Revised Manuscript *07 November 2017*

Energy Levels of Light Nuclei
$A = 9$

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

(References closed December 01, 1958)

The original work of Fay Ajzenberg-Selove was supported by the US Department of Energy [DE-FG02-86ER40279]. Later modification by the TUNL Data Evaluation group was supported by the US Department of Energy, Office of High Energy and Nuclear Physics, under: Contract No. DEFG05-88-ER40441 (North Carolina State University); Contract No. DEFG05-91-ER40619 (Duke University).

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^{9}Li

(Not illustrated)

Mass of ^{9}Li: From the threshold for ^{9}Be(d, 2p)^{9}Li, $E_{\rm d} = 19 \pm 1$ MeV (1951GA30), the mass excess of ^{9}Li is determined as $M - A = 28.1 \pm 1$ MeV.

1. ^{9}Li(β^{-})^{9}Be* $\rightarrow$ ^{8}Be + n $\qquad Q_{\rm m} = 12.4$

^{9}Li decays to excited states of ^{9}Be which decay by neutron emission. The mean of the reported half-lives is 0.169 ± 0.003 sec (1951GA30, 1952HO25). See also (1952SH44, 1953FR03, 1955BE1E, 1956FL1A, 1958TA04).

2. ^{9}Be(d, 2p)^{9}Li $\qquad Q_{\rm m} = -15.5$

The threshold is 19 ± 1 MeV (1951GA30).

3. ^{11}B(γ, 2p)^{9}Li $\qquad Q_{\rm m} = -31.4$

See (1952SH44, 1958TA04).

4. ^{12}C(γ, 3p)^{9}Li $\qquad Q_{\rm m} = -47.3$

See (1953RE19, 1958TA04).

The following reactions are not reported: ^{7}Li(t, p)^{9}Li ($Q_{\rm m} = -2.9$), ^{9}Be(n, p)^{9}Li ($Q_{\rm m} = -13.3$), ^{9}Be(t, ^{3}He)^{9}Li ($Q_{\rm m} = -14.1$) and ^{11}B(n, ^{3}He)^{9}Li ($Q_{\rm m} = -23.6$).

^{9}Be

(Fig. 10)

GENERAL:

Theory: See (1955DA1E, 1955FR1F, 1956BL1B, 1956DE1C, 1956KU1A, 1957BA1H, 1957PA1A, 1958KU1B).

Table 9.1: Energy levels of ^{9}Be

E_x in ^{9}Be (MeV)	$J^\pi; T$	Γ (keV)	Decay	Reactions
0	$\frac{3}{2}$		stable	2, 7, 13, 14, 15, 16, 17, 18, 19, 20, 22, 25, 26, 27
1.75 ± 0.02	$\frac{1}{2}^{(+)}$	150	n, γ	7, 10, 14, 15, 16, 17, 25
2.430 ± 0.002	$(\frac{5}{2}^-)$	< 1	(n), α	7, 13, 14, 15, 16, 17, 20, 22, 25, 26
3.04 ± 0.016	$(\leq \frac{3}{2})$	161 ± 15		7, 15, 16, 17, 22, 25
(4.74 ± 0.08)		1250		7, 15, 16
6.76 ± 0.06				13, 15, 16, 17
(7.94 ± 0.08)				15
(9.1 ± 0.2)		1200		7
(11.3 ± 0.2)			n, γ	10, 15, 17
(13.3)			n, γ	10
(14.5)				15
17.28		200	(d, p, n)	3, 4
17.48		50	(d, p, n)	3, 4, 15
(18.1)		(300)	(d, p, n)	3, 4
(18.6)			(d, p)	3
19.6			(d, p)	3, 15
(21.7 ± 0.1)			p, γ, n	11, 15

1. (a) ^{6}Li(t, d)^{7}Li $Q_{\rm m} = 0.994$ $E_{\rm b} = 17.687$

   (b) ^{6}Li(t, p)^{8}Li $Q_{\rm m} = 0.803$

   (c) ^{6}Li(t, n)^{8}Be $Q_{\rm m} = 16.021$

   (d) ^{6}Li(t, α)^{5}He $Q_{\rm m} = 15.158$

   (e) ^{6}Li(t, n)^{4}He + ^{4}He $Q_{\rm m} = 16.115$

The differential cross section at $90°$ for reaction (a) rises steeply from 8.8 mb/sr at $E_{\rm t} = 0.72$ MeV to 19 mb at 0.90 MeV, and then more slowly to 21 mb at $E_{\rm t} = 1.15$ MeV. For reaction (d), the differential cross section at $90°$ 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 (R.W. Crews, quoted in (1957JA37)).

