Energy Levels of Light Nuclei
$A = 9$

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Abstract: An evaluation of $A = 5$–10 was published in *Nuclear Physics* 78 (1966), p. 1. This version of $A = 9$ 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 TUNL/NNDC format.

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Table 9.1: Energy levels of ^{9}Li

E_x (MeV ± keV)	$J^\pi; T$	$\tau_{1/2}$ (sec)	Decay	Reactions
g.s.	$(\frac{3}{2})^-; \frac{3}{2}$	0.172 ± 0.003	β^-	1, 2, 3, 4, 6, 8
2.691 ± 5				2

^{9}Li

(Figs. 15 and 18)

GENERAL: See (1964GR1J).

Mass of ^{9}Li : From the Q-value for ^{7}Li(t, p)^{9}Li: $Q = -2.397 \pm 0.020$ MeV, the mass excess of ^{9}Li is 24.965 ± 0.020 MeV (1964MI04, 1965MA54).

1. ^{9}Li(β^-)^{9}Be $\qquad Q_m = 13.615$

^{9}Li decays to the ground state (25 ± 15 %) and to the 2.43 MeV, neutron-unstable state of ^{9}Be (75 ± 15 %). The β-endpoints are 13.5 ± 0.3 MeV and 11.0 ± 0.4 MeV; $\log ft = 5.5 \pm 0.2$ and 4.7 ± 0.2, respectively. Delayed neutrons of energy 0.7 ± 0.2 MeV are associated with the 11 MeV branch; there are indications of a weak neutron group with $E_n \approx 3 - 4.5$ MeV (1963AL18). (1963NE07) finds E_β(max) $= 13.1 \pm 0.5$ MeV, $\log ft = 5.0 \pm 0.3$. The mean of reported half lives is 172 ± 3 msec (1951GA30, 1952HO25, 1952SH44, 1961HI01, 1963AL18, 1965BE1P). The fact that the decay to ^{9}Be($\frac{3}{2}^-$) is allowed indicates $J^\pi(^9\text{Li}) = \frac{1}{2}^-, \frac{3}{2}^-$ or $\frac{5}{2}^-$; if ^{9}Be*(2.43) has $J^\pi = \frac{5}{2}^-$, the allowed decay excludes $\frac{1}{2}^-$ (1963AL18). See also (1964ER1C).

2. ^{7}Li(t, p)^{9}Li $\qquad Q_m = -2.397$

At $E_t = 11.28$ MeV, two groups are observed: the ground state group yields $Q_0 = -2.397 \pm 0.020$ MeV. The first excited state has $E_x = 2.691 \pm 0.005$ MeV; no other states are seen with $E_x < 4.0$ MeV. The angular distribution of ground-state protons appears to require $L = 0$ and $L = 2$ transfer, consistent with the expected $J^\pi = \frac{3}{2}^-$ (1964MI04). See also (1961HI01, 1964RO1G).

3. ^{9}Be(n, p)^{9}Li $\qquad Q_m = -12.832$

See (1959AL83, 1963AL18).

4. ^{9}Be(d, 2p)^{9}Li $\qquad Q_{\rm m} = -15.057$

See (1951GA30).

5. ^{9}Be(t, ^{3}He)^{9}Li $\qquad Q_{\rm m} = -13.596$

Not observed.

6. (a) ^{11}B(γ, 2p)^{9}Li $\qquad Q_{\rm m} = -30.875$
   (b) ^{11}B(p, 3p)^{9}Li $\qquad Q_{\rm m} = -30.875$

See (1952SH44, 1958TA04, 1963NE07) for reaction (a), and (1965BE1P) for (b).

7. ^{11}B(n, ^{3}He)^{9}Li $\qquad Q_{\rm m} = -23.157$

Not observed.

8. ^{12}C(γ, 3p)^{9}Li $\qquad Q_{\rm m} = -46.832$

See (1953RE19, 1958TA04).

^{9}Be
(Figs. 16 and 18)

GENERAL: See (1958BL57, 1959BA1D, 1959BR1E, 1959PI45, 1959TH16, 1960HE04, 1960KU1B, 1960PH1A, 1960SP08, 1960TA1C, 1960VA1H, 1961BA1G, 1961BA1E, 1961CL10, 1961GU1B, 1961KU1C, 1962BA1C, 1962IN02, 1962SC12, 1962TA1H, 1963HI1B, 1963MA1E, 1963SC1P, 1964AM1D, 1964BA29, 1964BA1Y, 1964BE1M, 1964GR1J, 1964NE1E, 1964RE1C, 1964ST1B, 1965BO1M, 1965KU1E, 1965MU1A, 1965NE1C, 1965RO1H, 1965WO01).

Ground State :

$\mu = -1.1776$ nm; $Q = \pm 0.03$ b (1965FU1G).

Table 9.2: Energy levels of ^{9}Be

$E_{\rm x}$ (MeV $\pm$ keV)	$J^\pi; T$	Γ (keV)	Decay	Reactions
g.s.	$\frac{3}{2}^-; \frac{1}{2}$		stable	2, 3, 4, 9, 10, 11, 12, 13, 18, 19, 20, 21, 22, 23, 24, 25, 28, 29, 30, 32, 33, 34, 36, 39
1.665 ± 20	$\frac{1}{2}^+; \frac{1}{2}$	200 ± 20	n_0, γ	4, 10, 12, 15, 18, 19, 20, 24, 28, 34, 39
2.429 ± 2	$\frac{5}{2}^-; \frac{1}{2}$	1.0 ± 0.2	n_0, n_1, γ	4, 10, 12, 13, 15, 18, 19, 20, 24, 28, 32, 34, 35, 39, 40
3.032 ± 11	$(\frac{5}{2})^+; \frac{1}{2}$	265 ± 17	n_0	4, 10, 12, 15, 19, 20, 24, 28, 34, 35, 39
4.70 ± 50	$\frac{3}{2}^+, \frac{5}{2}^+; \frac{1}{2}$	730 ± 150	n_1	4, 10, 15, 20, 24, 33
6.66 ± 50	$\frac{7}{2}^-; \frac{1}{2}$	1300 ± 120	n_1	10, 15, 18, 20, 24, 28, 33
(7.94 ± 80)		≈ 1000		15, 20
11.30 ± 50		640 ± 70	γ, n	10, 15, 20, 28, 33
11.82 ± 20		410 ± 30	γ, n	10, 12, 15
13.72		≈ 600	(γ, n)	10, 15
14.392 ± 5	$(\frac{3}{2}^-); \frac{3}{2}$	0.8	γ	10, 20
16.674 ± 8		42 ± 5		10, 20
16.973 ± 2	$; \frac{3}{2}$	< 0.47	γ, n, p, d	4, 5, 6
17.28	$(\frac{5}{2})^-$	195	n, p, d, α	5, 6, 7, 20
17.48	$(\leq \frac{7}{2})^+$	47	n, p, d, α	5, 6, 7, 20
(18.1)			n, p, d	5, 6
(18.6)			p, d, α	5, 6
18.94			n, t	1, 20
19.6			p, d	6
(20.47 ± 40)			γ	15
(20.73 ± 40)			γ	15
(21.1 ± 500)		broad		20
(22.4 ± 700)		4700	γ, n, p	15, 16, 20
(23.9 ± 600)	+	6900		33

1. (a) ^{6}Li(t, d)^{7}Li $\quad Q_m = 0.995 \quad E_b = 17.688$
(b) ^{6}Li(t, p)^{8}Li $\quad Q_m = 0.803$
(c) ^{6}Li(t, n)^{8}Be $\quad Q_m = 16.023$
(d) ^{6}Li(t, α)^{5}He $\quad Q_m = 15.160$

The differential cross section for reaction (a) at $90°$ measured up to $E_t = 1.90$ MeV increases rapidly with energy below the coulomb barrier and then approaches a constant value. At 1.50 MeV, the total cross section for formation of the ground state of ^{7}Li is 190 mb; that for the first excited state is 4 times less (1961HO21: see also (1957JA37)). Angular distributions for both groups show maxima in the forward hemisphere. It is suggested that the large cross section indicates a cluster exchange process − here the exchange of t and d (1961HO1F, 1961HO21).

The $0°$ differential cross section for reaction (c) increases monotonically between 0.10 and 2.4 MeV (1960SE12, 1961VA43, 1962SE1A) except for a resonance at $E_t = 1.875$ MeV, corresponding to an excited state of ^{9}Be at 18.937 MeV. The total cross section for neutron production at $E_t = 2.12$ MeV is 324 ± 32 mb (1961VA43). See also (1963JA1E).

The $90°$ differential cross section for reaction (d) rises from 0.75 mb/sr at 0.62 MeV to 5.7 mb/sr at 1.8 MeV and then decreases slowly to 5.3 mb/sr at 2.2 MeV (see (1957JA37)). See also ^{5}He, ^{7}Li, ^{8}Li and ^{8}Be.

2. ^{6}Li(α, p)^{9}Be $\quad Q_m = -2.126$
$Q_0 = -2.1256 \pm 0.012$ (1965BR28).

Angular distributions of ground-state protons have been measured at $E_\alpha = 10.15$, 11.5 and 13.5 MeV (1960MA15) 13.6 and 14.7 MeV (1962KO13) and 30 MeV (1960KL03). At 30 MeV, strong backward peaking is evident (1960KL03). A qualitative account of the observations can be given if heavy-particle stripping (p + ^{5}He + α) is assumed (1962HO1C). See also (1956WA29).

