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Energy Levels of Light Nuclei
$A = 5$

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

(Not illustrated)

The possible existence of a particle-stable ^{5}H is discussed by (1957BL1A, 1960GO36, 1960ZE03, 1961BA1C, 1961YA04, 1963AR06, 1964AN06, 1964GO25, 1964GO1B, 1964VL1A, 1965BA1A). According to (1957BL1A), a $T = \frac{3}{2}$ level of ^{5}He-^{5}Li might be formed by ^{3}H or ^{3}He and a deuteron in the singlet state, at an energy ≈ 2.3 MeV above the 16.7 MeV level. If this is the case, a mass excess, $M - A = 30.5$ MeV † is indicated, and ^{5}H is 0.6 MeV stable against ^{3}H + 2n. Consideration of empirical pairing energies indicate that ^{5}H is particle-stable only if the first $T = 1$ state of ^{4}He is at $E_x < 22$ MeV (1960GO36) (^{4}H unstable by < 1.4 MeV). On the other hand, if ^{8}He is particle-stable, it is unlikely that the tetraneutron is bound by as much as 1 MeV and hence unlikely that ^{5}H is stable (1964GO25, 1964GO1B). In the Q_m below, the mass excess of ^{5}H is taken to be 31.1 MeV, i.e., ^{5}H is assumed to be just unbound.

1. ^{3}H(t, p)^{5}H $\qquad Q_m \approx -8.5$

A search for delayed neutrons with $E_t = 15.6$ MeV yielded negative results: $\sigma \leq 1$ mb (1963EC1A).

2. (a) ^{7}Li(γ, 2p)^{5}H $\qquad Q_m \approx -30.8$
   (b) ^{7}Li(p, 3p)^{5}H

With bremsstrahlung $E_{max} = 320$ MeV, a β-emitter is reported with $\tau_{1/2} = 110$ msec, $E_\beta > 15$ MeV, ascribed to reaction (a): the activation cross section is 1.8 ± 0.6 μb (1963NE02). However, other investigations with the same reaction led to a negative result (1958TA03, 1962CE03, 1964SH18): the activation cross section is < 0.03 μb if $\tau_{1/2} = 10$ msec, < 0.09 μb if $\tau_{1/2} = 110$ msec ((1962CE03), and C.N. Waddell, private communication).

^{7}Li has been bombarded with 2 GeV protons in an attempt to produce reaction (b). No evidence is found for the 110 msec activity: the activation cross section is ≤ 1 μb. The ratio of reaction (b) to the ^{11}B(p, 3p)^{9}Li reaction is at least 100 times less than that found by (1963NE02) for the corresponding photon induced reactions (1964SC02). At $E_p = 160$ MeV, the upper limit to the cross section is ≈ 0.2 μb, assuming $\tau_{1/2}$ is in the range 0.1 to 100 sec (1965BE1P).

See also (1964NE02, 1964VO1D) and (1964BO1N: ^{7}Li(π^-, pn)^{5}H).

† All mass excesses are given in terms of the ^{12}C standard ($M - A \equiv 0$).

^{5}He

(Figs. 1 and 3)

GENERAL:

See (1959BA1D, 1959BR1E, 1959MI1C, 1959SA11, 1960PE14, 1960PH1A, 1961BA1E, 1961TA05, 1962DI1B, 1962IN02, 1962IN1A, 1963KU1B, 1964BA1Y, 1964BE1M, 1964GR1J, 1964SA1F, 1964ST1B, 1965BO1M).

1. ^{3}H(d, γ)^{5}He $\qquad Q_{\rm m} = 16.632$

The ratio of the yields of (16.7 MeV) γ-rays and neutrons is $\approx 2\times10^{-5}$ at $0°$ and $90°$, $E_{\rm d} = 0.47$ MeV. The yield is of the same order of magnitude as that for the mirror reaction ^{3}He(d, γ)^{5}Li (1959CO57). [This yield would appear to lead to a value of Γ_γ considerably lower than the $\Gamma_\gamma = 11$ eV reported for the mirror reaction: see (1955SA52)].

2. (a) ^{3}H(d, n)^{4}He $\qquad Q_{\rm m} = 17.590 \qquad E_{\rm b} = 16.632$

(b) ^{3}H(d, 2n)^{3}He $\qquad Q_{\rm m} = -2.988$

(c) ^{3}H(d, pn)^{3}H $\qquad Q_{\rm m} = -2.225$

Excitation curves and angular distributions for reaction (a) from $E_{\rm d} = 8$ keV to 19 MeV are summarized by (1956FO1A, 1957JA37, 1960BR1E, 1960BR1F, 1960ST25, 1961GO02, 1964BR1P). See also (1964PA1F). Below $E_{\rm d} = 100$ keV, the cross section follows the Gamow function, $\sigma = (A/E)\exp(-44.40E^{-1/2})$ (1953JA1A, 1954AR02). A strong resonance, σ(peak) $= 5.0$ b, appears at $E_{\rm d} = 107$ keV. There is some evidence of resonant behavior between $E_{\rm d} = 3$ and 9 MeV (1960ST25: see also (1956GA51, 1957BA21)).

In the region $E_{\rm d} = 10$ to 500 keV, the cross section is closely fitted with the assumption of s-wave formation of a $J = \frac{3}{2}^+$ state with the parameters given in Table 5.3 (1952AR1A, 1952CO35, 1955KU03). Analysis in terms of complex eigenvalue theory is discussed by (1963MA1N, 1964JE1B).

