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Energy Levels of Light Nuclei
$A = 6$

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Abstract: An evaluation of $A = 5$–10 was published in *Nuclear Physics* 78 (1966), p. 1. This version of $A = 6$ 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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^{6}He

(Figs. 4 and 7)

GENERAL:

See (1960PH1A, 1960TA1C, 1961AH1A, 1961BA1E, 1962IN02, 1962IN1A, 1963BO1K, 1963MO1F, 1963VL1A, 1964GR1J, 1964WA1E, 1965BO1C, 1965LO1G).

$Ground\ state : J = 0$ (1958CO68).

1. ^{6}He(β^-)^{6}Li $Q_{\rm m} = 3.510$

The decay proceeds to the ground state of ^{6}Li(1^+) and is a super-allowed Gamow-Teller transition. Recently reported end points are: $E_\beta = 3.50 \pm 0.05$ (1952WU22), 3.50 ± 0.02 (1956SC40), 3.508 ± 0.015 (1963VI06), 3.508 ± 0.004 MeV (1963JO04). The weighted mean decay energy, including recoil energy of 1.4 keV, leads to ^{6}He-^{6}Li $= 3509.8 \pm 3.8$ keV (1963JO04). Half lives are listed in Table 6.2. With a half life of 802 msec and E_{β^-}(max) $= 3508.4$ keV, $ft = 802$ (1965BA2C).

The electron-neutrino correlation has the form $W(\theta) = 1 + \alpha(\nu/c)\cos\theta$ with $\alpha = -0.39 \pm 0.05$ (1958HE46, 1959AL10), $\alpha = -0.353^{+0.033}_{-0.053}$ (1961RI03), $\alpha = -0.319 \pm 0.028$ (1963VI06), $\alpha = -0.3343 \pm 0.0030$ (1963JO15), in good agreement with the expected value $\alpha = -\frac{1}{3}$ for pure axial vector interaction. An upper limit to the possible contribution of tensor interaction is 0.4% (1963JO15). See also (1958CS88, 1959AL1E, 1959UB1A, 1961KO1H, 1961YU01, 1963CA1H, 1963DA04, 1963KI1D, 1964DE1G, 1965LO1H).

2. (a) ^{3}H(t, n)^{5}He $Q_{\rm m} = 10.374$ $E_{\rm b} = 12.302$
(b) ^{3}H(t, α)2n $Q_{\rm m} = 11.332$

At $E_{\rm t} = 1.9$ MeV, the α-spectrum observed at $30°$ extends from 1 to 7 MeV, with peaks at $E_\alpha = 2$ and 5 MeV. The same general shape is observed at other angles and for $E_{\rm t} = 0.95$ to 2.1 MeV. These peaks are attributed to a two-stage process involving formation and breakup of ^{5}He in the $\rm P_{\frac{3}{2}}$ and $\rm P_{\frac{1}{2}}$ states and are superposed on the three-body spectrum, reaction (b). Structure observed near the end point may indicate a correlation between the two neutrons (1958JA06). Alpha spectra observed at $\theta = 90°$, $E_{\rm t} = 0.2$ to 1.0 MeV, likewise exhibit a structure indicating appreciable contribution of ^{5}He$_{\rm g.s.}$; a peak ascribed to $\alpha + {\rm n}^2$ is reported (1961GO18).

At $E_{\rm t} = 1.48$ MeV, the neutron spectrum shows a continuum from 0 to 12 MeV with a broad peak at 11.3 MeV, corresponding to formation of ^{5}He in the ground state (1957BA10).

The cross section for neutron production rises monotonically from 0.1 to 2.2 MeV (1951AG30, 1957JA37, 1958JA06). The total cross section rises monotonically from 10 mb at $E_{\rm t} = 60$ keV to 82 mb at 1.14 MeV (1962GO1Q). At $E_{\rm t} = 1.90$ MeV, the total cross section for production

Table 6.1: Energy levels of ^{6}He

E_x (MeV $\pm$ keV)	$J^\pi; T$	Γ (keV)	Decay	Reactions
g.s.	$0^+; 1$		β^-	1, 5, 7, 8, 9, 10, 11, 12
1.797 ± 25	$(2)^+$	113 ± 20	n	9, 10, 11, 12
(≈ 15)	$(1^-, 2^-)$			9

of α-particles is 106 ± 5 mb (1958JA06). The zero-energy cross section factor $S_0 \approx 300$ keV · b (1964PA1A). See also (1964BA2B).

3. ^{3}H(t, t)^{3}H $E_b = 12.302$

Differential scattering cross sections have been measured at $E_t = 1.58$ to 2.01 MeV by (1956HO12). At $E_t = 1.90$ MeV, $\theta = 30°$, $\sigma(\theta) = 286$ mb/sr ($\pm$5%) (1958AL05). A phase shift analysis shows only ^{1}S hard-sphere scattering, with $R = 2.35$ fm (1955FR1C).

4. ^{4}He(t, p)^{6}He $Q_m = -7.512$

Not reported.

5. ^{6}Li(n, p)^{6}He $Q_m = -2.727$

See ^{7}Li and (1960VA1D).

6. ^{6}Li(t, ^{3}He)^{6}He $Q_m = -3.491$

Not reported.

7. ^{6}Li(γ, p)^{6}He $Q_m = -9.980$

See (1954TI16) and ^{7}Li.

Table 6.2: Half life of ^{6}He [a]

$\tau_{1/2}$ (msec)	Reference	$\tau_{1/2}$ (msec)	Reference
850 ± 50	(1946SO05)	799 ± 3	(1954KL36)
870 ± 60	(1947CA15)	850 ± 30	(1955RU06)
820 ± 60	(1948KN13)	852 ± 16	(1956VE10)
823 ± 13	(1949HO24)	830 ± 20	(1958HE46)
860 ± 30	(1952SH44)	797 ± 3 [a]	(1962BI14)
840 ± 30	(1952VE1A)	862 ± 17	(1962MA38)
830 ± 30	(1953BA04)	830 ± 20	(1963VI06)

[a] It is suggested that the longer half lives found in the older measurements may be due to impurities (1962BI14). We adopt here the mean of all cited values, weighted by the square of stated errors: 802 ± 3 msec.