3. ^{6}Li(^{6}Li, ^{3}He)^{9}Be $\quad Q_m = 1.895$

See (1964KI02).

4. ^{7}Li(d, γ)^{9}Be $\quad Q_m = 16.693$

In the region $E_d = 0.1$ to 1.1 MeV, a resonance in the yield of capture γ-rays is observed at $E_d = 362 \pm 3$ keV (1965WO01), 361 ± 2 keV (1965IM01), corresponding to an excited state in ^{9}Be at 16.973 ± 0.002 MeV. The width of the level is less than 470 eV (c.m.). The small width

Table 9.3: Electromagnetic transitions in ^{9}Be

Transition	Remarks	Reactions
$1.67 \to$ g.s.	Γ(E1) $= 4.5$ eV	18
$2.43 \to$ g.s.	Γ(M1) $= 0.12$ eV	18
	Γ(E2) $= 2.6 \times 10^{-3}$ eV	18
$6.66 \to$ g.s.	Γ(E2) $= 0.109$ eV	18
$14.39 \to$ g.s.	Γ(M1) $= 18$ eV	18
$14.39 \to 2.43$	$\Gamma_\gamma = 31$ eV	10, 18
$16.97 \to$ g.s.	rel. intensity $= 100$	4
$\to 1.67$	8.5	4
$\to 2.43$	10.6	4
$\to 3.03$	≤ 4.5	4
$\to 4.70$	9.6	4
$20.47 \to$ g.s.		15
$20.73 \to$ g.s.		15
$22.4 \to$ g.s.	giant resonance: $\Gamma \approx 4.7$ MeV	16

of the level and the correspondence with ^{9}Li*(2.69) argues for $T = \frac{3}{2}$ (1965WO01). The angular distribution of the γ-rays to the ground state is isotropic to within 7%. The branching ratios to the ground state, and to the levels at 1.67, 2.43, 3.03 and 4.70 MeV are $100/8.5 \pm 4.3/10.6 \pm 5.3/\leq 4.5/9.6 \pm 4.8$. An upper limit for non-resonant, direct capture is 1.6 μb. The neutron decay of ^{9}Be*(2.43) and ^{9}Be*(4.70) is observed (1965IM01).

5. (a) ^{7}Li(d, n)^{8}Be $\quad Q_{\rm m} = 15.028 \quad E_{\rm b} = 16.693$
   (b) ^{7}Li(d, α)^{5}He $\quad Q_{\rm m} = 14.165$
   (c) ^{7}Li(d, n)^{4}He + ^{4}He $\quad Q_{\rm m} = 15.122$

The cross sections for reactions (a) and (b) have been measured for $E_{\rm d} = 70$ to 110 keV (1955RA14), 30 to 250 keV (1953SA1A) and 330 to 400 keV (1965IM01). The 0.36 MeV resonance is observed here also, in the yield of neutrons with $E_{\rm n} > 10$ MeV: the ratio of the partial width of the 16.97 MeV level for emission of neutrons to ^{8}Be$_{\rm g.s.}$ to that for emission of γ-rays is ≈ 1.5, while $\Gamma_{\alpha_0}/\Gamma_\gamma < 20$ (1965IM01).

The yield of neutrons has been measured from 0.2 to 4.8 MeV by (1952BA64, 1957SL01: see also (1947BE1A, 1949WH1A)), and the yield of α-particles has been measured from $E_{\rm d} = 0.2$ to 0.3 MeV by (1964MA60) and for 0.7 to 3.0 MeV by (1963PA04). Resonances for neutron

Table 9.4: Resonances in ^{7}Li + d

^{7}Li(d, p)^{8}Li		^{7}Li(d, n)^{8}Be	^{7}Li(d, α)^{5}He	E_x (MeV)	J^π
E_{res}	Γ (keV)	E_{res}	E_{res}		
0.361 [a]	< 0.5			16.973	
0.77 [b]	250	0.68 [e]	(0.7) [f]	17.28	$(\frac{3}{2}, \frac{5}{2})^-$
1.02 [b]	60	0.98 [e]	(1.0) [f]	17.48	$(\frac{1}{2} \rightarrow \frac{7}{2})^+$
(1.375) [c]	51			(17.76)	
2.0 [d]		(1.8) [e]		(18.1)	
2.5 [d]			(2.5) [f]	(18.6)	
3.7 [d]				19.6	

[a] (1965IM01, 1965WO01); see also ^{7}Li(d, γ)^{9}Be.
[b] (1952BA64, 1954BA46).
[c] (1960SE08: see also (1952BA64)).
[d] (1956BE1A: see also (1963SE1F)).
[e] (1952BA64, 1957SL01).
[f] (1963PA04).

production are observed at $E_d = 0.68$, 0.98 and (1.8) MeV (Table 9.4). At $E_d = 0.90$ MeV, α-particles from reaction (b) are isotropic within 2%, consistent with formation by s-wave deuterons (1957RI39). The angular correlation of ground-state α-particles with those resulting from the breakup of ^{5}He indicates $J = \frac{5}{2}^-$ for the ^{9}Be level mainly responsible for the reaction at $E_d = 0.9$ MeV (1956RI37); a similar observation at $E_d = 0.16$ MeV suggests $J = \frac{3}{2}^-$ for the responsible level (1957FA10). See also (1964FE01). At $E_d = 0.9$ MeV, reactions (a) and (c) account for less than 10% of the disintegrations at this energy (1956RI37). Polarization of ground-state neutrons has been measured by (1962HE06).

The excitation function for reaction (b) shows indications of the $E_d = 0.7$ and 1.0 MeV resonances (unresolved in this work) as well as broad structure at $E_d = 2.5$ MeV. There is no indication of resonance at 1.8 MeV in this ground-state α-yield. Also reported are α-particles from reaction (a) associated with the ^{8}Be excited states at 11.3, 16.6 and 16.9 MeV; the α-particles from the decay of the 11.3 MeV state seem to show resonance behavior at $E_d = 0.7$, 1.0 and 1.75 MeV. It is not clear whether the α-particles corresponding to ^{8}Be*(16.6) show resonance at $E_d = 2.5$ MeV or whether the ^{8}Be*(16.9) α-particles are appearing at this point (1963PA04). See also (1964BI10, 1965BI1F, 1965JO19), ^{5}He and ^{8}Be.

6. ^{7}Li(d, p)^{8}Li $\qquad Q_m = -0.192 \qquad E_b = 16.693$

The yield of ^{8}Li (ground-state protons) has been measured for $E_{\rm d} = 0.29$ to 0.78 MeV. A resonance is observed at $E_{\rm d} = 360 \pm 3$ keV with $\Gamma < 2$ keV. The ratio $\Gamma_{\rm p}/\Gamma_{\gamma}$ is ≈ 0.5 (1965IM01, 1965WO01): see also ^{7}Li(d, γ)^{9}Be.

The yield of ^{8}Li($\rm p_0 + p_1$) has been measured in the range $E_{\rm d} = 0.4$ to 3.3 MeV by (1952BA64, 1954BA46, 1960KA05) and from 1.1 to 4 MeV by (1956BE1A: stacked foils). Ground-state protons have been examined from $E_{\rm d} = 1.0$ to 4.0 MeV by (1960SE08, 1963SE1F). Resonances are reported at 0.77, 1.02, (1.375), 2.0, 2.5 and 3.7 MeV (Table 9.4), apparently superposed on a rising background. The total cross section at $E_{\rm d} = 0.77$ MeV is 150 ± 35 mb (1954BA46), 176 ± 15 mb (1960KA05), From $E_{\rm d} = 1.0$ to 4.0 MeV, angular distributions are unusually well described by stripping theory; the resonance at $E_{\rm d} = 1.375$ MeV shows no effect on the angular distribution (1960SE08, 1963SE1F).

The yield of 0.95 MeV γ-rays from ^{7}Li(d, p)^{8}Li* rises smoothly from $E_{\rm d} = 1.9$ to 3.3 MeV. Above $E_{\rm d} = 2.3$ MeV, the isotropy of the γ-rays is taken to indicate predominance of the stripping process (1962CH14).

7. ^{7}Li(d, d)^{7}Li $\qquad E_{\rm b} = 16.693$

The upper limit for the relative partial width for elastic scattering at $E_{\rm d} = 0.36$ MeV (^{9}Be* = 16.97), $\Gamma_{\rm d_0}/\Gamma_{\gamma}$, is 400 (1965IM01).

The elastic scattering has been studied from $E_{\rm d} = 0.4$ to 1.8 MeV by (1964FO13). The scattering cross sections lie below the Rutherford values at the lower energies. A marked increase occurs in the range $E_{\rm d} = 0.8$ to 1.0 MeV, and a conspicuous anomaly occurs at $E_{\rm d} = 1.0$ MeV. A rising background is ascribed to other overlapping resonances. The scattering below $E_{\rm d} = 1.0$ MeV can be satisfactorily accounted for by s-waves: the variation of parameters is consistent with $-$ but does not require $-$ a level at $E_{\rm d} = 0.8$ MeV. The resonance at 1 MeV appears to be due to p-wave deuterons (1964FO13). See also ^{7}Li and (1958RO49).

