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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 A*227 (1974), 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 NNDC/TUNL format.

(References closed December 31, 1973)

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Table of Contents for $A = 5$

Below is a list of links for items found within the PDF document. Figures from this evaluation have been scanned in and are available on this website or via the link below.

^{5}n
(Not illustrated)

^{5}n has not been observed in the interaction of π^- and ^{14}N and ^{16}O: see (1972AG01).

^{5}H
(Fig. 3)

From the work of (1967AD05)[†] on the ^{3}He(^{3}He, n)^{5}Be reaction (see ^{5}Be) it follows that ^{5}H is unstable by more than 2.1 MeV to decay into ^{3}H + 2n (using Coulomb corrections based on the 16.7 MeV states in ^{5}He–^{5}Li). [With the "conventional" correction of (1966LA04, p.2) ^{5}H is unbound by > 0.7 MeV.] A study of ^{9}Be(α, ^{8}B)^{5}H at $E_\alpha = 129$ MeV shows no evidence for sharp ^{5}H states for several MeV above ^{3}H + 2n (1968MC02). In ^{3}H(t, p)^{5}H, at $E_{\rm t} = 22.25$ MeV, a broad peak appears in the proton spectrum which may correspond to a ^{5}H state at ^{3}H + 2n + 1.8 MeV, but which could also result from a four-body breakup (1968YO06). Several recent attempts to observe ^{5}H formation in ^{7}Li(π^-, pn) and ^{7}Li(π^-, d) have been unsuccessful: see (1965CO1D, 1968BO32, 1969MI10). See (1966LA04) for a review of the earlier work, (1965AR04), and (1965AR08, 1966DE1E, 1968CE1A, 1970WA1G, 1971WA08).

^{5}He
(Figs. 1 and 3)

GENERAL: (See also (1966LA04).):

Shell model calculations: (1966FR1B, 1967BO1C, 1967EL03, 1967YA1A, 1968EL1A, 1968GO01, 1969EL1B, 1969GO1G, 1970IR01, 1970RA1D, 1970ZO1A, 1971RA15, 1971WA08, 1972KA38, 1972LE1L, 1973HA49).

Cluster calculations: (1965NE1B, 1966HO06, 1967BE1G, 1969ME1C, 1969WI1C, 1971LE1N, 1972DE30).

Special levels: (1971RA15, 1973FE1J).

Electromagnetic transitions: (1966HO06, 1973HA49).

General reviews: (1966DE1E).

Reactions involving pions: (1969GO1C, 1969KO30, 1972GA11, 1973EI01).

Special reactions: (1971CH31, 1972CH31, 1972PN1A, 1973GR22).

† References are collected at the end of this article.

Other topics: (1967BO1C, 1967EL03, 1968GO01, 1968HE1D, 1969GI1A, 1969HE1L, 1969SC1J, 1970SU1B, 1970ZO1A, 1971BA2Y, 1971CH50, 1971ZA1D, 1972CA37, 1972GI11, 1972JA14, 1972KA38, 1972LE1L, 1972MA57, 1972RI10, 1973MA20, 1973RA1E, 1973RO1R).

States of ^{5}He‡ :

Ground state: The ground and first excited states of ^{5}He comprise the components $^{2}P_{3/2}$ and $^{2}P_{1/2}$ formed by $l = 1$ scattering of a neutron by an α-particle. Shape parameters of the state are best described by tabulated phase shifts, but it is sufficiently narrow to appear as a distinct group in many reactions. The central energy of this group is generally taken as defining the "mass" of ^{5}He.

First excited state: Ordinarily appears as a broad continuum in particle spectra, centered several MeV (3–5) above the ground state. The resonant phase shift goes through $\frac{1}{2}\pi$ at $E_{\rm cm} = 6.43$ MeV, about 5.5 MeV above the ground state.

16.8 MeV: Conspicuous in the ^{3}H + d reactions, the state is almost entirely of a $3 + 2$ configuration, with relative angular momentum zero, and a quite small reduced width for neutron ($l_{\rm n} = 2$) emission. Properties of the state are listed in Table 5.2.

19.9 MeV: In the range $E_{\rm x} = 20 - 25$ MeV, there appears to be a number of broad overlapping states, principally of $3 + 2$ configuration, with even parity. There is some indication from ^{7}Li(p, ^{3}He), [^{7}Li(p, t)] that they have mainly $S = \frac{3}{2}$. Among this manifold, a level at 19.9 ± 0.4 MeV is reported to form a well-defined group ($\Gamma = 3$ MeV) in ^{7}Li(p, ^{3}He). There are indications of another structure near $E_{\rm x} = 24 - 25$ MeV.

1. ^{3}H(d, γ)^{5}He $\qquad Q_{\rm m} = 16.70$

At low energies the reaction is dominated by a resonance at $E_{\rm d} = 107$ keV; the mirror reaction shows resonance at $E_{\rm d} = 430$ keV. (1970BE1A) have measured the cross section for emission of 16.7 MeV γ-rays for $E_{\rm d} = 25$ to 100 keV: the ratio σ(d, γ)/σ(d, n) is approximately constant at $(2.1 \pm 0.6) \times 10^{-4}$, leading to $\Gamma_{\gamma} = 14 \pm 4$ eV, where $\Gamma_{\rm n}$ is taken as 66 keV. (1963BU07) have measured thick target yields from $E_{\rm d} = 150$ to 1300 keV. The derived cross sections are analyzed into resonant and direct-capture contributions: the cross section at resonance is here reported as $60\ \mu$b [vs. 1 mb reported by (1970BE1A)]. At $E_{\rm d} = 1025 \pm 47$ keV, the differential cross section id $0.44 \pm 0.12\ \mu$b/sr (90°) and the γ to n branching ratio is an order of magnitude smaller: 2.3×10^{-5}. The angular distribution of the γ-rays is forward peaked and the total cross section is estimated to be $4.8\ \mu$b (1970KO09). A cluster model calculation of major even parity states predicts a broad peak in dipole strength due mainly to a $\frac{5}{2}^{+}$ state in a cluster of positive parity states some 4 MeV above the $\frac{3}{2}^{+}$ state (1971WA08).

‡ Similar considerations prevail for ^{5}Li.

Table 5.1: Energy levels of ^{5}He [a]

E_x (MeV)	$J^\pi; T$	$\Gamma_{c.m.}$ (MeV)	Decay	Reactions
g.s.	$\frac{3}{2}^-; \frac{1}{2}$	0.60 ± 0.02 [b]	n, α	1, 5, 7, 9, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26
4 ± 1.5	$\frac{1}{2}^-; \frac{1}{2}$	4 ± 1.5	n, α	5, 7, 11, 12, 14, 20
16.76 ± 0.13	$\frac{3}{2}^+; \frac{1}{2}$	0.10 ± 0.05	γ, n, d, t, α	1, 2, 6, 7, 9, 12, 14, 19, 20
19.9 ± 0.4 [a]	$(\frac{3}{2}, \frac{5}{2})^+; \frac{1}{2}$	3 ± 0.6	n, d, t, α	2, 4, 6, 11, 17, 19, 20
$24 - 25$		broad		19, 20

[a] See also the discussion "States of ^{5}He" section in ^{5}He.

[b] See Table 5.2 in (1966LA04).

Table 5.2: Resonance parameters for ^{3}H(d, n)^{4}He and ^{3}He(d, p)^{4}He

E_r (keV)	Γ_{lab} (keV)	l_d	J^π	$l_{n,p}$	R (fm)	E_λ (keV)	γ_d^2 (keV)	$\gamma_{n,p}^2$ (keV)	θ_d^2 [c]	$\theta_{n,p}^2$ [c]	E_x (MeV)
107 [a]	135	0	$\frac{3}{2}^+$	2	5.0	-464	2000 ± 500	50 ± 10	1.0	0.018	16.76
					7.0	-126	715	17	0.7	0.011	
450 [b]	≈ 450	0	$\frac{3}{2}^+$	2	5.0	-391	2930	42	1.4	0.013	16.66
					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 $3\hbar^2/2MR^2$.