The angular distribution of neutrons is isotropic at and below resonance, and shows increasing forward peaking at higher energies (1957JA37). (1961GO02) report that the distributions in the range $E_{\rm d} = 6.2$ to 11.4 MeV are all peaked forward with a second maximum at about $65°$ which becomes more pronounced with increasing energy, and a rise at back angles. It does not appear that plane wave stripping theory, including heavy-particle stripping can account for the observed distributions (1961GO02: see also (1960ST25)). See also (1951BU1B).

A test of parity violation using polarized 150 keV deuterons yields $|{\rm Re}\ F| < 4.5 \times 10^{-3}$ (1964HE1G).

The polarization of neutrons has been studied at $E_{\rm d} = 0.1$ and 0.17 MeV by (1961RU1A, 1962SE09), at 0.6 and 1.2 MeV by (1965BO13), from 0.1 to 7.7 MeV by (1961PE13, 1964PE14),

Table 5.1: Energy levels of ^{5}He

E_x (MeV)	J^π	Γ (MeV)	Decay	Reactions
g.s.	$\frac{3}{2}^-$	0.58 ± 0.02	n, α	5, 6, 7, 9, 11, 12, 13, 14, 15, 16, 18, 19
2.6 ± 0.4	$\frac{1}{2}^-$	4 ± 1	n, α	5, 6, 7, 16, 18
16.70 ± 0.020	$\frac{3}{2}^+$	0.081	γ, n, d, t, α	1, 2, 4, 7, 8
(≈ 20)				2

from 6 to 11 MeV by (1964WA22), from 8 to 20 MeV by (1964AL1E) and at 10 MeV by (1961TR05). See also (1959GO1G, 1960WI1B, 1963HA1G).

For $E_d > 3.7$ MeV, deuteron breakup (reaction (c)) is possible, and above $E_d = 5.0$ MeV production of ^{3}He (reaction (b)) may occur. Time-of-flight neutron spectra observed for $E_d = 5$ to 12 MeV exhibit two maxima, the lower corresponding to the three-body distribution arising from ^{3}H(d, 2n)^{3}He and the upper to ^{3}H(d, n)^{4}He* $\rightarrow$ p + ^{3}H with formation of an excited state of ^{4}He at 20.1 ± 0.06 MeV (1962LE12, 1962PO04, 1963PO02: see also (1959SM97)). Analysis of the observed distributions by stripping theory including final state interaction in the (t + p) channel indicates a ^{1}S$_0$ resonance at $E_{c.m.} = 0.4$ MeV, $\gamma_p^2 = 4.2$ MeV, $R = 3.0$ fm. The assignment $T = 1$ would imply a bound ^{4}H (1962WE1E, 1963WE10, 1964WE1B). The apparent non-existence of a stable ^{4}H or of a corresponding ^{4}Li state argues for $T = 0$ (1963KA28, 1964NE02): see also ^{3}H(d, p)^{4}H.

See also (1960BR10, 1960JU04, 1961DI1B, 1963RU1A, 1964TR1C).

3. ^{3}H(d, p)^{4}H

If ^{4}H is particle-stable, its mass excess lies in the range 23.0 to 18.5 MeV; Q_m for this reaction is -2.2 to $+2.3$ MeV. Over this range, the cross section for formation of ^{4}H is $< 4 \times 10^{-3}$ of the corresponding cross section in ^{3}H(d, n)^{4}He*(20.1) (1951MC37, 1960ST25, 1964IM03, 1964RO08). There have also been attempts to observe ^{4}H in the bombardment of ^{6}Li by 160 MeV protons (1965BE1P), of Li by 250 MeV bremsstrahlung (1964NE02), of ^{7}Li by 14 MeV neutrons (1964PO03, 1964PO1B), of ^{12}C by 300 MeV protons (1955RE44) and in the ^{10}B(^{7}Li, ^{4}H)^{13}N reaction (1959NO40): all these attempts have given negative results. Some evidence is reported by (1962AR05, 1963AR06) for the formation of ^{4}H in the ^{4}He(γ, π^+)^{4}H with 1 GeV bremmstrahlung: the atomic mass excess of 26.5 to 30 MeV would correspond to $E_x = 24.1$ to 27.6 MeV in ^{4}He. See, however, (1963LO1C, 1964SM1B, 1964VO1D). Evidence for a bound ^{4}H is reported in $\pi^- + {}^6$Li and ^{7}Li by (1965CO1D). See also (1964CA05, 1964GO25, 1964GO1B, 1964WE1B, 1965AJ03).

Table 5.2: Ground state of ^{5}He [a]

$Q(^4\text{He} + \text{n})$ (keV)	$\Gamma_{\text{c.m.}}$ (keV)	Reaction	Reference
900 ± 70		6	1953AL1A
950 ± 70		6	1953MO61
800 ± 100		6	1960YO06
790 ± 30	630 ± 36	6	1963SM03
920 ± 40		7	1964ST25
880 ± 50		9	1954FR22
	550 ± 30	9	1957WA01
850 ± 50	570 ± 20	9	1964OH01
1090 ± 100	1100	12	1954FR03
890 ± 90	690 ± 200	14	1955LE24
970 ± 40	700 ± 200	15	1956CR47
900 ± 100		18	1951FR1A
900 ± 100	300 ± 100	18	1953CU20
1400 ± 20		18	1955KH31
860 ± 90	660 ± 200	18	1955LE24
1000 ± 50		18	1958WE27
891 ± 51	577 ± 15		mean

[a] See (1964OH01). Cited Q values represent peaks in particle spectra; because of penetration factors, they require corrections if the energy corresponding to $90°$ n-α phase shift is desired. For reactions 7 and 9, (1964OH01) give $Q(90°) = -900 \pm 40$ and -930 ± 70 keV respectively. In the present article we have preferred to use the (1965MA54) value of -958 ± 19 keV.

