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Energy Levels of Light Nuclei
$A = 16$

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Abstract: An evaluation of $A = 5$–24 was published in *Nuclear Physics* 11 (1959), 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 December 1, 1958)

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^{16}N
(Fig. 31)

GENERAL:

Theory: See (1954FL1A, 1956KA1C, 1957EL1B).

1. ^{16}N(β^-)^{16}O $Q_{\rm m} = 10.402$

From the character of the beta decay, it is concluded that ^{16}N(0) has $J^\pi = 2^-$. See ^{16}O.

2. ^{7}Li(^{14}N, ^{5}Li)^{16}N $Q_{\rm m} = 0.589$

See (1958AL1D).

3. ^{9}Be(^{7}Li, ^{8}Li)^{8}Be $Q_{\rm m} = 0.368$ $E_{\rm b} = 20.585$

The cross section for this reaction has been measured from $E(^7{\rm Li}) = 1.1$ to 2.0 MeV. At the higher energy it is approximately 1 mb (1957NO17).

4. ^{13}C(α, p)^{16}N $Q_{\rm m} = -7.416$

Not reported.

5. ^{14}C(d, γ)^{16}N $Q_{\rm m} = 10.481$

At $E_{\rm d} = 1.16$ MeV, the cross section is $\lesssim$ 0.1 mb (1957BO04). At $E_{\rm d} = 2.0$ MeV, $\sigma \leq 0.6$ mb (1956DO37).

6. ^{14}C(d, n)^{15}N $Q_{\rm m} = 7.987$ $E_{\rm b} = 10.481$

See (1950HU72) and ^{15}N.

Table 16.1: Energy levels of ^{16}N

E_x (MeV ± keV)	J^π	$\tau_{1/2}$ or Γ (keV)	Decay	Reactions
0	2^-	$\tau_{1/2} = 7.37 \pm 0.04$ sec	β^-	1, 2, 5, 12, 13, 16, 19, 24
0.120 ± 1	0^-	$\tau_{1/2} = 5.7$ μsec	γ	16, 24
0.295 ± 4	3^-		γ	16, 24, 25
0.392 ± 3	1^-		γ	16, 24, 25
(3.53 ± 30)		sharp		16
3.980 ± 20		sharp		16
4.80 ± 50		230 ± 40		16
(5.01 ± 50)				16
5.25 ± 50	$2^-, 3^\pm$	200	n	14, 16
12.2		270	d, p	7
12.62		190	d, p	7
12.8		165	d, p	7

7. ^{14}C(d, p)^{15}C $\quad Q_m = -1.007 \quad E_b = 10.481$

The excitation function has been studied from $E_d = 0.6$ to 3.0 MeV (1954RI1B, 1956DO37). Resonances are observed at 2.0, 2.45 and 2.7 MeV, with c.m. widths of 270, 190 and 165 keV, respectively, corresponding to ^{16}N*(12.2, 12.62, 12.8 MeV) (1956DO37). See also (1950HU72, 1954RI1B) and ^{15}C.

8. ^{14}C(d, α)^{12}B $\quad Q_m = 0.358 \quad E_b = 10.481$

See (1950HU72).

9. ^{14}C(t, n)^{16}N $\quad Q_m = 4.223$

Not reported.

10. ^{14}C(^{3}He, p)^{16}N $\quad Q_m = 4.988$

Not reported.

11. ^{14}C(α, d)^{16}N $Q_{\rm m} = -13.363$

Not reported.

12. ^{14}N(t, p)^{16}N $Q_{\rm m} = 4.851$

See (1953CU1D).

13. ^{15}N(n, γ)^{16}N $Q_{\rm m} = 2.494$

The thermal cross section is 24 ± 8 μb (1958HU18), 80 ± 30 μb (1952FE1A).

14. ^{15}N(n, n)^{15}N $E_{\rm b} = 2.494$

The total cross section has been measured for $E_{\rm n} = 2.8$ to 3.3 MeV: a resonance is observed at $E_{\rm n} \approx 2.95$ MeV. $\sigma_{\rm max} = 4$ b, $\Gamma = 140 \pm 40$ keV, corresponding to $E_{\rm x} \approx 5.26$ MeV, $J = 2^-$ or $3^\pm$ (1956BA1A).

15. ^{15}N(n, α)^{12}B $Q_{\rm m} = -7.629$ $E_{\rm b} = 2.494$

See (1948JE03).

16. ^{15}N(d, p)^{16}N $Q_{\rm m} = 0.267$
$Q_0 = 0.286$ (1957VA11);
$Q_0 = 0.269 \pm 0.010$ (1957WA01).

Levels derived from observed proton groups and γ-rays are listed in Table 16.2. Gamma transitions are shown in the inset of Fig. 31 (Energy Level Diagram of ^{16}N). Even at $E_{\rm d} = 2.7$ MeV, the stripping angular distribution patterns to the low-lying states are well-developed, and the theory yields quite good fits (1956ZI1A, 1957WA01). Shell-model theory in intermediate coupling predicts a close group of 4 levels within about 700 keV, with $J = 0$, 1, 2, 3, odd parity (order

Table 16.2: Levels of ^{16}N from ^{15}N(d, p)^{16}N

E_x [a] (keV)	$\Gamma_{c.m.}$ (keV)	l_n [b]	J^π [b]	θ^2 [c]
0	sharp	2	2^-	0.05
120 ± 1	sharp	0	0^-	0.19
294 ± 5	sharp	2	3^-	0.05
392 ± 3	sharp	0	1^-	0.18
(3530 ± 30)	sharp			
3980 ± 20	sharp			
4800 ± 50	230 ± 40			
(5010 ± 50)				
5250 ± 50	290 ± 50			

[a] (1957WA01: $E_d = 14.8$ MeV). No other proton groups are observed corresponding to ^{16}N* < 9 MeV. Energies of first three excited states are from γ-ray measurements (1957FR56, 1957WI1B).
[b] (1957WA01) and (1956ZI1A: $E_d = 2.75$ MeV); J assignments from stripping and gamma decay data: see text.
[c] (1957WA01).

uncertain), arising from the configurations $p_{\frac{1}{2}}^{-1}s_{\frac{1}{2}}$ and $p_{\frac{1}{2}}^{-1}d_{\frac{5}{2}}$. Levels from $p_{\frac{1}{2}}^{-1}d_{\frac{3}{2}}$ should lie several MeV higher (1953IN1A, 1957EL1B). These results are strikingly confirmed by the experimental evidence. The ground state is assigned $J = 2^-$ on the basis of the β-decay (see ^{16}N(β^-)^{16}O). The first excited state may have $J = 0^-$ or 1^- from the stripping pattern; however, the half-life $\tau_{1/2} = 6.7 \pm 0.5$ μsec (1957FR56), 5.43 ± 0.22 μsec (1959ZI18) is much too long for dipole radiation, and $J = 0^-$ is indicated (1957WI1B). The third excited state ($E_x = 392$ keV), again limited to $J = 0^-$ or 1^- by the stripping pattern, decays to both ^{16}N(0) and ^{16}N*(0.12); $J = 0^-$ is therefore excluded and $J = 1^-$ indicated. Of the possibilities $J = 1^-$, 2^-, 3^- for the second excited state, ^{16}N*(0.285), $J = 1^-$ is rendered unlikely by the low intensity of γ-decay to the second excited state and by the absence of an $l_n = 0$ component in the stripping pattern (1956ZI1A, 1957WA01, 1957WI1B). The assignment $J = 3^-$ is strongly favored by the (p-γ) angular correlation (1957FR56).