8. (a) ^{7}Li(d, t)^{6}Li $\qquad Q_{\rm m} = -0.995 \qquad E_{\rm b} = 16.693$

(b) ^{7}Li(d, ^{3}He)^{6}He $\qquad Q_{\rm m} = -4.486$

The cross section for reaction (a) rises steeply from threshold to 95 mb at $E_{\rm d} = 2.4$ MeV and then more slowly to about 165 mb at $E_{\rm d} = 4.1$ MeV (1955MA20). See also ^{6}He and ^{6}Li.

9. ^{7}Li(t, n)^{9}Be $\qquad Q_{\rm m} = 10.435$

See (1959AJ77, 1962SE1A) and ^{10}Be.

Table 9.5: Excited states of ^{9}Be from ^{7}Li(^{3}He, p)^{9}Be [a]

(1955AL57)		(1958MO99)	(1963CA02, 1965MA1E)		(1965CO1F)	
E_x	Γ	E_x	E_x	Γ	E_x	Γ
1.80 ± 100	< 400	1.83 ± 40	1.70 ± 30	340	1.80	
2.39 ± 80	< 200	$\equiv 2.428$	2.430 ± 9		2.428 ± 6	< 35
3.06 ± 80	< 300	3.10 ± 40	3.01 ± 90	190	3.03 ± 20	270 ± 30
4.74 ± 80	1200	4.80 ± 150 [b]			4.51 ± 100	730 ± 150
9.1 ± 200	1200				6.67 ± 100	1400 ± 200
					11.29 ± 50	640 ± 70
					11.82 ± 20	410 ± 30
					13.72	600
					14.392 ± 5 [c]	0.8
					16.674 ± 8	42 ± 5

[a] E_x in MeV $\pm$ keV, Γ in keV. See also (1954MO92).
[b] $\Gamma = 1250 \pm 250$ keV.
[c] (1965GR08, 1965LY01).

10. ^{7}Li(^{3}He, p)^{9}Be $\qquad Q_m = 11.199$

Observed proton groups are listed in Table 9.5 (1955AL57, 1958MO99, 1963CA02, 1965CO1F, 1965MA1E). The γ-decay of the narrow 14.39 MeV state to the ground and 2.4 MeV states indicates $\Gamma_{\gamma 0}/\Gamma_p = 0.023 \pm 0.005$, $\Gamma_{\gamma 1}/\Gamma_p = 0.04 \pm 0.01$. Assuming $\Gamma_{\gamma 0} = 18$ eV (see ^{9}Be(e, e′)), $\Gamma = 0.8 \pm 0.3$ keV for the 14.39 MeV state. This level is presumed to be the lowest $T = \frac{3}{2}$ state of ^{9}Be, analogous to the ^{9}Li ground state (1965GR08, 1965LY01). There is some evidence also for the γ-decay of a state at ≈ 17 MeV, presumably the $T = \frac{3}{2}$ analogue of the first excited state of ^{9}Li (1965GR08: see also ^{7}Li(d, γ)). See also (1961WO05) and ^{10}B.

11. ^{7}Li(α, d)^{9}Be $\qquad Q_m = -7.154$

The ground-state angular distribution has been observed at $E_\alpha = 48$ MeV (1960CE01). See also (1962MA59).

12. ^{7}Li(^{6}Li, α)^{9}Be $\qquad Q_m = 15.220$

At $E(^7\text{Li}) = 2.9$ MeV, α-particle groups are observed corresponding to ^{9}Be*(0, 1.75, 2.4, 3.0, 11.9 ± 0.2 MeV); the last has $\Gamma = 500 \pm 100$ keV. No other levels are observed for $E_x < 13.0$ MeV (1964ME07). See also (1963GA02, 1963HU02, 1964KI02, 1965BE1X).

13. ^{9}Li(β^-)^{9}Be $\quad Q_m = 13.615$

^{9}Li decays to the ground state (25 ± 15 %) and to ^{9}Be*(2.4) (75 ± 15 %): $\log ft = 5.5 \pm 0.2$ and 4.7 ± 0.2, respectively. The allowed character of the transition is consistent with $^9\text{Be*}(2.4) = \frac{5}{2}^-$ and $^9\text{Li}(0) = \frac{3}{2}^-$ or $\frac{5}{2}^-$ (1963AL18). See also ^{9}Li.

14. ^{9}Be(γ, γ)^{9}Be

See (1964LO1C).

15. (a) ^{9}Be(γ, n)^{8}Be $\quad Q_m = -1.665$

(b) ^{9}Be(γ, α)^{5}He $\quad Q_m = -2.528$

(c) ^{9}Be(γ, n)^{4}He + ^{4}He $\quad Q_m = -1.570$

(d) ^{9}Be(γ, 2n)^{7}Be $\quad Q_m = -20.561$

The photoneutron cross section has been measured from threshold ($E_\gamma = 1664 \pm 4$ keV: (1956CO56)) to 320 MeV: see Table 9.6. A sharp peak occurs just above threshold, at $E_\gamma = 1.70$ MeV (1960WA06, 1961JA13) followed by a weak maximum at 2.4 MeV, a strong sharp peak at 2.95 MeV, and a broad maximum at 4.6 MeV (1961JA13). (1959TH15) find well-defined peaks at 11.3 ± 0.2 and 13.3 ± 0.2 MeV, with integrated cross sections of 4.0 and 3.9 MeV · mb. A considerable yield in the range $8 - 11$ MeV is also indicated (1959TH16). The giant resonance occurs at $20 - 22$ MeV (1953JO1B, 1953NA1A, 1956CO59). At $E_\gamma = 6.1$ MeV, the main processes appear to involve ^{9}Be(γ, n)^{8}Be*(2.9) and reaction (b) (1954CA1A). For $E_\gamma = 18$ to 25 MeV, ≈ 80% of (γ, n) processes lead to ^{8}Be*(16.6) (1964BE30). See also (1960SE1D, 1965KO08, 1965KO1B).

The total nuclear absorption cross section is about 2 mb at $E_\gamma = 10$ MeV: a deep minimum at ≈ 13 MeV is followed by a rise to ≈ 5 mb at 18 MeV and a slow decrease to ≈ 3 mb at 35 MeV (1965WY02). Fine structure is reported at $E_\gamma = 20.47 \pm 0.04$ and 20.73 ± 0.04 MeV (1964TE04). See also (1962MI15).

Measurements involving time-of-flight analysis of the neutron energies show the 1.7 and 3 MeV resonances in ground-state neutrons (n_0), but ascribe the 4.6 MeV structure to slow neutrons, arising from reactions (b), (c) or from n_1 to ^{8}Be*(2.9): ground-state neutrons account for < 10% of the total at this energy. The yield of n_0 remains essentially constant from 5 to 16 MeV, aside from a broad maximum near 10 MeV and a shallow minimum at 13 MeV. The yield of n_1 rises

Table 9.6: The ^{9}Be(γ, n)^{8}Be cross section

E_γ (MeV)	σ (mb)	References
1.69 (^{124}Sb)	1.262 ± 0.069	1959GI48
	1.31 ± 0.08	1962JO17
1.69 (brems.)	1.2 ± 0.12	1960WA06
1.70 (brems.)	1.15 ± 0.15	1961JA13
1.72 (^{206}Bi)	1.22 ± 0.11	1962JO17
1.77 (^{56}Mn)	0.6	1948RU1A: see 1953HA1B, 1957ED01
1.78 (^{28}Al)	0.88 ± 0.06	1962JO17
1.85 (^{88}Y)	0.654 ± 0.031	1959GI48
2.185 (^{144}Pr)	0.39	1953HA1B
2.40 (brems.)	0.55 ± 0.1	1961JA13
2.5 (^{140}La)	0.5	1948RU1A: see 1953HA1B
2.61 (THC$''$)	0.39 ± 0.02	1957ED01
2.76 (^{24}Na)	0.7	1948RU1A: see 1953HA1B
	0.674 ± 0.05	1950SN67
2.95 (brems.)	1.2 ± 0.2	1961JA13
4.4 (^{15}N(p, α)^{12}C)	0.186 ± 0.32	1957ED01
4.6 (brems.)	1.0 ± 0.3	1961JA13
6.2 (^{19}F(p, α)^{16}O)	1.13 ± 0.1	1957ED01
8.1 (^{13}C(p, γ)^{14}N)	1.38 ± 0.16	1957ED01
10 [a] (brems.)	1.6	1953NA1A
11.25 ± 0.2 [b] (brems.)	4.7	1959TH15
12 (brems.)	≈ 0	1959TH15
13.25 ± 0.2 [c] (brems.)	3.3	1959TH15
14.2 (brems.)	0.1	1959TH15
16 (brems.)	1.0	1959TH15
18 (brems.)	0.8	1953NA1A, 1959TH15
22 [d] (brems.)	3.0	1953NA1A
$25 - 320$ (brems.)	$3 - 2$	1953JO1B

[a] Broad resonance: $\Gamma \approx 8$ MeV.
[b] $(2J + 1)\Gamma_\gamma = 530$ eV.
[c] $(2J + 1)\Gamma_\gamma = 720$ eV.
[d] Giant resonance.

sharply near 6 MeV, showing signs of a sharp peak at 7 MeV and remains high until about 10 MeV where it falls rapidly to a minimum at $13 - 14$ MeV. There is evidence of a broad peak near 12 MeV (1963DE1J). For $E_\gamma = 5.6$ to 8.5 MeV, the relative contribution of n_0 ranges from 0.5 to 0.3 (1963BO32).

