$^-$</td>
</tr>
<tr>
<td></td>
<td>3.365 ± 10</td>
<td>3.358 ± 15</td>
<td></td>
<td></td>
<td>(1$^+$)</td>
</tr>
<tr>
<td>(3.53 ± 30)</td>
<td>3.523 ± 10</td>
<td>3.524 ± 15</td>
<td>$^g$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.98 ± 20</td>
<td>3.964 ± 10</td>
<td>3.964 ± 15</td>
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<td></td>
<td>(2, 3)$^+$</td>
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<tr>
<td></td>
<td>4.325 ± 10</td>
<td>4.324 ± 15</td>
<td>(1$^+$)</td>
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<tr>
<td></td>
<td>4.715 ± 10</td>
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</tr>
<tr>
<td>4.80 ± 50 $^e$</td>
<td>4.780 ± 10</td>
<td>4.787 ± 15</td>
<td>$^g$</td>
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<tr>
<td>(4.90 ± 10)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>(5.01 ± 50)</td>
<td>5.032 ± 10</td>
<td>5.065 ± 15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.128 ± 10</td>
<td>5.139 ± 15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.150 ± 10</td>
<td>5.139 ± 15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.25 ± 50 $^e$</td>
<td>5.231 ± 10</td>
<td>5.240 ± 15</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>5.310 ± 10</td>
<td>5.240 ± 15</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>5.523 ± 10</td>
<td>5.528 ± 15</td>
<td>$^g$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.739 ± 10</td>
<td>5.740 ± 15</td>
<td>$^g$</td>
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</tr>
<tr>
<td></td>
<td>6.01 ± 15 $^k$</td>
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<td></td>
<td></td>
<td>h</td>
</tr>
<tr>
<td></td>
<td>6.170 ± 10</td>
<td>6.168 ± 15</td>
<td></td>
<td></td>
<td>h</td>
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<tr>
<td>(6.28 ± 10)</td>
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<td></td>
<td>h</td>
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<tr>
<td>6.376 ± 10</td>
<td>6.37 ± 15 $^k$</td>
<td></td>
<td></td>
<td></td>
<td>h</td>
</tr>
<tr>
<td>6.431 ± 10</td>
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<td></td>
<td></td>
<td>h</td>
</tr>
<tr>
<td>6.514 ± 10</td>
<td>6.512 ± 15</td>
<td></td>
<td></td>
<td></td>
<td>h</td>
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<tr>
<td>6.609 ± 10</td>
<td>6.620 ± 15</td>
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<td>(6.79 ± 10)</td>
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<td></td>
<td>h</td>
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<tr>
<td>6.847 ± 10</td>
<td>6.852 ± 15</td>
<td></td>
<td></td>
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<td>h</td>
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Table 16.8: Levels of $^{15}\text{N}(d, p)^{16}\text{N}$ and $^{18}\text{O}(d, \alpha)^{16}\text{N}$ (continued)

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$^a(1957\text{WA01}, 1963\text{GI11})$</th>
<th>$^a(1966\text{HE10})$</th>
<th>$^b,f(1966\text{HE10})$</th>
<th>$^{b}(1970\text{BO08})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.034 ± 10</td>
<td></td>
<td></td>
<td>7.01 ± 15 $^k$</td>
<td></td>
</tr>
<tr>
<td>7.135 ± 10</td>
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<td>7.141 ± 15</td>
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<tr>
<td>7.250 ± 10</td>
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<td>7.247 ± 15</td>
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<td>7.577 ± 10</td>
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<td>7.596 ± 15</td>
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<td>7.638 ± 10</td>
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<td>7.64 ± 15 $^k$</td>
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<td>7.676 ± 10</td>
<td></td>
<td>7.683 ± 15</td>
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</tr>
<tr>
<td>7.840 ± 10</td>
<td></td>
<td></td>
<td>7.88 ± 15 $^k$</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>8.06 ± 15 $^k$</td>
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<td></td>
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<td>8.18 ± 15 $^k$</td>
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<td>h</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8.49 ± 30 $^i$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8.819 ± 15 $^j$</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>9.035 ± 15</td>
<td>(9.16 ± 30)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>(9.34 ± 30)</td>
<td>(9.459 ± 15)</td>
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<td>(9.66 ± 40)</td>
<td>(9.794 ± 15 $^j$)</td>
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<tr>
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<td></td>
<td>9.90 ± 30</td>
<td>10.055 ± 15 $^j$</td>
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<td></td>
<td></td>
<td></td>
<td>(10.17 ± 30)</td>
<td>(10.26 ± 30)</td>
</tr>
</tbody>
</table>
a $^{15}\text{N}(d, p)^{16}\text{N}$.
b $^{18}\text{O}(d, \alpha)^{16}\text{N}$.
c $J^\pi$ assignment from angular distribution analyses and gamma decay (1956ZI1A, 1957WA01, 1970BO08).
d From $\gamma$-decay studies (1963GI11). (1957FR56, 1957WI1B) found $E_x = 120 \pm 1, 294 \pm 5$ and $392 \pm 3$ keV.
e $\Gamma_{\text{c.m.}} = 230 \pm 40$ and $290 \pm 50$ keV, respectively (1957WA01).
f See also (1970BO08).
g Angular distribution reported in $^{18}\text{O}(d, \alpha)^{16}\text{N}$ at $E_d = 10.0 - 11.2$ MeV but $L$ not determined (1970BO08).
h Alpha group seen but $E_x$ not determined.
i $\Gamma$ for this level and the ones listed below $\leq 40 - 50$ keV (1970BO08).
j These levels appear to be correlated with thresholds for neutron emission to excited states of $^{15}\text{N}$ (1970BO08, 1970BO09).
k T.I. Bonner, private communication.

23. $^{16}\text{O}(n, p)^{16}\text{N}$ \hspace{1cm} $Q_m = -9.639$

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

24. $^{16}\text{O}(t, ^3\text{He})^{16}\text{N}$ \hspace{1cm} $Q_m = -10.403$

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

25. $^{17}\text{O}(d, ^3\text{He})^{16}\text{N}$ \hspace{1cm} $Q_m = -8.288$

Not reported.

26. $^{18}\text{O}(n, t)^{16}\text{N}$ \hspace{1cm} $Q_m = -13.346$

Not reported.

27. $^{18}\text{O}(p, ^3\text{He})^{16}\text{N}$ \hspace{1cm} $Q_m = -14.110$
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 (1969GA1P).

28. $^{18}\text{O}(d, \alpha)^{16}\text{N}$

$Q_m = 4.244$

$Q_0 = 4.249 \pm 0.015$ (1966HE10);

$Q_0 = 4.244 \pm 0.004$ (1967SP09).

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 a $2s_{1/2}$ neutron with $^{15}\text{N}^*(6.32, 7.30, 7.57)$ (1970BO08, 1970BO09). $\tau_m$ for $^{16}\text{N}^*(0.4) = 42 \pm 10$ psec; $|M|^2$ for the M1 transition to $^{16}\text{N}^*(0.1)$ is 0.0350 W.u. (1969NI09). See also (1961LO10, 1964AM1A, 1964MA57) and $^{20}\text{F}$ in (1972AJ02).

29. $^{18}\text{O}(^6\text{Li}, ^8\text{Be})^{16}\text{N}$

$Q_m = 2.677$

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

30. $^{19}\text{F}(n, \alpha)^{16}\text{N}$

$Q_m = -1.524$

Angular distributions have been reported for $E_n = 4.7$ to 14.4 MeV: see (1966BH05, 1966KN02, 1968AN1F, 1968RE07). See also (1959KO60, 1960BO1B, 1965HA1G), (1959AJ76) and $^{20}\text{F}$ in (1972AJ02).
\(^{16}\text{O}\)  
(Figs. 3 and 5)

GENERAL: (See also \(1959\text{AJ76}.\))


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

1. $^6\text{Li}(^{14}\text{N}, \alpha)^{16}\text{O}$

   $Q_m = 19.264$

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

2. (a) $^{10}\text{B}(^6\text{Li}, p)^{15}\text{N}$
   (b) $^{10}\text{B}(^6\text{Li}, d)^{14}\text{N}$
   (c) $^{10}\text{B}(^6\text{Li}, t)^{13}\text{N}$
   (d) $^{10}\text{B}(^6\text{Li}, ^3\text{He})^{13}\text{C}$
   (e) $^{10}\text{B}(^6\text{Li}, \alpha)^{12}\text{C}$

   $Q_m = 18.751$ (a) $E_b = 30.877$ $Q_m = 10.141$ $Q_m = 5.845$ $Q_m = 8.085$ $Q_m = 23.716$

   At $E(^6\text{Li}) = 4.9$ MeV, the cross sections for reactions (a) to (e) leading to low-lying states in the residual nuclei are proportional to $(2J_f + 1)$: 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). See also (1963MO1B, 1964GA1E, 1967CA1D, 1970GI05).
<table>
<thead>
<tr>
<th>$E_x$ in $^{16}$O (MeV ± keV)</th>
<th>$J^\pi; T$</th>
<th>$\Gamma_{c.m.}$ (keV) or $\tau_m$</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0$^+; 0$</td>
<td>–</td>
<td>stable</td>
<td>1, 3, 5, 11, 12, 13, 14, 15, 16, 17, 18, 24, 25, 26, 27, 28, 35, 36, 37, 38, 39, 43, 44, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81</td>
</tr>
<tr>
<td>6.0502 ± 1.0</td>
<td>0$^+; 0$</td>
<td>72 ± 7 psec</td>
<td>$\pi$</td>
<td>11, 12, 24, 27, 35, 36, 37, 44, 47, 55, 56, 58, 61, 66, 67, 70, 71, 79, 80</td>
</tr>
<tr>
<td>6.13066 ± 0.18</td>
<td>3$^−; 0$</td>
<td>24 ± 2 psec</td>
<td>$\gamma$</td>
<td>3, 4, 11, 12, 25, 27, 35, 36, 37, 43, 44, 47, 55, 56, 57, 58, 61, 64, 66, 67, 70, 71, 74, 79, 80</td>
</tr>
<tr>
<td>6.9168 ± 0.6</td>
<td>2$^+; 0$</td>
<td>6.8 ± 0.4 fsec</td>
<td>$\gamma$</td>
<td>11, 12, 25, 27, 35, 36, 37, 43, 44, 55, 56, 57, 58, 61, 64, 66, 70, 71, 74, 79</td>
</tr>
<tr>
<td>7.11867 ± 0.35</td>
<td>1$^−; 0$</td>
<td>10.6 ± 0.9 fsec</td>
<td>$\gamma$</td>
<td>9, 11, 12, 25, 27, 35, 36, 37, 43, 44, 47, 55, 56, 57, 58, 61, 64, 66, 67, 70, 71, 74</td>
</tr>
<tr>
<td>8.8717 ± 0.5</td>
<td>2$^−; 0$</td>
<td>180 ± 16 fsec</td>
<td>$\gamma$</td>
<td>4, 11, 12, 25, 35, 36, 43, 44, 47, 56, 57, 61, 66, 67, 70, 74</td>
</tr>
<tr>
<td>9.597 ± 21</td>
<td>1$^−; 0$</td>
<td>$\Gamma = 510 \pm 60$</td>
<td>$\gamma, \alpha$</td>
<td>5, 9, 11, 12, 35, 44, 47, 61</td>
</tr>
<tr>
<td>9.8469 ± 2.8</td>
<td>2$^+; 0$</td>
<td>1.1</td>
<td>$\gamma, \alpha$</td>
<td>5, 9, 11, 12, 25, 35, 36, 43, 44, 47, 55, 57, 61, 70, 74, 79</td>
</tr>
<tr>
<td>10.353 ± 4</td>
<td>4$^+; 0$</td>
<td>27 ± 4</td>
<td>$\gamma, \alpha$</td>
<td>5, 9, 11, 12, 25, 35, 36, 44, 57, 61, 66, 74</td>
</tr>
<tr>
<td>10.952 ± 3</td>
<td>0$^−; 0$</td>
<td>$\tau_m = 8 \pm 5$ fsec</td>
<td>$\gamma$</td>
<td>35, 36, 43, 44</td>
</tr>
<tr>
<td>11.080 ± 3</td>
<td>3$^+; 0$</td>
<td>57 ± 19 fsec</td>
<td>$\gamma$</td>
<td>35, 36, 43, 44, 57, 74</td>
</tr>
<tr>
<td>11.096 ± 3</td>
<td>4$^+; 0$</td>
<td>$\Gamma = 0.3 \pm 0.1$</td>
<td>$\alpha$</td>
<td>9, 11, 12, 25, 35, 36, 43, 44, 57, 74</td>
</tr>
<tr>
<td>11.26</td>
<td>0$^+; 0$</td>
<td>2500</td>
<td>$\alpha$</td>
<td>9, 43, 44</td>
</tr>
<tr>
<td>(11.44)</td>
<td>3$^−; 0$</td>
<td>830</td>
<td>$\alpha$</td>
<td>9</td>
</tr>
<tr>
<td>11.521 ± 4</td>
<td>2$^+; 0$</td>
<td>74 ± 4</td>
<td>$\gamma, \alpha$</td>
<td>5, 11, 35, 36, 55, 61</td>
</tr>
<tr>
<td>11.63</td>
<td>3$^−; 0$</td>
<td>1200</td>
<td>$\alpha$</td>
<td>9, 11</td>
</tr>
<tr>
<td>12.053 ± 3</td>
<td>0$^+; 0$</td>
<td>1.5 ± 0.5</td>
<td>$\alpha$</td>
<td>9, 11, 35, 36, 55, 76, 61</td>
</tr>
<tr>
<td>12.441 ± 4</td>
<td>1$^−; 0$</td>
<td>97 ± 6</td>
<td>$\gamma, p, \alpha$</td>
<td>5, 7, 9, 11, 35, 36, 39, 40, 42, 43, 44</td>
</tr>
<tr>
<td>12.528 ± 1</td>
<td>2$^−; 0$</td>
<td>$\leq 0.5$</td>
<td>$\gamma, p, \alpha$</td>
<td>11, 35, 36, 39, 40, 42, 43, 44, 55, 77</td>
</tr>
<tr>
<td>12.795 ± 5</td>
<td>0$^−; 1$</td>
<td>38 ± 4</td>
<td>$\gamma, p$</td>
<td>35, 39, 40, 43, 44</td>
</tr>
</tbody>
</table>
Table 16.9: Energy Levels of $^{16}$O $^8$ (continued)

<table>
<thead>
<tr>
<th>$E_x$ in $^{16}$O (MeV ± keV)</th>
<th>$J^\pi; T$</th>
<th>$\Gamma_{c.m.}$ (keV) or $\tau_m$</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.9666 ± 0.9</td>
<td>$2^−; 1$</td>
<td>$2.0 ± 0.2$</td>
<td>$\gamma, p, \alpha$</td>
<td>35, 39, 40, 42, 43, 44, 45, 55</td>
</tr>
<tr>
<td>13.02 ± 10</td>
<td>$2^+$</td>
<td>$150 ± 11$</td>
<td>$\alpha$</td>
<td>9, 55</td>
</tr>
<tr>
<td>13.093 ± 6</td>
<td>$1^−; 1$</td>
<td>$127 ± 8$</td>
<td>$\gamma, p, \alpha$</td>
<td>5, 7, 9, 11, 34, 35, 39, 40, 42, 44, 55</td>
</tr>
<tr>
<td>13.129 ± 10</td>
<td>$3^−; 0$</td>
<td>$128 ± 11$</td>
<td>$p, \alpha$</td>
<td>7, 9, 36, 44</td>
</tr>
<tr>
<td>13.14 ± 100</td>
<td>$2^+$</td>
<td>$≈ 250$</td>
<td>$\gamma, p, \alpha$</td>
<td>5, 42</td>
</tr>
<tr>
<td>13.2582 ± 2.5</td>
<td>$3^−; 1$</td>
<td>$21 ± 1$</td>
<td>$\gamma, p, \alpha$</td>
<td>5, 7, 9, 11, 35, 40, 42, 43, 44, 67</td>
</tr>
<tr>
<td>13.6634 ± 2.7</td>
<td>$1^+; 0$</td>
<td>$64 ± 3$</td>
<td>$p, \alpha$</td>
<td>35, 36, 40, 42, 57</td>
</tr>
<tr>
<td>13.869 ± 10</td>
<td>$4^+$</td>
<td>$85 ± 14$</td>
<td>$p, \alpha$</td>
<td>9, 11, 35, 42, 57</td>
</tr>
<tr>
<td>13.9782 ± 2.4</td>
<td>$2^−$</td>
<td>$22 ± 2$</td>
<td>$p, \alpha$</td>
<td>35, 40, 42, 61</td>
</tr>
<tr>
<td>14.00 ± 50</td>
<td>$0^+$</td>
<td>$170 ± 50$</td>
<td>$\gamma$</td>
<td>55</td>
</tr>
<tr>
<td>14.0</td>
<td>$0^+$</td>
<td>$4800$</td>
<td>$\alpha$</td>
<td>9</td>
</tr>
<tr>
<td>14.39 ± 25</td>
<td>$4^+; 0$</td>
<td>$30 ± 30$</td>
<td></td>
<td>11, 25, 35, 36</td>
</tr>
<tr>
<td>(14.53)</td>
<td></td>
<td></td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>14.82 ± 30</td>
<td>$6^+; 0$</td>
<td>$69 ± 30$</td>
<td>$\alpha$</td>
<td>9, 11, 25, 36</td>
</tr>
<tr>
<td>14.922 ± 6</td>
<td>$4^+$</td>
<td>$51 ± 7$</td>
<td>$p, \alpha$</td>
<td>34, 35, 40, 42, 61</td>
</tr>
<tr>
<td>15.22 ± 35</td>
<td>$2^−$</td>
<td>$70 ± 15$</td>
<td>$p, \alpha$</td>
<td>11, 40, 42, 57, 67</td>
</tr>
<tr>
<td>15.26 ± 50</td>
<td>$2^+; (0)$</td>
<td>$660 ± 90$</td>
<td>$\gamma, p, \alpha$</td>
<td>11, 39, 40, 42, 55</td>
</tr>
<tr>
<td>15.42 ± 40</td>
<td>$(1^−, 3^−)$</td>
<td>$95 ± 25$</td>
<td>$p, \alpha$</td>
<td>7, 9, 34, 40, 42, 67</td>
</tr>
<tr>
<td>15.792 ± 14</td>
<td>$(T = 0)$</td>
<td>$≈ 60$</td>
<td></td>
<td>11, 35, 36</td>
</tr>
<tr>
<td>16.218 ± 13</td>
<td>$1^+; 1$</td>
<td>$19 ± 6$</td>
<td>$\gamma, n, p$</td>
<td>35, 39, 40, 41, 48, 55, 57</td>
</tr>
<tr>
<td>16.23 ± 15</td>
<td>$6^+; 0$</td>
<td>$125 ± 50$</td>
<td>$\alpha$</td>
<td>9, 11, 12, 34, 35, 36</td>
</tr>
<tr>
<td>16.30 ± 30</td>
<td>$0(−)$</td>
<td>$240 ± 30$</td>
<td>$n, p$</td>
<td>41</td>
</tr>
<tr>
<td>16.407 ± 24</td>
<td>$2^+$</td>
<td>$45$</td>
<td>$\gamma, n, p, \alpha$</td>
<td>5, 6, 7, 9, 55</td>
</tr>
<tr>
<td>16.80 ± 100</td>
<td>$(3^+)$</td>
<td>$≤ 100$</td>
<td>$\gamma$</td>
<td>55</td>
</tr>
<tr>
<td>16.94</td>
<td>$2^+$</td>
<td>$≈ 280$</td>
<td>$\alpha, ^8$Be</td>
<td>10</td>
</tr>
<tr>
<td>17.142 ± 12</td>
<td>$1^−; 1$</td>
<td>$33 ± 5$</td>
<td>$\gamma, n, p, \alpha$</td>
<td>6, 7, 9, 35, 36, 39, 40, 41, 44, 48, 55, 57</td>
</tr>
<tr>
<td>17.17</td>
<td>$2^+$</td>
<td>$200$</td>
<td>$\alpha, ^8$Be</td>
<td>10, 44</td>
</tr>
<tr>
<td>17.30 ± 15</td>
<td>$1^−; 1$</td>
<td>$90 ± 10$</td>
<td>$\gamma, n, p, \alpha$</td>
<td>6, 9, 39, 40, 41, 48, 55</td>
</tr>
<tr>
<td>17.55</td>
<td>$(4^+)$</td>
<td>$165$</td>
<td>$(\gamma), n, \alpha$</td>
<td>6, 9, 48</td>
</tr>
<tr>
<td>17.63 ± 15</td>
<td>$≥ 1; 1$</td>
<td>$59 ± 10$</td>
<td>$(\gamma), n, p, \alpha$</td>
<td>7, 9, 41, 55, 57</td>
</tr>
<tr>
<td>17.755 ± 15</td>
<td>$0^+, 2^+$</td>
<td>$≈ 30$</td>
<td>$\alpha, ^8$Be</td>
<td>10, 35</td>
</tr>
<tr>
<td>17.82 ± 40</td>
<td>$4^+$</td>
<td>$225$</td>
<td>$n, \alpha, ^8$Be</td>
<td>6, 9, 10, 35</td>
</tr>
<tr>
<td>17.86 ± 15</td>
<td>$≥ 1; 1$</td>
<td>$101 ± 10$</td>
<td>$n, p$</td>
<td>41</td>
</tr>
<tr>
<td>18.018 ± 15</td>
<td>$4^+; 0$</td>
<td>$14$</td>
<td>$(n), p, \alpha, ^8$Be</td>
<td>7, 9, 10, 35, 41</td>
</tr>
<tr>
<td>18.05 ± 15</td>
<td>$(4^+); 1$</td>
<td>$26 ± 5$</td>
<td>$\gamma, n, p, \alpha$</td>
<td>6, 9, 35, 39, 41</td>
</tr>
</tbody>
</table>
Table 16.9: Energy Levels of $^{16}$O $^\pi$ (continued)