The observed γ-branching of ^{16}N*(0.395) is in accord with the theory, which predicts lifetimes in the range 1 to 7×10^{-11} sec. A considerable enhancement through collective excitation is required to account for the lifetime of the first excited state. The reduced neutron widths are expected to be of the order of the single-particle limit. Calculation of level shifts and comparison of observed reduced widths suggests that the ^{16}O* analogues to the first four states of ^{16}N are

^{16}O*(12.95, 12.78, 13.24, 13.09 MeV) (1957EL1B): see also (1957WI1B) and ^{15}N(p, p)^{15}N.

17. ^{15}N(t, d)^{16}N $Q_m = -3.765$

Not reported.

18. ^{15}N(α, ^{3}He)^{16}N $Q_m = 18.084$

Not reported.

19. ^{16}O(n, p)^{16}N $Q_m = -9.619$

The possibility that ^{16}N might have a long-lived ($\approx$ sec) isomeric state has been examined, with negative result (1956TO1A). See also (1952LI24) and ^{17}O.

20. ^{16}O(t, ^{3}He)^{16}N $Q_m = -10.384$

Not reported.

21. ^{17}O(d, ^{3}He)^{16}N $Q_m = -8.271$

Not reported.

22. ^{18}O(n, t)^{16}N $Q_m = -13.349$

Not reported.

23. ^{18}O(p, ^{3}He)^{16}N $Q_m = -14.114$

Not reported.

24. ^{18}O(d, α)^{16}N $\quad Q_{\rm m} = 4.237$

$Q_0 = 4.237 \pm 0.009$ (1955PA50).

Alpha groups are observed at $E_{\rm d} = 0.85$ MeV corresponding to ^{16}N*(0, 116 ± 6, 300 ± 12, 391 ± 12 keV). No other states are observed below $E_{\rm x} = 1.24$ MeV (1955PA50). See also (1957BO04) and ^{20}F.

25. ^{19}F(n, α)^{16}N $\quad Q_{\rm m} = -1.500$

At $E_{\rm n} = 4.87$ MeV, an α-group has been observed with $Q = -1.77 \pm 0.15$ MeV, probably corresponding to a transition to one or more excited states of ^{16}N (1955JA18). See also (1956TO1A) and ^{20}F.

^{16}O

(Fig. 32)

GENERAL:

Theory: See (1954DE1E, 1954FL1A, 1955HE1E, 1955JA1D, 1955MA1K, 1955MA1L, 1955SC1B, 1955WI1F, 1956EL1C, 1956FE1E, 1956JA1C, 1956KA1D, 1956MO1D, 1956PE1A, 1956RE1C, 1956WI1D, 1957EL1B, 1957FE1D, 1957GR1G, 1957HE1B, 1957RE1A, 1957TA1C, 1957TO1A, 1958CA1G, 1958DA1E, 1958DA1F, 1958FE1C, 1958FE1D, 1958HA1F, 1958MO17, 1958RA1F, 1958UM1A, 1958WI1E).

1. ^{12}C(α, γ)^{16}O $\quad Q_{\rm m} = 7.148$

Resonant capture radiation to ^{16}O$_{\rm g.s.}$ is observed at $E_\alpha \approx 3.24$ MeV, corresponding to the known $J = 1^-$ state at 9.58 MeV: see ^{12}C(α, α)^{12}C. The radiative width of 6×10^{-3} eV implies a $T = 1$ admixture of the order of 3×10^{-4}, an amount slightly lower than usual for ^{16}O states. It is suggested that the $T = 1$ admixture may derive from ^{16}O*(13.09), $J = 1^-$; $T = 1$ (1957BL01): see also (1953JO1A, 1956WI1D). This state does not arise in any natural way from p^{-1}s, or p^{-1}d (1957EL1B). The integrated capture cross section to $E_\alpha = 1.60$ MeV is < 30 μb-MeV (1955AL16). See also (1958PH37). The relevance of the capture of alpha particles by ^{12}C to the buildup of the elements in stars is discussed by (1956CA1F, 1956HA1C, 1956HA1D, 1957BU66, 1957SA1B).

2. ^{12}C(α, n)^{15}O $\quad Q_{\rm m} = -8.452 \quad E_{\rm b} = 7.148$

See (1939KI1A).

3. ^{12}C(α, αn)^{11}C $\quad Q_{\rm m} = -18.722 \quad E_{\rm b} = 7.148$

See (1953LI28).

4. ^{12}C(α, p)^{15}N $\quad Q_{\rm m} = -4.965 \quad E_{\rm b} = 7.148$

See ^{15}N.

5. ^{12}C(α, d)^{14}N $\quad Q_{\rm m} = -13.579 \quad E_{\rm b} = 7.148$

Table 16.3: Energy Levels of ^{16}O

E_x (MeV ± keV)	$J^\pi; T$	τ_m or Γ (keV)	Decay	Reactions
0	0^+; 0	–	stable	1, 18, 24, 27, 34, 36, 37, 38, 43
6.056 ± 10	0^+; 0	$\tau_m = 72 \pm 7$ psec	π	9, 18, 35, 36, 38, 43
6.135 ± 10	3^-; 0	$\tau_m = 12 \pm 6$ psec	γ	18, 24, 27, 35, 36, 38, 43
6.923 ± 10	2^+; 0	$\tau_m = 12 \pm 3$ fsec	γ	18, 33, 36, 38, 43
7.121 ± 10	1^-; 0	$\tau_m = 10 \pm 3$ fsec	γ	18, 24, 27, 33, 36, 38, 43
8.875 ± 10	2^-; 0		γ	18, 24, 27, 36, 38, 43
9.58	1^-; 0	650	α, γ	1, 6
9.843 ± 12	2^+; 0	0.8	α	6, 36, 43
10.363 ± 14	4^+; 0	27	α	6, 36, 43
(10.804)				(43)
10.937 ± 10	0^-; 0		γ	(18), 24, (43)
11.070 ± 10	3^+; (0)		γ	(6), 18, 24, 36, 43
11.25	0^+; 0	2500	α	6
11.51 ± 30	2^+; 0	80	α	6, 36
11.62	3^-; 0	1200	α	6
12.02 ± 30			(γ)	36
(12.29)		40	γ	20
12.43 ± 10	1^-; 0	89	α, γ, p	6, 20, 22
12.52 ± 10	2^-	0.8	p, γ, α	20, 22, 36
12.78 ± 10	0^-; 1	38	p, γ	20, 21
12.96 ± 10	2^-; 1	2 ± 0.2	p, α	21, 22
13.09 ± 10	1^-; 1	130 ± 10	p, γ, α	20, 21, 22, 36
13.25 ± 10	3^-; 1	21 ± 1	p, α	21, 22
13.65 ± 10	1^+; 0	64 ± 3	p, α	21, 22
13.97 ± 10	2^-	22 ± 2	p, α	21, 22
14.93 ± 40	4^+	43 ± 10	p, α	22
15.21 ± 40	2^-, 3^+	72 ± 15	p, α	22
15.25 ± 60	2^+	720 ± 100	p, α	22
15.41 ± 50		96 ± 25	p, α	22
15.79		30	p, α	22