Angular distributions of neutrons from the 1.67 and 4.6 MeV levels are isotropic; those from the 2.4 MeV level show slightly higher yield at $\theta = 90°$. Neutrons from the 3.0 MeV level have the distribution $\sigma(\theta) = 1+(1.0\pm0.2)\sin^2\theta$, compatible with E1 excitation to a $\frac{5}{2}^+$ D-state (1961JA13: see also (1949HA1A, 1961BA1G)). Some fore and aft asymmetry may indicate the presence of odd-parity amplitudes (1965PH1B). The fact that the 3.0 MeV state is strongly excited in (γ, n) and not in $180°$ (e, e′) (M1 excitation) also indicates positive parity (1961BL1D). The same argument suggests positive parity (E1 transitions) for levels at 1.7, 6.8, 7.9, 9.2, 11.3 and 13.3 MeV (1959TH16). For $E_\gamma = 5.6$ to 8.5 MeV, angular distributions are of the form $1 + A\sin^2\theta$, with $A = 0.20$ to 0.27, consistent with $P_{\frac{3}{2}} \rightarrow D_{\frac{3}{2}}$ transitions (1962BO08, 1962BO21, 1963BO32). Evidence for polarization of neutrons is reported by (1964CO17). See also (1959KU84, 1961VA09, 1964AL33).

Calculations of the (γ, n) cross section near threshold have been made by (1960FR1B), using a single-particle model with a diffuse-surface Saxon-Woods potential and assuming a $\frac{1}{2}^+$ level at $E_x = 1.70$ MeV. A good account of the observations is obtained, but with a rather large diffuseness parameter, $a = 1.2$ fm, in the final state. If the parameter is taken to be $a = 0.6$ fm, the calculated cross section is about 1.6 times too high. According to (1961BL1D), a model in which the neutron in ^{9}Be(0) is strongly coupled to a deformed ^{8}Be core leads to a sizable probability of excitation of the core to the 2^+ state, reducing the calculated cross section at 1.7 MeV. The 4.7 MeV structure is then ascribed to transformations in which ^{8}Be is left in the excited 2^+ state. A calculation of the low-energy excitation function has been made by (1963CO05) using the same model as (1960FR1B) but fixing the final state diffuseness parameter at $a = 0.6$ fm, and varying the final state potential depth. The slope and magnitude of the observed (γ, n) cross section are best accounted for by a bound s-state, with energy 19^{+9}_{-5} keV below threshold (1963CO05). (1961BA1G) considers couplings of 1s and 1d neutrons to ^{8}Be(0) and ^{8}Be(2^+). With the 1.7 MeV level assumed $\frac{1}{2}^+$, $\frac{3}{2}^+$ and $\frac{5}{2}^+$ levels are predicted at 4.88 and 4.05 MeV, respectively. It is suggested that the 3.03 MeV level is an unresolved combination of $\frac{1}{2}^-$ and $\frac{5}{2}^+$. See also (1961GU1C, 1961KO1J, 1962CU05, 1962KO11, 1963CO1D, 1963SA09, 1964BI1E, 1964FR1C, 1964MA2E, 1965WE1E).

The cross section for reaction (c) is < 1 μb at $E_\gamma = 1.63$ MeV (1952AL26, 1952AL30). For reaction (d) see (1957LO1A).

16. (a) ^{9}Be(γ, p)^{8}Li $\qquad Q_m = -16.885$

(b) ^{9}Be(γ, np)^{7}Li $\qquad Q_m = -18.917$

The yield shows structure in the energy region corresponding to the ^{9}Be levels at $17 - 19$ MeV (1962CL06), followed by the giant resonance at $E_\gamma = 22.2$ MeV (1953HA1A: $\Gamma = 4.7$ MeV, $\sigma =$

2.72 mb), ≈ 23 MeV (1962CL06: $\sigma = 2.64 \pm 0.30$ mb). The angular and energy distributions of photoprotons in various energy intervals have been studied by (1956CO59, 1956KL19, 1962CH26, 1963KI1C, 1965KO08). At $E_{\text{brems.}}$(peak) $= 335$ MeV, the polarization of photoprotons at $45°$, $56°$ and $90°$ is small and is consistent with zero (1962LI13). See also (1959CH25, 1961MA36, 1962CU05, 1962MI15, 1962VO1D) and (1959AJ76).

17. (a) ^{9}Be(γ, d)^{7}Li $\quad Q_{\text{m}} = -16.693$
(b) ^{9}Be(γ, t)^{6}Li $\quad Q_{\text{m}} = -17.688$

The cross section for reaction (a) is appreciable only for γ-energies greater than the sum of the threshold energy and the binding energy of the most weakly bound nucleon in ^{7}Li. The main processes involved are then thought to be those in which the emission of deuterons is accompanied by one or more nucleons (1962BA62, 1962CH26, 1962VO1D). See also (1959CH25, 1960SH1D, 1962CU05, 1962MA1F, 1963BA1K, 1964SH1B, 1965KO08) and (1959AJ76).

18. ^{9}Be(e, e)^{9}Be

Elastic scattering of electrons has been studied at $E_{\text{e}} = 42$, 80, 125, 150, 190 and 300 MeV (1953HO79, 1954MC45, 1959ME24, 1963GO04). Analysis of the 190 and 300 MeV results has been carried out in terms of various models for the charge distribution; the r.m.s. radius is about 2.60 ± 0.2 fm, depending on the model. At large values of momentum transfer, a static spherical distribution seems inadequate and a contribution from the quadrupole distribution may be required (1959ME24). According to (1960WA1J) the 300 MeV data can be matched with a Fermi distribution plus a quadrupole distortion consistent with $Q = 0.02$ b. See also (1961WA1C, 1963GU1A). Magnetic scattering at $\theta = 180°$ gives indication of both M1 and M3 contributions (1965RA1C: see also (1963GO04)).

Inelastic scattering reveals a number of levels from 1.6 to 16.9 MeV (see Table 9.7). Of these, only the 2.43, (14.7), and (16.9) MeV levels are strong in $180°$ scattering, where M1 transitions should dominate (1960BA47, 1962BA1D, 1962ED02). Studies of the 2.4 and 6.7 MeV levels at smaller angles reveal strong E2 components; quantitative comparison with form factors and absolute cross sections predicted by the α-rotational model (1960IN1A) indicate $J^{\pi} = \frac{5}{2}^{-}$ and $\frac{7}{2}^{-}$, respectively, for these two levels. The excitation energies and transition widths are consistent with the assumption that they are members of a K $= \frac{3}{2}^{-}$ rotational band based on the ground state. The derived intrinsic g.s. quadrupole moment $Q_0 = 0.26 \pm 0.01$ b is nearly twice that obtained from the spectroscopic value $Q_0 = 5 \times 0.029$ b (1963NG01). In both this work and calculations of (1962KU1C) the rotational α-model shows increasing deviations from experiment for momentum transfer $q > 1$ fm^{-1}; the Nilsson model has the same fault, but in opposite sense. An intermediate coupling model with enhanced quadrupole charge distribution is superior (1962KU1C). See also (1961WA1C, 1965RA1D).

Table 9.7: Levels of ^{9}Be from ^{9}Be(e, e′)^{9}Be*

E_x in ^{9}Be (MeV)	Γ (keV)	Transition	J^π	Γ_γ (eV)	Reference
1.6 ± 0.2		(E1)	$(\frac{1}{2})^+$	4.5 ± 0.6	(1963NG01)
2.47 ± 0.02		M1	$\frac{5}{2}^-$	0.13 ± 0.03	(1960BA47)
				0.12 ± 0.02	(1962ED02)
		E2		$(2.6 \pm 0.1) \times 10^{-3}$	(1963NG01)
6.4 ± 0.1	2 ± 0.5	E2	$\frac{7}{2}^-$	0.109 ± 0.005	(1963NG01)
14.7 ± 0.3		M1	$(\frac{3}{2})^-$	18 ± 9	(1962ED02)
16.9 ± 0.4					(1960BA47)

Comparison of the inelastic scattering from the 1.6 MeV level at two angles indicates that this level is most probably excited by E1 (1963NG01). The fact that the 1.6, 3.0 and 4.7 MeV levels appear strongly in (γ, n) but not in (e, e′) at $180°$ suggests that these levels are excited by E1 transitions (1962ED02). [The 14.7 MeV level is presumably the $T = \frac{3}{2}$, $J = (\frac{3}{2})^-$ analogue of the ^{9}Li ground state; the 16.9 MeV level may correspond to the first excited state.] In the range 17 to 49 MeV, inelastic scattering appears to be largely via E1, E3, M2 to the exclusion of M1, E2, M3 (1962NG02, 1963NG1B, 1964NG1A).