4. ^{3}H(d, d)^{3}H $\qquad E_b = 16.632$

Differential cross sections are tabulated for $E_d = 0.96$ to 3.2 MeV (1952ST69), $E_d = 5.6$, 5.9, 8.3, 12.3 and 14.4 MeV (1960BR10) and $E_d = 10$ MeV (1952AL36). The angular distributions at the higher energies are characterized by minima on either side of $\theta = 90°$; the central maximum moves towards higher angles as the energy is increased. Distributions are closely similar to ^{3}He(d, d)^{3}He (1960BR10).

Table 5.3: Resonance parameters for ^{3}H(d, n)^{4}He and ^{3}He(d, p)^{4}He [d]

E_r (keV)	Γ_{lab} (keV)	l_d	J^π	$l_{n,p}$	R fm	E_λ (keV)	γ^2_d (keV)	$\gamma^2_{n,p}$ (keV)	θ^2_d [c]	$\theta^2_{n,p}$ [c]	E_x (MeV)
107 [a]	135	0	$\frac{3}{2}^+$	2	5.0	-464	2000	56	1.0	0.018	16.70
					7.0	-126	715	17	0.7	0.011	
430 [b]	≈ 450	0	$\frac{3}{2}^+$	2	5.0	-391	2930	42	1.4	0.013	16.65
					7.0	129	780	12	0.7	0.008	

[a] ^{3}H(d, n)^{4}He.
[b] ^{3}He(d, p)^{4}He.
[c] Units of $3\hbar^2/2MR^2$.
[d] See also (1960BA1M, 1964JE1B).

Elastic scattering at $\theta = 90°$, observed from $E_{c.m.} = 100$ to 260 keV can be closely fitted by the one-level Breit-Wigner formula (1958BA82, 1960BA1M). See also (1960LA1B).

5. ^{3}H(t, n)^{5}He $\qquad Q_m = 10.374$

This reaction has been studied for $E_t = 0.95$ to 2.10 MeV (1958JA06: see also (1957BA10)). In addition to the neutron group corresponding to ^{5}He$_{g.s.}$, the spectrum contains an excess of medium energy neutrons, attributed to direct three-body reaction or to a broad excited state of ^{5}He. The alpha particles show a double peaking, reflecting the influence of the P$_{\frac{3}{2}}$ ground state, superimposed on a distribution arising from the P$_{\frac{1}{2}}$ state and direct three-body decay (1958JA06). See also ^{6}He.

6. ^{3}He(t, p)^{5}He $\qquad Q_m = 11.138$

Proton and alpha-particle spectra have been studied at $E_t = 1.9$ MeV by (1963SM03). The protons exhibit a conspicuous peak at the high-energy end of a continuous distribution: the peak corresponds to the ground state of ^{5}He with a binding energy of -0.79 ± 0.03 MeV and has a width Γ(lab) $= 525 \pm 30$ keV; see Table 5.2. In the α-distribution a sharp peak is seen, corresponding to ^{3}He(t, d)^{4}He, plus a broad distribution with considerable structure. A knee at the high-energy limit is ascribed to ^{3}He(t, α)n + p with the neutron and proton interacting in the ^{1}S$_0$ state; a binding energy of -0.1 ± 0.05 MeV is obtained, in good agreement with the value -0.074 deduced from n-p scattering. The structure observed in the proton and alpha continua is quantitatively accounted for by appropriate superposition of the processes ^{3}He(t, p)^{5}He$_{g.s.} \rightarrow \alpha$+n, ^{3}He(t, n)^{5}Li$_{g.s.} \rightarrow \alpha$+p, and

^{3}He(t, p + α + n) in the ratios $\sigma = 1.37/0.90/2.40$. The experiment does not distinguish the direct three-body process from those involving ^{5}He*, ^{5}Li*(^{2}P$_{\frac{1}{2}}$) (1963SM03). See also (1953AL1A, 1953MO61, 1960YO06, 1961BA40).

7. ^{4}He(n, n)^{4}He $\qquad E_b = -0.958$

The coherent scattering length (thermal, bound) is 3.0 fm (1961WI1A). The thermal scattering cross section is 0.73 ± 0.05 b (1964ST25). Total cross sections for $E_n = 0.0004$ eV to 20 MeV are given in (1958HU18, 1960HU1A, 1964ST25): recent measurements have been made at $E_n = 0.1$ to 6.2 MeV and 12 to 20 MeV (1960VA04), $E_n = 1$ to 20 MeV (1959BA1K: ±1% to ±5%), $E_n = 7$ to 12 MeV (1960FO09, 1962AU03: ±3%), $E_n = 10$ to 25 MeV (1965HO1D), $E_n = 20$ to 29 MeV (1963SH06, 1964SH1A: ±1% to ±2%), and $E_n \approx 147$ MeV (1964PA19).

The total cross section has a peak of 7.8 b (1960VA04) at $E_n = 1.15 \pm 0.05$ MeV, $E_{c.m.} = 0.92 \pm 0.04$ MeV, with a width of about 1.2 MeV (1964ST25). A second resonance is observed at $E_n = 22.15 \pm 0.12$ MeV, corresponding to the 16.7 MeV $J = \frac{3}{2}^+$ level (1959BO54, 1964SH1A): $\Gamma_{c.m.} = 100 \pm 50$ keV, $\Gamma_n = \Gamma_d = 50 \pm 35$ keV (1960HU1A). The change in cross section and in the angular distributions at resonance is consistent wih $J = \frac{3}{2}$, $\Gamma_d \approx \Gamma_n$ (1964SH1A). Attempts to detect additional resonances at $E_n = 5.5$ to 16 MeV (1959BA02) and at $E_n = 20$ to 29 MeV (1964SH1A), 22 to 29 MeV (1965BE03) have been unsuccessful. If the "19 MeV" excited state of ^{5}He exists, the change in total cross section is less than a few percent if its width is greater than about 100 keV; it is pointed out that a $T = \frac{3}{2}$ level would be isospin forbidden in the present reaction (1964SH1A).