2. (a) ^{3}H(d, n)^{4}He $\quad Q_m = 17.5900 \quad E_b = 16.70$

(b) ^{3}H(d, 2n)^{3}He $\quad Q_m = -2.9885$

(c) ^{3}H(d, pn)^{3}H $\quad Q_m = -2.2246$

Below $E_d = 100$ keV, the cross section for reaction (a) follows the Gamow function, $\sigma = (A/E)\ \exp\ (-44.40\ E^{-1/2})$ (1953JA1A, 1954AR02). A strong resonance, σ(peak) $= 5.0$ b, appears at $E_d = 107$ keV: see Table 5.2. From $E_d = 10$ to 500 keV, the cross section is well fitted with the assumption of s-wave formation of a $J^\pi = \frac{3}{2}^+$ state (1952AR1A, 1952CO35, 1955KU03). Excitation curves and angular distributions for reaction (a) have been measured from $E_d = 8$ keV to 21 MeV: see (1966LA04) for earlier references and (1966KO19: differential cross section $(90°)$; $E_d = 0.115$ to 1.65 MeV), (1968IV01: excitation functions at 3 angles; $E_d = 3.97$ to 10.99 MeV), (1973MC05: angular distributions, at ≈ 1 MeV intervals; absolute $0°$ cross sections to within ± 3.1%; $E_d = 5.0$ to 15.7 MeV) and (1968SI1B: differential cross sections $(0°)$, angular distributions; $E_d = 7.0$, 11.4, 15.0 and 19.0 MeV; relative cross sections at 1 MeV intervals, $E_d = 7.0$ to 21.0 MeV). There is some evidence of resonant behavior between $E_d = 3$ and 9 MeV (1960ST25). See also (1968SI1B, 1973MC05).

A study of reaction (a) with polarized deuterons at $E_d = 0.2$ to 1.0 MeV indicates intervention of the s-wave, $J^\pi = \frac{1}{2}^+$ channel, as well as possible p-waves above $E_d = 0.3$ MeV (1965TR01, 1971GR32). This effect is evidently very small below $E_d = 100$ keV (1971OH1B). At higher energies, the neutron polarization $P_1(\theta_1)$ shows an angular distribution that peaks typically at $\theta_1 = 30°$ lab, then goes negative with increasing angle and has a minimum between $90°$ and $130°$, depending upon energy. (1971MU04) have made an extensive study of $P_1(30°)$ for $E_d = 5$ to 15 MeV and, with deuterium as target, for $E_t = 4.5$ to 19.5 MeV (neutrons near $135°$ lab). The polarization increases monotonically from 0.03 at $E_d = 3$ MeV to ≈ 0.5 at $E_d = 6.5$ MeV and then with a lower slope to 0.69 at $E_d = 13$ MeV. The change in the slope may be caused by excited states of ^{5}He near 20 MeV. Comparison with the ^{3}He(d, p)^{4}He mirror reaction at corresponding cm energies shows excellent agreement between the polarization values in the two reactions up to $E_d = 6$ MeV, but then the proton polarization becomes ≈ 15% higher, converging back to the neutron values at $E_d \approx 12-13$ MeV. This may be due to experimental factors (1971MU04). Using polarized deuterons (1971HI07) find that the average ratio of vector analyzing power of ^{3}He(d, p) to ^{3}H(d, n) is 1.016 ± 0.015 at $E_d = 6$ MeV and 1.035 ± 0.020 at 10 MeV. The vector analyzing power of the two reactions agree to within ± 0.025 at all angles. This agreement between the mirror reactions is in apparent conflict with the result of (1971MU04). See also reaction 3 in ^{5}Li. For other polarization measurements see Table 5.3.

(1968BO35) have examined the parity non-conserving effects inn this strong reaction with polarized deuterons ($E_d = 0.14$ MeV). The experiment measured the ratio of the number of neutrons emitted parallel and anti-parallel to the direction of the initial polarization vector. The magnitude of the real part of the parity violating amplitude, F, is $\lesssim 3.8 \times 10^{-3}$.

The energy spectrum of ^{3}He particles in reaction (b) has been studied at $E_d = 10.9$ MeV at several angles: no evidence was found for a bound dineutron [$< 5\ \mu$b/sr at $6°$ and $7.5°$]. Strong variations of the spectral shape with angle indicate that the Watson-Migdal approximation is inadequate and that several other first-order processes must be included. The determination of the

Table 5.3: ^{3}H(d, n)^{4}He polarization studies

$E_{\rm d}$ (MeV)	Refs.
51, 76, 93 keV	(1971OH1B)
0.1, 0.17 MeV	(1961RU1A, 1962SE09)
0.1 – 7.7	(1961PE13, 1964PE14)
0.125	(1968BE05)
0.2 – 1.0	(1971GR32)
0.3 – 1.8	(1968HE16, 1969HE1H)
0.4 – 1.7	(1969WI1D)
0.6, 1.2	(1965BO13)
1.0 – 5.0	(1972SM05)
2.1 – 2.9	(1965CH15)
2.1 – 5.8	(1967BU11)
$E_{\rm d} = 5$ – 15, $E_{\rm t} = 4.5$ – 19.5	(1970BR30, 1971MU04)
6 – 10	(1971HI07)
6 – 11	(1964WA22)
8 – 20	(1964AL1E)
10	(1961TR05)
17	(1972RY01)

nn scattering length is ambiguous (1970LA10, 1970LA1K). This problem is also discussed by (1971GR45: $E_{\rm d} = 13.4$ MeV), (1970SL1A: $E_{\rm d} = 31.9$ MeV), (1966BA1H: $E_{\rm d} = 29.8$, 32.5 MeV), (1971GR12: $E_{\rm t} = 22$ MeV) and (1972BA32: $E_{\rm d} = 83$ MeV). A discussion and comparison of attempts to measure the $^{1}S_{0}$ nn scattering length is presented by (1971GR45): based on kinematically complete measurements and using the Watson-Migdal treatment, they find $a_{\rm nn} = -16.0 \pm 1.0$ fm. Intervention of n–^{3}He final state interactions is believed to be small in this work (1971GR45). See also (1973GR1L, 1973JE02). At $E_{\rm t} = 22$ MeV no clear evidence is seen for sequential processes via excited states of ^{4}He (1971GR12).

Analysis of reaction (c) at $E_{\rm d} = 20$ MeV is consistent with the existence of a broad resonance in the ^{3}H+p system correspoding to ^{4}He*(22.) (1968NE1D): see (1973FI04) for a general discussion of the states of ^{4}He. n-p final-state interaction enhancement has been studied by (1973SL03) at $E_{\rm d} = 35$ MeV. They find that only when $E_{\rm n,p} \leq 1$ MeV is agreement with the Watson-Migdal theory obtained, even if the data far from dominant n-t final-state interaction and p-t quasi-free scattering is chosen. See also (1966LA04).

See also (1965FL1A, 1966BR02, 1966BR1F, 1966BR1E, 1966BU09, 1966VA1A, 1967BO1D, 1967NE1B, 1968OH1A, 1969BU19, 1969ME1B, 1970HA1L, 1971MC1L, 1971OH1A, 1971PO1C,

1971SC1L, 1973GE1G), (1968TO1F, 1970SL1B, 1971HA2G, 1971WA1D, 1972OH1D, 1972SC1R) and (1965DU1A, 1965GO1B, 1966BA1J, 1966HU16, 1967OH1A, 1968HA1F, 1969HA1M, 1969HE1K, 1970PO1A, 1970SE1B, 1971DE20, 1971OH1C, 1971SI30, 1972SE09; theor.).

3. ^{3}H(d, p)^{4}H $\rightarrow$ ^{3}H + n $Q_{\rm m} = -2.2246$ $E_{\rm b} = 16.70$

See (1967JA07, 1973SL03) and (1973FI04).

4. ^{3}H(d, d)^{3}H $E_{\rm b} = 16.70$

The elastic scattering has been studied for $E_{\rm d} = 2.6$ to 11.0 MeV. The excitation curves show an interference at $E_{\rm x} \approx 19$ MeV and a braod ($\Gamma > 1$ MeV) resonance corresponding to $E_{\rm x} = 20.0 \pm 0.5$ MeV, also seen in ^{3}He(d, d) [see ^{7}Li]. Together with data from ^{3}H(d, n)^{4}He, this work favors an assignment $D_{3/2}$ or $D_{5/2}$ with a mixture of doublet and quartet components (channel spin $\frac{1}{2}$ and $\frac{3}{2}$) if only one state is involved (1967TO02, 1968IV01) [any appreciable doublet component would, however, be in conflict with results from ^{7}Li(p, ^{3}He)^{5}He]. Measurements of differential cross section and analyzing power using polarized deuterons with $E_{\rm d} = 3.2$ to 12.3 MeV show resonance-like behavior in the vector analyzing power near $E_{\rm d} = 5$ MeV. The anomaly appears in the odd Legendre coefficients and is interpreted in terms of a $(\frac{1}{2}, \frac{3}{2})^{-}$ excited state of ^{5}He with $E_{\rm x} \approx 19.6$ MeV. Broad structure in the differential cross section near 6 MeV, principally in the even Legendre coefficients, corresponds to an even parity state ^{5}He*(20.0) (1971KI02)[§] . See also (1966BA1J, 1966BA1M, 1966DE1F, 1969BE1M, 1970HE1C, 1973CH27, 1974CH02; theor.) and (1966LA04).

