Energy Levels of Light Nuclei
$A = 5$

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Abstract: An evaluation of $A = 5$–10 was published in *Nuclear Physics A*320 (1979), 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.

(References closed in 1978)

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Table of Contents for $A = 5$

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^{5}n

(Not illustrated)

^{5}n has not been observed: see (1972AG01) and (1977DE08).

^{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 5H 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). 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). A recent study of the ^{7}Li(^{6}Li, ^{8}B)^{5}H reaction at $E(^{6}{\rm Li}) = 93.3$ MeV shows no evidence for the formation of a narrow ^{5}H ground state: at $\theta_{\rm lab} = 14.7°$ the yield near the predicted location of the ^{5}H$_{\rm g.s.}$, above the phase-space curve, is ≈ 100 nb/sr. MeV compared to an order of magnitude greater yield for the final state interaction in ^{4}H (1977WE03, 1977WE1B). Attempts to observe ^{5}H formation in ^{7}Li + π^{-} have also been unsuccessful: see (1974AJ01). See also (1975BE31; theor.).

^{5}He

(Figs. 1 and 3)

GENERAL: (See also (1974AJ01).)

Model calculations: (1974JA30, 1974LE22, 1975DI04).

Special states: (1974GO13, 1974IR04, 1974JA30, 1974LE22, 1975DI04, 1976IR1B).

Special reactions: (1973FE1A, 1974FE1A, 1975FE1A, 1976VA29, 1978ME1C).

Reactions involving pions: (1973BA30, 1978FI1E).

Other topics: (1974GO13, 1974IR04, 1976BI1A, 1976IR1B, 1977SH1B, 1978GO1D).

Ground state of ^{5}He: (1975BE31, 1977HI09).

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

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 [a]	n, α	1, 4, 6, 8, 9, 10, 11, 12, 13, 14, 15, 18, 19, 20, 21, 22, 23, 26, 27, 29, 30
4 ± 1	$\frac{1}{2}^-; \frac{1}{2}$	4 ± 1	n, α	4, 6, 10, 18, 22
16.76 ± 0.13	$\frac{3}{2}^+; \frac{1}{2}$	0.10 ± 0.05	γ, n, d, t, α	1, 2, 5, 6, 8, 9, 11, 13, 14, 15, 21, 22
19.8 ± 0.4 [b]	$(\frac{3}{2}, \frac{5}{2})^+; \frac{1}{2}$	2.5 ± 0.5	n, d, t, α	2, 3, 5, 8, 9, 10, 13, 14, 15, 19, 21, 22
$24 - 25$ [b]		broad		21, 22

[a] See Table 5.2 in (1966LA04) and reactions 6 and 20 here.

[b] See (1974AJ01), pp. $7 - 8$.

$(2.1 \pm 0.6) \times 10^{-4}$, leading to $\Gamma_\gamma = 14 \pm 4$ eV, where Γ_n is taken as 66 keV. (1963BU07) have measured thick target yields from $E_d = 150$ 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 μb [versus 1 mb reported by (1970BE1A)]. At $E_d = 1025 \pm 47$ keV, the differential cross section is 0.44 ± 0.12 μb/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 μb (1970KO09). The cross section for γ_0 has been measured (at $90°$) for $E_d = 2.0$ to 12.0 MeV and angular distributions were obtained at $E_d = 4$, 8, 10 and 12 MeV for γ_0 (1975BA1E; and C.A. Barnes, private communication). See also (1974AJ01).

2. (a) ^{3}H(d, n)^{4}He $\quad Q_m = 17.5894 \quad E_b = 16.70$

(b) ^{3}H(d, 2n)^{3}He $\quad Q_m = -2.9884$

(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, $\sigma = (A/E)\exp(-44.40E^{-1/2})$ (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 (1974AJ01) for earlier references and (1976DR1A, 1976DR1B; preliminary work; angular distributions at $E_d = 7.00$ and 10.00 MeV, 13.36 and 16.50 MeV (partial) and at

Table 5.2: Resonance parameters for the $\frac{3}{2}^+$ states observed in ^{3}H(d, n)^{4}He and ^{3}He(d, p)^{4}He [a]

E_r (keV)	Γ_{lab} (keV)	l_d	J^π	l_{np}	R (fm)	E_λ (keV)	γ^2_d (keV)	γ^2_{np} (keV)	θ^2_d [d]	θ^2_{np} [d]	E_x (MeV)
107 [b]	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 [c]	≈ 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] See also (1974KR07, 1976AH1A, 1977BO24, 1977DO01).

[b] ^{3}H(d, n)^{4}He.

[c] ^{3}He(d, p)^{4}He.

[d] Units of $3\hbar^2/2MR^2$.

$E_t = 10.48$ and 14.98 MeV; 0° excitation function for $E_d = 7$ to 16.5 MeV), (1975MA28; angular distributions at $E_d = 8$ to 16 MeV, in 1 MeV steps; 0° excitation function for same interval) and (1977JA07; dσ/dΩ at $E_t = 20.00$ MeV; very accurate).

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). 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 c.m. energies shows excellent agreement between the polarization values in the two reactions up to $E_d = 6$ MeV, but then the proton polarization becomes $\approx 15\%$ 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). For earlier polarization measurements see Table 5.3 in (1974AJ01). Polarization studies are also reported by (1976SU06; $E_d = 7$ MeV), (1976LI15; $E_d = 3.5$ to 12.8 MeV), (1976OH02; $E_{\vec{t}} = 5.37$ to 10.50 MeV) and (1975SA1A; preliminary; $E_d = 38$ MeV; looked at pol. of 50 MeV neutrons). See also (1977DR1B). The $K_y^{y'}(0°)$ determined for $E_{\vec{t}} = 5.37$ to 10.50 MeV show a minimum at $E_{\vec{t}} = 9.6$ MeV (1976OH02). See also (1978CA13; $E_d = 0.7$ MeV).