Information on angular distributions is summarized in (1963GO1M). Recent measurements of differential cross sections are reported for $E_n = 2.0$ to 20.9 MeV (1962AU03), $E_n = 1.79$ MeV (1963YO05), $E_n = 2.37$ to 2.87 MeV (1962DE01), $E_n = 6.4$ to 6.9 MeV (1959MA1E), $E_n = 14.9$ MeV (1963MA1M) and $E_n = 16$ to 26 MeV (1964SH1A). Both the total cross sections and the angular distributions are well accounted for, below 15 MeV, by the phase shifts determined by (1952DO30, 1953SE1A) for ^{4}He(p, p)^{4}He with a shift in E_λ of about 1 MeV (DGS phase shifts). The s-wave phase shift decreases monotonically with increasing energy, and can be accounted for by hard-sphere scattering with $R = 2.6$ fm. The P$_{\frac{3}{2}}$ shift shows strong resonance behavior near 1 MeV, while the P$_{\frac{1}{2}}$ shift changes more slowly, possibly indicating a broad P$_{\frac{1}{2}}$ level at several MeV excitation (1952DO30). For $E_n = 16$ to 22 MeV, the GTP phase shifts involving d- and f-waves (1958GA13) are preferred (1963MA29, 1964SH1E, 1964SH1A: see, however, (1962AU03)). See also (1965RO1Q). At $E_n = 23.7$ MeV, the angular distribution determined from phase shifts that are consistent with polarization and cross section data of (1963MA29) does not agree with the experimental curve (1964SH1A).

Polarization of neutrons scattered by ^{4}He has been discussed by (1952AD09, 1953SE1A, 1953SI1A, 1959SA1D), and asymmetry in elastic scattering using partially polarized neutrons has been studied for $E_n = 2$ to 24 MeV by (1961TR05, 1963MA29, 1963OT01, 1964PE14, 1964WA22). See also (1963HA1G, 1965DA1F).

Theoretical discussions of n, α scattering are given by (1958HO1B, 1959NA1A, 1959PI42, 1960BU1F, 1960MC1D, 1960MI1B, 1960NA1B, 1960SA07, 1960SA1L, 1960SI1C, 1961TA1E, 1962LA1E, 1962MI1B, 1963FA1A, 1963PI03, 1964CR1B).

8. ^{4}He(n, d)^{3}H $\quad Q_m = -17.590 \quad E_b = -0.958$

See (1960YO06, 1962AU03, 1964SH1A).

9. (a) ^{4}He(d, p)^{5}He $\quad Q_m = -3.182$

(b) ^{4}He(d, pn)^{4}He $\quad Q_m = -2.225$

The proton spectrum observed at $E_d = 14.8$ MeV shows a prominent peak, of width $\Gamma_{c.m.} = 550 \pm 30$ keV, and a monotonic continuum of lower energy protons, attributed to reaction (b). There is no evidence of structure corresponding to possible sharp excited states of ^{5}He (1956WA1B, 1957WA01: see also (1960AR1A)). At $E_d = 8$ and 14 MeV, $\theta = 21°$, the proton peak is well fitted with DGS phase shifts for the α-n final state interaction (1964RO1D). The ground state group, analyzed by stripping theory, gives $\theta^2 = 0.05$, more than a factor of 10 smaller than is indicated by ^{4}He(n, n)^{4}He (see ^{5}Li: ^{4}He(p, p)^{4}He) (1956WA1B, 1957WA01). At $E_d = 7.7$ to 11 MeV, proton spectra indicate $Q = 850$ keV for $^5\text{He} \rightarrow {}^4\text{He} + \text{n}$. Correction to the energy corresponding to an (n, α) phase shift of 90° gives $Q = 930 \pm 70$ keV, $\Gamma = 570 \pm 20$ keV. Similar treatment of (n, α) data yields $Q = 900 \pm 40$ keV (1964OH01): see Table 5.2.

Neutron time-of-flight spectra have been obtained at $E_d = 7.9$, 8.9 and 10 MeV (1962LE12) and 18.6 MeV (1961RY01). Two maxima are observed in the distribution, attributed to ^{4}He(d, n)^{5}Li$_{g.s.}$ and ^{4}He(d, p)^{5}He$_{g.s.}$ $\rightarrow \alpha + \text{n}$ (1962LE12). The peak shapes have been analyzed in terms of $\alpha + \text{n}$, $\alpha + \text{p}$ final state interactions by (1961RY01). See also (1963ER02, 1965IS1D, 1965NA1D, 1965NA1E).

10. ^{4}He(t, d)^{5}He $\quad Q_m = -7.215$

Not reported.

11. ^{6}Li(γ, p)^{5}He $\quad Q_m = -4.655$

See ^{6}Li.

12. ^{6}Li(n, d)^{5}He $\qquad Q_m = -2.430$

At $E_n = 14$ MeV, a well-defined ground-state group ($\Gamma_{c.m.} = 0.8$ MeV) is observed, as is a continuum extending to $E_x \approx 4$ MeV in ^{5}He. Both angular distributions are consistent with $l_p = 1$ (1954FR03). See also ^{7}Li, and (1964SL1A, 1964TO1C).