5. (a) ^{3}H(t, n)^{5}He $Q_{\rm m} = 10.44$

(b) ^{3}H(t, 2n)^{4}He $Q_{\rm m} = 11.3324$

At $E_{\rm t} = 0.5$ MeV, the reaction appears to proceed via three channels: (i) direct breakup into ^{4}He + 2n, the three-body breakup shape being modified by the n-n interaction; (ii) sequential decay via ^{5}He(0); (iii) sequential decay via a broad excited state of ^{5}He. The branching ratios at $\theta = 90°$ are 0.7: 0.2: 0.1. The width of ^{5}He(0) is estimated to be 0.74 ± 0.18 MeV. Some evidence is also shown for ^{5}He* at $E_{\rm x} \approx 2$ MeV, $\Gamma \approx 2.4$ MeV (1965WO03). For reaction (b), see ^{6}He.

6. (a) ^{3}He(t, p)^{5}He $Q_{\rm m} = 11.20$

(b) ^{3}He(t, pn)^{4}He $Q_{\rm m} = 12.0963$

[§] Tensor analyzing powers have been measured for $E_{\rm d} = 5.0$ to 11.5 MeV by (1973DE51).

Table 5.4: Recent ^{4}He(n, n)^{4}He polarization studies

E_n (MeV)	Refs.
0.262	(1966JE01)
1.02, 2.44	(1968SA25)
3.4, 7.8	(1970ST15)
6.0, 10.0, 16.4, 23.1, 23.7	(1966HO07)
11 – 30	(1972BR10)
12.0, 16.2	(1966BU09)
14, 17.1	(1973LI1K)
15	(1973TO06)
21 – 29	(1971MU04)
25, 28, 34	(1965AR10, 1967HO1D)

Some evidence is reported at $E_t = 22.25$ MeV in reaction (a) for a broad state of ^{5}He at $E_x \approx 20$ MeV, in addition to a sharp peak corresponding to ^{5}He*(16.7) (1968YO06). For reaction (b) see ^{6}Li. See also (1966LA04).

7. ^{4}He(n, n)^{4}He $\qquad E_b = -0.89$

The coherent scattering length (thermal, bound) is 3.0 ± 0.1 fm (1973MU14). The thermal scattering cross section is 0.773 ± 0.009 b and the absorption cross section at 2200 m/sec $\sigma^0_{n,\gamma}$ is < 0.05 b (1969RO16). (1973MU14) adopt 0.76 ± 0.01 b for $\overline{\sigma}_s$. Total cross sections for $E_n = 4 \times 10^{-4}$ eV to 147 MeV are summarized in (1958HU18, 1960HU1A, 1964ST25, 1966LA04). Recent measurements include those by (1969RO16: $E_n = 0.187$ to 6.195 eV), (1973GO38: $E_n = 0.7$ to 20.0 MeV), (1966ME14: 77.2, 88.2, 110.0, 129.4, 150.9 MeV) and (1968EN1A: 10 GeV/c).

Earlier angular distribution studies are summarized in (1970GA1A). Other recent work is reported by (1968MO26, 1970MO31: $E_n = 0.2$ to 7.0 MeV), (1969CR1B, 1972CR01: $E_n = 0.55$, 0.84, 1.16, 1.33 MeV) and (1971NI06: 17.6, 20.9 and 23.7 MeV). Recent polarization studies are listed in Table 5.4.

The total cross section has a peak of 7.6 b (1973GO38) [see also (1960VA04)] at $E_n = 1.15 \pm 0.05$ MeV, $E_{cm} = 0.92 \pm 0.04$ 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 $J^\pi = \frac{3}{2}^+$ state (1959BO54, 1964SH1A): $\Gamma_{c.m.} = 100 \pm 50$ keV, $\Gamma_n = \Gamma_d = 50 \pm 35$ keV (1960HU1A) [(1966HO07) find that the data are fitted best by $\Gamma_n < \Gamma_d$ although $\Gamma_n > \Gamma_d$ is not excluded]. Attempts to detect additional resonances in the total cross section have been unsuccessful: see (1966LA04).

The $P_{3/2}$ phase shift shows strong resonance behavior near 1 MeV, while the $P_{1/2}$ shift changes more slowly, indicating a broad $P_{1/2}$ level at several MeV excitation (1952DO30, 1966HO07, 1970AR1B, 1972ST01). (1966HO07) have constructed a set of phase shifts for $E_n = 0$ to 31 MeV, $l = 0$, 1, 2, 3 using largely p-α phase shifts. They have measured differential cross sections from 6 to 30 MeV, with special attention to the region near 22.15 MeV and have fitted the data with the assumed phase shifts. At the $\frac{3}{2}^+$ state the best fit to all data is given by $E_{\rm res} = 17.669$ MeV ± 10 keV, $\gamma_{\rm d}^2 = 2.0$ MeV $\pm$25%, $\gamma_{\rm n}^2 = 50$ keV $\pm$25% (see Table 5.2). The polarization has been calculated from the phase shifts and is presented as a contour plat (1966HO07).

(1968MO26) have carried out accurate angular distribution measurements for $E_n = 0.2$ to 7.0 MeV and deduced an independent set of p-wave phase shifts, assuming that s-wave shifts are those those of a hard sphere, $R = 2.44$ fm. The derived total cross sections fit existing data satisfactorily, and polarization results of (1968SA25) and (1963MA29) are well accounted for. Both single-level dispersion formula and Woods-Saxon potential parameters are deduced. A more extensive optical model analysis for $E_n = 0$ to 20 MeV has been carried out by (1968SA1B).

(1970AR1B, 1973AR1N, 1973AR1P) have analyzed existing differential cross sections and polarization data with phase shifts constrained to analytic (effective range) energy dependence, for $E_n = 0$ to 21 MeV. As compared with the (1966HO07) values, the $P_{1/2}$ phase shift is higher in the range 3 to 10 MeV, and both $S_{1/2}$ and $P_{3/2}$ are larger for $E_n = 10$ to 16 MeV. D- and F-wave phase shifts are also determined (1973AR1P).

A single-level-with-background R-matrix parameterization has been carried out by (1972ST01), fitting differential cross section data for $E_n = 0$ to 20 MeV and polarization analyzing power for 0 to 15 MeV. Parameters for $P_{3/2}$ and $P_{1/2}$ levels are $E_{\rm res} = 0.97$ and 6.43 MeV, and $\gamma^2 = 7.55$ and 12.30 MeV, respectively. See also (1973NI1B). Polarization measurements at six energies from $E_n = 11$ to 30.3 MeV are reported by (1972BR10) together with derived phase shifts. Partial waves as high as $l = 4$ are required, but none shows resonance, other than the $D_{3/2}$. See also (1969RO20).

See also (1966BR1E, 1969MA1H, 1973GA17), (1966BA1K, 1971RH1A, 1971ST1J, 1971WA1D, 1972SC1T) and (1966BA1J, 1966DE1F, 1966PE1C, 1966TO04, 1967SC1E, 1967SW1B, 1969ER1B, 1968SE1A, 1968BA1U, 1969BE1M, 1969CO1E, 1969GE1A, 1969HE1L, 1969KU1D, 1968TH1C, 1969VO1E, 1970ER1A, 1970FE1C, 1970GN1A, 1970HE1C, 1970HO32, 1970OM1A, 1970RE1A, 1971BA1Y, 1971BA74, 1971EF01, 1971GI1B, 1971PI04, 1971PL06, 1971TH09, 1972AD02, 1972IK01, 1972KI1F, 1972LO1K, 1972ZH1B, 1973AD01, 1973PL02, 1974CH02; theor.).

8. ^{4}He(n, d)^{3}H $Q_m = -17.5900$ $E_b = -0.89$

See (1964DE1B, 1966ME03) and (1966LA04).

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

(b) ^{4}He(d, pn)^{4}He $Q_m = -2.2246$

A typical proton spectrum consists of a peak corresponding to formation of the ground state of ^{5}He, plus a lower continuum of protons ascribed to deuteron breakup (reaction (b)). Ground-state protons show pronounced azimuthal asymmtery when the reaction is induced by 8.5, 10 and 11 MeV vector polarized deuterons. A DWBA calculation is in only qualitative agreement (1967TR05, 1971KE16). See also (1972AV1E).

Coincidence studies of the final state interactions (α + p) and (α + n) have been carried out at $E_{\rm d} = 14.2$ MeV (1967FU1D), $E_\alpha = 18.0$ and 24.0 MeV (1970AS02), 42 MeV (1967WA08, 1968WA01), $E_\alpha = 70$ MeV (1973TR04) and $E_{\rm d} = 78$ MeV (1968BO1M). Spectra of α-particles in coincidence with protons exhibit peaks corresponding to ^{5}He$_{\rm g.s.}$ as well as broad spectator peaks which occur where the neutron laboratory energy is a minimum (1967WA08, 1968WA01): see ^{5}Li. [For earlier work see (1966LA04)]. See also (1971LE02).