Table 16.3: Energy Levels of ^{16}O (continued)

E_x (MeV ± keV)	$J^\pi; T$	τ_m or Γ (keV)	Decay	Reactions
16.21	1^+	23	p, n	23
16.3	0^-	250	p, n	23
16.44		24	p, α	22
(16.82)			p, α	22
(16.93)			p, α	22
17.0		≈ 200	p, n	23
17.12		41	p, n	23
17.29		84	p, n	23
17.5		≈ 250	p, n	23
17.63		66	p, n	23
17.85		100	p, n	23
17.96		49	p. n	23
18.05		38	p, n	23
22.05		broad	d, n	11
23.05		broad	d, n	11
23.54		300	α	6
24.38		broad	d, n	11
(25.7)			^{3}He, p, α	7, 8
(26.4)			^{3}He, p	7

The angular distribution at $E_\alpha = 42$ MeV shows three peaks and three valleys in the range $\theta_{\rm c.m.} = 40°$ to $150°$. The location of peaks and the absolute cross sections agree closely with those obtained in the inverse reaction at $E_d = 20$ MeV. The experiment provides a test of the hypothesis of invariance under time reversal and places an upper limit of a few per cent on possible T-R odd forces (1958BO71).

6. ^{12}C(α, α)^{12}C $\qquad E_b = 7.148$

Resonances derived from a phase-shift analysis of the elastic scattering are exhibited in Table 16.4 (1953HI05, 1954BI96). At the upper limit of these experiments (^{16}O*(12.5)), the existence of higher $J = 0^+$ and 2^+ levels is indicated by a pronounced increase in the $l = 0$ and $l = 2$ phase shifts (1953HI05, 1954BI96). The inelastic scattering for $E_\alpha = 20.4$ to 22.6 MeV indicates

Table 16.4: Resonances in ^{12}C(α, α)^{12}C

E_α (MeV)	Γ_{lab} (keV)	θ^2_α	^{16}O* (MeV)	J^π
3.24 [a]	860	0.85	9.58	1^-
3.582 [a]	1	0.0015	9.835	2^+
4.28 [b]	36	0.26	10.36	4^+
5.27 [b]	10		(11.10) [d]	
5.47 [b]	3300	0.76	11.25	0^+
5.82 [b]	106	0.03	11.51	2^+
5.96 [b]	1600	0.73	11.62	3^-
7.04 [b]	230	0.04	12.43	1^-
21.85 [c]	400		23.54	

[a] (1953HI05).
[b] (1954BI96).
[c] (1955RA1B).
[d] Assignment to present reaction not certain.

a resonance at $E_\alpha = 21.85 \pm 0.1$ MeV, $\Gamma \approx 0.4$ MeV (^{16}O*(23.54)). The asymmetry of the angular distribution is said to indicate at least one other level, of opposite parity (1955RA1B). See also (1954DE1E; theor.) and ^{12}C.

7. ^{13}C(^{3}He, p)^{15}N $\qquad Q_m = 10.668 \qquad E_b = 22.780$

The yields of ground state protons have been studied at several angles in the region $E(^3\text{He}) = 1.4$ to 4.8 MeV. There are indications of resonances at $E(^3\text{He}) \approx 3.6$ and 4.5 MeV (^{16}O*(25.7 and 26.4)) (1956SC01, 1957IL01). See also ^{15}N.

8. ^{13}C(^{3}He, α)^{12}C $\qquad Q_m = 15.632 \qquad E_b = 22.780$

The ground state α-group shows a broad weak resonance at $E(^3\text{He}) \approx 3.6$ MeV (1956WO1C). See also ^{12}C.

9. ^{13}C(α, n)^{16}O $\qquad Q_m = 2.203$

A threshold for ^{16}O*(6.05) is observed at $E_\alpha = 5.05$ MeV (1956BO61). See also (1951JO1C) and ^{17}O.

10. ^{14}C(^{3}He, n)^{16}O $\quad Q_m = 14.607$

Not reported.

11. ^{14}N(d, n)^{15}O $\quad Q_m = 5.073 \quad E_b = 20.728$

Excitation functions have been measured for $E_d = 0.6$ to 4.5 MeV (1955MA85, 1956JO1D, 1957JO1C, 1957NO1C, 1958MO14, 1958WE31). The yield of ground-state neutrons shows broad but well-defined peaks at $E_d = 1.52$, 2.62, and 4.19 MeV; $E_x = 22.05$, 23.05, and 24.38 MeV. It is not clear whether the structure is to be attributed to resonances or to surface interaction (1958WE31). See also ^{15}O.

12. ^{14}N(d, p)^{15}N $\quad Q_m = 8.615 \quad E_b = 20.728$

Excitation functions and angular distributions are reported by (1954JO1F: $E_d = 0.4$ to 0.6 MeV) (1956KO26, 1956VA17: $E_d = 0.2$ to 0.7 MeV), and (1958BO18: $E_d = 0.6$ to 1.0 MeV): see also (1957JA37). At the lower energies, both stripping and compound nucleus effects are reported, although the distributions for $E_d = 0.6$ to 1.0 MeV (1958BO18) appear to be explicable entirely on the basis of overlapping resonance levels. See also ^{15}N and (1954ST1C).

13. ^{14}N(d, d)^{14}N $\quad E_b = 20.728$

See ^{14}N.

14. ^{14}N(d, t)^{13}N $\quad Q_m = -4.292 \quad E_b = 20.728$

See (1942BO1A).

15. ^{14}N(d, α)^{12}C $\quad Q_m = 13.579 \quad E_b = 20.728$

The cross section rises gradually from $E_{\rm d} = 0.45$ to 0.90 MeV (1954CA1D). Angular distributions for $E_{\rm d} = 0.6$ to 1.0 MeV indicate that the stripping contribution is small in this range (1958BO18). The angular distribution at $E_{\rm d} = 20$ MeV agrees closely with that of the inverse reaction at $E_\alpha = 42$ MeV (1958BO71): see ^{12}C(α, d)^{14}N, (1957FI1C) and ^{12}C.