13. ^{6}Li(p, 2p)^{5}He $\qquad Q_m = -4.655$

At $E_p = 155$ to 450 MeV, the summed proton spectra show two peaks, with $Q = -4.5 \pm 1.5$ and -20.3 ± 1.5 MeV (1962GA09), -4.8 ± 0.3 and -22.4 ± 0.7 MeV (1964TI02), -4.9 ± 0.3 and -22.7 ± 0.3 MeV (1965TY1A). The higher energy peak corresponds to ejection of an $l = 1$ proton: ^{6}Li $\rightarrow$ ^{5}He$_{g.s.}$ + p, while the lower peak results from ejection of an $l = 0$ proton, presumably leaving ^{5}He in the 16.7 MeV, $\frac{3}{2}^+$ state. See ^{6}Li.

14. ^{6}Li(d, ^{3}He)^{5}He $\qquad Q_m = 0.839$

At $E_d = 14.5$ MeV, the ground state group is observed: $\Gamma_{c.m.} = 0.69 \pm 0.2$ MeV (1955LE24). The ^{3}He spectrum has been measured at several angles at $E_d = 14.8$ MeV; the shape is analyzed in terms of an $(n + \alpha)$ model of ^{5}He, using the known $(n - \alpha)$ phase shifts. The angular distribution of ground state neutrons fits the Butler formula at forward angles with $l = 1$, $R = 6$ fm; a value $\theta_0^2 = 0.15$ is obtained (1960HA14). See also (1959HA29).

15. ^{6}Li(t, α)^{5}He $\qquad Q_m = 15.160$

The width of the ground state $\Gamma_{c.m.} = 0.7 \pm 0.2$ MeV (1956CR47). See also (1961HO01) and (1959AJ76).

16. ^{7}Li(n, t)^{5}He $\qquad Q_m = -3.425$

See (1954AL24, 1964SL1A, 1964VA1E, 1964VA19) and ^{8}Li.

17. (a) ^{7}Li(p, ^{3}He)^{5}He $\qquad Q_m = -4.189$
(b) ^{7}Li(p, pd)^{5}He $\qquad Q_m = -9.683$

These reactions have not been reported. For reaction (b) see (1964BA1C).

18. ^{7}Li(d, α)^{5}He $\qquad Q_{\rm m} = 14.164$

The angular correlation of ground-state α-particles and those resulting from the breakup of ^{5}He is consistent with $J^{\pi} = \frac{3}{2}^{-}$ (1951FR1A, 1956RI37) as is the (α-n) correlation (1957FA10). See also (1964BR31).

High resolution spectra ($E_{\rm d} = 1.0$ MeV) show only the ground state peak, superposed on a continuous distribution (1958WE27). The ground state has a width of 0.66 ± 0.2 MeV (1955LE24). At $E_{\rm d} = 0.15$ to 0.20 MeV, α-α coincidence studies indicate a group corresponding to $E_{\rm x} = 2.6 \pm 0.4$ MeV, $\Gamma = 4.0 \pm 1.0$ MeV with intensity 50% greater than the ground state group. No other excited states with $E_{\rm x} < 7$ MeV are seen (1964FE01); see also (1960HA09, 1964JO1D, 1964MA1F, 1964SA1G, 1965BI1F, 1965IM01, 1965JO19).

19. ^{9}Be(γ, α)^{5}He $\qquad Q_{\rm m} = -2.528$

See ^{9}Be.

^{5}Li
(Figs. 2 and 3)

GENERAL:

See (1959BA1D, 1959MI1C, 1960PE14, 1960PH1A, 1961VA17, 1962DI1B, 1962IN02, 1963KU1B, 1964BA1Y, 1964GR1J, 1964SA1F, 1964ST1B).

1. ^{3}He(d, γ)^{5}Li $\quad Q_\mathrm{m} = 16.388$

The excitation curve measured from $E_\mathrm{d} = 0.2$ to 2.85 MeV shows a broad maximum at $E_\mathrm{d} = 0.45 \pm 0.04$ MeV ($E_\gamma = 16.6 \pm 0.2$ MeV, $\sigma = 50 \pm 10$ μb, $\Gamma_\gamma = 11 \pm 2$ eV). Above this maximum, non-resonant capture is indicated by a slow rise of the cross section. The radiation appears to be isotropic to $\pm$10% at $E_\mathrm{d} = 0.58$ MeV, consistent with s-wave capture (1954BL89). See also (1961TO1E).

2. ^{3}He(d, n)^{4}Li

(1964IM03) have searched for high-energy beta rays from ^{4}Li in this reaction. With $E_\mathrm{d} = 0.5$ to 2.3 MeV, upper limits of $\sigma = 3$ to 8×10^{-3} μb are obtained. Other searches for ^{4}Li have been made by (1959AR61, 1959BA27, 1962TO12, 1964CL03). See also (1963KA28, 1964BE1L, 1964KI1C, 1964KO1E, 1965DA1G). The astrophysical interest in ^{4}Li is discussed by (1958FO1C, 1964BA1X, 1964BA2A, 1964PA1A).

