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Energy Levels of Light Nuclei
$A = 5$

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Abstract: An evaluation of $A = 5$–24 was published in *Nuclear Physics* 11 (1959), p. 1. This version of $A = 5$ differs from the published version in that we have corrected some errors discovered after the article went to press. Figures and introductory tables have been omitted from this manuscript. Reference key numbers have been changed to the TUNL/NNDC format.

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^{5}H
(Not illustrated)

The possible existence of a particle-stable ^{5}H is discussed by (1957BL1A) who point out that a $T = \frac{3}{2}$ level of ^{5}He-^{5}Li might plausibly be formed by combination of ^{3}H or ^{3}He and a deuteron in the singlet ($T = 1$) state at an energy ≈ 2.3 MeV higher than the known $16.7 - 16.8$ MeV level. If such a level exists, calculation of Coulomb corrections and n-^{1}H mass difference suggests a mass excess of 32.22 MeV for ^{5}H, which would be 0.35 MeV stable against ^{3}H$+$2n. Presumably ^{5}H would then decay by β-emission (≈ 19 MeV) followed by neutron emission (1957BL1A). A search for delayed neutrons from ^{7}Li(γ, 2p)^{5}H with 320-MeV bremsstrahlung yielded no evidence of formation of ^{5}H (1958TA1A). It is concluded that less than 1% of the expected yield of ^{7}Li(γ, 2p)^{5}H leads to a particle-stable product (1958TA1A); see also (1958CE1A). A reaction yielding ^{5}H might be ^{3}H(t, p)^{5}H with $Q \approx -8.1$ MeV, assuming the mass of ^{5}H given by (1957BL1A).

^{5}He
(Fig. 1)

1. ^{3}H(d, γ)^{5}He $\qquad Q_\mathrm{m} = 16.629$

At $E_\mathrm{d} = 160$ keV, the capture cross section is less than 0.5 mb. This limit is not inconsistent with $\Gamma_\gamma \approx 11$ eV as estimated from the mirror reaction ^{3}He(d, γ)^{5}Li (1955SA52).

2. (a) ^{3}H(d, n)^{4}He	$Q_\mathrm{m} = 17.586$	$E_\mathrm{b} = 16.629$
(b) ^{3}H(d, 2n)^{3}He	$Q_\mathrm{m} = -2.991$	
(c) ^{3}H(d, pn)^{3}H	$Q_\mathrm{m} = -2.226$	
	$Q_0 = 17.580 \pm 0.025$ (1957MA1C).	

Excitation curves and angular distributions for reaction (a) from $E_\mathrm{d} = 8$ keV to 10 MeV are summarized by (1956FO1A, 1957JA37). Additional data are given for $E_\mathrm{d} = 0.04$ to 0.73 MeV by (1957BA1F, 1957BA1G), for $E_\mathrm{d} = 1.0$ to 5.8 MeV by (1956GA51) and for $E_\mathrm{d} = 0.25$ to 7.0 MeV by (1957BA21). Below $E_\mathrm{d} = 100$ keV, the cross section follows the Gamow function, $\sigma = (A/E)\exp(-44.40E^{-1/2})$ (1953JA1A, 1954AR02). A strong resonance, σ(peak) $= 5.0$ b, appears at $E_\mathrm{d} = 107$ keV. A precision measurement (± 5%) of the cross section at $E_\mathrm{t} = 1.50$ MeV gives 20.0 and 19.6 mb/sr (c.m.) at $30°$ and $60°$ (lab), respectively (1958AL05). There is some question as to whether a broad maximum exists between 4 and 8 MeV (1956GA51, 1957BA21).

In the region $E_\mathrm{d} = 10$ to 500 keV, the cross section is closely fitted with the assumption of s-wave formation of a $J = \frac{3}{2}^+$ state, with the parameters given in Table 5.2. For a given interaction

Table 5.1: Energy levels of ^{5}He

E_x in ^{5}He (MeV)	J^π	Γ (MeV)	Decay	Reactions
0	$\frac{3}{2}^-$	0.55 ± 0.03	n, α	5, 6, 8, 9, 10, 11, 12, 13, 14, 16, 17
$3 - 6$	$\frac{1}{2}^-$	$3 - 5$	n, α	8, 14
16.69	$\frac{3}{2}^+$	0.08	n, d, t, α	2, 8
(≈ 20)		> 1	n, d, t, α	2

radius, two sets of parameters are obtained, depending upon whether Γ_n/Γ_d is assumed > 1 or < 1 (1952AR30, 1952CO35). Agreement with the mirror reaction, ^{3}He(d, p)^{4}He, is obtained with the second choice (1955KU03). The fact that the proton width is relatively small suggests that this level arises from excitation of the ^{4}He core. See also (1951FL1A, 1954JO1C, 1955JO1A, 1957DA1B, 1958LE1A) and (1955HA1B; theor.).