16. ^{14}N(d, 4α) $Q_{\rm m} = 6.298$ $E_{\rm b} = 20.728$

See (1947FO1A).

17. ^{14}N(t, n)^{16}O $Q_{\rm m} = 14.470$

Not reported.

18. ^{14}N(^{3}He, p)^{16}O $Q_{\rm m} = 15.235$

At $E(^3{\rm He}) = 2.1$ MeV, proton groups corresponding to ^{16}O levels up to $E_{\rm x} = 13.6$ MeV have been identified. In the region $E_{\rm x} \approx 11$ MeV, four groups are resolved, corresponding to ^{16}O*(10.94, 11.087 ± 0.020, 11.25, 11.51). The first two are presumably those observed in ^{15}N(d, n)^{16}O at 10.937 and 11.063 MeV. The gamma decay of ^{16}O*(8.88, 10.94 and 11.07) has been studied with coincidence techniques: branching ratios are given in Fig. 33 (Gamma-ray transitions in ^{16}O). From the observed transition intensities and from (p-γ) and (γ-γ) correlations, the assignment $J = 2^-$ for ^{16}O*(8.88) is confirmed, and assignments of $J = 0^-$ and 3^+ are fixed for ^{16}O*(10.94 and 11.07), respectively. For the 10.94 MeV state, $\Gamma_\alpha/\Gamma_\gamma < 0.2$, indicating an upper limit for the intensity of possible opposite-parity admixture of $\approx 2 \times 10^{-9}$ (1959BR68, 1959KU78). See also (1957BR17, 1957LI1D, 1958BR1D).

19. ^{14}N(α, d)^{16}O $Q_{\rm m} = -3.116$

Not reported.

20. ^{15}N(p, γ)^{16}O $Q_{\rm m} = 12.113$

Ground-state capture radiation resonances occur at $E_{\rm p} = 190$, 338 keV (1958HE52) and 1050 keV (1952SC28, 1957HA98, 1958HE52): see Table 16.5. The large radiative width, $\Gamma_\gamma = 150$ eV, of the latter indicates E1 radiation and $J = 1^-$; $T = 1$ for ^{16}O*(13.09); on the other hand, the large

α-width speaks for a strong admixture of $T = 0$ (1953WI1B, 1956WI1D: see also (1957BA03)). The 338 keV resonance is relatively weak, $\Gamma_\gamma = 8$ eV. The Breit-Wigner formula with destructive interference between these two $J = 1^-$ states gives a good account of the γ_0 yield from $E_p = 200$ to 1200 keV (1958HE52). Cascade radiation, via ^{16}O*(6 and 7), is weakly resonant at $E_p = 340$ keV (1958HE52): at the higher resonance, the relative amount of cascade radiation is $< 1.3 \times 10^{-3}$ (1953DE1A, 1954GO1F). No further resonances for ground-state radiation appear for $E_p < 3.3$ MeV with intensity $> 2\%$ of that at $E_p = 1050$ keV (1957BA03). Within a few microbarns, the cross section for $E_p < 3$ MeV is completely accounted for by the 13.09 MeV state; a small rise from $E_p = 3$ to 4 MeV may reflect higher resonances. This result is in disagreement with that of (1955SP1B) on the inverse reaction in which a level at ^{16}O*(14.7) ($E_p = 2.8$ MeV) is reported. The isotropy of the radiation over the entire range from $E_p = 1$ to 4 MeV places an upper limit of 3% on the relative intensity of $p^{-1}d$ in the 13.09 MeV state (1957WI1H); see also (1957EL1B).

At $E_p = 429$ keV (1958HE52) and 710 keV (1957HA98), resonances for cascade radiation are found; neither produces any detectable ground state radiation. See also (1958CA13).

21. ^{15}N(p, p)^{15}N $\qquad E_b = 12.113$

Elastic scattering studies are reported for $E_p = 600$ to 1800 keV by (1957HA98) and for $E_p = 950$ to 3960 keV by (1956BA1H); see Table 16.5. The $E_p = 710$ keV state, (^{16}O*(12.78)) having $J = 0^-$, does not appear in the (p, α) reaction or in the ground-state capture: see ^{15}N(p, γ)^{16}O. The assignment $J = 3^-$ to the state at $E_p = 1210$ keV (^{16}O*(13.25)) is in disagreement with the observed angular distribution in ^{15}N(p, α_1)^{12}C* but is confirmed by the α_1-γ correlation. The reason for this discrepancy is not known (1957HA98).

By comparison of J^π assignments and reduced widths, it is concluded that the ^{16}O levels formed at $E_p = 898$, 710, 1210, and 1028 keV are the analogues of the first four states of ^{16}N (1956WI1G, 1956WI1H, 1957EL1B, 1957HA98). It is pointed out that the $E_p = 340$ and 429 keV states are also possible candidates, and that in any case appreciable isobaric spin mixing is to be expected (1957HA98). See also (1956WI1D).

Elastic scattering at $\theta = 132°$ shows structure at $E_p = 3000$ keV and a large peak of undetermined origin at $E_p = 3920 \pm 40$ keV (1956BA1H). See also (1958CA13).

22. ^{15}N(p, α)^{12}C $\qquad Q_m = 4.964 \qquad E_b = 12.113$

Two groups of α-particles occur, to ^{12}C(0) (α_0) and to ^{12}C*(4.43, $J = 2^+$) (α_1, γ). Observed resonances are exhibited in Table 16.5. The cross section for (p, α_0) is 5×10^{-7} b at $E_p = 100$ keV (1950SC1A: see also (1952SC28, 1957BA03)). See (1957JA37).

Angular distributions (p-α_0) have been studied in the range $E_p = 230$ to 960 keV by (1953CO1D), $E_p = 500$ to 1000 keV by (1953NE1B), $E_p = 920$ to 1260 keV by (1957HG01). At and below the 338 keV resonance, the distribution is isotropic. Strong $\cos\theta$ terms develop for $E_p > 400$

Table 16.5: Levels of ^{16}O from ^{15}N(p, p)^{15}N, ^{15}N(p, γ)^{16}O and ^{15}N(p, α)^{12}C