At $E_\alpha = 70$ MeV, a kinematically complete experiment shows evidence for sequential decay in reaction (a), proceeding through excited states of ^{5}He. Peaks in the coincident yield of protons and deuterons are ascribed to narrow states at $E_{\rm x} = 16.7 \pm 0.1$ MeV, $\Gamma = 80 \pm 30$ keV, at $E_{\rm x} = 18.6 \pm 0.1$, 18.8 ± 0.1 and 19.2 ± 0.1 MeV, all with $\Gamma = 180 \pm 60$ keV (1973TR04).

See also (1968TA11, 1971AL1B, 1972LA1L) and (1966HE1B, 1967NA1D, 1969NA09, 1972BL1F, 1972NA1D, 1973DE2B; theor.).

10. ^{4}He(t, d)^{5}He $Q_{\rm m} = -7.15$

Not reported.

11. ^{6}Li(γ, p)^{5}He $Q_{\rm m} = -4.59$

At $E_\gamma = 60$ MeV, the proton spectrum shows prominent peaks attributed to ^{5}He*($0 + 4.0$, 20 ± 2) (1973GA16). See also (1973DE17) and ^{6}Li.

12. ^{6}Li(e, ep)^{5}He $Q_{\rm m} = -4.59$

At $E_{\rm e} = 1180$ MeV, two values of Q are observed: $Q = -3.5 \pm 1.0$ MeV, corresponding to ^{5}He(0), and $Q = -19.0 \pm 1.0$ MeV, corresponding to ^{5}He*(16.7). Angular distributions at $E_{\rm p} = 1158$ MeV show that the first represents ejection of a proton with $l > 0$ and the second, an s-proton (1972AN24, 1972AN27, 1972AN29).

13. (a) ^{6}Li(n, d)^{5}He $Q_{\rm m} = -2.37$

(b) ^{6}Li(n, nd)^{4}He $Q_{\rm m} = -1.4737$

The angular distribution of ground state deuterons has been studied at $E_{\rm n} = 14.4$ MeV (1965VA05). DWBA analysis does not reproduce either its shape or the cross section: this may be due to neglect of the deuteron knock-on process (1971MI12). At $E_{\rm n} = 152$ MeV, two broad structures in the forward spectrum are interpreted as being due to transitions to ^{5}He*(0, 14). The $Q = -17$ MeV peak is the stronger of the two (1966ME03, 1967ME11). For reaction (b) see (1967VA12). See also (1970VA1L, 1971HE1M, 1973BO1Y) and (1966WE1B). See also (1966LA04).

14. ^{6}Li(p, 2p)^{5}He $\quad\quad Q_{\rm m} = -4.59$

At $E_{\rm p} = 100$ to 460 MeV, the summed proton spectra show two peaks [$Q = -4.9 \pm 0.3$ and -22.7 ± 0.3 MeV (1966TY01)]. The lower peak corresponds to ejection of an $l = 0$ proton, presumably leaving ^{5}He in the $\frac{3}{2}^{+}$ state at 16.7 MeV. See also (1966LA04). At $E_{\rm p} = 100$ MeV, the $\frac{1}{2}^{-}$ first excited state of ^{5}He is weakly excited (1972MA61). At $E_{\rm p} = 100$ and 155 MeV, transitions to states above 20 MeV are reported by (1965RO15, 1967RO06, 1972MA61). See also (1965CO1E, 1966BE1B, 1968ZU1A, 1969RU1A, 1973BH1A), (1967KO1B, 1967SH1C, 1968SA1C, 1972KO13, 1973CH1Q; theor.) and ^{6}Li.

15. (a) ^{6}Li(d, ^{3}He)^{5}He $\quad\quad Q_{\rm m} = 0.90$
(b) ^{6}Li(d, n^{3}He)^{4}He $\quad\quad Q_{\rm m} = 1.795$

At $E_{\rm d} = 14.5$ MeV, the ground state group is observed (1955LE24). See also (1960HA14, 1971IN1C). A study of the proximity process ^{3}He(n, p)^{3}H in the final state of reaction (b) has led to an estimate of the lifetime of $^{5}{\rm He}_{\rm g.s.}$, $\tau = 1.4 \times 10^{-21}$ sec (to within a factor of 2 or 3) (1972KA44). See also (1968LE15).

16. ^{6}Li(t, α)^{5}He $\quad\quad Q_{\rm m} = 15.22$

The width of the ground state is 605 ± 45 keV (1966BI1A). See also (1967BE13) and (1966LA04).

17. ^{7}Li(π^{+}, 2p)^{5}He $\quad\quad Q_{\rm m} = 128.51$

The two-proton spectrum shows broad structures attributed to the ground state of ^{5}He, and to p^{-1}s^{-1} and s^{-2} states at ≈ 20 and (≈ 35) MeV excitation (1965CH12).

18. (a) ^{7}Li(n, t)^{5}He $\qquad Q_m = -3.36$

(b) ^{7}Li(n, tn)^{4}He $\qquad Q_m = -2.4668$

The angular distriibution of ground state tritons has been measured at $E_t = 14.4$ MeV: it is fairly well reproduced by DWBA (1970MI05). Reaction (b) mainly proceeds as a sequential process through ^{5}He$_{g.s.}$ (1967VA12). See also (1972AN1Q, 1973LI02), (1967BA1E; theor.) and (1966LA04).

19. ^{7}Li(p, ^{3}He)^{5}He $\qquad Q_m = -4.12$

At $E_p = 43.7$ MeV, angular distributions of the ^{3}He groups to the ground state of ^{5}He ($\Gamma = 0.80 \pm 0.04$ MeV) and to levels at 16.7 and 19.9 ± 0.4 MeV ($\Gamma = 2.7$ MeV) have been determined. The angular distribution of the ^{5}He ground state group indicates substantial mixing of $L = 0$ and $L = 2$ transfer. The distribution to ^{5}He*(16.7) is consistent with $L = 1$. Since no transitions are observed in the ^{7}Li(p, t)^{5}Li reaction to the analogue 20 MeV state in ^{5}Li [see ^{5}Li], the transition is presumably S-forbidden and the putative states in ^{5}He-^{5}Li near 20 MeV are $^4D_{3/2}$ or $^4D_{5/2}$ [compare ^{3}H(d, d)] (1966CE05). Particle-particle coincidence data have been obtained at $E_p = 43.7$ MeV. They suggest the existence of ^{5}He*(20.0) with $\Gamma = 3.0 \pm 0.6$ MeV and of a broad state at ≈ 25 MeV. No $T = \frac{3}{2}$ states decaying via $T = 1$ states in ^{4}He were observed (1968MC02). See also (1967JO1B, 1969DE04, 1970CO1M).

20. (a) ^{7}Li(d, α)^{5}He $\qquad Q_m = 14.23$

(b) ^{7}Li(d, n)^{4}He^{4}He $\qquad Q_m = 15.1233$

At $E_d = 24$ MeV, the α-particle spectrum from reaction (a) shows structures corresponding to the ground and 16.7 MeV states and to states at $E_x \approx 20.2$ and 23.8 MeV with $\Gamma \approx 2$ MeV and ≈ 1 MeV, respectively (1972BA30). See also (1966BI1A, 1966MI09, 1966PO1D) and ^{9}Be.

Spectra measured in reaction (b) suggest the involvement of a ^{5}He state with $E_x = 2.6 \pm 0.4$ MeV, $\Gamma = 4.0 \pm 1.0$ MeV (1964FE01), $E_x = 5.2 \pm 0.2$ MeV, $\Gamma = 5.6^{+0.3}_{-0.6}$ MeV (1965AS06, 1966AS04), $E_x = 2.6 \pm 0.2$ MeV, $\Gamma = 7 \pm 2$ MeV (1972GI10). See also (1972ST08, 1973HE26). Study of n-α coincidences for $E_d = 2.6$ to 4.0 MeV shows that reaction (b) proceeds mainly by sequential decay, primarily via ^{5}He(0) and excited states of ^{8}Be (1967VA11). See also (1966AS04, 1966MI09, 1967JE01, 1972DE44, 1973HE26). Attempts to observe n-α rescattering effects, following formation of ^{8}Be*(16.63, 16.91) have been unsuccessful at $E_d = 1.90$ to 2.10 MeV (1972BR08), 2.07 and 2.09 MeV (1971SW10) and 3.0, 3.2 and 3.6 MeV (1968VA12). The upper limit for the rescattering yield is 1% of the yield from sequential decay via intermediate states in ^{5}He and ^{8}Be (1968VA12). Positive results are reported for $E_d = 2.07$ to 2.25 MeV by (1969TH02). See also (1967BE13, 1967FL12, 1967WI1C, 1968GA1E, 1968WI1E, 1971HU1H, 1973HE06, 1973KA32), ^{8}Be, ^{9}Be and (1966LA04).