The angular distribution of neutrons is isotropic at and below resonance, and shows increasing forward peaking at higher energies (1957JA37). Angular distributions at $E_d = 6$ MeV are almost identical to those of ^{3}H(d, p)^{4}H (1957BR23). At $E_d = 10$ MeV, the distribution is dominated by the stripping process, with $l_p = 0$ (1951BU1B). Again, close correspondence is found with the mirror reaction. See also (1955HE89, 1956BA1D, 1958LE1A, 1958PA09).

At $E_d = 12$ to 14 MeV, reactions (b) and (c) are observed (1956BO44, 1958BR14). The ^{3}He distributions from (b) show no evidence for a bound dineutron or for a well-defined virtual state, although some interaction between the neutrons does appear to occur. Absolute differential cross sections are reported (1958BR14).

For $E_d > 3.71$ MeV, deuteron breakup (reaction (c)) is energetically possible. The cross section for this process has been studied for $E_d = 3.8$ to 6.0 MeV by (1955HE90). At $E_d = 14$ MeV, the number of low-energy (4 to 10 MeV) neutrons is about three times as large as observed in the corresponding reaction ^{3}He(d, pn)^{3}He. The difference may indicate formation of a $T = 0$, 22-MeV excited state of ^{4}He via ^{3}H(d, n)^{4}He* (1956BO1F, 1956BO43, 1956BO44: see, however, (1958BR14)). See also (1954CO1B, 1955BA1G, 1955BE1B, 1956FO1A, 1957BL1A) and (1955LA1B, 1956BL1A, 1958PO1A; theor.).

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

Assuming the atomic mass excess of ^{4}H $= 26$ MeV (if first $T = 1$ state in ^{4}He has $E_x = 22$ MeV), Q_m for this reaction would be -4 MeV. This reaction has not been observed (1951MC37). An attempt has also been made by (1955RE44) to observe the β-decay of ^{4}H formed in the 300-MeV proton bombardment of ^{12}C. The results are negative: if $\tau_{1/2} = (2 \text{ to } 4) \times 10^{-3}$ sec, $\sigma < 1$ μb; if $\tau_{1/2} = (4 \text{ to } 10) \times 10^{-3}$ sec, $\sigma < 10$ μb. See also (1957NO17: ^{10}B(^{7}Li, ^{4}H)^{13}N).

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 ($\times 10^{-13}$ cm)	E_λ (keV)	γ^2_d (keV)	$\gamma^2_{n,p}$ (keV)	θ^2_d [c]	$\theta^2_{n,p}$ [c]	E_x (MeV)
107 [a]	135	0	$\frac{3}{2}^+$	2	5.0	-464	2000	56	1.0	0.018	16.69
					7.0	-126	715	17	0.7	0.011	
430 [b]	≈ 450	0	$\frac{3}{2}^+$	2	5.0	-391	2930	42	1.4	0.013	16.81
					7.0	129	780	12	0.7	0.008	

[a] ^{3}H(d, n)^{4}He: (1952AR30, 1952CO35, 1955KU03). See also (1957BA1F, 1957BA1G).

[b] ^{3}He(d, p)^{4}He: (1955KU03).

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

4. ^{3}H(d, d)^{3}H $\quad E_b = 16.629$

Differential cross sections for $E_d = 0.96$ to 3.2 MeV are tabulated by (1952ST69) and for $E_d = 10$ MeV by (1952AL36); see also (1957BR23, 1957JA37). The distributions are closely similar to those for ^{3}He(d, d)^{3}He. See also (1958BA82).

