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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 A*227 (1974), 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}H

(Not illustrated)

^{6}H has not been observed in the interaction of π^- and ^{14}N: see (1972AG01).

^{6}He

(Figs. 4 and 7)

GENERAL: (See also (1966LA04).)

Model calculations: (1965VO1A, 1966BA26, 1967HE01, 1967TH02, 1968BA35, 1968FA1B, 1968GO24, 1968VA1H, 1969HE1G, 1969LA19, 1969SO08, 1969TH1C, 1970AH1C, 1971JA06).

Meson and muon interactions: (1970DE1M, 1970PA1E, 1972MU07, 1972TR1E, 1973BA2G, 1973BA62, 1973KA1D, 1973MU11, 1973VE1F, 1974VE02).

Special reactions: (1965WH10, 1967AU1B, 1969KR20, 1970KR1G, 1972VO06, 1973FO09, 1973KO1D).

Astrophysical questions: (1970BA1M).

Other topics: (1965RA1A, 1965VO1A, 1967AN1A, 1968EW1A, 1968LE02, 1969AL1D, 1969GI1A, 1969HO1M, 1969LA19, 1969IN1A, 1969SH1A, 1970AL14, 1970FO1B, 1970PA1D, 1970SU1B, 1971LO13, 1971ST40, 1972CA37, 1972GH1A, 1972PN1A, 1973JU2A).

Ground state properties: (1965VO1A, 1968LE02).

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

The decay proceeds to the ground state of ^{6}Li [$J^\pi = 1^+$] and is a super-allowed Gamow-Teller transition. The half-life is 808.1 ± 2.0 msec. Using this $\tau_{1/2}$ and E_{β^-}(max) $= 3508.4 \pm 3.8$ keV (1963JO04), log $ft = 2.911 \pm 0.003$ (D.E. Alburger and D.H. Wilkinson, private communication). See Table 6.2 in (1966LA04) for a listing of earlier $\tau_{1/2}$ determinations.

The internal bremsstrahlung spectrum has been measured by (1965BI09). The electron-neutrino correlation results are in good agreement with pure axial vector interaction. An upper limit to the possible admixture of tensor interaction is 0.4% (1963JO15). See also the discussion in (1970PA23).

See also (1964FO1A; astrophys. considerations), (1968DA1J), (1966BA1A, 1966BA26, 1968GO24, 1968LE02, 1968VA1H, 1969KA1B, 1969KU13, 1969LA1D, 1970DA21, 1972LA07, 1973HA49, 1974VE02, 1973WI11; theor.) and (1966LA04).

Table 6.1: Energy levels of ^{6}He

E_x (MeV ± keV)	$J^\pi; T$	$\tau_{1/2}$ or $\Gamma_{c.m.}$	Decay	Reactions
g.s.	$0^+; 1$	$\tau_{1/2} = 808.1 \pm 2.0$ msec	β^-	1, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22
1.797 ± 25	$(2)^+; 1$	$\Gamma = 113 \pm 20$ keV	n, α	4, 7, 13, 14, 15, 20
(13.4 ± 500)		$\Gamma \approx 1.2$ MeV		13
(15.3 ± 300)	$1^-, 2^-$		γ	5, 13
(23.2 ± 700)		broad	γ	5

2. (a) ^{3}H(t, n)^{5}He $\quad Q_m = 10.44 \quad E_b = 12.303$
   (b) ^{3}H(t, 2n)^{4}He $\quad Q_m = 11.3324$
   (c) ^{3}H(t, d)^{4}H $\quad Q_m = -9.2$
   (d) ^{3}H(t, 3n)^{3}He $\quad Q_m = -9.2460$

The cross section for neutron production (reactions (a) and (b)) rises monotonically from 40 keV to 2.2 MeV (1951AG30, 1957JA37, 1958JA06, 1971ST13). The zero-energy cross-section factor $S_0 \approx 300$ keV · b (1964PA1A). At $E_t = 1.90$ MeV, the total cross section for production of α-particles is 106 ± 5 mb (1958JA06).

A kinematically complete study of reaction (b) gives $a_{nn} = -15.0 \pm 1.0$ fm for the $^1S_0$ scattering length (1972KU08): see this paper for a review of other a_{nn} determinations. See also (1970GR17, 1970PO05, 1972KU1N), (1969LA1F) and (1970SL1B).

For reaction (a) see also ^{5}He. For reaction (c) see (1967JA07) and (1968ME03). For reaction (d) see (1968OH04). For a review of the earlier work see (1966LA04).

3. ^{3}H(t, t)^{3}H $\quad E_b = 12.303$

Differential cross sections have been measured for $E_t = 1.58$ to 2.01 MeV (1956HO12) and at 1.90 MeV (1958AL05). See also (1968TH01; theor.).

4. ^{4}He(t, p)^{6}He $\quad Q_m = -7.511$

At $E_t = 22$ MeV, angular distributions of the protons to ^{6}He*(0, 1.80) have been measured. No other states are observed with $E_x \lesssim 4.2$ MeV (1971ST05). See also (1970BA1V).

5. ^{6}Li(π^-, γ)^{6}He $\qquad Q_m = 136.059$

The excitation of ^{6}He*(0, 1.8) and possibly of (broad) states at $E_x = 15.6 \pm 0.5$, 23.2 ± 0.7 and 29.7 ± 1.3 MeV is reported by (1973BA62) from E_γ measurements using a pair spectrometer. $4.4 \pm 0.6\%$ of stopped pions were absorbed radiatively: the branching ratios of ^{6}He*(0, 1.8) are $0.31 \pm 0.04\%$ and $0.15 \pm 0.03\%$, respectively (1973BA62).

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

At $E_n = 14$ MeV the p_0 angular distribution is similar in shape to the angular distributions in ^{6}Li(p, p′)^{6}Li*(3.56) and in ^{6}Li(p, n)^{6}Be$_{g.s.}$. The ratios of the cross sections for these isobaric analog transitions are consistent with charge independence (1972ME05). See also (1967ME11, 1970ME1J, 1973BO1Y), (1969MA1L; theor.) and ^{7}Li.

7. ^{6}Li(t, ^{3}He)^{6}He $\qquad Q_m = -3.491$

At $E_t = 22$ MeV, the only states which are observed with $E_x \lesssim 8.5$ MeV are ^{6}He(0) and ^{6}He*(1.80) (1971ST05).

8. ^{6}Li(^{3}He, 3p)^{6}He $\qquad Q_m = -10.446$

This reaction has been studied at $E(^{3}\text{He}) = 53.2$ MeV (1970BA41).

9. ^{6}Li(^{6}Li, ^{6}Be)^{6}He $\qquad Q_m = -7.797$

Differential cross sections have been measured at $E(^{6}\text{Li}) = 32$ and 36 MeV for the reaction going to the ground states of ^{6}He and ^{6}Be (1973WH02): see reaction 16 in ^{6}Li and ^{12}C in (1975AJ02). See also (1973WH1C).

10. ^{7}Li(γ, p)^{6}He $\qquad Q_m = -9.978$

At $E_\gamma = 60$ MeV, the proton spectrum shows two prominent peaks attributed to ^{6}He*($0 + 1.8$, 18 ± 3) (1973GA16). See also (1970SA14) and ^{7}Li.

11. ^{7}Li(e, e′p)^{6}He $Q_m = -9.978$

See (1966MU1A, 1969BA1F; theor.) and ^{7}Li.

12. ^{7}Li(n, d)^{6}He $Q_m = -7.753$

At $E_n = 14.4$ MeV, the angular distribution of the deuterons to ^{6}He(0) has been measured and analyzed by DWBA (1970MI05, 1971MI12). See also (1966ME03, 1967ME11, 1973LI02) and ^{8}Li.

13. ^{7}Li(p, 2p)^{6}He $Q_m = -9.978$

The summed proton spectrum at $E_p = 156$ MeV shows peaks corresponding to ^{6}He*(0, 1.80) [partially resolved] and $E_x = (13.4 \pm 0.5)$ MeV [$\Gamma \approx 1.2$ MeV] and (15.3 ± 0.3) MeV [partially resolved]. The angular correlation for ^{6}He*(15.3) is consistent with that for a pure s-state. There is no indication of the expected ^{33}P states in the interval $E_x = 4$ to 10 MeV (1967RO06). For a summary of the earlier work see Table 6.3 in (1966LA04) [(1966TY01) has now been published: see (1966TY01)]. See also (1965RO15, 1969RU1A) and (1967KO1B; theor.).

14. ^{7}Li(d, ^{3}He)^{6}He $Q_m = -4.488$

Angular distributions of the ^{3}He groups to ^{6}He*(0, 1.80) have been measured at $E_d = 14.4$ MeV (1955LE24) and 22 MeV (1971ST05): they are consistent with $l = 1$ and therefore with $J^\pi = 0^+, 2^+$ for these two states. The cross sections for formation of these two states at $E_d = 23.6$ MeV have been compared with those for formation of the analog states of ^{6}Li*(3.56, 5.37) in ^{7}Li(d, t)^{6}Li: see reaction 21 in ^{6}Li (1971DE08). There is no evidence for any other states of ^{6}He with $E_x < 10.7$ MeV (1971ST05). See also (1970BA1V).

15. ^{7}Li(t, α)^{6}He $Q_m = 9.837$

The energy of the first excited state is 1.797 ± 0.025 MeV, $\Gamma = 113 \pm 20$ keV (1965AJ01). ^{6}He*(1.80) decays into ^{4}He+2n. The branching ratio Γ_γ/Γ_n is $< 4 \times 10^{-4}$ (1964HU1A), $\Gamma_\gamma/\Gamma_\alpha \leq 2 \times 10^{-6}$ (1966LI1A). Angular distributions of the α_0 and α_1 groups have been measured at $E_t = 13$ MeV (1965AJ01) and 22 MeV (1971ST05): they are consistent with $l = 1$ pickup and therefore with $J^\pi = 0^+, 2^+$ for ^{6}He*(0, 1.80). No other α-groups are reported corresponding to ^{6}He states with $E_x < 12$ MeV (1965AJ01), $E_x < 24$ MeV (1971ST05: $E_t = 16 \to 22$ MeV; region between $E_x \approx 13$ and 16 MeV was obscured by presence of breakup α-particles). See also (1966SE1D, 1970AB12) and (1966LA04).

16. ^{7}Li(^{3}He, ^{4}Li)^{6}He $\quad Q_{\rm m} = -12.9$

This reaction has been studied at $E(^3{\rm He}) = 53.2$ MeV (1970BA41).

17. ^{7}Li(^{7}Li, ^{8}Be)^{6}He $\quad Q_{\rm m} = 7.278$

See (1968ST12).

18. ^{9}Be(n, α)^{6}He $\quad Q_{\rm m} = -0.602$

The α_0 angular distribution has been measured at $E_{\rm n} = 14.4$ MeV (1967PA03). See also (1969OG01, 1969VA1F), (1966LA04) and ^{10}Be.

19. ^{9}Be(p, ^{4}Li)^{6}He $\quad Q_{\rm m} = -24.1$

This reaction has been studied at $E_{\rm p} = 45$ MeV: the shape of the angular distribution to the ground state is very different from that for the (p, α_2) reaction to the analog state in ^{6}Li, indicating different reaction mechanisms (1970DE17, 1971DE2B).

20. ^{9}Be(t, ^{6}Li)^{6}He $\quad Q_{\rm m} = -5.386$

At $E_{\rm t} = 23.5$ MeV angular distributions have been obtained for the transitions involving ^{6}He in the ground and 1.8 MeV states and ^{6}Li in the ground, 2.19 and 3.56 MeV states (1973VO08): see also reaction 26 in ^{6}Li.