See also (1952PE02), ^{5}He, ^{7}Li, ^{8}Li and ^{8}Be.

2. ^{6}Li(α, p)^{9}Be $Q_{\rm m} = -2.125$

See (1956WA29).

3. ^{7}Li(d, p)^{8}Li $Q_{\rm m} = -0.192$ $E_{\rm b} = 16.693$

Cross sections have been measured for $E_{\rm d} = 0.4$ to 1.8 MeV by (1952BA64), and for $E_{\rm d} = 0.7$ to 3.3 MeV by (1954BA46); see (1957JA37). The yield for $E_{\rm d} = 1.1$ to 4.0 MeV has been measured by (1956BE1A). Resonances are observed at 0.80 and 1.04 MeV (1952BA64, 1954BA46), 1.4 MeV (1952BA64: see, however, (1954BA46)), 2.0, 2.5 and 3.7 MeV (1956BE1A: see, however, (1954BA46)). See also (1955AJ61).

4. (a) ^{7}Li(d, n)^{8}Be $Q_{\rm m} = 15.026$ $E_{\rm b} = 16.693$

   (b) ^{7}Li(d, α)^{5}He $Q_{\rm m} = 14.163$

   (c) ^{7}Li(d, n)^{4}He + ^{4}He $Q_{\rm m} = 15.121$

The cross section for (a) has been measured for $E_{\rm d} = 70$ to 110 keV by (1955RA14) and that for (b) has been measured for $E_{\rm d} = 30$ to 250 keV by (1953SA1A). Resonances for neutron production occur, in the range $E_{\rm d} = 0.2$ to 4.8 MeV, at $E_{\rm d} = 0.68$ ($\Gamma = 250$ keV), 0.98 ($\Gamma = 60$ keV) and 1.8 MeV ($\Gamma = 400$ keV) (1952BA64, 1957SL01). At $E_{\rm d} = 0.90$ MeV, the α-particles in reaction (b) are isotropic to within 2%, consistent with formation by s-wave deuterons. No evidence is found for direct interaction effects at this energy (1957RI39). The angular correlation of ground-state α-particles with those resulting from breakup of ^{5}He indicate $J = \frac{5}{2}^{-}$ (1956RI37), $J = \frac{3}{2}^{-}$ (1957FA10), for the ^{9}Be level mainly responsible for this reaction at $E_{\rm d} = 0.9$ MeV.

Reactions (a) and (c) account for less than 10% of the disintegrations at this energy (1956RI37). See also ^{5}He, ^{8}Be and (1956CA1B).

5. (a) ^{7}Li(d, d)^{7}Li $E_b = 16.693$
(b) ^{7}Li(d, t)^{6}Li $Q_m = -0.994$
(c) ^{7}Li(d, ^{3}He)^{6}He $Q_m = -4.512$

The cross section for reaction (b) rises steeply from threshold to 95 mb at $E_d = 2.4$ MeV, and then more slowly to about 165 mb at $E_d = 4.1$ MeV (1955MA20). See also ^{6}He and ^{7}Li.

6. ^{7}Li(t, n)^{9}Be $Q_m = 10.435$

Not observed.

7. ^{7}Li(^{3}He, p)^{9}Be $Q_m = 11.200$

At $E_d = 0.7$ and 1 MeV, proton groups are observed corresponding to excited states of ^{9}Be at 1.83 ± 0.04 MeV ($\Gamma < 0.4$ MeV), 2.39 ± 0.08 MeV ($\Gamma < 0.2$ MeV), 3.10 ± 0.04 MeV ($\Gamma < 0.3$ MeV), 4.74 ± 0.08 MeV ($\Gamma = 1.25 \pm 0.25$ MeV) and (9.1 ± 0.2 MeV) ($\Gamma = 1.2$ MeV) (1954MO92, 1955AL57, 1958MO99). The 1.8-MeV level admits a description in terms of an s-wave n-^{8}Be interaction with a scattering length $a = 23 \times 10^{-13}$ cm (1958MO99: see ^{11}B(d, α)^{9}Be).

8. ^{7}Li(α, d)^{9}Be $Q_m = -7.151$

Not observed.

