Energy Levels of Light Nuclei
$A = 15$

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Abstract: An evaluation of $A = 5$–24 was published in *Nuclear Physics* 11 (1959), p. 1. This version of $A = 15$ differs from the published version in that we have corrected some errors discovered after the article went to press. Figures and introductory tables have been omitted from this manuscript. Reference key numbers have been changed to the NNDC/TUNL format.

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^{15}C
(Fig. 28)

GENERAL:

Mass of ^{15}C: From the Q of the ^{14}C(d, p)^{15}C reaction given by (1956DO41) ($Q_0 = -1.007 \pm 0.001$ MeV), and using the Wapstra masses for ^{14}C, d and ^{1}H, the mass excess of ^{15}C is 14.305 ± 0.005 MeV. Application of Coulomb corrections indicates an excitation of 11.72 to 11.87 MeV for the first $T = \frac{3}{2}$ state of ^{15}N (1956BA16, 1956DO37, 1957MU99).

1. ^{15}C(β^-)^{15}N $\qquad Q_m = 9.777$

The half-life is 2.25 ± 0.05 sec. The β-spectrum is complex, with 32 ± 2 % of transitions ($\log ft = 6.0$) to the ^{15}N ground state (E_β(max) $= 9.82 \pm 0.04$ MeV) and 68% ($\log ft = 4.1$) to the upper of the 5.3 MeV levels of ^{15}N. A 5.299 ± 0.006 MeV γ-ray is observed (1959AL1M): no other γ-rays with $E_\gamma > 5.3$ MeV are observed with intensities > 5%, and the intensity of a 1.9 MeV γ-ray (expected if the ^{15}N*(7.16) level were involved) is < 10% (1956DO37). The internal pair conversion coefficient of the 5.30 MeV γ-ray is consistent with E1. All data are consistent with $J = \frac{1}{2}^+$ for the 5.305 MeV state in ^{15}N and $J = \frac{1}{2}^+$ for ^{15}C (1959AL1M). See also (1955AJ61, 1956BA16, 1956DO37).

2. ^{9}Be(^{7}Li, p)^{15}C $\qquad Q_m = 9.098$

At $E(^7$Li$) = 2.0$ MeV ($\theta = 90°$) proton groups are observed corresponding to the ground state of ^{15}C and to excited states at 0.62 ± 0.06, 2.48 ± 0.05, 3.08 ± 0.04, 4.26 ± 0.04, 5.93 ± 0.04, 6.58 ± 0.04, and 8.16 ± 0.06 MeV. The ground state Q is 9.04 ± 0.05 MeV (1957MU99). In an earlier experiment, (1957NO14) found $Q_0 = 9.05 \pm 0.05$ and $Q_1 = 8.35 \pm 0.05$ MeV ($E_x = 0.70 \pm 0.05$ MeV). Calculation of Coulomb and (n $-$ ^{1}H) energy difference places the analogue state of ^{15}N at 11.72 to 11.87 MeV. Identification with the known $J = \frac{1}{2}^+$; $T = \frac{3}{2}$ level of ^{15}N at 11.61 MeV supports $J = \frac{1}{2}^+$ for ^{15}C$_{\rm g.s.}$ (1956BA16, 1957MU99, 1957NO14).

3. ^{14}C(d, p)^{15}C $\qquad Q_m = -1.007$

$Q_0 = -1.007 \pm 0.001$ (1956DO41).

Identification of ^{15}C$_{\rm g.s.}$ with ^{15}N*(11.62), $J^\pi = \frac{1}{2}^+$; $T = \frac{3}{2}$, is suggested by (1956BA16). Proton groups corresponding to the ground state and to levels at 0.7 ± 0.1 and 6.2 ± 0.15 MeV are reported by (1958MO95). The weak activity previously reported at $E_d < 1.3$ MeV, indicating a $Q \approx 0.1$ MeV (see (1955AJ61)), is now attributed to contamination (1956BO1L). See also ^{16}N.

Table 15.1: Energy levels of ^{15}C

E_x (MeV $\pm$ keV)	J^π	$\tau_{1/2}$	Decay	Reactions
0	$(\frac{1}{2}^+, \frac{3}{2}^+)$	2.25 ± 0.05 sec	β^-	1, 2, 3
0.66 ± 50				2, 3
2.48 ± 50				2
3.08 ± 40				2
4.26 ± 40				2
5.93 ± 40				2
(6.2 ± 150)				3
6.58 ± 40				2
8.16 ± 60				2

4. ^{14}C(n, γ)^{15}C $\qquad Q_m = 1.220$

The capture cross section is < 1 μb (1951YA1A, 1955HU1B, 1958HU18).

The following reactions leading to ^{15}C are not reported: ^{13}C(t, p)^{15}C ($Q_m = 0.909$), ^{14}C(t, d)^{15}C ($Q_m = -5.039$), ^{14}C(α, ^{3}He)^{15}C ($Q_m = -19.358$), ^{15}N(n, p)^{15}C ($Q_m = -8.994$), ^{18}O(n, α)^{15}C ($Q_m = -5.024$).

^{15}N
(Fig. 29)

GENERAL:

Theory: See (1956KA1C, 1957FE1A, 1957HA1E, 1957PE1D, 1958FR1C).

1. ^{9}Be(^{7}Li, n)^{15}N $\qquad Q_m = 18.092$

See (1957NO17).

2. ^{11}B(α, n)^{14}N $\qquad Q_m = 0.152 \qquad E_b = 10.993$

Reported resonances are listed in Table 15.3 (1954BE08, 1954TR09, 1955SH46, 1956BO61, 1958HA1B: see also (1950HO80)). Some absolute cross sections are given by (1956BO61). See also ^{14}N.

Table 15.2: Energy levels of ^{15}N

E_x (MeV ± keV)	J^π	Γ (keV)	Decay	Reactions
0	$\frac{1}{2}^-$	–	stable	1, 5, 11, 16, 19, 20, 27, 28, 31, 32, 33, 34, 36, 37, 38
5.276 ± 6	$\leq \frac{7}{2}^+$		γ	5, 11, 16, 19, 20, 27, 32
5.305 ± 6	$\frac{1}{2}^+, \frac{3}{2}^+$		γ	5, 11, 16, 19, 20, 27, 32
6.328 ± 6	$\leq \frac{5}{2}^-$		γ	5, 11, 16, 20, 27, 32, 34
7.164 ± 6	$\leq \frac{7}{2}^+$		γ	13, 20, 27
7.309 ± 6	$\frac{1}{2}^+, \frac{3}{2}^+$		γ	16, 20, 27
7.572 ± 8	$\leq \frac{7}{2}^+$		(γ)	16, 27
8.316 ± 6	$\frac{1}{2}^+, \frac{3}{2}^+$		γ	20, 27
8.575 ± 8	$\leq \frac{7}{2}^+$		γ	20, 27
9.062 ± 10	$\frac{1}{2}^+, \frac{3}{2}^+$		γ	20, 27
9.165 ± 10			γ	20, 27
9.834 ± 10			(γ)	27
10.069 ± 10	$\leq \frac{5}{2}^-$		γ	27
10.458 ± 10			γ	13, 27
10.548 ± 10	$\frac{5}{2}, \frac{7}{2}$		γ	13, 27
10.710 ± 10	$\frac{3}{2}^+$		γ	13, 14, 27
10.815 ± 10	$\frac{3}{2}^-$		γ	13, 27
11.243 ± 10	$> \frac{1}{2}^-$	3.3	n	21, 27
11.299 ± 10	$\frac{1}{2}^-$	5.5 ± 1	γ, n, p	13, 15, 21, 23
11.438 ± 10	$\frac{1}{2}^+$	40 ± 3	γ, n, p, α	2, 13, 15, 21, 23
11.61	$\frac{1}{2}^{+\,a}$	450	γ, n, p	13, 15, 30
11.773 ± 10	$\frac{3}{2}^+$	39 ± 3	n, p, α	2, 15, 21, 23
11.885 ± 10	$\frac{3}{2}^-$	20 ± 2	n, p, α	2, 15, 21
11.950 ± 10	$> \frac{1}{2}$	≤ 3	n, α	2, 21
11.972 ± 10	$\frac{1}{2}^-$	16	n, p, α	15, 21
12.103 ± 10	$\frac{5}{2}$	19 ± 5	n, p, α	2, 3, 15, 21
12.152 ± 10	$\frac{3}{2}$	49	n, p, α	2, 3, 15, 21, 23, 24
12.333 ± 10	$\frac{5}{2}$	21 ± 3	n, p, α	15, 21
12.502 ± 10	$\frac{5}{2}^+$	28	n, p, α	2, 3, 15, 21, 24
12.928 ± 10	$\frac{3}{2}^-$	60	n, p, α	3, 15, 21
12.93	$\frac{7}{2}^-$	30	p, α	3
13.15		< 2	n, p, α	2, 3