5. ^{3}H(t, n)^{5}He $\quad Q_m = 10.371$

The ground state of ^{5}He has been observed at $E_t = 1.48$ MeV (1957BA10) and 1.9 MeV (1958JA06). The neutron spectrum contains an excess of medium-energy neutrons, attributed to direct three-body reaction or to a broad excited state of ^{5}He. An earlier reported peak corresponding to a 2.6-MeV excited state (1951LE1A) is not confirmed (1957BA10). The alphas show a double peaking, reflecting the influence of the $P_{3/2}$ ground state, superposed on a distribution arising from the $P_{1/2}$ state and direct three-body disintegration (1958JA06); see ^{6}He.

6. ^{3}H(^{3}He, p)^{5}He $\quad Q_m = 11.136$

$Q_0 = 11.18 \pm 0.07$ (1953AL1A);

$Q_0 = 11.13 \pm 0.07$ (1953MO61).

The spectrum shows a well-defined proton peak corresponding to the ground state, superposed on a background attributed to the three-body breakup (1953AL1A, 1953MO61). See also (1954GO18).

7. ^{3}H(α, d)^{5}He $Q_\mathrm{m} = -7.215$

Not observed.

8. ^{4}He(n, n)^{4}He $E_\mathrm{b} = -0.957$

Total cross sections for $E_\mathrm{n} = 0.0004$ eV to 20 MeV are given in (1955HU1B, 1957HU1D, 1958HU18); angular distributions of (1952AD09) and (1953SE29) are given in (1956HU1A): additional data for $E_\mathrm{n} = 2.6$ to 4.1 MeV are given by (1957ST1B), for $E_\mathrm{n} = 14$ MeV by (1954SM97, 1955SH1D) and at $E_\mathrm{n} = 15.7$ MeV by (1954AL28). The current experimental and theoretical situation is surveyed by (1958HO1B). The total cross section has a peak of 7.4 b at $E_\mathrm{n} = 1.15 \pm 0.05$ MeV, $E_\mathrm{c.m.} = 0.95$, with a width of ≈ 1.7 MeV (1951BA85), $\Gamma_\mathrm{c.m.} = 1.4 \pm 0.2$ MeV (1958HU18). The thermal cross section is 0.78 b (1951HI1A), 0.71 ± 0.1 b (1951MC63), 0.74 ± 0.04 b (1955SO56).

Both the total cross sections and the angular distributions are well accounted for by the phase shifts determined by (1949CR1A, 1952DO30) for ^{4}He(p, p)^{4}He with a shift in E_λ of about 1 MeV: see also (1955CL1A; theor.). Earlier discrepancies in the range 3 to 4 MeV (1952HU1A) appear to have been resolved by (1957ST1B). In a polarization measurement, (1957LE1B, 1957LE1C) find $\delta(\mathrm{P}_{1/2}) = 12 \pm 1°$ at $E_\mathrm{n} = 2.45$ MeV, in disagreement with the value $\delta = 20°$ derived from ^{4}He(p, p)^{4}He, but agreeing with a low cross section point at $E_\mathrm{n} = 2.61$ MeV reported by (1953SE29). The s-wave phase shift decreases monotonically with increasing energy, and can be accounted for by hard-sphere scattering, with $R = 2.9 \times 10^{-13}$ cm (1952AD09, 1952DO30: see, however, (1954BR1B, 1954HO1B, 1955HO1C, 1956VA1C)). The $\mathrm{P}_{3/2}$ shift shows strong resonance behavior near 1 MeV, while the $\mathrm{P}_{1/2}$ shift changes more slowly, possibly indicating a broad $\mathrm{P}_{1/2}$ level at several-MeV excitation (1952DO30). At $E_\mathrm{n} = 15.7$ MeV the angular distribution is best accounted for with $\delta(\mathrm{D}_{3/2}) = -14°$, $\delta(\mathrm{D}_{5/2}) = -7°$, the latter being somewhat less than the hard-sphere value, suggesting a higher resonance (1954AL28). Theory: see ^{5}Li. (For present purpose, the ground state of ^{5}He is assumed to correspond to the maximum in the total cross section; $E_\mathrm{c.m.} = 0.95$ MeV).

A resonance is reported at $E_\mathrm{n} = 22.15 \pm 0.13$ MeV, $\Gamma \leq 120$ keV, corresponding to the 16.7-MeV level (see ^{3}H(d, n)^{4}He) (1957BO14). See also (1957IN1A).

Polarization of neutrons scattered in He has been discussed by (1952AD09, 1953SE29, 1953SI1A, 1955LE1D, 1956LE1B, 1957LE1B, 1957LE1C, 1957WH1A, 1958PA09) and others.