Reaction (b) has been studied for $E_d = 10.9$ to 83 MeV: see (1974AJ01). A discussion and comparison of attempts to measure $^1S_0$ nn scattering length is presented by (1971GR45; $E_d = 13.4$ MeV): based on kinematically complete measurements and using the Watson-Migdal treatment, they find $a_{nn} = -16.0 \pm 1.0$ fm. Intervention of n–^{3}He final state interactions is believed to be small in this work (1971GR45). At $E_t = 22$ MeV no clear evidence is seen for sequential processes via excited states of ^{4}He (1971GR12).

A reanalysis of the work of (1963PO02) on reaction (c) by (1974SC04) leads to the suggestion of a resonance at $E_{c.m.} = 2.9 \pm 0.3$ MeV [$E_x = 19.6$ MeV], $\Gamma_{c.m.} = 1.9 \pm 0.2$ MeV, consistent with $J^\pi = \frac{3}{2}^-$ [see, however, Table 5.1]. n-p final-state interaction enhancement has been studied by (1973SL03) at $E_d = 35$ MeV. They find that only when $E_{np} \leq 1$ MeV is in agreement with the Watson-Migdal theory obtained, even if data far from dominant n-t final-state interaction and p-t quasi-free scattering are chosen. See also (1974AL01).

See also (1974AD11), (1974GE1B, 1974WI1D, 1975CR1A, 1975ST1A, 1975ST1B, 1976BL1A, 1976BR1B, 1976JA1C, 1976MO1A, 1977BE1H, 1977KI1C, 1977MC1C; applied topics), (1973LI1B, 1975KU1C, 1975SE07, 1975SO1C, 1976HA1C, 1976SE1B, 1976WA1C, 1977SE09; reviews), (1975FO19; astrophysics) and (1974KE1B, 1974ST14, 1975DO1B; theor.).

3. ^{3}H(d, d)^{3}H $\quad E_b = 16.70$

The elastic scattering has been studied for $E_d = 2.6$ to 11.0 MeV. The excitation curves show an interference at $E_x \approx 19$ MeV and a broad ($\Gamma > 1$ MeV) resonance corresponding to $E_x = 20.0 \pm 0.5$ MeV, similar to that seen in ^{3}He(d, d) [see ^{5}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 $E_{\vec{d}} = 3.2$ to 12.3 MeV show resonance-like behavior in the vector analyzing power near $E_d = 5$ 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 $E_x \approx 19.6$ 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). Tensor analyzing powers have been measured for $E_d = 5.0$ to 11.5 MeV (1973DE51), at $E_{\vec{t}} = 10.5$ MeV (1976OH02) and at $E_{\vec{d}} = 11.4$ and 14.4 MeV (1974DO05; angular distributions of tensor and vector polarizations). See also (1974ST14, 1975AB1C, 1975DO1B, 1976BA1E; theor.).

4. (a) ^{3}H(t, n)^{5}He $\quad Q_m = 10.44$
(b) ^{3}H(t, 2n)^{4}He $\quad Q_m = 11.3321$

At $E_t = 0.5$ 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 $E_x \approx 2$ MeV, $\Gamma \approx 2.4$ MeV (1965WO03). For reaction (b), see ^{6}He and (1974LA02).

5. (a) ^{3}He(t, p)^{5}He $\quad Q_m = 11.20$
   (b) ^{3}He(t, pn)^{4}He $\quad Q_m = 12.0959$

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 and (1975SC28, 1977JO1A).

6. ^{4}He(n, n)^{4}He $\quad E_b = -0.89$

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 $\bar{\sigma}_s$. Total cross sections for $E_n = 4 \times 10^{-4}$ eV to 150.9 MeV and at 10 GeV/c are summarized in (1974AJ01, 1976GAYV). Angular distribution measurements are summarized in (1970GA1A, 1974AJ01). Polarization studies are displayed in Table 5.4 of (1974AJ01): recent work includes that of (1976BO05: $E_n = 1.5$ to 6.0 MeV; used an absolutely calibrated source of polarized neutrons), (1976LI15: $E_n = 20$ to 30 MeV; $A_y(\theta)$ is the same for ^{4}He + n and ^{4}He + p) and (1978YO1A: $E_{\bar{n}} = 50$ MeV). See also (1974TO03).

The total cross section has a peak of 7.6 b (1973GO38) 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 $J^\pi = \frac{3}{2}^+$ 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 $E_{res} = 17.669$ MeV $\pm$ 10 keV, $\gamma_d^2 = 2.0$ MeV $\pm$ 25%, $\gamma_n^2 = 50$ keV $\pm$ 25% (see Table 5.2). The polarization has been calculated from the phase shifts and is presented as a contour plot (1966HO07). The work of (1976LI15) indicates some discrepancies with the results of (1966HO07) [below $E_n = 22$ MeV] and with the measurements of (1972BR10).

A recent R-function analysis of the ^{4}He+n data below 21 MeV (including the absolute neutron analyzing power measurement of (1976BO05) and the accurate cross section measurements of (1973GO38)) has led to a set of phase shifts and analyzing powers which are based on the ^{4}He + n data alone (rather than also including the ^{4}He + p data). At $r = 3.3$ fm the values obtained for the $P_{1/2}$ and $P_{3/2}$ resonances are, respectively, $E_{\rm c.m.} = 1.97$ and 0.77 MeV, $\Gamma_{\rm c.m.} = 5.22$ and 0.64 MeV (1977BO24). See also (1974KR07). For earlier analyses, see (1974AJ01).