21. ^{7}Li(^{6}Li, 2α)^{5}He $\quad Q_{\rm m} = 12.76$

See (1965BE1C).

22. ^{9}Be(γ, α)^{5}He $\quad Q_{\rm m} = -2.46$

See ^{9}Be.

23. ^{9}Be(p, pα)^{5}He $\quad Q_{\rm m} = -2.46$

Studies of this reaction have been carried out at $E_{\rm p} = 26.0$, 35.0 and 46.8 MeV (1972QU01) and at 57 MeV (1968RO19). Observation of protons and alphas in coincidence at selected angles shows quasifree scattering of the incident protons by S-state α-clusters in ^{9}Be (1968RO19, 1972QU01): see ^{9}Be. See also (1969YA1B, 1970GO12).

24. ^{9}Be(α, 2α)^{5}He $\quad Q_{\rm m} = -2.46$

The population of ^{5}He(0) has been observed at $E_{\alpha} = 28$ MeV (1965YA02) and at 32.3 and 37.4 MeV (1968YA02). See also (1965HI1B, 1965KU1B, 1966HI1A, 1967ME1C) and ^{9}Be.

25. ^{11}Be(d, n)^{4}He^{4}He^{4}He $\quad Q_{\rm m} = 6.4577$

At $E_{\rm d} = 10.4$ and 12.0 MeV, this reaction involves ^{5}He(0) and states in ^{8}Be and ^{9}Be (1971RE19).

26. ^{12}C(n, n)^{4}He^{4}He^{4}He $\quad Q_{\rm m} = -7.2748$

See ^{12}C in (1968AJ02).

^{5}Li

(Figs. 2 and 3)

GENERAL: (See also (1966LA04).):

Shell model calculations: (1966FR1B, 1968GO01, 1969GO1G, 1970RA1D, 1971RA15, 1972LE1L, 1973HA49).

Cluster calculations: (1965NE1B, 1971HE05).

Special levels: (1970HE1D, 1971HE05, 1971RA15, 1973JO1J).

Electromagnetic transitions: (1973HA49).

General reviews: (1966DE1E).

Special reactions: (1971CH31).

Other topics: (1968GO01, 1970RA1J, 1971CH50, 1971ZA1D, 1972CA37, 1972HA57, 1972JA14, 1972LE1L, 1973RO1R).

1. ^{3}He(d, γ)^{5}Li $\qquad Q_m = 16.39$

Excitation curves and angular distributions have been measured for $E_d = 0.2$ to 2.85 MeV (1954BL89), $E_d = 0.2$ to 1.2 MeV (1968BU09), $E_d = 1$ to 5 and $E(^3\text{He}) = 2$ to 5.5 MeV (1968KR03), $E(^3\text{He}) = 2$ to 26 MeV (1972KI01), $E(^3\text{He}) = 2.3$ to 11.2 MeV (1968DE14) and $E(^3\text{He}) = 3.7$ to 12 MeV (1970SC18).

A broad maximum in the cross section is observed at $E_d = 0.45 \pm 0.04$ MeV [^{5}Li*(16.66)]: $\sigma = 50 \pm 10$ μb, $\Gamma_\gamma = 11 \pm 2$ eV (1954BU06: $\gamma_0 + \gamma_1$); $\sigma_{\gamma_0} = 21 \pm 4$ μb, $\Gamma_{\gamma_0} = 5 \pm 1$ eV (1968BU09). See also (1968KR03). The radiation at resonance is isotropic, consistent with s-wave capture: see (1954BU06, 1968BU09, 1968KR03). Study of γ_0 and γ_1 yield $\Gamma = 2.6 \pm 0.4$ MeV for the ground state width, and $E_x = 7.5 \pm 1.0$ MeV, $\Gamma = 6.6 \pm 1.2$ MeV for the $\frac{1}{2}^-$ state. The ratio of γ_0 to γ_1 is 1.00 ± 0.2 and 1.9 ± 0.4 at $E_d = 480$ and 1025 keV (1968BU09).

An excess in the cross section at higher bombarding energies is interpreted by (1972KI01) as being due to a state at $E_x \approx 18$ MeV: even parity is deduced from the relative intensity of γ_0 and γ_1. It is presumed to be the $\frac{1}{2}^+$ state reported in reactions 3 and 7. A broad peak is also observed at $E_x \approx 20.7$ MeV in the γ_0 cross section. The cross section for γ_1 is ≈ 0. The observations are consistent with $J^\pi = \frac{5}{2}^+$: angular distributions appear to require at least one other state with significant strength near 19 MeV (1972KI01). (1970SC18) also report this state but find $E_x = 19.7 \pm 0.2$ MeV [$\Gamma = 5.0$ MeV]: $(2J + 1)\,\Gamma_{\gamma_0} = 1.32$ keV ($\pm$50%), suggesting E1 (if only one state is involved). See also (1971WA08; theor.).

Table 5.5: Energy levels of ^{5}Li [a]

E_x (MeV)	$J^\pi; T$	$\Gamma_{c.m.}$ (MeV)	Decay	Reactions
g.s.	$\frac{3}{2}^-; \frac{1}{2}$	≈ 1.5	p, α	1, 5, 6, 7, 9, 10, 11, 12, 13, 14, 15, 16
$5 - 10$	$\frac{1}{2}^-; \frac{1}{2}$	5 ± 2	p, α	1, 7, 12, 14, 15, 16
16.66 ± 0.07	$\frac{3}{2}^+; \frac{1}{2}$	≈ 0.3	γ, p, d, ^{3}He, α	1, 3, 4, 5, 7, 12, 14
(18 ± 1)	$(\frac{1}{2}^+); \frac{1}{2}$	broad	γ, p, d, ^{3}He, α	1, 3, 7
(20.0 ± 0.5) [a]	$(\frac{3}{2}, \frac{5}{2})^+; \frac{1}{2}$	≈ 5	γ, p, d, ^{3}He, α	1, 3, 4, 7, 14

[a] See also discussions in reactions 3, 4, 7, 14 and 15.

2. ^{3}He(d, n)^{4}Li $\quad Q_m = -5.324$

This reaction has not been observed: see (1966LA04) and reaction 7 in ^{4}Li in (1968ME03).

3. (a) ^{3}He(d, p)^{4}He $\quad Q_m = 18.3538 \quad E_b = 16.39$
   (b) ^{3}He(d, np)^{3}He $\quad Q_m = -2.22464$
   (c) ^{3}He(d, 2p)^{3}H $\quad Q_m = -1.4608$
   (d) ^{3}He(d, 2d)^{1}H $\quad Q_m = -5.4938$

Below 100 keV the cross section follows the simple Gamow form: $\sigma = (18.2 \pm 10^3/E)exp(-91E^{-1/2})$ b (E in keV) (1953JA1A, 1954AR02). The zero-energy cross section factor $S_0 = 6700$ keV · b (1964PA1A). A pronounced resonance occurs at $E_d = 430$ keV, $\Gamma \approx 450$ keV. The peak cross section is given as 695 ± 14 mb (1952BO68, 1955KU03): see Table 5.2. See also (1970CA1K, 1972PL02). Excitation functions for gorund state protons have also been reported by (1966NE1A: $E(^3\text{He}) = 0.39$ to 1.46 MeV), (1971GR47: $E_d = 2.8$ to 11.5 MeV), (1972BA30: $E_d = 9.4$ to 17.8 MeV) and (1972KI02: $E(^3\text{He}) = 18.7$ to 44.1 MeV). Angular distribution and polarization measurements are summarized in Table 5.6. Below $E_d = 1.1$ MeV, the polarization analyzing power of the reaction is minimally affected by p-wave contributions (less than a few percent). However, at $E_d = 500$ keV, the analyzing power is reduced by 12 ± 5% by intervention of the s-wave $J^\pi = \frac{1}{2}^+$ channel (1966BR02, 1967MC01, 1971LE27). See also (1971RO35, 1972SI1F, 1973OH02). (1971LE13) have evaluated matrix elements for $l = 1$ at $E_d = 0.43$ MeV. Vector polarization effects at $E_d > 1$ MeV disagree with the predictions of stripping theory (1966BR02). See also (1971ZA1C). Contour maps, T_{ab} $vs.$ θ, E_d for the vector and tensor analyzing powers are presented for $E_d = 0$ to 12 MeV by (1971GR47). See also

(1971KL02, 1973CL13). Energy dependence of the angular distributions indicate resonance-like behavior at $E_x = 16.6$, 17.5, 20.0, 20.9 and 22.4 MeV in ^{5}Li (1971GR47). See also (1972SE09, 1973CL13). At $E_d \approx 6$ MeV (1971KL02) find the angular distribution more complex than could be accounted for by a single $^2D_{3/2}$ or $^2D_{5/2}$ level at $E_x \approx 20$ MeV [see ^{3}He(d, d)]. For E_d(cm) = 7 to 18 MeV, differential cross sections fall monotonically with no indication of states of ^{5}Li with $23.4 < E_x < 34$, with $\Gamma > 0.8$ MeV and with appreciable widths for decay into ^{3}He + d (1972KI02). See also (1972BA30). The analyzing power for ^{3}He polarization has been studied by (1971HA02, 1971HU1B, 1971LE13, 1971LE27): see (1971ST1J). For a discussion of excitation of ^{4}He excited states in reaction (a) see (1973FI04).