21. (a) ^{10}B(^{7}Li, ^{6}He)^{11}C $\quad Q_{\rm m} = -1.287$
(b) ^{11}B(^{7}Li, ^{6}He)^{12}C $\quad Q_{\rm m} = 5.979$

See (1968ST12).

22. ^{11}B(d, ^{7}Be)^{6}He $\quad Q_{\rm m} = -11.563$

See reaction 20 in ^{7}Be and reaction 32 in ^{6}Li (1972GO1P).

^{6}Li
(Figs. 5 and 7)

GENERAL: (See also (1966LA04).)

Shell model: (1961KO1A, 1965CO25, 1966BA26, 1966GA1E, 1966HA18, 1966WI1E, 1967BO1C, 1967CO32, 1967PI1B, 1967WO1B, 1968BO1N, 1968CO13, 1968GO01, 1968LO1C, 1968VA1H, 1969GU10, 1969RA1C, 1969SA1C, 1969VA1C, 1970LA1D, 1970SU13, 1970ZO1A, 1971CO28, 1971JA06, 1971LO03, 1971NO02, 1972LE1L, 1972LO1M, 1972VE07, 1973HA49, 1973JO1K, 1973KU03).

Cluster and α-particle model: (1965NE1B, 1966HA12, 1967AL1D, 1967BA1H, 1967HA1J, 1967LO1E, 1967SI1C, 1967TH02, 1968BA35, 1968HA1G, 1968KU1B, 1968SA1C, 1969AL1E, 1969BE1N, 1969CH40, 1969CL1D, 1969HA1N, 1969HA1P, 1969JA13, 1969KU13, 1969ME1C, 1969NE1C, 1969SM1A, 1969TH1C, 1969TR1B, 1969VE1B, 1970CH1N, 1970FA11, 1970IT02, 1970JA21, 1970KU1F, 1970NE1F, 1971AM1A, 1971AM03, 1971AU01, 1971CH06, 1971HA59, 1971HU1F, 1971KU06, 1971NO02, 1971PA11, 1971ST31, 1972EL04, 1972JA21, 1972KU12, 1972KU20, 1972OS01, 1973KR07, 1973KU03, 1973KU12, 1973MA51, 1973RA23, 1973WE07).

Special levels: (1964MI16, 1965LO1C, 1966BA26, 1967JA1F, 1968GO24, 1968LE02, 1969GU10, 1969WA1F, 1970AL14, 1971CO28, 1971JA06, 1971LO03, 1971MU19, 1971NO02, 1972NI15, 1973MA1K, 1973MA51).

Electromagnetic transitions: (1962MO1A, 1965CO25, 1966BA26, 1966HA12, 1967BA1H, 1968CO13, 1968LE02, 1969BE1N, 1969HA1F, 1969HA1N, 1969LA1D, 1969VA1C, 1970LA1D, 1971LO10, 1971MU19, 1971ST31, 1972NA05, 1973HA49, 1973HA1V, 1974VE02, 1973WE18).

Astrophysical questions: (1967DA1C, 1967MI1A, 1968HA1C, 1972CL1A, 1972KO1E, 1972RA30, 1973AU1H, 1973LA19, 1973RE1G, 1973WE18, 1974AU1A).

Special reactions: (1964GR1D, 1965GR1C, 1967AU1B, 1967BE1L, 1968YI01, 1969GA18, 1969YI1A, 1971DI19, 1972OB1B, 1972OS02, 1972RA30, 1973KU03, 1973LA19, 1973OS1C, 1973PF02, 1973VO1G).

Muon and neutrino interactions: (1965LO1B, 1968DE1L, 1969GA1N, 1969KR1C, 1969KU13, 1969WU1A, 1970DE1M, 1970DE1N, 1970FA15, 1970KI1C, 1971DE2D, 1971ER1C, 1971WI10, 1972MI1M, 1972MU07, 1973BE07, 1973BE51, 1973DO07, 1973MU11, 1974WI1T).

Pion capture and reactions: (1966DA1A, 1966DE1G, 1966KO1C, 1966TA1A, 1967CH1F, 1967KO1C, 1967KO1D, 1967LE1D, 1967ME1F, 1967SA1D, 1968AL1F, 1968BA1X, 1968CH1G, 1968CH1H, 1968DE1L, 1968GR1D, 1968KU1B, 1968NG1A, 1968NO1A, 1968PE1B, 1968WI1B, 1968ZU1A, 1969AL1E, 1969BU1C, 1969CA1B, 1969GO1C, 1969KO30, 1969MI10, 1969MO1E, 1969NE1C, 1970AL1K, 1970BA59, 1970BA1E, 1970CA1L, 1970CH1L, 1970CH1N, 1970DE1N, 1970JA23, 1970KO23, 1970NE1F, 1970PA1E, 1971AM1A, 1971CA1J, 1971FA09, 1971GR1Y, 1971KO02, 1971PA11, 1971WE1J, 1972FA14, 1972HU1A, 1972JA21, 1972ME1F, 1972SA10, 1972SW1A, 1972TR1E, 1972VE07, 1973BA2R, 1973BA2V, 1973BA62, 1973BR1J, 1973CH1V,

1973DO1F, 1973KA1D, 1973MA11, 1973NI1C, 1973NY04, 1973PE1E, 1973VE1F, 1974VE02).

Kaon reactions: (1973BA1Y).

Other topics: (1965BE1F, 1965CO25, 1965LO1C, 1966FL1A, 1966FR1C, 1966HA18, 1966NA1A, 1966WI1E, 1967AL1D, 1967BL1D, 1967BO1C, 1967CA17, 1967FR1A, 1967RI1A, 1967SI1C, 1967WO1B, 1968CI1D, 1968GO01, 1968GO24, 1968KU1C, 1968LE02, 1968LE1F, 1968RI1L, 1968SA1D, 1969AF1A, 1969AL1D, 1969CH40, 1969GU10, 1969IN1A, 1969LA1D, 1969LE1G, 1969RA21, 1969SA1C, 1969SH20, 1969WA1F, 1969YE1A, 1970AL14, 1970FO1B, 1970HA1N, 1970KA1K, 1970KR1H, 1970LO1E, 1970PA1D, 1970SH1B, 1970SU13, 1970WI11, 1970ZO1A, 1971DE1V, 1971HU1F, 1971KU06, 1971WE1K, 1971ZA1D, 1972AB14, 1972AN05, 1972CA37, 1972EL04, 1972GH1A, 1972LE1L, 1972LO1M, 1972NI15, 1972RI10, 1973BA1Y, 1973CH08, 1973CL09, 1973JO1K, 1973KR07, 1973KU03, 1973MA51, 1973MA48, 1973RO1R).

Ground-state properties: (1965CO25, 1966BA26, 1966WI1E, 1967SH05, 1967SH14, 1968GO24, 1968LE02, 1968PE16, 1968PE1B, 1969AF1A, 1969CH25, 1969CH40, 1969GU08, 1969JA1H, 1969LA1D, 1969TR1B, 1969VA1C, 1970AF02, 1970CH1M, 1970JA21, 1970LA1D, 1971CH06, 1971HA59, 1971ST31, 1972LE1L, 1972LO1M, 1972VA36, 1973DO1F, 1973MA1K, 1973MA51, 1973SU1B, 1974VE02).

$\mu = 0.82202$ nm (1969FU11, 1971SH26);

$Q = -0.0008$ b (1969FU11, 1971SH26).

1. (a) ^{3}He(^{3}H, γ)^{6}Li	$Q_m = 15.795$	$E_b = 15.795$
(b) ^{3}He(^{3}H, p)^{5}He	$Q_m = 11.20$	
(c) ^{3}He(^{3}H, p)^{4}He + n	$Q_m = 12.0963$	
(d) ^{3}He(^{3}H, n)^{5}Li	$Q_m = 10.13$	
(e) ^{3}He(^{3}H, d)^{4}He	$Q_m = 14.3209$	
(f) ^{3}He(^{3}H, ^{3}H)^{3}He		
(g) ^{3}He(^{3}H, dn)^{3}He	$Q_m = -6.2576$	
(h) ^{3}He(^{3}H, p2n)^{3}He	$Q_m = -8.4822$	
(i) ^{3}He(^{3}H, 2d)^{2}H	$Q_m = -9.5267$	
(j) ^{3}He(^{3}H, pd)^{3}H	$Q_m = -5.4938$	

Capture γ-rays (reaction (a)) to the first three states of ^{6}Li [γ_0, γ_1, γ_2] have been observed for $E(^3\text{He}) = 0.5$ to 20.0 MeV (1968BL10, 1970YO1A), 1 to 3 MeV (1963KO04), 5 to 20 MeV (1966NU01) and 5.4 to 25.8 MeV (1971VE10, 1973VE1B). In addition the yields of γ_3, γ_4 have been measured for $E(^3\text{He}) = 12.6$ to 25.8 MeV (1971VE10, 1973VE1B). The γ_2 excitation

Table 6.2: Energy levels of ^{6}Li

E_x (MeV ± keV)	$J^\pi; T$	$\Gamma_{c.m.}$ (keV)	Decay	Reactions
g.s.	$1^+; 0$	–	–	1, 2, 6, 7, 8, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 40, 41, 42, 43, 44, 45, 46
2.185 ± 3	$3^+; 0$	26.3	γ, d, α	1, 2, 5, 6, 10, 11, 12, 13, 14, 15, 16, 20, 21, 22, 24, 28, 29, 36, 39
3.562 ± 5	$0^+; 1$	< 5	γ	1, 6, 8, 10, 11, 12, 13, 14, 16, 20, 21, 22, 24, 32, 45, 46
4.31 ± 30	$2^+; 0$	1500 ± 200 [a]	γ, d, α	1, 5, 10, 12, 13, 20, 22, 24
5.366 ± 15	$2^+; 1$	540 ± 20	γ	1, 10, 12, 20, 21, 22
5.7 ± 100	$1^+; 0$		d, α	5
25.0 ± 1000	$(4)^-; 1$	≈ 4000	γ, (n), t, ^{3}He	1
26.6 ± 400	$(3^-); 0$	broad	γ, (n), t, ^{3}He	1

[a] F.C. Barker, private communication.

function does not show resonance structure. However, the γ_0, γ_1, γ_3 and γ_4 yields do show broad maxima at $E(^3\mathrm{He}) = 5.0 \pm 0.4$ [γ_0, γ_1], 20.6 ± 0.4 [γ_1], ≈ 21 [γ_3] and 21.8 ± 0.8 [γ_4] MeV. The magnitude of the ground state capture cross section is well accounted for by a direct capture model; that for the γ_1 capture indicates a non-direct contribution above $E(^3\mathrm{He}) = 10$ MeV, interpreted as a resonance due to a state with $E_x = 25 \pm 1$ MeV, $\Gamma_{c.m.} = 4$ MeV, $T = 1$ (because the transition is E1, to a $T = 0$ final state) [the E1 radiative width $|M|^2 \gtrsim 5.2/(2J + 1)$ W.u.], $J^\pi = (2, 3, 4)^-$, $\alpha + \mathrm{p} + \mathrm{n}$ parentage (1973VE09, 1973VE1B). The γ_4 resonance is interpreted as being due to a broad state at $E_x = 26.6$ MeV with $T = 0$. $J^\pi = 3^-$ is consistent with the measured angular distribution (1973VE1B). The ground and first excited state reduced widths for ^{3}He + t parentage, $\theta_0^2 = 0.8 \pm 0.2$ and $\theta_1^2 = 0.6 \pm 0.3$ (1971VE10, 1973VE09, 1973VE1B). (1970YO04) calculate that the upper limit to the t + ^{3}He clustering is $\theta_0^2 = 0.69$, $\theta_1^2 = 0.55$, $\theta_2^2 = 0.48$ for the first states of ^{6}Li.