9. (a) ^{4}He(d, p)^{5}He $Q_\mathrm{m} = -3.184$
(b) ^{4}He(d, pn)^{4}He $Q_\mathrm{m} = -2.226$

$Q = -3.10 \pm 0.05$ (1954FR22) for reaction (a).

The proton spectrum observed at $E_{\rm d} = 14.8$ MeV, $\theta = 19.5°$, shows a prominent peak, of width $\Gamma_{\rm c.m.} = 550 \pm 30$ keV, and a monotonic continuum of lower energy protons, attributed to reaction (b). There is no evidence of structure corresponding to possible sharp excited states of ^{5}He. Cross sections for the ground-state group are $d\sigma/d\Omega = 25 \pm 5$ mb/sr at $\theta_{\rm c.m.} = 18°$ and 15 ± 4 mb/sr at $\theta_{\rm c.m.} = 24°$. The dimensionless reduced width of the ground-state group, analyzed by stripping theory is $\theta^2 = 0.05$, more than a factor of 10 smaller than is indicated by ^{4}He(n, n)^{4}He (see ^{4}He(p, p)^{4}He in ^{5}Li) (1956WA1B, 1957WA01). For reaction (b), see ^{6}Li.

10. ^{6}Li(γ, p)^{5}He $\quad\quad$ $Q_{\rm m} = -4.655$

The threshold is $E_\gamma = 4.64 \pm 0.08$ MeV (1958RY77); see ^{6}Li.

11. ^{6}Li(n, d)^{5}He $\quad\quad$ $Q_{\rm m} = -2.428$

At $E_{\rm n} = 14$ MeV, a well-defined ground-state group ($\Gamma_{\rm c.m.} = 0.8$ MeV) is observed, as is a continuum extending to $E_{\rm x} \approx 4$ MeV in ^{5}He. Angular distributions of the ground-state group and of the continuum indicate $l_{\rm p} = 1$ for the ground state transition and are not inconsistent with $l_{\rm p} = 1$ for the continuum (1954FR03): see ^{6}Li and reaction 8 in ^{7}Li.

12. ^{6}Li(d, ^{3}He)^{5}He $\quad\quad$ $Q_{\rm m} = 0.839$

At $E_{\rm d} = 14.5$ MeV, the ground-state group is observed: $Q_0 = 0.91 \pm 0.09$ MeV, $\Gamma_{\rm c.m.} = 0.69 \pm 0.2$ MeV (1955LE24).

13. ^{6}Li(t, α)^{5}He $\quad\quad$ $Q_{\rm m} = 15.158$

$Q_0 = 15.15 \pm 0.04$ (1956CR47).

The width of the ground state $\Gamma_{\rm c.m.} = 0.7 \pm 0.2$ MeV (1956CR47). See also (1954AL35, 1956BA1E, 1956MA09).

14. ^{7}Li(n, t)^{5}He $\quad\quad$ $Q_{\rm m} = -3.423$

The angular distribution exhibits a forward maximum at $E_{\rm n} = 14$ MeV. The total cross section is 55 ± 8 mb (1954FR03). At $E_{\rm n} = 14$ MeV, events corresponding to transitions to the ground state and possibly to a level at 2.4 ± 0.6 MeV are observed in Li-loaded photoplates; the latter group may actually be due to a level at 9.25 MeV in ^{7}Li (1954AL24): see ^{7}Li(n, n′)^{7}Li*.

15. ^{7}Li(p, ^{3}He)^{5}He $\qquad Q_{\rm m} = -4.188$

Not reported.

16. ^{7}Li(d, α)^{5}He $\qquad Q_{\rm m} = 14.163$

$Q_0 = 14.26 \pm 0.09$ (1955LE1C);
$Q_0 = 13.719 \pm 0.02$ (1955KH31, 1955KH35);
$Q_0 = 14.15 \pm 0.22$ (1957FA10);
$Q_0 = 14.11 \pm 0.08$ (1958WE27).