Reaction (b) has been studied at $E_d = 10.92$ MeV (1972NI02), 11.0 MeV (1970LA10, 1970LA1K), $E(^3\text{He}) = 16.5$ MeV (1971LI04), 18 MeV (1965ZU02), 18.0 and 24.0 MeV (1970AS02), $E(^3\text{He}) = 27$ MeV (1971WA18, 1973WA13) and $E_d = 27.5$ MeV (1973CH05). See also (1966LA04). The spectra show the influence of neutron-proton final state interaction. Sequential decay via excited states of ^{4}He is also reported: see (1970AS02, 1972NI02) and (1973FI04).

Reaction (c) has been investigated at $E_d = 10.9$ MeV (1972NI02), 11 MeV (1965TO01, 1970LA10, 1970LA1K), 15.2 and 20.2 MeV (1967NE1B, 1968NE1D), $E(^3\text{He}) = 16.5$ MeV (1971LI04), 18 MeV (1965ZU02), 18.0 and 24.0 MeV (1970AS02), 19.9 MeV (1971GR12), $E_d = 20.7$ MeV (1970WA15), 24 to 33 MeV (1963BI14, 1964CO1A), 29.8 MeV (1970SL1A), $E(^3\text{He}) = 27$ MeV (1971WA18, 1973WA13), 30 MeV (1973TR1H), $E_d = 39.1$ MeV (1971RU07, 1971RU1E), $E_d = 36$ MeV and $E(^3\text{He}) = 53$ MeV (1967MO08, 1967MO1E, 1968MO10) and at $E_d = 83$ MeV (1972BA32). See also (1972SC1R, 1973SL03). The triton spectra are characterized by p-p final state interaction and by sequential decay via ^{4}He*, as in reaction (b). (1970LA10, 1970LA1K) have analyzed the data of (1968MO10) using all first order interactions, in PWBA. The calculations indicate that complex exchange processes cannot be ignored, and that estimates of the nucleon-nucleon scattering length from such experiments are highly ambiguous (1970LA10, 1970LA1K).

Under kinematic conditions such that two outgoing particles have small relative kinetic energy, a DWBA analysis with two-body interactions has some success in accounting for spectral shapes: see (1967HE1B, 1971CH31, 1971WA18, 1972WA22, 1973WA13, 1973SL03). Reaction (d) has been studied at $E(^3\text{He}) = 26.8$ MeV (1972WA22).

See also (1965DA05, 1967ME14, 1967RO07, 1968FI1D, 1968GO1N, 1968HO1D, 1969ME1B, 1971FO1J, 1970HO1L, 1970RO1L, 1970WI1G, 1971AL1B, 1971WA18, 1972RO1M, 1974PR1D), (1968TO1F, 1971BA1U, 1971HA2G, 1972OH1D) and (1965DU1A, 1965HE1A, 1966BA1J, 1966CS1A, 1966DE1D, 1966DU1A, 1967DE1G, 1968DE1K, 1968HA1F, 1968TA1J, 1969HE1K, 1969SE1B, 1970BR1L, 1970KH03, 1970PO1A, 1971DE20, 1971HA1L, 1971KH03, 1971SE1G, 1972OT05, 1973GA1H, 1973GR1L, 1973LI19; theor.).

4. ^{3}He(d, d)^{3}He $\qquad E_b = 16.39$

In the range $E_d = 380$ to 570 keV, the scattering cross section is consistent with s-wave formation of the $J^\pi = \frac{3}{2}^+$ state at 16.66 MeV (1954BR05). The excitation curves for $E_d = 1.96$

Table 5.6: Measurements of angular distributions and polarization in ^{3}He(d, p)^{4}He [a]

Angular distributions to ^{4}He(0)		Polarization [b]	
Energy (MeV)	Refs.	E_d (MeV)	Refs.
$E_d = 0.25 - 0.85$	(1970CA1K)	$0.19 - 0.50$	(1972OH1C)
$E_d = 2.8 - 11.5$	(1971GR47)	$0.30 - 2.5$	(1971RO35)
$E_d = 5.9, 7.5, 10.4, 12, 12.3, 13.7$	(1960ST25)	$0.31 - 2.94$	(1966BR02)
		$0.34 - 0.73$	(1972GA1N)
$E(^3\text{He}) = 18.7 - 44.1$	(1972KI02)	$0.37 - 1.09$	(1972SI1F)
		0.43	(1971LE13, 1971LE27)
$E_d = 23.2 - 27.0$	(1964BI06)	0.45	(1970AD1C)
		0.45, 0.70, 0.98, 1.5, 2.0, 2.5	(1971HU1B)
		2	(1968SL1A)
		2.0, 2.8, 3.9, 6.0	(1973CL13)
		$2 - 11.2$	(1971GR15)
		$2.23 - 13.0$	(1971KL02)
		$2.8 - 10.0$	(1971LE1G)
		$2.8 - 11.5$	(1971GR47)
		$3.0 - 12.0$	(1963BR10)
		4, 6, 8, 10	(1969PL01)
		$4.0 - 14.0$	(1973HA51)
		$4.78 - 11.88$	(1970HA1M, 1971HA02)
		5.55, 7.97, 10.68	(1966WE03)
		6.0, 7.7, 10	(1968ZA1A, 1971ZA1C)
		6, 8, 10	(1970WA1L)
		6, 10	(1971HI07)
		6.49, 9.30	(1971KO09)
		$6.7 - 15.8$	(1973LI1L)
		9	(1973KA08)
		10, 12, 14	(1968ST1H, 1969ST1F)
		52	(1969BR22)

[a] See also (1957JA37).
[b] See also (1966LA04).

to 10.99 MeV show a broad resonance ($\Gamma > 1$ MeV) corresponding to $E_x = 20.0 \pm 0.5$ MeV. From the behavior of the angular distributions an assignment of ${}^2D_{3/2}$ or $({}^2D, {}^4D)_{5/2}$ is favored, if only one state is involved [see, however, ^{7}Li(p, t)^{5}Li] (1967TO02). [There is some evidence that there is more than one D-wave state in this E_x region: see reaction 3]. See also (1969DA1F, 1972AL1P). In the range E_d(cm) $= 7$ to 18 MeV differential cross sections show only a monotonic variation with energy. There is no evidence for any other resonances from $E_x = 23$ to 34 MeV (1972BA30, 1972KI02). See also (1970WI1G). Angular distributions have been measured at a number of energies from $E(^3\text{He}) = 18.7$ to 44.1 MeV (1972KI02). Polarization measurements are reported for $E_d = 4.0$ to 11.5 MeV (1972KO07), 4 to 12 MeV (1973BA2P), 4.78 to 11.88 MeV (1970HA1M, 1971HA02), 5.7, 7.1, 8.4 and 9.4 MeV (1973LO1D), 6, 8 and 10 MeV (1969PL01), 9.9 and 11.9 MeV (1970WA32) and 10 and 12 MeV (1971DO1C). Strong variations of the angular distributions for all components of the analyzing power are observed between $E_d = 4.0$ and 8.0 MeV: it is suggested that one or more positive parity states are involved ($18.8 < E_x < 21.2$ MeV). At higher energies potential scattering is the dominant mode (1972KO07). See also (1971BA1U, 1971ST1J) and (1966BA1J, 1966BA1M, 1967HE1B, 1970BR1L, 1970HE1D, 1971HA1L, 1972TA1E, 1973CH27, 1974CH02; theor.).

5. (a) ^{3}He(t, n)^{5}Li $\quad Q_m = 10.13$
   (b) ^{3}He(t, np)^{4}He $\quad Q_m = 12.0963$

For reaction (a) see (1966LA04) and (1971KL04). For reaction (b) see (1970GR17) and ^{6}Li.