See also (1974MA1C, 1977YO1B), (1975FI1B, 1976OH1B, 1976WA1B, 1976WA1C) and (1974BA34, 1974DO10, 1974GH01, 1974JA1F, 1974ST14, 1975BA76, 1975CA05, 1975LO1A, 1975TH12, 1976AH1A, 1976AL1E, 1976CH1B, 1976SP1A, 1977BA1N, 1977BE50, 1977CH1C, 1977LA1C, 1977LE1D, 1977PH01, 1977ST1D, 1977TH09, 1978AH01, 1978FO1G, 1978FR02, 1978KO13, 1978LE1H, 1978MA37; theor.).

7. ^{4}He(n, d)^{3}H $\quad Q_{\rm m} = -17.5894 \quad E_{\rm b} = -0.89$

See (1976BR1B), (1974AJ01) and (1976BA1E; theor.).

8. (a) ^{4}He(d, p)^{5}He $\quad Q_{\rm m} = -3.12$
(b) ^{4}He(d, pn)^{4}He $\quad Q_{\rm m} = -2.2246$

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 asymmetry 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).

Reaction (b) has been studied for $E = 9$ to 165 MeV: see (1974AJ01) and $E_{\rm d} = 6.8$ and 7.8 MeV (1978KA11), 8.9 MeV (1977SA21), at $E_{\vec{\rm d}} = 15$ MeV (1978NA08), $E_\alpha = 21.9$ and 23.7 MeV (1974RA10), 22.5 MeV (1977PR06), 27.2 MeV (1974GR40) and 165 MeV (1974HO11). See also ^{6}Li.

At $E_{\rm d} = 8.9$ MeV, the FSI (final state interaction) is very important (1977SA21). In the kinematically complete experiment of (1977PR06) at $E_\alpha = 22.5$ MeV, the results are in quite good agreement with the predictions of the sequential decay model: the slight deviations are assumed to be due to the omission of Coulomb interaction effects and to the restriction to partial waves with $l \leq 2$. At $E_\alpha = 70$ MeV, a kinematically complete experiment shows evidence for sequential decay, 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). The fine structure near 19 MeV is not confirmed in other experiments [see, however, reaction 12].

See also (1974HE21, 1974NA10, 1975HE09, 1976KO21, 1976LI1E, 1977BR25, 1978FI1E, 1978KO13), ^{5}Li and ^{6}Li.

9. ^{4}He(t, nd)^{4}He $\quad Q_{\rm m} = -0.4105$

At $E_\alpha = 70$ MeV, there is indication of the population of ^{5}He*(0, 16.7) and of a structure with $E_{\rm x} = 18 - 20$ MeV (1974LA1A, 1975AL1A; preliminary results).

10. ^{6}Li(γ, p)^{5}He $\quad Q_{\rm m} = -4.59$

At $E_\gamma = 60$ MeV, the proton spectrum shows two prominent peaks attributed to ^{5}He*($0 + 4.0$, 20 ± 2) (1973GA16, 1976MA34). See also (1973DE17), (1975MA1E) and ^{6}Li.

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

At $E_{\rm p} = 1180$ MeV, the exciation of ^{5}He*(0, 16.7) is reported: the latter state is formed with the ejection of an s-proton (1972AN24, 1972AN27, 1972AN29). See also (1975ME27; theor.).

12. (a) ^{6}Li(n, d)^{5}He $\quad Q_{\rm m} = -2.37$
(b) ^{6}Li(n, nd)^{4}He $\quad Q_{\rm m} = -1.4735$

Angular distributions of ground state deuterons have been studied at $E_{\rm n} = 6.57$ and 6.77 MeV (1977RO01), 14.4 MeV (1965VA05) and 56.3 MeV (1977BR17). In the latter experiment, angular distributions have also been obtained to ^{5}He*(16.7, 18.5 ± 0.5, 20.5 ± 0.5). The observation of the two highest states is not certain: if they exist their widths are less than the instrumental width, 1.6 MeV (1977BR17). For reactrion (b) see (1967VA12). See also (1974AJ01).

13. ^{6}Li(p, dπ^+)^{5}He $\quad Q_{\rm m} = -142.72$

See (1976HU1A).

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

At $E_{\rm p} = 100$ MeV the population of ^{5}He*(0, 16.7) and possibly of a broad structure at $E_{\rm x} \approx 19$ MeV is observed: momentum distributions for ^{5}He*(0, 16.7) and angular correlation measurements are also reported. The main features of the data are reasonably well described by DWIA (1974BH03). For the earlier work see (1974AJ01). See also (1975VO04, 1977RO1E) and (1974GH03, 1974PR10, 1975CH1C, 1976OH04; theor.).

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

At $E_d = 14.5$ MeV, ^{5}He$_{g.s.}$ is populated (1955LE24). At $E_d = 80$ MeV, the population of ^{5}He*(16.7) as well as a broad state near $E_x = 19$ MeV is reported (1975DI1A, 1975DI1B; abstracts). For reaction (b) see (1974AJ01).

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

See (1974AJ01).

17. (a) ^{6}Li(α, ^{5}Li)^{4}He + n $\quad Q_m = -5.66$
(b) ^{6}Li(α, αp)^{5}He $\quad Q_m = -4.59$

See (1975GR42) for reaction (a) and (1978CA1E) for reaction (b).

18. ^{7}Li(γ, d)^{5}He $\quad Q_m = -9.62$

See (1975DE37) in ^{7}Li.

19. (a) ^{7}Li(π^+, 2p)^{5}He $\quad Q_m = 128.51$
(b) ^{7}Li(π^-, 2n)^{5}He $\quad Q_m = 126.94$

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). For reaction (b) see (1977BA1M).