Table 15.2: Energy levels of ^{15}N (continued)

E_x (MeV $\pm$ keV)	J^π	Γ (keV)	Decay	Reactions
13.18		6	n, p, α	2, 3
13.36	$\frac{3}{2}^-$	20	n, α	2, 3
13.41	$\frac{5}{2}^+$	30	p, α	3
13.61	$(\frac{5}{2}^-)$	15	n, α	2, 3
13.71		30	n, α	2
13.85		50	n, α	2
14.08		≈ 7	n, α	2
14.17		25	n, α	2
14.63		53	n, α	2
14.90			n, α	2
15.01			n, α	2
15.08			n, α	2
15.29			n, α	2
15.37			n, α	2
15.61			n, α	2
15.92			n, α	2
15.93			n, α	2
15.99			n, α	2
16.04			n, α	2
16.47			p	7
16.72		≈ 90	n, p, d	6, 7
16.90		≈ 350	n, d	6
17.11		broad	d, α	9
17.24		≈ 170	t, d	8
17.37		≈ 350	p, α, t, d, n	6, 7, 8, 9
17.58		≈ 170	t, d	8
17.70		≈ 500	d, n, α	6, 9
17.72		48 ± 9	p, α, d, t	7, 8, 9
18.07		19 ± 4	α, d	9
18.09		≈ 45	p, d, t	7, 8
18.28		230 ± 60	n, p, α, d	6, 7, 9
19.16		≈ 130	n, d	6

[a] $T = \frac{3}{2}$.

3. ^{11}B(α, p)^{14}C $Q_{\rm m} = 0.780$ $E_{\rm b} = 10.993$

Reported resonances are listed in Table 15.3 (1955SH46, 1958LE23, 1959LE28). Angular distributions of the ground state protons have been measured at 150 energies in the range $E_\alpha = 2$ to 4 MeV. The assignment $J = \frac{5}{2}^+$ to ^{15}N*(12.50) agrees with an independent determination in ^{14}N(n, n)^{14}N (1958LE23). Partial widths for several resonances are listed by (1959LE28). See also ^{14}C.

4. ^{12}C(t, p)^{14}C $Q_{\rm m} = 4.634$ $E_{\rm b} = 14.848$

See (1951PO1A).

5. ^{12}C(α, p)^{15}N $Q_{\rm m} = -4.965$

Proton groups have been observed corresponding to the ground state of ^{15}N and to ^{15}N*(5.4, 6.5) and to other unresolved excited states up to $E_{\rm x} \approx 13.5$ MeV (1951BU1D, 1951BU1E, 1957SH1C). Angular distributions have been studied at $E_\alpha = 30.5$ MeV (1957HU1E) and 41.5 MeV (1957SH1C). They all show strong anisotropic structure typical of direct interaction. The ground state angular distribution is qualitatively similar to that of the inverse reaction. An excellent fit is obtained to the data $> 30°$ under the assumption l (triton) $= 1$, $R = 5.10 \times 10^{-13}$ cm (1957SH1B, 1957SH1C: see also (1957BU52)).

6. ^{13}C(d, n)^{14}N $Q_{\rm m} = 5.319$ $E_{\rm b} = 16.161$

Observed resonances are displayed in Table 15.4 (1950RI57, 1955MA76). Absolute cross sections are given by (1955MA76). See also ^{14}N and (1957JA37).

7. ^{13}C(d, p)^{14}C $Q_{\rm m} = 5.947$ $E_{\rm b} = 16.161$

Observed resonances are displayed in Table 15.4 (1941BE1A, 1950CU13, 1953KO42, 1956MA46). Angular distributions have been measured at a number of energies in the range $E_{\rm d} = 0.3$ to 2.8 MeV (1953KO42, 1956KO26, 1956MA46, 1956VA17). At most energies some stripping contribution is observed, although compound nucleus formation appears to be quite important for $E_{\rm d} < 3$ MeV (1956MA46). There is some disagreement on absolute cross sections; see (1953KO42, 1956MA46, 1956VA17, 1957HO63). See also ^{14}C.

Table 15.3: Resonances in $^{11}B + \alpha$

E_α (MeV)	Γ_{lab} (keV)	Particle out	E_x (MeV)	J^π	Ref.
0.60		n	11.43		a
1.03		n	11.75		a
1.18		n	11.86		a
1.30		n	11.95		a
1.51		n, p	12.10		b
1.58		n, p	12.15		b
2.06	66	n_0, p_0	12.50	$\frac{5}{2}^+$	c
2.63	80	n_0, p_0	12.92	$\frac{3}{2}^-$	d
2.64	40	p_0	12.93	$\frac{7}{2}^-$	e
2.94	< 3	n_0, p_0	13.15		d
2.99	8	n_0, p_0	13.18		d
3.23	29	n_0, p	13.36	$\frac{3}{2}^-$	d
3.30	40	p	13.41	$\frac{5}{2}^+$	e
3.56	20	n_0, p	13.61	$(\frac{5}{2}^-)$	d
3.71	40	n_0	13.71		f
3.90	70	n_0, (n_1)	13.85		f
4.21	≈ 10	n_0, n_1	14.08		f
4.33	35	n_0	14.17		f
4.96	72	n_0	14.63		f
5.34		n_0	14.90		g
5.49		n_0	15.01		g
5.58		n_0	15.08		g
5.86		n_0	15.29		g
5.98		n_0, n_2	15.37		g
6.30		n_0, (n_2)	15.61		g
6.72		n_0, (n_2)	15.92		g
6.74		n_0, n_2	15.93		g
6.82		n_0, n_2	15.99		g
6.89			16.04		g

[a] (1954BE08), and private communication.
[b] (1955SH46).
[c] (1955SH46, 1956BO61, 1958HA1B, 1958LE23, 1959LE28).
[d] (1956BO61, 1958HA1B, 1958LE23, 1959LE28).
[e] (1959LE28).
[f] (1956BO61, 1958HA1B).
[g] (1958HA1B).

Table 15.4: Resonances in ^{13}C + d

E_d (MeV)	Emitted particles	Γ (keV)	^{15}N* (MeV)	References
0.37	p		16.47	(1956VA17)
0.64	n, p_0	≈ 100	16.72	(1950CU13, 1950RI57, 1953KO42, 1956MA46, 1956VA17)
0.85	n	≈ 400	16.90	(1950RI57)
1.10	α_0	broad	17.11	(1956MA35)
1.24 ± 0.04	t_0	≈ 200	17.24	(1956MA35)
1.40 ± 0.04	p_0, α_0, t_0	≈ 400	17.37	(1956MA35, 1956MA46)
1.55 [a]	n	≈ 100		(1941BE1A, 1950RI57)
1.64 ± 0.04	t_0	≈ 200	17.58	(1956MA35)
1.78 ± 0.05	n, α_0	≈ 600	17.70	(1950RI57, 1955MA76, 1956MA35)
1.80 ± 0.01	(p_0), α_1, t_0	55 ± 10	17.72	(1956MA35, 1956MA46)
2.20 ± 0.01	α_0, α_1	22 ± 4	18.07	(1956MA35)
2.23 ± 0.02	p_0, t	≈ 50	18.09	(1956MA35, 1956MA46)
2.45 ± 0.03	n, p_0, α_0	270 ± 70	18.28	(1955MA76, 1956MA35, 1956MA46)
3.46 ± 0.03	n	≈ 150	19.16	(1955MA76)

[a] Possibly to be identified with 1.40 MeV resonance (1956MA35).