E_p (keV)	Γ_{lab} (keV)	Γ_p (keV)	$\sigma(\alpha_0)$ (mb)	$\sigma(\alpha_1)$ (mb)	$\sigma(\gamma_0)$ (μb)	$\sigma(\gamma_1)$ (μb)	θ_p^2 (%)	$J^\pi; T$	E_x (MeV)
(190)	40				res [f]				12.29
338 [a]	94	0.8 [a, f]	75 [a, f]	0.03 [f]	7 [f]	0.4 [f]	4 [f, c]	$1^-; 0$ [c]	12.430
429 ± 1 [a]	0.9	0.020 [f]	n.r. [g]	200 [a, f]		1300 [f]	4 [b]	2^-	12.515
710 ± 7 [b]	40 ± 4	40 [b]	n.r.	n.r.	n.r.	res	11	$0^-; 1$ [b]	12.779
898 ± 1 [a]	2.2 ± 0.2	1.2	n.r.	800			8.8	$2^-; 1$	12.955
1028 ± 10 [b]	140 ± 10	110	500 [i]	15	1000 [a]	< 1.3 [h]	10	$1^-; 1$	13.088
1210 ± 3 [a]	22.5 ± 1	4.1	600 [i]	425 [d]			7.4	$3^-; 1$	13.247
1640 ± 3 [c]	68 ± 3	10	n.r. [d]	340			0.8	$1^+; 0$	13.651
1979 ± 3	23 ± 2	0.5 [c]	n.r.	35				2^- [d]	13.968
3000 ± 30 [d]	45 ± 10		50	600				4^+	14.93
3300 ± 35	75 ± 15		n.r.	270				$2^-, 3^+$	15.21
3350 ± 50	750 ± 100		50	205				2^+	15.25
3520 ± 40	100 ± 25		100	80					15.41
3920 [e]	30			res [e]					15.79
4610	25			res					16.44
(5020)				(res)					(16.82)
(5140)				(res)					(16.93)

[a] (1952SC28); values for 338-kev resonance corrected for s-wave penetration: observed $E_{max} = 360$ keV, σ_{α_0}(max) $= 90$ mb.
[b] (1957HA98).
[c] (1957HG01).
[d] (1957BA03).
[e] (1956LI1C); see also Table 16.6.
[f] (1958HE52).
[g] n.r. = non-resonant.
[h] (1954GO1F).
[i] (1952SC28): (1957HG01) find 340 and 300 mb respectively.

keV, with $\cos^2\theta$ terms gradually increasing above 700 keV, and higher-order terms above 1 MeV. The terms in $\cos\theta$ indicate interference between states of opposite parity. Analysis of this effect led (1953CO1D) to the conclusion that the resonances in question were $E_p = 338$ keV, assigned $J = 0^+$, and $E_p = 1028$ keV, $J = 1^-$. Subsequent work has shown, however, that the lower state is $J = 1^-$, formed by s-wave protons: evidently the interfering even parity state or states remain to be identified; see also ^{12}C(α, α)^{12}C. The 1028 keV resonance has a large width both for α-particles and E1 radiation and appears to have a mixed character as regards isobaric spin (1953WI1A, 1953WI1B, 1956WI1D, 1957HA98).

Analysis of the (p-α_0) distribution at the $E_p = 1210$ keV resonance indicates $J = 3^-$, although $J = 4^+$ is not clearly excluded (1957HG01). Angular distributions of (p, α_1) and the 4.4 MeV γ-ray have been studied at the $E_p = 429$, 898, and 1210 keV resonances by (1952BA1C, 1952SE1B, 1953KR1B). Channel-spin ratios have been interpreted in terms of L-S and j-j coupling models by (1953CH1A). The α_1-distribution at $E_p = 1210$ keV appears to require $J = 4^+$ (1953KR1B, 1957HA98), but the (α_1-γ) correlation requires $J = 3^-$, in agreement with elastic scattering results; the reason for this discrepancy is not clear (1957HA98). Angular distributions of the 4.4 MeV γ-rays are reported for $E_p = 1050$ and 1640 keV by (1954KR1C) and for various energies from $E_p = 1210$ to 3900 keV by (1957BA03). See also (1958CA13).

A pronounced anomaly appears at $E_p = 1.87$ MeV in the (p, α_0) excitation curve which is faintly reproduced in (p, α_1) but not in (p, p) (1957HG01).

23. ^{15}N(p, n)^{15}O $\qquad Q_m = -3.542 \qquad E_b = 12.113$

The excitation function has been measured from threshold to 6.4 MeV, and angular distributions have been studied at several energies: see Table 16.6. Only four levels are found with $\Gamma \lesssim 40$ keV, as contrasted with the ten or more reported in ^{16}O(γ, n)^{15}O (1958JO28).

24. ^{15}N(d, n)^{16}O $\qquad Q_m = 9.886$

Slow neutron thresholds have been observed at $E_d = 1.192$ and 1.335 MeV, corresponding to ^{16}O*(10.937 ± 0.010, 11.063 ± 0.015) (1957WE1A). At $E_d = 5.1$ MeV, in this reaction, and at $E_p = 5.77$ MeV in ^{19}F(p, α)^{16}O, four γ-ray lines are observed which are assigned to ^{16}O: $E_\gamma = 2.73$ ($8.87 \rightarrow 6.14$), 3.86 ± 0.04 ($10.94 \rightarrow 7.12$), 6.14 ($6.14 \rightarrow 0$), and 7.1 MeV ($6.9 + 7.1 \rightarrow 0$). The 10.94 MeV state is not observed to decay in any way other than through the $J = 1^-$ state at 7.12 MeV; upper limits to transitions to ^{16}O*(0, 6.06, 6.14, 6.92, 8.87) are, respectively, 5, 1, 6, 20, and 40% of the observed cascade. The strong transition to ^{16}O*(7.1), $J = 1^-$, suggests $J = 0^-$ for ^{16}O*(10.94), although $J = 1^+$ is not ruled out. The γ-γ correlation strongly favors $J = 0^-$. It is suggested that this γ-emitting state is to be identified with the first neutron threshold: ^{16}O*(10.94), above, and is distinct from either the (doubtful) ^{16}O*(11.1) reported in ^{12}C(α, α)^{12}C or the ^{16}O*(11.08) reported in ^{16}O(p, p$'$)^{16}O*. Possibly both ^{16}O*(10.94 and 11.08) are involved

Table 16.6: Resonances in ^{15}N(p, n)^{15}O (1958JO28)

E_p (MeV)	Γ_{lab} (keV)	J^π	E_x in ^{16}O (MeV)
4.372	24	1^+	16.21
≈ 4.5	≈ 250	0^-	16.3
≈ 5.3	≈ 200		17.0
5.35	44		17.12
5.52	90		17.29
≈ 5.8	≈ 250		17.5
5.88	70		17.63
6.12	105		17.85
6.24	52		17.96
6.33	40		18.05

in ^{14}N(^{3}He, p)^{16}O (1957BE61). It is noted that the ^{19}F(p, α)^{16}O spectrum of (1956SQ1A) shows three groups in this range, of which one is definitely attributed to ^{16}O*(11.085) (1957WE1A). The 8.87 MeV state has a 7 ± 2 % direct transition to ^{16}O$_{g.s.}$ (1957BE61). Angular distributions of ground-state neutrons for $E_d = 1.1$ to 5.2 MeV are well accounted for by the exchange stripping theory of (1957OW03) (1958WE31: see ^{17}O). See also (1955AJ61) and (1957EL1B; theor.).