19. (a) ^{9}Be(n, n)^{9}Be

(b) ^{9}Be(n, 2n)^{8}Be $\qquad Q_m = -1.665$

The neutron spectrum observed when ^{9}Be is bombarded with 3.7 MeV neutrons exhibits a structure which is consistent with the excitation of the ground states and the levels at 1.7, 2.4 and 3.1 MeV, with subsequent neutron emission from the latter two. It is concluded that the (n, 2n) process at this energy proceeds mainly via discrete states of ^{9}Be (1957HU14, 1958WA05). Time-of-flight studies from $E_n = 2.6$ to 6.0 MeV show that about $\frac{1}{2}$ of the inelastic processes involve ^{9}Be*(2.43). A continuous distribution may be ascribed either to ^{9}Be*(1.7) or to (n, 2n). Examination of the spectra at $E_n = 3.5$ MeV yields the result that the 2.43 MeV level decays only 12 ± 5 % via ^{8}Be$_{g.s.}$ (1959MA34). At $E_n = 14$ MeV, evidence is found for the participation of the 6.8 MeV level. A search for an angular correlation between outgoing neutrons yielded a negative result (1963JE05). At $E_n = 14$ MeV, the cross section for production of ^{9}Be*(2.4) is 200 ± 45 mb (1961CO1E), 200 ± 100 mb (1961MY01), 170 ± 30 mb (1958AN32) comparison with σ(n, 2n) $= 500$ mb (1964ST25) indicates that about $\frac{1}{3}$ of the (n, 2n) processes proceed via ^{9}Be*(2.4) (1958AN32). Elastic and inelastic neutron angular distributions show forward peaking at $E_n = 14$ MeV (1958AN32, 1958NA09). See also (1958BE1E, 1959CH1E, 1959SA04,

1959WI41, 1960BA24, 1960BA28, 1960LU1B, 1960MC04, 1963OP1A, 1964BO31, 1964CR1B, 1965LO1K, 1965RO1U) and ^{10}Be.

20. ^{9}Be(p, p)^{9}Be

Elastic scattering has been studied at $E_p = 6$ MeV (1963BL20), 5 to 15 MeV (1964BI19), 10 MeV (1956RA32), 6, 8 and 12 MeV (1963TE1B), 12 MeV (1958SU14), 14.5, 20 and 31.5 MeV (1956KI54), 16.6 to 36.6 MeV (1965AR1E), 18.9 MeV (1956DA03), 31 MeV (1953WRZZ, 1954FI35, 1956BE14), 48 MeV (1965WI1H), 142 MeV (1961TA06), 143 MeV (1964ST16), 160 MeV (1965RO1T), 316 MeV (1956CH80) and 725 MeV (1965MC04). All angular distributions show pronounced diffraction maxima characteristic of the optical model. Analysis in terms of the diffuse-surface optical model is discussed by (1957ME21). See also (1956KL55, 1959HI1H, 1959JO43, 1960NE09, 1960NE11, 1960SA28, 1961IS05, 1961JO18, 1961RE03, 1964CR1B, 1964SA1L, 1964VE1A).

Inelastic scattering is observed to states at 1.7, 2.4, 3.1, 4.8, 6.8, 7.9, 11.3 MeV and others: see Table 9.8. The structure at ^{9}Be*(1.7) is unsymmetrical, rising abruptly from threshold at $Q = -1.669$ MeV to a peak within < 14 keV (1962BR09). The width at half-maximum is 175 ± 25 keV (c.m.), indicating dominant s-wave emission of neutrons (1960SP08). According to (1960SP08) the structure does not represent a true state, but results from the spatial localization of the low-energy neutron and ^{8}Be after emission of the inelastically scattered proton. Using a specialized density-of-states function, they obtain a good match to the experimental shape in this hypothesis. See also (1963PH1A). On the other hand, (1962BA1C) find an equally good fit with a density-of-states function of Breit-Wigner shape, corresponding to a $J^\pi = \frac{1}{2}^+$ level at $E_x = 1.75$ MeV with width $\gamma_0^2 = 1.01$ MeV ($R = 4.35$ fm), parameters which also fit the (γ, n) cross section. At $E_p = 18.9$ MeV, the 1.7 MeV group is not observed; the upper limit to the intensity of the group is < 2% of that to the 2.4 MeV state (1962SC12). See also (1955GO48, 1956BO18, 1958MI1C, 1958SU14, 1964BI19, 1964SC1F, 1965WI1H).

The energy of the 2.4 MeV level is given as 2433 ± 5 (1951BR72), 2434 ± 5 (1956BO18), 2432 ± 4 (1955GO48), 2430 ± 5 keV (1960SP08); the width is ≤ 1 keV (1955GO48), ≤ 3 keV (1960SP08). Angular distributions of protons leading to the 2.4 MeV state are not well matched by plane wave direct interaction calculations (1962SC12). The 12 MeV data suggest $l = 0$ and 2 ($J^\pi = \frac{1}{2}^-$ or $\frac{5}{2}^-$) (1958SU14) while the 31 MeV data are best fitted by $l = 2$ (1956BE14, 1958SU14, 1962SC12). It appears that the relative inelastic cross sections for various levels are largely independent of bombarding energy or particle; in particular, the 2.4 and 6.8 MeV levels are always strong and the 1.7, 3.0 and 4.8 MeV levels always weak. It is suggested that the strong excitation of the former is relative to a collective enhancement of electric multipole transition strengths connecting them to the ground state (1958BL57, 1959PI45, 1962SC12). The excitation energies and inelastic cross sections are consistent with the assumption that they have $J^\pi = \frac{5}{2}^-$ and $\frac{7}{2}^-$, respectively. On the collective model, they are members of the ground state $K = \frac{3}{2}^-$ band: the $J = \frac{9}{2}^-$ member is then expected at $10 - 11$ MeV (1958BL57). See also (1964JA03, 1965HA17).

Table 9.8: Levels of ^{9}Be from ^{9}Be(p, p′)^{9}Be* [a]

(1955GO48, 1956BO18, 1960SP08)			(1956BE14)	(1952BR52)	(1958SU14)	(1962SC12)	(1965HA17)	
E_x	Γ	J^π	E_x	E_x	E_x	E_x	E_x	Γ
1.675 ± 2 [b]	175 ± 25	$\frac{1}{2}^+$			1.83			
2.432 ± 3	≤ 1		2.46 ± 50 [c]	2.5	2.43	2.43 [c]	2.35 ± 100	
3.030 ± 30	250 ± 50	$\frac{3}{2}^+, \frac{5}{2}^+$			(3.1)	3.04		
			5.0 ± 300		4.8	4.74	4.8 ± 200	
			6.76 ± 60 [d]	6.8	6.8	6.76 [e]	6.5 ± 300	1200 ± 200
			7.94 ± 80				7.9 ± 300	≈ 1000
			11.3 ± 200	11.6			11.2 ± 300	≈ 1000
			(14.5)				14.4 ± 300	≈ 1000
							16.7 ± 300	broad
			(17.5)				17.4 ± 300	broad
			(19.9 ± 100)				19.0 ± 400	broad
			(21.7 ± 100)				21.1 ± 500	broad
							22.4 ± 700	broad

[a] E_x in MeV $\pm$ keV, Γ in keV. See also (1951BR72, 1956ST30, 1958TY46, 1964JA03, 1965WI1H).
[b] Low-energy cutoff.
[c] $J^\pi = \frac{1}{2}^-, \frac{5}{2}^-$.
[d] $J^\pi = \frac{1}{2}^+, \frac{5}{2}^+, \frac{7}{2}^+$.
[e] $\Gamma = 1200 \pm 300$ keV.

The 3 MeV state has a width 250 ± 50 keV (1960SP08): $E_x = 3.03 \pm 0.03$ MeV (1956BO18), 3.04 ± 0.05 MeV (1960SP08). Comparison of the width with that of the mirror level ^{9}B*(2.79) suggests that the level decays either to ^{8}Be(0) via d-wave or to ^{8}Be(2^+) via s-wave: $J = \frac{3}{2}^+, \frac{5}{2}^+$ (1960SP08). See also (1955GR12, 1958TY46, 1960LU1B, 1961IS05, 1963BA1R, 1963BL20, 1963RU05).

21. ^{9}Be(p, d)^{8}Be $\qquad Q_m = 0.559$

Angular distributions of ground-state deuterons have been studied at $E_p = 4.9$, 5.5 MeV (1961RE03), 5 to 8 MeV (1951HA1A), 6.8 MeV (1960NE09, 1960NE11), 7 MeV (1964YA1A), 10 MeV (1956RA32), 12 MeV (1958SU14), 16.5 MeV (1956RE04), 22 MeV (1953CO1C), 31 MeV (1956BE14), 95 MeV (1956SE1A) and 155 MeV (1963BA1R, 1963RA01). The distributions in the range $E_p = 5$ to 31 MeV are substantially identical, contrary to the prediction of the simple Butler theory with fixed cut-off radius (1956GL25). An analysis by (1961RE03) (see Table 9.9), shows good agreement for the 12 to 31 MeV data with inclusion of a volume interaction, leading to $\theta_n^2 = 1.2\%$. Polarization of the deuterons has been studied at $E_p = 3$ MeV (1961LA17). See also (1960BA26, 1965MO27).

At $E_p = 95$ MeV, states of ^{8}Be near 16 to 18 MeV are strongly excited (1956SE1A). At $E_p = 155$ MeV, states at ≈ 16.6 and ≈ 18.9 MeV are excited with $0°$ differential cross sections of 3.6 and 1.15 mb/sr, respectively (1963BA1R, 1963RA01).

Table 9.9: Neutron reduced widths from ^{9}Be(p, d)^{8}Be (1961RE03)

$E_{\rm p}$ (MeV)	$\theta_{\rm n}^2$ (cut off) [a]	$\theta_{\rm n}^2$ (transp) [b]	Reference
4.85	0.0128 ± 0.0009	no fit	(1961RE03)
5.49	0.0146 ± 0.0010	no fit	(1961RE03)
12.0	0.024 ± 0.005	0.018	(1958SU14)
16.5	0.024 ± 0.007	0.012	(1956RE04)
22.0	no fit	0.012	(1953CO1C)
31.3	no fit	0.012	(1956BE14)

[a] Butler theory with cut-off radius.