6. (a) ^{3}He(^{3}He, p)^{5}Li $\quad Q_m = 10.89$
   (b) ^{3}He(^{3}He, 2p)^{4}He $\quad Q_m = 12.8601$
   (c) ^{3}He(^{3}He, 3p)^{3}H $\quad Q_m = -6.9546$

The spectrum of protons shows a pronounced peak corresponding to $^5\text{Li}_{\text{g.s.}}$ superposed on a continuum (1965BA1D, 1965BA1E, 1972DE46: $E(^3\text{He}) = 3$ to 18 MeV): the ^{5}Li breaks up with a strong angular asymmetry (1968BA1N). The α-spectra $E(^3\text{He}) = 6.9$, 7.9, 9.1 MeV) have been analyzed in terms of final state interactions including both p-p and p-α interactions (1972DE46). At $E(^3\text{He}) = 43.7$ and 53.0 MeV, the spectra show a prominent peak at the high energy end whose angular distributions exhibit a pronounced diffraction pattern (1967SL01, 1968MO10). See also (1965ZU02, 1966NE1A, 1966BL02, 1967MO1E, 1968BL06) and (1973LI1M; theor.). A search for a three-proton enhancement (reaction (c)) was unsuccessful at $E(^3\text{He}) = 44$ MeV (1968TO01) and 53 MeV (1968MO10). See also (1966LA04).

7. ^{4}He(p, p)^{4}He $\quad E_b = -1.97$

Table 5.7: Measurements of elastic scattering and polarization in ^{4}He(p, p)^{4}He [a]

Elastic scattering angular distribution		Polarization	
E_p (MeV)	Refs.	E_p (MeV)	Refs.
11.157, 12.040, 13.600, 14.230	(1973JA1M)	0.2 – 0.5	(1967AD1B)
12.0, 14.2, 17.5	(1969GA12)	0.9 – 3.2	(1967BR02, 1967BR03)
19.9 – 39.8	(1972BA24)	2.1 – 4.3	(1965BL02)
20.6, 23.3, 26.1, 27.7	(1968AL1B)	2.38 – 4.46	(1966DR01)
22.2 – 24.8	(1968DA04)	4.58, 5.95, 7.89, 9.89, 11.94	(1971SC04)
25.0 – 29.2	(1971PL07)	6.00, 7.89, 9.89, 11.16	(1967JA09)
39.8 – 47.7	(1973DA1M)	7.9, 9.9, 11.9	(1971OH04)
46	(1969BU10)	10	(1968PL02)
48.8	(1967DA08)	12.0	(1972KE17)
85	(1973VO1M)	12.0, 14.2, 17.5	(1969GA12)
100	(1970GO36)	14.5	(1965RO22)
141	(1972NI04)	17.5 – 27	(1966WE03)
144	(1972JA07)	20 – 45	(1972BA24)
587	(1968BO1K, 1972BO29)	22.2 – 24.8	(1968DA04)
1000	(1967PA25)	25.0 – 29.2	(1971PL07)
		48	(1966GR08)
		70, 80	(1969PE01)
		544	(1968GO1M, 1972BO29)

[a] See also Table 5.5 (1966LA04) for a summary of earlier work.

Differential cross sections and polarizations have been measured at many energies: see Table 5.5 in (1966LA04) and Table 5.7 here.

Phase shifts below $E_\mathrm{p} = 3.2$ MeV have been determined by (1967BR03) based on polarization measurements of (1967BR02) and available differential cross sections. The results are in essential agreement with earlier phase shifts of (1949CR1A) but are considerably more precise. In this range, the s-wave phase shift is that of a hard sphere with $R = 2.48$ fm; d-wave shifts are zero. The $P_{3/2}$ phase shift shows a pronounced resonance corresponding to $^5\mathrm{Li}_\mathrm{g.s.}$ while the $P_{1/2}$ shift changes slowly over a range of several MeV, suggesting that the first excited state is very broad and located 5–10 MeV above the ground state: see (1959AJ76, 1966LA04) for reviews of earlier results.

From $E_\mathrm{p} = 3$ to 18 MeV (1971SC04) have analyzed available polarization and differential cross section data to produce a set of phase shifts constrained to an analytic (effective range expansion) energy dependence. d- and f-wave phase shifts are positive and become of some importance above 8 MeV. A polarization contour plot is presented for $E_\mathrm{p} = 1$ to 18 MeV (1971SC04). See also (1968MO26, 1971AR20, 1973AR1N). An R-matrix (single level plus background) formalism is used by (1972ST01). For $P_{1/2}$ and $P_{3/2}$ the resonance energies are given by $E_\mathrm{R} = 8.10$ and 2.06 MeV and the reduced widths $\gamma^2 = 12.30$ and 8.02 MeV, respectively (1972ST01). See also (1973NI1B).

A resonance is observed at $E_\mathrm{p} = 23$ MeV, corresponding to the known $\frac{3}{2}^+$ state at $E_\mathrm{x} = 16.7$ MeV (1968AL1B, 1968DA04). An anomaly in the polarization is also observed at this energy (1966WE03, 1968DA04, 1972BA24). A further broad feature in the polarization excitation function ($\theta = 102°$) is observed at $E_\mathrm{p} = 30$ MeV ($E_\mathrm{x} = 22$ MeV) (1972BA24). Cross sections for $23 < E_\mathrm{p} < 45$ MeV show no further evidence of excited states (1969BU10).

An extensive phase shift analysis, using complex phases with $l \leq 4$ over a range $E_\mathrm{p} = 20$ to 40 MeV was made by (1972PL02), using mainly polarization and differential cross section data of (1972BA24). The $D_{3/2}$ level is fit with R-matrix formalism, including background interference, with the following parameters: $E_\mathrm{x} = 16.68$ MeV, $\gamma_\mathrm{p}^2 = 122$ keV, $\gamma_\mathrm{d}^2(l = 0) = 1.58$ MeV (negative sign), $\gamma_\mathrm{d}^2(l = 2) = 1.58$ MeV, $\theta_\mathrm{p}^2 = 0.014$, $\theta_\mathrm{d}^2 = 0.765$.

The $E_\mathrm{p} = 30$ MeV structure is not reflected in anomalous behavior of any single phase shift. Strong absorption of even partial waves may indicate broad overlapping positive-parity levels, $J^\pi = \frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+, \frac{7}{2}^+$ of d + ^{3}He character near $E_\mathrm{x} = 22$ MeV, but there is no umambiguous identification of excited states other than the $\frac{3}{2}^+$ state in the p-α results (1972PL02). In an alaysis of data of (1971PL07) for $E_\mathrm{p} = 25$ to 29 MeV, (1971RA27) report evidence for a $\frac{5}{2}^+$ level at $E_\mathrm{x} = 20$ MeV [$\Gamma_\mathrm{el}/\Gamma_\mathrm{total} = 0.15$, $\Gamma_\mathrm{tot} = 8$ MeV] and a $\frac{1}{2}^+$ level at $E_\mathrm{x} = 18 \pm 1$ MeV.

Other phase-shift analyses are reported by (1971AR20, 1973AR1N: 0 to 23 MeV), (1972ST01: 0.3 to 20 MeV), (1967BR02, 1967BR03: 0.9 to 3.2 MeV), (1966WE03: 14.3 to 31.0 MeV), (1967DA08: 29, 40, 48 MeV) and (1969PE01: 63, 70, 80 and 94 MeV). See also (1968PL02, 1973AR1P, 1973HO1U).

Elastic scattering at $E_\mathrm{p} = 587$ MeV (1972BO29) and at 1 GeV (1967PA25) reflect the mass distribution and multibody correlations within the α-particle.

Alpha-proton bremsstrahlung is observed at $E_\mathrm{p} = 7.0$ to 12.0 MeV (1971WO07, 1972WO1E), and at $E_\alpha = 20$ MeV (1967BO1B). See also (1972AN1P). Cross section measurements have also been carried out at $E_p = 23.4$ to 48.5 MeV (1973DA1N, 1973DA1P), 180 to 560 MeV (1972SC1M) and at 1 GeV (1967IG1A). For inelastic scattering to excited states of ^{4}He, see (1973FI04). For pion production, see (1972GU1D).