The angular correlation of ground state alpha particles and those resulting from the break up of ^{5}He is $W(\theta) = 1 + 1.2\sin^2\theta$, excluding a $J = \frac{1}{2}$ assignment, bur consistent with $J = \frac{3}{2}$ (1951FR1A). (1956RI37) reports $W(\theta) = \sin^2\theta$, also consistent with $J = \frac{3}{2}^-$. The $(\alpha - {\rm n})$ correlation observed at $E_{\rm d} = 0.16$ MeV, yields $W(\theta) = 1 + (0.75 \pm 0.05)\sin^2\theta$ and is again consistent with the assignment $J = \frac{3}{2}^-$ for the ground state of ^{5}He (1957FA10). The coincidence α-spectrum agrees in shape with a computed spectrum based on the ^{4}He(n, n)^{4}He cross sections (1956RI37).

The width of the ground state of ^{5}He is $0.3{\pm}0.1$ MeV (1953CU20), $0.66{\pm}0.2$ MeV (1955LE24). The work of (1953CU20, 1956JU1B) at $E_{\rm d} = 0.6$ to 1.5 MeV appears to indicate an excited state at $E_{\rm x} = 2.5 \pm 0.2$ MeV, $\Gamma \approx 1.5 \pm 0.3$ MeV. High-resolution magnetic spectra, observed for $E_{\rm d} = 1.0$ to 2.2 MeV show only the ground state peak, superposed on a continuous distribution, with no evidence of an excited-state group. The shape of the ground state peak is well accounted for with the parameters $\gamma^2 = 17.6 \times 10^{-13}$ MeV-cm, $R = 2.9 \times 10^{-13}$ cm, taken from (n, α) scattering data (1958WE27).

17. ^{9}Be(γ, α)^{5}He $\qquad Q_{\rm m} = -2.529$

See ^{9}Be.

Table 5.3: Energy levels of ^{5}Li

E_x (MeV)	J^π	Γ (MeV)	Decay	Reactions
0	$\frac{3}{2}^-$	≈ 1.5	p, α	2, 5, 6, 9, 10, 11, 12, 13
$5-10$	$\frac{1}{2}^-$	$3-5$	p, α	6
16.81	$\frac{3}{2}^+$	≈ 0.3	d, ^{3}He, p, α, γ	2, 3, 4

^{5}Li
(Fig. 2)

1. ^{3}H(^{3}He, n)^{5}Li $\qquad Q_m = 10.297$

Not reported.

2. ^{3}He(d, γ)^{5}Li $\qquad Q_m = 16.555$

The excitation curve measured from $E_d = 0.2$ to 2.85 MeV shows a broad maximum at $E_d = 0.45 \pm 0.04$ MeV ($E_\gamma = 16.6 \pm 0.2$, $\sigma = 50 \pm 10$ μb, $\Gamma_\gamma = 11 \pm 2$ eV). Above this maximum, non-resonant capture is indicated by a slow rise of the cross section. The radiation appears to be isotropic to $\pm 10\%$ at $E_d = 0.58$ MeV, consistent with s-wave capture (1954BL89). See also (1955KU1B), (1955BA1G; theor.).

3. (a) ^{3}He(d, p)^{4}He $\qquad Q_m = 18.351 \qquad E_b = 16.555$
(b) ^{3}He(d, np)^{3}He $\qquad Q_m = -2.226$

Cross sections and angular distributions for reaction (a) from $E_d = 35$ keV to 10 MeV are given in (1957JA37); see also (1957BO79, 1957FI1A). 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). A pronounced resonance occurs at $E_d = 430$ keV, of about 450-keV width. The peak cross section is given as 0.695 ± 0.014 b by (1952BO68, 1955KU03) and 0.92 ± 0.07 b by (1953YA02, 1954FR01). The resonance is closely fitted with the one-level dispersion formula, using the parameters listed in Table 5.2 (see ^{3}H(d, n)^{4}He). See also (1955BA1G, 1955HA1B, 1955JO1A, 1956KL1A), (1958PO1A; theor.).

The angular distribution of protons is isotropic near resonance and shows froward peaking at higher energies; the similarity to ^{3}H(d, n)^{4}He is very close. See also (1955KU1B, 1957BO79, 1957BR23).

Above $E_{\rm d} = 3.71$ MeV, deuteron breakup (reaction (b)) is observed (1955HE90).