<table>
<thead>
<tr>
<th>$E_\pi$ in $^{16}$O (MeV ± keV)</th>
<th>$J^\pi; T$</th>
<th>$\Gamma_{c.m.}$ (keV) or $\tau_m$</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.132 ± 24</td>
<td></td>
<td>220 ± 60</td>
<td>n, p, α</td>
<td>6, 41</td>
</tr>
<tr>
<td>18.18 ± 25</td>
<td>2$^+$</td>
<td>390 ± 80</td>
<td>n, α</td>
<td>6</td>
</tr>
<tr>
<td>18.46 ± 25</td>
<td></td>
<td>≈ 160</td>
<td>n, p</td>
<td>41</td>
</tr>
<tr>
<td>18.6 (1$^−$, 5$^−$)</td>
<td></td>
<td>140</td>
<td>α</td>
<td>9</td>
</tr>
<tr>
<td>18.71 (0$^+$, 2$^+$)</td>
<td></td>
<td>260 ± 30</td>
<td>n, p, α, $^8$Be</td>
<td>10, 41</td>
</tr>
<tr>
<td>18.79 (4$^+$)</td>
<td></td>
<td>220</td>
<td>n, p, α, $^8$Be</td>
<td>6, 7, 9, 10</td>
</tr>
<tr>
<td>(18.983 ± 15)</td>
<td></td>
<td>≈ 25</td>
<td></td>
<td>35</td>
</tr>
<tr>
<td>18.99 ± 30</td>
<td>1$^−$; 1</td>
<td>300 ± 100</td>
<td>γ, p</td>
<td>39, 55</td>
</tr>
<tr>
<td>19.04 ± 50</td>
<td>2$^−$; 1</td>
<td>400 ± 50</td>
<td>γ, α</td>
<td>9, 55</td>
</tr>
<tr>
<td>19.06 ± 60</td>
<td>2$^+$; 1</td>
<td>≈ 120</td>
<td>γ, p</td>
<td>39, 40, 48</td>
</tr>
<tr>
<td>19.12 (2$^+$, 4$^+$)</td>
<td></td>
<td>41</td>
<td>(n), α</td>
<td>6, 9</td>
</tr>
<tr>
<td>19.24 ± 25</td>
<td>2$^−$; 1</td>
<td>90 ± 10</td>
<td>γ, n, p</td>
<td>39, 41</td>
</tr>
<tr>
<td>19.25 (5$^−$)</td>
<td></td>
<td>23</td>
<td>(n), α</td>
<td>6, 9</td>
</tr>
<tr>
<td>19.34 6$^+$</td>
<td></td>
<td>50</td>
<td>α, $^8$Be</td>
<td>10</td>
</tr>
<tr>
<td>(19.382 ± 15)</td>
<td>π = +</td>
<td>≈ 30</td>
<td>α</td>
<td>9, 35</td>
</tr>
<tr>
<td>19.48 ± 30</td>
<td>1$^−$; 1</td>
<td>300 ± 80</td>
<td>γ, n, p, α</td>
<td>9, 39, 41, 48, 55</td>
</tr>
<tr>
<td>19.62</td>
<td></td>
<td>240</td>
<td>n, α</td>
<td>6</td>
</tr>
<tr>
<td>19.80 ± 150</td>
<td>(2, 3; 1)</td>
<td>120 ± 40</td>
<td>γ, n, p, α</td>
<td>9, 35, 39, 41</td>
</tr>
<tr>
<td>20.087</td>
<td></td>
<td>310</td>
<td>n, α</td>
<td>6</td>
</tr>
<tr>
<td>20.3</td>
<td></td>
<td>≈ 1500</td>
<td>p, α</td>
<td>7</td>
</tr>
<tr>
<td>(20.348 ± 15)</td>
<td></td>
<td>≈ 30</td>
<td>γ, n</td>
<td>35, 48</td>
</tr>
<tr>
<td>20.36 ± 70</td>
<td>2$^−$</td>
<td>500 ± 100</td>
<td>γ</td>
<td>55</td>
</tr>
<tr>
<td>20.39 ± 25</td>
<td>≥ 2</td>
<td>150 ± 30</td>
<td>γ, n, p, α</td>
<td>6, 9, 39, 41</td>
</tr>
<tr>
<td>20.55 ± 25</td>
<td>≥ 1</td>
<td>140 ± 30</td>
<td>n, p, α</td>
<td>9, 41</td>
</tr>
<tr>
<td>20.8 (8$^+$)</td>
<td></td>
<td>≈ 600</td>
<td>γ</td>
<td>11, 12, 39</td>
</tr>
<tr>
<td>20.81</td>
<td></td>
<td>&lt; 25</td>
<td>n, α</td>
<td>6</td>
</tr>
<tr>
<td>20.89 ± 25</td>
<td></td>
<td>≈ 250</td>
<td>γ, n, p</td>
<td>39, 41, 48, 49</td>
</tr>
<tr>
<td>(21.0) (7$^−$)</td>
<td></td>
<td>750</td>
<td>(γ), α</td>
<td>9, 48</td>
</tr>
<tr>
<td>21.01 ± 20</td>
<td>1$^−$; 1</td>
<td>260 ± 60</td>
<td>γ, n, α</td>
<td>5, 48, 55</td>
</tr>
<tr>
<td>21.02 ± 20</td>
<td></td>
<td>55</td>
<td>(γ), n, α</td>
<td>6, 48</td>
</tr>
<tr>
<td>(21.1) (5$^−$)</td>
<td></td>
<td>900</td>
<td>α</td>
<td>9</td>
</tr>
<tr>
<td>(21.2) (6$^+$)</td>
<td></td>
<td>450</td>
<td>n, α</td>
<td>6, 9, 11</td>
</tr>
<tr>
<td>21.68</td>
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<td>55</td>
<td>γ, n, α</td>
<td>6, 48</td>
</tr>
<tr>
<td>21.79</td>
<td></td>
<td>55</td>
<td>γ, n, p, d, α</td>
<td>6, 29, 39, 48</td>
</tr>
<tr>
<td>22.04</td>
<td></td>
<td>60</td>
<td>γ, n, d, α</td>
<td>6, 11, 29, 39</td>
</tr>
<tr>
<td>22.07</td>
<td></td>
<td>340</td>
<td>n, α</td>
<td>6, 11</td>
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Table 16.9: Energy Levels of $^{16}$O $^a$ (continued)

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

$^a$ See also Tables 16.12, 16.19 and 16.26.
3. $^{10}$B($^{14}$N, $^8$Be)$^{16}$O \hspace{1cm} Q_m = 14.708 \\
\tau_m \text{ for } ^{16}$O$^*$$(6.13) = 21^{+1}_{-1}$ psec. The ground state E3 transition has a strength of 62 W.u. (1969NI09).

4. $^{11}$B($^7$Li, 2n)$^{16}$O \hspace{1cm} Q_m = 12.169 \\
\tau_m \text{ for } ^{16}$O$^*$$(8.88) = 0.37 \pm 0.13$ psec. The transition energy for 8.88 $\rightarrow$ 6.13 is 2740.4 $\pm$ 1.0 keV (1969TH01).

5. $^{12}$C($\alpha$, $\gamma$)$^{16}$O \hspace{1cm} Q_m = 7.161 \\
The yield of capture $\gamma$-rays has been studied for $E_\alpha < 23.5$ MeV: see Table 16.10. The cross section rises from $(1.1 \pm 0.4) \times 10^{-3}$ $\mu$b at $E_\alpha = 1.86$ MeV to $(29 \pm 4) \times 10^{-3}$ $\mu$b at $E_\alpha = 3.11$ MeV. At $E_\alpha = 1.6$ MeV, the capture cross section is $< 0.3 \times 10^{-3}$ $\mu$b (1970JA09). At higher energies resonances are observed. These are displayed in Table 16.11 (1960ME02, 1964LA16, 1965MI05, 1967SU02). Widths for $\gamma$-emission have been measured for several of the corresponding $^{16}$O states: see Table 16.12 (1963GO31, 1964LA16, 1966GO18, 1967GO08, 1967SU02). See also (1969BR1L) and (1967GI1C, 1969GI1B; theor.). The asymmetries in the angular distributions in this reaction and in the inverse reaction $^{16}$O($\gamma$, $\alpha$)$^{12}$C are the same within one standard deviation: there is no evidence for failure of time reversal invariance (1970VO13). The relevance of this reaction to the buildup of elements in stars is discussed by (1967ST1M, 1967WI1B, 1970TO1C, 1970WE1A, 1970WE1F) and in earlier papers listed in (1959AJ76).

6. $^{12}$C($\alpha$, n)$^{15}$O \hspace{1cm} Q_m = -8.507 \hspace{1cm} E_b = 7.161 \\
Cross section measurements have been made from threshold to $E_\alpha = 24.7$ MeV: see Table 16.10. Observed resonances are displayed in Table 16.11 (1963NE05, 1968BL08, 1970BE1T). See also (1962GO1J, 1963GO1J, 1965AL1J, 1965TS1A) and (1963KE1A; theor.). See also $^{15}$O in (1970AJ04).

7. $^{12}$C($\alpha$, p)$^{15}$N \hspace{1cm} Q_m = -4.965 \hspace{1cm} E_b = 7.161 \\
The yield of protons corresponding to the ground state of $^{15}$N has been studied for $E_\alpha = 7.7$ to 23 MeV: see Table 16.10. Observed resonances are displayed in Table 16.11 (1960PR13, 1964AT1A, 1964CA07, 1965MI05, 1968MO1H, 1970BE1T, 1970NE1H). See also (1963KE1A; theor.) and $^{15}$N in (1970AJ04).
Table 16.10: Recent $^{12}$C + α yield curves $^a$

<table>
<thead>
<tr>
<th>$E_\alpha$ (MeV)</th>
<th>Yield of</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.91 − 3.16</td>
<td>$\gamma_{\text{capt.}}$</td>
<td>(1968JA1K, JA69K)</td>
</tr>
<tr>
<td>2.60 − 3.25</td>
<td>$\gamma_{\text{capt.}}$</td>
<td>(1968AD1D)</td>
</tr>
<tr>
<td>2.8 − 8.3</td>
<td>$\gamma_{\text{capt.}}$</td>
<td>(1964LA16)</td>
</tr>
<tr>
<td>6.9 − 8.4</td>
<td>$\gamma_{\text{capt.}}$</td>
<td>(1964MI12, 1965MI05)</td>
</tr>
<tr>
<td>8.75 − 23.50</td>
<td>$\gamma_{\text{capt.}}$</td>
<td>(1967SU02)</td>
</tr>
<tr>
<td>thresh. − 19</td>
<td>n($\sigma_t$)</td>
<td>(1963NE05)</td>
</tr>
<tr>
<td>thresh. − 22.7</td>
<td>n($\sigma_t$)</td>
<td>(1968BL08)</td>
</tr>
<tr>
<td>13 − 16</td>
<td>n$_0$</td>
<td>(1970BE1T)</td>
</tr>
<tr>
<td>13.7 − 24.7</td>
<td>$^{15}$O</td>
<td>(1969SP1B)</td>
</tr>
<tr>
<td>15 − 19</td>
<td>n($\sigma_t$)</td>
<td>(1962CA03)</td>
</tr>
<tr>
<td>7.7 − 8.4</td>
<td>p$_0$</td>
<td>(1965MI05)</td>
</tr>
<tr>
<td>9.6 − 17.6</td>
<td>p$_0$</td>
<td>(1964CA07)</td>
</tr>
<tr>
<td>12.4 − 16.0</td>
<td>p$_0$</td>
<td>(1967IV1B)</td>
</tr>
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<td>13 − 16</td>
<td>p$_0$</td>
<td>(1970BE1T)</td>
</tr>
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<td>13 − 23</td>
<td>p$_0$</td>
<td>(1968BL08)</td>
</tr>
<tr>
<td>15.8 − 19.0</td>
<td>p$_0$</td>
<td>(1960PR13)</td>
</tr>
<tr>
<td>15.9 − 26.3</td>
<td>p$_0$</td>
<td>(1965TE01)</td>
</tr>
<tr>
<td>19 − 23</td>
<td>p$_1$ + p$_2$</td>
<td>(1968BL08)</td>
</tr>
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<td>19.7 − 22.1</td>
<td>p$_0$</td>
<td>(1963YA1C)</td>
</tr>
<tr>
<td>20 − 23</td>
<td>p$_0$</td>
<td>(1964AT1A)</td>
</tr>
<tr>
<td>2.5 − 4.8</td>
<td>$\alpha_0$</td>
<td>(1962JO09)</td>
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<tr>
<td>2.8 − 6.6</td>
<td>$\alpha_0$</td>
<td>(1968CL04)</td>
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<td>4 − 13.3</td>
<td>$\alpha_0$</td>
<td>(1969MA1U)</td>
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<td>(1966LA09)</td>
</tr>
<tr>
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<td>(1964MI08)</td>
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<td>$\alpha_0$</td>
<td>(1966LA09)</td>
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<tr>
<td>6.6 − 8.5</td>
<td>$\alpha_0$</td>
<td>(1968MO08)</td>
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<td>7.3 − 8.4</td>
<td>$\gamma_{4.4}$</td>
<td>(1964MI12)</td>
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<td>7.4 − 10.6</td>
<td>$\gamma_{4.4}$</td>
<td>(1964LA16)</td>
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<td>7.7 − 8.3</td>
<td>$\alpha_1$, $\gamma_{4.4}$</td>
<td>(1965MI05)</td>
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<tr>
<td>8.5 − 10.5</td>
<td>$\alpha_0$, $\alpha_1$</td>
<td>(1970OP01)</td>
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</table>
Table 16.10: Recent $^{12}\text{C} + \alpha$ yield curves $^a$ (continued)

<table>
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<tr>
<th>$E_\alpha$ (MeV)</th>
<th>Yield of</th>
<th>Refs.</th>
</tr>
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<tbody>
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</tr>
<tr>
<td>9.8 – 19.1</td>
<td>$\alpha_0$</td>
<td>(1964CA07)</td>
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<td>$\alpha_0$</td>
<td>(1967KR1D)</td>
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<td>12.0 – 17.3</td>
<td>$\alpha_2$</td>
<td>(1970MO22)</td>
</tr>
<tr>
<td>12.8 – 26.3</td>
<td>$\alpha_0$, $\alpha_1$</td>
<td>(1966IF01)</td>
</tr>
<tr>
<td>13.5 – 23.5</td>
<td>$\alpha_1$</td>
<td>(1963LU08)</td>
</tr>
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<td>13.5 – 30.5</td>
<td>$\alpha_0$</td>
<td>(1963LU08)</td>
</tr>
<tr>
<td>14.4 – 18.8</td>
<td>$\gamma_{4.4}$</td>
<td>(1962CA03)</td>
</tr>
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<td>14.5</td>
<td>$\alpha_0$, $\alpha_1$</td>
<td>(1968MO1H)</td>
</tr>
<tr>
<td>14.6 – 18.1</td>
<td>$\alpha_3$</td>
<td>(1970MO22)</td>
</tr>
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<td>15 – 22.7</td>
<td>$\alpha_0$</td>
<td>(1962JO14)</td>
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<td>(1964MI08)</td>
</tr>
<tr>
<td>17.3 – 23.4</td>
<td>$\alpha_0$, $\alpha_1$</td>
<td>(1964JO14)</td>
</tr>
<tr>
<td>18.9 – 30.1</td>
<td>$\alpha_0$, $\alpha_1$</td>
<td>(1970MO06)</td>
</tr>
<tr>
<td>20 – 24</td>
<td>$\alpha_0$</td>
<td>(1968AG03, 1969AG06)</td>
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<tr>
<td>20.2 – 22.8</td>
<td>$\alpha_1$</td>
<td>(1964AT1A)</td>
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<tr>
<td>27.0 – 35.5</td>
<td>$\alpha_0$, $\alpha_1$</td>
<td>(1961MI03)</td>
</tr>
<tr>
<td>11.9 – 19.4</td>
<td>$^8\text{Be}$</td>
<td>(1967CH21)</td>
</tr>
</tbody>
</table>

$a$ See also (1959AJ76).