Elastic scattering (reaction (f)) angular distributions have been measured at $E(^3\mathrm{He}) = 5.00$, 7.00, 9.00, 11.00 MeV (1968IV01), 5.8 to 19.9 MeV (1968BA76) and 27.7 and 32.3 MeV (1970BA29). Excitation functions are reported for $E(^3\mathrm{He}) = 4.48$ to 11.94 MeV (1968IV01), 4.3 to 21.4 MeV

(1968BA76) and 24.7 to 33.4 MeV (1970BA29). At the lower energies the elastic yield is structureless and decreases monotonically with energy (1968IV01). Above $E(^3\text{He}) = 15$ MeV a marked change in the angular distributions is attributed to a broad resonance in the $l = 3$ partial wave (1968BA76) which is reported by (1970BA29) to be located at ^{6}Li*(29.0) [$\Gamma \approx 4$ MeV] (see, however, reaction (a) above): the resonance is tentatively associated with the ^{1}F and ^{3}F levels predicted from the one-channel resonating group theory (1967TH1C, 1968TH01). See also (1968OH04, 1973NO07) and (1972BR1Q, 1972JA1K, 1972KU20; theor.).

Angular distributions and total cross section measurements for reactions (b), (c) and (e) are listed in (1966LA04). Angular distributions of deuterons (reaction (e)) at $E_\text{t} = 1.04$ to 1.52 MeV (1969NA16), $E_\text{t} = 1.51$ to 3.27 MeV (1972WA1L) and at $E(^3\text{He}) = 0.29$ to 0.80 MeV (1973NO07) are approximately (to within 1%) symmetric about 90°, as expected from isospin conservation: see also reaction 4. On the basis of a composite of available measurements (1973NO07) suggest that two broad resonances occur in the differential cross sections at $\theta_\text{c.m.} = 10°$ and 90° corresponding to ^{6}Li states at $E_\text{x} \approx 16.2$ MeV and ≈ 17 MeV, with $J^\pi; T$ possibly 2^+; 1 and 1^-; 0, respectively. For reaction (e) see also (1968ME03) and (1967BI1C; theor.). Measurements for reaction (c) lead to a n-p scattering length $a_\text{np} = -21 \pm 3$ fm (1972KU08). See also (1968BL06, 1970BE1N, 1970GR17, 1971BE21, 1972KU1N, 1973RO2A, 1973SL03).

The angular distribution and polarization of the neutrons in reaction (d) has been measured at $E(^3\text{He}) = 2.70$ and 3.55 MeV. The excitation function for $E(^3\text{He}) = 0.7$ to 3.8 MeV decreases monotonically with energy (1971KL04). The excitation function for the n_0 group ($\theta_\text{lab} = 20°$) has been measured for $E(^3\text{He}) = 14$ to 26 MeV; evidence for a broad structure at $E(^3\text{He}) = 20.5 \pm 0.8$ MeV, $\Gamma \approx 6$ MeV is reported [$E_\text{x} = 26.1$ MeV] (1973VE1B, 1974CH15). See also (1969VA1G, 1973GR1L, 1973LI19; theor.).

For reactions (g), (h), (i) and (j) see (1973SL03: $E(^3\text{He}) = 50$ MeV): evidence for quasi-free reaction mechanism is observed in reactions (c), (i) and (j) and for d-d, p-^{3}He and d-^{3}He quasi-free scattering in reactions (i), (h) and (g), respectively.

2. ^{3}H(α, n)^{6}Li $\qquad Q_\text{m} = -4.784$

This reaction has been observed for $E_\alpha = 11.0$ to 18.3 MeV: see ^{7}Li. Neutron groups corresponding to ^{6}Li*(0, 2.19) were detected (1967SP10).

3. ^{4}He(d, γ)^{6}Li $\qquad Q_\text{m} = 1.4737$

At $E_\text{d} = 1.06$ MeV [^{6}Li*(2.19)], $\sigma < 0.1$ mb (1954SI07). At $E_\text{d} = 3.1$ MeV [^{6}Li*(3.56)] $\Gamma_{\text{d},\alpha} < 0.2$ eV (1958WI15).

4. (a) ^{4}He(d, n)^{5}Li $\qquad Q_\text{m} = -4.19 \qquad E_\text{b} = 1.4737$

(b) ^{4}He(d, p)^{5}He $Q_m = -3.12$

(c) ^{4}He(d, t)^{3}He $Q_m = -14.3209$

(d) ^{4}He(d, d)p + ^{3}H $Q_m = -19.8147$

(e) ^{4}He(d, d)d + d $Q_m = -23.8476$

For reaction (a) see ^{5}Li, (1966LA04) and (1971NO1C). The proton yield (reaction (b)) gives no evidence of states in ^{6}Li with $6.5 < E_x < 8.7$ MeV (1964OH01). Polarization measurements at $E_d = 8.5$, 10 and 11 MeV (1971KE16) and 11 to 17 MeV (1972AV1E) indicate scattering through the first two states of ^{5}He. The vector analyzing power has been measured at $E_d = 32.1$ and 41.0 MeV (1973CO2A, 1973DA1Q: detected ^{3}H and ^{3}He).

Studies of the t and ^{3}He differential cross sections (reaction (c)) at $E_\alpha = 48.3$ MeV (1971WA20) and at $E_\alpha = 49.9$, 64.3 and 82.1 MeV (1970GR07, 1972GR07) show pronounced deviations from $90^\circ_{\text{c.m.}}$ symmetry which are angle and energy dependent. [See analysis in (1973ED02)]. The observed asymmetries can be accounted for in terms of the p and the n separation energies in ^{4}He (1972GR07). The asymmetry remains but is considerably smaller at $E_\alpha = 166$ MeV (1973BA2U): it is attributed in part to Coulomb effects. See also (1969HA1Q, 1973FI04) and (1970RI16, 1971KO14, 1971MU17, 1972KN05, 1973BE2H; theor.).

For reactions (d) and (e) see (1972LI04: $E_d = 52$ MeV).

5. (a) ^{4}He(d, d)^{4}He $E_b = 1.4737$

(b) ^{4}He(d, pn)^{4}He $Q_m = -2.22464$

Elastic scattering differential cross-section measurements have been carried out previously at many energies up to 27.3 MeV: see (1966LA04) for a listing of the previous work. Recently, measurements have been reported at $E_d = 2.48$ MeV (1964MA50), 3 to 14 MeV (1968MA03), 12.00 MeV (1971JE01), 14.2 MeV (1967FU1D), 27.1 to 39.6 MeV (1969HA1Q) and at $E_\alpha = 166$ MeV (1969BR19). Polarization measurements are listed in Table 6.3. See also the reviews by (1966DA1B, 1971PL1C), (1972OH02) who set up a convenient parametrization for $1+0 \rightarrow 1'+0'$ polarization transfer phenomena, and (1973OH01, 1973OH02).

Phase shift analyses have been carried out for $E_d = 0.3$ to 4.2 MeV (1955GA74), 2 to 10 MeV (1967MC02), 3 to 10 MeV (1964SE07), 3 to 11 MeV (1970KE17), 3 to 11.5 MeV (1972SC14) and 10 to 27 MeV (1967DA1B). See also (1968MA03). (1973TH1F) have recalculated the phase shifts, including distortion of the deuteron cluster. This effect is important in the even-l cases. It leads to larger phase shifts than in calculations which do not include distortion, and in sharp resonance structure above 12 MeV. The pre ′67 analyses were based on the analyses of differential cross section measurements; the newer ones also include the fitting of polarization measurements. On the basis of these analyses it is found that the d-wave shifts are split and exhibit resonance at $E_x = 2.18$ (^{3}D$_3$), 4.8 (^{3}D$_2$) and 5.7 MeV (^{3}D$_1$): the parameters of these states are displayed in Table 6.4. A good fit to all data below $E_d = 11$ MeV is found with partial waves of $l \leq 3$

Table 6.3: Polarization measurements in ^{4}He(d, d)^{4}He [a]

E_d (MeV)	Refs.
1.07	(1967ME14)
$2-9$	(1967MC01, 1967MC02)
$2.50-11.01$	(1967TR05)
$2.8-6.7$	(1967YO01)
[and $E_\alpha = 4.1-11.1$]	
$3-11$	(1970KE17)
$3.0-11.5$	(1969GR20, 1969KO1N, 1970GR12, 1970KO08)
$4.8-9.0$	(1973OH02)
$6.0-10.5$	(1967CL07)
7.02, 9.70	(1971KO09)
7.07	(1970DA19)
7.74	(1972MI1L)
8.1	(1966DO1B)
9.0	(1967BE15)
$9-14$	(1969ST1F)
9.80	(1971KE1E)
11.13, 11.50, 12.00	(1971ST1K)
11.5	(1969OH02)
$11.5-17.0$	(1973CH35)
$11.6-17.5$	(1973OH01)
15	(1972HA2D)
$15-45$	(1972LE1U)
17.7, 19.7, 21.4	(1966AR1B, 1967AR03)
20.5, 25.2, 29.4	(1972FI1G)

[a] See also (1966LA04).

Table 6.4: Levels of ^{6}Li from ^{4}He(d, d)^{4}He [a]

E_d (MeV)	1.070 ± 0.003 [b]	4.8 ± 0.1	6.4 ± 0.1
$J^\pi;\ T$	$3^+; 0$	$2^+; 0$	$1^+; 0$
E_x (MeV)	2.185	4.7	5.7
Reduced elastic width			
$\gamma^2_{\lambda,\ l=0}$			0.003
$\gamma^2_{\lambda,\ l=2}$	0.8	1.6	3.1
Reduced width for proton emission			
$\gamma^2_{\lambda,\ l=1}$		1.3	0.8
Reduced width for neutron emission			
$\gamma^2_{\lambda,\ l=1}$		1.3	0.8
Interaction radius a (fm)	3.5	4.2	4.1

[a] (1972SC14). See also (1964SE07, 1967MC02, 1969LI06, 1970KE17).
[b] (1955GA74).

(1972SC14). The p-wave phase shifts are small which is strong evidence against the existence of the $T = 0$ p-wave triplet reported earlier by (1964SE07): see (1967MC02, 1969KO1N, 1970KE17, 1972SC14). For $E_d = 11.5$ to 17 MeV, the vector analyzing power iT_{11} at a given angle is fairly constant (at $\theta_{c.m.} = 90°$ it is close to zero): this is also indicative of the absence of negative parity states in that region (1973CH35). At higher energies the $l = 3$ and 4 partial waves become important. The $l = 0$, 1 and 2 waves continue smoothly their low-energy behavior. [See, however, (1973TH1F)]. The interaction appears to be dominated by absorption (1967DA1B). See also (1969HA1Q, 1969KR14, 1969LI06).