8. ^{13}C(d, t)^{12}C $Q_m = 1.313$ $E_b = 16.161$

Observed resonances are listed in Table 15.4. Angular distributions and absolute cross sections are reported (1956MA35). See also ^{12}C.

9. ^{13}C(d, α)^{11}B $Q_m = 5.167$ $E_b = 16.161$

Observed resonances are listed in Table 15.4. Angular distributions and absolute cross sections are reported. Analysis of the narrow $E_\alpha = 2.2$ MeV resonance suggests that it is formed by $l_d = 3$ or 4 (1956MA35). See also ^{11}B.

10. ^{13}C(t, n)^{15}N $Q_m = 9.903$

Not reported.

Table 15.5: Low-energy ^{14}C(p, γ)^{15}N resonances [a]

E_p (keV)	^{15}N* (MeV)	$\omega\Gamma_p$ (eV)	$\omega\Gamma_{\gamma 0}$ (eV)	$\omega\Gamma_{\gamma 5}$ (eV)	$\omega\Gamma_{\gamma 3,4}$ (eV)	l_p	J^π
261	10.458	$\approx 5 \times 10^{-4}$ [b]	$\approx 1 \times 10^{-4}$	$\approx 4 \times 10^{-4}$	$\approx 1 \times 10^{-4}$	≤ 4	
351	10.542	≥ 0.04	$\leq 3 \times 10^{-4}$	0.018 [d]	0.025 [e]	≤ 3	$(\frac{5}{2}^{\pm}, \frac{7}{2}^{-})$
527	10.706	≈ 200 [c]	0.36	0.18		2	$\frac{3}{2}^{+}$
634	10.806	≈ 0.4 [b]	0.11	0.04			

[a] (1957HE1C, 1958HE48, 1959HE1D); see also Table 15.6.

[b] Estimated from γ-intensities in ^{14}N(d, p)^{15}N: see (1958RA13).

[c] $\theta_p^2 \approx 0.2$ (1957HE1C, 1959HE1D).

[d] To ^{15}N*(5.28).

[e] To ^{15}N*(7.16). The ground state transition ($7.16 \to 0$) is 3 times as strong as ($7.16 \to 5.28$) (1959HE1D).

11. ^{13}C(^{3}He, p)^{15}N $\qquad Q_m = 10.668$

Proton groups have been observed corresponding to the ground state of ^{15}N and to the levels at 5.3 MeV (unresolved) and 6.3 MeV; $E(^3\text{He})$ to 4.5 MeV. Angular distributions show strong forward and backward peaking, roughly symmetric about $90°$, and may indicate either compound nucleus formation or exchange stripping (1956SC01, 1957IL01, 1957JO1B). See also (1957BR18) and ^{16}O.

12. ^{13}C(α, d)^{15}N $\qquad Q_m = -7.683$

Not observed.

13. ^{14}C(p, γ)^{15}N $\qquad Q_m = 10.214$

Resonances for capture γ-radiation are listed in Tables 15.5 and 15.6. The energies of the first four resonances (Table 15.5) agree well with level energies derived from ^{14}N(d, p)^{15}N (1958HE48, 1959HE1D); corresponding values given by (1955BA44) are 8 to 10 keV higher. Quoted limits on l_p in Table 15.5 are based on estimates of Γ_p. The assignment $\frac{3}{2}^{+}$ to ^{15}N*(10.71) is based on ^{14}C(p, p)^{14}C (1958HE48, 1959HE1D); the assignment $\frac{3}{2}^{-}$ gives a more satisfactory account of the p, γ_0 angular distribution both for this level and for ^{15}N*(10.81) (1955BA44); $J = \frac{3}{2}^{+}$ is, however, not excluded for either (1957BA18). Combination of ^{15}N*(10.81) and ^{15}N*(9.84) permits a good acc-

Table 15.6: Resonances in ^{14}C(p, γ_0)^{15}N and ^{14}C(p, n)^{14}N

E_p [a] (keV)	Yields [b] 10^{-11} γ/p	10^{-8} n/p	Γ [b] (keV)	Γ_n [b] (keV)	Γ_p [b] (keV)	Γ_α [a] (keV)	Γ_{γ_0} [b] (eV)	J^π [b]	l_n	θ_n^2 [c]	l_p	θ_p^2 [c]	E_x (MeV)
361	0.01						(< 0.004) [h]						10.551
537	5.7						(0.12) [h]	$(\frac{3}{2}^-)$ [h]					10.715
646	0.49						(0.010) [h]	$(\frac{3}{2}^-)$					10.817
1163 ± 2	3.1	20	12	1.6	10.4	0	0.29	$\frac{1}{2}^-$ [e]	1	0.002	1	0.04	11.299
1312 ± 3	7.9	120	43 ± 5 [d]	24.4	15.0	0	2.4	$\frac{1}{2}^+$ [f]	0	0.01	0	0.007	11.438
1500	49	88	520 [d]	18.4	506		26.3	$\frac{1}{2}^+$ [g]	0	0.001	0	1.0	11.61
1668 ± 3		17	37	36.5	0.5	0		$\frac{3}{2}^+$	0	0.01	2	0.004	11.771
1788 ± 3		1.5	24.5	24.5	0.03	0.05		$\frac{3}{2}^-, (\frac{5}{2}^-)$	1	0.01	3	0.003	11.883
1884 ± 3		5.6	21.5	21.2	0.3	0.26		$\frac{1}{2}^-$	1	0.009	1	0.0004	11.972
2025 ± 4		40	18	17.2	0.8	0.6		$\frac{5}{2}^{(-)}$ [e]	1	0.007	3	0.05	12.104
2079 ± 4		290	53	38	15	2.2		$\frac{3}{2}^{(+)}$ [e]	0	0.008	2	0.06	12.154
2272 ± 4		10	22	21.7	0.3	0.1		$\frac{5}{2}^{(+)}$	2	0.007	2	0.0009	12.335
2450 ± 4			34 ± 4	28	0.3	5.5		$(\frac{3}{2})$					12.501
2908 ± 4			71 ± 5										12.928

[a] (1956SA06).
[b] (1955BA44): see comparable values in (1951RO16, 1956SA06).
[c] θ^2 as defined by (1955BA44).
[d] (1956FE1C).
[e] See also (1953KA1A).
[f] Assignment from ^{14}N(n, n)^{14}N: see also (1953KA1A).
[g] $T = \frac{3}{2}$.
[h] Compare Table 15.5.

ount of the low energy (n, n) and (n, γ) cross sections (1959HE1D). The thermal (n, p) cross section can be ascribed to the $E_p = 1.5$ MeV resonance (^{15}N*(11.61)) (1955BA44: see also ^{14}N(n, γ)^{15}N).

Strong interference effects in the (p, γ) yield curve indicate that the $E_p = 1.31$ and 1.50 MeV states have the same J^π (the former is given as $\frac{1}{2}^+$ from ^{14}N(n, n)^{14}N) and that the $E_p = 1.16$ MeV state has opposite (odd) parity: $J = \frac{1}{2}^-, \frac{3}{2}^-$; $J = \frac{1}{2}^-$ is favored by σ(n, n).

The $E_p = 1.66$ MeV state has even parity. Assignments for these four levels indicated in Table 15.6 are consistent with the ^{14}C(p, n)^{14}N results (1955BA44: see also (1953KA1A)). The state at $E_p = 1.50$ MeV probably has $T = \frac{3}{2}$ and corresponds to ^{15}C$_{\rm g.s.}$ (1955BA44, 1956BA16: see ^{14}C(p, n)^{14}N). See also (1954SP1B, 1956FE1C).

14. ^{14}C(p, p)^{14}C $\qquad E_b = 10.214$

Elastic scattering has been studied for $E_p = 340$ to 690 keV. At the $E_p = 527$ keV resonance (see Table 15.5), the scattering is consistent with d-wave formation of a $J = \frac{3}{2}^+$ state, $\Gamma_p = 0.2$ keV. No anomalies are observed at $E_p = 351$ or 635 keV (1958HE48, 1959HE1D).