8. ^{7}Li(n, d)^{6}He $\quad Q_m = -7.755$

See ^{8}Li.

9. ^{7}Li(p, 2p)^{6}He $\quad Q_m = -9.980$

The summed proton spectrum at $E_p = 155$ to 450 MeV shows two peaks with $Q \approx -11.6$ and -25.4 MeV corresponding to ^{6}He*(0, 1.80), and an excited state with $J = 1^-$ or 2^- at $E_x \approx 15$ MeV: see Table 6.3. Angular distributions indicate that the higher energy peak corresponds to ejection of a p-proton while the lower results from removal of an s-proton: see (1957TY35, 1958MA1B, 1958TY49, 1961GA09, 1961PU1A, 1962GA09, 1962GA23, 1962GO1P, 1962TI01, 1964TI02, 1965RI1A, 1965TY1A). See also ^{7}Li.

10. ^{7}Li(d, ^{3}He)^{6}He $\quad Q_m = -4.486$

At $E_d = 14.4$ MeV, the ground state and the 1.80 MeV level are observed. The angular distributions analyzed by pick-up theory indicate even parity for both states (1955LE24); $\theta^2 = 0.025$ and 0.008 (1960MA32). See also (1960HA14).

11. ^{7}Li(t, α)^{6}He $\quad Q_m = 9.834$

Table 6.3: ^{6}He levels from ^{7}Li(p, 2p)^{6}He

Q $(l = 1)$ (MeV)	Γ (MeV)	Q $(l = 0)$ (MeV)	Γ (MeV)	Reference
10.5 ± 1.6		24.9 ± 1.6		(1958TY49)
10.2 ± 1.6		23 ± 1.5		(1962GA09)
11.5 ± 2.5		25 ± 2.5		(1962GO1P)
10.1 ± 1.4		24.1 ± 1.5		(1961PU1A)
11.8 ± 0.3		25.5 ± 0.4		(1965TY1A)
11.3 ± 0.5	5.0	25.8 ± 0.6	5.5	(1964TI02)
11.6 ± 0.2		25.4 ± 0.3		mean

The energy of the first excited state is 1.71 ± 0.01 MeV, $\Gamma \lesssim 100$ keV (1954AL35, 1960AL10); 1.797 ± 0.025 MeV, $\Gamma = 113 \pm 20$ keV (1965AJ01). Evidence gas also been reported for states at 3.4 ± 0.2 MeV (1960AL10), (6.0 ± 0.9) and for one or more states at 9.3 ± 0.7 MeV (1956MA1R, 1956MA50): see, however (1965AJ01). The width of the proton group corresponding to the 1.8 MeV state and the absence of ^{6}He* recoils implies that this state decays predominantly into ^{4}He $+$ 2n (1954AL35, 1963MA1P, 1965AJ01). The branching ratio Γ_γ/Γ_n is $< 4 \times 10^{-4}$ (1964HU1A). Angular distributions at $E_t = 0.24$ keV are consistent with $J = 0$ and 2 for the ground state and 1.8 MeV level, respectively (1954AL38). At $E_t = 13$ MeV, the two angular distributions are strongly peaked forward (1965AJ01). See also (1956MA09, 1961HO01, 1961HO23) and ^{10}Be.

12. ^{9}Be(n, α)^{6}He $\qquad Q_m = -0.601$

(1964GA11) report α-groups to excited states at $E_x = 1.66 \pm 0.26$, 3.29 ± 0.38 and 6.05 ± 0.26 MeV. See also (1963AL18) and ^{10}Be.

^{6}Li

(Figs. 5 and 7)

GENERAL:

See (1955AU1A, 1955LA1C, 1956ME1A, 1957FR1B, 1957HU1C, 1957LE1E, 1958PI1A, 1959BA1M, 1959BR1E, 1959FE1B, 1959SK1A, 1959UB1A, 1960AN1B, 1960JA1G, 1960KO1D, 1960PH1A, 1960TA1C, 1960WA1F, 1961BA1E, 1961KO1G, 1961SH1B, 1961TA05, 1961VA1G, 1962CO1D, 1962CR09, 1962DI1B, 1962FO08, 1962GA09, 1962IN02, 1962IN1C, 1962IN1A, 1962JA06, 1962ME1C, 1962NA1B, 1962SA1F, 1962ST1E, 1962WA1E, 1963BO1K, 1963BU1C, 1963DA04, 1963EL1D, 1963HA1H, 1963JA1C, 1963JO07, 1963KL1A, 1963KU03, 1963KU1B, 1963MO1F, 1963OL1B, 1963SA1F, 1963SC1J, 1963SC30, 1963VL1A, 1963WA1H, 1964GR1J, 1964JI1A, 1964MA1G, 1964MI16, 1964NE1E, 1964OL1A, 1964SA1F, 1964SH05, 1964ST1B, 1964WA1E, 1965BE1R, 1965BE1H, 1965BO1C, 1965DA1H, 1965EL1B, 1965GO1L, 1965HA1L, 1965JA04, 1965JA1L, 1965LO1G, 1965LO1H, 1965MA1N, 1965MU1A, 1965NE1C, 1965RA1E, 1965SA1J).

Ground state :

$\mu = +0.82201$ nm (1965FU1G: see also (1962SC15)).

$Q = (-)0.5$ mb (1958TO34);

$Q = -(0.80 \pm 0.08)$ mb (1964WH01).