20. (a) ^{7}Li(n, t)^{5}He $\quad Q_m = -3.36$
(b) ^{7}Li(n, tn)^{4}He $\quad Q_m = -2.467$

The angular distribution of the t$_0$ group has been measured at $E_t = 14.4$ MeV: it is fairly well reproduced by DWBA (1970MI05). Reaction (b) at $E_n = 14.4$ MeV proceeds as a sequential process primarily involving ^{7}Li*(4.63) and ^{5}He$_{g.s.}$ (1974AN02). See also (1974TU1A) and (1974AJ01) for the earlier work.

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

(b) ^{7}Li(p, pd)^{5}He $\qquad Q_m = -9.618$

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 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). In reaction (b) at $E_p = 100$ MeV ^{5}He*(0, 19.9) are strongly populated while ^{5}He*(16.7) is very weak. Positive parity is suggested for ^{5}He*(19.9) (1975CH1B; preliminary).

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

(b) ^{7}Li(d, n)^{4}He^{4}He $\qquad Q_m = 15.123$

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). The width of the ground state of ^{5}He is 615 ± 30 keV (1973GA28). Angular distributions are reported for $E_d = 0.6$ to 1.25 MeV.

Spectra measured in reaction (b) suggest the involvement of the $P_{1/2}$ state: the values suggested are inconsistent with each other because of the difficulty of evaluating the contribution of other reactions: see (1974AJ01) for the earlier values and see (1976FO21) for a discussion of some of the problems involved in these. (1976FO21) suggest a width for ^{5}He$_{\text{g.s.}} = 0.6$ MeV and $E_x = 4.1 \pm 0.2$, $\Gamma_{\text{c.m.}} = 4.4 \pm 0.2$ MeV for the $P_{1/2}$ state. Reaction (b) proceeds mainly via excited states of ^{8}Be and ^{5}He$_{\text{g.s.}}$: see, e.g., (1967VA11). See also (1973HU12, 1974DA28, 1974GR44, 1978AR10, 1978SP03). Attempts to observe n-α rescattering effects following formation of ^{8}Be*(16.63, 16.91) have been unsuccessful: an upper limit of 1% of the yield from sequential decay is given by (1968VA12). See (1974AJ01) for more complete references to the older work. See also ^{8}Be and ^{9}Be.

23. ^{7}Li(^{3}He, d^{3}He)^{5}He $\qquad Q_m = -9.62$

See (1976WA12).

24. ^{7}Li(α, ^{6}Li)^{4}He + n $\qquad Q_m = -7.251$

See (1975GR42).

25. ^{9}Be(γ, α)^{5}He $\quad Q_m = -2.47$

See ^{9}Be.

26. ^{9}Be(p, pα)^{5}He $\quad Q_m = -2.47$

Studies of this reaction have been carried out at $E_p = 26.0$ to 57 MeV [see (1974AJ01)] and at $E_p = 100$ MeV (1977RO02). In the latter experiment good agreement is found with DWIA calculations: the average value of $S_\alpha = 0.45 \pm 0.02$ (1977RO02). See also ^{9}Be.

27. ^{9}Be(t, ^{7}Li)^{5}He $\quad Q_m = 0.096$

See (1976VO1A).

28. ^{9}Be(^{3}He, α^{3}He)^{5}He $\quad Q_m = -2.47$

See ^{9}Be.

29. (a) ^{9}Be(α, 2α)^{5}He $\quad Q_m = -2.47$
(b) ^{9}Be(α, ^{8}Be)^{5}He $\quad Q_m = -2.56$

Reaction (a) has been studied at $E_\alpha = 28$ to 37.4 MeV: see (1974AJ01). See also (1974GR42, 1977BR1E). Reaction (b) has been studied at $E_\alpha = 65$ MeV: only the ground state of ^{5}He is observed for $E_x \lesssim 25$ MeV; $S_\alpha = 0.53$ (1976WO11).

30. ^{11}B(d, n)^{4}He^{4}He^{4}He $\quad Q_m = 6.4575$

At $E_d = 3.75$ MeV (1978GR07), 10.4 and 12.0 MeV (1971RE19), this reaction involves ^{5}He$_{g.s.}$ and states in ^{8}Be and ^{9}Be (1971RE19, 1978GR07) and ^{12}C (1978GR07).

31. ^{12}C(n, n)^{4}He^{4}He^{4}He $\quad Q_m = -7.2748$

See ^{12}C in (1975AJ02).

^{5}Li

(Figs. 2 and 3)

GENERAL: (See also (1974AJ01).)

Model calculations: (1975KR1A).

Special states: (1974GO13, 1974IR04, 1976IR1B).

Astrophysical questions: (1974RA1C, 1978ME1C).

Special reactions: (1975BR1A, 1976VA29, 1978ME1C).

Reactions involving pions: (1973AR1B, 1974AM01).

Applied topics: (1975HU1A).

Other topics: (1974GO13, 1974IR04, 1976IR1B, 1978GO1D).

Ground state of ^{5}Li: (1975BE31).

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 5 MeV and $E(^3\text{He}) = 2$ to 26 MeV: see (1974AJ01).

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). 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 (±50%), suggesting E1 (if only one state is involved).

2. ^{3}He(d, n)^{4}Li $\qquad E_b = 16.39$

Table 5.3: 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, 13, 14, 15, 16, 17
$5 - 10$	$\frac{1}{2}^-; \frac{1}{2}$	5 ± 2	p, α	1, 5, 7, 13, 15, 16, 17
16.66 ± 0.07	$\frac{3}{2}^+; \frac{1}{2}$	≈ 0.3	γ, p, d, ^{3}He, α	1, 3, 4, 7, 13, 15
(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, 5, 7, 13, 15

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

This reaction has not been observed: see (1966LA04) and (1974POZN; abstract). See also (1978MC1C).