15. ^{14}C(p, n)^{14}N $\qquad Q_m = -0.628 \qquad E_b = 10.214$

Resonances reported by (1951RO16, 1953KA1A, 1954BA1C, 1955BA44, 1956SA06) are listed in Table 15.6: see also (1959GI47). Neutron distributions are essentially isotropic at the $E_p = 1.16$, 1.31 and 1.50 MeV resonances and agree with the assignments derived from ^{14}C(p, γ)^{15}N and ^{14}N(n, n)^{14}N; the distribution at $E_p = 1.67$ MeV favors $J = \frac{3}{2}$. At $E_p = 1.79$ MeV, the distributions favor $\frac{5}{2}^-$, but $\frac{3}{2}^-$ is not excluded (1955BA44: see also (1953KA1A)); a computation of the cross section favors $J = \frac{3}{2}$ (1956SA06). At $E_p = 1.88$ MeV, the angular distribution is consistent with the $J = \frac{1}{2}^-$ assignment from ^{14}N(n, n)^{14}N and at $E_p = 2.02$ MeV the appearance of a $P_4(\cos\theta)$ term supports the assignment $J = \frac{5}{2}$, excluding $J = \frac{5}{2}^+$ (1955BA44: compare Table 15.7). Parities of this and the next two states disagree with ^{14}N(n, n)^{14}N results. The $E_p = 2.27$ MeV state has $J = \frac{3}{2}$ or $\frac{5}{2}$; the $\sigma_{\rm nn}$ clearly indicates the latter (1955BA44, 1956SA06).

For ^{15}N*(11.61) ($E_p = 1.50$ MeV), the proton reduced width indicates a single-particle level, while the neutron reduced width is only 10^{-3}. This behavior is taken to indicate that the level has $T = \frac{3}{2}$ and corresponds to ^{15}C$_{\rm g.s.}$; the predicted energy from M(^{15}C) is ^{15}N*(11.7 to 11.9 MeV) (1955BA44, 1956BA16).

16. ^{14}C(d, n)^{15}N $\qquad Q_m = 7.987$

Neutron groups have been observed corresponding to levels in ^{15}N at 5.34, 6.32, and 7.46 MeV (1950HU72). See also (1956FR1A; theor.).

17. ^{14}C(^{3}He, d)^{15}N $Q_{\rm m} = 4.720$

Not reported.

18. ^{14}C(α, t)^{15}N $Q_{\rm m} = -9.599$

Not reported.

19. ^{15}C(β^-)^{15}N $Q_{\rm m} = 9.777$

See ^{15}C.

20. ^{14}N(n, γ)^{15}N $Q_{\rm m} = 10.842$
$Q_0 = 10.833 \pm 0.008$ (1957BA18).

The thermal cross section is 80 ± 20 mb (1957BA18). Observed γ-rays are given in Table 15.7 together with the ^{15}N levels with which they are presumed to be associated. The decay scheme is in good accord with that derived from ^{14}N(d, p)^{15}N (1957BA18). It does not appear that any of the known levels in this region can account for the large thermal cross section. The $J = \frac{1}{2}^+$; $T = \frac{3}{2}$ level at ^{15}N*(11.61) gives the same capture radiation spectrum and accounts very well for the thermal ^{14}N(n, p)^{14}C cross section, but contributes only 0.4 mb to $\sigma_{\rm n\gamma}$. The required level is presumably to be found below the neutron threshold, ^{15}N*(10.2 to 10.7 MeV), and should have a large neutron and a small proton width, $= \frac{1}{2}^+$ or $\frac{3}{2}^+$, and $\Gamma_{\gamma_0} = 1$ eV (1955BA44): compare ^{14}C(p, γ) (1959HE1D). See also (1958RA13).

21. ^{14}N(n, n)^{14}N $E_{\rm b} = 10.842$

The coherent scattering cross section is 11.0 ± 0.5 b; the total scattering cross section is 11.4 ± 0.5 b (bound atoms, epithermal neutrons: see (1958HU18)). The large thermal scattering reflects a nearby bound level (1949ME51). The approximate equality of the two values indicates that the scattering has little spin dependence (1955FO27). See (1959HE1D).

Resonances in the range $E_{\rm n} = 0.4$ to 2.3 MeV are listed in Table 15.8 (1951JO23, 1952HI12, 1955FO27, 1955HU1B, 1957HU1D, 1958HU18). Angular distributions at and between these resonances have been studied by (1950BA1C, 1955FO27). The potential s-wave phase shift approximately fits hard-sphere scattering ($R = 3.7 \times 10^{-13}$ cm) for $E_{\rm n} < 1.3$ MeV: from 1.3 to 1.7 MeV, an abrupt increase (negative) appears, which may be associated with a shape resonance. The

Table 15.7: Gamma radiation from ^{14}N(n, γ)^{15}N (1957BA18, 1958BA52)

E_γ (MeV)	γ rays/100 captures [a]	Assignment [b]
10.833 ± 0.008	11	$C \rightarrow 0$
> 9.152	≤ 0.3	
9.152 ± 0.010	1	$9.16 \rightarrow 0$
9.03 ± 0.03	0.2	$9.06 \rightarrow 0$
8.54 ± 0.04	0.2	$8.57 \rightarrow 0$
8.313 ± 0.013	4	$8.32 \rightarrow 0$
7.305 ± 0.012	9	$7.31 \rightarrow 0$
(7.164)	≤ 0.8	
6.323 ± 0.008	17	$6.33 \rightarrow 0$
5.559 ± 0.005	14	$C \rightarrow 5.28$
5.530 ± 0.008	18	$C \rightarrow 5.31$
5.293 ± 0.007	35	$5.31 \rightarrow 0$
5.263 ± 0.010	22	$5.28 \rightarrow 0$
4.497 ± 0.011	16	$C \rightarrow 6.33$
3.669 ± 0.016	17	$C \rightarrow 7.16$ [c]
3.520 ± 0.016	15	$C \rightarrow 7.31$
(3.267)	≤ 6	

[a] The intensity of the $7.57 \rightarrow 0$ transition is ≤ 0.7.
[b] C = capture state.
[c] The direct ground state decay is ≤ 0.8.

p-wave phase shift is somewhat smaller than the hard-sphere value; the d-wave shift is $< 3°$ (1955FO27: $E_n < 2.0$ MeV).

The narrow $E_n = 430$ keV resonance is formed by $l_n \geq 1$; the proton width is very small, and the level has not been detected in ^{14}C + p. The $E_n = 495$ keV resonance appears strongly in ^{14}N(n, p)^{14}C and ^{14}C(p, n)^{14}N, but not in elastic scattering. The two resonances at $E_n = 639$ and 998 keV are s-wave, assigned $J = \frac{1}{2}^+$ and $\frac{3}{2}^+$, respectively from $\sigma_{max} - \sigma_{min}$ (1951JO23, 1952HI12). According to (1956FE1C) an additional broad $J = \frac{1}{2}^+$ level is located in this region (^{14}C(p, n)^{14}N; $E_p = 1.5$ MeV: ^{14}N* = 11.61 MeV), presumably the first $T = \frac{3}{2}$ state. This level has not appeared in ^{14}N(n, n)^{14}N; see e.g. (1955FO27). The $E_n = 1120$ keV resonance is given as $J = \frac{3}{2}$ or $\frac{5}{2}$ from cross sections; the angular distributions favor $\frac{3}{2}^-$ (1955FO27). The narrow 1188 keV resonance does not appear in (^{14}C + p) (1956SA06). Aside from the $J = \frac{1}{2}^-$ resonance at $E_n = 1211$ keV, the