9. ^{9}Li(β^-)^{9}Be* $\rightarrow$ ^{8}Be + n $Q_m = 12.4$

See ^{9}Li.

10. (a) ^{9}Be(γ, n)^{8}Be $Q_m = -1.667$
(b) ^{9}Be(γ, α)^{5}He $Q_m = -2.529$
(c) ^{9}Be(γ, n)^{4}He + ^{4}He $Q_m = -1.572$
(d) ^{9}Be(γ, 2n)^{7}Be $Q_m = -20.565$

The photo-neutron cross section has been studied from threshold ($E_\gamma = 1.664 \pm 0.004$ MeV: (1956CO56)) to 320 MeV: see Table 9.2. A sharp peak, $\Gamma < 50$ keV, $\sigma \approx 100$ mb, occurs at $E_\gamma = 1.70$ MeV (1956CO56). A further broad maximum appears at $E_\gamma \approx 10$ MeV, followed by the giant resonance at $20 - 22$ MeV (1953JO1B, 1953NA1A: see (1956CO59)). Measurements from 6 to 18 MeV show pronounced peaks at 11.3 and 13.3 MeV and a broad, low peak at 16 MeV, immediately preceding the giant resonance (1959SP1B). At $E_\gamma = 6.1$ MeV the main processes appear to involve ^{9}Be(γ, n)^{8}Be*(2.9) and ^{9}Be(γ, α)^{5}He (1954CA1A). Angular distributions for $E_\gamma = 1.7$ and 1.8 MeV are spherically symmetric; at $E_\gamma = 2.76$ MeV, $W(\theta) = 1.2 + \sin^2\theta$ (1949HA1A: see also (1954NI1B, 1956FA30)).

Calculations of (1949GU1A) and (1956MA1M) envisage E1 transitions to p^{4}s and p^{4}d configurations, with levels at ≈ 1.8 and ≈ 5 MeV (assuming a fixed well depth). The angular distributions and general trend of the cross section are well accounted for, as is the ratio of σ(γ, n)/σ(e, e′n) (1958BA60: 6 to 17 MeV). (1956CO56) state, on the other hand, that the 1.70-MeV peak is to be attributed to an M1 transition.

See also (1954ER1B, 1955JO1B, 1958BA60, 1958CH31) and (1956CZ1B, 1956CZ1C, 1956DE1C, 1957KO1B; theor.).

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

11. (a) ^{9}Be(γ, p)^{8}Li $\qquad Q_{\rm m} = -16.885$
(b) ^{9}Be(γ, np)^{7}Li $\qquad Q_{\rm m} = -18.919$

The yield has a broad maximum, $\Gamma = 4.7$ MeV, at $E_\gamma = 22.2$ MeV where $\sigma = 2.72$ mb (1953HA1A). The angular and energy distributions of photoprotons produced by bremsstrahlung with $E_{\rm max} = 25$ to 80 MeV has been studied by (1956CO59, 1956KL19). The angular distributions can be accounted for by the direct interaction of γ-rays with individual nucleons (1956KL19). The energy distributions indicate that transitions to levels in the residual nucleus play an important part in the direct photo effect (1956KL19). (1956CO59) suggest, on the other hand, that the relatively large proportion of low-energy protons indicates predominance of a (γ, n) process, followed by proton emission from ^{8}Be levels at high excitation. See also (1953HE1B, 1953NA1A, 1957CH24, 1958CH31, 1958PA1B, 1958ST1A, 1958WH35).

12. (a) ^{9}Be(γ, d)^{7}Li $\qquad Q_{\rm m} = -16.693$
(b) ^{9}Be(γ, t)^{6}Li $\qquad Q_{\rm m} = -17.687$
(c) ^{9}Be(γ, α)^{5}He $\qquad Q_{\rm m} = -2.529$

See (1955AJ61), (1956CO59, 1958WH35) and ^{9}Be(γ, n)^{8}Be.