8. $^{12}\text{C}(\alpha, d)^{14}\text{N}$ \hspace{2cm} $Q_m = -13.575$ \hspace{2cm} $E_h = 7.161$

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

9. $^{12}\text{C}(\alpha, \alpha)^{12}\text{C}$ \hspace{2cm} $E_h = 7.161$

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

<table>
<thead>
<tr>
<th>$E_\alpha$ (MeV ± keV)</th>
<th>$\Gamma_{\text{c.m.}}$ (keV)</th>
<th>Outgoing particles$^a$ (x)</th>
<th>$\Gamma_x$ (keV)</th>
<th>$^{16}\text{O}^*$ (MeV)</th>
<th>$J^\pi; T$</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.322 ± 30</td>
<td>550</td>
<td>$\gamma_0$ $\alpha_0$</td>
<td>(2.2 ± 0.5) x 10^{-5}</td>
<td>9.58</td>
<td>1$^-$</td>
<td>(1953HI1A, 1962JO09, 1964LA16, 1968CL04)</td>
</tr>
<tr>
<td>3.575 ± 10</td>
<td>1.1</td>
<td>$\gamma_0$ $\alpha_0$</td>
<td>(5.9 ± 0.6) x 10^{-6}</td>
<td>9.842</td>
<td>2$^+$</td>
<td>(1953HI1A, 1960ME02, 1962JO09, 1964LA16)</td>
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<tr>
<td>4.241 ± 25</td>
<td>195</td>
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<td></td>
<td>10.341</td>
<td>4$^+$</td>
<td>(1962JO09)</td>
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<tr>
<td>4.260 ± 15</td>
<td>27 ± 4</td>
<td>$\gamma_0$ $\alpha_0$</td>
<td></td>
<td>10.355</td>
<td></td>
<td>(1964LA16)</td>
</tr>
<tr>
<td>5.245 ± 8</td>
<td>0.3 ± 0.1</td>
<td>$\alpha_0$</td>
<td></td>
<td>11.094</td>
<td>4$^+$</td>
<td>(1966LA09)</td>
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<tr>
<td>5.47</td>
<td>2500</td>
<td>$\alpha_0$</td>
<td></td>
<td>11.26</td>
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<td>(1954BI1A)</td>
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<tr>
<td>5.71</td>
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<td>3$^-$</td>
<td>(1968CL04)</td>
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<td>5.809 ± 18</td>
<td>73 ± 5</td>
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<td>(0.66 ± 0.09) x 10^{-3}</td>
<td>11.517</td>
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<td>(1960ME02, 1964LA16)</td>
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<td>5.96</td>
<td>1200</td>
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<td>11.63</td>
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<td>(1954BI1A)</td>
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<td>6.518 ± 10</td>
<td>1.5 ± 0.5</td>
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<td>(1966LA09)</td>
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<tr>
<td>7.045 ± 5</td>
<td>99 ± 7</td>
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<td>(7 ± 1) x 10^{-3}</td>
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<td></td>
<td></td>
<td>p</td>
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<td></td>
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<tr>
<td>7.82 ± 10</td>
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<td>150 ± 11</td>
<td>13.02</td>
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<td>(1968MO08)</td>
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<tr>
<td>7.915 ± 10</td>
<td>113 ± 15</td>
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<td>8.8 x 10^{-2}</td>
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<td>(1964LA16, 1964MI12, 1965MI05, 1968MO08)</td>
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<td></td>
<td></td>
<td>p</td>
<td>100</td>
<td></td>
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<td></td>
<td></td>
<td>$\alpha_0$</td>
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<td></td>
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<tr>
<td></td>
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<td>$\alpha_1$</td>
<td>1</td>
<td></td>
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<td></td>
<td>$\alpha_0$</td>
<td>90 ± 14</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>$\alpha_1$</td>
<td>$\approx$ 20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.98 ± 100</td>
<td>$\approx$ 250</td>
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<td></td>
<td>13.14</td>
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<td>(1964LA16, 1965MI05)</td>
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$^a$ Notation: $\gamma_0$, $\alpha_0$, $\alpha_1$; $p$
Table 16.11: Resonances in $^{12}$C + α (continued)

<table>
<thead>
<tr>
<th>$E_\alpha$ (MeV ± keV)</th>
<th>$\Gamma_{\text{c.m.}}$ (keV)</th>
<th>Outgoing particles $^a$</th>
<th>$\Gamma_x$ (keV)</th>
<th>$^{16}\text{O}^*$ (MeV)</th>
<th>$J^\pi; T$</th>
<th>Refs.</th>
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<td>8.130 ± 15</td>
<td>26 ± 7</td>
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<td>$\alpha_0, \gamma_{4.4}$</td>
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<td>13.88</td>
<td>4$^+$</td>
<td>(1964LA16, 1964MI08, 1970OP01)</td>
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<tr>
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<td>4800</td>
<td>$\alpha_0$</td>
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<tr>
<td>10.08</td>
<td>400</td>
<td>$\gamma_{4.4}, (\alpha_0)$</td>
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<td>14.72</td>
<td></td>
<td>(1964CA07, 1964LA16, 1964MI08)</td>
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<td>10.18</td>
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<td>6$^+$</td>
<td>(1964CA07, 1964LA16, 1964MI08, 1970OP01)</td>
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<td>10.25</td>
<td>55</td>
<td>$p_0, \alpha_0$</td>
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<td>14.85</td>
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<td>11.02</td>
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<td>$(1^-, 3^-)$</td>
<td>(1964CA07, 1964MI08)</td>
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<tr>
<td>(11.08)</td>
<td>280</td>
<td>$p_0, \alpha_0$</td>
<td></td>
<td>15.47</td>
<td></td>
<td>(1964CA07)</td>
</tr>
<tr>
<td>11.5</td>
<td>≈ 400</td>
<td>$\alpha_0, \alpha_1, \gamma_{4.4}$</td>
<td></td>
<td>15.8</td>
<td>3$^-$</td>
<td>(1964CA07, 1964MI08)</td>
</tr>
<tr>
<td>12.1</td>
<td>280</td>
<td>$\alpha_0$</td>
<td></td>
<td>16.2</td>
<td>6$^+$</td>
<td>(1964CA07)</td>
</tr>
<tr>
<td>12.32 ± 25</td>
<td>45</td>
<td>$\gamma_0, n, p_0, \alpha_0, \alpha_1, \gamma_{4.4}$</td>
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<td>16.40$^b$</td>
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<td>(1964CA07, 1964MI08, 1967SU02, 1968BL08)</td>
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<td>12.5</td>
<td>730</td>
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<td>16.5</td>
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<tr>
<td>12.9</td>
<td>400</td>
<td>$\alpha_0$</td>
<td></td>
<td>16.8</td>
<td>$(4^+)$</td>
<td>(1964CA07)</td>
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<td>≈ 280</td>
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<td>$n, (p_0), \alpha_0, \alpha_1, \gamma_{4.4}$</td>
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<td>17.10</td>
<td>$(1^-, 2^+, 0^+)$</td>
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<tr>
<td>13.35</td>
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<td>17.17</td>
<td>2$^+$</td>
<td>(1967CH21)</td>
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<tr>
<td>13.50</td>
<td>&lt; 100</td>
<td>$n$</td>
<td></td>
<td>17.28</td>
<td></td>
<td>(1968BL08)</td>
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<tr>
<td>13.59</td>
<td>150</td>
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<td>17.35</td>
<td></td>
<td>(1964MI08)</td>
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<td>13.86</td>
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<td>$n, \alpha_0$</td>
<td></td>
<td>17.55</td>
<td>$(4^+)$</td>
<td>(1964CA07, 1968BL08)</td>
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<tr>
<td>13.95</td>
<td>110</td>
<td>$p_0, \alpha_0$</td>
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<td>17.62</td>
<td></td>
<td>(1964CA07, 1970BE1T)</td>
</tr>
<tr>
<td>14.1</td>
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<td></td>
<td></td>
<td>17.7</td>
<td>0$^+$, 2$^+$</td>
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<tr>
<td>14.21</td>
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<td></td>
<td>17.81</td>
<td>4$^+$</td>
<td>(1964MI08, 1967CH21)</td>
</tr>
</tbody>
</table>
Table 16.11: Resonances in $^{12}$C + $\alpha$ (continued)

<table>
<thead>
<tr>
<th>$E_{\alpha}$ (MeV ± keV)</th>
<th>$\Gamma_{c.m.}$ (keV)</th>
<th>Outgoing particles $^a$ (x)</th>
<th>$\Gamma_x$ (keV)</th>
<th>$^{16}$O* (MeV)</th>
<th>$J^\pi; T$</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.483 ± 15</td>
<td>14</td>
<td>$p_0, \alpha_0, \alpha_1, ^8$Be</td>
<td>18.018</td>
<td>4$^+$; 0</td>
<td>(1967CH21, 1968MO1H)</td>
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<tr>
<td>14.50</td>
<td>40</td>
<td>$n, \alpha_0, \alpha_1, \gamma_{4.4}$</td>
<td>18.03</td>
<td>(4$^+$)</td>
<td>(1964CA07, 1964MI08, 1968BL08)</td>
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</tr>
<tr>
<td>14.59 ± 40</td>
<td>220 ± 60</td>
<td>$n_0$</td>
<td>18.10</td>
<td></td>
<td>(1963NE05, 1968BL08, 1970BE1T)</td>
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<tr>
<td>14.70 ± 25</td>
<td>390 ± 80</td>
<td>n</td>
<td>18.18</td>
<td>2$^+$</td>
<td>(1967SU02)</td>
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</tr>
<tr>
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<td>$p_0, (\alpha_0), \alpha_1, \gamma_{4.4}$</td>
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<td></td>
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<td>(1964CA07, 1964MI08)</td>
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<td>(4$^+$)</td>
<td>(1964CA07, 1964MI08, 1967CH21, 1968BL08)</td>
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<td>(1964CA07)</td>
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<td>(4$^+$)</td>
<td>(1964CA07)</td>
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Table 16.11: Resonances in $^{12}$C + α (continued)

<table>
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<tr>
<th>$E_\alpha$ (MeV ± keV)</th>
<th>$\Gamma_{c.m.}$ (keV)</th>
<th>Outgoing particles $^a$</th>
<th>$\Gamma_x$ (keV)</th>
<th>$^{16}$O* (MeV)</th>
<th>$J^\pi; T$</th>
<th>Refs.</th>
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<td>240 ± 80</td>
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<td>n</td>
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<td>(1970NE1H)</td>
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</tr>
<tr>
<td>(21.2)</td>
<td>680</td>
<td>$\alpha_0$</td>
<td>(23.1)</td>
<td>(1968AG03, 1969AG06)</td>
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<tr>
<td>21.28</td>
<td>≈ 20</td>
<td>$\alpha_0$, $\alpha_1$</td>
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<td>21.67</td>
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<td>n</td>
<td>23.40</td>
<td>(1968BL08)</td>
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<td>21.85</td>
<td>300</td>
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<td>23.54</td>
<td>(1955RA1B, 1970HA15)</td>
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<td>22.14</td>
<td>120</td>
<td>n</td>
<td>23.75</td>
<td>(1968BL08)</td>
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</tr>
<tr>
<td>22.32</td>
<td>≈ 25</td>
<td>$\alpha_0$, $\alpha_1$</td>
<td>23.89</td>
<td>(1970HA15)</td>
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<td></td>
</tr>
<tr>
<td>22.37</td>
<td>165</td>
<td>n</td>
<td>23.93</td>
<td>(1968BL08)</td>
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<tr>
<td>30</td>
<td>broad</td>
<td>$\alpha_0$, $\alpha_1$</td>
<td>30</td>
<td>(1961MI03)</td>
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<td></td>
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</tbody>
</table>

$^a$ $p_0$, $\alpha_0$, and $\alpha_1$ correspond to groups to $^{15}$N(0), $^{12}$C(0) and $^{12}$C*(4.4); $\gamma_4.4$ corresponds to the $\gamma$-decay of $^{12}$C*(4.4); $\gamma_0$ corresponds to capture $\gamma$-rays.

$^b$ $\Gamma_{\gamma}/\Gamma = 0.2$, 0.7 and 6 eV, respectively for $^{16}$O*(16.40, 18.19, 21.04) (1967SU02).
Table 16.12: Radiative decays in $^{16}$O

<table>
<thead>
<tr>
<th>$E_i$ (MeV)</th>
<th>$J_i^\pi$: $T$</th>
<th>$E_f$ (MeV)</th>
<th>$J_f^\pi$: $T$</th>
<th>Branch (%)</th>
<th>$\Gamma_\gamma$ (eV)</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.05</td>
<td>0(^\pm):0</td>
<td>0</td>
<td>0(^\pm):0</td>
<td>100</td>
<td>3.66 ± 0.55(^b)</td>
<td>(1968ST31)</td>
</tr>
<tr>
<td>6.13</td>
<td>3(^\pm):0</td>
<td>0</td>
<td>0(^\pm):0</td>
<td>100</td>
<td>(2.3 ± 1.1) × 10(^{-5})</td>
<td>(1968ST31)</td>
</tr>
<tr>
<td>6.92</td>
<td>2(^\pm):0</td>
<td>0</td>
<td>0(^\pm):0</td>
<td>&gt; 99</td>
<td>(80 ± 7) × 10(^{-3})</td>
<td>(1968ST04, 1968ST31)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.05</td>
<td>0(^\pm):0</td>
<td>(2.7 ± 0.7) × 10(^{-2})</td>
<td>(93 ± 10) × 10(^{-3})</td>
<td>(1968ST04, 1968ST31)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2(^\pm):0</td>
<td>(2.9 ± 1.1) × 10(^{-2})</td>
<td>(100 ± 15) × 10(^{-3})</td>
<td>(1967AR1A)</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>7(^\pm):0</td>
<td>(2.3 ± 0.5) × 10(^{-2})</td>
<td>(110 ± 5) × 10(^{-3})</td>
<td>(1970SW03)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>9(^\pm):0</td>
<td>(2.9 ± 0.4) × 10(^{-2})</td>
<td>≥ 9 × 10(^{-3})</td>
<td>(1965FU05)</td>
</tr>
<tr>
<td></td>
<td>7.12</td>
<td>1(^\pm):0</td>
<td>0</td>
<td>&gt; 99</td>
<td>2.7 × 10(^{-5})</td>
<td>(1963GO31)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.05</td>
<td>0(^\pm):0</td>
<td>≤ 3.5 × 10(^{-3})</td>
<td>≤ 3.0 × 10(^{-6})</td>
<td>(1970SW03)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3(^\pm):0</td>
<td>(8 ± 2) × 10(^{-2})</td>
<td>(5.3 ± 2.1) × 10(^{-5})</td>
<td>(1963GO31)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>7(^\pm):0</td>
<td>(7 ± 1.4) × 10(^{-2})</td>
<td>≥ 6 × 10(^{-4})</td>
<td>(1967LO08)</td>
</tr>
<tr>
<td></td>
<td>8.87(^d)</td>
<td>2(^\pm):0</td>
<td>0</td>
<td>7 ± 2</td>
<td>9 ± 4</td>
<td>(1957BE61)</td>
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<td></td>
<td></td>
<td></td>
<td>0(^\pm):0</td>
<td>7.2 ± 0.8</td>
<td>(2.41 ± 0.35) × 10(^{-4})</td>
<td>(1957MC35)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>0(^\pm):0</td>
<td>0.112 ± 0.033</td>
<td>(2.9 ± 1.0) × 10(^{-6})</td>
<td>(1957MC35)</td>
</tr>
<tr>
<td>6.13</td>
<td>3(^\pm):0</td>
<td>74</td>
<td>7(^\pm):0</td>
<td>76.0 ± 3.0</td>
<td>(1.70(^+0.35)(^{-0.50})) × 10(^{-3}) (E2)</td>
<td>(1968WI15)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3(^\pm):0</td>
<td>76.0 ± 3.0</td>
<td>(8.5(^+4.0)(^{-2.5})) × 10(^{-4}) (M1)</td>
<td>(1967PI01)</td>
</tr>
<tr>
<td>6.92</td>
<td>2(^\pm):0</td>
<td>5</td>
<td>4(^\pm):0</td>
<td>4.2 ± 0.8</td>
<td>(1.72 ± 0.25) × 10(^{-4})</td>
<td>(1968WI15)</td>
</tr>
<tr>
<td>7.12</td>
<td>1(^\pm):0</td>
<td>14</td>
<td>1(^\pm):0</td>
<td>12.6 ± 2.0</td>
<td>12.6 ± 2.0</td>
<td>(1968WI15)</td>
</tr>
<tr>
<td>9.60</td>
<td>1(^\pm):0</td>
<td>0</td>
<td>0(^\pm):0</td>
<td>12.6 ± 2.0</td>
<td>(22 ± 5) × 10(^{-3})</td>
<td>(1964LA16)</td>
</tr>
</tbody>
</table>
Table 16.12: Radiative decays in $^{16}$O a (continued)

<table>
<thead>
<tr>
<th>$E_i$ (MeV)</th>
<th>$J_i^\pi: T$</th>
<th>$E_f$ (MeV)</th>
<th>$J_f^\pi: T$</th>
<th>Branch (%)</th>
<th>$\Gamma_\gamma$ (eV)</th>
<th>Refs. c</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.05</td>
<td>0$^+$: 0</td>
<td>6.05</td>
<td>0$^+$: 0</td>
<td>4.3 ± 1.4</td>
<td>$(1.8 ± 4) \times 10^{-3}$</td>
<td>A</td>
</tr>
<tr>
<td>6.13</td>
<td>3$^-$: 0</td>
<td>6.13</td>
<td>0$^+$: 0</td>
<td>≤ 5</td>
<td>$(1.2 ± 0.4) \times 10^{-3}$</td>
<td>(1969BR1L), B</td>
</tr>
<tr>
<td>9.85</td>
<td>2$^+$: 0</td>
<td>0</td>
<td>0$^+$: 0</td>
<td>61 ± 4</td>
<td>$(&lt; 0.6) \times 10^{-3}$</td>
<td>A</td>
</tr>
<tr>
<td>10.35</td>
<td>4$^+$: 0</td>
<td>6.05</td>
<td>0$^+$: 0</td>
<td>18 ± 4</td>
<td>$(1.89 ± 0.42) \times 10^{-3}$</td>
<td>(1967GO08), B</td>
</tr>
<tr>
<td>10.95</td>
<td>0$^-$: 0</td>
<td>6.05</td>
<td>0$^+$: 0</td>
<td>&lt; 5</td>
<td>$(1.2 ± 0.4) \times 10^{-3}$</td>
<td>(1969BR1L), B</td>
</tr>
<tr>
<td>11.08</td>
<td>3$^+$: 0</td>
<td>6.13</td>
<td>3$^-$: 0</td>
<td>&lt; 6</td>
<td>&lt; 1.0 × 10^{-3}</td>
<td>(1969BR1L), B</td>
</tr>
<tr>
<td>11.52</td>
<td>2$^+$: 0</td>
<td>6.92</td>
<td>2$^+$: 0</td>
<td>&gt; 99</td>
<td>$(4.0 ± 0.8) \times 10^{-2}$</td>
<td>(1966GO08)</td>
</tr>
<tr>
<td>12.44</td>
<td>1$^-$: 0</td>
<td>7.12</td>
<td>1$^-$: 0</td>
<td>&lt; 100</td>
<td>$(4.6 ± 0.6) \times 10^{-2}$</td>
<td>(1964LA16)</td>
</tr>
</tbody>
</table>

a: 'best' value

1.89 ± 0.42 × 10^{-3} (1967GO08), B

3.0 ± 0.7 × 10^{-2} (HO66C), B
Table 16.12: Radiative decays in $^{16}$O (continued)

<table>
<thead>
<tr>
<th>$E_i$ (MeV)</th>
<th>$J_i^\pi: T$</th>
<th>$E_f$ (MeV)</th>
<th>$J_f^\pi: T$</th>
<th>Branch (%)</th>
<th>$\Gamma_\gamma$ (eV)</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.53 $^a$</td>
<td>$2^-: 0$</td>
<td>0</td>
<td>$0^+: 0$</td>
<td>$1.2 \pm 0.4$</td>
<td>$(87 \pm 29) \times 10^{-3}$</td>
<td>B</td>
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<tr>
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<td>6.05</td>
<td>0</td>
<td>$0^+: 0$</td>
<td>$(21 \pm 6) \times 10^{-3}$</td>
<td>(1968ST31)</td>
</tr>
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<td>6.13</td>
<td>$3^-: 0$</td>
<td>$60 \pm 5.7$</td>
<td>$2.1 \pm 0.2$</td>
<td>(1968GO07), B</td>
</tr>
<tr>
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<td>$\leq 0.34$</td>
<td>(1968GO07), B</td>
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<td>$2^-: 0$</td>
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<td>$0.86 \pm 0.10$</td>
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<td>$\leq 0.1$</td>
<td>(1968GO07)</td>
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<tr>
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<td>6.92</td>
<td>$2^+: 0$</td>
<td>$\leq 0.1$</td>
<td>(1968GO07)</td>
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<tr>
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<td>7.12</td>
<td>$1^-: 0$</td>
<td>$\approx 100$</td>
<td>$2.5 \pm 0.2$</td>
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<td>$2.3 \pm 0.2$</td>
<td>(1968GO07), B</td>
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<td></td>
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<td>$2^+: 0$</td>
<td>$\leq 2.7$</td>
<td>$\leq 0.1$</td>
<td>(1968GO07), B</td>
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<tr>
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<td>$12 \pm 2.7$</td>
<td>$0.44 \pm 0.10$</td>
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<td>(1968GO07), B</td>
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<td>(1969BR1L)</td>
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<td>$0.58 \pm 0.12$</td>
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<td>$3^-: 0$</td>
<td>$63 \pm 5.5$</td>
<td>$2.3 \pm 0.2$</td>
<td>(1968GO07), B</td>
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<td>(1968GO07), B</td>
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<tr>
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<td>7.12</td>
<td>$1^-: 0$</td>
<td>$12 \pm 2.7$</td>
<td>$0.44 \pm 0.10$</td>
<td>(1968GO07), B</td>
</tr>
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<td>8.87</td>
<td>$2^-: 0$</td>
<td>$25 \pm 2.7$</td>
<td>$0.90 \pm 0.10$</td>
<td>(1968GO07), B</td>
</tr>
<tr>
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<td></td>
<td>9.60</td>
<td>$1^-: 0$</td>
<td>$\leq 7.2 \times 10^{-3}$</td>
<td>(1969BR1L)</td>
<td></td>
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<tr>
<td>13.25</td>
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<td>6.13</td>
<td>$3^-: 0$</td>
<td>$&gt; 85$</td>
<td>$(9.2 \pm 1.5) \times 10^{-2}$</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.92</td>
<td>$2^+: 0$</td>
<td>$\leq 2.0$</td>
<td>(1966GO1H)</td>
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<td>7.12</td>
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<td>$3.1 \pm 0.8$</td>
<td>$1.4 \pm 0.4$</td>
<td>(1969BR1L), B</td>
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<td>8.87</td>
<td>$2^-: 0$</td>
<td>$\leq 0.1$</td>
<td>(1966GO1H)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.60</td>
<td>$1^-: 0$</td>
<td>$\leq 2 \times 10^{-2}$</td>
<td>(1969BR1L)</td>
<td></td>
</tr>
<tr>
<td>16.22</td>
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<td>0</td>
<td>$0^+: 0$</td>
<td>$86.2$</td>
<td>$5.1 \pm 0.8$</td>
<td>(1970ST06)</td>
</tr>
</tbody>
</table>

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Table 16.12: Radiative decays in $^{16}$O \(^a\) (continued)

| $E_i$ (MeV) | $J_i^\pi: T$ | $E_f$ (MeV) | $J_f^\pi: T$ | Branch (%) | $\Gamma_\gamma$ (eV) | Refs. | € |
|--------------|--------------|--------------|--------------|------------|------------------|-------|
| 17.14        | 1$^-$; 1     | 6.05         | 0$^+$; 0     | 13.8 ± 4.3 |                  | (1963GO22), B |
| 17.30        | 1$^-$; 1     | 6.05         | 0$^+$; 0     | ≤ 1.3      |                  | (1963GO22)   |

A: J. Lowe, O. Karban and P.M. Rolph, private communication.
B: I am indebted to Dr. P. Chevallier for pointing out errors and omissions in this table.