Table 15.8: Resonances in $^{14}N + n$

E_n (keV)	Γ_{lab} (keV)	Γ_n (keV)	Γ_p (keV)	Γ_α (keV)	l_n	J^π	θ^2_n [a] (%)	θ^2_p [a] (%)	θ^2_α [a] (%)	$^{15}N*$ (MeV)	References [b]
430 ± 5	3.5	< 3	< 0.01		≥ 1	$\geq \frac{3}{2}$				11.243	(1951JO23, 1952HI12)
495 ± 5	7.5	< 3	< 10		(1)	$\frac{1}{2}^-$ [c]	(0.1)	(1.8)		11.301	(1952HI12)
639 ± 5	43	34	9		0	$\frac{1}{2}^+$	0.9	0.4		11.439	(1951JO23, 1952HI12)
998 ± 5	46	45	0.8		0	$\frac{3}{2}^+$	1.0	0.6		11.774	(1951JO23, 1952HI12)
1120 ± 6	19	19	0.20	[d]	1	$\frac{3}{2}^-$	0.8	0.08		11.887	(1951JO23, 1952HI12, 1955FO27)
1188 ± 6	≤ 3.2	< 2	< 0.1		≥ 1	$\geq \frac{3}{2}$				11.950	(1952HI12)
1211 ± 7	13	12	0.4	[d]	1	$\frac{1}{2}^-$	0.5	0.2		11.972	(1952HI12)
1350 ± 7	22	21	1.0	[d]	(2)	$\frac{5}{2}^{(+)}$	6	0.7		12.102	(1951JO23, 1952HI12, 1955FO27)
1401 ± 8	54	42	10	2	1	$\frac{3}{2}^{(-)}$	1.5	0.7	5	12.150	(1951JO23, 1952HI12, 1955FO27)
1595 ± 8	22	21	0.4	0.2	(1)	$\frac{5}{2}^{(-)}$	0.7	3.0		12.331	(1952HI12, 1955FO27)
1779 ± 10	24	18	6	0.2	2	$(\frac{5}{2}^+)$	3.0	0.07	14	12.503	(1952HI12, 1955FO27)
2250		0.48Γ			1	$(\frac{3}{2}^-)$				12.94	(1953ME1B, 1955FO27, 1957HU1D)

[a] θ^2 as defined by (1952HI12).
[b] See (1958HU18).
[c] Assignment by (1956SA06), based on quoted σ_{nn}, $\sigma_{n\alpha}$, σ_{np}.
[d] See Table 15.6.

remaining J^π assignments disagree with those derived from $^{14}C + p$ (compare (1955FO27) and (1955BA44)). For the $E_n = 2250$ keV resonance, (1955FO27) find $J = \frac{3}{2}^-$, while (1953ME1B) report $J = \frac{1}{2}^-$. From $E_n = 1.8$ to 4.0 MeV, there is evidence for considerable structure in the cross section curve, but little agreement as to the exact location of the levels involved. (1953ME1B) list 14 maxima in the total cross section for $E_n = 1.9$ to 3.6 MeV. Angular distributions have been studied by (1954HU1B) for energies between 3.2 and 3.9 MeV. The observed distributions can be accounted for by seven levels in the range 2.5 to 4.4 MeV with $J = \frac{3}{2}^+$ to $\frac{7}{2}^+$ (1954SP1C, 1954SP1D). See also (1955AJ61, 1956BE98, 1956FL1B, 1957HU1D).

22. $^{14}N(n, 2n)^{13}N$ $\qquad Q_m = -10.551$ $\qquad E_b = 10.842$

At $E_n = 14.3$ MeV, the cross section is 4.5 ± 0.8 mb (1955HU1B), 19 ± 10 mb (1958AS63), 8.5 mb (1958RA18). See also (1955SM1B).

23. ^{14}N(n, p)^{14}C $\qquad Q_m = 0.628 \qquad E_b = 10.842$

The thermal cross section is 1.75 ± 0.05 b (1958HU18). A major portion of this cross section can be ascribed to ^{15}N*(11.61) (1955BA44). Resonances reported by (1950JO57) occur at $E_n = 495$, 640, (993), and 1415 keV; parameters are listed in Table 15.8 (1955HU1B, 1958HU18). Many additional levels have been reported through analysis of particle groups induced by continuous neutron spectra: see (1952AJ38, 1953GI1B, 1957BE71).

24. ^{14}N(n, α)^{11}B $\qquad Q_m = -0.152 \qquad E_b = 10.842$

(1950JO57) report resonances at $E_p = 1415$ and 1800 keV: see Table 15.8 (1955HU1B). See also ^{14}N(n, p)^{14}C above.

25. ^{14}N(n, d)^{13}C $\qquad Q_m = -5.319 \qquad E_b = 10.842$

See (1952LI24, 1957CA07, 1957ZA1A), ^{14}N and ^{13}C.

26. (a) ^{14}N(n, t)^{12}C $\qquad Q_m = -4.007 \qquad E_b = 10.842$
(b) ^{14}N(n, t)^{4}He^{4}He^{4}He $\qquad Q_m = -11.287$

For reaction (a), see (1953FI28). For reaction (b), see (1956FR18).

27. ^{14}N(d, p)^{15}N $\qquad Q_m = 8.615$

Proton groups corresponding to levels of ^{15}N are listed in Table 15.9. The J^π assignments are based on stripping analysis of angular distributions (1950MA65, 1952GI01, 1954SP01, 1955SH28, 1956DO41, 1956GR37, 1957WA01). A detailed comparison of the experimental observations with shell-model calculations is made by (1957HA1E: see also (1957WA01)). Angular distributions have also been studied by (1954EB02, 1954JO1F, 1956VA17, 1958BO18). The ratio of the reduced widths of the ground states of ^{15}N and ^{15}O is 1.71 (1956CA1D: $E_d = 9$ MeV).

Observed gamma rays are listed in Table 15.10 (1955BE81, 1958RA13). The observation of a 10.81 MeV γ-ray indicates a small proton width for the ^{15}N level; it is suggested that this level may account for the large (n, γ) cross section (1958RA13). According to (1955BA44, 1958HE48), however, the γ-spectra are quite different: see Tables 15.5 and 15.7. A 1.88 MeV γ-ray is reported by (1954TH1B), attributed to ^{15}N*($7.16 \rightarrow 5.2$). A p-γ correlation experiment suggests that the 5.3 MeV radiation is dipole (1954ST1C). The relative intensities of the 7.31 MeV γ-ray and of the ^{15}O 6.81 MeV radiation have been determined at several energies by (1955BE1G). See (1956EL1B, 1956FR1A, 1957HA1E, 1957SH1B; theor.).

28. ^{14}N(t, pn)^{15}N $Q_m = 2.357$

See (1952CU1B).

29. ^{14}N(α, ^{3}He)^{15}N $Q_m = -9.736$

Not reported.

30. ^{15}N(γ, p)^{14}C $Q_m = -10.214$

With bremsstrahlung of $E_{max} = 18.7$ and 24.6 MeV, photoprotons corresponding to the ground state and excited states of ^{14}C are observed. Peaks in the yield appear at $E_\gamma = 11.6$, ≈ 15, ≈ 18.6 MeV, in addition to the giant resonance at ≈ 20 MeV. The first peak corresponds to excitation of ^{15}N* ($J = \frac{1}{2}^+$; $T = \frac{3}{2}$): the angular distribution is consistent with isotropic emission. At 15 MeV, the distribution indicates dipole absorption, while the giant resonance shows a predominantly $\sin^2\theta$ distribution (1958RH1A, 1958RH30).

31. ^{15}O(β^+)^{15}N $Q_m = 2.759$

See ^{15}O.

32. ^{16}O(γ, p)^{15}N $Q_m = -12.113$

Transitions have been observed to the 5.3 and 6.3 MeV levels of ^{15}N (1955ST1D, 1957SV1A). See also ^{16}O.

33. ^{16}O(n, d)^{15}N $Q_m = -9.884$

See (1952LI24).