Table 9.2: Photoneutron cross section of ^{9}Be

E_γ (MeV)	σ (mb)	Refs.
1.69 (^{124}Sb)	1.262 ± 0.069	(1959GI48)
1.70 (brems.) [a]	100	(1956CO56)
1.77 (^{56}Mn)	0.6	(1948RU1A: see (1953HA1B, 1957ED01))
1.85 (^{88}Y)	0.654 ± 0.031	(1959GI48)
2.185 (^{144}Pr)	0.39	(1953HA1B)
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)
4.4 (^{15}N(p, α)^{12}C)	0.186 ± 0.32	(1957ED01)
6.2 (^{19}F(p, α)^{16}O)	1.13 ± 0.16	(1957ED01)
8.1 (^{13}C(p, γ)^{14}N)	1.38 ± 1.16	(1957ED01)
10 (brems.) [b]	1.6	(1953NA1A)
11.3 (brems.)	4.2	(1959SP1B)
12 (brems.)	0.1	(1959SP1B)
13.3 (brems.)	3.0	(1959SP1B)
14.2 (brems.)	0.1	(1959SP1B)
15 (brems.)	0.9	(1959SP1B)
17 (brems.)	0.8	(1953NA1A)
22 (brems.) [c]	3.0	(1953NA1A)
$25 - 320$ (brems.)	$3 - 2$	(1953JO1B)

[a] Resonance width < 50 keV.

[b] Broad resonance: $\Gamma \approx 8$ MeV.

[c] Giant resonance.

13. ^{9}Be(e, e$'$)^{9}Be*

Elastic scattering has been studied at $E_\mathrm{e} = 125$, 150 and 190 MeV (1953HO79, 1954MC45). An r.m.s. radius of $(2.2\pm0.2)\times10^{-13}$ cm is obtained (1957HO1E: see also (1956HO93)). Inelastic peaks corresponding to levels at 2.54 and 6.96 MeV are reported by (1954MC45). Comparison of $\sigma(\gamma$, n) and σ(e, e$'$n) for $E_\mathrm{e} = 6$ to 17 MeV indicates that the transitions are mainly E1 (1958BA60). See also (1957EH1A, 1958EH1A).

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

(b) ^{9}Be(n, 2n)^{8}Be $\qquad Q_\mathrm{m} = -1.667$

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 known states at 0, 1.5, 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). At the same bombarding energy (1955FO1B) observe two discrete groups in coincidence, suggesting the process ^{9}Be(n, n$'$)^{9}Be*(2.43) $\rightarrow$ n + ^{8}Be: see, however, (1957BO83: ^{9}Be(α, α')^{9}Be*). Using monochromatic neutrons with $E_\mathrm{n} = 2.6$ to 3.25 MeV, (1957FI52) finds a sharp threshold for (n, 2n) at $E_\mathrm{n} = 2.7$ MeV, corresponding to excitation of ^{9}Be*(2.43). On the other hand, (1958MA22) find evidence for (n, 2n) at $E_\mathrm{n} = 2.6$ MeV, below the threshold for (n, n$'$); at $E_\mathrm{n} = 5$ to 6 MeV, the spectra show neutrons from the direct (n, 2n) process. At $E_\mathrm{n} = 14$ MeV, the cross section for production of ^{9}Be* is 170 ± 30 mb; comparison with σ(n, 2n) $= 530 \pm 40$ mb indicates that about $\frac{1}{3}$ of the (n, 2n) processes proceed via ^{9}Be*(2.4) (1958AN32). See also (1957RO57) and (1958BE1E; theor.).

A search for γ-transitions from the 1.8 and 2.4-MeV levels yields upper limits of 0.3 and 0.2 mb, respectively, for $E_\mathrm{n} = 2.56$ MeV and 1.8 and 0.3 mb for $E_\mathrm{n} = 2.74$ MeV (1956DA23).

Elastic and inelastic neutron angular distributions show forward peaking at $E_\mathrm{n} = 14$ MeV (1958AN32, 1958NA09): see ^{10}Be, (1958RE1A, 1958TO1A).

15. ^{9}Be(p, p)^{9}Be

Elastic scattering has been studied at $E_\mathrm{p} = 14.5$, 20 and 31.5 MeV by (1956KI54), at 10 MeV by (1956RA32), at 12 MeV by (1958SU14), at 17 MeV by (1956DA03), at 31 MeV by (1953WRZZ, 1954FI35, 1956BE14): see also ^{10}B. 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, 1956SH1C).