In the range $E_\alpha = 30$ to 80 MeV there is no difference in the cross sections for ^{2}H(α, αp)n and ^{2}H(α, αn)p, indicating that spin statistics play a dominant role in the deuteron breakup reactions and that charge and FSI effects are unimportant when quasi-free scattering conditions are satisfied (1972AL04). However, it is also found that the shapes of the quasi-free peaks do not remain the same for the two cases over the above energy range (1972AL1T). Reaction (b) appears to proceed at least partly via ^{6}Li*(4.3) [whose E_x was assumed to be 4.57 MeV]. An upper limit for the $T = 1$ impurity amplitude of this state is estimated to be 10^{-2} (1972DE49). For other work on reaction (b), see (1968WA01, 1970AS02, 1970BO1Q, 1972HO1H, 1973CH05) and reactions 9 in ^{5}He and in ^{5}Li. See also (1965TO01, 1967FU1D).

See also (1967PL02, 1971AR1C), (1971HA2G), (1966RA1B, 1967HA1H, 1967LA22, 1967NA1E, 1968FI1E, 1968LA13, 1968PA1K, 1968TH02, 1969JA1J, 1969JA1G, 1969LI06, 1969NA09, 1969SC1K,

1969SH20, 1969TA1G, 1969TH1C, 1969VA1G, 1970AL1K, 1970CH1K, 1970HA1N, 1970HO32, 1970KU15, 1970NE1F, 1971KU22, 1971TE1B, 1972BL1F, 1972KU20, 1972NA1D, 1972RI10, 1973AU1K, 1973CH27, 1973NA12, 1973TH1E; theor.) and (1966LA04).

6. (a) ^{4}He(^{3}He, p)^{6}Li $\qquad Q_{\rm m} = -4.020$
   (b) ^{4}He(^{3}He, n2p)^{4}He $\qquad Q_{\rm m} = -7.7184$

Angular distributions have been measured at $E(^{3}{\rm He}) = 8$ to 18 MeV (1967SP10; p_0), 11 to 18 MeV (1967SP10; p_1), 26 MeV (1965EC1A; p_0, p_1, p_2), 28 MeV (1971KL1E; p_0, p_1, p_2), $E_\alpha = 42$ MeV (1970VI01; p_0, p_1) and 71.7 and 81.4 MeV (1973HA50: formation of ^{6}Li*(0, 2.19, 3.56)). At $E_\alpha = 63.7$, 71.7 and 81.4 MeV, the α spectra show that the sequential decay (reaction (b)) involves ^{6}Li*(2.19) and possibly ^{5}Li (1973HA50). See also (1961CH09, 1970BA1V) and ^{7}Be.

7. ^{6}He(β^-)^{6}Li $\qquad Q_{\rm m} = 3.510$

See ^{6}He.

8. ^{6}Li(γ, γ)^{6}Li

The width, Γ_γ, of ^{6}Li*(3.56) is 8.1 ± 0.5 eV. $\Gamma_{\alpha,{\rm d}}$ for the forbidden decay of this state into $\alpha +$ d is < 1.3 eV (1969RA20). The measurements by (1968CR07) are incorrect: see the discussion in (1969RA20). (1973SA21) reports $\Gamma_\gamma = 6.5^{+2.4}_{-1.7}$ eV. See also Table 6.5 and (1966LA04).

9. (a) ^{6}Li(γ, n)^{5}Li $\qquad Q_{\rm m} = -5.66$
   (b) ^{6}Li(γ, p)^{5}He $\qquad Q_{\rm m} = -4.59$
   (c) ^{6}Li(γ, d)^{4}He $\qquad Q_{\rm m} = -1.4737$
   (d) ^{6}Li(γ, t)^{3}He $\qquad Q_{\rm m} = -15.7946$
   (e) ^{6}Li(γ, pd)^{3}H $\qquad Q_{\rm m} = -21.288$
   (f) ^{6}Li(γ, nd)^{3}He $\qquad Q_{\rm m} = -22.052$

Measurements of reaction (a) with monochromatic γ-rays have been made for $E_\gamma = 5.4$ to 9.0 MeV (1964GR40) and 10 to 32 MeV (1965BE42). The cross section for reactions (a), (b) and (f) shows a possible peak at 6.75 MeV (1964GR40), a maximum at ≈ 12 MeV ($\sigma \approx 1.6$ mb) and a gentle decrease to 0.6 mb at 32 MeV (1965BE42). Other maxima in the cross section for neutron

Table 6.5: Levels of ^{6}Li from ^{6}Li(e, e′) and ^{6}Li(γ, γ') [a]

E_x (MeV)	$J^\pi; T$	$\Gamma_{\gamma 0}$ (eV)	Type	$\Gamma_{\gamma 0}/\Gamma_w$	Refs.
2.183 ± 0.009 [g]	$3^+; 0$	$(4.40 \pm 0.34) \times 10^{-4}$	E2	16.5	(1969EI06) [f]
		$(3.9 \pm 0.5) \times 10^{-4}$	E2	14.4	(1967AR1A)
3.563 ± 0.010	$0^+; 1$	8.31 ± 0.36	M1	8.8	(1969EI06) [f]
		8.9 ± 0.4	M1	9.4	(1967AR1A)
		8.1 ± 0.5 [b]	M1	8.6	(1969RA20)
4.27 ± 0.04	$2^+; 0$	$(5.4 \pm 2.8) \times 10^{-3}$	E2	7.2	(1969EI06) [h]
5.37 [c]	$2^+; 1$	0.16	M1		(1963BA19)
		0.19 ± 0.04 [d]	M1		(1970HU09)
[e]					

[a] See Table 6.6 in (1966LA04) for earlier references.

[b] From ^{6}Li(γ, γ').

[c] $E_x = 5.32 \pm 0.05$ MeV, $\Gamma = 330^{+120}_{-40}$ keV (1969HU05), $E_x = 5.38 \pm 0.02$ MeV, $\Gamma = 530 \pm 30$ keV (1970HU09), $E_x = 5.41 \pm 0.04$ MeV, $\Gamma = 540 \pm 30$ keV (1971NE03), $\Gamma = 440 \pm 100$ keV (1969EI06). The excitation of this state shows a transverse angular dependence (1969EI06).

[d] Probable value, but 0.08 ± 0.04 eV cannot be excluded: see (1970HU09).

[e] For possible transitions from higher states, see (1963BA19) and (1966LA04: Table 6.6). However, see discussion in reaction 10 (1973CA1M).

[f] See also (1968EI03).

[g] $B(\text{E2}; 1^+ \to 3^+) = 24\, e^2 \cdot \text{fm}^4$ (1971DI19; Coulomb excitation).

[h] $\Gamma = 690 \pm 120$ keV.

production are reported in (1965BA16, 1965HA19, 1966CO1B, 1966PA12) and in (1966LA04). See also (1966HI1B, 1968OD1A).

The cross section for photoproton production (reaction (b)) is generally flat up to 90 MeV with a slight evidence of a hump at ≈ 16 MeV excitation (1970WO10). Additional peaks are reported by (1969SO13). The energy distribution of the photoprotons has been measured at $E_{\text{brem.}} = 95$ to 102 MeV: the data are consistent with the predictions of the quasi deuteron model with a characteristic pair momentum parameter of 80 MeV/c (1968MA19). See also (1965BA16, 1965MA46, 1967DE12, 1973DE17, 1973GA16), (1973CO1N) and ^{5}He.

The cross section for reaction (c) is $\lesssim 5\ \mu$b in the range $E_\gamma = 2.6$ to 17 MeV consistent with the expected inhibition of dipole absorption by isospin selection rules: see (1959AJ76, 1966LA04). See also (1965MA46) and (1973PA17).

The cross section for reaction (d) shows a peak at $E_\gamma \approx 21$ MeV with $\sigma_{\text{max}} = 5.1$ mb. The angular distribution of the tritons at that energy is asymmetric around 90°, indicating interference between E1 and E2 absorption (1968MU1A, 1970MU05). Between 19 and 35 MeV the cross section decreases from 0.46 ± 0.24 mb to 0.11 ± 0.06 mb (1968SH10). See also (1965BA16, 1965MA46, 1970WO10, 1973DE17), and (1966LA04). The cross sections reported in this reaction are not in agreement with those found in the inverse reaction: see reaction 1 and e.g. (1973VE09, 1973VE1B). For reaction (e) see (1968MU1A, 1970MU05, 1973DE17).

See also the review articles by (1966FU1C, 1967SH1E, 1968SC1B, 1973AR1L), (1965DA06, 1966SH06, 1969ME1D, 1972CR1E) and (1966FE1B, 1966KU12, 1967AU1C, 1967NE1C, 1968CO13, 1969CL1D, 1969MA1N, 1970KU02, 1971AU01, 1971GH1A, 1971GH1B, 1971MU19, 1972KU05, 1972WE03, 1973MA2C, 1973RA1G, 1973SH08, 1973SR1B; theor.).

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

(b) ^{6}Li(e, ep)^{5}He $\qquad Q_{\rm m} = -4.59$

(c) ^{6}Li(e, ed)^{4}He $\qquad Q_{\rm m} = -1.4737$

Elastic scattering has been measured at $E_{\rm e} = 85$ to 140 MeV (1966RA29), 200 to 499 MeV (1971LI10) and 200 to 600 MeV (1967SU1A). The elastic scattering shows a diffraction minimum at $q^2 = 8$ fm^{-2}. The diffraction feature in F^2 indicates a lowering of the central charge density (1971LI10). A model-independent analysis of the scattering yields $r_{\rm rms} = 2.51 \pm 0.10$ fm (1972BU01). See also (1967SU1A, 1969MO1J, 1971LI10, 1971NE03). Measurement of the ratio of elastic charge scattering from ^{6}Li and from ^{7}Li as a function of (momentum transfer)^2 yields $\langle r^2\rangle_6^{1/2}/\langle r^2\rangle_7^{1/2} = 1.001 \pm 0.008$ (1971VA20).

The population of excited states of ^{6}Li has been reported at $E_{\rm e} = 41$ to 59 MeV (1969EI06: ^{6}Li*(2.19, 3.56, 4.27, 5.37)), 63 to 128 MeV (1968HU03, 1968HU1C, 1969HU05: ^{6}Li*(3.56)), 89 to 175.4 MeV (1971NE03: ^{6}Li*(2.19, 3.56, 5.36)), 109.0 to 166.9 MeV (1969NE1B: ^{6}Li*(3.56)), 109.0 to 281.7 MeV (1969NE1B: ^{6}Li*(2.19)) and 200 and 499 MeV (1971LI10: ^{6}Li*(2.19)). The inelastic electron groups are superposed on a rather large quasi-continuous background [see, e.g., (1969HU05)]. See also (1968EI03, 1970BR1E, 1972THZF, 1973TH1B, 1973YE1B). Table 6.5 summarizes the results. See (1966LA04) for a summary of the earlier reported results.

Because of the astrophysical implications of a 0^+ state in ^{6}Be near the ^{3}He + ^{3}He binding energy, several attempts have been made to locate the analog state in ^{6}Li at $E_{\rm x} \approx 15.2$ MeV. The results were negative: $\Gamma_\gamma < 11$ eV for the M1 width of the $0^+ \rightarrow 1^+$ transition to the ground state of ^{6}Li (1973CA1M: $E_{\rm e} = 65$ MeV; looked a $E_{\rm x} = 9.0$ to 16.8 MeV), $\Gamma_\gamma < 3$ eV (1973FA04: $E_{\rm e} = 37$, 50, 60 MeV), $\Gamma_\gamma < 8.8$ eV (1973BI1M: $E_{\rm e} = 100$ MeV).