25. ^{15}N(^{3}He, d)^{16}O $\qquad Q_m = 6.619$

Not reported.

26. ^{15}N(α, t)^{16}O $\qquad Q_m = -7.700$

Not reported.

27. ^{16}N(β^-)^{16}O $\qquad Q_m = 10.402$

^{16}N decays to several states of ^{16}O: reported branching fractions are listed in Table 16.7. The ground-state transition, with E_β(max) $= 10.33 \pm 0.08$ MeV (1957MO1A), 10.40 ± 0.05 MeV (1958BR95), has the unique first-forbidden shape corresponding to $\Delta J = 2$, yes, fixing J^π of ^{16}N as 2^- (1957MO1A, 1958BR95, 1959AL1M). This assignment is also indicated by the fact

Table 16.7: Beta-decay of ^{16}N

Final State		A		B		C		D
^{16}O* (MeV)	J^{π}	Branch (%)	$\log f_0t$	Branch (%)	$\log f_0t$	Branch (%)	$\log f_0t$	
0	0^+	26 ± 2	6.7	28	6.67 [a]	24 ± 2	8.2 [b]	
6.06	0^+	≤ 0.015	≥ 8.2					
6.14	3^-	68	4.5	54	4.6	55 ± 4	4.5	14 ± 1
6.92	2^+							
7.12	1^-	4.9	5.1	18	4.6	21 ± 4	4.4	1
8.88	2^-	1.1	4.4					

A: (1956WI1A, 1958AL13, 1959AL1M): includes data of B, C, D.
B: (1958BR95).
C: (1957MO1A).
D: γ-rays (1951MI1B, 1956TO1A, 1957BO04).
[a] $\log(f_1t) = 8.0$.
[b] $\log(f_1t)$.

that the transitions to ^{16}O*(6.1 and 7.1) are both allowed (1951MI1B). There appears to be some discrepancy between the branching ratios of ^{16}O*(6.1 and 7.1) as determined by decomposition of the β-spectrum (1958BR95) and by comparison of the γ-ray intensities (1951MI1B, 1957BO04: see, however, (1959AL1M)). The low ft-value for ^{16}O*(7.1) presents some difficulty for the theory (1957EL1B). Transitions to the nuclear pair emitting state are $< 1.5 \times 10^{-4}$: $\log ft > 8.2$ (1958AL13: see also (1956EL1C, 1957EL1B)). A 1.1% branch leads to ^{16}O*(8.87) which decays via the 7.1, 6.9, and 6.1 MeV levels in the ratio 3 : 1 : 30. Since the β-transition is allowed, J^{π} of ^{16}O*(8.8) is 1^-, 2^- or 3^-; the first and last would permit α-decay, so $J^{\pi} = 2^-$. The γ-branching and the γ-γ correlation ($8.88 \rightarrow 6.1 \rightarrow$ g.s.) are consistent with this assignment (1956WI1A).

The half-life is 7.35 ± 0.05 sec (1947BL1A), 7.38 ± 0.05 sec (1954MA97). (1956TO1A) finds no evidence for β-decay of excited states of ^{16}N.

28. ^{16}O(γ, n)^{15}O $\quad Q_{\rm m} = -15.655$

$E_{\rm thresh.} = 15.60 \pm 0.05$ (1957BA27: see also (1955BA1P)).

The cross section exhibits a slow rise for ≈ 3 MeV above threshold followed by the usual giant resonance. Characteristics of the giant resonance are: $E_{\gamma} = 24$ MeV, $\Gamma = 3.5$ MeV, $\sigma_{\rm max} = 10$ mb; $\int \sigma {\rm d}E = 40$ MeV-mb (1951JO1B, 1953MO1B, 1954FE16, 1957CA1D).

Discontinuities in the activation curve are said to indicate absorption into discrete levels of ^{16}O: see Table 16.8 (1955BA1P, 1955CO1C, 1955PE1D, 1957BA27, 1958BE74, 1958KA1D). From the cross section it would appear that a substantial fraction of the absorption takes place through discrete levels (1954KA1A, 1955PE1D). However, in a measurement of the absorption in water for $E_\gamma = 15$ to 25 MeV, using various detectors including ^{16}O, (1958SI1A) conclude that the absorption is generally continuous, with only a small contribution from discrete, narrow levels. See also (1954BI04, 1955CA1E, 1955SA1F, 1957SP1A, 1957SV1A, 1958LI1D, 1958WO51), (1955MO1C, 1956WI1D, 1957BA1H, 1957EL1B, 1958FE1C, 1958FE1D, 1958WI1E; theor.) and (1955AJ61).

29. ^{16}O(γ, p)^{15}N $\qquad Q_{\rm m} = -12.113$

Resonances are observed at $E_\gamma = 19.6$, 20.6, 22.4 MeV; $\int \sigma {\rm d}E = 2$, 2, and 20 MeV-mb for ground-state protons (1956CO59), $E_\gamma = 20.7$, 21.9, 24.0 MeV (1956LI1D). See also (1955JO1D). The 22 MeV resonance appears to be the giant resonance. Proton angular distributions have been measured by (1956CO59, 1956LI1D, 1957MI1C). A resonance reported at $E_\gamma = 14.7$ MeV (1955SP1B: see also (1956CO59)) does not appear in the inverse reaction ^{15}N(p, γ)^{16}O (1955WI1F, 1957WI1H). (1958SI1A) find that the absorption in the range $E_\gamma = 15$ to 25 MeV is generally continuous, with only small contributions from narrow resonances: see also ^{16}O(γ, n)^{15}O. See also (1955ST1D, 1956JO1C, 1957BR55, 1957MI1B, 1957SV1A, 1958LI1D, 1958MI89, 1958PE1A) and (1955MO1B, 1956GO1G, 1957BA1K, 1957WI1J; theor.).

30. ^{16}O(γ, α)^{12}C $\qquad Q_{\rm m} = -7.148$

The cross section for production of ^{12}C exhibits a maximum near 17.5 MeV ($\Gamma \approx 5$ MeV), σ(max) ≈ 50 μb (1953MI31). Evidence is also reported for excited states of ^{16}O*((14.2), 16.75, 17.3, 22.6, (23.15), and 24.6) with $J = 2^+$; $T = 0$ (1954ST89). See also (1955HA1D, 1955TI1A, 1956DA1C) and (1955AJ61).

31. ^{16}O(γ, 4α) $\qquad Q_{\rm m} = -14.429$

The cross section for production of 4-pronged stars shows a number of maxima: see Table 16.9 (1952GO1A, CO54I, 1956DA1C). An appreciable fraction of the stars appear to involve excited states of ^{12}C and ^{8}Be (1955AJ61, 1956DA1C: see, however, (1953MI31)). See also (1955RA1E, 1955HA1D) and (1955AJ61).