Inelastic scattering is observed corresponding to levels at (1.8), 2.43, 3.1, 5.0, 6.8, 7.9, 11.3, (14.5), (17.5), (19.9) and (21.7) MeV: see Table 9.3. It is not clear whether the structure observed near 1.8 MeV is properly to be attributed to a level at this energy or to a three-body breakup,

Table 9.3: Levels of ^{9}Be from ^{9}Be(p, p′), (d, d′) and (α, α')

E_x (MeV)	Γ (keV)	J^π
0		
(1.8)	150 [a]	$(\frac{1}{2}^+)$ [a]
2.433 ± 0.003	≤ 1 [a]	$\frac{1}{2}^-$, $\frac{5}{2}^-$
3.03	> 280 [e]	$\leq \frac{3}{2}$
5.0 ± 0.3 [b]		
6.76 ± 0.06 [c]		$\frac{1}{2}^-$, $\frac{5}{2}^-$, $\frac{7}{2}^-$
7.94 ± 0.08 [b]		$\frac{3}{2}^+$, $\frac{5}{2}^+$, $\frac{9}{2}^+$, $\frac{11}{2}^+$
11.3 ± 0.2 [d]		
(14.5) [b]		
(17.5) [b]		
19.9 ± 0.1 [b]		$\frac{1}{2}^-$, $\frac{3}{2}^-$, $\frac{5}{2}^-$
21.7 ± 0.1 [b]		$\frac{1}{2}^-$, $\frac{3}{2}^-$, $\frac{5}{2}^-$ or $\frac{1}{2}^+$, $\frac{5}{2}^+$, $\frac{7}{2}^+$

[a] (1955GO48, 1957BO83, 1958SU14).

[b] (1956BE14).

[c] This level may be double: see (1952BR52, 1956BE14, 1956ST30, 1958SU14, 1958TY46).

[d] (1952BR52, 1956BE14, 1956ST30).

[e] See ^{11}B(d, α)^{9}Be (1958KA31).

modified by the proximity of the neutron threshold. If the former is correct, the level width is 0.15 MeV and $J = \frac{1}{2}^+$ (1955GO48, 1958SU14). If a three-body breakup is involved, some interaction between the neutron and the ^{8}Be must be involved: (1956BO18) find a satisfactory fit to the observed shape with an s-wave scattering length of 20×10^{-13} cm; see also (1958MI1C) and ^{11}B(d, α)^{9}Be. It is suggested by (1956SU67, 1958SU14) that the observed structure is to be understood in terms of a heavy particle stripping process and it is conjectured that the 4.8-MeV level may reflect the same effect, involving ^{8}Be*(2.9); see, however, (1958MI1C).

A continuous distribution of neutrons, observed for $E_p > 4.5$ MeV is attributed to formation of ^{9}Be*(2.4) with subsequent breakup into n + ^{8}Be*(2.9) (1959MA20). Breakup into (^{8}Be + n) occurs in 12 ± 5 % of transitions (J.B. Marion, private communication).

The energy of the 2.4-MeV level is given as 2433 ± 5 (1951BR72), 2434 ± 5 (1956BO18), 2432 ± 4 keV (1955GO48); the width is ≤ 1 keV (1955GO48). Analysis of angular distributions at $E_p = 12$ MeV in terms of direct interaction plus compound nucleus formation indicate $J = \frac{1}{2}^-$ or $\frac{5}{2}^-$ (1958SU14). At $E_p = 31$ MeV, analysis indicates $J = \frac{1}{2}^+$, $\frac{3}{2}^+$ or $\frac{5}{2}^+$ (1956BE14: see, however, (1958SU14)). Results at $E_p = 10$ MeV are consistent with odd parity (1956RA32). See also ^{10}B(n, d)^{9}Be and (1952DA1B).

The 3.03 ± 0.03 MeV level has a width > 0.28 MeV; the Wigner limit then restricts l_n to 0 or 1, $J \leq \frac{3}{2}$ (1956BO18: see, however, ^{11}B(d, α)^{9}Be). Angular distributions for the higher levels have been studied by (1956BE14); the resulting spin assignments are given in Table 9.3. See also (1954FI35, 1955GR12, 1958TY46) and (1956BL1B; theor.).

16. ^{9}Be(d, d′)^{9}Be*

Elastic scattering angular distributions have been studied at $E_d = 24$ MeV by (1958SU14). See also (1947GU1A, 1952EL01) and ^{11}B.