The harmonic oscillator parameters of the 1p and 1s shells in ^{6}Li are $q_{\rm p} = 50 \pm 5$ MeV/c and $q_{\rm s} = 108 \pm 9$ MeV/c (1972AN27). For reaction (b) see also (1970WO10, 1971HE1K, 1973HE1L) and ^{5}He. For reaction (c) see (1966AL1F, 1971HE1K, 1972GE1H, 1973HE1L, 1973JU1E). See also (1972TI03).

See also the reviews by (1966GO1C, 1968GO1J, 1972LO1L), (1970AN1G, 1971MO06) and (1966BO1B, 1966GR1D, 1966KU1B, 1966LO1F, 1966MA1F, 1967AL1D, 1967BO1E, 1967HA1J, 1967KA1A, 1967WO1B, 1968BO1N, 1968CI1D, 1968KU1B, 1969AL1E, 1969AU1A, 1969CH25, 1969CI1A, 1969GE08, 1969HA1N, 1969JA1H, 1969KU1C, 1969KU13, 1969MA1M, 1969NE1C,

1969SU1D, 1969VI02, 1970CH1M, 1970CI1B, 1970JA08, 1970JA21, 1970LA1D, 1970LO1J, 1970SP1C, 1970SU13, 1970VA15, 1971CH06, 1971CH23, 1971DE1T, 1971DRZW, 1971LO03, 1971LO07, 1971LO08, 1972BR20, 1972EL11, 1972JE05, 1972KU20, 1973BA65, 1973DE18, 1973DO1H, 1973DO07, 1973HI03, 1973MA51, 1973RA04, 1973RA23, 1973WE18; theor.).

11. ^{6}Li(n, n′)^{6}Li*

Angular distributions have been reported at $E_{\rm n} = 1.00$ to 2.30 MeV (1967KN1A; n_0), 4.8, 5.7, 7.5 MeV (1968HO03; n_0), 10 MeV (1967CO01; n_0, n_1), 14.0 MeV (1966ME1C; n_0, n_1) and 14.2 MeV (1970AB04; n_0, n_1). See (1966LA04) for earlier references. The population of ^{6}Li*(3.56) is weak: see (1966LA04, 1968HO03). See, however, (1966ME1C). See also (1971MI12; theor.) and ^{7}Li.

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

(b) ^{6}Li(p, 2p)^{5}He $\qquad Q_{\rm m} = -4.59$

(c) ^{6}Li(p, pd)^{4}He $\qquad Q_{\rm m} = -1.4737$

(d) ^{6}Li(p, p^{3}H)^{3}He $\qquad Q_{\rm m} = -15.795$

(e) ^{6}Li(p, pn)^{5}Li $\qquad Q_{\rm m} = -5.66$

(f) ^{6}Li(p, 2d)^{3}He $\qquad Q_{\rm m} = -19.828$

Proton angular distributions have been measured recently at $E_{\rm p} = 3.6$ to 9.4 MeV (1967HA07, 1967HA08; p_1), 4.3 to 9.4 MeV (1967HA07, 1967HA08; p_2), 14.0 MeV (1968ME25; p_0, p_1, p_2), 24.4 MeV (1968AU05, 1968AU06; p_2), 25.9, 29.9, 35.0, 40.1, 45.4 MeV (1972BR20; p_0, p_1), 25.9, 45.4 MeV (1972BR20; p_2), 33.6 MeV (1970KU1D; p_0), 49.8 MeV (1971MA13, 1971MA44; p_0, p_1), 100 MeV (1968LI1C; p_0), 144 MeV (1972JA07; p_0), 152 MeV (1966RO1C; p_0), 155 MeV (1968GE04; p_0), 155 MeV (1965JA1A: ^{6}Li*(2.2 ± 0.05, 3.6 ± 0.1, 4.5, 5.5)), 185 MeV (1970HU13; p_0, p_1, p_2) and 600 MeV (1973GA1M; p_0). See also (1970KO36). See (1966LA04) for a listing of the earlier references.

Inelastic groups corresponding to excited states of ^{6}Li are displayed in Table 6.6: no others appear for $E_{\rm x} < 16$ MeV (1968MA02). See also (1969KO1M, 1970BA1V) and (1968GL1A, 1968NE1B, 1969MA1G, 1969NE1A, 1969TI02, 1969WA11, 1973RA04; theor.).

Angular correlations of protons (reaction (b)) corresponding to ^{5}He(0) show an $l = 1$ character, but with an anomalously low peak-to-valley ratio, as compared e.g. with ^{7}Li, suggesting a significant s-wave contribution (1967RO06: $E_{\rm p} = 156$ MeV); and see discussion in (1972MA61) relating both to this transition and to the one involving ^{5}He*(16.8). See also (1965BE1E, 1970TH1F, 1972MI1N, 1973MI1J, 1973CO2B), (1966LA04) and (1966JA1A, 1967JA1C, 1967JA1D, 1967JA1E, 1968KU1B, 1968SA1C, 1968TA1K, 1969JA1D, 1969KO1J, 1971KO27, 1973BA65, 1973CH1Q; theor.)

Table 6.6: Levels of ^{6}Li from (p, p′), (d, d′), ^{9}Be(p, α), ^{7}Li(d, t)

Reaction	Refs.	E_x (MeV ± keV)	$\Gamma_{c.m.}$ (keV)
^{6}Li(p, p′)^{6}Li*	(1968MA02) [a]	2.14 ± 50	
^{6}Li(p, p′)^{6}Li*	(1957BR12)	2.188	25.4
^{6}Li(d, d′)^{6}Li*	(1957BR12)	2.186	24.5
^{9}Be(p, α)^{6}Li	(1957BR12)	2.192	29
^{9}Be(p, α)^{6}Li	(1963GR29)	2.19 ± 20	< 35
^{7}Li(d, t)^{6}Li	(1957BR12)	(2.18)	< 27
mean	(1957BR12)	2.188 ± 6	26.3
^{6}Li(p, p′)^{6}Li*	(1968MA02)	3.49 ± 50	
^{6}Li(p, p′)^{6}Li*	(1957BR12)	3.559	< 5
^{9}Be(p, α)^{6}Li	(1957BR12)	3.561	
^{9}Be(p, α)^{6}Li	(1963GR29)	3.55 ± 20	< 35
mean	(1957BR12)	3.560 ± 6	< 5
^{6}Li(p, p′)^{6}Li*	(1968MA02)	4.45 ± 80	300 ± 50
^{9}Be(p, α)^{6}Li	(1963GR29)	4.40 ± 120	350 ± 150
^{6}Li(p, p′)^{6}Li*	(1965HA17)	4.4 ± 200	≈ 600
^{6}Li(d, d′)^{6}Li*	(1975BR21)	4.32 ± 40	1820 ± 110
^{6}Li(p, p′)^{6}Li*	(1968MA02)	5.28 ± 80	300 ± 50
^{9}Be(p, α)^{6}Li	(1963GR29)	5.32 ± 60	280 ± 60
^{6}Li(p, p′)^{6}Li*	(1965HA17)	5.4 ± 200	≈ 1000
^{6}Li(p, p′)^{6}Li*	(1965HA17)	≈ 6.5	
^{6}Li(p, p′)^{6}Li*	(1965HA17)	≈ 7.5	

[a] (1968MA02) also report a state at $E_x = 4.03 \pm 0.08$ MeV, $\Gamma = 1.5 \pm 0.2$ MeV.

Reaction (c) has been studied at $E_p = 9$ and 10 MeV (1968VA02), 19 MeV (1971LI1N, 1973LI22), 45 MeV (1970BR1N), 56.5 and 61.5 MeV (1969RO04, 1970JA17), 100 MeV (1971MA61, 1973GO2A), 118.1 MeV (1972BA2L), 156 MeV (1968BA09, 1973BA01), 590 MeV (1972AL21, 1973KI1M) and 1 GeV (1967SU1C). At $E_p = 590$ MeV, in a kinematically complete experiment, the width of the momentum distribution of a deuteron in ^{6}Li is found to be 124 ± 4 MeV/c (1972AL21) [see also preliminary report by (1973KI1M)], while (1970JA17) find 70 ± 8 MeV/c at $E_p = 56.5$ MeV. See also (1973CH1R). The probability for a deuteron cluster in ^{6}Li is estimated to be 0.45 ± 0.08 (1971MA61), 0.13 ± 0.05 (1973LI22). At $E_p = 9$ and 10 MeV sequential decay via ^{6}Li*(0, 2.19, 4.6, 6.0) dominates the yield: the final state interactions do not support the previously proposed [see (1966LA04)] negative-parity states in ^{6}Li (1968VA02). See also (1966SE1C, 1971GA1J, 1973CO2B), (1968KO1E) and (1965NE1B, 1966ZE1A, 1968RO1F, 1969BO1G, 1969HO1K, 1969JA13, 1969NA1H, 1970JA1L, 1970MI1J, 1973RO2B; theor.). See also reaction 9 in ^{7}Li (1973WE07).

Angular correlation studies in reaction (d) give evidence for an appreciable ^{3}He + ^{3}H configuration in ^{6}Li(0) (1968BA09, 1970BA1T, 1973GO2A). At $E_p = 590$ MeV, in a kinematically complete experiment, the width of the momentum distribution is determined to be 168 ± 34 MeV/c (1973DO12). See also (1969KO1G, 1973RA1G) and ^{7}Be. For reaction (e) see (1972MI1N, 1973MI1J). For reaction (f) see (1973CO2B).

13. (a) ^{6}Li(d, d′)^{6}Li*

(b) ^{6}Li(d, pn)^{6}Li	$Q_m = -2.22464$
(c) ^{6}Li(d, 2d)^{4}He	$Q_m = -1.4737$
(d) ^{6}Li(d, αt)^{1}H	$Q_m = -2.559$
(e) ^{6}Li(d, α^3He)n	$Q_m = -1.795$

Angular distributions of deuterons have been measured at $E_d = 4.5$ to 5.5 MeV (1970PO03; d_0), 8 to 12 MeV (1970BI1B, 1971BI11; d_0), 11.8 MeV (1968LU02; d_0, d_1), 14.7 MeV (1969MA13; d_0, d_1) and 19.6 MeV (1971CHYH; d_0). The $T = 1$, 0^+ state, ^{6}Li*(3.56), is not appreciably populated. See also (1966LA04) and (1966BR1G). ^{6}Li*(4.31) has been studied at $E_d = 20$ and 25 MeV: a single-level, many-channel fit yields $\Gamma = 1.82 \pm 0.11$ MeV (1975BR21). See also (1968LE15). See Table 6.6 for a summary of the results on excited states.

At $E_d = 21$ MeV reaction (b) shows spectral peaking (characteristic of $^1S_0$ for the pn system [$T = 1$]) when ^{6}Li*(3.56) is formed, in contrast with the much broader shape (characteristic of $^3S_1$) seen when ^{6}Li*(0, 2.19) are populated (1972BR03). See also (1973CH05). A study of reaction (c) at $E_d = 52$ MeV shows that the α-clustering probability, $N_{\text{eff}} = 0.12^{+0.12}_{-0.06}$ if a Hankel function is used (1973HA31) [see this reference also for a discussion of other results on momentum distributions and α-clustering probability in ^{6}Li]. The α-particle and the deuteron clusters in ^{6}Li have essentially a relative orbital momentum of $l = 0$. The D-state probability of the ground state of ^{6}Li is $\approx 5\%$ of the S-state (1973HA31). Quasi-free scattering is an important process even for $E_d = 6$ to 11 MeV (1973MI20). Interference effects are evident in reaction (c) proceeding through

^{6}Li*(2.19, 4.31): this is due to the experiment being unable to determine whether the detected particle was emitted first or second in the sequential decay (1968LE15). See also (1973JA21). For reactions (d) and (e) see (1968LE15) and (1974GR02).