\(^a\) See also Tables 16.19, 16.21, and 16.26.

\(^b\) Monopole matrix element in fm\(^2\).

\(^c\) See also (1962GO07, 1962GO15, 1963GO22, 1967GI07).

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

\(^e\) See also (1967PI01).

\(^f\) $4.3 \times 10^{-2}$ W.u. (BE69W).

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

In a study of the yield of $\alpha_0$ and $\alpha_1$ for $E_\alpha = 18.9$ to 30.1 MeV, (1970MO06) find that the cross section for the $\alpha_1$ group is in general greater than that for the $\alpha_0$ group [see also (1964MI08)]. Recent phase-shift analyses are reported by (1968CA11, 1969CL08, 1970MO06). The inclusion of the bound level of $^{16}$O\(^8\) at 7.12 MeV produces an improved fit to the low-energy p-wave phase shift data and leads to $\theta_\alpha^2$ for $^{16}$O\(^8\)(7.12) = 0.71\(^{+0.37}_{-0.18}\) (1969CL08). The energy dependence of the $\alpha_1$-\(\gamma_4\) angular correlation has been studied for $E_\alpha = 18$ to 24 MeV by (1968KL07).

Astrophysical considerations are discussed by (1970MO22).

The non-elastic cross section at $E_\alpha = 40$ MeV has been measured by (1963IG01, 1963WI1D). Polarization measurements have been made at $E_\alpha = 22.5$ MeV by (1964EI01) and at $E_\alpha = 22.75$ MeV by (1970HA15). At the higher energy the cross section is free of resonance structure (1970HA15). Spallation studies are reported by (1968JA1J, 1968JU1A, 1969JU03, 1970BA48, 1970JA1Q, 1970JU1B, 1970RA30, 1970SC1F).


10. $^{12}$C($\alpha$, $^8$Be)$^8$Be

\[ Q_m = -7.464 \]

\[ E_\beta = 7.161 \]

The yield of $^8$Be shows a number of resonances for $E_\alpha = 11.85$ to 19.4 MeV, some of which are attributed to rotational states of $^{16}$O: see Table 16.11. $J^n$ assignments were made from angular distribution studies (1967CH21). Levels seen in this reaction are attributed by (1967AB02, 1967AB04) to a rotational band generated by an axially symmetric 8p-8h state.
11. $^{12}\text{C}(^6\text{Li}, d)^{16}\text{O}$ \hspace{1cm} $Q_m = 5.689$

At $E(^6\text{Li}) = 20$ and $29$ MeV and at $E(^{12}\text{C}) = 18$ to $24$ MeV, deuteron groups are observed to many of the states with $E_x \leq 16.2$ MeV (1967LO01, 1968ME10, 1970CO26). The spectrum at $E(^6\text{Li}) = 20$ MeV is dominated by the groups corresponding to $^{16}\text{O}^*(10.34, 14.8, 16.2)$ with $J^\pi = 4^+, 6^+$ and $6^+$, respectively (1967BE24, 1968ME10, 1970CO26). In addition, the excitation of a state at $E_x \approx 20.8$ MeV ($\Gamma \approx 600$ keV) is reported by (1970CO26): it may be the $8^+$ member of the first even parity rotational band in $^{16}\text{O}$, which is believed to have a predominantly 4p-4h character (1970CO26). See also (1969GO19). Measured angular distributions are listed in Table 16.13. (1967LO01) have analyzed their data to obtain $\theta_2^{\alpha}$ for all $^{16}\text{O}$ states with $E_x < 10.4$ MeV. See also (1960SH01, 1963OL1A, 1967CA1D, 1967DZ01, 1968OG1A, 1969CO1D, 1969GI1B, 1970CO26, 1970PU01). As in $^{12}\text{C}(^6\text{Li}, d)^{16}\text{O}$, the spectra are dominated by groups corresponding to the $4^+$ and $6^+$ states at $^{16}\text{O}^*(10.34, 14.8, 16.2)$ and by $^{16}\text{O}^*(20.8)$. Table 16.13 lists the measured angular distributions. From these distributions and the weak excitation of $^{16}\text{O}^*(8.87)$ it is concluded that the reaction proceeds predominantly by a direct $\alpha$-transfer (1970PU01). See also (1963OL1A, 1967CH34, 1967OG1A, 1968DA20, 1968OG1A, 1970OG1A, 1969DA14, 1970DO07, 1970DU1E; theor.) and $^{18}\text{F}$ in (1972AJ02).

12. $^{12}\text{C}(^7\text{Li}, t)^{16}\text{O}$ \hspace{1cm} $Q_m = 4.694$

At $E(^7\text{Li}) = 15$ to $31.5$ MeV, triton groups are observed to many of the states with $E_x \leq 16.2$ MeV (1969GI1B, 1969GO19, 1970CO26, 1970PU01). As in $^{12}\text{C}(^6\text{Li}, d)^{16}\text{O}$, the spectra are dominated by groups corresponding to the $4^+$ and $6^+$ states at $^{16}\text{O}^*(10.34, 14.8, 16.2)$ and by $^{16}\text{O}^*(20.8)$. Table 16.13 lists the measured angular distributions. From these distributions and the weak excitation of $^{16}\text{O}^*(8.87)$ it is concluded that the reaction proceeds predominantly by a direct $\alpha$-transfer (1970PU01). See also (1963OL1A, 1967CH34, 1967OG1A, 1968DA20, 1968OG1A, 1970OG1A, 1969DA14, 1970DO07, 1970DU1E; theor.) and $^{18}\text{F}$ in (1972AJ02).

13. (a) $^{12}\text{C}(^{10}\text{B}, ^6\text{Li})^{16}\text{O}$ \hspace{1cm} $Q_m = 2.700$
(b) $^{12}\text{C}(^{11}\text{B}, ^7\text{Li})^{16}\text{O}$ \hspace{1cm} $Q_m = -1.503$
(c) $^{12}\text{C}(^{12}\text{C}, 2\alpha)^{16}\text{O}$ \hspace{1cm} $Q_m = -0.113$

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

14. $^{12}\text{C}(^{14}\text{N}, ^{10}\text{B})^{16}\text{O}$ \hspace{1cm} $Q_m = -4.452$


15. (a) $^{12}\text{C}(^{16}\text{O}, ^{12}\text{C})^{16}\text{O}$ \hspace{1cm} $Q_m = 0.934$
(b) $^{12}\text{C}(^{18}\text{O}, ^{14}\text{C})^{16}\text{O}$
Table 16.13: Angular distribution studies of $^{12}\text{C}(^6\text{Li}, d)^{16}\text{O}$ and $^{12}\text{C}(^7\text{Li}, t)^{16}\text{O}$

(a)

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

(b)

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

$^a$ $E(^{12}\text{C}) = 18$ to 24 MeV.
Table 16.14: $^{13}$C + $^3$He excitation functions

<table>
<thead>
<tr>
<th>$E(^3\text{He})$ (MeV)</th>
<th>Particles</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 – 3.5</td>
<td>$\gamma_0$</td>
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</tr>
<tr>
<td>1.4 – 2.65</td>
<td>$n_0$, $n_3$</td>
<td>(1963DU12)</td>
</tr>
<tr>
<td>1.4 – 5.80</td>
<td>$n_0$</td>
<td>(1965DI07)</td>
</tr>
<tr>
<td>2.3 – 3.2</td>
<td>$n_0$</td>
<td>(1961JO24)</td>
</tr>
<tr>
<td>7.5 – 11</td>
<td>$n_0$</td>
<td>(1964DE1C)</td>
</tr>
<tr>
<td>2.0 – 6.0</td>
<td>$p_0 \rightarrow p_6$</td>
<td>(1970ST1M)</td>
</tr>
<tr>
<td>4.0 – 8.0</td>
<td>$p_0$, $p_{1+2}$</td>
<td>(1968WE15)</td>
</tr>
<tr>
<td>5.2 – 8.0</td>
<td>$^3$He</td>
<td>(1967WE06, 1968WE15)</td>
</tr>
<tr>
<td>1.3 – 2.0</td>
<td>$\alpha_0$</td>
<td>(1960BA25)</td>
</tr>
<tr>
<td>1.5 – 5.7</td>
<td>$\gamma_{12.7}$, $\gamma_{15.1}$</td>
<td>(1968MO1J)</td>
</tr>
<tr>
<td>1.5 – 8.0</td>
<td>$\gamma_{15.1}$</td>
<td>(1968WE13)</td>
</tr>
<tr>
<td>2.1 – 4.9</td>
<td>$\gamma_{15.1}$</td>
<td>(1964KU09)</td>
</tr>
<tr>
<td>2.0 – 8.5</td>
<td>$\alpha_0$, $\alpha_1$</td>
<td>(1968WE13, 1968WE15)</td>
</tr>
<tr>
<td>2.6 – 12</td>
<td>$\gamma_{15.1}$</td>
<td>(1969TA09)</td>
</tr>
<tr>
<td>4.0 – 8.0</td>
<td>$\alpha_2$</td>
<td>(1968WE15)</td>
</tr>
<tr>
<td>8 – 12</td>
<td>$\alpha_0$</td>
<td>(1969TA09)</td>
</tr>
<tr>
<td>2 – 6</td>
<td>$^8\text{Be}$</td>
<td>(1968JA07)</td>
</tr>
</tbody>
</table>

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

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


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

See (1970JA1B).

18. $^{13}$C($^3$He, $\gamma$)$^{16}$O  \[ Q_m = 22.793 \]
Table 16.15: Resonances in $^{13}$C + $^{3}$He

<table>
<thead>
<tr>
<th>$E(^3\text{He})$ (MeV ± keV)</th>
<th>$\Gamma_{\text{c.m.}}$</th>
<th>Outgoing particles</th>
<th>$^{16}\text{O}^*$ (MeV)</th>
<th>$J^\pi; T$</th>
<th>Refs.</th>
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<tbody>
<tr>
<td>1.55</td>
<td>$\approx 80$</td>
<td>$n_0, n_3$</td>
<td>24.05</td>
<td></td>
<td>(1963DU12)</td>
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<tr>
<td>1.55 ± 100</td>
<td>450</td>
<td>$\gamma_0$</td>
<td>24.05</td>
<td></td>
<td>(1966PU01)</td>
</tr>
<tr>
<td>2.0</td>
<td>$\approx 250$</td>
<td>$n_0$</td>
<td>24.4</td>
<td></td>
<td>(1965DI07)</td>
</tr>
<tr>
<td>2.6 ± 100</td>
<td></td>
<td>$\alpha\gamma_{15.1}$</td>
<td>24.9</td>
<td>$(T = 1)$</td>
<td>(1964KU09, 1968MO1J, 1968WE13, 1969TA09)</td>
</tr>
<tr>
<td>2.87 ± 50</td>
<td>600</td>
<td>$\gamma_0$</td>
<td>25.12</td>
<td></td>
<td>(1966PU01)</td>
</tr>
<tr>
<td>(3.6)</td>
<td></td>
<td>$p, \alpha\gamma_{15.1}$</td>
<td>25.7</td>
<td></td>
<td>(1956SC01, 1957IL1A, 1964KU09)</td>
</tr>
<tr>
<td>4.1 ± 100</td>
<td>a</td>
<td>$\alpha\gamma_{15.1}$</td>
<td>26.1</td>
<td>$(T = 1)$</td>
<td>(1964KU09, 1969TA09)</td>
</tr>
<tr>
<td>5.2 ± 100</td>
<td>a</td>
<td>$\alpha\gamma_{15.1}$</td>
<td>27.0</td>
<td>$(T = 1)$</td>
<td>(1968MO1J, 1968WE13, 1969TA09)</td>
</tr>
<tr>
<td>5.6 ± 100</td>
<td>$\approx 600$</td>
<td>$\alpha\gamma_{15.1}, ^8\text{Be}$</td>
<td>27.3</td>
<td>$(2^+; T = 1)$</td>
<td>(1968JA07, 1968WE13)</td>
</tr>
<tr>
<td>6.0 ± 100</td>
<td>$\approx 500$</td>
<td>$p_0, p_{1+2}, ^3\text{He}, \alpha_0, \alpha_1, \alpha_2$</td>
<td>27.6</td>
<td>$(3^-; T = 0)$</td>
<td>(1968WE15)</td>
</tr>
<tr>
<td>6.5 ± 100</td>
<td>a</td>
<td>$\alpha\gamma_{15.1}$</td>
<td>28.1</td>
<td>$(T = 1)$</td>
<td>(1968WE13, 1969TA09)</td>
</tr>
<tr>
<td>6.8 ± 100</td>
<td>a</td>
<td>$\alpha_0, \alpha_1, \alpha_2$</td>
<td>28.3</td>
<td>$(T = 0)$</td>
<td>(1968WE13)</td>
</tr>
<tr>
<td>7.5 ± 100</td>
<td>a</td>
<td>$\alpha\gamma_{15.1}$</td>
<td>28.9</td>
<td>$(T = 1)$</td>
<td>(1969TA09)</td>
</tr>
<tr>
<td>8.6 ± 100</td>
<td>a</td>
<td>$\alpha\gamma_{15.1}$</td>
<td>29.8</td>
<td>$(T = 1)$</td>
<td>(1969TA09)</td>
</tr>
<tr>
<td>9.4 ± 100</td>
<td>a</td>
<td>$\alpha\gamma_{15.1}$</td>
<td>30.4</td>
<td>$(T = 1)$</td>
<td>(1969TA09)</td>
</tr>
<tr>
<td>10.1 ± 100</td>
<td>a</td>
<td>$\alpha\gamma_{15.1}$</td>
<td>31.0</td>
<td>$(T = 1)$</td>
<td>(1969TA09)</td>
</tr>
</tbody>
</table>

*a Widths (lab.) 0.5 – 1 MeV (1969TA09).
The yield of ground state $\gamma$-rays for $E(\text{He}) = 1.0$ to 3.5 MeV shows two strong resonances corresponding to $^{16}\text{O}^*(24.1, 25.1)$ [see Table 16.15] (1966PU01). See also (1970MO1A).

19. $^{13}\text{C}(\text{He}, n)^{15}\text{O}$  

$Q_m = 7.125$  

$E_b = 22.793$

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

20. $^{13}\text{C}(\text{He}, p)^{15}\text{N}$  

$Q_m = 10.667$  

$E_b = 22.793$

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

21. $^{13}\text{C}(\text{He}, \alpha)^{12}\text{C}$  

$E_b = 22.793$

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

22. $^{13}\text{C}(\text{He}, \alpha)^{12}\text{C}$  

$Q_m = 15.631$  

$E_b = 22.793$

Yields of $\alpha_0$, $\alpha_1$, $\alpha_2$ and $\gamma$-rays from the decay of $^{12}\text{C}^*(12.71, 15.11)$ have been studied at many energies: see Table 16.14. Observed resonances are displayed in Table 16.15: those seen in the yield of 15.1 MeV $\gamma$-rays are assumed to correspond to $^{16}\text{O}$ states which have primarily a $T = 1$ character since $^{12}\text{C}^*(15.11)$ has $T = 1$ (1964KU09, 1968MO1J, 1968WE15, 1968WE13, 1968WE1C, 1969TA09). See also (1968WE1F) and $^{12}\text{C}$ in (1968AJ02).

23. $^{13}\text{C}(\text{He}, ^8\text{Be})^8\text{Be}$  

$Q_m = 8.168$  

$E_b = 22.793$

The excitation function for $^8\text{Be}_{g.s.}$ has been studied for $E(\text{He}) = 2$ to 6 MeV. It shows a strong resonance at $E(\text{He}) = 5.6$ 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. $^{16}\text{O}^*(27.3)$ does not belong to the rotational band studied by (1967CH21) in $^{12}\text{C}(\alpha, ^8\text{Be})^8\text{Be}$: $J^\pi$ for such a rotational state at $E_x = 27$ MeV would have to be $14^+$. The off-resonance cross section is comparable to typical cross sections observed in the $(\text{He}, \alpha)$ process (1968JA07).
24. $^{13}$C($\alpha$, n)$^{16}$O \quad Q_m = 2.215

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

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

At $E(^6$Li) = 20 MeV, triton groups corresponding to $^{16}$O states with $E_x < 16.9$ MeV have been observed. Angular distributions have been obtained for $^{16}$O*(6.13, 6.92, 7.12, 8.87, 9.85, 10.34, 11.10). The triton groups corresponding to $^{16}$O*(11.09) dominate the spectra; $^{16}$O*(14.4, 14.8) were also strongly excited (1969BA50). See also (1969GI1B, 1970OA1A).

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

See (1969GI1B, 1970JA1B).

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

At $E(^3$He) = 11 to 16 MeV, neutron groups are observed to $T = 2$ states at $E_x = 22.717 \pm 0.008$ 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 $^{16}$O, the analog states to $^{16}$C*(0, 1.75). $J^\pi$ for $^{16}$O*(24.52) is found to be $2^+$ from angular distribution measurements (1970AD01). Angular distributions are also reported at 2.1 to 3.4 MeV (1961JO24; n$_0$) and at 6 MeV (1970HO08; n$_0$, n$_{1+2}$, n$_{3+4}$). See also (1969BA1Z) and $^{17}$O.