Inelastic groups are reported corresponding to levels at (1.7), 2.4, 3.01 ± 0.1 ($\Gamma \approx 0.3$), 4.8 and 6.8 MeV (1955RA41, 1956GR37, 1958MI1C, 1958SU14). The structure at $Q = -1.7$ MeV may be accounted for as a three-body breakup with an s-wave (n-^{8}Be) interaction characterized by a scattering length of 20×10^{-13} cm, or by a resonance of about single-particle width. In either case a $J = \frac{1}{2}^{+}$ level of ^{9}Be is indicated near the binding energy (1955RA41, 1958MI1C: see also ^{11}B(d, α)^{9}Be). The angular distribution of the $Q = -2.43$ MeV group has been studied at $E_d = 15$ MeV (1956HA90) and $E_d = 24$ MeV (1958SU14). Analysis by direct interaction theory yields $l = 2$, $J = \frac{1}{2}^{-}$, $\frac{5}{2}^{-}$ or $\frac{7}{2}^{-}$ (1958SU14: see, however, (1956HA90)). See also (1956SU1A).

17. ^{9}Be(α, α')^{9}Be*

Elastic scattering has been studied at $E_\alpha = 48$ MeV by (1958SU14).

Inelastic groups are observed corresponding to ^{9}Be* $= (1.8)$, 2.4, (3.1), 6.8 and 11.3 MeV (1955RA41, 1956FA02, 1958SU14). The group corresponding to the 1.8-MeV “level” has a peak at $Q = -1.83 \pm 0.03$ MeV, $\Gamma \approx 200$ keV. It is suggested, however, that just such a structure would be expected from a heavy particle stripping process in which the proton also escapes, preferentially with the maximum possible energy. In this case, the 4.8-MeV “level” might arise from a similar process, in which the final nucleus is now ^{8}Be*(2.9). 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). Measurement of the momentum and angular distributions of α-particles from the breakup of ^{9}Be*(2.4) indicate 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 (1956BL1B, 1958PI1B; theor.).

18. (a) ^{9}Be(p, d)^{8}Be $\quad Q_m = 0.560$
(b) ^{9}Be(d, t)^{8}Be $\quad Q_m = 4.592$

At $E_p = 95$ MeV, two groups of deuterons are observed from reaction (a), corresponding to ^{8}Be$_{\rm g.s.}$ and to states near 17 MeV. It is suggested that these reflect the “snatching” of the loosely bound neutron or of one of the tightly bound “alpha-particle” neutrons, respectively. Angular distributions lend some support to the α-particle model of ^{9}Be; the occurrence of high momenta for the tightly bound neutrons indicates the operation of strong short-range two-body forces (1956SE1A).

Angular distributions at $E_{\mathrm{p}} = 6.5$ and 22 MeV, and at $E_{\mathrm{d}} = 7.7$ MeV are analyzed in terms of pickup theory, using a square-well (n-^{8}Be) interaction to represent the ground state of ^{9}Be (1955DA1D, 1955DA1E). See also ^{10}B, ^{11}B.

19. (a) ^{10}B(γ, p)^{9}Be $\quad Q_{\mathrm{m}} = -6.585$

(b) ^{10}B(γ, p)^{8}Be + n $\quad Q_{\mathrm{m}} = -8.251$

For reaction (a) see (1956GO1F, 1956GO1G). For reaction (b) see ^{8}Be and ^{10}B.

20. ^{10}B(n, d)^{9}Be $\quad Q_{\mathrm{m}} = -4.358$

At $E_{\mathrm{n}} = 14$ MeV, the ground state and the level at 2.43 MeV are observed. No other deuteron groups were detected below $E_{\mathrm{x}} \approx 5.5$ MeV. The angular distribution of the deuterons, analyzed by pickup theory, indicate odd parity, $\frac{1}{2} < J \leq \frac{9}{2}$ for both states (1954RI15). See also (1956FR18), (1955FR1F; theor.) and ^{11}B.

21. ^{10}B(d, ^{3}He)^{9}Be $\quad Q_{\mathrm{m}} = -1.091$

Not observed.

22. ^{10}B(t, α)^{9}Be $\quad Q_{\mathrm{m}} = 13.228$

At $E_{\mathrm{t}} = 1$ MeV, α-groups are observed corresponding to ^{9}Be levels at 2.39 and 3.06 MeV (1955AL57).

23. ^{11}B(n, t)^{9}Be $\quad Q_{\mathrm{m}} = -9.564$

Not observed.

24. ^{11}B(p, ^{3}He)^{9}Be $\quad Q_{\mathrm{m}} = -10.329$

Not observed.

25. ^{11}B(d, α)^{9}Be $\quad Q_{\rm m} = 8.022$
$Q_0 = 8.015 \pm 0.010$ MeV (1956BO18).