[b] Volume interaction.

22. ^{9}Be(p, α)^{6}Li $\qquad Q_{\rm m} = 2.126$

Angular distributions and excitation functions for $E_{\rm p} = 3$ to 12 MeV suggest direct interaction. Analysis with DWBA in terms of ^{9}Be $\rightarrow$ ^{6}Li + t($l = 1$) yields fair agreement for α_0 but not for α_1 (1963BL20). The observed large cross section at back angles suggests that ^{9}Be is better described as ^{4}He + ^{5}He (1963SC1P). See also (1964YA1A, 1965MO27).

23. (a) ^{9}Be(p, 2p)^{8}Li $\qquad Q_{\rm m} = -16.885$

(b) ^{9}Be(p, pd)^{7}Li $\qquad Q_{\rm m} = -16.693$

(c) ^{9}Be(p, pα)^{5}He $\qquad Q_{\rm m} = -2.528$

The summed proton spectrum in reaction (a), observed at $E_{\rm p} = 155$ to 450 MeV shows two peaks, with $Q = -16.7 \pm 0.3$ and $Q = -25.8 \pm 0.4$ MeV, corresponding to removal of a p-proton and an s-proton respectively (1958MA1B, 1958TY49, 1961PU1A, 1962GA09, 1962GA23, 1962IN1A, 1963BE1A, 1963BE42, 1963BO1R, 1963RI1B, 1964BA1C, 1964TI02, 1965RI1A, 1966TY01).

At $E_{\rm p} = 155$ MeV, p-α correlations (reaction (c)) give evidence for a substructure ^{9}Be = ^{5}He + ^{4}He in a relative s-state with a probability of 7% (1963RU05).

For reaction (b), see ^{7}Li.

24. ^{9}Be(d, d)^{9}Be

Elastic scattering has been studied at intermediate energies by (1961BA06, 1962GR14: 7.8 MeV), (1963FR1F: 12.8 MeV), (1961IS04, 1963SA1G: 14.7 to 18.1 MeV), (1964HE01: 15.8

MeV), (1958SU14: 24 MeV), (1962SL03: 27.7 MeV). All show pronounced diffraction patterns. See also (1947GU1A, 1952EL01, 1959ZA01) and ^{11}B.

Inelastic groups are reported to states at 1.7, 2.4, 3.0, 4.8 and 6.8 MeV (1955RA41, 1956GR37, 1958MI1C, 1958SU14). The angular distributions to the 2.4 MeV state have been studied at $E_{\rm d} = 15$, 24 and 27.7 MeV (1956HA90, 1958SU14, 1962SL03). Analysis by direct interaction theory yields $l = 2$, $J = \frac{1}{2}^-$, $\frac{5}{2}^-$ or $\frac{7}{2}^-$. See also (1958BL57, 1959BL31, 1960EL09, 1960LU1B).

25. ^{9}Be(d, t)^{8}Be $\qquad Q_{\rm m} = 4.592$

Comparison of (d, t) and (p, d) pickup cross sections leads to an estimated form factor for the triton of 4 ± 1 fm^{-1} (1961RE03); this values is about 4 times larger than that estimated by (1960MA32).

26. ^{9}Be(^{3}He, ^{3}He)^{9}Be

See (1960IG01, 1962WE1C, 1964GO1J).

27. ^{9}Be(^{3}He, α)^{8}Be $\qquad Q_{\rm m} = 18.913$

See ^{8}Be.

28. (a) ^{9}Be(α, α)^{9}Be

(b) ^{9}Be(α, 2α)^{5}He $\qquad Q_{\rm m} = -2.528$

Elastic scattering has been studied at $E_\alpha = 9.5$ to 20 MeV (1965TA1C), 18.4 MeV (1964LU02), 23.8 MeV (1964GR39), 28 MeV (1964YA1A), 42 MeV (1956FA02: see (1958BL57)) and 48 MeV (1958SU14). Inelastic groups are observed to ^{9}Be*(1.8, 2.4, 3.0, 6.8, 11.3) (1955RA41, 1958SU14, 1964LU02, 1964YA1A). The angular distribution of the groups corresponding to the 1.8 MeV "level" is consistent with $J^\pi = \frac{1}{2}^+$ (1964LU02). The angular distribution of the $Q = -2.4$ MeV group, at $E_\alpha = 48$ MeV, indicates $l = 2$, $J = \frac{1}{2}^-$, $\frac{5}{2}^-$ or $\frac{7}{2}^-$ (1958SU14). Analysis based on the rotational model leads to a deformation coefficient $\beta_2 = 0.46$ (1959BL31), 0.34 ± 0.01 (1964GR39).

Measurement of the momentum and angular distributions of α-particles from the breakup of ^{9}Be*(2.4) indicates that the decay proceeds mainly via ^{4}He$+^{5}$He, or by direct three-body breakup. Gamma decay is < 1%, neutron emission to ^{8}Be(0) is < 10% (1957BO83: see also (1959MA34) in ^{9}Be(n, n$'$)^{9}Be*, and (1962ST12)). At $E_\alpha = 25.4$ MeV, the continuum has been analyzed in terms of a combination of three- and four-body breakup. At low energies the results are consistent with a mixture of $^9\mathrm{Be} + \alpha \to {}^8\mathrm{Be}(0) + \alpha + \mathrm{n}$, $^9\mathrm{Be}^*(2.4) \to 2\alpha + \mathrm{n}$ or $^5\mathrm{He} + {}^4\mathrm{He}$ (1962BR14). The third excited state is located at $E_\mathrm{x} = 3.04 \pm 0.03$ MeV, with $\Gamma = 300 \pm 50$ keV (1964LU02). See also (1958BL57, 1959PI45, 1962ST12, 1964GO1K, 1965SA1K) and ^{13}C.

29. ^{9}Be(^{7}Li, ^{8}Li)^{8}Be $\qquad Q_\mathrm{m} = 0.367$

Angular distributions of ^{8}Li nuclei observed for $E(^7\mathrm{Li}) = 2$ to 4.0 MeV, show pronounced peaks at $\theta_\mathrm{lab} = 60°$ to $30°$. The decrease of peak angle with increasing energy suggests a neutron transfer process (1957NO17, 1959NO40, 1960NO1A). The radial distribution of the ^{9}Be neutron is deduced for $R = 15$ to 30 fm (1960AL1H, 1960GE1B). See also (1963LE10, 1965PO1F).

30. (a) ^{9}Be(^{14}N, ^{14}N)^{9}Be
(b) ^{9}Be(^{16}O, ^{16}O)^{9}Be

Elastic scattering in reactions (a) and (b) for $E_\mathrm{c.m.} = 3$ to 15 MeV has been studied for angles near $90°$ (c.m.). The fact that no diffraction structure was found may reflect a more diffuse surface for ^{9}Be than for ^{12}C (1961KU1D, 1963KU1L). At $E(^{14}\mathrm{N}) = 27.3$ MeV no agreement is found with the predictions of a sharp cut-off model for elastic scattering (1959HA28). See also (1963WI1G).

31. ^{10}B(γ, p)^{9}Be $\qquad Q_\mathrm{m} = -6.587$

See (1956GO1G).

32. ^{10}B(n, d)^{9}Be $\qquad Q_\mathrm{m} = -4.363$

At $E_\mathrm{n} = 14$ MeV, groups are observed corresponding to ^{9}Be*(0, 2.43); no other groups are observed below $E_\mathrm{x} \approx 5.5$ MeV. The angular distributions of the deuterons indicate odd parity, $\frac{1}{2} < J \leq \frac{9}{2}$ for both states (1954RI15). See also (1955FR1F, 1956FR18, 1963CE1B, 1964TO1C) and ^{11}B.

33. ^{10}B(p, 2p)^{9}Be $\qquad Q_\mathrm{m} = -6.587$

The summed proton spectrum at $E_{\rm p} = 460$ MeV yields $Q = -6.7 \pm 0.5$, -11.9 ± 0.5, -17.1 ± 0.6 (all $l \neq 0$), and $Q = -30.5 \pm 0.6$ MeV ($l = 0$) (1966TY01). See also (1958TY49, 1961PU1A, 1962GA09, 1962GA23). See also (1963RI1B, 1964TI02) and ^{10}B.

34. ^{10}B(d, ^{3}He)^{9}Be $\quad Q_{\rm m} = -1.094$

At $E_{\rm d} = 10$ MeV, $\theta = 30°$, groups corresponding to ^{9}Be*(0, 1.7, 2.4, 3.0) are observed with relative intensities 1.0/0.07/0.70/0.16 (1965SY02).

35. ^{10}B(t, α)^{9}Be $\quad Q_{\rm m} = 13.227$

At $E_{\rm t} = 1$ MeV, α-groups are observed corresponding to ^{9}Be*(2.39, 3.06) (1955AL57). See also (1963HO19).

36. ^{10}B(^{14}N, ^{15}O)^{9}Be $\quad Q_{\rm m} = 0.706$

At $E(^{14}{\rm N}) = 27.5$ MeV, the ground state angular distribution shows a single maximum at $\theta_{\rm c.m.} = 30°$ ($\sigma(\theta) = 1.3$ mb/sr). The total ground-state transfer cross section is 1.34 ± 0.30 mb, corresponding to an interaction radius $R_{\rm min} \approx 2.2(A_1^{\frac{1}{3}} + A_2^{\frac{1}{3}})$ fm (1962NE01).