1. (a) ^{3}He(^{3}H, γ)^{6}Li	$Q_{\rm m} = 15.793$	$E_{\rm b} = 15.793$
(b) ^{3}He(^{3}H, p)^{5}He	$Q_{\rm m} = 11.138$	
(c) ^{3}He(^{3}H, p)^{4}He + n	$Q_{\rm m} = 12.096$	
(d) ^{3}He(^{3}H, n)^{5}Li	$Q_{\rm m} = 10.131$	
(e) ^{3}He(^{3}H, d)^{4}He	$Q_{\rm m} = 14.321$	
(f) ^{3}He(^{3}H, ^{3}H)^{3}He		

Capture γ-rays (reaction (a)) to the first three states of ^{6}Li have been observed for $E(^{3}\text{He}) = 1$ to 3 MeV: the differential cross section for the ground state transition ($90°$) varies from 1.4 μb/sr at $E(^{3}\text{He}) = 1.1$ MeV to 8 μb/sr at 3.0 MeV. At $E(^{3}\text{He}) = 1.1$ MeV the transitions to the 2.18 and 3.56 MeV states each have intensities $\approx 15\%$ that of the ground-state transition (1963KO04).

Angular distributions and total cross sections for reactions (b), (c) and (e) are given by (1963KU18) for $E_{\rm t} = 0.46$ to 1.09 MeV. The total cross section has also been determined for $E(^{3}\text{He}) = 0.1$ to 0.8 MeV (1953MO61), $E_{\rm t} = 0.15$ to 0.97 MeV (1960YO06), and at $E_{\rm t} = 1.9$ MeV (1963SM03). In the range $E_{\rm t} = 0.46$ to 1.09 MeV, the cross section increases from 27 to 53 mb (1963KU18). At

Table 6.4: Energy levels of ^{6}Li

E_x (MeV $\pm$ keV)	$J^\pi; T$	Γ (keV)	Decay	Reactions
g.s.	1^+; 0		stable	1, 4, 5, 6, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 23, 24
2.184 ± 2	3^+; 0	25 ± 1	γ, d, α	1, 4, 5, 8, 9, 10, 12, 13, 14, 15, 17, 18, 19, 21
3.562 ± 4	0^+; 1	< 5	γ	1, 4, 7, 9, 12, 17, 18, 19, 21
4.57 ± 34	2^+; 0	350 ± 150	d, α	4, 9, 12, 14, 19
5.36 ± 15	; (1)	320 ± 50		9, 12, 18, 19, 21
6.0 ± 200	1^+; 0		d, α	4
(6.77)	(2^-); 0		d, α	4, 8, 12
(7.8)	(1^-); 0		d, α	4, 8, 12
(9)	(0^-); 0		d, α	4, 9
(12.5)			γ, n	8
(14.0)	$+$			9
(15.8)	$+$			9

$E_t = 1.9$ MeV, it is 53 mb (1963SM03). The zero-energy cross section factor $S_0 \approx 1000$ keV $\cdot$ b (1964BA2B, 1964PA1A). See also (1961BA40).

The angular distribution of deuterons is isotropic at $E_t = 360$ keV (1953MO61), but from 0.5 to 1 MeV it shows an increasingly strong maximum at $90°$. It is suggested that the reaction proceeds via compound nucleus formation and that $l = 1$ is required (1963KU18).

For reaction (d), see (1963SM03). For reaction (f), see (1965LE02). See also (1963IN1A, 1963KU1H).

2. ^{4}He(d, γ)^{6}Li $\qquad\qquad$ $Q_m = 1.472$

An upper limit for capture radiation at $E_d = 1.06$ MeV (^{6}Li* $= 2.18$ MeV) is 0.1 mb (1954SI07). A search for resonant capture radiation at $E_d = 3.1$ MeV (^{6}Li* $= 3.56$ MeV) yields $\Gamma_{d\alpha} < 0.2$ eV. It is concluded that the intensity of parity non-conserving parts of the wave functions, $F^2 \lesssim 10^{-7}$ (1958WI15).

3. (a) ^{4}He(d, n)^{5}Li $Q_m = -4.190$ $E_b = 1.472$
(b) ^{4}He(d, p)^{5}He $Q_m = -3.182$
(c) ^{4}He(d, pn)^{4}He $Q_m = -2.225$

Neutron spectra have been measured at $0°$ for $E_d = 7.9$, 8.9 and 9.9 MeV, and at several angles at the higher energy. The neutrons show forward peaking, indicative of stripping via reaction (a). The differential cross section ($0°$) plotted for $E_d = 4.5$ to 18.6 MeV shows a monotonic rise from 0.5 to 150 mb/sr (1962LE12: see also (1964RO1D)). Neutron spectra at $E_d = 18.6$ MeV ($\theta = 0°$ and $180°$) indicate participation of reactions (a) ($0°$) and (b) ($180°$) (1961RY01). The proton spectra are also forward peaked at $E_d = 20.2$ MeV (1960AR1A) and 24 and 27 MeV (1963ER02). The proton yield over the range from 6.5 to 8.7 MeV excitation in ^{6}Li gives no evidence of a 7.4 MeV, $T = 0$ state (see Table 6.8) (1964OH01).

At $E_d = 20.2$ MeV, the (d, pn) cross section is nearly as large as that for the elastic scattering at $\theta \approx 45°$ (1960AR1A). Reaction (c) is presumably forbidden by isospin selection rules near threshold (1955HE90). See also (1965TO01).

4. ^{4}He(d, d)^{4}He $E_b = 1.472$

Elastic scattering studies have been carried out by (1949BL66: 0.9 to 3.5 MeV), (1953LA28: 1.0 to 1.2 MeV), (1955GA26: 0.3 to 4.6 MeV), (1947GU1A: 6.5 MeV), (1951BU1C: 7.9 MeV), (1964SE07, 1964SE1G: 2.9 to 11.5 MeV), (1964OH02: 3.5 to 10 MeV), (1962ST19: 6.0 to 13.7 MeV), (1963RO23, 1964RO1D: 5.7 to 14.3 MeV), (1951AL26: 10.3 MeV), (1954FR22: 13.7 and 19.0 MeV), (1960AR1A: 20.2 MeV), (1964BR43: 21 MeV), (1963VA14: 24.9 MeV), (1963ER02: 21.3 to 27.3 MeV).