3. (a) ^{3}He(d, p)^{4}He $\quad Q_\mathrm{m} = 18.354 \quad E_\mathrm{b} = 16.388$
(b) ^{3}He(d, np)^{3}He $\quad Q_\mathrm{m} = -2.225$
(c) ^{3}He(d, 2p)^{3}H $\quad Q_\mathrm{m} = -1.461$

Cross sections and angular distributions for reaction (a) from $E_\mathrm{d} = 35$ keV to 10 MeV are given in (1957JA37). Below 100 keV the cross section follows the simple Gamow form: $\sigma = (18.2 \times 10^3/E)\mathrm{exp}(-91E^{-1/2})$ b (E in keV) (1953JA1A, 1954AR02). The zero-energy cross section factor $S_0 = 6700$ keV $\cdot$ b (1964PA1A). A pronounced resonance occurs at $E_\mathrm{d} = 430$ keV of about 450 keV width. The peak cross section is given as 0.695 ± 0.014 b by (1952BO68, 1955KU03: see also (1953YA02, 1954FR01)). The resonance is closely fi tted with the one-level dispersion formula using the parameters listed in Table 5.3. See also (1963MA1N, 1964HU1C, 1964JE1B).

The angular distribution of protons is isotropic near resonance and shows froward peaking at higher energies. Differential cross sections have been measured at $E_\mathrm{d} = 5.9$, 7.5, 10.4, 12.3 and

Table 5.4: Energy levels of ^{5}Li

E_x (MeV)	J^π	Γ (MeV)	Decay	Reactions
g.s.	$\frac{3}{2}^-$	≈ 1.5	p, α	1, 5, 6, 7, 9, 11, 12, 13, 14, 15, 16
$5 - 10$	$\frac{1}{2}^-$	$3 - 5$	p, α	7
16.65	$\frac{3}{2}^+$	≈ 0.3	γ, p, d, ^{3}He, α	1, 3, 4, 7
20.0 ± 0.5	$(\frac{3}{2}^+, \frac{5}{2}^+)$		d, ^{3}He	4

13.7 MeV (1960ST25), and $E_d = 23.2$ to 27.0 MeV (1964BI06). The similarity to ^{3}H(d, n)^{4}He is very close, and the angular distributions show pronounced direct interaction effects (1963BI08, 1964BI06). See also (1960BR1E).

The polarization of the protons has been studied as a function of E_d and θ for the range $E_d =$ 3.0 to 12.0 MeV by (1963BR10), at $E_d = 0.77$ and 1.88 MeV by (1963VA1H), at $E_d = 1.5$, 2.1 and 2.6 MeV by (1964FA01), at $E_d = 2$ MeV by (1964VA1G), and at $E_d = 8.3$ MeV by (1965RO02). (1963BR10) report polarizations as high as 0.76, in good agreement with the mirror reaction. See also (1959GO1G, 1964MC1E, 1964SE1F, 1965BA15, 1965TA1J).

Proton groups have been reported corresponding to ^{4}He excited states at $E_x = 19.94 \pm 0.02$ MeV ($\Gamma = 140 \pm 25$ keV) and 21.24 ± 0.2 MeV ($\Gamma = 1.1 \pm 0.2$ MeV) (1965PA01: $E(^3\text{He}) =$ 31.8 MeV). At $E_d = 6$ to 10 MeV (1964YO03) report a forward-peaked group corresponding to $E_x = 20.08 \pm 0.05$ MeV with $\Gamma = 0.2 \pm 0.05$ MeV. See also (1960ST25, 1963YN02, 1965DO1H, 1965ME1D).

Above $E_d = 3.71$ MeV, deuteron breakup (reaction (b)) is observed: see (1955HE1B, 1964DO1F). The ^{3}He spectrum at forward angles gives evidence of a strong singlet p-n interaction (1965TO01).

The triton spectrum (reaction (c)) has been studied at $E_d = 11$ MeV (1965TO01), 12 to 14 MeV (1965HE1A, 1965JA1D), 20 and 25 MeV (1964AR08) and 24 to 33 MeV (1963BI14, 1964CO1A). At small forward angles, a pronounced peak is observed at the high-energy end of the continuum, indicating a strong p-p final state interaction. See also (1964DO1F).

4. ^{3}He(d, d)^{3}He $\qquad E_b = 16.388$

Differential cross sections for $E_d = 0.4$ to 3 MeV are plotted in (1957JA37), and for $E_d = 5.6$, 5.9, 8.3, 12.3 and 14.4 MeV are tabulated in (1960BR10). Measurements are also reported for $E_d = 2$ to 11 MeV (1965TO1E), 23.2 to 27.0 MeV (1964BI06) and 29 MeV (1962GA22). See also (1952AL36, 1959MC65, 1960BR19, 1960MC1E, 1963BI08).

In the range $E_d = 380$ to 570 keV ($\theta_{c.m.} = 65°$) the scattering cross section is considerably below Rutherford scattering and is consistent with s-wave formation of a $J = \frac{3}{2}^+$ state. Above $E_d = 2$ MeV, the distributions are very similar to those reported in ^{3}H(d, d)^{3}H (1954BR05, 1960BR10). The angular distributions obtained by (1960BR10) are not symmetric around $90°$. Two minima are observed around $90°$: the central maximum shifts towards larger angles with increasing energy. (1965TO1E) report a broad state of ^{5}Li with $E_x = 20.0 \pm 0.5$ MeV, formed by d-wave deuterons ($J^\pi = \frac{3}{2}^+$ or $\frac{5}{2}^+$). See also (1960BA1M, 1965GR1Q).

5. ^{3}He(t, n)^{5}Li $\qquad Q_m = 10.131$

The ground-state group is observed in addition to continuum neutrons at $E(^3\text{He}) = 3.2$ MeV: $\sigma = 21 \pm 4$ mb, $Q_0 = 10.3 \pm 0.2$ MeV. The angular distributions indicate some direct interaction. This reaction appears to be an order of magnitude more intense than the mirror reaction ^{3}H(^{3}He, p)^{5}He (1961BA40: but see (1963SM03)).