32. (a) ^{16}O(γ, nα)^{11}C $\qquad Q_{\rm m} = -25.870$

(b) ^{16}O(γ, t)^{13}N $\qquad Q_{\rm m} = -25.020$

Table 16.8: Levels in ^{16}O from ^{16}O(γ, n)^{15}O

E_γ (MeV)			
(1955PE1D)	(1954KA1A)	(1955BA1P, 1957BA27)	(1955CO1C, 1958BE74)
15.85	15.9 [a]	(15.8)	15.93 [b]
16.03		16.03	16.17 [b]
16.47	16.4	16.50	16.37 [c]
16.75	16.7	(16.7)	
16.95	16.9	16.82	16.84 [c]
17.02		17.04	
17.13	17.1		
17.18			
17.55			
17.68			
17.84			
18.04			
18.70			
19.01	18.9		
19.18	19.3		
20.33			
20.58			
20.79	20.7		
20.93			
21.21			
21.52	21.54 ± 0.05		
	21.96 ± 0.05		
22.37			
22.54			
22.76			
23.02			

[a] See also (1958KA1D).
[b] (1958BE74).
[c] (1955CO1C).

Table 16.9: Maxima in ^{16}O(γ, 4α) [a]

E_γ (MeV)		
(1952GO1A)	(1956DA1C)	(CO54I)
22.6	22.5	23.2
25.8	(26.0)	24.7
	(27.5)	27.2
29.5	(29.5)	29.2
	32.5	
	(35.2)	

[a] Maxima in number of 4-pronged stars.

See (1955SC36, 1957ER24).

33. ^{16}O(γ, γ')^{16}O*

Measurement of the resonance scattering cross section for 6.9 and 7.1 MeV γ-rays from ^{19}F(p, α)^{16}O yields mean lifetimes of $(1.2 \pm 0.3) \times 10^{-14}$ and $(1.0 \pm 0.3) \times 10^{-14}$ sec for ^{16}O*(6.92 and 7.12), respectively. Values obtained from self absorption measurements are consistent with these. The observed life of the $7.1 \rightarrow$ g.s., E1 transition is consistent with an isobaric spin inhibition of the order of 300 (see (1955MA1K)). The lifetime of the 6.9 MeV state is longer than that expected from a collective model but can be accounted for by one version of the α-particle model (1957SW17). See also (1956KA1D, 1957GR1G; theor.) and ^{19}F(p, α)^{16}O.

34. ^{16}O(e, e')^{16}O*

Elastic scattering angular distributions at $E_e = 240$, 360, and 420 MeV strongly favor a shell-model charge distribution based on a harmonic well with a length parameter $a = (1.76 \pm 0.02) \times 10^{-13}$ cm. The rms radius of the charge distribution is 2.70×10^{-13} cm (1958EH1B); see also (1956FE1B, 1957HO1E, 1958FE1D, 1958RA43).

35. ^{16}O(n, n')^{16}O*

At $E_n = 7.06$ MeV, a 6.094 ± 0.06 MeV γ-ray is observed with a cross section of 104 ± 25 mb (1956DA23). See also (1954TH42, 1955BE1H).

36. ^{16}O(p, p′)^{16}O*

At $E_{\rm p} = 19$ MeV, proton groups are observed corresponding to ^{16}O*(6.14, 7.02, 8.87, 9.85, 10.34, 11.08, 11.51, 12.02, 12.53, 13.06, and (13.39) MeV) (± 30 keV). Of these, three have not been reported elsewhere: ^{16}O*(11.08, 12.02, 13.39). The level at 11.08 MeV decays via cascade through the 6 to 7 MeV states; it is presumably not to be identified with the (doubtful) 11.10 MeV state reported by (1954BI96) in ^{12}C(α, α)^{12}C since the 10 keV width of the latter would preclude observation of the γ-decay. If it is a pure γ-emitting state, $J = 2^-$ is favored. The 12.02 MeV state appears to give weak γ-radiation; the state at 12.53 MeV yields 4.4 MeV γ-rays via ^{16}O(p, p′α)^{12}C* as expected from its behavior in $^{15}{\rm N}+{\rm p}$. The 8.87 MeV state cascades 80% via ^{16}O*(6.1) and 20% via ^{16}O*($6.9 - 7.1$) (1955HO68).

At higher bombarding energies, evidence is reported for the excitation of states at 6 to 7, 12.5, and ≈ 20 MeV (1956ST30, 1957TY36: $E_{\rm p} = 96$ and 177 MeV). The elastic scattering at high energies is generally characterized by direct interaction and may be described in terms of the optical model: see (1953BU72, 1955FU1A, 1955KI43, 1956BU95, 1956KI54, 1957CH32, 1957GI14, 1957VA1B). Polarization of scattered protons has been studied at $E_{\rm p} = 173$ MeV by (1957AL39, 1957HI98, 1957MA58). See also (1955KO1A, 1957JA1B, 1958MA1B, 1958TY49).

37. ^{16}O(d, d)^{16}O

See ^{18}F.

38. ^{16}O(α, α')^{16}O*

Both elastic and inelastic scattering distributions (^{16}O*($6 - 7$, 8.8)) have been studied at $E_\alpha = 19$ MeV by (1957CO1H, 1958CO59). The elastic scattering shows strong diffraction effects.

39. ^{17}O(p, d)^{16}O $\qquad Q_{\rm m} = -1.919$

Not reported.

40. ^{17}O(d, t)^{16}O $\qquad Q_{\rm m} = 2.113$

Not reported.

41. ^{17}O(^{3}He, α)^{16}O $\quad Q_{\rm m} = 16.432$

Not reported.

42. ^{18}O(p, t)^{16}O $\quad Q_{\rm m} = -3.730$

Not reported.

43. ^{19}F(p, α)^{16}O $\quad Q_{\rm m} = 8.119$

$Q_0 = 8.110 \pm 0.010$ (1956SQ1A).

Levels derived from observed α-particle groups are listed in Table 16.10 (1956SQ1A, 1957YO04: see also (1952AJ38)). There is some evidence for a broad level near 9.58 MeV (compare ^{12}C(α, α)^{12}C) and for two additional unidentified groups which may represent levels near 11 MeV (see ^{15}N(d, n)^{16}O); no other groups appear with intensity > 5% of that corresponding to ^{16}O*(8.87) (1956SQ1A). (1957YO04) find no other groups corresponding to ^{16}O*($6 - 9$) with dσ/d$\Omega > 0.4$ mb/sr. The indicated assignments for the first five states derive from a variety of evidence; see (1955AJ61).

6.06-MeV state

$W_\pi = 6.065 \pm 0.009$ MeV (1956AL1G). The angular correlation of the monopole pairs is given by $W(\theta) = 1 + (0.955 \pm 0.007)\cos\theta$, consistent with $J = 0^+ \rightarrow 0^+$ (1955GO1E, 1958AR1B: see also (1954DE36)). The mean life is $(7.2 \pm 0.7) \times 10^{-11}$ sec, considerably longer than is given by the α-model (1954DE36). Calculations on various models are summarized by (1957GR1G); see also (1956EL1C, 1957EL1B, 1957FE1D).