Phase shift analyses have been carried out for the range $E_d = 0.3$ to 4.2 MeV by (1955GA74) and for 3 to 10 MeV by (1964SE07); see also (1964MC1F). Extrapolated phase shifts based on an optical model have been calculated by (1960GA08). The experimental s-wave phase shift decreases monotonically from $E_d = 0.3$ to 10 MeV: in the range 0 to 4 MeV it can be accounted for by hard-sphere scattering with $r = 5$ fm; if a radius of 3.5 fm is chosen, a contribution from the ground state is required, with θ^2_α(g.s.) $= 0.51$ (1955GA74, 1960GA08). The d-wave phase shifts are split and exhibit resonance at $E_x = 2.18$ (^{3}D$_3$), 4.87 (^{3}D$_2$) and 6.24 MeV (^{3}D$_1$): see Table 6.5 (1955GA74, 1964SE07). Single level analysis of the p-wave phase shifts indicate the possible presence of 2^-, 1^- and 0^- levels at 6.8, 7.8 and 9 MeV (1964SE07: see, however, (1964MC1F)). Preliminary analysis of data in the range $E_d = 5.6$ to 12.5 MeV shows no effect from the presumptive $T = 1$ levels at $E_x = 5.35$, 6.63 and 8.37 MeV (1963RO23), nor from the suggested $T = 0$ state at 7.4 MeV (1964MC1F). At $E_d = 21$ to 27 MeV, increasing complexity of the angular distributions suggest $l = 3$ wave contributions (1963ER02). See also (1964MC1F).

A (d+α) model has been constructed by (1960GA08) to reproduce the phase shifts of (1955GA74); with this model, phase shifts and polarization parameters have been extrapolated to 14 MeV. Polarization parameters have also been calculated for $E_d = 1.07$ MeV (1959GO1H, 1959PO1C),

Table 6.5: Levels of ^{6}Li from ^{4}He(d, d)^{4}He

E_{res} (MeV)	Γ (keV)	l_d	J^π	E_x [a] (MeV)	θ_d^2 [b]	Reference
		0	1^+	0	0.51	1955GA74
1.070 ± 0.003	35 ± 5	2	3^+	2.184	0.80	1955GA74
4.57 ± 0.08 }				4.6	1.0	1955GA74
5.10 }		2	2^+	4.87	1.59	1964SE07
$5.1 - 6.5$ }				5.7		1955GA74
7.16 }		2	1^+	6.24	1.59	1964SE07
7.95		1	2^-	6.77	0.27	1964SE07
9.5		1	1^-	7.8	0.21	1964SE07
11.6		1	0^-	9	0.21	1964SE07

[a] See also (1964MC1F).

[b] $R = 3.5$ fm.

at 2 and 3.5 MeV by (1959PH1B). A measurement at $E_d = 1.07$ MeV is consistent with expectation (1961PO01). Tensor polarization parameters for $E_d = 4$ to 7.5 MeV, measured by (1964MC1E, 1964SE1F), are in fair agreement with calculations of (1960GA08, 1964SE07). See also (1960DU1C, 1965GR1Q, 1965SE1E).

5. ^{4}He(^{3}He, p)^{6}Li $\qquad Q_m = -4.021$

Differential cross sections for formation of the ground and 2.18 MeV states of ^{6}Li have been measured for $E_\alpha = 27.5$ to 41 MeV. Protons to the 3.56 MeV state were not observed: intensity $< \frac{1}{5}$ of ground state group (1961CH09).

6. ^{6}He(β^-)^{6}Li $\qquad Q_m = 3.510$

See ^{6}He.

7. ^{6}Li(γ, γ)^{6}Li

The width, Γ_γ, of the 3.56 MeV state is in good agreement with that expected from the intermediate coupling shell model (8.7 eV): see Table 6.6 (1959CO67, 1963SK02). See also (1961VA1G, 1962BO17, 1962SE02).

Table 6.6: Levels of ^{6}Li from ^{6}Li(e, e′) and ^{6}Li(γ, γ)

E_x (MeV)	J^π	Γ_γ (eV)	B(E2↑) [a] (fm^4)	Reference
2.18	3^+	$4^{+3}_{-1.5} \times 10^{-4}$	32 ± 3	(1960BA47)
		3×10^{-5}		(1959DA04) [b]
3.56 [e]	0^+	6.2 ± 0.6		(1960BA47)
		4.7 ± 0.9		(1963BA19) [c]
		9 ± 2		(1963BE25)
		$9.1^{+2.0}_{-1.5}$		(1959CO67) [d]
		$8.8^{+1.9}_{-1.3}$		(1963SK02) [d]
4.52	2^+		18.2 ± 1.5	
5.35	(2^+)	0.16	7 ± 2	(1963BA19)
(7.40)	(1^+)		6 ± 2	
(8.37)	(1^+)		4 ± 2	
(9.3)	$0^+/1^+/2^+$	15/5/3		(1963BA19)
(14.0)	$0^+/1^+/2^+$	24/8/5		(1963BA19)
(15.8)	$0^+/1^+/2^+$	37.5/12.5/7.5		(1963BA19)

[a] (1963BE25, 1963BE53): E2 transition assumed; preliminary values.

[b] From ^{6}Li(γ, d).

[c] (1963BA19): M1 transitions assumed.

[d] From ^{6}Li(γ, γ).

[e] See also (1964GO15).