14. ^{6}Li(^{3}He, ^{3}He)^{6}Li

Angular distributions have been measured at $E(^3\text{He}) = 8$ to 20 MeV (1968LU02: g.s.), 21, 24 and 27 MeV (1966VA1B, 1967BL1E: g.s., 2.19), 24.6 and 27 MeV (1971GI1E, 1972GI07: g.s., 2.19, 3.56), 34 MeV (1971CHYH: g.s.) and 217 MeV (1973WI07: g.s.). At $E(^3\text{He}) = 24.0$ MeV the population of ^{6}Li*(0, 2.19, 3.56, 4.53, 5.37) is reported by (1973VE1B). See also (1967CO1J) and (1973DU1D; theor.).

15. (a) ^{6}Li(α, α')^{6}Li*
(b) ^{6}Li(α, 2α)^{2}H $\qquad Q_\text{m} = -1.4737$

Angular distributions (reaction (a)) have been measured at $E_\alpha = 3.0$ and 4.0 MeV (1972BO07; α_0), 12.54 to 18.54 MeV (1970BI1B, 1971BI12; α_0), 25 MeV (1968DO13; α_0, α_1), 29.4 MeV (1968MA25, 1969MA13; α_0, α_1), 36.5 MeV (1971CHYH; α_0), 104 MeV (1968HA1D, 1969HA14, 1970HA1G; α_0) and 166 MeV (1972BA89; α_0). See (1966LA04) for earlier references. In the range $E_\alpha = 12.5$ to 18.5 MeV the optical model gives good agreement with the elastic angular distributions when a target spin-orbit potential is included (1971BI12). At $E_\alpha = 104$ MeV the elastic angular distribution shows a pronounced diffraction pattern (1969HA14) while at 166 MeV there is some backward peaking in addition to a single strong forward peak (1972BA89). See also (1969TR1B, 1970FO1B, 1970MI1J, 1973CL1K; theor.) and (1969HO1K).

Reaction (b) has been studied by (1969PU01, 1970WA1U, 1971WA19) at $E_\alpha = 50.4$, 59.0, 60.5, 70.3 and 79.6 MeV. At each of these energies several coincident energy spectra of the two α-particles were taken, with special emphasis on those angles at which zero lab momentum is possible for the residual deuteron. From the measurements at these particular angles, off-mass-shell α-α cross sections were extracted and were found to be in excellent agreement with the free α-α cross sections at comparable energies: see ^{8}Be. The momentum distribution for α-particles in ^{6}Li has a width of 29 ± 2 MeV/c. The effective number of $\alpha +$d clusters for ^{6}Li(0), $N_\text{eff} = 0.08 \pm 0.04$. The knockout process appears to occur only in the nuclear surface region (1971WA19).

Reaction (b) has also been studied at $E_\alpha = 23.6$ MeV (1969BA18), 25 MeV (1968DO13, 1969DO02), 29.4 MeV (1968MA25), 37.5 and 43.5 MeV (1971DE15), 42.8 MeV (1970GA14), 55 MeV (1968PI04, 1969PI11, 1970PI1D), 64.3 MeV (1970JA17). See also (1967MO1F, 1969VE1B, 1973JA21, 1974DO1G). The reaction ^{6}Li(α, αx)Y has been studied at $E_\alpha = 50$ MeV [x = p, d, t, ^{3}He, α]: p, d, and α clustering is strong, t and ^{3}He clustering is weak (1971LA20). See also (1968BA1H, 1969DO03, 1970BU1C, 1970MI12, 1972KO1J, 1972AV04; theor.).

16. ^{6}Li(^{6}Li, ^{6}Li)^{6}Li

Angular distributions of elastically scattered ^{6}Li ions have been measured at $E(^{6}\text{Li}) = 3.2$ to 7.0 MeV (1966PI02), 8 to 14.5 MeV (1973GR34), 12, 20 and 28 MeV (1971FO08), 30 MeV (1971DA33), 32.0 MeV (1970NA02: also ^{6}Li*(3.56)), and 32.0 and 36.0 MeV (1973WH02: for both ^{6}Li*(3.56)). A microscopic DWBA analysis (including the tensor interaction and exchange) gives good agreement with the data (except at forward angles) and with the cross sections for this reaction and for the reaction to the analog ground states of ^{6}He and ^{6}Be (1973WH02). See also reaction 9 in ^{6}He. (1971FO08) report that the reaction mechanism is dominated by absorption. See also ^{12}C in (1975AJ02) and (1972CL14, 1973PE13; theor.).

17. ^{6}Li(^{16}O, ^{16}O)^{6}Li

At $E(^{16}\text{O}) = 36$ MeV the elastic angular distribution has been measured by (1971OR02).

18. ^{7}Li(n, 2n)^{6}Li $\qquad Q_{\text{m}} = -7.251$

See (1965GO1C, 1969VA1F) and ^{8}Li.

19. ^{7}Li(γ, n)^{6}Li $\qquad Q_{\text{m}} = -7.2506$

See (1969GA1M, 1969ME1D, 1969MU1C) and ^{7}Li.

20. (a) ^{7}Li(p, d)^{6}Li $\qquad Q_{\text{m}} = -5.026$
(b) ^{7}Li(p, 2d)^{4}He $\qquad Q_{\text{m}} = -6.500$
(c) ^{7}Li(p, pd)^{5}He $\qquad Q_{\text{m}} = -9.61$

Angular distributions of deuterons (reaction (a)) have been recently studied at $E_{\text{p}} = 30.3$ MeV (1969DE04: ^{6}Li*(0, 2.19, 3.56)), 33.6 MeV (1967KU10, 1970KU1D: ^{6}Li*(0, 2.19, 3.56, 5.37)), 100 MeV (1968LE01, 1969LI02: ^{6}Li*(0, 2.19, 3.56, 5.6)) and 155.6 MeV (1968BE72, 1969BA05, 1969TO1A: ^{6}Li*(0, 2.2 ± 0.08, 3.6 ± 0.1, 4.5 ± 0.15, 5.5 ± 0.1)). No states other than those reported above have been observed up to $E_{\text{x}} = 18$ MeV (1967KU10), 20 MeV (1969BA05). See also (1966LA04) and (1970BA1V, 1972AZ03). At $E_{\text{p}} = 12$ MeV (1969CO06) have studied the ratio of the cross section of the (p, d) reaction to that for the (p, d) reaction, in which singlet deuterons are formed: σ(p, d)/σ(p, d) $= 41.0$.

A kinematically complete experiment at $E_{\text{p}} = 45$ MeV shows that reaction (b) proceeds via low lying excited states of ^{6}Li (1972FU07). See also (1967JO1B). For reaction (c) see (1969DE04).

21. ^{7}Li(d, t)^{6}Li $\qquad Q_m = -0.993$

The angular distributions of the tritons to ^{6}Li*(0, 2.19, 3.56) at $E_d \approx 15$ MeV indicate $l_n = 1$, and therefore even parity, for the first three states of ^{6}Li: see (1966LA04). A careful study at $E_d = 10 - 12$ MeV, in a region in ^{9}Be which is free of sharp resonances, shows that the t_0 angular distributions which have both fore and aft maxima can be reproduced using a multi-interaction, exact finite-range two-mode DWBA formalism (1970ZE1C, 1971ZA07, 1973WE09).

A study at $E_d = 23.6$ MeV of the relative cross sections of the analog reactions ^{7}Li(d, t)^{6}Li (to the first two $T = 1$ states at 3.56 and 5.37 MeV) and ^{7}Li(d, ^{3}He)^{6}He (to the ground and 1.80 MeV excited state) shows that ^{6}Li*(3.56, 5.37) have high isospin purity ($\alpha^2 < 0.008$): this is explained in terms of antisymmetrization effects which prevent mixing with nearby $T = 0$ states (1971DE08). See also (1970BA1V) and (1971WE1L, 1973DU1D; theor.).

22. ^{7}Li(^{3}He, α)^{6}Li $\qquad Q_m = 13.328$

Angular distributions have been reported at $E(^3\text{He}) = 5.1$ to 12 MeV (1969LI06; α_1), 5.1 and 7.5 MeV (1969LI06; α_2), 5.5 to 9.0 MeV (1969LI06; α_0), 6.0 and 7.5 MeV (1970OR03; α_0, α_1, α_2), 8.7 MeV (1969MA1J; α_1), 8.7 and 9.7 MeV (1969MA1J; α_0), 16 to 18 MeV (1970ZE1C, 1971ZA07; α_0) and 21, 24 and 27 MeV (1966VA1B, 1967BL1E; α_0, α_1, α_2). See also (1969OR01) and ^{10}B. At $E(^3\text{He}) = 16$ to 18 MeV, in a region where there are no sharp or strong resonances in the compound nucleus, both the forward and the backward maxima in the α_0 angular distributions are reproduced by conventional DWBA without inclusion of exchange terms. However, the cross section derived from zero range DWBA is a factor of 25 smaller than the observed cross section. For finite range analysis no appreciable renormalization is necessary (1971ZA07). See also (1973WE1V; theor.).

At $E(^3\text{He}) = 3.8$ to 5 MeV, α groups are observed to the ground state and to excited states at $E_x = 2.17 \pm 0.02$, 3.55 ± 0.02 and 5.34 ± 0.02 MeV [$\Gamma = 560 \pm 40$ keV]: no evidence is seen for other excited states below $E_x = 10$ MeV previously reported by (1960AL10), even after a spectrum was taken at the energy [$E(^3\text{He}) = 0.9$ MeV] at which the earlier work was done (1968CO07). (1969LI06) observe states at $E_x = 2.179 \pm 0.008$, 3.568 ± 0.008 and 5.36 ± 0.03 MeV [$\Gamma \approx 0.54 \pm 0.04$ MeV].

At $E(^3\text{He}) = 11$ to 12 MeV only structureless broad spectra are observed in the region $15.6 \leq E_x \leq 16$ MeV: there is no evidence for a sharp $T = 1$ analog of a state in ^{6}Be near the ^{3}He + ^{3}He binding energy postulated for astrophysical considerations (1972MA1W).

Several attempts have been made to look at the isospin decay of ^{6}Li*(5.37) [$J^\pi = 2^+$; $T = 1$] via ^{7}Li(^{3}He, α)^{6}Li* $\rightarrow$ d + α: the branching is $< 2\%$ (1971CO22), $< 1\%$ (1973BR20). If $\Gamma(5.37) = 560$ keV [see above] $\Gamma_d \leq 12$ keV and $\theta^2_d(5.37) \leq 0.5\%$ (1971CO22). See, however, (1973BR20). $\Gamma_p/\Gamma = 0.35 \pm 0.10$ and $\Gamma_{p+n}/\Gamma = 0.65 \pm 0.10$ for ^{6}Li*(5.37) (1973AR05). See also (1970KA1M, 1971AR37, 1972KA08) and (1966LA04).

23. ^{9}Be(γ, t)^{6}Li $\qquad Q_m = -17.689$

See (1959AJ76).

24. (a) ^{9}Be(p, α)^{6}Li $\qquad Q_m = 2.125$

(b) ^{9}Be(p, d)^{4}He^{4}He $\qquad Q_m = 0.651$

$Q_0 = 2.1254 \pm 0.0018$ (1967OD01: see also (1967SP09)).