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

The $\gamma_0$ yield has been studied for $E_d = 0.5$ to 5.5 MeV. The yield shows a resonance at $E_d = 2.2$ MeV corresponding to a state in $^{16}$O at $E_x = 22.7$ MeV, formed with a cross section of $\approx 6 \mu$b. The angular distribution of $\gamma_0$ at resonance is on the whole consistent with E1. Structure at $E_x = 22.2$ and 24.5 MeV is also reported (1966SU05, 1966SU1C). See also (1961SU17, 1963SU09). (1969GI1B) attributes the 2.2 MeV resonance to a 2p-2h 1$^-$; $T = 1$ state whose formation is possible because of polarization of the deuterons and isospin impurity. See also Tables 16.16 and 16.17 and (1967GI1C, 1969MA1N, 1969RA1F, 1969WE1H; theor.).
Table 16.16: Summary of recent $^{14}$N + d yield and polarization measurements

(a) Yield measurements

<table>
<thead>
<tr>
<th>$E_d$ (MeV)</th>
<th>Particles</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 – 5.5</td>
<td>$\gamma_0$</td>
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<tr>
<td>0.15 – 0.70</td>
<td>$n_0$</td>
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</tr>
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<td>0.66 – 5.62</td>
<td>$n_0$</td>
<td>(1960RE07)</td>
</tr>
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<td>1.2 – 2.8</td>
<td>$n_0$</td>
<td>(1960EL04)</td>
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<td>1.3 – 5.4</td>
<td>$n_0$</td>
<td>(1965JA1F)</td>
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<td>1.53 – 2.90</td>
<td>$n_0$</td>
<td>(1960MO18)</td>
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<td>0.5 – 5.5</td>
<td>$p_0$</td>
<td>(1962GO21)</td>
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<td>(1961SJ1B)</td>
</tr>
<tr>
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<td>(1967BE09)</td>
</tr>
<tr>
<td>1.05 – 3.15</td>
<td>$p_{1+2}, p_3 \rightarrow p_7$</td>
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</tr>
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<td>5.9 – 12.2</td>
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</tr>
<tr>
<td>1.05 – 3.3</td>
<td>$\alpha_0 \rightarrow \alpha_3$</td>
<td>(1969GO14)</td>
</tr>
<tr>
<td>1.1 – 2.5</td>
<td>$\alpha_0, \alpha_1$</td>
<td>(1964MA53)</td>
</tr>
<tr>
<td>1.1 – 3.1</td>
<td>$\alpha_0, \alpha_1$</td>
<td>(1962IS02)</td>
</tr>
<tr>
<td>1.3 – 2.2</td>
<td>$\alpha_0$</td>
<td>(1966EU01)</td>
</tr>
<tr>
<td>1.4 – 2.4</td>
<td>$\alpha_0, \alpha_3$</td>
<td>(1964MA53)</td>
</tr>
<tr>
<td>1.5 – 3.0</td>
<td>$\alpha_0$</td>
<td>(1961IS03)</td>
</tr>
<tr>
<td>2 – 4</td>
<td>$\alpha_0, \alpha_1$</td>
<td>(1962AL09)</td>
</tr>
<tr>
<td>2 – 12</td>
<td>$\alpha_0, \alpha_1, \alpha_2$</td>
<td>(1964CH1B, 1964CH1C)</td>
</tr>
<tr>
<td>2.3 – 5.8</td>
<td>$\alpha_0, \alpha_1, \alpha_2$</td>
<td>(1967BO37)</td>
</tr>
</tbody>
</table>
Table 16.16: Summary of recent $^{14}$N + d yield and polarization measurements $^a$ (continued)

<table>
<thead>
<tr>
<th>$E_d$ (MeV)</th>
<th>Particles</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8 − 12</td>
<td>$\gamma_{15.11}$</td>
<td>(1965BR08)</td>
</tr>
<tr>
<td>3.5 − 4.5</td>
<td>$\alpha_0 \rightarrow \alpha_3$, $\alpha_5 \rightarrow \alpha_7$</td>
<td>(1965SC12)</td>
</tr>
<tr>
<td>11.3, 12.6</td>
<td>$\alpha_0, \alpha_1$</td>
<td>(1966DR04)</td>
</tr>
</tbody>
</table>

(b) **Polarization measurements**

<table>
<thead>
<tr>
<th>$E_d$ (MeV)</th>
<th>Particles</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.32</td>
<td>$n_0$</td>
<td>(1964EP01)</td>
</tr>
<tr>
<td>1.65 − 2.90</td>
<td>$n_0$</td>
<td>(1965BU1A)</td>
</tr>
<tr>
<td>3.1 − 3.7</td>
<td>$n_0$</td>
<td>(1967ME17)</td>
</tr>
<tr>
<td>3.7</td>
<td>$n_0$</td>
<td>(1965BA24, 1968BA52)</td>
</tr>
<tr>
<td>4.2 − 6</td>
<td>$n_0$</td>
<td>(1970BU15)</td>
</tr>
<tr>
<td>10, 12</td>
<td>$p_0$</td>
<td>(1970FI07)</td>
</tr>
<tr>
<td>13.6</td>
<td>$p_0$</td>
<td>(1963GO1L, 1967GO27)</td>
</tr>
</tbody>
</table>

$^a$ See also (1959AJ76).

29. $^{14}$N(d, n)$^{15}$O

| $Q_m = 5.068$ | $E_b = 20.736$ |

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

30. $^{14}$N(d, p)$^{15}$N

| $Q_m = 8.610$ | $E_b = 20.736$ |

Quite a lot of structure is observed in the yield curves of various proton groups for $E_p = 0.5$ to 5.5 MeV: see Table 16.16 for a summary of recent yield and polarization measurements, and (1961SJ1B, 1962GO21, 1967BO37, 1969GO14) for data showing the fluctuations. Angular distributions have been obtained at many energies: see Table 15.16 in (1970AJ04). Resonant structure reported by (1962GO21, 1970NE1H), is displayed in Table 16.17. See also (1961JO13) and (1959AJ76).
Table 16.17: Structure in $^{14}\text{N} + \text{d}$

<table>
<thead>
<tr>
<th>$E_d$ (MeV)</th>
<th>Resonant channel</th>
<th>$J^\pi; T$</th>
<th>$E_x$ (MeV)</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>$n_0$</td>
<td></td>
<td>21.9</td>
<td>(1960RE07)</td>
</tr>
<tr>
<td>1.7 ± 0.1</td>
<td>$\gamma_0, n_0, \alpha_0, \alpha_1, \alpha_2, \alpha_3$</td>
<td></td>
<td>22.2</td>
<td>(1962IS02, 1965JA1F, 1966SU05, 1967LA16)</td>
</tr>
<tr>
<td>1.85</td>
<td>$n_0, \alpha_0$</td>
<td></td>
<td>22.35</td>
<td>(1961IS03, 1965BU1A)</td>
</tr>
<tr>
<td>2.0 ± 0.1</td>
<td>$\alpha_0, \alpha_3$</td>
<td>1$^-$; 1</td>
<td>22.7</td>
<td>(1961IS03, 1965JA1F, 1966SU05, 1967FL10)</td>
</tr>
<tr>
<td>2.2</td>
<td>$\gamma_0, n_0, d_0, \alpha_0$</td>
<td></td>
<td>22.74</td>
<td>(1970NE1H)</td>
</tr>
<tr>
<td>2.271 ± 0.005</td>
<td>$p_0, p_{1+2}, (\alpha_0), \alpha_2$</td>
<td>0$^+$; (2)</td>
<td>22.721</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>$\alpha_0$</td>
<td></td>
<td>22.9</td>
<td>(1961IS03)</td>
</tr>
<tr>
<td>2.6</td>
<td>$(n_0, p_0), \alpha_1$</td>
<td></td>
<td>23.0</td>
<td>(1960RE07, 1962AL09, 1962GO21, 1962IS02, 1965JA1F)</td>
</tr>
<tr>
<td>2.8</td>
<td>$(n_0, p_0), d_0, \alpha_0$</td>
<td></td>
<td>23.2</td>
<td>(1962AL09, 1962GO21, 1965JA1F, 1967FL10)</td>
</tr>
<tr>
<td>3.3</td>
<td>$n_0, p_0, d_0, \alpha_0$</td>
<td></td>
<td>23.6</td>
<td>(1962AL09, 1962GO21, 1965JA1F, 1967FL10)</td>
</tr>
<tr>
<td>4.2</td>
<td>$\gamma_0, n_0, p_0, d_0, \gamma_{15.11}$</td>
<td></td>
<td>24.4</td>
<td>(1960RE07, 1962GO21, 1965BR08, 1965JA1F, 1966SU05, 1967FL10)</td>
</tr>
<tr>
<td>4.58</td>
<td>$p_0, d_0, \gamma_{15.11}$</td>
<td></td>
<td>24.74</td>
<td>(1965BR08, 1967FL10)</td>
</tr>
<tr>
<td>4.9</td>
<td>$n_0, p_0$</td>
<td></td>
<td>25.0</td>
<td>(1960RE07, 1962GO21)</td>
</tr>
<tr>
<td>5.95</td>
<td>$d_1, \gamma_{15.11}$</td>
<td></td>
<td>25.94</td>
<td>(1965BR08, 1970DU04)</td>
</tr>
<tr>
<td>7.1</td>
<td>$\gamma_{15.11}$</td>
<td></td>
<td>26.9</td>
<td>(1965BR08)</td>
</tr>
<tr>
<td>7.4</td>
<td>$d_2$</td>
<td></td>
<td>27.2</td>
<td>(1970DU04)</td>
</tr>
<tr>
<td>7.7</td>
<td>$d_1$</td>
<td></td>
<td>27.4</td>
<td>(1970DU04)</td>
</tr>
<tr>
<td>(8.5)</td>
<td>$(\gamma_{15.11})$</td>
<td></td>
<td>(28.2)</td>
<td>(1965BR08)</td>
</tr>
<tr>
<td>10.2</td>
<td>$d_2$</td>
<td></td>
<td>29.6</td>
<td>(1970DU04)</td>
</tr>
</tbody>
</table>

$^a$ See reactions 28, 29, 30, 31, 32, 33 and 34.
The yield of elastically scattered deuterons has been studied for $E_d = 0.65$ to 5.5 MeV: see Table 16.16. Angular distributions for various deuteron groups have been measured at many energies: see Table 14.23 in (1970AJ04) and (1967FL10, 1970DU04). (1967FL10) report a number of resonances in the $d_0$ yield corresponding to states in $^{16}\text{O}$ 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 $E_x = 7.4$ and 10.2 MeV (1970DU04). The $d_1$ resonance at $E_d = 5.9$ MeV is also reported in the (isospin-forbidden) yield of 15.11 MeV $\gamma$-rays to the $1^+; T = 1$ state of $^{12}\text{C}$: see reaction 33. For a display of the information on reported resonances, see Table 16.17. See also (1968NO1C; theor.).

(a) $^{14}\text{N}(t, n)^{16}\text{O}$  \[ Q_m = 14.479 \]  \[ E_b = 20.736 \]

(b) $^{14}\text{N}(t, np)^{15}\text{N}$  \[ Q_m = 2.353 \]

(c) $^{14}\text{N}(t, n\alpha)^{12}\text{C}$  \[ Q_m = 7.318 \]

At $E_t = 2.2$ to 2.6 MeV, the two-stage reaction (b) proceeds via $^{16}\text{O}^*(14.94, 16.22)$ (1961JA14) while reaction (c) proceeds via $^{16}\text{O}^*(13.10, 15.42)$ (1962SI04).
Table 16.18: $^{16}\text{O}$ states from $^{14}\text{N}(^{3}\text{He}, \text{p})^{16}\text{O}$ $^{a,b}$

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

$^a$ (1964BR08): $E(^{3}\text{He}) = 3.74$ and $3.97$ MeV; $E_x < 15$ MeV.

$^b$ (1968CO1R, 1968CO1T): $E(^{3}\text{He}) = 12.99$ MeV; $E_x > 15$ MeV.

35. (a) $^{14}\text{N}(^{3}\text{He}, \text{p})^{16}\text{O}$
    $Q_m = 15.243$

(b) $^{14}\text{N}(^{3}\text{He}, \text{pα})^{12}\text{C}$
    $Q_m = 8.081$

At $E(^{3}\text{He}) = 3.7, 4.0$ and $13.0$ MeV, high-resolution spectral studies have led to $E_x$ and $\Gamma$ determinations for 33 excited states of $^{16}\text{O}$ with $E_x < 21.1$ MeV: see Table 16.18 (1964BR08, 1968CO1R, 1968CO1T). The separation of $^{16}\text{O}^*(6.05, 6.13)$, is $81.0 ± 1.0$ keV (C.P. Browne, private communication). The states with $E_x > 15$ MeV are believed to have $T = 1$ (1968CO1T). Angular distributions have been measured at $E(^{3}\text{He}) = 2.5$ to 5.5 MeV (1963GO09; p0), 4.5 and 5.5 MeV (1963GO09; p1+2, p5), 8.0 to 10.6 MeV (1962BI01) and 13.0 MeV (1968CO1T: see Table 16.18).

The branching ratios of $^{16}\text{O}^*(8.87, 10.95, 11.08)$ are listed in Table 16.12 (1959BR68, BE69W). These, as well as p-$\gamma$ angular correlation measurements, lead to the assignments $J^\pi = 2^-, 0^-$ and
$3^+$, respectively for $^{16}\text{O}*(8.87, 10.95, 11.08)$ (1959BR68, 1959KU78). The mean lifetimes for these states are displayed in Table 16.19 (1968HE1K, 1969FI02, 1970BE27, 1970FI06).

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


36. (a) $^{14}\text{N}(\alpha, d)^{16}\text{O}$ $Q_m=-3.111$

(b) $^{14}\text{N}(\alpha, d\alpha)^{12}\text{C}$ $Q_m=-10.272$

The excitation of a number of $^{16}\text{O}$ states with $E_x<17.2$ MeV has been reported at $E_\alpha=40$ to 48 MeV by (1962CE01, 1962HA40, 1966RI04, 1970ZI03). In particular strong deuteron groups are reported to states with $E_x=14.40 \pm 0.03, 14.82 \pm 0.03, 15.80 \pm 0.04, 16.24 \pm 0.04$ and $17.17 \pm 0.04$ MeV, with $\Gamma_{c.m.} = 30 \pm 30, 69 \pm 30, 69 \pm 30, (60), 125 \pm 50$ and (70) keV, respectively (1970ZI03). Angular distributions of the deuteron groups corresponding to $^{16}\text{O}*(14.39, 14.82, 16.23)$ have been measured at $E_\alpha=40$ and 42 MeV. A $T=0$ state at $E_x \approx 13.1$ MeV is also reported (1966RI04); see, however, (1970ZI03). See also (1962CE01, 1962HA40). Angular distributions are also reported by (1959ZE1A: 43 MeV; d$_0$ and (1962CE01: 48 MeV; d$_0$, d$_{1+2}$, d$_5$).

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

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

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

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

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

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

39. $^{15}\text{N}(p, \gamma)^{16}\text{O}$ $Q_m=12.126$
<table>
<thead>
<tr>
<th>$^{16}\text{O}^*$ (MeV)</th>
<th>$\tau_m$</th>
<th>Reaction</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.05</td>
<td>72 ± 7 psec</td>
<td>$^{19}\text{F}(p, \alpha)$</td>
<td>(1954DE36)</td>
</tr>
<tr>
<td>6.13</td>
<td>25 ± 2 psec</td>
<td>$^{19}\text{F}(p, \alpha)$</td>
<td>(1965AL14)</td>
</tr>
<tr>
<td></td>
<td>12 ± 6 psec</td>
<td>$^{19}\text{F}(p, \alpha)$</td>
<td>(1958KO63)</td>
</tr>
<tr>
<td>6.92 $^a$</td>
<td>24 ± 2 psec</td>
<td></td>
<td>mean</td>
</tr>
<tr>
<td></td>
<td>12 ± 3 fsec</td>
<td>$^{16}\text{O}(\gamma, \gamma)$</td>
<td>(1957SW17)</td>
</tr>
<tr>
<td></td>
<td>9 $&lt; \tau &lt; 25$ fsec</td>
<td></td>
<td>(1958DU06)</td>
</tr>
<tr>
<td></td>
<td>6.4$^{+1.9}_{-1.6}$ fsec</td>
<td>$^{19}\text{F}(p, \alpha)$</td>
<td>(1970CO09)</td>
</tr>
<tr>
<td>7.12 $^a$</td>
<td>8.4 ± 1.6 fsec</td>
<td>$^{16}\text{O}(\gamma, \gamma)$</td>
<td>mean</td>
</tr>
<tr>
<td></td>
<td>10 ± 3 fsec</td>
<td>$^{16}\text{O}(\gamma, \gamma)$</td>
<td>(1957SW17)</td>
</tr>
<tr>
<td></td>
<td>4 $&lt; \tau &lt; 8$ fsec</td>
<td>$^{16}\text{O}(\gamma, \gamma)$</td>
<td>(1958DU06)</td>
</tr>
<tr>
<td></td>
<td>7.2 ± 1.7 fsec</td>
<td></td>
<td>mean</td>
</tr>
<tr>
<td>8.87 $^a$</td>
<td>240 ± 40 fsec</td>
<td>$^{14}\text{N}(^3\text{He}, p)$</td>
<td>(1970BE27)</td>
</tr>
<tr>
<td></td>
<td>192 ± 80 fsec</td>
<td>$^{14}\text{N}(^3\text{He}, p)$</td>
<td>(1968HE1K)</td>
</tr>
<tr>
<td></td>
<td>136$^{+46}_{-36}$ fsec</td>
<td>$^{14}\text{N}(^3\text{He}, p)$</td>
<td>(1970FI06)</td>
</tr>
<tr>
<td></td>
<td>150 ± 30 fsec</td>
<td>$^{19}\text{F}(p, \alpha)$</td>
<td>(1970GA09)</td>
</tr>
<tr>
<td></td>
<td>192 ± 29 fsec</td>
<td>$^{19}\text{F}(p, \alpha)$</td>
<td>(1967PI01)</td>
</tr>
<tr>
<td>10.95</td>
<td>180 ± 16 fsec</td>
<td></td>
<td>mean</td>
</tr>
<tr>
<td></td>
<td>8 ± 5 fsec</td>
<td>$^{14}\text{N}(^3\text{He}, p)$</td>
<td>(1970BE27)</td>
</tr>
<tr>
<td></td>
<td>$&lt; 48$ fsec</td>
<td>$^{14}\text{N}(^3\text{He}, p)$</td>
<td>(1968HE1K)</td>
</tr>
<tr>
<td></td>
<td>58$^{+120}_{-58}$ fsec</td>
<td>$^{14}\text{N}(^3\text{He}, p)$</td>
<td>(1970FI06) b</td>
</tr>
<tr>
<td>11.08</td>
<td>8 ± 5 fsec</td>
<td></td>
<td>“best” value</td>
</tr>
<tr>
<td></td>
<td>57 ± 19 fsec</td>
<td>$^{14}\text{N}(^3\text{He}, p)$</td>
<td>(1970BE27)</td>
</tr>
<tr>
<td></td>
<td>172 ± 60 fsec</td>
<td>$^{14}\text{N}(^3\text{He}, p)$</td>
<td>(1968HE1K)</td>
</tr>
<tr>
<td></td>
<td>184$^{+360}_{-146}$ fsec</td>
<td>$^{14}\text{N}(^3\text{He}, p)$</td>
<td>(1970FI06)</td>
</tr>
<tr>
<td></td>
<td>57 ± 19 fsec</td>
<td></td>
<td>“best” value</td>
</tr>
</tbody>
</table>

$^a$ See also (1969NY1A, 1969TH01).

$^b$ See also (1969FI02).

$^c$ See also Table 16.12.
The yield of ground state radiation ($\gamma_0$) has been measured for $E_p = 0.17$ to 18 MeV: see Table 16.20 for a summary of the measurements and Table 16.21 for a display of the observed resonances. Angular distributions of the $\gamma_0$ radiation have been measured at many energies. The cross section shows a great deal of structure in quite good agreement with the results of high-resolution studies of $^{16}O(\gamma, n)^{15}O$ and $^{16}O(e, ep)^{15}N$ (see reactions 49 and 56). The excitation energies corresponding to the most pronounced resonances are in good agreement with the predictions of the shell model (1964TA06). Above $E_p = 8$ MeV, the angular distributions indicate the presence of a very broad $2^+$ state ($E_x \approx 30$ MeV, $\Gamma \approx 5$ MeV), and imply the presence of a similarly broad $1^-$ state. In addition a number of weak $1^-$ states with $\Gamma \approx 0.5$ MeV appear to be present (1967EA02). The main part of the giant resonance at $E_x \approx 22.2$ MeV [$E_p = 10.7$ MeV] shows some structure (1967BL23). (1970BA33) suggest that $^{16}O^*(19.90, 20.39)$, observed in the $(\gamma_1 + \gamma_2)$ yield, are $2^+$ states from the coupling of the $1^-$ states at 12.44 and 13.10 MeV to the $3^-$ state at 6.13 MeV. Above $E_p = 14$ MeV, no pronounced structures are observed but there is some evidence for weak structures corresponding to $E_x \approx 25.5$ and 26.4 MeV (1967BL23).