34. ^{16}O(p, 2p)^{15}N $Q_m = -12.113$

Table 15.9: ^{15}N levels from ^{14}N(d, p)^{15}N

E_x (MeV) A	E_x (MeV) B	E_x (MeV) C	l_n	$(2J+1)\theta^2$ [j]	J^π
0			1 [a]	0.097	$\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$
5.276 ± 0.006	5.280 ± 0.010		2 [b]	0.03	$\leq \frac{7}{2}^+$
5.305 ± 0.006			X [b,c]		
6.328 ± 0.006	6.330 ± 0.010		1 [d]	0.035	$\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$
7.164 ± 0.006	7.165 ± 0.010		2 [e]	0.32	$\leq \frac{7}{2}^+$
7.309 ± 0.006	7.314 ± 0.010	7.307 ± 0.008	0 [e]	0.45	$\frac{1}{2}^+, \frac{3}{2}^+$
	7.575 ± 0.010	7.570 ± 0.008	2 [f]	0.41	$\leq \frac{7}{2}^+$
8.315 ± 0.006	8.316 ± 0.010	8.319 ± 0.008	0 [d]	0.40	$\frac{1}{2}^+, \frac{3}{2}^+$
	8.571 ± 0.010	8.577 ± 0.008	$0+2$ [g]	0.03	$\leq \frac{7}{2}^+$
	9.062 ± 0.010		0 [h]		$\frac{1}{2}^+, \frac{3}{2}^+$
	9.165 ± 0.010		X [c,h]		
	9.834 ± 0.010				
	10.069 ± 0.010		1 [e]	0.14	$\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$
	10.458 ± 0.010		X [c,h]		
	10.544 ± 0.010		X [c,h]		
	10.705 ± 0.010		X [c,h]		
	10.811 ± 0.010		X [c,h]		
	11.2		1 [i]	0.24	$\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$

A: (1950MA65); $E_d = 1.4$ MeV, $\theta = 90°$.

B: (1954SP01); $E_d = 5$ to 8.5 MeV, $\theta = 90°$. Accurate level separations are also given.

C: (1956DO41); E_x based on Q_m; Q's given by (1956DO41) are given to ± 1 or 1.5 keV.

[a] (1952GI01, 1957WA01).

[b] (1955SH28: see (1958WA1C)).

[c] Isotropic: no clear stripping pattern.

[d] (1952GI01, 1955SH28, 1956GR37, 1957WA01).

[e] (1955SH28, 1956GR37).

[f] (1956GR37): (1957WA01) find a possible $l = 0$ component.

[g] (1955SH28, 1957WA01).

[h] Sharp, Buechner and Sperduto, to be published.

[i] (1956GR37).

[j] (1956GR37, 1957HA1E, 1957WA01).

Table 15.10: Gamma rays from ^{14}N(d, p)^{15}N [a]

E_γ (MeV) [b]	Relative gamma intensity [c]
5.25 ± 0.04	47 [d]
6.33 ± 0.05	10
7.31 ± 0.04	33
8.321 ± 0.020	10
9.07 ± 0.04	3.0
10.03 ± 0.04	3.6
10.81 ± 0.04	0.8

[a] (1955BE81, 1958RA13).

[b] Doppler corrected.

[c] The ground state decay of a number of known levels of ^{15}N (see Table 15.9) has not been observed; the upper limit to the relative gamma intensity is given in parenthesis following the energy of the level: 7.17 (2.0), 7.58 (1.4), 8.57 (0.7), 9.17 (1.5), 9.83 (1.1), 10.46 (< 0.4), 10.54 (0.3). See also ^{14}N(n, γ)^{15}N.

[d] Includes some contribution from ^{14}N(d, n)^{15}O*.

At $E_p = 185$ MeV, the summed proton spectrum shows two peaks, corresponding to ejection of $p_{\frac{1}{2}}$ and $p_{\frac{3}{2}}$ protons with binding energies of ≈ 12 and ≈ 19 MeV, respectively. The separation is consistent with the interpretation of ^{15}N*(6.3) as a state with a hole in the $p_{\frac{3}{2}}$ shell (1958MA1B, 1958TY49).

35. ^{16}O(d, ^{3}He)^{15}N $\quad Q_m = -6.619$

Not reported.

36. ^{16}O(t, α)^{15}N $\quad Q_m = 7.700$

See (1956BA1E, 1956JA31, 1956MA09).

37. ^{17}O(d, α)^{15}N $\quad Q_m = 9.812$

$Q_0 = 9.807 \pm 0.012$ (1954PA39).

38. ^{18}O(p, α)^{15}N $Q_{\mathrm{m}} = 3.970$

$Q_0 = 3.961 \pm 0.009$ (1954MI60).

See (1952AJ38, 1955RI1A) and ^{19}F.

^{15}O
(Fig. 30)

GENERAL:

Theory: See (1957TA1C, 1958FR1C).

Mass of ^{15}O: The most precise determination of the mass difference ^{15}O – ^{15}N comes from ^{15}N(p, n)^{15}O, where (1958JO28) find $E_{\rm thresh.} = 3.7808 \pm 0.0011$ MeV: this value, with (n – ^{1}H) = 0.783 MeV leads to ^{15}O – ^{15}N $= 2.7595$. Including the (p, n) value of (1955KI28) and the two ^{15}O(β^{+})^{15}N values of (1957KI22), one obtains a weighted mean of ^{15}O – ^{15}N $= 2.7586 \pm 0.0012$, or ^{15}O (mass excess) $= 7.287 \pm 0.005$ MeV, 54 keV higher than the value of (1955WA1A).

1. ^{15}O(β^{+})^{15}N $\qquad Q_{\rm m} = 2.759$

The maximum positon energy is 1.723 ± 0.005 MeV, 1.736 ± 0.010 MeV; the mean of these and two values from ^{15}N(p, n)^{15}O is 1.733 ± 0.005 MeV (1957KI22); an earlier report by (1950BR29) appears to be in error. The half-life is 123.4 ± 1.3 sec (1954KL36), 121 ± 3 sec (1955BA83), 120 ± 2 sec (1957KI22), 123.95 ± 0.50 sec (1957PE12): mean $= 123.6 \pm 0.45$ sec. Log $ft = 3.64$. See also (1958BE1G; theor.).

2. ^{7}Li(^{14}N, ^{6}He)^{15}O $\qquad Q_{\rm m} = -2.706$

See (1958AL1D).

3. (a) ^{10}B(^{6}Li, n)^{15}O $\qquad Q_{\rm m} = 15.218$
   (b) ^{10}B(^{7}Li, 2n)^{15}O $\qquad Q_{\rm m} = 7.965$

See (1957NO17).

4. (a) ^{12}C(^{3}He, p)^{14}N $\qquad Q_{\rm m} = 4.772 \qquad E_{\rm b} = 12.071$
   (b) ^{12}C(^{3}He, n)^{14}O $\qquad Q_{\rm m} = -1.159$
   (c) ^{12}C(^{3}He, α)^{11}C $\qquad Q_{\rm m} = 1.856$
   (d) ^{12}C(^{3}He, d)^{13}N $\qquad Q_{\rm m} = -3.553$

Table 15.11: Energy levels of ^{15}O

$E_{\rm x}$ (MeV $\pm$ keV)	J^π	$\tau_{1/2}$ or Γ (keV)	Decay	Reactions
0	$(\frac{1}{2})^-$	$\tau_{1/2} = 123.6 \pm 0.45$ sec	β^+	1, 2, 3, 5, 12, 15, 18, 21
5.195 ± 10 5.247 ± 10			γ	7, 12, 21
6.15 ± 30	$(\leq \frac{5}{2}^-)$		γ	7, 12
6.792 ± 9 6.860 ± 9	$\frac{1}{2}^+, \frac{3}{2}^+$		γ	7, 12
7.560 ± 2	$\frac{1}{2}^+$	$\Gamma = 1.5 \pm 0.5$	p, γ	7, 9, 12
8.291 ± 4	$\frac{3}{2}^+$	3 ± 1	p, γ	7, 9, 12
8.747 ± 7	$\frac{1}{2}^+$	32	p, γ	7, 9
8.928 ± 5	$(\leq \frac{5}{2})$	4 ± 1	p, γ	7, 9
8.988 ± 6	$\frac{1}{2}^-, \frac{3}{2}^-$	4 ± 1	p, γ	7, 9, 12
9.47	$\frac{1}{2}$	510	p, γ	7, 9
9.497 ± 12		13 ± 4	p, γ	7, 9
9.619 ± 12		10 ± 3	p, γ	7, 9
9.666 ± 4		< 8	p	9
10.29 ± 80			p	9
10.47			p	9
10.949 ± 8	$\geq \frac{3}{2}$	77 ± 14	p	9
11.030 ± 10		< 14	p	9
11.780 ± 20		75	p	9
11.846 ± 15		65	p, α	9, 11
12.3		broad	p, α	11
12.5		broad	p, α	11
13.04 ± 20	$(\frac{5}{2}^-)$		p, α, ^{3}He	4, 11
13.1			p, ^{3}He	4
13.79	$(> \frac{5}{2})$		p, n, ^{3}He	4
14.09	$(\frac{1}{2}^+)$		p, n, ^{3}He	4
14.2			p, n, ^{3}He	4
14.5			p, ^{3}He	4
15.0			p, ^{3}He	4
15.6			p, ^{3}He	4
15.9			p, ^{3}He	4