Angular distributions of α-particles (reaction (a)) have been measured at $E_p = 0.11$ to 0.60 MeV (1973SI27; α_0), 0.3 to 0.9 MeV (1968BE1N; α_0), 6 to 11.5 MeV (1963BL20; α_0, α_1), 5.9 and 7 MeV (1964YA1A; α_0, α_1), 15.6 and 18.6 MeV (1962MA40; α_0, α_1), 26.7 and 38 MeV (1967AC01, 1969GA03, 1970GU06; α_0, α_1) and 45 MeV (1970DE17, 1971DE2B, 1971PE10, 1972DE01, 1972DE02; α_0, α_1, α_2 and ^{6}Li*(0, 3.56)). At $E_p = 45$ MeV the reaction appears to proceed by a direct process, with a rise at back angles attributed to a pickup process. The 3.56 MeV state decays by γ-emission: $E_\gamma = 3.572 \pm 0.012$ MeV; the internal pair spectrum is consistent with an M1 transition (1954MA26). The α-decay of ^{6}Li*(3.56) is forbidden by spin and parity conservation: Γ_α/Γ is measured to be < 0.025 (1971AR37). See also (1972KO1N). For the decay of ^{6}Li*(5.37) see reaction 22 (1973AR05). See also (1966DO1A, 1966LA20, 1970MA1K) and (1969TH1D, 1973ED02; theor.). See also ^{10}B and (1966LA04).

At $E_p = 9$ MeV, the yield of reaction (b) is dominated by final state interactions through ^{8}Be*(0, 2.9) and ^{6}Li*(2.19) with little or no yield from a direct three-body decay (1971EM01). See also (1967FI1D).

25. ^{9}Be(d, ^{5}He)^{6}Li $\qquad Q_m = -0.99$

Not reported: see (1964BL1C).

26. ^{9}Be(t, ^{6}He)^{6}Li $\qquad Q_m = -5.386$

Angular distributions of ^{6}He$_{\rm g.s.}$ + ^{6}Li$_{\rm g.s.}$, ^{6}Li$_{\rm g.s.}$ + ^{6}He$_{\rm g.s.}$, ^{6}Li$^*_{3.56}$ + ^{6}He$_{\rm g.s.}$, and ^{6}He$_{\rm g.s.}$ + ^{6}Li$^*_{3.56}$ [the second listed ion being the detected one] have been measured at $E_t = 23.5$ MeV. In the latter two cases the final state is composed of two isobaric analog states: angular distributions are symmetric about $90^\circ_{\rm c.m.}$, within the overall experimental errors. In the reaction leading to the ground states of ^{6}He and ^{6}Li differences from symmetry of as much as 40% are observed at forward angles.

Angular distributions involving ^{6}He$_{\rm g.s.}$ + ^{6}Li*(2.19) and ^{6}Li$_{\rm g.s.}$ + ^{6}He*(1.8) have also been measured (1973VO08).

27. ^{9}Be(^{3}He, ^{6}Li)^{6}Li $Q_{\rm m} = -1.895$

Angular distributions of the ^{6}Li ions have been obtained at $E(^{3}\text{He}) = 6$, 7, 8 and 10 MeV (1969TA05) and 7.0 and 9.0 MeV (1972YO02): these and the fairly smooth yield curves for $E(^{3}\text{He}) = 6$ to 9 MeV [see ^{12}C in (1975AJ02)] seem to suggest that the mechanism of the reaction is essentially direct. The triton spectroscopic factors in ^{9}Be are determined to be 0.073 and 0.052 at 7 and 9 MeV, respectively (1972YO02). See also (1971ZE03; theor.).

28. (a) ^{10}B(γ, α)^{6}Li $Q_{\rm m} = -4.460$

(b) ^{10}B(p, pα)^{6}Li $Q_{\rm m} = -4.460$

(c) ^{10}B(d, dα)^{6}Li $Q_{\rm m} = -4.460$

(d) ^{10}B(α, 2α)^{6}Li $Q_{\rm m} = -4.460$

(e) ^{10}B(α, ^{8}Be)^{6}Li $Q_{\rm m} = -4.552$

For reactions (a) and (b), see ^{10}B. For reaction (c) see (1970NA06). Reaction (d) has been studied at $E_\alpha = 28.4$ MeV (1967TA1C). Reaction (e) has been studied at $E_\alpha = 46$ MeV (1970ZE03). See also (1966GE12) and ^{10}B.

29. ^{10}B(d, ^{6}Li)^{6}Li $Q_{\rm m} = -2.987$

At $E_{\rm d} = 19.5$ MeV angular distributions have been measured for the ^{6}Li ions to ^{6}Li*(0, 2.19). The experimental cross sections of the ground state transition are two orders of magnitude greater than those predicted by the shell model, consistent with the cluster nature of ^{6}Li (1971GU07). See also (1972GA1E).

30. ^{10}B(^{3}He, ^{7}Be)^{6}Li $Q_{\rm m} = -2.874$

Angular distributions of the ^{7}Be ions [^{7}Be*(0, 0.43)] corresponding to formation of ^{6}Li*(0, 2.19) have been measured at $E(^{3}\text{He}) = 30$ MeV (1970DE12, 1972OH01).

31. ^{10}B(^{16}O, ^{20}Ne)^{6}Li $Q_{\rm m} = 0.270$

See (1968OK06).

32. ^{11}B(d, ^{7}Li)^{6}Li $Q_{\mathrm{m}} = -7.192$

Angular distributions of ^{6}Li ions are reported at $E_{\mathrm{d}} = 19.5$ MeV for transitions to ^{7}Li*(0, 0.48) (1971GU07). At $E_{\mathrm{d}} = 40$ MeV the cross section for the transition to ^{6}Li*(3.56) is half the cross section for the reaction ^{11}B(d, ^{7}Be)^{6}He to the analog state (the ground state of ^{6}He) [to within 10%] as predicted by isospin conservation (1972GO1P).

33. ^{11}B(^{3}He, ^{8}Be)^{6}Li $Q_{\mathrm{m}} = 4.570$

Angular distributions of ^{6}Li ions are reported at $E(^{3}\mathrm{He}) = 3.0$ and 5.2 MeV. The reaction has been observed to lead to ^{8}Be*(2.9) + ^{6}Li(0) and to ^{8}Be(0) + ^{6}Li*(3.56). It is suggested that ^{6}Li*(3.56) contains a far smaller admixture of the (^{3}He + t) configuration than does ^{6}Li(0) (1964YO06, 1967YO02). See also (1967YO1C).

34. ^{12}C(p, ^{7}Be)^{6}Li $Q_{\mathrm{m}} = -22.569$

Angular distributions of the ^{6}Li ions corresponding to the transition to ^{7}Be*$(0 + 0.43)$ have been measured at five energies in the range $E_{\mathrm{p}} = 36.0$ to 56.8 MeV and the data have been analyzed using zero-range and finite-range DWBA assuming the pickup of ^{5}He and ^{6}Li clusters as the dominant mechanism. The differential cross sections decrease with energy: at $E_{\mathrm{p}} = 36$ MeV, dσ/dΩ as large as 200 μb/sr are observed (1971HO1K, 1971HO25). The angular distribution has also been measured at $E_{\mathrm{p}} = 45$ MeV by (1971BR07).

35. ^{12}C(d, ^{8}Be)^{6}Li $Q_{\mathrm{m}} = -5.893$

Angular distributions of ^{6}Li ions are reported at $E_{\mathrm{d}} = 19.5$ MeV (1971GU07: transition to ^{8}Be(0)) and at 51.8 MeV (1970EI05: transitions to ^{8}Be*(0, 2.9)).

36. ^{12}C(^{3}He, ^{9}B)^{6}Li $Q_{\mathrm{m}} = -11.571$

Angular distributions of ^{6}Li ions have been obtained at $E(^{3}\mathrm{He}) = 28$ MeV (1971KL1E), 30.0 and 40.7 MeV (1972OH01) and 35.7 MeV (1969ZE1A, 1970FO1D).

37. ^{12}C(α, ^{10}B)^{6}Li $Q_{\mathrm{m}} = -23.715$

Angular distributions have been obtained of ^{6}Li and ^{10}B ions corresponding to transitions to ^{6}Li*(0, 2.19) and ^{10}B*(0, 0.72, 2.15) (1972RU03: $E_{\alpha} = 42$ MeV).

38. ^{12}C(^{6}Li, ^{12}C)^{6}Li

See ^{12}C in (1968AJ02, 1975AJ02) and (1968NO1C; theor.).

39. ^{13}C(p, ^{8}Be)^{6}Li $\quad Q_{\rm m} = -8.615$

At $E_{\rm p} = 45$ MeV, the angular distributions of the ^{6}Li ions corresponding to the transitions to ^{8}Be*(0, 2.9) have been measured: the cross sections, integrated from $20°$ to $85°$ c.m., are, respectively, 1.9 and 2.7 μb (1971BR07).

40. (a) ^{14}N(α, ^{12}C)^{6}Li $\quad Q_{\rm m} = -8.799$
(b) ^{14}N(α, αd)^{12}C $\quad Q_{\rm m} = -10.2725$

For reaction (a) see ^{12}C in (1968AJ02, 1975AJ02). Reaction (b), studied at $E_{\alpha} = 22.9$ MeV, appears to involve ^{6}Li*(2.19) (1969BA17).

41. ^{16}O(p, ^{11}C)^{6}Li $\quad Q_{\rm m} = -22.185$

See (1969HO1H).

42. ^{16}O(d, ^{12}C)^{6}Li $\quad Q_{\rm m} = -5.688$

Angular distributions of ^{6}Li ions have been obtained at $E_{\rm d} = 19.5$ MeV corresponding to formation of ^{12}C*(0, 4.4) (1971GU07). See also ^{12}C in (1968AJ02, 1975AJ02).

43. ^{16}O(^{3}He, ^{13}N)^{6}Li $\quad Q_{\rm m} = -9.238$

Angular distributions of ^{6}Li ions have been measured at $E(^{3}{\rm He}) = 30.0$ and 40.7 MeV (1972OH01). See also ^{13}N in (1970AJ04).

44. ^{16}O(α, ^{14}N)^{6}Li $\qquad Q_m = -19.263$

Angular distributions have been obtained of ^{6}Li and ^{14}N ions corresponding to the population of the ground states (1972RU03: $E_\alpha = 42$ MeV).

45. ^{19}F(d, ^{15}N)^{6}Li $\qquad Q_m = -2.539$

Angular distributions of ^{6}Li ions have been measured corresponding to formation of ^{15}N*(0, 5.3, 6.3) (1971GU07: $E_d = 19.5$ MeV). See also ^{15}N in (1970AJ04).

46. ^{19}F(^{3}He, ^{16}O)^{6}Li $\qquad Q_m = 4.095$

Angular distributions have been measured at $E(^{3}\text{He}) = 11$ MeV (1971ST06: $^{6}\text{Li}_{\text{g.s.}} + {}^{16}\text{O}_{\text{g.s.}}$, $^{6}\text{Li}_{\text{g.s.}} + {}^{16}\text{O}_{6.06+6.14}$, $^{6}\text{Li}_{3.56} + {}^{16}\text{O}_{\text{g.s.}}$), 22.4, 30.0 and 40.7 MeV (1972OH01: $^{6}\text{Li}_{\text{g.s.}} + {}^{16}\text{O}_{\text{g.s.}}$ except at 30.0 MeV where also $^{6}\text{Li}_{3.56} + {}^{16}\text{O}_{\text{g.s.}}$) and at 28 MeV (1970KL09: $^{6}\text{Li}_{\text{g.s.}} + {}^{16}\text{O}_{\text{g.s.}}$, $^{6}\text{Li}_{3.56} + {}^{16}\text{O}_{\text{g.s.}}$). The angular distributions involving $^{16}\text{O}_{\text{g.s.}}$ show pronounced diffraction structure. The direct-reaction mechanism appears to involve coupling ^{3}He and t with $l = 0$ angular momentum to either a singlet or triplet state (1970KL09). The ratio $\sigma_{\text{g.s.}}/\sigma_{3.56} = 2.24 \pm 0.07$ rather than 3 (from the ratios of $2J + 1$) but this is accounted for by the Q-value dependence of the cross sections (1970KL09). See also ^{16}O in (1971AJ02).