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

40. $^{15}N(p, p)^{15}N$  \hspace{1cm} $E_b = 12.126$

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

41. $^{15}N(p, n)^{15}O$  \hspace{1cm} $Q_m = -3.542$  \hspace{1cm} $E_b = 12.126$

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

<table>
<thead>
<tr>
<th>$E_p$ (MeV)</th>
<th>Particles</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.17 – 0.63</td>
<td>$\gamma_0$</td>
<td>(1960HE02)</td>
</tr>
<tr>
<td>0.2 – 1.6</td>
<td>$\gamma_0$</td>
<td>(1952SC1B)</td>
</tr>
<tr>
<td>0.4 – 1.9</td>
<td>$\gamma_0$</td>
<td>(1968GO07)</td>
</tr>
<tr>
<td>1 – 14</td>
<td>$\gamma_0$</td>
<td>(1967EA02)</td>
</tr>
<tr>
<td>4.1 – 12.8</td>
<td>$\gamma_0$, $\gamma_{1+2}$</td>
<td>(1970BA33)</td>
</tr>
<tr>
<td>1 – 14.4</td>
<td>$\gamma_0$</td>
<td>(1964TA05, 1964TA06)</td>
</tr>
<tr>
<td>10 – 15</td>
<td>$\gamma_0$</td>
<td>(1959CO1C, 1961CO02)</td>
</tr>
<tr>
<td>10.5 – 18</td>
<td>$\gamma_0$</td>
<td>(1967BL23)</td>
</tr>
<tr>
<td>3.8 – 6.4</td>
<td>$n_0$</td>
<td>(1958JO28, 1958WE1C)</td>
</tr>
<tr>
<td>3.8 – 12</td>
<td>$n_0(\sigma_t)$</td>
<td>(1968BA42)</td>
</tr>
<tr>
<td>4.0 – 13.6</td>
<td>$n_0$</td>
<td>(1961WO03, 1963HA46)</td>
</tr>
<tr>
<td>0.6 – 1.8</td>
<td>$p_0$</td>
<td>(1957HA1A)</td>
</tr>
<tr>
<td>1.0 – 3.6</td>
<td>$p_0$</td>
<td>(1959BA15)</td>
</tr>
<tr>
<td>2.7 – 11.7</td>
<td>$p_0$</td>
<td>(1962DE09)</td>
</tr>
<tr>
<td>9 – 11.7</td>
<td>$p_{1+2}$</td>
<td>(1969DR1C)</td>
</tr>
<tr>
<td>10.3 – 11.5</td>
<td>$p_3$</td>
<td>(1969DR1C)</td>
</tr>
<tr>
<td>0.2 – 1.6</td>
<td>$\alpha_0$, $\gamma_{4.4}$</td>
<td>(1952SC1B)</td>
</tr>
<tr>
<td>0.27 – 0.41</td>
<td>$\gamma_{4.4}$</td>
<td>(1960HE02)</td>
</tr>
<tr>
<td>0.4 – 1.9</td>
<td>$\gamma_{4.4}$</td>
<td>(1968GO07)</td>
</tr>
<tr>
<td>0.8 – 1.65</td>
<td>$\gamma_{4.4}$</td>
<td>(1969CL07)</td>
</tr>
<tr>
<td>0.9 – 2.9</td>
<td>$\alpha_0$</td>
<td>(1957HA1B)</td>
</tr>
<tr>
<td>1 – 3.6</td>
<td>$\alpha_0$, $\gamma_{4.4}$</td>
<td>(1959BA15)</td>
</tr>
<tr>
<td>3.3 – 12.6</td>
<td>$\alpha_0$, $\alpha_1$</td>
<td>(1962RO04, 1963RO01)</td>
</tr>
<tr>
<td>3.4 – 3.7</td>
<td>$\alpha_0$, $\alpha_1$</td>
<td>(1968VA1M)</td>
</tr>
<tr>
<td>6.7 – 15.2</td>
<td>$\alpha_0$</td>
<td>(1967NO02)</td>
</tr>
<tr>
<td>9.1 – 15.2</td>
<td>$\alpha_1$</td>
<td>(1967NO02)</td>
</tr>
</tbody>
</table>

$^a$ See also (1959AJ76).
Table 16.21: Levels of $^{16}$O from $^{15}$N(p, $\gamma$)$^{16}$O, $^{15}$N(p, p)$^{15}$N and $^{15}$N(p, $\alpha$)$^{12}$C

<table>
<thead>
<tr>
<th>$E_p$ (keV)</th>
<th>$\Gamma_{\gamma_0}$ a,f (eV)</th>
<th>$\Gamma_{\gamma_1}$ a,f (eV)</th>
<th>$\Gamma_p$ a (keV)</th>
<th>$\Gamma_{\alpha_0}$ a (keV)</th>
<th>$\Gamma_{\alpha_1}$ a (keV)</th>
<th>$\Gamma_{lab}$ (keV)</th>
<th>$J^\pi$, $T$</th>
<th>$E_x$ (MeV)</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>338</td>
<td>7 ± 1</td>
<td>0.12 ± 0.04</td>
<td>1.1</td>
<td>93</td>
<td>0.025</td>
<td>94</td>
<td>1−; 0</td>
<td>12.443</td>
<td>(1952SC1B, 1960HE02, 1966AD04, 1957HA1B)</td>
</tr>
<tr>
<td>429 ± 1</td>
<td>(21 ± 6) × 10$^{-3}$</td>
<td>2.1 ± 0.2</td>
<td>0.020</td>
<td>n.r.</td>
<td>0.90</td>
<td>0.9</td>
<td>2−; 0</td>
<td>12.528</td>
<td>(1952SC1B, 1960HE02, 1968GO07)</td>
</tr>
<tr>
<td>710 ± 7</td>
<td>40</td>
<td>n.r.</td>
<td>40 ± 4</td>
<td>0−; 1</td>
<td>12.791</td>
<td>(1957HA1A)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>897.37 ± 0.29 (78 ± 16) × 10$^{-3}$</td>
<td>1.2</td>
<td>n.r.</td>
<td>0.69 ± 0.07</td>
<td>2.0 ± 0.2</td>
<td>2−; 1</td>
<td>12.9668</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1028 ± 10</td>
<td>31 ± 8</td>
<td>110</td>
<td>r.</td>
<td>r.</td>
<td>140 ± 10</td>
<td>1−; 1</td>
<td>13.089 b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1050 ± 150</td>
<td></td>
<td></td>
<td>$\Gamma_p\Gamma_{\alpha_0} = 500$ keV$^2$</td>
<td>2$^+$</td>
<td>13.1</td>
<td>(1966AD04)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_p$ (keV)</td>
<td>$\Gamma_{\gamma 0}$ a,f (eV)</td>
<td>$\Gamma_{\gamma 1}$ a,f (eV)</td>
<td>$\Gamma_p$ a (keV)</td>
<td>$\Gamma_{\alpha 0}$ a (keV)</td>
<td>$\Gamma_{\alpha 1}$ a (keV)</td>
<td>$\Gamma_{lab}$ (keV)</td>
<td>$J^\pi; T$</td>
<td>$E_x$ (MeV)</td>
<td>Refs.</td>
</tr>
<tr>
<td>------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>-------------</td>
<td>-----------</td>
<td>-------</td>
</tr>
<tr>
<td>1640 ± 3</td>
<td>10</td>
<td>n.r.</td>
<td>59 ± 6</td>
<td>68 ± 3</td>
<td>1+; 0</td>
<td>13.663</td>
<td>1957HA1A, 1957HA1B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1890 ± 20</td>
<td></td>
<td></td>
<td>90 ± 20</td>
<td>13.90</td>
<td></td>
<td>1959BA15, 1957HA1B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1979 ± 3</td>
<td>0.5</td>
<td>n.r.</td>
<td>23 ± 2</td>
<td>13.980</td>
<td></td>
<td>1957HA1B, 1959BA15, 1962DE09</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3000 ± 30</td>
<td>r.</td>
<td>r.</td>
<td>45 ± 10</td>
<td>14.94</td>
<td></td>
<td>1962DE09</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3300 ± 35</td>
<td>r.</td>
<td>n.r.</td>
<td>75 ± 15</td>
<td>15.22</td>
<td></td>
<td>1959BA15, 1959BA15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3350 ± 50</td>
<td>≈ 0.6</td>
<td>≈ 125</td>
<td>r.</td>
<td>15.26</td>
<td></td>
<td>1959BA15, 1967EA02</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3520 ± 40</td>
<td>r. g</td>
<td>r.</td>
<td>100 ± 25</td>
<td>15.42</td>
<td></td>
<td>1962DE09, 1970BA33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4280 ± 20)</td>
<td>r.</td>
<td>r.</td>
<td>100 ± 25 (1 → 4)</td>
<td>15.42</td>
<td></td>
<td>1970BA33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5200</td>
<td>r.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>17.01, 1967EA02</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5350 ± 20</td>
<td>16</td>
<td>26 d</td>
<td>65</td>
<td>17.14</td>
<td></td>
<td>1962DE09, 1967EA02</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 16.21: 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)
Table 16.21: Levels of $^{16}$O from $^{15}$N(p, $\gamma$)$^{16}$O, $^{15}$N(p, p)$^{15}$N and $^{15}$N(p, $\alpha$)$^{12}$C (continued)

<table>
<thead>
<tr>
<th>$E_p$</th>
<th>$\Gamma_{\gamma_0}$ a,f</th>
<th>$\Gamma_{\gamma_1}$ a,f</th>
<th>$\Gamma_p$ a</th>
<th>$\Gamma_{\alpha_0}$ a</th>
<th>$\Gamma_{\alpha_1}$ a</th>
<th>$\Gamma_{lab}$</th>
<th>$J^\pi; T$</th>
<th>$E_x$ (MeV)</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>keV</td>
<td>(eV)</td>
<td>(eV)</td>
<td>(keV)</td>
<td>(keV)</td>
<td>(keV)</td>
<td>(keV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5490 ± 20</td>
<td>67</td>
<td>45 e</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>110</td>
<td>1−; 1</td>
</tr>
<tr>
<td>6320 ± 20</td>
<td>n.r.</td>
<td>≤ 5 g</td>
<td>(r.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60</td>
<td>2, 3; 1</td>
</tr>
<tr>
<td>7330 ± 30</td>
<td>38</td>
<td>≤ 3 g</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>260</td>
<td>1−; 1</td>
</tr>
<tr>
<td>7420</td>
<td>r.</td>
<td>≈ 30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>130</td>
<td>2+; (1)</td>
</tr>
<tr>
<td>7600 ± 30</td>
<td>n.r.</td>
<td>1.5 g</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td>2, 3; 1</td>
</tr>
<tr>
<td>7840 ± 30</td>
<td>59</td>
<td>(r.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>350</td>
<td>1−; 1</td>
</tr>
<tr>
<td>8300 ± 20</td>
<td>n.r.</td>
<td>8 h,i</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>75</td>
<td>2, 3; 1</td>
</tr>
<tr>
<td>8830 ± 20</td>
<td>n.r.</td>
<td>47 h,i</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>150</td>
<td>2, 3; 1</td>
</tr>
<tr>
<td>9300 ± 100</td>
<td>170</td>
<td>(r.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>700</td>
<td>(T = 1)</td>
</tr>
<tr>
<td>10590</td>
<td>r.</td>
<td>(r.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(22.05)</td>
<td></td>
</tr>
<tr>
<td>10700 ± 100</td>
<td>870</td>
<td>(r.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>700</td>
<td>(T = 1)</td>
</tr>
<tr>
<td>10770</td>
<td>r.</td>
<td>(r.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(22.21)</td>
<td></td>
</tr>
</tbody>
</table>
Table 16.21: Levels of $^{16}$O from $^{15}$N(p, $\gamma$)$^{16}$O, $^{15}$N(p, p)$^{15}$N and $^{15}$N(p, $\alpha$)$^{12}$C (continued)

<table>
<thead>
<tr>
<th>$E_p$ (keV)</th>
<th>$\Gamma_{\gamma0}$ a,f (eV)</th>
<th>$\Gamma_{\gamma1}$ a,f (eV)</th>
<th>$\Gamma_p$ a (keV)</th>
<th>$\Gamma_{\alpha0}$ a (keV)</th>
<th>$\Gamma_{\alpha1}$ a (keV)</th>
<th>$\Gamma_{lab}$ (keV)</th>
<th>$J^\pi; T$</th>
<th>$E_\infty$ (MeV)</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>11450 ± 50</td>
<td>120 r.</td>
<td>27 g</td>
<td>350</td>
<td>T = 1</td>
<td>22.85 (26.4)</td>
<td>1967BL23</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(1970BA33)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14300</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(1961CO02)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(1967CO23)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a n.r. = non resonant; r. = resonant.
b This state has a large p$^{-1}$d component (1967EA02).
c $\Gamma_n = 6$ keV (1964TA06).
d $\Gamma_n = 19$ keV (1964TA06).
e $\Gamma_n = 45$ keV (1964TA06).
g These values are for $\gamma_1 + \gamma_2$. 

h The decay is through $^{16}$O*(6.13) (A.R. Barnett and J. Lowe, private communication).
i There is no indication (< 10%) of decay to $^{16}$O*(6.92, 7.13) (1970BA33).
42. (a) $^{15}\text{N}(p, \alpha)^{12}\text{C}$
   
   \[ Q_m = 4.965 \quad E_h = 12.126 \]

   (b) $^{15}\text{N}(p, t)^{13}\text{N}$
   
   \[ Q_m = -12.906 \]

   (c) $^{15}\text{N}(p, ^3\text{He})^{13}\text{C}$
   
   \[ Q_m = -10.667 \]

   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 $E_p = 0.2$ to 15.2 MeV: see Table 16.20. Several resonances are reported for $E_p < 3.5$ MeV (1952SC1B, 1957HA1B, 1959BA15, 1959VA04, 1960HE02, 1964BO13, 1966AD04, 1968GO07, 1969CL07): see Table 16.21, and see also (1959AJ76). At higher energies, there is continuing structure in the yield curves, which is interpreted in terms of fluctuations: see (1962RO04, 1964TE1D, 1964TE1E, 1964TE1F).

   Angular distributions have been obtained at many energies: see $^{12}\text{C}$ in (1968AJ02). Angular correlation measurements lead to $J^\pi = 2^-$, $1^-$, $3^-$, and $1^+$, respectively for the resonances at $E_p = 0.898$, 1.08, 1.21, and 1.64 (1969CL07). For polarization measurements see (1966AD04). See also (1963MI1C, 1964EC03, 1969BR1L, 1963MI1H, Table 16.12 and (1965MA1H; theor.).

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

43. $^{15}\text{N}(d, n)^{16}\text{O}$

   \[ Q_m = 9.901 \]

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

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

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

44. $^{15}\text{N}(^3\text{He}, d)^{16}\text{O}$

   \[ Q_m = 6.632 \]

   Angular distributions of the deuterons corresponding to a number of states of $^{16}\text{O}$ have been measured at $E(^3\text{He}) = 11$ MeV (1969BO13) and at $E(^3\text{He}) = 16.0$ and 24.9 MeV (1969FU08): $l$ and $S$ values derived from DWBA analyses are shown in Table 16.23. See also (1963PA01, 1965SE01, 1968SE1C, 1969FU1J).
Table 16.22: Resonances in $^{15}$N(p, n)$^{15}$O (1968BA42) $^a$

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


$^b$ Probably a doublet: see (1968BA42).

$^c$ 1$^{-}$ is from (p, $\gamma$); $J \geq 2$ is required from (p, n) yield.

$^d$ $T$-assignments by energy and width comparisons with states in $^{16}$N.
Table 16.23: States in $^{16}\text{O}$ from $^{15}\text{N}(d, n)^{16}\text{O}$ and $^{15}\text{N}(^3\text{He}, d)^{16}\text{O}$

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

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

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45. $^{15}\text{N}(\alpha, \text{t})^{16}\text{O}$  

$Q_m = -7.688$

Not reported.

46. $^{15}\text{N}^{(11}\text{B}, 10\text{Be})^{16}\text{O}$  

$Q_m = 0.898$

See (1967PO13, 1969BR1D).

47. $^{16}\text{N}(\beta^-)^{16}\text{O}$  

$Q_m = 10.422$

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

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

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

48. (a) $^{16}\text{O}(\gamma, \text{n})^{15}\text{O}$  

$Q_m = -15.668$

(b) $^{16}\text{O}(\gamma, 2\text{n})^{14}\text{O}$  

$Q_m = -28.887$


The absorption cross section and the $(\gamma, \text{n})$ cross section are marked by a number of resonances. The reported structure is displayed in Table 16.25 (1962BU23, 1962FI04, 1963BU18, 1963FU05, 1963GE13, 1964BR03, 1964TE04, 1965CA1B, 1965DO05, 1966CO08, 1967DO1A, 1967MI15, 1970IV01). There are still conflicting reports on which structures are real [there are relatively few results obtained with monochromatic $\gamma$-rays] and on their widths, when these are given. For curves
Table 16.24: Beta decay of $^{16}$N

<table>
<thead>
<tr>
<th>Final state</th>
<th>Branch (%)</th>
<th>log $f t$ a</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}$O (MeV)</td>
<td>$J^\pi$</td>
<td>26 ± 2 e</td>
</tr>
<tr>
<td>0</td>
<td>0+</td>
<td></td>
</tr>
<tr>
<td>6.05</td>
<td>0+</td>
<td>(1.2 ± 0.4) $\times 10^{-2}$ f</td>
</tr>
<tr>
<td>6.13</td>
<td>3-</td>
<td>68 ± 2 e</td>
</tr>
<tr>
<td>7.12</td>
<td>1-</td>
<td>4.9 ± 0.4 e</td>
</tr>
<tr>
<td>8.87 b</td>
<td>2-</td>
<td>1.0 ± 0.2 e</td>
</tr>
<tr>
<td>9.60 c</td>
<td>1-</td>
<td>(1.20 ± 0.05) $\times 10^{-3}$ g</td>
</tr>
<tr>
<td>9.85 d</td>
<td>2+</td>
<td>(6.5 ± 2.0) $\times 10^{-7}$ h</td>
</tr>
</tbody>
</table>