Table 15.12: Resonances in ^{12}C + ^{3}He

$E(^3$He) [a] (MeV)	Resonant for:	E_x (MeV)	J^π
1.21	p_0, p_2	13.04	$(\frac{5}{2}^-)$
1.3	p_0, p_1, p_2, p_3	13.1	
2.15	p_0, n	13.79	$(> \frac{5}{2})$
2.52	p_0, p_1, p_2, p_3, n	14.09	$(\frac{1}{2}^+)$
2.7	p_1, p_2, n	14.2	
3.0	p_0, p_1, p_2	14.5	
3.6	p_0, p_1, p_2	15.0	
4.4	p_0, p_1, p_2	15.6	
4.8	p_0, p_1, p_2	15.9	

[a] The first five resonances are primarily from (1957BR18), the last four are from (1958JO20).

Resonances in the yields of reactions (a) and (b) are displayed in Table 15.12 (1957BR18, 1958JO20). Differential cross sections and angular distributions have been determined to $E(^3\text{He}) = 5$ MeV for the p_0, p_1 and p_2 groups. At low energies, the distributions tend to be symmetric; at the higher energies they become more complex; they seem to conform neither to compound nucleus or stripping theory, and it must be concluded that features of both processes are present (1957BR18, 1958JO20). Consideration of the relative yields of the first four resonances lead to the tentative J^π assignments given in the table (1957BR18). Neutron angular distributions have been determined in the range $E(^3\text{He}) = 1.89$ to 2.51 MeV: they are asymmetric at the higher energies. The ratio of the cross sections of the (^{3}He, n) and (^{3}He, p_1) reactions (both to the first $T = 1$ states of the $A = 14$ triad) has been determined at a number of energies for $E(^3\text{He}) = 1.8$ to 2.6 MeV. The ratio approaches the theoretically predicted value of 2 at the higher energies. The ratio of the (^{3}He, α_0) to the (^{3}He, n_0) cross sections has been determined at two energies; the large cross section for the former suggests a direct interaction (1957BR18). The yields of ^{11}C and ^{13}N have been determined for $E(^3\text{He}) = 13$ to 21 MeV by (1958CO1G). See also ^{11}C, ^{14}N and ^{14}O.

5. ^{12}C(α, n)^{15}O $\qquad Q_m = -8.507$

See (1939KI1A, 1957KI22).

6. ^{13}C(^{3}He, n)^{15}O $\qquad Q_m = 7.126$

Table 15.13: Resonances from ^{14}N(p, γ)^{15}O (1951DU08)

E_p [e] (keV)	Γ [e] (keV)	$\omega\Gamma_\gamma$ [e] (eV)	J^π	^{15}O* [e] (MeV)
277	1.9 ± 0.5 [c]	0.013 [b]	$(\frac{5}{2})$ [b], $(\frac{1}{2}^+)$ [c]	7.559
1064 ± 2	4.8 ± 1	0.63	$\frac{3}{2}$ [d]	8.293
1550 ± 20	50 ± 20	0.16	$\frac{1}{2}^+$ [a]	8.747
1748 ± 5	11 ± 3	0.21		8.931
1815 ± 4	7 ± 1.5	0.52		8.994
2356 ± 8	14 ± 4	2.4		9.499
2489 ± 7	11 ± 3	3.3		9.623
2600 ± 50 [f]	1270 ± 50	46	$(\frac{1}{2}^+, \frac{3}{2}^+)$	9.73

[a] From ^{14}N(p, p)^{14}N.
[b] (1955BA83).
[c] (1956OV1A, 1957PIZZ).
[d] (1957GA1B, 1957GO1E, 1957GO1H).
[e] See also Table 15.14 (^{14}N(p, p)^{14}N).
[f] Presumably to be identified with ^{15}O*(9.465), see Table 15.14 (1959FE1E).

Not reported.

7. ^{14}N(p, γ)^{15}O $\qquad Q_m = 7.300$

Observed resonances are listed in Table 15.13 (1951DU08, 1955BA83, 1956OV1A, 1957PIZZ). The cross section increases from $(8.5\pm3.7)\times10^{-12}$ b at 100 keV to $(140\pm30)\times10^{-12}$ b at 135 keV (1957LA13). Extrapolation of the 278 keV resonant yield and s-wave background from the broad 2600 keV resonance yields cross section values in good agreement with those of (1957LA13). Judging from ^{15}N, one level near 7 MeV in ^{15}O remains undiscovered (1957PIZZ); see ^{14}N(p, p)^{14}N.

At the 277 keV resonance (E_x = 7.56 MeV), capture gamma rays resulting from cascades through ^{15}O states at 5.2, 6.1 and 6.7 MeV are observed, with partial radiative widths of 0.003 eV, 0.008 eV and 0.002 eV, respectively ($\pm25\%$). The direct ground state transition has not been observed: the relative intensity is less than 5% of the 6.10 MeV line (1955BA83: see also (1952JO1C)). Asymmetry (7 ± 3 %) in the ratio of 6.1 and 5.2 MeV γ-rays indicates that the 7.56 MeV state is not formed by s-waves. It is suggested that $J = \frac{5}{2}$ (1955BA83). (1956OV1A, 1957PIZZ) find, on the other hand, that the 0.75 and 1.35 MeV γ-rays are isotropic and conclude that $J = \frac{1}{2}^+$: see ^{14}N(p, p)^{14}N. The transition ($7.56 \rightarrow 5.2$) appears to involve ^{15}O*(5.20) and not ^{15}O*(5.25) (B. Povh and D. Hebbard, private communication). (It is not clear why the ground state decay (E1) should not occur.) The structure formerly attributed to a broad resonance at $E_p = 0.7$ MeV (1951DU08) is probably due to direct capture (see (1957HA03)). At the 1.06 MeV resonance ($E_x = 8.28$ MeV), transitions are observed through the 5.2 and $6.8 - 6.9$ MeV states in addition to the direct ground state transition (1953LI1D). A p-γ correlation study indicates $J = \frac{3}{2}$ for the 8.28 MeV state (1957GA1B, 1957GO1E, 1957GO1H, 1958GO46, 1958GO68).

8. ^{14}N(p, n)^{14}O $\quad Q_m = -5.930 \quad E_b = 7.300$

See (1958TA03) and ^{14}O.

9. (a) ^{14}N(p, p)^{14}N $\quad E_b = 7.300$
(b) ^{14}N(p, p$'$)^{14}N*

The yield of elastic protons, of inelastic protons and of 2.3 MeV γ-rays has been examined to $E_p = 5.2$ MeV: see Table 15.14. The scattering anomalies are superposed on a background which decreases less rapidly than the Rutherford cross section; for $E_p < 2.3$ MeV, the background is largely s-wave, with some p-wave contribution above $E_p = 1.5$ MeV (see (1956BA1H, 1956TA16, 1957BO58, 1957HA03, 1958FE05, 1959FE71)). (1959FE1E) finds that two s-wave and one p-wave phase shifts are required to fit the non-resonant angular distributions above $E_p = 1$ MeV.

Data taken near the 277 keV resonance, ^{15}O* $= 7.56$ MeV, at three angles, are consistent only with s-wave formation. The magnitude of the anomaly indicates $J = \frac{1}{2}^+$, $\Gamma = 1.5$ keV (1956OV1A, 1957PIZZ). The 1054 keV resonance, ^{15}O* $= 8.28$ MeV, is also formed by s-waves, but the anomaly indicates $J = \frac{3}{2}^+$ (1957HA03: see, however, (1956TA16)). Calculation of level shifts suggests identification of these two states with ^{15}N*(8.32, 8.57). The mirror of ^{15}O*(6.79) is probably ^{15}N*(7.31); ^{15}O*(6.86) may correspond either to ^{15}N*(7.16) or ^{15}N*(7.57). In either case, one ^{15}O level remains to be discovered in this region (1957PIZZ: see also (1957HA03)). The 1544 keV resonance is again s-wave, $J = \frac{1}{2}^+$. Assignments for the $E_p = 1737$ and 1799 keV resonances are not certain (1957HA03). The broad resonance at $E_p = 2.3$ MeV, ^{15}O*(9.465), is s-wave, $J = \frac{1}{2}^+$ (1958FE05, 1959FE1E). It is suggested that the apparent breadth of this level reported in ^{14}N(p, γ) may reflect some contribution from direct capture (1959FE1E).