6.14-MeV state

The mean life is $(1.2 \pm 0.6) \times 10^{-11}$ sec (1958KO63), 0.5 to 1×10^{-11} sec (1955DE51). This transition rate is somewhat faster than that predicted on the α-particle model (1956KA1D) and is an order of magnitude faster than indicated by shell-model calculations (1957EL1B). It accounts for about one third of the total E3 width to the ground state from $T = 0$ states (1958KO63). See also (1958KN1B).

6.92-MeV state

$E_\gamma = 6.97 \pm 0.05$ MeV (1955BE62: Doppler corrected). The mean life is $\leq 2.5 \times 10^{-14}$ sec (1956DE22: see also (1955DE51)). Compare ^{16}O(γ, γ')^{16}O*: (1957SW17).

7.12-MeV state

Table 16.10: ^{16}O levels from ^{19}F(p, α)^{16}O

A		B		
E_x (MeV)	Γ (keV)	E_x (MeV)	$\frac{d\sigma}{d\Omega}$ [a]	J^π
0	< 20	0		0^+
6.051 ± 0.010	< 20	6.058 ± 0.017	0.1	0^+
6.131 ± 0.010	< 20	6.138 ± 0.011	0.8	3^-
6.920 ± 0.010	< 20	6.926 ± 0.011	1	2^+
7.120 ± 0.010	< 20	7.122 ± 0.011	2	1^-
8.874 ± 0.012	< 20	8.882 ± 0.011	0.6	2^-
9.852 ± 0.012	< 20			
10.363 ± 0.014	$\approx 25 - 30$			
11.085 ± 0.014	$\approx 25 - 30$			

A: (1956SQ1A): $E_p = 7$ MeV.
B: (1957YO04): $E_p = 5.2$ MeV; E_x calculated from reported Q-values and Q_m.
[a] Cross sections in mb/sr at $\theta = 180°$.

The mean life is $\leq 1.2 \times 10^{-14}$ sec (1955DE51); compare ^{16}O(γ, γ')^{16}O*: (1957SW17). A search for circular polarization of the γ-ray yields an upper limit of 2.0×10^{-3} indicating a maximum of $F^2 = 3 \times 10^{-8}$ for the intensity of any parity non-conserving part of the wave function (1958WI41).

8.87-MeV state

The direct ground state transition is 7 ± 2 % (1957BE61), 9 ± 4 % (1957MC35), 0.6% (1957WA1B) of the cascade decays. The cascade decays take place via the 6.14, 6.92, and 7.12 MeV states with relative intensities 27 : 1 : 3. The three γ-rays have energies 2.75 ± 0.02, 1.90 ± 0.03, and 1.72 ± 0.03 MeV, fixing the energy of the state as 8.87 ± 0.02 MeV. The observed branching ratios, together with the absence of α-decay fix the assignment as $J^\pi = 2^-$ (1956WI1A, 1957MC35). The separation of this state from the nearest 2^+ state (^{16}O*(9.85)) is too large to be accounted for in the α-model of (1954DE1E) (1956WI1A: see also (1956KA1D)).

10.94-MeV state

At $E_p = 5.77$ MeV, a γ-ray of energy 3.86 ± 0.03 MeV is observed in coincidence with the 7.1 MeV radiation, indicating a level energy of 10.98 ± 0.04 MeV. It is presumed that this level is to be identified with one of the unassigned groups observed by (1956SQ1A, 1957BE61). The direct ground state decay is < 5% and cascades via ^{16}O*(6.0, 6.1, 6.9, and 8.9) are less than 1, 6, 20, and 40%, respectively. The strong branch to ^{16}O*(7.1), $J = 1^-$, and the weakness of other branches suggests $J(10.94) = 0^-$, although 1^+ is not excluded. The γ-γ correlation favors $J = 0^-$ (1957BE61: see also ^{15}N(d, n)^{16}O). ((1957WA1B) find the γ-ray energy to be 3.86 ± 0.02 MeV and report a weak 4.9 MeV γ-ray). A search for possible nuclear pairs from the $0^- \rightarrow 0^+$ ground-state transition yielded an upper limit of $< 2 \times 10^{-5}$ for the pair branch (1958EK36). The importance of a definitive assignment of J^π for this state is stressed by (1957EL1B).

The influence of isobaric spin selection rules on cascade decays in ^{16}O has been discussed by (1953WI1E, 1956WI1D: see also (1955MA1K, 1955MA1L)). At $E_{\rm p} = 18.5$ MeV, the α_0 angular distribution has been studied by (1956LI37): see ^{19}F.

The reaction exhibits a large number of resonances: see ^{20}Ne. See also (1956IS1A, 1957BI75, MO57C, 1958MO1J).

^{16}F

(Not illustrated)

Mass of ^{16}F: From the threshold of the ^{14}N(^{3}He, n)^{16}F reaction and the Wapstra (1955WA1A) masses for ^{14}N, ^{3}He and n, the mass excess of ^{16}F is 15.63 ± 0.02 MeV. A semi-empirical computation of the level shifts of the low $T = 1$ levels of ^{16}N and ^{16}O suggests that the ground state of ^{16}F should have $J = 0^-$, and be unstable to proton emission by about 1 MeV (1957EL1B). Using the $(M - A)$ stated above, ^{16}F is unstable with respect to proton emission by 0.81 MeV. The binding energies of a deuteron, a ^{3}He-particle, and an α-particle in ^{16}F are, respectively, 10.24, 9.37 and 8.98 MeV.

1. ^{14}N(^{3}He, n)^{16}F $\qquad Q_{\rm m} = -1.18$

A slow neutron threshold has been observed at $E(^3\text{He}) = 1.434 \pm 0.015$ MeV corresponding to the ground state of ^{16}F ($Q_0 = -1.18 \pm 0.01$ MeV). There is some indication of another threshold corresponding to an excited state at ≈ 60 keV. The lifetime of ^{16}F for decay into ^{15}O + p is computed to be $\approx 10^{-19}$ sec (H. Bichsel, private communication). See also (1956BU22).

2. ^{16}O(p, n)^{16}F $\qquad Q_{\rm m} = -16.41$

See ^{17}F.

3. ^{16}O(^{3}He, t)^{16}F $\qquad Q_{\rm m} = -15.61$

Not reported.

References

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References are arranged and designated by the year of publication followed by the first two letters of the first-mentioned author's name and then by two additional characters. Most of the references appear in the National Nuclear Data Center files (Nuclear Science References Database) and have NNDC key numbers. Otherwise, TUNL key numbers were assigned with the last two characters of the form 1A, 1B, etc. In response to many requests for more informative citations, we have, when possible, included up to ten authors per paper and added the authors' initials.

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