47. ^{19}F(α, ^{17}O)^{6}Li $\qquad Q_m = -12.341$

Angular distributions of ^{6}Li ions have been measured at $E_\alpha = 28$ MeV for $^{6}\text{Li}_{\text{g.s.}} + {}^{17}\text{O}_{\text{g.s.}}$, $^{6}\text{Li}_{\text{g.s.}} + {}^{17}\text{O}_{0.87}$ and $^{6}\text{Li}_{3.56} + {}^{17}\text{O}_{\text{g.s.}}$ (1971KL1E). See also (1968MI05).

^{6}Be

(Figs. 6 and 7)

GENERAL: (See also (1966LA04).)

Model calculations: (1966BA26, 1968BA35, 1968FA1B, 1968VA1H, 1969TH1C, 1970LA1D).

Other topics: (1965GO1D, 1966GO1B, 1970FO1B, 1972AN05, 1972CA37, 1972GH1A, 1972JA14, 1973WE18).

1. (a) ^{3}He(^{3}He, γ)^{6}Be	$Q_m = 11.488$	$E_b = 11.488$
(b) ^{3}He(^{3}He, p)^{5}Li	$Q_m = 10.89$	
(c) ^{3}He(^{3}He, 2p)^{4}He	$Q_m = 12.8601$	
(d) ^{3}He(^{3}He, 3p)^{3}H	$Q_m = -6.9546$	
(e) ^{3}He(^{3}He, ^{3}He)^{3}He		
(f) ^{3}He(^{3}He, d)^{4}Li	$Q_m = -8.4$	

The yield of γ-rays to ^{6}Be*(1.7) (reaction (a)) increases smoothly from 0.4 to 9.3 μb (assuming isotropy) for $0.86 < E(^3\mathrm{He}) < 11.8$ MeV (90°). No transitions were observed to ^{6}Be(0) [$\sigma < 0.01$ μb at $E(^3\mathrm{He}) = 1.4$ MeV]. This is understood in terms of a direct capture of ^{3}He by ^{3}He in the singlet spin state and with zero angular momentum: the $0^+ \rightarrow 0^+$ γ transition is forbidden. Reaction (a) is thus of negligible astrophysical importance compared to reaction (c) (1967HA24) [see below]. The capture cross section from $E(^3\mathrm{He}) = 11$ to 27 MeV continues to increase smoothly with energy at first and then shows a broad structure centered at $E(^3\mathrm{He}) = 23 \pm 1$ MeV [$E_x = 23.0 \pm 0.5$ MeV], $\Gamma_{\mathrm{c.m.}} \approx 5$ MeV (1972VE1C, 1973VE1B, 1973VE1E) this appears to be a ^{33}F cluster resonance which decays by an E1 transition to ^{6}Be*(1.7). The γ-ray angular distributions are consistent with $J^\pi = 3^-$ (1973VE1B).

Measurements of the total cross section for reaction (c) have been carried out for $E(^3\mathrm{He}) = 60$ to 300 keV (1973DW1A) and 0.16 to 2.2 MeV (1969DW1A, 1971DW01). The measurements of (1973DW1A), down to $E_{\mathrm{c.m.}} = 30$ keV, eliminate the possibility of a resonance [which might help explain the observed absence of solar neutrinos], unless it is extremely narrow ($\Gamma \lesssim 100$ eV): $\theta_p^2 \approx 3\times10^{-6}$ (1973DW1A). (1972BB10) has commented that such a high ^{3}He+^{3}He cluster purity, a ^{6}Be state at ≈ 11.5 MeV is not expected. The cross section factor $S(E_{\mathrm{c.m.}}) = [5.5 - 3.1\ E_{\mathrm{c.m.}} + 1.4\ E^2_{\mathrm{c.m.}}]$ MeV · b [error in S is ±20% for $E_{\mathrm{c.m.}} > 40$ keV] (1973DW1A). Cross sections are also reported for $E(^3\mathrm{He}) = 0.5$ to 1.7 MeV by (1966WA18). See (1966LA04) for a discussion of earlier work and (1966BA1N, 1967SH1F, 1967TO1B, 1968BA1W, 1968MA1U, 1969BA1M, 1970MA57, 1972BA2M, 1972BB10, 1972FE12, 1972FO1H, 1972KO1M, 1972TO1D, 1973BA2C, 1973FO1J, 1973PA1Q, 1973TR1E) for a discussion of the astrophysical implications of reaction (c). From a kinematically complete study of reaction (c) (1972KU08, 1972KU1N) find $a_{\mathrm{pp}} = -7.6 \pm 0.6$ fm. (1970GR17) report $a_{\mathrm{pp}} = -7.52 \pm 0.22$ fm. A study of the proton

Table 6.7: Energy levels of ^{6}Be

E_x (MeV ± keV)	$J^\pi; T$	$\Gamma_{c.m.}$	Decay	Reactions
g.s.	(0^+); 1	92 ± 6 keV	p, α	2, 3, 4, 5, 6
1.67 ± 50	(2^+); 1	1.16 ± 0.06 MeV	p, α	1, 2, 3, 4
23.0 ± 0.5	$(3)^-$	≈ 5 MeV	^{3}He	1

spectrum at $E(^3\text{He}) = 6.9$, 7.9 and 9.1 MeV indicates that reaction (c) proceeds mainly via a direct mechanism (1972DE46). See also (1970BO1R, 1973RO2A) and ^{5}Li.

The elastic scattering (reaction (e)) has been studied for $E(^3\text{He}) = 3$ to 12 MeV (1963TO03), 9.1 and 11.1 MeV (1968IV01), 11.9 to 18.9 MeV (1968BA76), 17.9 to 32.0 MeV (1970JE02) and 18 to 80 MeV (1968BA1V). The excitation function shows a smooth monotonic behavior except for an anomaly at $E(^3\text{He}) = 25$ MeV in the $l = 3$ partial wave corresponding to a broad state in ^{6}Be at $E_x \approx 24$ MeV (1968BA1V, 1970JE02). Polarization measurements have been reported at $E(^3\text{He}) = 4.33$ to 9.83 MeV (1972BO42) and 9.3 to 17.5 MeV (1972HA64): the polarization is consistent with zero at $\theta \approx 63°$, consistent with a description of the scattering which leaves the P- and F-wave phase shifts unsplit (1972BO42, 1972HA64).

For reaction (f) see (1968ME03). See also (1968TO1F) and (1967TH1C, 1968SU1B, 1968TH01, 1969KR1F, 1970MA57, 1970NE1F, 1971BR46, 1972BR1Q, 1973GR1L, 1973TH01; theor.).

2. ^{4}He(^{3}He, n)^{6}Be $\qquad Q_m = -9.090$

Neutron groups have been observed to ^{6}Be*(0, 1.7) at $E(^3\text{He}) = 19.4$ MeV (1967AD05), 26 MeV (1966EC01) and 29.8 MeV (1966GU09): see Table 6.8. There is no evidence for other states of ^{6}Be with $E_x \lesssim 5$ MeV (1966EC01). See also (1970BA1V).

3. ^{6}Li(p, n)^{6}Be $\qquad Q_m = -5.070$

Neutron groups have been observed to ^{6}Be*(0, 1.7) as has the ground state threshold. The width of the ground state is 95 ± 28 keV (1967HO01). The parameters of ^{6}Be*(1.7) are displayed in Table 6.8 (1965BA39, 1966EC01, 1968BA41, 1968WA11, 1972AR22). Higher excited states have been reported by (1965BA39, 1968BA41, 1968WA11): there is very strong evidence that states analog to these do not exist in ^{6}He. At $E_p = 24.9$ MeV no evidence is found for a ^{6}Be state near $E_x = 11.5$ MeV (1973WO1D). See also reaction 4.

Angular distributions have been obtained at $E_p = 8.3$ to 18.0 MeV (1968WA11; n_0), 15 MeV (1968WA11; n_1) and 30.2 and 49.4 MeV (1968BA41, 1969CL06; n_0). See also (1969JU1A) and (1966LA04).

Table 6.8: Parameters of the first excited state of ^{6}Be

E_x (MeV $\pm$ keV)	$\Gamma_{c.m.}$ (MeV)	Refs.
1.82 ± 120		(1965BA39)
1.6 ± 100	1.1 ± 0.2	(1966EC01)
1.73 ± 100	1.7 ± 0.3	(1966GU09)
1.67 ± 80	1.13 ± 0.08	(1966MA36)
1.63 ± 100	1.20 ± 0.1	(1966RO06)
1.67 ± 50	1.18 ± 0.07	(1968WA11)
1.63 ± 160	1.16 ± 0.21	(1968BA41)
	0.85 ± 0.20	(1972AR22)
1.67 ± 50	1.16 ± 0.06	Best value

4. ^{6}Li(^{3}He, t)^{6}Be $\qquad Q_m = -4.306$

Triton groups have been observed to ^{6}Be*(0, 1.7). The width of the ground state is 89 ± 6 keV (1966WH01). The parameters of the excited state are displayed in Table 6.8 (1966MA36, 1966RO06). No other excited states have been seen with $E_x < 13$ MeV (1966MA36: E(^{3}He) $= 40$ MeV), < 10 MeV (1966RO06: E(^{3}He) $= 31$ MeV). An attempt has been made at E(^{3}He) $=$ 25.5 MeV (1973PA1C) and at 46.3 MeV (1973HA45) to observe a possible ^{6}Be state at E_x $=$ 11.5 MeV, of astrophysical interest: dσ/d$\Omega \lesssim 0.19$ μb/sr at $\theta_{c.m.} = 45°$ at the lower energy; dσ/d$\Omega \leq 1.6$ μb/sr at $8.4°$ and at 46.3 MeV. Upper limits for the spectroscopic factor are $S \leq 0.006$ (1973PA1C) and ≤ 0.001 (1973HA45). The ground-state angular distribution shows a pronounced oscillatory character, consistent with $l = 0$; that for the 1.7 MeV state is relatively structureless (1966RO06). Angular distributions are also reported by (1969NU1A; n_0: 14, 18 MeV) and by (1971GI1E, 1972GI07; n_0: 27.0 MeV). The α-decay spectra of ^{6}Be*(0, 1.7) have been studied by (1973GE1H).

5. ^{6}Li(^{6}Li, ^{6}He)^{6}Be $\qquad Q_m = -7.797$

See (1973WH02), and reaction 9 in ^{6}He and reaction 16 in ^{6}Li. See also (1973WH1C).

6. ^{9}Be(^{3}He, ^{6}He)^{6}Be $\qquad Q_m = -9.692$

This reaction has been observed at E(^{3}He) $= 37$ MeV [dσ/dΩ($13°$) $= 9$ μb/sr] (1967GO1E) and at 70 MeV (1973BE2J). No new states were observed with $E_x < 15$ MeV (1973BE2J).

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(Closed December 31, 1973)

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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