Elastic scattering has also been studied at $E_p = 9.8$ MeV (1957HI56), at 14.5, 20 and 31.5 MeV (1956KI54) and at 20.0 MeV (1957CH32). See also (1957JA1B) and ^{14}N.

10. ^{14}N(p, d)^{13}N $\quad Q_m = -8.324 \quad E_b = 7.300$

See ^{13}N and ^{14}N.

Table 15.14: Anomalies in ^{14}N(p, p)^{14}N and ^{14}N(p, p$'\gamma$)^{14}N

E_p (keV)	Γ (keV)	$\omega\Gamma_\gamma$ [e] (eV)	θ_p^2 [e] (%)	J^π	E_x (MeV)	References
278.1 ± 0.4	1.5 ± 0.5			$\frac{1}{2}$	7.560	a
1058 ± 3	3 ± 1	0.40	0.29 [b]	$\frac{3}{2}^+$	8.288	e, g, h
1550 ± 6	34	0.11	1.6 [b]	$\frac{1}{2}^+$	8.747	e, f, g, h
1740 ± 4	4 ± 1	0.076	0.13 [b]	$(\leq \frac{5}{2})$	8.924	e, f, g, h
			1.7 [c]			
1801 ± 5	4 ± 1	0.30	0.28 [d]	$(\frac{1}{2}^-, \frac{3}{2}^-)$	8.981	e, f, g, h
2320	550			$\frac{1}{2}^+$	9.465	f, i
2350 ± 10					9.494	f, g
2480 ± 10					9.614	f, g
2535 ± 3	< 8				9.666	j
3200 ± 10					10.29	f, k
3400 ± 10					10.47	f
3910 ± 8	82 ± 15			$\geq \frac{3}{2}$	10.949	j, l, m, n
4000 ± 8	< 15				11.033	j, l, m
4800 ± 20	80				11.780	l
4890 ± 10	70				11.864	l, m

[a] (1956OV1A, 1957PIZZ).
[b] Assuming s-waves.
[c] Assuming d-waves.
[d] Assuming p-waves.
[e] (1957HA03).
[f] (1957BO58).
[g] (1956FE1D, 1959FE71).
[h] (1956TA16).
[i] (1958FE05, 1959FE1E, 1959FE71).
[j] (1957OL1A).
[k] (1956BA1H).
[l] (1956BA34): ^{14}N(p, p$'\gamma$)^{14}N.
[m] (1955TH1A).
[n] (1958DO60).

Table 15.15: ^{15}O levels from ^{14}N(d, n)^{15}O

^{15}O* (MeV)	l_p	J^π
0	1 [b]	$\leq \frac{5}{2}^-$
5.29 ± 0.17 [a]	2	$(\leq \frac{7}{2}^+)$
6.15 ± 0.03 [c]	1	$(\leq \frac{5}{2}^-)$
6.792 ± 0.009[c] }	0	$\frac{1}{2}^+, \frac{3}{2}^+$
6.860 ± 0.009 }		
7.48 ± 0.16 [a]	1	$(\leq \frac{5}{2}^-)$
8.42 ± 0.16 [a]	1	$(\leq \frac{5}{2}^-)$
9.06 ± 0.16 [a]	1	$(\leq \frac{5}{2}^-)$

[a] (1953EV03): $E_d = 7.7$ MeV.
[b] (1953EV03) and (1956NO04, 1957NO1C: $E_d = 1.9$ MeV).
[c] From slow neutron thresholds (1955MA85).

11. ^{14}N(p, α)^{11}C $\qquad Q_m = -2.916 \qquad E_b = 7.300$

Broad resonances in the yield of ^{11}C are observed at $E_p = 4.94$, 5.3, 5.6 and 6.15 MeV, corresponding to ^{15}O*(11.91, 12.3, 12.5, 13.04) (1952BL64: stacked foil method).

12. ^{14}N(d, n)^{15}O $\qquad Q_m = 5.073$

$Q_0 = 5.15 \pm 0.16$ (1953EV03).

$Q_0 = 5.13 \pm 0.05$ (1957NO1C).

Neutron groups are listed in Table 15.15, together with J^π assignments obtained from stripping analysis of the angular distributions. Except for the ground state and the level(s) at 6.8 MeV, the fits to the theoretical distributions are not completely satisfactory, and the assignments must be treated with some reserve (1953EV03). See also (1956NO04, 1957NO1C). At $E_d = 9$ MeV, the ratio of the ground state reduced widths of ^{15}N and ^{15}O (from the maximum cross sections of the (d, p) and (d, n) reactions) is 1.71 (1956CA1D). Neutron thresholds have been observed at $E_d = 1.24 \pm 0.02$, 1.967 ± 0.004 and 2.044 ± 0.004 MeV, corresponding to ^{15}O*(6.15 ± 0.03, 6.792 ± 0.009, 6.860 ± 0.009) (1955MA85).

At $E_d = 4.0$ MeV, γ-radiation has been observed with $E_\gamma = 6.81 \pm 0.04$, 6.12 ± 0.06 and 5.26 ± 0.04 MeV (the latter probably includes ^{14}N(d, p)^{15}N) (1955BE81: corrected for Doppler shift). Relative cross sections for the ^{14}N(d, p)^{15}N*(7.31) and ^{14}N(d, n)^{15}O*(6.81) γ-rays are given by (1955BE1G) for three energies. See also (1956FR1A; theor.) and ^{16}O.

13. ^{14}N(^{3}He, d)^{15}O $Q_{\rm m} = 1.806$

Not reported.

14. ^{14}N(α, t)^{15}O $Q_{\rm m} = -12.513$

Not reported.

15. ^{15}N(p, n)^{15}O $Q_{\rm m} = -3.542$

$E_{\rm thresh.} = 3.776 \pm 0.008$;
$Q_0 = -3.539 \pm 0.008$ (1955KI28).
$E_{\rm thresh.} = 3.7808 \pm 0.0011$;
[$Q_0 = -3.5425 \pm 0.0011$] (1958JO28).

16. ^{15}N(^{3}He, t)^{15}O $Q_{\rm m} = -2.777$

Not reported.

17. ^{16}O(γ, n)^{15}O $Q_{\rm m} = -15.655$

See (1957SV1A).

18. ^{16}O(n, 2n)^{15}O $Q_{\rm m} = -15.655$

See (1955AJ61).

19. ^{16}O(p, d)^{15}O $Q_{\rm m} = -13.428$

Not reported.

20. ^{16}O(d, t)^{15}O $\qquad Q_{\rm m} = -9.396$

Not reported.

21. ^{16}O(^{3}He, α)^{15}O $\qquad Q_{\rm m} = 4.923$

At $E(^{3}{\rm He}) = 3$ MeV, α-groups are observed corresponding to levels at $E_{\rm x} = 5.195 \pm 0.01$ and 5.247 ± 0.01 MeV. The separation is 52 ± 5 keV (1959PO61). From a similar experiment, excitations of 5.185 and 5.244 MeV are reported (K.W. Allen, R. Middleton and S. Hinds, private communication). See also (1952PO27, 1953KU08).

22. ^{17}O(p, t)^{15}O $\qquad Q_{\rm m} = -11.316$

Not reported.

^{15}F

(Not illustrated)

Mass of ^{15}F: Calculation of Coulomb and (n − ^{1}H) mass differences from ^{15}C indicates that ^{15}F should be unstable to proton emission by 2.3 MeV (1957MU99): the mass excess of ^{15}F is 22.0 ± 1 MeV.

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(Closed 01 December 1958)

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