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


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

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


Table 16.25: Resonance structure in $^{16}$O $+$ $\gamma$

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>$\Gamma$ (keV)</th>
<th>$\Gamma_\gamma$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.23</td>
<td>17.10</td>
<td>16.2</td>
<td>16.3</td>
<td>16.21</td>
<td>17.21</td>
<td>17.55</td>
<td>18.25</td>
<td>18.44</td>
<td>32 c</td>
</tr>
<tr>
<td>17.10</td>
<td>17.14</td>
<td>17.1</td>
<td>17.3</td>
<td>17.30</td>
<td>17.21</td>
<td>17.55</td>
<td>18.25</td>
<td>18.44</td>
<td>45 c</td>
</tr>
<tr>
<td>(17.3)</td>
<td>17.30</td>
<td>17.3</td>
<td>17.30</td>
<td>± 30</td>
<td>17.21</td>
<td>17.55</td>
<td>18.25</td>
<td>18.44</td>
<td>300 d</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90 c</td>
</tr>
<tr>
<td>17.55</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt; 400 c</td>
</tr>
<tr>
<td>18.25</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>18.44</td>
<td>50 c</td>
</tr>
<tr>
<td>18.70</td>
<td>18.68</td>
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<td></td>
<td>300 d</td>
</tr>
<tr>
<td>19.1</td>
<td>19.08</td>
<td>19.1</td>
<td>19.06</td>
<td>± 60</td>
<td>19.1</td>
<td>19.0</td>
<td></td>
<td></td>
<td>200 c</td>
</tr>
<tr>
<td>(19.4)</td>
<td>19.47</td>
<td>19.6</td>
<td>19.56</td>
<td>± 100</td>
<td>19.6</td>
<td>19.4</td>
<td>19.53</td>
<td>600 d</td>
<td>375 d</td>
</tr>
<tr>
<td></td>
<td>19.9</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>300 c</td>
</tr>
<tr>
<td>20.2</td>
<td>20.45</td>
<td>20.20</td>
<td>± 150</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>40 c</td>
</tr>
<tr>
<td>20.88</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>200 c</td>
</tr>
<tr>
<td>(21.2)</td>
<td>21.02</td>
<td>± 40</td>
<td>21.10</td>
<td>21.0</td>
<td>21.0</td>
<td>21.0</td>
<td>20.9</td>
<td>20.75</td>
<td>700 d</td>
</tr>
<tr>
<td></td>
<td>21.35</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25 c</td>
</tr>
<tr>
<td></td>
<td>21.7</td>
<td>21.59</td>
<td>21.7</td>
<td>± 30</td>
<td>21.72</td>
<td>25 c</td>
<td>25 c</td>
<td>210 c</td>
<td>52 c</td>
</tr>
<tr>
<td></td>
<td>21.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>250 c</td>
</tr>
<tr>
<td></td>
<td>22.1</td>
<td>22.15</td>
<td>22.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>40 c</td>
</tr>
<tr>
<td>22.3</td>
<td>22.47</td>
<td></td>
<td></td>
<td>22.26</td>
<td>± 38</td>
<td>22.2</td>
<td>22.3</td>
<td>1000 d</td>
<td>2500 d</td>
</tr>
<tr>
<td></td>
<td>22.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>600 c</td>
</tr>
<tr>
<td>23.05</td>
<td>23.0</td>
<td>23.15</td>
<td>± 34</td>
<td>23.0</td>
<td>23.1</td>
<td>300 d</td>
<td>23.0</td>
<td>23.1</td>
<td>530 d</td>
</tr>
</tbody>
</table>
Table 16.25: Resonance structure in $^{16}$O + $\gamma$ $^a$ (continued)

<table>
<thead>
<tr>
<th>$E_\gamma$ (MeV ± keV) $^b$</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>$\Gamma$ (keV)</th>
<th>$\Gamma_\gamma$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.1</td>
<td>24.1</td>
<td>24.3</td>
<td>24.3</td>
<td>24.3</td>
<td>24.3</td>
<td>700 $^d$</td>
<td>1200 $^d$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24.3</td>
<td>24.4</td>
<td>25.0</td>
<td>25.2</td>
<td>24.9 ± 210</td>
<td>25.2</td>
<td>700 $^d$</td>
<td>1260 $^d$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.15</td>
<td>25.4</td>
<td>26.3</td>
<td>26.38 ± 180</td>
<td>25.55 ± 50</td>
<td>25.8</td>
<td>1000 $^d$</td>
<td>1000 $^d$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.8</td>
<td>27.4</td>
<td>27.45 ± 230</td>
<td>28.55 ± 195</td>
<td>29.6 ± 230</td>
<td>31.4 ± 140</td>
<td>33.0 ± 300 $^f$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A: (1962BU23, 1963BU18): $\gamma$-absorption. The structures are each several hundred keV wide.
B: (1964TE04): $\gamma$-absorption [monochromatic $\gamma$-rays]; (1962FI04, 1963FU05, 1964FI03): ($\gamma$, n).
C: (1963GE13): ($\gamma$, n). See also (1964DE1D).
D: (1965CA1B): ($\gamma$, n) and S.C. Fultz, private communication. See also (1964BR03).
E: (1966CO08): ($\gamma$, n).
F: (1967MI15): ($\gamma$, n).
G: (1965DO05, 1967DO1A): $\gamma$-absorption.
H: (1970IV01): ($\gamma$, n).

$^a$ See also (1959AJ76).
$^b$ See also study of “breaks” by (1959KI89, 1960GE06).
$^c$ (1963GE13).
$^d$ (1967DO1A).
$^e$ There is some indication that this broad peak is composed of two narrower structures at $E_\gamma = 20.86$ and 21.05 MeV. There is also some indication of structure at $E_\gamma = 20.62$ MeV (1964TE04). See also (1962FI04).
$^f$ Six additional structures to $E_\gamma = 60.2$ MeV are reported by (1966CO08).
$^g$ Several additional structures are also reported for $E_x = 16.4 - 17.0$ MeV. $\Gamma_p$ and $\Gamma_n$ are also listed (1963GE13).

(Note: This footnote is not labeled in the tabular.)

49. $^{16}$O($\gamma$, p)$^{15}$N

$Q_m = -12.126$

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

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

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


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

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

51. $^{16}$O($\gamma$, $\alpha$)$^{12}$C $Q_m = -7.161$

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

52. $^{16}$O($\gamma$, 4$\alpha$) $Q_m = -14.436$

See (1959AJ76) and (1958MA1A, 1962GO1E, 1964GR08, 1964TO1B, 1965RO1J).
Table 16.26: Excited states observed in $^{16}\text{O}(e, e')^{16}\text{O}^*$

<table>
<thead>
<tr>
<th>$E_x \text{MeV} \pm \text{keV}$</th>
<th>$J^\pi; T$</th>
<th>Mult.</th>
<th>$\Gamma$ keV</th>
<th>$\Gamma_{7\nu}$ eV</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.05</td>
<td>0$^+$</td>
<td>E0</td>
<td>3.66 ± 0.55</td>
<td>(1968ST31)</td>
<td></td>
</tr>
<tr>
<td>6.13</td>
<td>3$^-$</td>
<td>E3</td>
<td>(2.3 ± 1.1) × 10$^{-5}$</td>
<td>(1968ST31)</td>
<td></td>
</tr>
<tr>
<td>6.92</td>
<td>2$^+$</td>
<td>E2</td>
<td>0.093 ± 0.010</td>
<td>(1968ST04, 1968ST31)</td>
<td></td>
</tr>
<tr>
<td>6.92</td>
<td>2$^+$</td>
<td></td>
<td>0.100 ± 0.015</td>
<td>(1967AR1A)</td>
<td></td>
</tr>
<tr>
<td>9.85</td>
<td>2$^+$</td>
<td>E2</td>
<td>0.010 ± 0.004</td>
<td>(1968ST04, 1968ST31)</td>
<td></td>
</tr>
<tr>
<td>11.0 ± 250</td>
<td>2$^+$</td>
<td>E2</td>
<td>&lt; 0.1</td>
<td>(1966ST13)</td>
<td></td>
</tr>
<tr>
<td>11.52</td>
<td>2$^+$</td>
<td>E2</td>
<td></td>
<td>2.7</td>
<td>(1966VA02)</td>
</tr>
<tr>
<td>12.0 ± 250</td>
<td>2$^+$</td>
<td>E2</td>
<td>0.55 ± 0.07</td>
<td>(1968ST04, 1968ST31)</td>
<td></td>
</tr>
<tr>
<td>12.05</td>
<td>0$^+$</td>
<td>E0</td>
<td>0.52 ± 0.13</td>
<td>(1967AR1A)</td>
<td></td>
</tr>
<tr>
<td>12.53</td>
<td>2$^-$</td>
<td>M2</td>
<td>0.021 ± 0.006</td>
<td>(1968ST31)</td>
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<tr>
<td>12.97</td>
<td>2$^-$</td>
<td>M2</td>
<td>0.108 ± 0.015</td>
<td>(1970KI02)</td>
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<tr>
<td>13.0</td>
<td>2$^+$</td>
<td>E2</td>
<td>0.85 ± 0.09</td>
<td>(1970KI02)</td>
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<tr>
<td>13.10 ± 250</td>
<td>1$^-$; 1</td>
<td>E1</td>
<td>0.071 ± 0.002</td>
<td>(1970KI02)</td>
<td></td>
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<tr>
<td>14.00 ± 50</td>
<td>0$^+$</td>
<td>E0</td>
<td>1.0 ± 0.3</td>
<td>(1966VA02)</td>
<td></td>
</tr>
<tr>
<td>14.00 ± 50</td>
<td>0$^+$</td>
<td>E0</td>
<td>1.0 ± 0.3</td>
<td>(1966VA02)</td>
<td></td>
</tr>
<tr>
<td>15.15 ± 150</td>
<td>2$^+$</td>
<td>E2</td>
<td>4.40 ± 0.44</td>
<td>(1968ST04, 1968ST31, 1970KI02)</td>
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<tr>
<td>16.21 ± 30</td>
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<td>M1</td>
<td>0.078 ± 0.016</td>
<td>(1968ST31)</td>
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<tr>
<td>16.46 ± 70</td>
<td>2$^+$</td>
<td>E2</td>
<td>0.071 ± 0.002</td>
<td>(1970KI02)</td>
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<tr>
<td>16.80 ± 100</td>
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<td>0.89</td>
<td>(1968ST31)</td>
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<tr>
<td>17.20</td>
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<td>31 ± 8</td>
<td>(1966VA02, 1968ST31)</td>
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<tr>
<td>17.60 ± 100</td>
<td>(2$^-$)</td>
<td></td>
<td>48.5 ± 12.8</td>
<td>(1970KI02)</td>
<td></td>
</tr>
<tr>
<td>18.50 ± 100</td>
<td>(2$^-$)</td>
<td></td>
<td></td>
<td>(1970KI02)</td>
<td></td>
</tr>
<tr>
<td>19.00 ± 100</td>
<td>1$^-$; 1</td>
<td>E1</td>
<td>51 ± 20</td>
<td>(1965VA1D, 1970ST06)</td>
<td></td>
</tr>
<tr>
<td>19.04 ± 50</td>
<td>2$^-$; 1</td>
<td>M2</td>
<td>0.07 ± 0.04</td>
<td>(1970ST06)</td>
<td></td>
</tr>
<tr>
<td>19.50 ± 100</td>
<td>1$^-$; 1</td>
<td>E1</td>
<td>1.0 ± 0.3</td>
<td>(1970ST06)</td>
<td></td>
</tr>
<tr>
<td>20.36 ± 70</td>
<td>2$^-$</td>
<td>M2</td>
<td>0.08 ± 0.04</td>
<td>(1970ST06)</td>
<td></td>
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<tr>
<td>20.95 ± 50</td>
<td>1$^-$; 1</td>
<td>E1</td>
<td>300 ± 100</td>
<td>(1965VA1D, 1968DR01)</td>
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</tr>
<tr>
<td>22.0 ± 250</td>
<td>1$^+$</td>
<td>M1</td>
<td>300 ± 100</td>
<td>(1965VA1D)</td>
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</tbody>
</table>
### Table 16.26: Excited states observed in $^{16}\text{O}(e,e')^{16}\text{O}^*$ (continued)

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>$J^\pi; T$</th>
<th>Mult.</th>
<th>$\Gamma$ (keV)</th>
<th>$\Gamma_{\gamma_0}$ (eV)</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.8 ± 250</td>
<td>1$^-$; 1</td>
<td>E1</td>
<td>2000 – 3000</td>
<td>5300</td>
<td>(1961IS06, 1962BI19)</td>
</tr>
<tr>
<td>23.7 ± 250</td>
<td>(2$^-$; 1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24.4 ± 250</td>
<td>2$^+$</td>
<td>E2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.5 ± 250</td>
<td>1$^-$; 1</td>
<td>E1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26.7 ± 250</td>
<td>1$^+$</td>
<td>M1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44.5</td>
<td>(1$^-$; 1)</td>
<td></td>
<td>2000 – 3000</td>
<td>19000</td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>(1$^-$; 1)</td>
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<td></td>
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</table>

<table>
<thead>
<tr>
<th>$A$</th>
<th>$B$</th>
<th>$C$</th>
<th>$D$</th>
<th>$E$</th>
<th>$F$</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


\(b\) Monopole matrix element in fm\(^2\).

\(c\) Unresolved doublet.

\(d\) See, however, (1969SI10).

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

(b) $^{16}\text{O}(\gamma$, breakup)


54. $^{16}\text{O}(\gamma, \gamma')^{16}\text{O}^*$

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 $60\, N\, Z / A \, \text{MeV} \cdot \text{mb}$ by a factor 1.4. See also (1959PE32, 1960RE05, 1962SE02). For lifetime measurements of $^{16}\text{O}^*(6.9, 7.1)$, see Table 16.19 (1957SW17, 1958DU06); for widths, see Table 16.12 (1970SW03). The separation between the (7.12) and (6.92) $\gamma$-lines is $199.8 \pm 0.5$ keV (1970SW03). Based on $7118.67 \pm 0.35$ keV (Table 16.9), $E_x$ for the lower state is $6918.9 \pm 0.6$ keV. See also (1962BA58, 1968SI1A; theor.).

55. (a) $^{16}\text{O}(e, e')^{16}\text{O}^*$

(b) $^{16}\text{O}(e, ep)^{15}\text{N}$ \(Q_m = -12.126\)
The $^{16}\text{O}$ charge radius, $r_{\text{rms}} = 2.65 \pm 0.04$ fm (1966CR07), $2.674 \pm 0.022$ fm (using a distorted wave approximation), $2.712 \pm 0.022$ fm (using a Born approximation) (1970SI02), $2.666 \pm 0.033$ fm (1969BE21). See also (1959EH1A, 1959ME24).

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


See also (1959AJ76).

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

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


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

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

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

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

$Q_m = -12.126$

$Q_m = -20.736$

$Q_m = -7.161$

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

<table>
<thead>
<tr>
<th>$E_n$ (MeV)</th>
<th>Angular distribution of groups</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.51 − 2.25</td>
<td>$n_0$</td>
<td>(1962MA05)</td>
</tr>
<tr>
<td>3.07 − 4.67</td>
<td>$n_0$</td>
<td>(1966LI03)</td>
</tr>
<tr>
<td>14.0</td>
<td>$n_0$, $n_1+2+3+4$</td>
<td>(1963BA46)</td>
</tr>
<tr>
<td>14.1</td>
<td>$n_0$, $n_1+2$, $n_3+4$</td>
<td>(1969ME15)</td>
</tr>
<tr>
<td>14.1</td>
<td>$n_0$, $n_1+2$, $n_3+4$, $n_5$</td>
<td>(1966MC01)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$E_p$ (MeV)</th>
<th>Angular distribution of groups</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.47 − 2.98</td>
<td>$p_0$</td>
<td>(1965GO08)</td>
</tr>
<tr>
<td>5.91</td>
<td>$p_0$</td>
<td>(1968AN13, 1968AN27)</td>
</tr>
<tr>
<td>6.9 − 15.6</td>
<td>$p_0$</td>
<td>(1960KO09)</td>
</tr>
<tr>
<td>7.2 − 10.5</td>
<td>$p_0$, $p_1$, $p_2$, $p_3$, $p_4$</td>
<td>(1964DA02)</td>
</tr>
<tr>
<td>7.3 − 13.3</td>
<td>$p_0$</td>
<td>(1959HU17)</td>
</tr>
<tr>
<td>12.9 − 15.6</td>
<td>$p_{1+2}$</td>
<td>(1960KO09)</td>
</tr>
<tr>
<td>13.8 − 18.2</td>
<td>$p_0$</td>
<td>(1964KE01)</td>
</tr>
<tr>
<td>13.9 − 15.6</td>
<td>$p_{3+4}$</td>
<td>(1960KO09)</td>
</tr>
<tr>
<td>14.8 − 19.2</td>
<td>$p_0$, $p_{1+2}$, $p_{3+4}$, $p_5$</td>
<td>(1964DA07)</td>
</tr>
<tr>
<td>19.8 − 30.5</td>
<td>$p_0$</td>
<td>(1969KA14)</td>
</tr>
<tr>
<td>20.9</td>
<td>$p_0$</td>
<td>(1969BA23)</td>
</tr>
<tr>
<td>23.4 − 46.1</td>
<td>$p_0$</td>
<td>(1968CA1D)</td>
</tr>
<tr>
<td>23.4 − 46.1</td>
<td>$p_{1+2}$, $p_5$</td>
<td>(1968AU1C, 1970AU1C)</td>
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<td>25.5 − 45.1</td>
<td>$p_0$</td>
<td>(1969SN03)</td>
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<td>30.3</td>
<td>$p_0$</td>
<td>(1964RI1B)</td>
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<td>31</td>
<td>$p_0$</td>
<td>(1964KI1C)</td>
</tr>
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<td>49.5</td>
<td>$p_0$</td>
<td>(1967FA06)</td>
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<td>100</td>
<td>$p_0$</td>
<td>(1970HO07)</td>
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<td>$p_0$</td>
<td>(1961TA06)</td>
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<td>185</td>
<td>$p$ to $^{16}$O*(11.5, 13.1, 15.3, 18.7, 20.2)</td>
<td>(1965HA17)</td>
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<tr>
<td>185</td>
<td>$p_2$, $p_3$, $p_4$</td>
<td>(1969SU03)</td>
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</table>
Table 16.27: Recent $^{16}$O(n, n), (p, p), (d, d), (t, t), ($^3$He, $^3$He), ($\alpha$, $\alpha$) angular distribution studies (continued)

<table>
<thead>
<tr>
<th>$E_d$ (MeV)</th>
<th>Angular distribution of groups</th>
<th>Refs.</th>
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</thead>
<tbody>
<tr>
<td>1.95 – 3.63</td>
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</tr>
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<td>4.0</td>
<td>$d_0$</td>
<td>(1966GA09)</td>
</tr>
<tr>
<td>4.0 – 6.0</td>
<td>$d_0$</td>
<td>(1970DA14)</td>
</tr>
<tr>
<td>8.0 – 10.5</td>
<td>$d_0$</td>
<td>(1963CA17, 1963CA1E, 1963CA1F, 1963GA1D)</td>
</tr>
<tr>
<td>10.95</td>
<td>$d_0$</td>
<td>(1960TA08)</td>
</tr>
<tr>
<td>11.8</td>
<td>$d_0$</td>
<td>(1967FI07)</td>
</tr>
<tr>
<td>12</td>
<td>$d_0$</td>
<td>(1967AL06)</td>
</tr>
<tr>
<td>13.6</td>
<td>$d_0$</td>
<td>(1963NE1C, 1964NE1D)</td>
</tr>
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<td>14.25</td>
<td>$d_0, d_1, d_2, d_3, d_4$</td>
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</tr>
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<td>15.8</td>
<td>$d_0$</td>
<td>(1966CO24)</td>
</tr>
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<td>26.3</td>
<td>$d_0$</td>
<td>(1962MA25, 1964TE1C)</td>
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<td>28</td>
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<td>(1968GA13)</td>
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<td>34.4</td>
<td>$d_0$</td>
<td>(1967NE1E)</td>
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<td>52</td>
<td>$d_0$</td>
<td>(1966DU08, 1968HI1B)</td>
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<th>Refs.</th>
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<td>$t_0$</td>
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<table>
<thead>
<tr>
<th>$E(\alpha)$ (MeV)</th>
<th>Angular distribution of groups to $^{16}$O</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
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<td>1.94, 2.37</td>
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<td>(1961SI09)</td>
</tr>
<tr>
<td>2.7 – 4.0</td>
<td>g.s.</td>
<td>(1965JI1A)</td>
</tr>
<tr>
<td>8.5, 9.4</td>
<td>g.s.</td>
<td>(1965AL05)</td>
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<tr>
<td>9.80 – 11.74</td>
<td>g.s.</td>
<td>(1969BR07, 1969NU02)</td>
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<td>12</td>
<td>g.s.</td>
<td>(1965YO1B)</td>
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<tr>
<td>15</td>
<td>g.s.</td>
<td>(1969ZU02)</td>
</tr>
<tr>
<td>16.6, 25.8, 36.6</td>
<td>g.s.</td>
<td>(1965AR1E)</td>
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<tr>
<td>17.3</td>
<td>g.s.</td>
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<td>18</td>
<td>g.s.</td>
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<td>28.9</td>
<td>g.s.</td>
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<td>29</td>
<td>g.s.</td>
<td>(1963AG1A)</td>
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<table>
<thead>
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<th>$E_{\alpha}$ (MeV)</th>
<th>Angular distribution of groups</th>
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<td>5.0 – 12.5</td>
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<td>(1969JO18)</td>
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</table>
Table 16.27: Recent $^{16}$O(n, n), (p, p), (d, d), (t, t), ($^3$He, $^3$He), (α, α) angular distribution studies (continued)