6. ^{3}He(^{3}He, p)^{5}Li $\qquad Q_m = 10.895$

The spectrum of protons has been measured at $E(^3\text{He}) = 0.36$ MeV (1954GO18), 4.9 MeV (1965AL1L), 3 to 18 MeV (1965BA1D, 1965BA1E). A pronounced peak corresponding to the formation of $^5\text{Li}_{\text{g.s.}}$ is observed, superposed on a continuum; analysis with final state interaction characterized by $\gamma^2 = 7$ MeV, $E_\lambda = 4.16$ MeV yields a good fit to the data (1965BA1D). See also (1963BA53, 1964TO1D). At small forward angles the α-spectrum has a pronounced peak, indicating a strong p-p interaction (1964AR08, 1965TO01).

7. ^{4}He(p, p)^{4}He $\qquad E_b = -1.965$

References for the principal measurements of cross sections and polarizations are listed in Table 5.5, together with a selection of papers dealing with derived phase shifts and polarization. Measured cross sections, phase shifts and polarizations up to $E_p = 11$ MeV are tabulated by (1964BA08). In this range $l = 0$ and $l = 1$ phase shifts are well determined, $l = 2$ less well.

Semi-empirical phase shifts including $l \leq 2$ and $l \leq 3$ for $E_p = 10$ to 40 MeV have been calculated by (1958GA13). Although these phase shifts give a reasonably good account of observed differential cross sections (1957BR28, 1959BU98, 1959SA14), the observed polarization shows striking deviations beginning at $E_p \approx 29$ MeV (1963CR09, 1963HW01, 1963WE11). At 40 MeV (1963SU03) find that complex phase shifts with $l \leq 3$ provide a satisfactory fit; (1963GI1G) use real phase shifts with $l \leq 4$.

In the region 0 to 11 MeV, the s-wave phase shift is satisfactorily accounted for by hard-sphere scattering with radius $R = 2.5$ fm. The course of the p-wave phase shifts is given by the Breit-Wigner dispersion formula with the following parameters, calculated with a radius $R = 3.0$ fm (1964BA08: see also (1952AD09, 1952DO30)):

Table 5.5: Measurements of elastic scattering and polarization in $^{4}He(p, p)^{4}He$

Elastic scattering		Polarization	
Energy (MeV)	Reference	Energy (MeV)	Reference
1 – 3.6	1949FR20		
1 – 4	1963SE1L	1 – 3.6	1958SC27, 1960SC1C
2 – 5.5	1958MI93		
2 – 11	1964BA08	3.2 – 3.5	1952HE15
5.1	1951BR93	4.0 – 4.8	1964DR04
5.8	1954KR1B, 1955LU60	4.5	1964MA18
		3.6 – 11.9	1963BR19
7.5; 9.5	1956PU41	5.32	1956JU10
9.2 – 14.5	1959SA14, 1960SA1M	6, 9, 11.5	1960SA07
9.5	1954FR22, 1957GI14	8.5	1961RO13
9.8	1955WI26	10	1961RO05
9.8	1954CO69	14.5	1962RO20
11.4 – 18	1957BR28	14.5	1958BR24
17.5	1956BR29	19 – 25	1963WE11
19.4	1956VA1B, 1957VA1B	22 – 48	1963CR09
20	1959BU98	22	1960NI1B
21 – 28	1964AL1N	38	1962HW1A, 1963HW01
27.9	1957WI22	38.7	1965BO1R
31	1953CO62, 1964BU1B	48	1964GR1K
40	1957BR24	66, 147	1959CO64
53	1964CA1B	312	1956CH1C
55	1964HA13, 1964HA1P, 1964HA49	725	1965MC04
66, 147	1959CO64, 1963PA1H		
95	1958SE74		
141, 154	1964PA19		
312	1956CH1C		
725	1965MC04		

Phase shift and polarization calculations	
Energy (MeV)	Reference
1 – 3.6	1949CR1A

Table 5.5: Measurements of elastic scattering and polarization in ^{4}He(p, p)^{4}He (continued)

Elastic scattering		Phase shift and polarization calculations	
Energy (MeV)	Reference	Energy (MeV)	Reference
		5.8	1955LU60
		5.8, 9.5	1954KR1B, 1952DO30
		1 – 18	1957BR28, 1958BR24
		1 – 18	1958MI93, 1959PH37
		2 – 11	1964BA08
		7.5	1956PA23
		9 – 15	1959SA14
		10 – 40	1958GA13
		40	1963SU03, 1963GI1G

^{2}P$_{\frac{3}{2}}$ $E_{\rm res,lab} = 2.65$, $E_\lambda = 4.79$, $\gamma^2 = 8.23$ MeV, $\theta^2 = 0.95$.
^{2}P$_{\frac{1}{2}}$ $E_\lambda = 20.2$, $\gamma^2 = 15.3$ MeV, $\theta^2 = 1.76$.

No evidence is found for other resonance levels below $E_{\rm x} = 16.6$ MeV (1959HI70, 1959SA14, 1964BA08). An anomaly at $E_{\rm p} = 23$ MeV corresponding to ^{5}Li*(16.6) is reported by (1963WE11). Model calculations of phase shifts are discussed by (1958GA13, 1958HO1B, 1959KE1A, 1959PI42, 1960BU1F, 1960HE15, 1962LA1E, 1962RO1F, 1964GI1E). See also (1959KE1A, 1960MC1D, 1960SI1C, 1963KA1G, 1964CR1B, 1964HO1F, 1965GI1E, 1965GR1U) and (1959AJ76).