3. (a) ^{3}He(d, p)^{4}He $\quad Q_m = 18.3532 \quad E_b = 16.39$
   (b) ^{3}He(d, np)^{3}He $\quad Q_m = -2.2246$
   (c) ^{3}He(d, 2p)^{3}H $\quad Q_m = -1.4608$
   (d) ^{3}He(d, 2d)^{1}H $\quad Q_m = -5.4936$

Below 100 keV the cross section follows the simple Gamow form: $\sigma = (18.2 \times 10^3/E)\exp(-91E^{-1/2})$ 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. Excitation functions for ground state protons have also been reported for $E(^3\text{He}) = 0.39$ to 1.46 MeV and 18.7 to 44.1 MeV and for $E_d = 2.8$ to 17.8 MeV: see (1974AJ01). Angular distributions have been measured for $E_d = 0.25$ to 27 MeV and $E(^3\text{He}) = 18.7$ to 44.1 MeV [see Table 5.6 in (1974AJ01)]. At $E_d = 10.02$ MeV differential cross sections have been measured at four angles to better than 3% (1974JA15). Polarization measurements have been carried out at many energies: see Table 5.6 in (1974AJ01) and Table 5.4 here.

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). Contour maps, T_{ab} versus θ, E_d, for the vector and tensor analyzing powers are presented for $E_d = 0$ to 12 MeV by (1971GR47). Energy dependence of the angular distributions indicate resonance-like bevavior at $E_x = 16.6$, 17.5, 20.0, 20.9 and 22.4 MeV in ^{5}Li (1971GR47). At $E_d \approx 6$ MeV (1971KL02) find the angular distribution more complex than

Table 5.4: Polarization measurements in ^{3}He(d, p)^{4}He [a]

$E_{\vec{d}}$ (MeV)	Refs.
0.344, 0.465, 0.727	(1974GA21)
$0.34 - 11.60$	(1976SC15)
0.75, 1.5 [b]	(1976BR1C) [c]
$1 - 6$	(1976DR1C, 1977DR1B) [c]
6.44 [d]	(1977ST06)
$6.6 - 15.8$	(1974TR02)
$8.5 - 10.5$ [e]	(1976GR10)
12 [b,f]	(1974BE67)
15 [g]	(1976ME13)
$15 - 40$	(1975RO1C, 1976RO1G) [c]
27 [h]	(1976OK1A) [c]
30, 35, 40 [i]	(1976RO1H) [c]

[a] See Table 5.6 in (1974AJ01) for a listing of the earlier work.

[b] $E_{\rm d}$.

[c] Preliminary results.

[d] Measurement to better than 1% of iT_{11}.

[e] Maximum value of the tensor analyzing power ($A_{\rm yy}$) at 9.28 MeV is nearly 1.

[f] $^3\vec{\rm He}$ target.

[g] Reactions 3(b) and 3(c).

[h] $E(^3\vec{\rm He})$.

[i] Reaction 3(b).

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(c.m.) = 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).

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

Elastic scattering angular distribution and cross sections		Polarization	
E_p (MeV)	Refs.	$E_{\vec{p}}$ (MeV)	Refs.
$0.5 - 3.0$	(1974KR07)	3.6, 6.35, 12.2	(1974LI1C, 1976LI1G)
11.16, 12.04, 13.60, 14.23	(1977DO01)	$3.74 - 8.94$	(1976BR17)
85.0	(1974VO05)	6.36	(1977ME06)
156	(1975CO1B)	11.93, 17.00	(1977HA06)
$185 - 500$	(1978MC06)	45.04, 52.34	(1977SA1E)
200, 350, 500	(1977ST30)	$185 - 500$	(1978MC06)
350, 650, 1050, 1150	(1977AS01)	560, 800, 1030,	(1977KL03)
438, 648, 1036	(1976BE45)	1270, 1730	
[$E_\alpha = 4.00, 5.08, 6.09$ GeV/c]			
560, 800, 1030, 1270, 1730	(1977KL08)		
580, 720	(1975VE09)		
600	(1976FA09)		
788	(1978FO33)		
1000	(1977AL1E)		
1050	(1974BA14, 1978BE30)		
$E_\alpha = 7.0$ GeV/c	(1977GE01)		
[$E_p = 1050$]			
2680	(1975IG1B, 1977IG1A, 1977IG1B, 1977IG1C)		
4.89 GeV	(1978NA1H)		
$50 - 500$ GeV/c	(1978SM1C)		

[a] See also Tables 5.5 in (1966LA04) and 5.7 in (1974AJ01) for a listing of the earlier work.

Reactions (b), (c) and (d) have been studied at $E_d = 22.3$ and 35 MeV and at $E({}^3\text{He}) = 30$, 33.5 and 52.5 MeV by (1977SL04) and analyzed with a PWIA: Fourier transforms of the wave functions were obtained. At $E({}^3\text{He}) = 35.9$ MeV, the spectra in reactions (b) and (c) are dominated by the nucleon-nucleon FSI: the results were fitted with a fully antisymmetrized PWBA and with DWBA (1974WA06, 1975WA31). At $E_{\vec{d}} = 15$ MeV (1976ME13) have measured the vector and the two tensor analyzing powers for reactions (b) and (c). (1974SC04, 1976SC26) have studied the excitation function for reaction (c) for $E_d = 2.2$ to 6 MeV in a kinematically complete experiment. They have extracted the p + t FSI going via ^{4}He*(20.1) [$J^\pi = 0^+$] and suggest that the reaction goes primarily via a $J^\pi = \frac{3}{2}^-$, $T = \frac{1}{2}$ state of ^{5}Li located 0.8 ± 0.2 MeV above threshold [i.e.,

$E_x = 18.9 \pm 0.2$ MeV]. This suggests that the attraction of a $p_{3/2}$ nucleon to ^{4}He*(0^+) is stronger than is the attraction of such a nucleon to ^{4}He$_{\text{g.s.}}$ (1976SC26). See also (1975RU04) for reaction (c). See (1974AJ01) for the earlier work.