Alpha-particle groups are reported to states at (1.75), 2.4 and 3.0 MeV. The structure corresponding to the 1.75-MeV state can be explained in terms of an (n-^{8}Be) interaction with a scattering length a of 20×10^{-13} cm or in terms of a resonance near threshold, with $\theta^2 \approx 1$ (1956BO18, 1958MI1C). (1958KA31) find, on the other hand, that a value of $a \geq 80 \times 10^{-13}$ cm is required to fit their distribution and suggest that the (n-^{8}Be) interaction must be very near resonance on this model. The energy of the 2.4-MeV state is given as 2422 ± 5 keV by (1951VA08), 2431 ± 6 keV (1954EL10), 2424 ± 5 keV (1956BO18). The next state is located at 3.02 ± 0.03 (1955LE36), 3.05 ± 0.03 MeV (1956BO18). The width is ≈ 0.3 MeV (1956BO18), $\Gamma_{\rm c.m.} = 161 \pm 15$ keV (1958KA31). See also (1955HO48).

26. ^{12}C(n, α)^{9}Be $\quad Q_{\rm m} = -5.709$

At $E_{\rm n} = 14$ MeV, the cross section to the ground state of ^{9}Be is 80 ± 20 mb; that to the 2.43-MeV level, $\sigma_{2.43}$, is $10 \leq \sigma_{2.43} \leq 210$ mb (1955GR21).

27. ^{13}C(γ, α)^{9}Be $\quad Q_{\rm m} = -10.654$

See (1953MI31).

^{9}B
(Fig. 11)

1. ^{6}Li(^{3}He, p)^{8}Be $\qquad Q_{\mathrm{m}} = 16.786 \qquad E_{\mathrm{b}} = 16.598$

The excitation functions for protons leading to the ground and 2.9-MeV excited states of ^{8}Be have been measured for $E(^{3}\mathrm{He}) = 0.9$ to 5.1 MeV ($\theta = 0°$ and $150°$, lab.). Resonances are observed at $E(^{3}\mathrm{He}) = 1.6$ MeV ($\Gamma = 0.25$ MeV, ^{9}B* $= 17.6$ MeV) and 3.0 MeV ($\Gamma = 1.5$ MeV, ^{9}B* $= 18.6$ MeV) (1956SC01). However, J.W. Butler (private communication) suggests that the decrease in the yield for $E(^{3}\mathrm{He}) \gtrsim 3$ MeV can be accounted for by competition from the ^{6}Li(^{3}He, n)^{8}B reaction with a threshold at 2.966 MeV. Angular distributions, taken at 6 energies, are isotropic at ≈ 1 MeV and become increasingly asymmetric at higher energies. In particular, the ground state protons exhibit strong backward peaking for $E(^{3}\mathrm{He}) \gtrsim 3$ MeV (1956SC01).

2. ^{6}Li(α, n)^{9}B $\qquad Q_{\mathrm{m}} = -3.979$

See (1956RO06).

3. ^{7}Li(^{3}He, n)^{9}B $\qquad Q_{\mathrm{m}} = 9.346$

Not reported.

4. ^{9}Be(p, n)^{9}B $\qquad Q_{\mathrm{m}} = -1.854$

The width of the ground state is < 2 keV (1951ST76). At $E_{\mathrm{p}} = 6.59$ MeV, a neutron group is observed corresponding to a level at 2.37 ± 0.04 MeV. A continuous distribution of neutrons, attributed to the (p, p′n) reaction, is also observed (1953AJ09, 1959MA20: see also (1950JO1B) and ^{9}Be). For $E_{\mathrm{p}} = 2$ to 5.8 MeV, two neutron thresholds have been observed at $E_{\mathrm{p}} = 2.060 \pm 0.003$ and 4.645 ± 0.005 MeV (^{9}B* $= 2.326 \pm 0.006$ MeV $+ \frac{1}{2}\Gamma$). The continued slow neutron yield above threshold suggests $l = 1$ neutron emission (1955MA84). A broad threshold reported at $E_{\mathrm{p}} = 3.6$ MeV appears to have been due to variation in counter sensitivity. It is possible, however, that part of the continuum neutron spectrum arises from a ^{9}B level expected near 1.4 MeV (1959MA20). See also (1957KI1B, 1958BO63).