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Angular Distributions</th>
<th>References</th>
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</thead>
<tbody>
<tr>
<td>8.64, 9.31, 10.15</td>
<td>$\alpha_0$, $\alpha_0$, $\alpha_{1+2}$, $\alpha_{3+4}$, $\alpha_5$</td>
<td>(1967BR1F)</td>
</tr>
<tr>
<td>18.3</td>
<td>$\alpha_0, \alpha_{1+2}, \alpha_{3+4}, \alpha_5$</td>
<td>(1959CO70)</td>
</tr>
<tr>
<td>20.0 – 23.2</td>
<td>$\alpha_0$</td>
<td>(1969AG06, 1969FE10)</td>
</tr>
<tr>
<td>20.1, 21.5</td>
<td>$\alpha_{1+2}, \alpha_{3+4}$</td>
<td>(1970FE07)</td>
</tr>
<tr>
<td>20.2 – 23.4</td>
<td>$\alpha_0$</td>
<td>(1968CE1B)</td>
</tr>
<tr>
<td>21.2 – 22.7</td>
<td>$\alpha_0$</td>
<td>(1962JO14)</td>
</tr>
<tr>
<td>22.5</td>
<td>$\alpha_0, \alpha_{1+2}, \alpha_{3+4}, \alpha_5$</td>
<td>(1963CR04, 1965BL03)</td>
</tr>
<tr>
<td>23.05</td>
<td>$\alpha_0$</td>
<td>(1968TA1Q)</td>
</tr>
<tr>
<td>24.7</td>
<td>$\alpha_0$</td>
<td>(1964BU1C)</td>
</tr>
<tr>
<td>25.4 – 32.2</td>
<td>$\alpha_0$</td>
<td>(1970CO13)</td>
</tr>
<tr>
<td>27.3</td>
<td>$\alpha_0, \alpha_{1+2}, \alpha_{3+4}, \alpha_5, \alpha_6+7, \alpha_8$</td>
<td>(1965KO1A)</td>
</tr>
<tr>
<td>28.5</td>
<td>$\alpha_0, \alpha_{1+2}, \alpha_{3+4}, \alpha_5, \alpha_6+7, \alpha_9$</td>
<td>(1964KO02, 1965KO07)</td>
</tr>
<tr>
<td>31.8, 39.5</td>
<td>$\alpha_0, \alpha_{1+2}, \alpha_{3+4}, \alpha_5$</td>
<td>(1964BO1E, 1965PR1E)</td>
</tr>
<tr>
<td>38.1</td>
<td>$\alpha_0, \alpha_{1+2}, \alpha_{3+4}$</td>
<td>(1960AG01)</td>
</tr>
<tr>
<td>40</td>
<td>$\alpha_0, \alpha_{1+2}, \alpha_{3+4}$</td>
<td>(1959YA01)</td>
</tr>
<tr>
<td>40.5</td>
<td>$\alpha_0, \alpha_2, \alpha_3, \alpha_4, \alpha_5$</td>
<td>(1966HA19)</td>
</tr>
<tr>
<td>40.6</td>
<td>$\alpha_{1+2}$</td>
<td>(1965BU05)</td>
</tr>
<tr>
<td>41.9, 49.7</td>
<td>$\alpha_0$</td>
<td>(1965VA11)</td>
</tr>
<tr>
<td>56</td>
<td>$\alpha_0$</td>
<td>(1968GA1C)</td>
</tr>
<tr>
<td>50, 80.7</td>
<td>$\alpha_0, \alpha_2, \alpha_{3+4}, \alpha_5$</td>
<td>(1968RE1F)</td>
</tr>
<tr>
<td>65</td>
<td>$\alpha_0$ (and see Table 16.29)</td>
<td>(1964HA16)</td>
</tr>
<tr>
<td>104</td>
<td>$\alpha_0$</td>
<td>(1968HA1D, 1969HA14)</td>
</tr>
</tbody>
</table>


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

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

For reaction (c) see (1967SU1C, 1968FR1J) and (1963SH1A, 1964BA1P, 1968KO1P, 1968RO1F; theor.). For reaction (d) see (1961KO02, 1962FO03, 1962RO25, 1962VA1A, 1965ZH1A, 1967CH04, 1970GO12). For spallation studies, see reaction 7 in $^{17}$F.
Table 16.28: Energy levels of $^{16}\text{O}$ from $^{16}\text{O}(p, p')^{16}\text{O}^*$

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>(1955HO1B)$^a$</th>
<th>(1969SU03)$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.14 ± 30</td>
<td>6.13 ± 40</td>
<td>6.92</td>
</tr>
<tr>
<td>7.02 ± 30</td>
<td></td>
<td>7.12</td>
</tr>
<tr>
<td>8.87 ± 30</td>
<td>8.75 ± 150</td>
<td></td>
</tr>
<tr>
<td>9.85 ± 30</td>
<td>9.70 ± 150</td>
<td></td>
</tr>
<tr>
<td>10.34 ± 30</td>
<td>10.25 ± 150</td>
<td></td>
</tr>
<tr>
<td>11.08 ± 30</td>
<td></td>
<td>11.35 ± 100</td>
</tr>
<tr>
<td>11.51 ± 30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.02 ± 30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.53 ± 30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.06 ± 30</td>
<td>12.93 ± 100</td>
<td></td>
</tr>
<tr>
<td>(13.39 ± 30)</td>
<td></td>
<td>13.80 ± 150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.15 ± 150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16.30 ± 150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17.10 ± 150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17.70 ± 150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18.80 ± 150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19.80 ± 150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20.35 ± 150</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(22.1 ± 150)</td>
</tr>
</tbody>
</table>

$^a$ $E_p = 19$ MeV.

$^b$ $E_p = 185$ MeV.
58. $^{16}$O(d, d')$^{16}$O*


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

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

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


61. (a) $^{16}$O($\alpha$, $\alpha'$)$^{16}$O*

(b) $^{16}$O($\alpha$, 2$\alpha$)$^{12}$C $Q_m = -7.161$


Reaction (b) proceeds via excited states of $^{16}$O: see (1962VA25, 1964DO1C, 1968PA12) and (1970PI1D). See also (1968BA1H; theor.).
Table 16.29: Energy levels of $^{16}$O from $^{16}$O$(\alpha, \alpha')^{16}$O* 
(1964HA16, 1966HA19)

<table>
<thead>
<tr>
<th>$E_x$ a (MeV)</th>
<th>$L$</th>
<th>$\lambda$</th>
<th>$B(\lambda) \downarrow /e^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.137 b</td>
<td>3</td>
<td>E3</td>
<td>90 fm$^6$</td>
</tr>
<tr>
<td>6.903</td>
<td>2</td>
<td>E2</td>
<td>7.7 fm$^4$</td>
</tr>
<tr>
<td>6.973</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.876 b</td>
<td>3 c</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.797</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.308</td>
<td>e</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.069</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.480</td>
<td>e</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.997</td>
<td>e</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.492 d</td>
<td>e</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.989 d</td>
<td>e</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.966</td>
<td>e</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.975</td>
<td>e</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

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

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

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

For reaction (a), see (1969KR03). For reaction (b), see (1968OK06, 1969KR03). For reaction (c), see (1968OK06, 1969VO10, 1970SC1G).
64. $^{16}$O($^{12}$C, $^{12}$C)$^{16}$O


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


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

The angular distributions of elastically scattered $^{16}$O ions have been measured at $E(^{16}$O) = 14 to 30 MeV (1961BR15), 25 to 63 MeV (1969MA40), and at 140.4 MeV (1962WI09). At the highest energy the angular distribution corresponding to the excitation of $^{16}$O to the first four excited states (unresolved) has also been measured (1962WI09). See also (1962RO15). Excitation curves are reported by (1961BR15, 1965CA02, 1967SI1D, 1968PA1V, 1969MA40, 1970SP1E). Very striking structure is observed in the elastic scattering for $E(^{16}$O) = 34 to 72 MeV: see (1969MA40).


67. $^{17}$O(p, d)$^{16}$O $Q_m = -1.918$

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

68. $^{17}$O(d, t)$^{16}$O $Q_m = 2.115$

Not reported.
69. $^{17}\text{O}(^{3}\text{He}, \alpha)^{16}\text{O}$ $Q_m = 16.435$

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

70. $^{18}\text{O}(p, t)^{16}\text{O}$ $Q_m = -3.707$

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

71. $^{18}\text{O}(\alpha, ^6\text{He})^{16}\text{O}$ $Q_m = -11.219$

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

72. $^{18}\text{O}(^7\text{Li}, ^9\text{Li})^{16}\text{O}$ $Q_m = -6.104$

See (1969TO1D).

73. $^{18}\text{O}(^{12}\text{C}, ^{14}\text{C})^{16}\text{O}$ $Q_m = 0.934$

See (1968GO1Q).

74. $^{19}\text{F}(p, \alpha)^{16}\text{O}$ $Q_m = 8.115$

$Q_0 = 8.122 \pm 0.009$ (1967SP09).
Table 16.30: Angular distributions of $\alpha$-particles in $^{19}$F(p, $\alpha$)$^{16}$O

<table>
<thead>
<tr>
<th>$E_0$ (MeV)</th>
<th>Alpha-particle group(s)</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.49 − 0.72</td>
<td>$\alpha_0$</td>
<td>(1959BR67)</td>
</tr>
<tr>
<td>2.64 − 3.35</td>
<td>$\alpha_0$</td>
<td>(1966MO25)</td>
</tr>
<tr>
<td>4.26 − 12.00</td>
<td>$\alpha_0$</td>
<td>(1963WA12)</td>
</tr>
<tr>
<td>4.1 − 6.5</td>
<td>$\alpha_0$</td>
<td>(1960TE03)</td>
</tr>
<tr>
<td>6.0 − 7.4</td>
<td>$\alpha_0$</td>
<td>(1961YA09)</td>
</tr>
<tr>
<td>8.0 − 14.2</td>
<td>$\alpha_0$</td>
<td>(1959OG15)</td>
</tr>
<tr>
<td>18.5</td>
<td>$\alpha_0$</td>
<td>(1956LI37)</td>
</tr>
<tr>
<td>22.8</td>
<td>$\alpha_0$, $\alpha_{1+2}$, $\alpha_{3+4}$</td>
<td>(1963HO24)</td>
</tr>
<tr>
<td>26.7</td>
<td>$\alpha_0$</td>
<td>(1970GU06)</td>
</tr>
<tr>
<td>30.5</td>
<td>$\alpha_0$</td>
<td>(1967CO05)</td>
</tr>
<tr>
<td>38</td>
<td>$\alpha_0$</td>
<td>(1969GA03)</td>
</tr>
<tr>
<td>44.5</td>
<td>$\alpha_0$</td>
<td>(1966CR05, 1967CR05)</td>
</tr>
</tbody>
</table>

Angular distributions of various $\alpha$-particle groups have been obtained at many energies: see Table 16.30. Observed excited states are displayed in Table 16.31 (1956SQ1A, 1957YO04, 1965BE1J, 1967CH19, 1967DO1C). In addition to the very accurate $\gamma$-ray energies listed in Table 16.31, (1970GA09) report $E_\gamma = 2741.5 \pm 0.5$ keV for the (8.87 → 6.13) transition. The E0 transition (6.05 → 0; $0^+ \rightarrow 0^+$) has been investigated in some detail: $E = 6051 \pm 5$ keV (1962NE02), 6052 ± 4 keV (1963LE06). The internal conversion to pair production ratio is $(4.00 \pm 0.46) \times 10^{-5}$ (1963LE06). See also (1962NE02, 1963GO18). The ratio of double $\gamma$-emission to pair production, $\Gamma_{E1E1}/\Gamma_{E0}(\pi)$, is $\leq 1 \times 10^{-4}$ (1964AL18). Gamma-ray branching ratios and widths for $\gamma$-emission have been obtained for many transitions: see Table 16.12 (1960PI04, 1962GO07, 1962GO15, 1963GO31, 1965FU05, 1966LO06, 1967GI07, 1967LO08, 1967PI01, 1968EV03, 1968WI15). For lifetime measurements see Table 16.19 (1954DE36, 1958KO63, 1965AL14, 1967PI01, 1970CO09, 1970GA09).


75. $^{19}$F(d, n$\alpha$)$^{16}$O  \hspace{1cm} Q_m = 5.890

74
Table 16.31: $^{16}$O levels from $^{19}$F($p$, $\alpha$)$^{16}$O

<table>
<thead>
<tr>
<th>$E_x$ (MeV ± keV)</th>
<th>(\Gamma^a) (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>((1956SQ1A))</td>
<td>((1957YO04))</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6.051 ± 10</td>
<td>6.058 ± 17</td>
</tr>
<tr>
<td>6.131 ± 10</td>
<td>6.138 ± 11</td>
</tr>
<tr>
<td>6.920 ± 10</td>
<td>6.926 ± 11</td>
</tr>
<tr>
<td>7.120 ± 10</td>
<td>7.122 ± 11</td>
</tr>
<tr>
<td>8.874 ± 12</td>
<td>8.882 ± 11</td>
</tr>
<tr>
<td>9.852 ± 12</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>10.363 ± 14</td>
<td>≈ 25 – 30</td>
</tr>
<tr>
<td>11.085 ± 14</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) \((1956SQ1A)\).

\(^b\) From \(\gamma\)-ray measurements: \(E_\gamma = 6129.70 \pm 0.28\) and \(7117.02 \pm 0.49\) keV \((1967CH19)\). \((1965BE1J)\) report \(E_\gamma = 6127.8 \pm 1.2\) keV \((1967DO1C)\) \(E_\gamma = 6129 \pm 2\) keV.

See \((1965PE01)\).

76. $^{19}$F($^3$He, $^6$Li)$^{16}$O \hspace{1cm} Q_m = 4.094

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

77. $^{19}$F($\alpha$, $^7$Li)$^{16}$O \hspace{1cm} Q_m = -9.232

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

78. (a) $^{20}$Ne($p$, $p\alpha$)$^{16}$O \hspace{1cm} Q_m = -4.730

(b) $^{20}$Ne($\alpha$, $2\alpha$)$^{16}$O \hspace{1cm} Q_m = -4.730

75
For reaction (a) see (1967CH04, 1969EP1C). For reaction (b) see (1968YA1C).

79. $^{20}$Ne(d, $^6$Li)$^{16}$O

$Q_m = -3.257$

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

80. $^{20}$Ne($^3$He, $^7$Be)$^{16}$O

$Q_m = -3.143$

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

81. $^{28}$Si($\alpha$, $^{16}$O)$^{16}$O

$Q_m = -9.592$

See (1967VA18).
GENERAL: See (1966LE1H, 1967DI1B).

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

1. $^{14}$N($^3$He, n)$^{16}$F

$$Q_m = -0.969$$
$$Q_0 = -0.970 \pm 0.015 \ (1968AD03);$$
$$Q_0 = -0.963 \pm 0.040 \ (1965ZA01).$$

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

2. $^{16}$O(p, n)$^{16}$F

$$Q_m = -16.212$$
$$Q_0 = -16.4 \pm 0.2 \ (1965GR15).$$

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

3. $^{16}$O($^3$He, t)$^{16}$F

$$Q_m = -15.448$$

Triton groups observed at $E(^3$He) = 40.2 MeV are displayed in Table 16.33. The angular distributions of the tritons to $^{16}$F$^*(0, 0.24)$ are similar, as are those of the tritons to $^{16}$F$^*(0.43, 0.71)$: comparison with analog states in $^{16}$N, $^{16}$O then suggests $J^\pi = 0^-, 1^-, 2^-$ and 3$, respectively, for these states (1965PE04). See also (1966TO04; theor.) and (1965RI1C, 1967HA1Q).
Table 16.32: Energy levels of $^{16}$F

<table>
<thead>
<tr>
<th>$E_x$ (MeV $\pm$ keV)</th>
<th>$J^\pi; T$</th>
<th>$\Gamma$ (keV)</th>
<th>Decay</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>(0$^-$); 1</td>
<td>50 $\pm$ 30</td>
<td>p</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>0.236 $\pm$ 20</td>
<td></td>
<td>&lt; 40</td>
<td>p</td>
<td>1, 3</td>
</tr>
<tr>
<td>0.425 $\pm$ 14</td>
<td></td>
<td>40 $\pm$ 30</td>
<td>p</td>
<td>1, 3</td>
</tr>
<tr>
<td>0.714 $\pm$ 14</td>
<td>(3$^-$)</td>
<td>&lt; 15</td>
<td></td>
<td>1, 3</td>
</tr>
<tr>
<td>3.78 $\pm$ 60</td>
<td></td>
<td>&lt; 40</td>
<td></td>
<td>1, 3</td>
</tr>
<tr>
<td>4.25 $\pm$ 50</td>
<td></td>
<td></td>
<td></td>
<td>2, 3</td>
</tr>
<tr>
<td>5.45 $\pm$ 50</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>5.9 $\pm$ 50</td>
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<td>2, 3</td>
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<tr>
<td>6.4 $\pm$ 50</td>
<td></td>
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<td>2, 3</td>
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Table 16.33: $^{16}$F levels from $^{14}$N($^3$He, n)$^{16}$F and $^{16}$O($^3$He, t)$^{16}$F

<table>
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<th>$^{16}$F$^*$ a (MeV $\pm$ keV)</th>
<th>$^{16}$F$^*$ b (MeV $\pm$ keV)</th>
<th>$\Gamma$ b (keV)</th>
<th>$^{16}$F$^*$ c (MeV $\pm$ keV)</th>
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<tr>
<td>0</td>
<td>0</td>
<td>50 $\pm$ 30</td>
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<tr>
<td>0.253 $\pm$ 35</td>
<td>0.20 $\pm$ 50</td>
<td>&lt; 40</td>
<td>d</td>
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<tr>
<td>0.422 $\pm$ 15</td>
<td>0.436 $\pm$ 30</td>
<td>40 $\pm$ 30</td>
<td>d</td>
</tr>
<tr>
<td>0.711 $\pm$ 15</td>
<td>0.736 $\pm$ 40</td>
<td>&lt; 15</td>
<td>d</td>
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<tr>
<td></td>
<td>3.78 $\pm$ 60</td>
<td>&lt; 40</td>
<td>d</td>
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<td></td>
<td>4.25 $\pm$ 50</td>
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<td></td>
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<td></td>
<td>5.45 $\pm$ 50</td>
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<td></td>
<td>5.9 $\pm$ 50</td>
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<td></td>
<td>6.4 $\pm$ 50</td>
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a $^{14}$N($^3$He, n)$^{16}$F: (1968AD03).
b $^{14}$N($^3$He, n)$^{16}$F: (1965ZA01).
c $^{16}$O($^3$He, t)$^{16}$F: (1965PE04).
d These states were observed but $E_x$ was not determined.
\[ ^{16}\text{Ne} \]
(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 \(^{14}\text{O}\) + 2p by 2.6 MeV. See also (1960GO1B, 1960GO1D, 1961BA1C, 1961GO1D, 1962GO1B, 1962GO28, 1964GA1C, 1965JA1C, 1966KE16). A search has been made for the two-proton decay of \(^{16}\text{Ne}\) in the bombardment of nickel by 150 MeV \(^{20}\text{Ne}\) ions: the cross section is either \(\leq 1.8 \mu\text{b}\) (if \(E_{pp} > 1\) MeV and \(\tau(^{16}\text{Ne}) \geq 10^{-8}\) sec), or else \(\tau(^{16}\text{Ne}) < 10^{-8}\) sec (1964KA28). See also (1965GO1D, 1966GO1B, 1966LE1H, 1970WA1G).
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(Closed 30 November 1970)

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