8. (a) ^{6}Li(γ, n)^{5}Li $\quad Q_m = -5.662$
   (b) ^{6}Li(γ, p)^{5}He $\quad Q_m = -4.655$
   (c) ^{6}Li(γ, d)^{4}He $\quad Q_m = -1.472$
   (d) ^{6}Li(γ, t)^{3}He $\quad Q_m = -15.793$

The total cross section for photoneutrons, measured with E(brems) $= 5$ to 20 MeV exhibits a peak at $E_\gamma = 12.5$ MeV, $\sigma = 2.8 \pm 0.53$ mb (1959RO62). Measurements with monochromatic γ-rays have been made for $E_\gamma = 5.4$ to 9.0 MeV by (1964GR40) and from 10 to 32 MeV by (1965BE42). The former work shows a smooth rise, with a possible peak at 6.75 MeV, while the latter yields a maximum at ≈ 12 MeV, $\sigma \approx 1.6$ mb and a gentle decrease to 0.6 mb at 32 MeV. See also (1951TI06, 1956ED15, 1964SH27). Another peak, at $E_\gamma \approx 26$ MeV is reported by (1963CO15): it is suggested that this peak corresponds to giant resonance excitation of the α-particle core (see also (1963BI10, 1963CO1D)); however, (1965BE42) find no evidence for this peak. At E(brems) $= 17.3$ MeV, 58% of the neutrons are ascribed to reaction (a), 31% to (b). A search for n-p correlations expected on the quasi-deuteron model for (γ, np) yielded a negative result (1960PR06). The integrated cross section (total neutrons) to 40 MeV is about 40 MeV · mb (1963CO15). See also (1964ER1B).

Photoprotons have been observed with E_γ up to 90 MeV: see (1959AJ76) and (1960BA45, 1962CH26, 1962VO1C). A peak in the proton spectrum corresponding to $E_x = 6.63$ or $E_x = 7.94$ MeV is reported by (1965SH1F). See also (1960KO14, 1961MA29, 1964BA2C, 1964ER1B, 1964MA1X).

The cross section for reaction (c) is $\lesssim 5$ μb in the range $E_\gamma = 2.6$ to 17 MeV (see (1959AJ76)) consistent with the expected inhibition of dipole absorption by isospin selection rules. In common with other (γ, d) reactions in light nuclei, an effective threshold first appears when sufficient energy is available to release at least one particle in addition to the deuteron (1962CH26, 1962VO1C, 1962VO1D). Resonant capture at the 2.18 MeV state is observed by (1959DA04): a value $\Gamma_\gamma = 30$ μeV is obtained. See also (1964KO1F).

For reaction (d), see (1962VO1C, 1964KO1F, 1965SH1F).

9. (a) ^{6}Li(e, e)^{6}Li

(b) ^{6}Li(e, p)^{5}He $\quad$ $Q_m = -4.655$

(c) ^{6}Li(e, d)^{4}He $\quad$ $Q_m = -1.472$

Elastic scattering has been studied at $E_e = 187$ (1955ST85, 1956HO93) and 426 MeV (1958BU17). Several different charge distributions provide acceptable fits to the observed form factors. The maximum charge density is 0.064 protons · fm^{-3}, $R_{rms} = 2.70 \pm 0.15$ fm (1958BU17, 1959ME24, 1960JA1G: see also (1958CA1B, 1963BO1K, 1963SC1J)). Magnetic elastic scattering at $E_e = 41.5$ MeV, $\theta = 180°$, has been studied by (1963GO04).

Inelastic spectra have been reported by (1960BA47: $E_e = 40$ MeV; $\theta = 132°, 160°$), (1963BA19: $E_e = 41.5$ MeV; $\theta = 180°$), (1964GO15: 75 MeV), (1963BI10: 101.4 MeV; $\theta = 60°$) and (1963BE25: 180 MeV). Table 6.6 summarizes the results. [For a review of the inelastic work to 1962, see (1962BA1D).] The inelastic spectrum of (1963BI10) shows two major absorption regions, from 9 to 17.5 MeV and from 17.5 to 32 MeV. Analysis of form factors on the assumption of E1 transitions leads to quite different values of $\langle r^2 \rangle$ for the two regions, supporting an α + d model. Fine structure is observed in both regions, possibly corresponding to discrete ^{6}Li levels (1963BE25, 1963BI10, 1964BI04). Form factors for ^{6}Li*(2.2) and (3.6) have been studied as a function of momentum transfer by (1963BE25, 1963BE53, 1964GO15). Interpretation in terms of nuclear models is discussed by (1963BE53, 1964KU1G, 1965DA1H). See also (1959ME1D, 1959UB1A, 1961PA1A, 1962JA06, 1965LO1J, 1965RA1D).

For reactions (b) and (c), see (1957KE1A).

10. ^{6}Li(n, n′)^{6}Li*

Inelastic neutron groups have been observed corresponding to the 2.18 MeV state with incident neutron energies up to 14 MeV. Differential cross sections are reported from $E_n = 3.4$ to 7.5 MeV (1963BA1V, 1963BA50), and at 14 MeV (1962WO07, 1964AR25, 1965ME05). Angular distributions up to $E_n = 7.5$ MeV show no obvious indication of direct interaction; at $E_n = 14$ MeV, both elastic and inelastic neutrons (n_0 and n_1) show sharp forward peaking. At both energies, the excitation of ^{6}Li*(3.56) is weak (1962WO07, 1963BA50). See also (1960KO1C, 1962EL1D, 1962JA1B, 1963EL1C, 1964PE20, 1965WE1E).

11. ^{6}Li(n, t)^{4}He $\qquad Q_m = 4.785$

(1956LI37) calculates $\theta_d^2 = 0.5$ for $^6\text{Li}_{\text{g.s.}}$ from the data of (1954FR03). See also ^{7}Li.