See also (1965JA1B, 1965KU13, 1966BL1B, 1967AU1A, 1967CA1E, 1968KO1F, 1968PA1J, 1969KO1M, 1970LI06, 1970RO1M, 1973CO1Y, 1973EK1A), (1966BA1K, 1966HA1F, 1966RO1B, 1970BO1P, 1971HA2G, 1971ST1J) and (1965HO1A, 1965HO1B, 1966RA1B, 1966TO04, 1967BA1F, 1967BA1G, 1967CZ1A, 1967SA1C, 1967TA1B, 1968BA1K, 1968CH35, 1968FR1F, 1968GL1A, 1968SA1B, 1968SC1D, 1968SE1A, 1968TA1E, 1968BA1U, 1969CO1E, 1969CR1A, 1969GE1A, 1969HE15, 1969LE03, 1968TH1C, 1970BA1F, 1970HE1D, 1970KU1C, 1970RE1A, 1970SA01, 1970TH1D, 1971BA1Y, 1971BA61, 1971BA74, 1971FE10, 1971HA1L, 1971IK01, 1971KR1A, 1971LO24, 1971MU1H, 1971PI04, 1971PL06, 1971RA15, 1971TH09, 1972BB19, 1972GR06, 1972IK01, 1972TH06, 1973AD01, 1973CL01, 1973FE1H, 1973LA14, 1973LY02, 1973PL02, 1973SA09, 1973UL1C, 1973YO1F, 1974CH02; theor.).

8. (a) ^{4}He(p, d)^{3}He	$Q_m = -18.3538$	$E_b = -1.97$
(b) ^{4}He(p, pn)^{3}He	$Q_m = -20.5785$	
(c) ^{4}He(p, 2p)^{3}H	$Q_m = -19.8147$	

Angular distributions of ^{3}He ions (reaction (a)) have been measured at $E_p = 27.9$ MeV (1957WI22), 31 MeV (1953BE14, 1964BU1B), 46.8 MeV (1969RO1L, 1969RO24), 49.5 MeV (1969HA16, 1970HA36), 53 MeV (1964CA1B), 55 MeV (1964HA13, 1964HA1P, 1964HA49), 94 MeV (1958SE74) and 155.4 MeV (1967BE35, 1970BE49). See also (1973VO1M). The excitation function shows no indication of resonances for $E_p = 38.5$ to 44.6 MeV (1969BU10). Polarization measurements have been carried out at $E_p = 32$, 40, 50 and 52.5 MeV (1973SA1W) and 55 and 63 MeV (1966BO1A). At $E_p = 141$ MeV the total reaction cross section (not including elastic scattering) is 79.5 ± 2.0 mb (1972NI04).

Reactions (b) and (c) have been studied at $E_p = 46.8$ MeV (1969RO1L,1969RO24, 1970RO17, 1970SA01), 49.5 MeV (1969HA16, 1970HA36) and 156 MeV (1967BE35, 1970BE49). See also (1973KI1L, 1973RO1Z). Angular distributions have been measured in the region of the final state interactions. The t and ^{3}He spectra show peaks due to sequential reaction processes via continuum resonance states in ^{4}He: see (1973FI04). See also (1967AU1A, 1968PA1J) and (1969DO1G, 1969NA1F, 1973HA46, 1973JU02; theor.). For ^{4}He(p, $2N + \chi\pi$) see (1965KU1C).

9. (a) ^{4}He(d, n)^{5}Li	$Q_m = -4.19$
(b) ^{4}He(d, np)^{4}He	$Q_m = -2.22464$

Reaction (b) has been studied at $E_d = 14.2$ MeV (1967FU1D), $E_\alpha = 29.2$ MeV (1968TA11), 38.8 MeV (1971LE02), 42 MeV (1967WA08, 1968WA01) and at $E_\alpha = 18.0$ and 24.0 MeV

(1970AS02). See also (1971CH1T). The data indicate that at 42 MeV, direct breakup, with quasi-free α-p scattering taking place and the n acting as a spectator, is at least as important a mechanism as the final state interaction in the ^{5}Li ground state (1967WA08, 1968WA01): see ^{5}He. See also (1967NA1D, 1969NA09, 1972NA1D; theor.) and (1966LA04) for the earlier references.

10. ^{4}He(^{3}He, np)^{5}Li $\quad Q_m = -9.68$

See (1973HA50).

11. ^{6}Li(γ, n)^{5}Li $\quad Q_m = -5.66$

See ^{6}Li and (1965BA16).

12. (a) ^{6}Li(p, d)^{5}Li $\quad Q_m = -3.44$
(b) ^{6}Li(p, pd)^{4}He $\quad Q_m = -1.4737$

Deuteron groups are observed to ^{5}Li*(0, 16.7). Angular distributions have been measured at $E_p = 18.6$ MeV (1955LI09; d_0), 33.6 MeV (1967KU10, 1970KU1D; d_0, d_2), 100 MeV (1969LI02; d_0) and 156 MeV (1968BE72, 1969BA05, 1969TO1A; d_0, d_2). See (1969TO1A) for spectroscopic factors. In addition, the excitation of a state with $E_x = 3.72 \pm 0.10$, $\Gamma = 6.3 \pm 0.5$ MeV is reported by (1966SE1C). [See, however, (1967KU10, 1970KU1D)]. (1969BA05) confirm the population of the first excited state. See also (1966SE1C, 1972AZ03) and (1968JA1D; theor.).

At $E_p = 9$ and 10 MeV (1968VA02) and at $E_p = 45$ MeV (1971BR12), the p-α final state interaction corresponding to ^{5}Li(0) is observed.

13. (a) ^{6}Li(d, t)^{5}Li $\quad Q_m = 0.59$
(b) ^{6}Li(d, pt)^{4}He $\quad Q_m = 2.5592$

Angular distributions of the tritons to the ground state of ^{5}Li have been measured at $E_d = 15$ and 20 MeV (1959VL24, 1960HA14). See also (1971IN1C). For reaction (b) see (1968LE15).

14. (a) ^{6}Li(^{3}He, α)^{5}Li $\quad Q_m = 14.91$
(b) ^{6}Li(^{3}He, pα)^{4}He $\quad Q_m = 16.880$

At $E(^3\text{He}) = 25.5$ MeV, the spectra show ^{5}Li*(0, 16.7) and two broad peaks at $E_x \approx 19.8$ and 22.7 MeV with $\Gamma_{cm} = 2$ and 1 MeV, respectively (1972BA30).

Cylindrical asymmetry observed in the breakup of ^{5}Li(0) is attributed to the short lifetime of the ^{5}Li imtermediate state and to the memory retained by the proton of its localization at the time of formation of ^{5}Li (1967RE03, 1968RE10). The first excited state of ^{5}Li also appears to be involved (1972TH08, 1972TH1B). See also (1964MA57, 1966LO10, 1967HO1C, 1968VI03, 1969VI05, 1970GA1G), (1966LA04), (1970DE41, 1972TH04; theor.) and ^{8}Be.

15. (a) ^{7}Li(p, t)^{5}Li $\qquad Q_m = -4.43$

(b) ^{7}Li(p, pα)^{3}H $\qquad Q_m = -2.467$

At $E_p = 43.7$ MeV, a triton group is observed to ^{5}Li(0) ($\Gamma = 1.55 \pm 0.15$ MeV): the angular distribution is consistent with a substantial mixing of $L = 0$ and 2 transfer. There is some evidence for a very broad excited state between $E_x = 2$ and 5 MeV. ^{5}Li*(16.7, 20.0) were not observed. The formation of ^{5}Li*(16.7) ($^4S_{3/2}$) would be S-forbidden: the absence of ^{5}Li*(20.0) would indicate that this state(s) is also of quartet character [see reaction 19 in ^{5}He] (1966CE05). See also (1966BA1L, 1967PO1C). Weak, broad states at $E_x = 22.0 \pm 0.5$ MeV and 25.0 ± 0.5 MeV and possibly 34 MeV are reported by (1968MC02) in a coincidence experiment in which 3- and 4-particle breakup was analyzed. The t_0 angular distribution has also been studied at $E_p = 16.6$ MeV (1965OG03) and 30.3 MeV (1969DE04).

For reaction (b) see (1967JO1C).

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

At $E(^3\text{He}) = 2.45$ and 6.00 MeV the reaction proceeds in part via the first two states of ^{5}Li (1966WA16).

17. ^{12}C(p, 2α)^{5}Li $\qquad Q_m = -9.24$

Not observed: see (1972MA62).

^{5}Be

(Fig. 3)

The absence of any group structure in the neutron spectrum in the reaction ^{3}He(^{3}He, n)^{5}Be at $E(^3\text{He}) = 18.0$ to 26.0 MeV indicates that ^{5}Be(0) is at least 4.2 MeV unstable with respect to ^{3}He + 2p [$(M - A) > 33.7$ MeV]. With Coulomb corrections adjusted to match the 16.7 MeV states of ^{5}He–^{5}Li, this observation places the first $T = \frac{3}{2}$ level in these nuclei above $E_x = 21.4$ MeV (1967AD05). [With the "conventional" correction (1966LA04, p.2) $E_x > 20.3$ MeV].

See also (1968CE1A, 1970WA1G).

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(Closed December 31, 1973)

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