See also (1974TA1A, 1975GL08, 1976GO1B), (1974LA1C, 1974PR1B, 1975HE1C, 1975HU1A; applied topics), (1975SE07, 1975SE1D, 1975SE1E, 1976SE03, 1976SE1B, 1976SE1C, 1977SE09, 1977SE1C, 1978FI1E, 1978SL1B; reviews) and (1974AL01, 1974CH02, 1974DO10, 1974KE1B, 1975DO1B, 1975NE11, 1975YA12, 1977CH1D, 1977CO1B, 1978KO13, 1978SE01; 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 $E_d = 1.96$ 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 (1967TO02). [There is some evidence that there is more than one D-wave state in this E_x region: see reaction 3]. See also (1976AL22: $E_d = 1.01$ to 2.95 MeV). In the range E_d(c.m.) $= 7$ 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). Angular distributions have been measured at a number of energies from $E(^3\text{He}) = 18.7$ to 44.1 MeV (1972KI02) and at $E(^3\text{He}) = 10.00$ MeV (1974JA15, dσ/dΩ to ± 1%) and $E_d = 39$ MeV (1975RU04).

Polarization measurements have been reported for $E_d = 4.0$ to 12 MeV [see (1974AJ01)] and polarization analyzing powers have been studied at $E_{\vec{d}} = 2.0$ to 11.5 MeV (1975JE1A; abstract), $E_{\vec{d}} = 3.73$ to 11.89 MeV (1974OH05; $^3\vec{\text{He}}$; also spin correlation parameters), $E_d = 5.35$ to 9.2 MeV (1974LO06; polarization transfer coefficients), $E_{\vec{d}} = 15$ to 40 MeV (1976RO1B, 1976RO1C; vector analyzing powers) and $E(^3\vec{\text{He}}) = 33$ MeV (1977KA10).

See also (1975TO1A) and (1973HA1F, 1974CH02, 1974CH1E, 1974LY03, 1975DO1B, 1975HA1E, 1975KA1D, 1975NE11, 1975TA1A, 1976DO1B, 1976LY1A, 1977KA1H, 1977SA1C; theor.).

5. (a) ^{3}He(t, n)^{5}Li $\qquad Q_m = 10.13$
(b) ^{3}He(t, np)^{4}He $\qquad Q_m = 12.0959$

Angular distributions have been measured at $E(^3\text{He}) = 2.0$ to 5.5 MeV for n_0 ($\Gamma_{\text{g.s.}} = 2.03 \pm 0.15$ MeV) and at 3.5 to 5.5 MeV (partial distributions) for n_1 to an excited state at $E_x = 10.21 \pm 0.28$ MeV, $\Gamma = 1.49 \pm 0.61$ MeV (1975AB11). At $E(^3\text{He}) = 14$ to 26 MeV, the spectra show the n_0 group and a broad resonance with $E_x = 20.5 \pm 0.8$ MeV (1974CH15). Reaction (b) has been studied at $E(^3\text{He}) = 0.31$ to 2.80 to attempt to detect a possible resonant energy dependence of the spin-singlet ($T = 1$) n-p FSI: a marked effect is not present (1975SC28). See also (1977JO1A) 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 $\quad Q_m = 12.8596$

(c) ^{3}He(^{3}He, 3p)^{3}H $\quad Q_m = -6.9544$

The spectrum of protons shows a pronounced peak at $E(^3\text{He}) = 3$ to 18 MeV corresponding to $^5\text{Li}_{\text{g.s.}}$ superposed on a continuum: see (1974AJ01). At $E(^3\text{He}) = 13.6$ MeV differential cross sections and polarizations have been measured for the p_0 group (1976IR02). A deuteron cluster transfer process may be involved (1976AS05). 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). Searches for three-proton enhancement (reaction (c)) have been unsuccessful: see (1974AJ01). See also (1976HE07; theor.).

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

Differential cross sections and polarizations have been measured at many energies: see Tables 5.5 in (1966LA04), 5.7 in (1974AJ01) and 5.5 here.

Phase shifts below $E_p = 18$ MeV have been determined by (1977DO01) based on all the available cross section and polarization measurements, using an R-matrix analysis program. The $P_{3/2}$ phase shift shows a pronounced resonance corresponding to $^5\text{Li}_{\text{g.s.}}$ 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. (1977DO01) find that the reduced widths of the P-wave resonance states are nearly the same. See also (1974KR07: $E_x = 2.3 \pm 0.5$ MeV, $\Gamma = 9.0 \pm 1.5$ MeV for the $P_{1/2}$ state). The $D_{5/2}$, $D_{3/2}$, $F_{7/2}$ and $F_{5/2}$ phase shift become greater than 1° at $E_p \approx$ 11, 13, 14 and 16 MeV, respectively (1977DO01). A contour plot of A_y is shown in (1973AR1N): the results are not significantly different from those of (1977DO01). The work of (1977DO01) relies heavily on the very accurate elastic scattering cross sections which they measured (better than 1%) and on the polarization measurements of (1977HA06) [absolute precision of ± 0.01]. It should be noted that $A_y = 0.984 \pm 0.005$ at $E_{\vec{p}} = 11.93$ MeV, $\theta_{\text{c.m.}} = 128.28°$ (1977HA06). For other phase-shift analyses, see (1976BR17) and (1974AJ01).