12. (a) ^{6}Li(p, p)^{6}Li

(b) ^{6}Li(p, 2p)^{5}He $\qquad Q_m = -4.655$

(c) ^{6}Li(p, pd)^{4}He $\qquad Q_m = -1.472$

(d) ^{6}Li(p, ^{3}He)^{4}He $\qquad Q_m = 4.021$

Elastic scattering has been studied at $E_p = 31$ MeV by (1963DE01), at 40 MeV by (1960CH1B), and at 155 MeV by (1964TA02). At the latter energy, the polarization at high momentum transfers, $q > 1.7$ fm^{-1} is strikingly different for ^{6}Li and ^{7}Li (1964TA02). Optical model analysis is discussed by (1963DE01, 1963JA1C). See also (1960SA28). Polarization of the scattered protons has been studied by (1962RO20, 1963HW01, 1964MA1Y).

Inelastic groups corresponding to several ^{6}Li states are observed: see Table 6.7. Angular distributions have been determined for $E_p = 4$ to 9 MeV (1963HA49), 31 MeV (1963DE01), 39.8 MeV (1959CH1B: see also (1963JA1C)), 155 MeV (1964JA03) and 185 MeV (1965HA17). The distributions at $E_p = 155$ to 185 MeV indicate dominant E2 transitions to ^{6}Li*(2.2, 4.6, 5.4) and M1 to ^{6}Li*(3.6) (1964JA03, 1965HA17). At $E_p = 149$ MeV, a 3.56 MeV γ-ray is observed with a cross section of 0.7 ± 0.3 mb (1961CL09). See also (1957LE1E, 1959SY1A).

Reaction (b) has been studied at $E_p = 155$ MeV (1961GA09, 1962GA09, 1962GA23), 185 MeV (1962TI01, 1964TI02) and 460 MeV (1965TY1A). The spectra of summed proton energies ($E_{p1} + E_{p2}$) show two peaks, with $Q = -4.8$ and $Q = -22.4$ MeV. As a function of angle of emission $\theta_1 = -\theta_2$, the higher energy peak exhibits a maximum at the angle corresponding to zero momentum of the target proton ($\theta_1 + \theta_2 \approx 90°$), while the lower has a minimum at this point. The higher peak is thus interpreted as a quasi-free scattering from an $l = 1$ proton $^6\text{Li} \rightarrow {}^5\text{He}_{\text{g.s.}} + \text{p}$ and the lower corresponding to a $l = 0$ proton, leaving ^{5}He* in a positive parity configuration with an excitation of about $16 - 17$ MeV (see $^5\text{He*} = 16.70$ MeV).

Calculations of expected momentum distributions with various wave functions are discussed by (1962BE1J, 1962BE1K, 1962DI1A, 1962IN1A, 1962IN1C, 1962SA1F, 1963BE42, 1963EL1C, 1963JO07, 1963RI1B, 1964LI1D, 1965JA04, 1965JA1J, 1965JA1M, 1965MC1F, 1965RI1A, 1965WI1G).

Table 6.7: Levels of ^{6}Li from (p, p′), (d, d′), ^{9}Be(p, α), ^{7}Li(d, t)

Reaction	E_x (MeV)	$\Gamma_{c.m.}$ (keV)	Reference
^{6}Li(p, p′)^{6}Li*	2.188	25.4	(1957BR12)
^{6}Li(d, d′)^{6}Li*	2.186	24.5	(1957BR12)
^{9}Be(p, α)^{6}Li	2.192	29	(1957BR12)
^{9}Be(p, α)^{6}Li	2.19 ± 0.02	< 35	(1963GR29)
^{7}Li(d, t)^{6}Li	(2.18)	< 27	(1957BR12)
mean	2.188 ± 0.006	26.3	(1957BR12)
^{6}Li(p, p′)^{6}Li*	3.559	< 5	(1957BR12)
^{9}Be(p, α)^{6}Li	3.561		(1957BR12)
^{9}Be(p, α)^{6}Li	3.55 ± 0.02	< 35	(1963GR29)
mean	3.560 ± 0.006	< 5	(1957BR12)
^{9}Be(p, α)^{6}Li	4.40 ± 0.12	350 ± 150	(1963GR29)
^{6}Li(p, p′)^{6}Li*	4.4 ± 0.2	≈ 600	(1965HA17)
^{9}Be(p, α)^{6}Li	5.32 ± 0.06	280 ± 60	(1963GR29)
^{6}Li(p, p′)^{6}Li*	5.4 ± 0.2	≈ 1000	(1965HA17)
^{6}Li(p, p′)^{6}Li*	≈ 6.5		(1965HA17)
^{6}Li(p, p′)^{6}Li*	≈ 7.5		(1965HA17)

As compared with the analogous case of ^{7}Li, there appears to be a difficulty here in accounting for the small width of the observed angular distribution.

At $E_{\rm p} = 155$ MeV, the angular correlation of outgoing protons and deuterons (reaction (c)) give evidence for a substructure ^{6}Li = ^{4}He + d in a relative $l = 0$ state with a probability of 20 to 31% (1963RU05). See also (1962RU04, 1963RI1B, 1963SA1F, 1963TA1D, 1964BA1P, 1964DE1F, 1964SA1H, 1965DE1Q, 1965JA1L).

For reaction (d) see (1963RU05, 1963TE1B) and ^{7}Be. (1956LI37) gives $\theta^2_{\rm d}$ for the ground state of ^{6}Li $= 0.30$ ($E_{\rm p} = 15$ MeV), 0.45 (18.5 MeV).

13. ^{6}Li(d, d′)^{6}Li*

Deuteron groups have been observed corresponding to the ground state and the 2.18 MeV level (1957BR12: $E_{\rm d} = 7.0$ and 7.5 MeV): see Table 6.7. The 3.56 MeV state is not observed at $E_{\rm d} = 7.5$ MeV, $\theta = 60°$, consistent with its $T = 1$ character. The shape of the angular distribution of the deuterons to the 2.18 MeV state ($E_{\rm d} = 14.7$ MeV) does not fit simple direct interaction theory (1960HA14: see also (1956HA90, 1964HA05, 1965JO09)). See also (1956SO21, 1956SO33, 1960EL09).