Inelastic (p, p′) spectra at 185 MeV give evidence of a peak near $Q = -22.5$ MeV (1958SE74, 1959HI70, 1962SA1E). At $E_{\rm p} = 55$ MeV, (1964HA13, 1964HA1P, 1964HA49) report an inelastic group corresponding to ^{4}He* $= 22.4 \pm 0.7$ MeV, $\Gamma = 1.7 \pm 0.5$ MeV. At $E_{\rm p} = 40$ MeV two groups are reported corresponding to ^{4}He* $= 20.48$ MeV, $\Gamma \approx 0.3$ MeV, and 21.95 MeV, $\Gamma \approx$ several MeV (1965WI10).

8. (a) ^{4}He(p, d)^{3}He $Q_{\rm m} = -18.354$ $E_{\rm b} = -1.965$
(b) ^{4}He(p, pn)^{3}He $Q_{\rm m} = -20.578$
(c) ^{4}He(p, 2p)^{3}H $Q_{\rm m} = -19.814$

Angular distributions for reaction (a) are reported at $E_{\rm p} = 27.9$ MeV (1957WI22), 31 MeV (1953BE14, 1964BU1B), 53 MeV (1964CA1B), 55 MeV (1964HA13, 1964HA1P, 1964HA49) and 94 MeV (1958SE74). The distributions are characterized by a strong forward peak and a secondary maximum. Analysis in terms of the momentum distribution of the picked-up neutron is discussed by (1958SE74). The 31 MeV data have been analyzed by DWBA: a quite satisfactory agreement in shape is obtained with large deuteron absorption. The observed distribution agrees well with that derived from the inverse reaction (1964BU1B). See also (1956EI05) and (1963WE11). For reaction (b), see (1957WI22) and (1956EI05). For reaction (c), see (1956EI05, 1957WI22, 1958SE74, 1965RI1A, 1965TY1A).

9. ^{4}He(d, n)^{5}Li $\quad$ $Q_{\rm m} = -4.190$

Neutron spectra are reported for $E_{\rm d} = 7.9$, 8.9 and 9.9 MeV (1962LE12), 13 MeV (1956BO1F, 1956BO43), and 18.6 MeV (1961RY01) and for $E_\alpha = 34.6$ MeV (1961RY01). The spectra show two peaks superimposed on a continuous distribution, one at high energy, ascribed to formation of ^{5}Li$_{\rm g.s.}$ and one at low energy, corresponding to ^{5}He$_{\rm g.s.}$. The observed spectra are well fitted with resonance final state interaction of ^{4}He + n, ^{4}He + p, characterized by $E_{\rm res} = 1.0$ and 2.1 MeV, respectively, $\gamma^2 = 12$ MeV · fm, $R = 2.6$ fm. A broad distribution underlying the peaks is ascribed to direct breakup (1961RY01). See also ^{5}He: ^{4}He(d, p)^{5}He and (1965NA1D, 1965NA1E).

10. ^{4}He(^{3}He, d)^{5}Li $\quad$ $Q_{\rm m} = -7.459$

Not reported.

11. ^{6}Li(γ, n)^{5}Li $\quad$ $Q_{\rm m} = -5.662$

See (1951SH63, 1951TI06, 1955TI1A, 1958RY77) and ^{6}Li.

12. ^{6}Li(p, d)^{5}Li $\quad$ $Q_{\rm m} = -3.438$

At $E_{\rm p} = 18.6$ MeV, the ground state appears as a broad, asymmetric peak ($\Gamma = 1.8$ MeV). The angular distribution conforms with stripping theory ($l_{\rm n} = 1$) at small angles (1955LI09). See also (1964SH07).

13. ^{6}Li(d, t)^{5}Li $\quad$ $Q_{\rm m} = 0.595$

At $E_{\rm d} = 1$ MeV a broad ground state triton group is observed ($\Gamma_{\rm c.m.} = 2.0$ MeV) (1958FR52). Angular distributions have been measured at $E_{\rm d} = 15$ MeV (1959HA29, 1960HA14) and 20 MeV (1959VL24). They are characteristic of $l = 1$; $\theta^2 = 0.24$ (1959VL24), $\theta^2 = 0.15$ (1960HA14). The spectrum shape is analyzed in terms of p-α scattering parameters by (1960HA14). See also (1959KU1C) and ^{8}Be.

14. ^{6}Li(^{3}He, α)^{5}Li $\qquad Q_{\rm m} = 14.916$

See (1953KU24, 1955AL57, 1965KA1F, 1965YO1D).

15. ^{7}Li(p, t)^{5}Li $\qquad Q_{\rm m} = -4.433$

See (1957MA04, 1959KO1C).

16. ^{10}B(^{3}He, pα)^{4}He^{4}He $\qquad Q_{\rm m} = 12.420$

See (1964ET02, 1965ET1A, 1965WA1M).

17. (a) ^{12}C(p, 2α)^{5}Li $\qquad Q_{\rm m} = -9.240$

(b) ^{16}O(p, 3α)^{5}Li $\qquad Q_{\rm m} = -16.401$

See (1961VA17) and (1962VA1A).

References

(Closed July 01, 1965)

References are arranged and designated by the year of publication followed by the first two letters of the first-mentioned author's name and then by two additional characters. Most of the references appear in the National Nuclear Data Center files (Nuclear Science References Database) and have NNDC key numbers. Otherwise, TUNL key numbers were assigned with the last two characters of the form 1A, 1B, etc. In response to many requests for more informative citations, we have, when possible, included up to ten authors per paper and added the authors' initials.

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