37. ^{11}B(n, t)^{9}Be $\quad Q_{\rm m} = -9.561$

Not reported.

38. (a) ^{11}B(p, ^{3}He)^{9}Be $\quad Q_{\rm m} = -10.325$
(b) ^{11}B(p, pd)^{9}Be $\quad Q_{\rm m} = -15.819$

Not reported. For reaction (b), see (1964BA1C).

39. ^{11}B(d, α)^{9}Be $\quad Q_{\rm m} = 8.028$

Alpha groups are reported corresponding to states at (1.75), 2.4 and 3.0 MeV (1956BO18, 1958KA31, 1958MI1C). The width of the 1.75 MeV structure is 224 ± 25 keV (1958KA31, 1966PU02). The energy of the 2.4 MeV state is 2422 ± 5 keV (1951VA08), 2431 ± 6 keV (1954EL10), 2424 ± 5 keV (1956BO18). The next state is at 3.02 ± 0.03 MeV (1955LE36), 3.05 ± 0.03 MeV (1956BO18). Its width is ≈ 0.3 MeV (1956BO18), $\Gamma_{\rm c.m.} = 257 \pm 25$ keV (1958KA31, 1966PU02). See also (1955HO48, 1961TE02, 1963RO22, 1964GR19, 1964YA1A).

The ratio of the γ-decay width to the total width, $\Gamma_{\rm rad}/\Gamma$, of the 2.4 MeV state is $(1.15 \pm 0.15) \times 10^{-4}$ (1964PU04). Since $\Gamma_{\rm rad}$ is known from (e, e′) (see (1962ED02) and Table 9.4), $\Gamma = 1.0 \pm 0.2$ keV. For the 1.7 MeV state $\Gamma_{\rm rad}/\Gamma < 2.6 \times 10^{-5}$ (1964PU04, 1966PU02).

40. ^{12}C(n, α)^{9}Be $\qquad Q_{\rm m} = -5.704$

Analysis of 128 cloud chamber stars involving ^{9}Be*(2.4) leads to the conclusion that the probability of ^{9}Be*(2.4) $\rightarrow$ n + ^{8}Be(0) is 13 ± 5 % (1965MO09). See also (1955GR21, 1962BA15, 1962BA25, 1963AL10, 1963DA12, 1963SE08, 1964BR25, 1964CH28).

41. ^{13}C(γ, α)^{9}Be $\qquad Q_{\rm m} = -10.651$

See (1953MI31).

^{9}B

(Figs. 17 and 18)

GENERAL: See (1959BA1D, 1960PH1A, 1960SP08, 1960TA1C, 1962BA1C, 1962IN02, 1964GR1J, 1964RE1C, 1964ST1B).

1. (a) ^{6}Li(^{3}He, p)^{8}Be $Q_{\rm m} = 16.787$ $E_{\rm b} = 16.601$
   (b) ^{6}Li(^{3}He, n)^{8}B $Q_{\rm m} = -1.975$

The excitation functions for protons leading to the ground and 2.9 MeV states of ^{8}Be (p_0 and p_1) have been measured for $E(^{3}\rm He) = 0.9$ to 17 MeV. Resonances are reported at $E(^{3}\rm He) = 1.6$ MeV ($\Gamma = 0.25$ MeV) and $E(^{3}\rm He) = 3.0$ MeV ($\Gamma = 1.5$ MeV) (1956SC01). Above 5 MeV, the p_0-yield at $0°$ increases monotonically with energy while that of the p_1 group decreases with energy. In the backward direction, there is a broad maximum in the yield at ≈ 6.5 MeV ($\Gamma \approx 4$ MeV) (1963MA02). The p_0 angular distribution is strongly backward below 7 MeV, and strongly forward at $E(^{3}\rm He) = 13$ and 17 MeV. At 9 MeV, the p_0 distribution is peaked in both the forward and the backward direction (1963MA02).

The yield of neutrons has been determined for $E(^{3}\rm He) = 3.0$ to 5.5 MeV. It increases linearly with energy above 3.4 MeV: at 5.5 MeV, the cross section is 21.5 ± 2.0 mb (1961FA04).

2. ^{6}Li(^{6}Li, t)^{9}B $Q_{\rm m} = 0.808$

See (1964KI02).

3. ^{6}Li(α, n)^{9}B $Q_{\rm m} = -3.977$

The ground-state threshold energy is 6.623 ± 0.020 MeV: $Q = -3.974 \pm 0.012$ MeV. Angular distributions at $E_{\alpha} = 8.0$, 10.0, 12.0 and 14.0 MeV all display strong forward peaking (1963ME08). At $E_{\alpha} = 14.4$ MeV, neutron groups are observed corresponding to the ground and 2.3 MeV states: the upper limit of the cross section to a state at ≈ 1.7 MeV is 100 μb/sr or $< 10\%$ of the ground-state group (1964BA29). See also ^{10}B.

4. ^{7}Li(^{3}He, n)^{9}B $Q_{\rm m} = 9.349$

Table 9.10: Energy levels of ^{9}B

E_x (MeV ± keV)	$J^\pi; T$	Γ (keV)	Decay	Reactions
g.s.	$> \frac{1}{2}^-; \frac{1}{2}$	0.54 ± 0.21	(p, α)	2, 3, 4, 6, 7, 9, 10, 11, 12, 14
(1.5)				6, 10, 12, 14
2.330 ± 2	$> \frac{1}{2}^-; \frac{1}{2}$	82 ± 8		3, 4, 6, 7, 10, 12, 14
2.830 ± 30	$\frac{3}{2}^+, \frac{5}{2}^+; \frac{1}{2}$	700 ± 160		4, 6, 12, 14
4.05 ± 30				6
(4.9)				6
(7.1)				4, 10
(9.7)				6, 10
11.62 ± 100		700 ± 100		6, 10, 12
12.06 ± 60	$\frac{1}{2}^-, \frac{3}{2}^-$	800 ± 150	p	4, 6, 8
14.01 ± 70		390 ± 110		4
14.670 ± 16	$; \frac{3}{2}$	< 45	γ	4, 6, 10
16.024 ± 25		180 ± 16		4, 6
17.185 ± 20		120 ± 40	p, d	4, 5
17.632 ± 8		71 ± 8	p, d, ^{3}He	1, 4, 5
(18.6)		1000	p, ^{3}He	1
(20.9)		≈ 4000	p, ^{3}He	1

At $E(^{3}\text{He}) = 1.2$ to 2.7 MeV, the ground state neutrons and a group corresponding to unresolved ^{9}B*(2.34, 2.81) are observed by time-of-flight, in addition to a continuum distribution. A broad maximum may indicate a level at $E_x \approx 7$ MeV (1961DU1B, 1963DU12). The ground state angular distribution has been analyzed in terms of DWBA: $L = 2$, $J^\pi \leq \frac{7}{2}^-$ is indicated (1963DU12). Analysis of the continuum in terms of plane wave stripping to ^{8}Be + n + p is reported by (1964DU1E).

At $E(^{3}\text{He}) = 5$ to 12.5 MeV, time-of-flight spectra yield evidence for levels at 12.06 ± 0.06, 14.01 ± 0.07, 14.670 ± 0.016, 16.024 ± 0.025, 17.19 and 17.63 MeV. The widths of the four lower states are 800 ± 200, 390 ± 110, < 45 and 180 ± 16 keV, respectively (1964DI1A, 1965DI03). The 14.67 MeV state is the first $T = \frac{3}{2}$ state in ^{9}B (1965DI03). It is observed to decay by γ-emission of about equal intensities to the ground and 2.3 MeV states of ^{9}B (1965GR08). See also (1959LE24, 1962SE1A) and ^{10}B.

5. ^{7}Be(d, p)^{8}Be $\qquad Q_m = 16.672 \qquad E_b = 16.486$

For $E_d = 0.75$ to 1.70 MeV, resonances in the yields of protons are observed at 0.900 ± 0.025 MeV (p_0, p_1) and 1.475 ± 0.010 MeV (p_1 only), with $\Gamma_{c.m.} = 120 \pm 40$ and 71 ± 8 keV, respectively (^{9}B* $= 17.19$ and 17.63 MeV) (1960KA17).

6. ^{9}Be(p, n)^{9}B $\quad\quad$ $Q_m = -1.851$

Neutron spectra show a level at 2.37 ± 0.04 MeV (1953AJ09: $E_p = 6.59$ MeV). Evidence is also reported for states at (1.4), 3.07, 4.14 and 4.93 MeV (1960SA03: $E_p = 14.1$ MeV), 4.7, 10.3, 11.3, 12.8, 14.7 and 16.6 MeV ((1958AD1A) and C. Waddell; private communication: ± 0.2 MeV; $E_p = 31.5$ MeV). See also (1961AD02, 1962BO33). At $E_p = 6.3$ and 7.4 MeV, the upper limit to the cross section for formation of a state at $E_x \approx 1.7$ MeV is 100 μb/sr (1964BA29). Angular distributions have been obtained for $E_p = 2.0$ to 4.3 MeV with special reference to the elucidation of the n-p interaction (1961AL07: see also (1965WA04)). Polarizations and angular distributions of ground-state neutrons have been measured from $E_p = 2.4$ to 8.5 MeV by (1963KE03, 1963KE09: see also ^{10}B). Angular distributions have also been measured at $E_p = 2.3$ to 2.6 MeV (1964AN1E), 3.5 to 10.9 MeV (1965WA04: measurement of the polarization for $E_p = 7$ to 11 MeV), 8 to 14 MeV (1960SA03), 18.5 MeV (1964AN1B). See also (1964SA1D).