A resonance is observed at $E_p = 23$ MeV, corresponding to the known $\frac{3}{2}^+$ state at $E_x = 16.7$ 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 $E_p = 30$ MeV ($E_x = 22$ MeV) (1972BA24). Cross sections for $23 < E_p < 45$ MeV show no further evidence of excited states (1969BU10). An extensive phase-shift analysis, using complex phases with $l \leq 4$ over the range $E_p = 20$ to 40 MeV has been made by (1972PL02), using mainly the 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: $E_x = 16.68$ MeV, $\gamma_p^2 = 122$ keV, $\gamma_d^2(l = 0) = 1.58$ MeV (negative sign), $\gamma_d^2(l = 2) = 1.58$ MeV, $\theta_p^2 = 0.014$, $\theta_d^2 = 0.765$.

The $E_p = 30$ 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 $E_x = 22$ MeV, but there is no unambiguous identification of excited states other than the $\frac{3}{2}^+$ state in the p-α results (1972PL02). In an analysis of the data of (1971PL07) for $E_p = 25$ to 29 MeV, (1971RA27) report evidence for a $\frac{5}{2}^+$ level at $E_x = 20$ MeV [$\Gamma_{el}/\Gamma_{total} = 0.15$, $\Gamma_{tot} = 8$ MeV] and a $\frac{1}{2}^+$ level at $E_x = 18 \pm 1$ MeV.

A recent analysis by (1975PL01) of the phase shifts below 50 MeV suggests a small D-state admixture to the dominant S-state configuration of ^{4}He$_{g.s.}$.

Total reaction cross sections have been measured at $E_p = 18$ to 48 MeV (1974SO06, 1976SO01) and at 0.87 and 2.1 GeV (1975JA1A). At an equivalent E_p of 1.05 GeV, the elastic distribution is characterized by a shallow first minimum (1977GE01) and is said to be in excellent agreement with the predictions of multiple-diffraction theory (1977WA06). Alpha-proton bremsstrahlung is observed at $E_p = 7.0$ to 12.0 MeV, at $E_\alpha = 20$ MeV [see (1974AJ01)] and at $E_p = 22$, 40 and 45 MeV (1975AN18). Coherent single pion production has been studied at $E_p = 18.6$ GeV/c (1977BR1C). See also (1973BE1A, 1978GL1B), (1975IG1A, 1975RO1B, 1975TO1A, 1976GR1D, 1977BR1E, 1977RI1B, 1978BR1E, 1978IG1B), (1973GU1A, 1973HA1F, 1974BA34, 1974BA38, 1974CH02, 1974CH1E, 1974CI02, 1974DO10, 1974HA43, 1974JA1F, 1974LY02, 1974SA1G, 1974UL1A, 1974WA02, 1975AH07, 1975BA05, 1975BA1G, 1975BA76, 1975BL04, 1975CA05, 1975CO1A, 1975DU1A, 1975GR1C, 1975GU17, 1975KA1D, 1975NA07, 1975RU01, 1975RU07, 1975TA1A, 1975WA16, 1976AH1A, 1976AL1E, 1976AR12, 1976AU04, 1976CH1B, 1976DO1C, 1976DU06, 1976LE22, 1976LE1E, 1976NA04, 1976RU04, 1976SP1A, 1977AL06, 1977AR01, 1977CH1C, 1977DY01, 1977JA12, 1977KA1E, 1977KA1F, 1977KA1H, 1977LA1C, 1977LE1E, 1977PH01, 1977TH07, 1977TH09, 1977WA1C, 1977WA1E, 1977YO04, 1978CL1C, 1978HE2B, 1978LA02, 1978LE23, 1978MA37, 1978ME05, 1978YE1A, 1978YO1B; theor.).

8. (a) ^{4}He(p, d)^{3}He	$Q_m = -18.3532$	$E_b = -1.97$
(b) ^{4}He(p, pn)^{3}He	$Q_m = -20.5778$	
(c) ^{4}He(p, 2p)^{3}H	$Q_m = -19.8140$	
(d) ^{4}He(p, pd)^{2}H	$Q_m = -23.8467$	

Angular distributions of ^{3}He ions (reaction (a)) have been measured for $E_p = 27.9$ to 155.4 MeV [see (1974AJ01)] and at $E_p = 85$ MeV (1974VO05), 275 to 500 MeV (1978CA05: back angles), 770 MeV (1976CO1C, 1977BA19) and at $E_\alpha = 3.98$ GeV/c (1977BE34). The 85 MeV data are in agreement with DWBA at forward angles but the back angle behavior probably results from the need to include two-nucleon pickup in the analysis (1974VO05). The differential cross section is strongly backward peaked at $E_p = 275$ and 500 MeV and the differential cross section is similar in slope and magnitude to that for ^{3}He(p, p), suggesting that deuteron exchange may be the major component of the reaction mechanism (1978CA05). The excitation function shows no indication of resonance for $E_p = 38.5$ to 44.6 MeV (1969BU10). Polarization measurements have been reported for $E_p = 32$ to 63 MeV [see (1974AJ01)] and at 45.04 and 52.34 MeV (1977SA1E) and 350, 400 and 500 MeV (1978CA05). At $E_\alpha = 6.85$ GeV/c, the integrated cross section for ^{3}He production (reactions (a) + (b)) is 24.1 ± 1.9 mb, suggesting an important component of ^{3}He in ^{4}He (1977BI05).