14. ^{6}Li(α, α)^{6}Li

Angular distributions of elastic and inelastic scattering (to the 2.18 MeV state) have been studied at $E_\alpha = 10.0$ and 12.5 MeV (1963BL20), at 24 MeV (1964GR39) and at 31.5 MeV (1956WA29). At $E_\alpha = 31.5$ MeV, a group is also observed to the 4.57 MeV state but not to the $T = 1$, 3.56 MeV level (1956WA29: see also (1964GR39)). See also (1962TE1D, 1963TE1B).

15. ^{6}Li(^{6}Li, ^{6}Li′)^{6}Li*

Angular distributions ($\theta_{\rm c.m.} = 12°$ to $40°$) to the ground and 2.18 MeV states have been measured at E(^{6}Li) $= 63$ MeV: they show diffraction-type structure. No evidence of the excitation of the 3.56 MeV $T = 1$ state is seen (1964GA01).

16. ^{7}Li(γ, n)^{6}Li $\qquad Q_{\rm m} = -7.253$

See ^{7}Li.

17. ^{7}Li(p, d)^{6}Li $\qquad Q_{\rm m} = -5.028$

At $E_p = 17.5$ MeV, angular distributions of deuteron groups corresponding to ^{6}Li(g.s.), (2.18) and (3.56), analyzed by Butler theory give $l_n = 1$ for all these states. The ratios of observed reduced widths (see ^{7}Li) are consistent with predictions of the shell model with pure, or nearly pure, LS coupling (1956RE04, 1959BE84, 1960MA32). See also (1961CL09). The bearing of this reaction and its inverse on tests of invariance under time reversal is discussed by (1959HE1C). See also (1964SH07).

18. ^{7}Li(d, t)^{6}Li $\qquad Q_m = -0.995$

At $E_d \approx 15$ MeV, the angular distributions of the tritons indicate $l_n = 1$ (even parity) for the first three states of ^{6}Li (1955LE24, 1957FR1B, 1959HA29, 1960HA14): reported reduced widths are listed in Table 7.7. (1960HA14) report a board asymmetric bump at $E_x \approx 5.4$ MeV, $\Gamma \approx 600$ keV; no sharp states are reported for $4.4 < E_x < 8.5$ MeV with $\sigma > 0.3$ mb/sr ($E_d = 14.9$ MeV, $\theta = 14°, 25°$). See also (1956SO21, 1956SO33, 1959KU1C, 1959VL24, 1961OG1A, 1961SL06, 1962SL04, 1963OG1A, 1964BL1C).

19. ^{7}Li(^{3}He, α)^{6}Li $\qquad Q_m = 13.325$

Alpha particle groups have been observed with $E(^3\text{He}) = 0.6$ to 0.9 MeV (1960AL10), 1.5 MeV (1963CA02), 0.8 to 3 MeV (1965PA03), 4 MeV (1961WO05, 1963KN1C), 0.8 to 5.1 MeV (1963LI16) and 1.3 to 5.5 MeV (1965FO07). (1963LI16) find no evidence for reported levels at 4.3 or 6.6 MeV; (1965CO1F) confirms the levels at 4.3 and 5.35 MeV but finds no evidence for the higher states reported by (1960AL10). The results are summarized in Table 6.8.

20. ^{9}Be(γ, t)^{6}Li $\qquad Q_m = -17.688$

See (1955AJ61).

21. ^{9}Be(p, α)^{6}Li $\qquad Q_m = 2.126$

$Q_0 = 2.1254 \pm 0.0018$ (1965BR28).

Alpha particle groups have been observed with $E_p = 7.2$ to 7.5 MeV (1957BR12), 10 MeV (1963GR29), 3.50 to 12.50 MeV (1963BL20), 15.6 and 18.6 MeV (1962MA40). The results are summarized in Table 6.7. Angular distributions of the α_0 and α_1 groups are reported for $E_p = 6$ to 11.5 MeV (1963BL20, 1963TE1B), 5.9 and 7 MeV (1964YA1A) and 15.6 and 18.6 MeV (1962MA40). See also ^{9}Be. The 3.56 MeV state is observed to decay by γ-radiation: $E_\gamma =$

Table 6.8: States in ^{6}Li from ^{7}Li(^{3}He, α)^{6}Li

(1960AL10)		(1963LI16)		(1963CA02, 1965MA1E)	(1965CO1F)	
E_x (MeV $\pm$ keV)	Γ (keV)	E_x (MeV $\pm$ keV)	Γ (keV)	E_x (MeV $\pm$ keV)	E_x (MeV $\pm$ keV)	Γ (keV)
0		0		0	0	≤ 30
2.19		2.179 ± 8	< 40	2.184 ± 10	2.17 ± 20	≤ 30
3.56 ± 60		3.568 ± 8	< 40	3.564 ± 11	3.55 ± 20	≤ 30
4.3 ± 200				4.59 ± 40	4.3 ± 150	≈ 500
5.35 ± 70	< 100	5.47 ± 40	≈ 600	5.34 ± 30	5.35 ± 20	360 ± 40
(5.6 ± 200)	(2000)					
6.63 ± 800	200					
7.40 ± 100	600					
(8.37 ± 80)	(200)					
(9.3 ± 200)	(≈ 600)					

3.572 ± 0.012 MeV; the internal pair spectrum is consistent with an M1 transition (1954MA26: see also (1960GO13)).

The γ-ray angular distribution and the ($\alpha - \gamma$) correlation are isotropic at $E_p = 2.56$ MeV, consistent with $J = 0$ for ^{6}Li*(3.56) (1956ST93). See also (1959LE1B, 1962HA23, 1963ED1A, 1964BA1C) and ^{10}B.

22. ^{9}Be(d, ^{5}He)^{6}Li $\qquad Q_m = -1.056$

Not reported: see (1964BL1C).