Table 9.4: Energy levels of ^{9}B

E_x in ^{9}B (MeV)	J^π	Γ (keV)	Decay	Reactions
0	$> \frac{1}{2}^-$	< 2	(p, α)	4, 5, 6, 7, 8, 9, 11
2.37 ± 0.02	$> \frac{1}{2}^-$	80	(p, α)	4, 7, 9, 11
2.83 ± 0.03		300		9
(7.0)				11
17.6		170	p, ^{3}He, α	1
(18.6)		1000	p, ^{3}He, α	1

5. ^{9}Be(^{3}He, t)^{9}B $\quad Q_m = -1.089$

The ground state angular distributions are peaked in the forward direction at $E(^3\text{He}) = 5.7$ MeV (S. Hinds and R. Middleton) and 21 MeV (1958WE1E).

6. ^{10}B(γ, n)^{9}B $\quad Q_m = -8.439$

See (1951SH63).

7. ^{10}B(p, d)^{9}B $\quad Q_m = -6.212$

At $E_p = 18.9$ MeV, deuteron groups are observed corresponding to the ground state of ^{9}B and to an excited state at 2.40 ± 0.15 MeV. The angular distributions to both states, analyzed by pickup theory, show an $l = 1$ transfer, indicating odd parity, $\frac{1}{2} < J \leq \frac{9}{2}$, for these states (1956RE04). The ratio of cross sections is in good agreement with an intermediate-coupling calculation (1955FR1F).

8. ^{10}B(d, t)^{9}B $\quad Q_m = -2.180$
$Q_0 = -2.187 \pm 0.010$ (1956BO18).

9. ^{10}B(^{3}He, α)^{9}B $\quad Q_m = 12.139$

At $E(^3\mathrm{He}) = 1$ MeV, alpha-particle groups have been observed corresponding to the ground state of ^{9}B and to an excited state at 2.58 ± 0.13 MeV (1955AL57). At $E(^3\mathrm{He}) = 2$ to 3 MeV, groups are observed corresponding to the ground state and to levels at $E_x = 2.37 \pm 0.02$ MeV and 2.83 ± 0.03 MeV. The widths are 80 keV and 300 keV for ^{9}B*(2.37) and ^{9}B*(2.83), respectively. There is no evidence of a well-defined state corresponding to ^{9}Be*(1.75) (1958PO61, 1959PO61). See also (1959SP17).

10. ^{11}B(p, t)^{9}B $\quad Q_m = -11.418$

Not observed.

11. ^{12}C(p, α)^{9}B $\quad Q_m = -7.563$
$Q_0 = -7.58 \pm 0.1$ (1955RE16).

At $E_p = 18.8$ MeV, alpha-particle groups have been observed to the ground state of ^{9}B and to an excited state at 2.39 ± 0.08 MeV. The two α-groups are superimposed on a background possibly due to ^{12}C(p, p$'$)^{12}C* $\rightarrow 3\alpha$. The average differential cross section for the ground state group at $E_p \approx 18$ MeV is 3 ± 1 mb/sr. No other groups were observed up to $E_x \approx 7.9$ MeV (1955RE16). The angular distribution of the ground state group at $E_p = 15.6$ to 18.6 MeV is consistent with triton pickup or knock-on theories, except for discrepancies at low angles (1958MA40). At $E_p = 29$ MeV, the reaction appears to go to the ground state and to a level at 3.2 ± 1.0 MeV (1955NE18: stars in a cloud chamber; $^{12}\mathrm{C} + \mathrm{p} \rightarrow \alpha + {^9\mathrm{B}} \rightarrow 3\alpha + \mathrm{p}$). At $E_p = 32$ MeV, groups corresponding to ^{9}B(0), ^{9}B*(2.4) and a new level at 7.0 MeV are observed (1958KN52).

^{9}C

(Not illustrated)

Comparison with the mass of ^{9}Li leads to an estimated mass excess of 32.3 ± 2 MeV (1955AJ61). Analysis of a single star attributed to β-decay of ^{9}C and subsequent breakup into p + 2α yields $Q > 15.4$ MeV, mass excess > 30.2 MeV (1956SW77). Stability against ^{8}B + p requires a mass excess < 32.9 MeV. Two reactions leading to ^{9}C which have not been reported are ^{7}Be(^{3}He, n)^{9}C ($Q_m = -7$) and ^{12}C(γ, 3n)^{9}C ($Q_m = -54$).

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(Closed December 01, 1958)

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