For $E_p = 2$ to 5.8 MeV, two neutron thresholds are observed at $E_p = 2.060 \pm 0.003$ MeV (^{9}B(0)) and 4.645 ± 0.005 MeV (^{9}B* $= 2.326 \pm 0.006$ MeV $+ \frac{1}{2}\Gamma$) (1955MA84). A broad threshold is observed at $E_p = 3.6$ MeV (1955MA84, 1961TA12) but its relevance to a ^{9}B level at ≈ 1.4 MeV is not clear (1959MA20, 1960SP08). An anomaly in the neutron yield curve at $E_p = 6.55 \pm 0.03$ MeV is ascribed to a state in ^{9}B at $E_x = 4.04 \pm 0.03$ MeV (1964BA16).

The width of the ground state is < 2 keV (1951ST76), 540 ± 210 keV; $\theta^2 < 0.25$ (1964TE01).

7. ^{9}Be(^{3}He, t)^{9}B $\quad\quad$ $Q_m = -1.087$

The ground-state tritons are peaked in the forward direction at $E(^3\text{He}) = 4.0$ and 4.4 MeV (1963BO1P), 5.7 MeV (1959HI69) and 25 MeV (1960WE04). At the higher energy, only the ground state and the excited state at 2.33 MeV are observed above the continuum up to $E_x = 15$ MeV; the tritons to the 2.3 MeV state show only weak diffraction maxima (1960WE04). See also (1960TA04, 1962WE1C, 1965CR1C).

8. ^{9}C(β^+)^{9}B $\rightarrow$ ^{8}Be + p $\quad\quad$ $Q_m = 16.76$

Delayed protons are observed corresponding to an excited state of ^{9}B at 12.05 ± 0.2 MeV with $\Gamma = 800 \pm 100$ keV (1965HA09): see ^{9}C.

9. ^{10}B(γ, n)^{9}B $\qquad Q_{\rm m} = -8.438$

See (1951SH63).

10. ^{10}B(p, d)^{9}B $\qquad Q_{\rm m} = -6.213$

At $E_{\rm p} = 18.9$ MeV, deuteron groups are observed leading to the ground and 2.3 MeV states (1956RE04). Assuming $J = \frac{3}{2}^-$ and $\frac{5}{2}^-$, respectively, for these two states the ratio of reduced widths is 1/0.8 (1960MA32). At $E_{\rm p} = 11$ MeV, a broad structure is observed which may indicate a level at $E_{\rm x} = 1.6$ to 2.0 MeV (1964FA06). At $E_{\rm p} = 155$ MeV, deuteron groups are observed corresponding to the ground state and to excited states at 2.4, 7.1, 9.7, 11.4 and 14.7 MeV (1963BA2F). See also (1964SH07).

11. ^{10}B(d, t)^{9}B $\qquad Q_{\rm m} = -2.180$

At $E_{\rm d} = 13.5$ MeV, the angular distribution of the ground state tritons can be fitted by PWBA with $l_{\rm n} = 1$, $R = 5.4$ fm (1964FU15). See also (1956BO18).

12. ^{10}B(^{3}He, α)^{9}B $\qquad Q_{\rm m} = 12.140$

Alpha particle spectra observed with $E(^3{\rm He})$ up to 10.5 MeV show the ground-state group and groups corresponding to levels at 2.3, 2.8 and 11.6 MeV (Table 9.11): no other well-defined levels appear for $E_{\rm x} < 10$ MeV (1959PO61, 1960SP08, 1960TA12, 1963EA03, 1963FI14). A broad distribution of alpha particles is observed in the region corresponding to $E_{\rm x} = 1.4$ MeV, variously interpreted as arising merely from a spatial localization of (^{8}Be + p) with comparatively low disintegration energy (1960SP08), or as an actual $\frac{1}{2}^+$ level (1962BA1C). In the latter case, the level has $E_{\rm x} \approx 1.2$ MeV, $\Gamma = 1$ MeV, $\gamma_{\rm p}^2 = 1$ MeV, $R = 4.35$ fm; a ground-state reduced width $\gamma^2 = \hbar^2/ma^2 = 2.46$ MeV is indicated (1962BA1C).

The ratio of widths for ^{9}B*(2.3)/^{9}Be*(2.4) suggests that both decay by $l = 0$ or 1 to ^{8}Be*(2^+). If $J^\pi = \frac{5}{2}^-$ is assumed, the fractional parentage coefficient for (^{8}Be(0) + $l = 3$) is $< 10^{-3}$. Comparison of ^{9}B*(2.8)/^{9}Be*(3.0) suggests decay either to ^{8}Be(2^+) + $l = 0$ or ^{8}Be(0) + $l = 2$ (1960SP08). (1965WA1M) find that the decay of ^{9}B*(2.3) is mainly via ^{5}Li + α, while ^{9}B*(2.8) decays mainly to ^{8}Be(0) + p. The apparent inhibition of ^{9}B*(2.3) $\rightarrow$ ^{8}Be(0) indicates $J \geq \frac{3}{2}$ (1965WA1M). See also (1964ET02, 1965ET1A).

13. ^{11}B(p, t)^{9}B $\qquad Q_{\rm m} = -11.412$

Table 9.11: Levels of ^{9}B from ^{10}B(^{3}He, α)^{9}B

E_x [a] (MeV)	Γ (keV)	Reference
2.330 ± 0.002	83 ± 9	(1960SP08)
2.333 ± 0.010		(1960TA12)
2.370 ± 0.020	80 ± 15	(1959PO61)
2.830 ± 0.030	≈ 300	(1959PO61)
2.790	700 ± 200	(1960SP08)
2.830 ± 0.10	700 ± 250	[b]
11.62 ± 0.10	700 ± 100	(1963FI14)

[a] Based on Q_m.
[b] G.D. Symons, private communication.

See (1965RE1A).

14. ^{12}C(p, α)^{9}B $\qquad Q_m = -7.554$

At $E_p = 15.6$ and 18.6 MeV, groups are observed leading to the ground and 2.3 MeV states, and angular distributions have been obtained for the ground state alphas (1955RE16, 1962MA40). (1955RE16) does not observe any other sharp groups up to $E_x \approx 7.9$ MeV (see also (1958KN52)). The evidence concerning a broad state at $E_x \approx 1.5$ MeV is not clear: see (1962SY01, 1964BA29, 1964SY02, 1965IS05). At $E_p = 16.0$ and 18.3 MeV, α-particles corresponding to an excited state at $E_x = 2.9 \pm 0.2$ MeV have been observed (1964BA29). Stars presumed to arise from the reaction ^{12}C + p $\rightarrow \alpha + {}^9$B $\rightarrow 3\alpha$ + p have been analyzed in terms of transitions through the ^{9}B ground and 2.3 MeV states (1955NE18, 1962VA1A, 1963VA04: $E_p = 29$ MeV). See also (1961SE1C).

^{9}C
(Fig. 18)

GENERAL: See (1955AJ61, 1956SW77, 1964GR1J, 1964WI1B, 1965JA1C, 1965WO01).

$Mass\ of\ ^{9}C$: The atomic mass excess of ^{9}C is 28.99 ± 0.07 MeV: see ^{12}C(^{3}He, ^{6}He)^{9}C (1965CE1A).

1. ^{9}C(β^{+})^{9}B $\rightarrow$ ^{8}Be + p $\qquad Q_{\rm m} = 16.76$

Two groups of delayed protons are observed, indicating a component of the β^{+} decay to a level of ^{9}B at 12.05 ± 0.2 MeV with $\Gamma = 800 \pm 100$ keV which then decays to p + ^{8}Be(g.s.) and ^{8}Be*(2.9). The half-life is 127 ± 3 msec. The allowed character of the decay suggests $J^{\pi} = \frac{1}{2}^{-}$, $\frac{3}{2}^{-}$ or $\frac{5}{2}^{-}$ for the ^{9}B state, assuming the ^{9}C(g.s.) has $J^{\pi} = \frac{3}{2}^{-}$. The near equality of intensity of the two proton groups to ^{8}Be(g.s.) and ^{8}Be*(2.9) favors $J^{\pi} = \frac{1}{2}^{-}$ for ^{9}B*(12.1) (1965HA09). See also (1961DA14).

2. ^{7}Be(^{3}He, n)^{9}C $\qquad Q_{\rm m} = -6.36$

Not reported.

3. ^{12}C(^{3}He, ^{6}He)^{9}C $\qquad Q_{\rm m} = -31.66$

At E(^{3}He) $= 65$ MeV, the transition to the ground state of ^{9}C has been observed with a differential cross section of ≈ 1.5 μb/sr for $\theta = 16^{\circ} - 26^{\circ}$ (1964CE04). The mass excess of ^{9}C is 28.99 ± 0.07 MeV (1965CE1A).

4. ^{10}B(p, 2n)^{9}C $\qquad Q_{\rm m} = -25.79$

The threshold energy is ≈ 29 MeV (1965RO1G). See also (1965HA09).

5. ^{11}B(p, 3n)^{9}C $\qquad Q_{\rm m} = -37.25$

See (1965HA09).

6. ^{12}C(p, d2n)^{9}C $\qquad Q_{\rm m} = -50.98$

The threshold energy is 52 ± 3 MeV (1965HA09).

References

(Closed July 01, 1965)

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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