23. (a) ^{10}B(γ, α)^{6}Li $\qquad Q_m = -4.461$
(b) ^{10}B(p, pα)^{6}Li $\qquad Q_m = -4.461$
(c) ^{10}B(α, 2α)^{6}Li $\qquad Q_m = -4.461$
(d) ^{10}B(n, dn2α) $\qquad Q_m = -5.933$
(e) ^{10}B(d, ^{6}Li)^{6}Li $\qquad Q_m = -2.989$

For reaction (a) see ^{10}B; for (b) see (1964BA1C); for (c) see (1963ME01); for (d) see (1956FR18); for (e) see (1964GE10).

24. (a) ^{11}B(d, ^{7}Li)^{6}Li $\quad Q_{\rm m} = -7.192$

(b) ^{11}B(^{3}He, ^{8}Be)^{6}Li $\quad Q_{\rm m} = 4.566$

Reaction (a) has not been reported: see (1964BL1C). For reaction (b), see (1964YO06).

Table 6.9: Energy levels of ^{6}Be

E_x (MeV)	J^π	Γ (keV)	Decay	Reactions
g.s.		92 ± 6	α, p	3, 4
(1.5 ± 0.2)				2, 3
$(18 - 24)$	$(^-)$		^{3}He	1

^{6}Be

(Figs. 6 and 7)

GENERAL:

See (1960TA1C, 1961GO1D, 1964GR1J, 1965BO1C, 1965JA1C, 1965LO1G).

Mass of ^{6}Be : From the Q-values of the ^{6}Li(p, n)^{6}Be reaction ($Q_0 = -5.069 \pm 0.010$ MeV) and the ^{6}Li(^{3}He, t)^{6}Be reaction ($Q_0 = -4.306 \pm 0.006$ MeV), we adopt ^{6}Be-^{6}Li $= 4.2872 \pm 0.005$ MeV. The mass excess of ^{6}Be is then 18.376 ± 0.005 MeV, based on ^{12}C $\equiv 0$.

1. (a) ^{3}He(^{3}He, 2p)^{4}He $\quad Q_m = 12.860 \quad E_b = 11.487$

 (b) ^{3}He(^{3}He, p)^{5}Li $\quad Q_m = 10.895$

 (c) ^{3}He(^{3}He, ^{3}He)^{3}He

The total cross section for proton production shows a monotonic increase for $E(^3\text{He}) = 100$ to 800 keV (1954GO18). The zero-energy cross section factor $S_0 \approx 1100$ keV · b (1964PA1A). The elastic yield (reaction (c)) does not show any structure for $E(^3\text{He}) = 3$ to 12 MeV: the yields at $\theta = 31°$, $55°$, $70°$ and $90°$ all decrease with increasing energy in a smooth fashion. The angular distributions at $E(^3\text{He}) = 3.0$, 5.9, 7.9, 9.9 and 11.9 MeV disagree with the theoretical predictions based on the resonating group structure method (1963TO03). The $90°$ and $45°$ cross sections continue to decrease smoothly up to $E(^3\text{He}) = 18$ MeV, implying that an odd-parity partial wave (probably $l = 3$) is beginning to contribute strongly to the cross section in a region corresponding to ^{6}Be* ($E_x > 18$ MeV) ((1965BA2B) and private communication). The $65°$ differential cross section increases by a factor of 2.6 between $E(^3\text{He}) = 12$ and 18 MeV (1965BA2B). This sharp upward trend is continued to $E(^3\text{He}) = 25$ MeV (1960GA1C). Elastic $\sigma(\theta)$ have also been obtained at $E(^3\text{He}) = 12$, 16, 19, 22 and 25 MeV (1965LE02), 29 MeV (1960BR19) and 30 MeV (1960MC1E). See also (1960BR27, 1964AR08, 1965BA1E, 1965TO01).

2. ^{4}He(^{3}He, n)^{6}Be $\quad Q_m = -9.091$

At $E(^3\text{He}) = 24.2 \pm 0.3$ MeV, two groups are reported corresponding to the ground state of ^{6}Be and to an excited state at ≈ 1.5 MeV (1964BR13).

3. ^{6}Li(p, n)^{6}Be

$Q_\text{m} = -5.070$
$Q_0 = -5.2 \pm 0.2$ MeV (1957BO1F);
$Q_0 = -5.05 \pm 0.2$ MeV (1959AJ81);
$Q_0 = -5.05 \pm 0.05$ MeV (1964BA16);
$Q_0 = -5.08 \pm 0.04$ MeV (1963GU07);
$Q_0 = -5.074 \pm 0.013$ MeV (1964HOZZ);
$Q_0 = -5.061 \pm 0.017$ MeV (1963FR1E).

At $E_\text{p} = 9$ (1957BO1F), 10 (1963GU07) and 10.5 MeV (1959AJ81), the ground-state neutron group is observed: $\Gamma < 300$ keV (1957BO1F), $\lesssim 150$ keV (1959AJ81), 140 ± 40 keV (1963GU07). The ground-state neutron threshold function indicates participation of both s- and p-wave neutrons (1964HOZZ). The ground-state width is 126 ± 15 keV (1963FR1E), 95 ± 28 keV (1964HOZZ). (1959AJ81) report evidence for an excited state at $E_\text{x} = 1.5 \pm 0.2$ MeV, $\Gamma < 100$ keV. However (1964HOZZ) does not observe any but the ground-state threshold up to $E_\text{x} \approx 3.8$ MeV.

4. ^{6}Li(^{3}He, t)^{6}Be

$Q_\text{m} = -4.306$

At $E(^3\text{He}) = 12$ MeV ($\theta = 2°$, $10°$), a triton group is observed corresponding to the ground state of ^{6}Be ($\Gamma = 89 \pm 6$ keV, $Q_0 = -4.306 \pm 0.006$ MeV). No other states of ^{6}Be are seen with $\Gamma < 1$ MeV up to $E_\text{x} = 2.8$ MeV (1964WH06).

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(Closed July 01, 1965)

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