Reaction (b) and (c) have also been reported at $E_p = 46.8$ to 156 MeV [see (1974AJ01)]. The (p, 2p) reaction (reaction (c)) has also been studied at 350 and 500 MeV (1978EP1C, 1978KO1F) and 600 MeV (1969PE15), while both that reaction and reaction (d) have been studied at $E_p = 156$ MeV (1975FR14). See also (1973KR1A, 1978GL1B), (1977TE1A, 1978IG1B), (1976CO1B; astrophysics) and (1974BA34, 1974CH02, 1974CH29, 1974DO10, 1974HA36, 1974KA1D, 1974RO19, 1974YO01, 1975HA03, 1975KA1D, 1977CL1A, 1977KA1D, 1977KA1G, 1977RE1A, 1978BI1C, 1978RO06; theor.).

9. (a) ^{4}He(d, n)^{5}Li $\quad Q_m = -4.19$
(b) ^{4}He(d, np)^{4}He $\quad Q_m = -2.2246$

Reaction (b) has been studied at $E_d = 14.2$ MeV and at $E_\alpha = 18.0$ to 42 MeV [see (1974AJ01)] and at $E_\alpha = 18$ MeV (1978SA07) and 21.9 and 23.7 MeV (1974RA10). The data show 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 FSI in the ^{5}Li$_{g.s.}$ (1968WA01). See also (1974HE21, 1976KO21, 1976LI1E, 1977BR25; theor.) and ^{6}Li.

10. ^{4}He(t, 2np)^{4}He $\quad Q_m = -8.3820$

See (1974LA1A, 1975AL1A; $E_\alpha = 70$ MeV; abstracts).

11. ^{4}He(^{3}He, np)^{5}Li $\quad Q_m = -9.68$

See (1973HA50).

12. ^{6}Li(γ, n)^{5}Li $\quad Q_m = -5.66$

See ^{6}Li.

13. (a) ^{6}Li(p, d)^{5}Li $\quad Q_m = -3.44$
(b) ^{6}Li(p, pd)^{4}He $\quad Q_m = -1.4735$
(c) ^{6}Li(p, pn)^{5}Li $\quad Q_m = -5.66$

Angular distributions have been measured at $E_\mathrm{p} = 18.6$ to 156 MeV [see (1974AJ01)] and at $E_\mathrm{p} = 185$ MeV (1974KA28, 1976FA03). In the latter experiment the spectra are characterized by a broad, asymmetric peak corresponding to ^{5}Li$_\mathrm{g.s.}$, a narrow peak [^{5}Li*(16.7)] and a broad peak at $E_\mathrm{x} \approx 20$ MeV. DWBA analysis leads to $C^2S = 0.64$ and 0.57 for ^{5}Li*(0, 16.7) (1976FA03). The first excited state of ^{5}Li is reported to be populated by (1969BA05; $E_\mathrm{p} = 156$ MeV). See also (1978IG1A: 0.65 and 0.8 GeV).

Reaction (b) has been studied at $E_\mathrm{p} = 9$ and 10 MeV, at 45 MeV [see (1974AJ01)] and 40, 45 and 50 MeV (1974BE46): the p-α FSI corresponding to ^{5}Li$_\mathrm{g.s.}$ is observed. See also (1975MI1A). For reaction (c) see (1977WA05). See also (1975ST1C, 1975VO04, 1978CH1G) and ^{6}Li.

14. (a) ^{6}Li(d, t)^{5}Li $\quad Q_\mathrm{m} = 0.59$

(b) ^{6}Li(d, pt)^{4}He $\quad Q_\mathrm{m} = 2.5592$

Angular distributions of the t$_0$ group have been measured at $E_\mathrm{d} = 15$ and 20 MeV: see (1974AJ01). For reaction (b) see (1977RO18: $E_\mathrm{d} = 0.47$ MeV), (1974MI10, 1977MI13; $E_\mathrm{d} = 7.5$ to 10.5 MeV) and (1975KO1A; theor.).

15. (a) ^{6}Li(^{3}He, α)^{5}Li $\quad Q_\mathrm{m} = 14.91$

(b) ^{6}Li(^{3}He, pα)^{4}He $\quad Q_\mathrm{m} = 16.880$

At $E(^3\mathrm{He}) = 25.5$ MeV, the spectra show ^{5}Li*(0, 16.7) and two broad peaks at $E_\mathrm{x} \approx 19.8$ and 22.7 MeV with $\Gamma_\mathrm{c.m.} = 2$ and 1 MeV, respectively (1972BA30). In a kinematically complete experiment at $E(^3\mathrm{He}) = 36$ MeV the population of ^{5}Li*(16.7, 20.2, 22.6) is reported (1976RA1B). The decay of the ground state has also been studied at $E(^3\mathrm{He}) = 1.25$ MeV (1974LI10) and at 1.47 to 1.75 MeV (1978GU15).

Cylindrical asymmetry observed in the breakup of ^{5}Li(0) is attributed to the short lifetime of the ^{5}Li intermediate 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): its parameters are given as $E_\mathrm{x} = 3.2 \pm 0.2$ MeV, $\Gamma = 1.5 \pm 0.5$ MeV (1975GA14). See also (1975GL08, 1976ST1B, 1977AR09) and ^{8}Be.

16. (a) ^{7}Li(p, t)^{5}Li $\quad Q_\mathrm{m} = -4.43$

(b) ^{7}Li(p, pα)^{3}H $\quad Q_\mathrm{m} = -2.467$

At $E_\mathrm{p} = 43.7$ 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 also for a very broad excited state between $E_\mathrm{x} = 2$ 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 20 in ^{5}He] (1966CE05). 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 three- and four-particle breakup was analyzed. The t_0 angular distribution has also been studied at $E_p = 16.6$ and 30.3 MeV: see (1974AJ01).

17. ^{10}B(^{3}He, pα)^{4}He^{4}He $\quad Q_m = 12.4192$

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

18. ^{12}C(p, 2α)^{5}Li $\quad Q_m = -9.24$

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 $E(^3$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). See also (1975BE31; theor.).

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(Closed 1978)

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