4. ^{3}He(d, d)^{3}He $\qquad E_{\rm b} = 16.555$

Differential cross sections for $E_{\rm d} = 0.4$ to 3 MeV are plotted in (1957JA37); see also (1952AL36, 1957BR23, 1957FI1A). In the range $E_{\rm d} = 380$ to 570 keV, $\theta_{\rm c.m.} = 65°$, the scattering cross section is considerably below Rutherford scattering and is consistent with s-wave formation of a $J = \frac{3}{2}^+$ state. Above $E_{\rm d} = 2$ MeV, the distributions are quite similar to those observed in ^{3}H(d, d)^{3}H (1952AL36, 1954BR05, 1957BR23).

5. ^{3}He(^{3}He, p)^{5}Li $\qquad Q_{\rm m} = 11.062$

The proton spectrum at E(^{3}He) $= 360$ keV shows an unresolved ground-state group superposed on a broad continuum. No evidence is found for well-defined proton groups of lower energy than the ground-state group (1954GO18). See also (1953AL1A), (1957BR18) and ^{6}Be.

6. ^{4}He(p, p)^{4}He $\qquad E_{\rm b} = -1.796$

Differential elastic scattering cross sections have been measured at numerous energies from 0.95 to 95 MeV, as indicated in Table 5.4; curves at several energies are given by (1957JA37) and (1957BR28). Phase shifts derived from the experimental data are listed in the table. At $E_{\rm p} = 40$ MeV, the differential cross section shows "diffraction" maxima and minima characteristic of the optical model (1957BR24: see also (1956BU95, 1957GI14, 1957HO1C, 1958GA13)). Recent surveys of the experimental and theoretical situation are reported by (1958GA13, 1958HO1B, 1958MI93).

Even at low energies, the phase shift analysis clearly requires a splitting of $P_{1/2}$ and $P_{3/2}$ levels, generally attributed to spin-orbit effect. Either order of the P-doublet can be used to fit the cross section data (1949CR1A, 1952DO30): that the $P_{3/2}$ state is the lower is established by measurements of the polarization of scattered protons (1952HE15, 1955SC1A, 1956JU10, 1958SC1A). The tabulated phase shifts apply to this case.

The $P_{3/2}$ phase shift shows a pronounced resonance effect, passing through $90°$ at $E_{\rm p} = 2.8$ MeV (1949CR1A), while the $P_{1/2}$ changes only slowly over a range of several MeV. Analysis by (1952DO30), based on resonance theory, yields for the $P_{3/2}$ level (ground state of ^{5}Li) $E_\lambda({\rm c.m.}) = -4.1$ MeV, $\gamma_\lambda^2 = 25 \times 10^{-13}$ MeV-cm and for the $P_{1/2}$, $E_\lambda({\rm c.m.}) = 3.4$ MeV, $\gamma_\lambda^2 = 105 \times 10^{-13}$ MeV-cm (see also (1952AD09)). (These widths correspond to $\theta_{\rm p}^2 = 0.9$ and 3.9 times the sum-rule limit, respectively, using $R = 2.9 \times 10^{-13}$ cm.) It thus appears that the $P_{1/2}$ state, if resonance theory is at all appropriate here, is extremely broad and located $5 - 10$ MeV above the ground state. A new analysis of all data < 18 MeV yields $E_{\rm res}$(lab) $= 2.6$ MeV, $\gamma_{\rm p}^2 = 12 \times 10^{-13}$ MeV-cm, $\theta_{\rm p}^2 = 0.40$ for the ground state and $E_{\rm res}$(lab) $= 10.8$ MeV, $\gamma_{\rm p}^2 = 30 \times 10^{-13}$ MeV-cm, $\theta_{\rm p}^2 = 1.0$ for the excited state, using $R = 2.6 \times 10^{-13}$ cm (1958MI93). The s-wave phase shifts are well accounted for by hard-sphere scattering, with $R = 2.9 \times 10^{-13}$ cm (1952AD09, 1952DO30: see, however, (1956VA1C)), $R = 2.0 \times 10^{-13}$ cm (1958MI93). Semi-empirical phase shifts and polarizations for $E_{\rm p} = 10$ to 40 MeV are given by (1958GA13).

Proton and neutron scattering in helium are discussed in terms of a central potential with spin-orbit interaction by (1954BR1B, 1954HO1B, 1954JA1A, 1954SA1B, 1955HO1C, 1958GA13). (1955HO1C) obtain a good account of the s- and p-wave interactions with a Gaussian potential and Serber exchange force. The effect of tensor forces is discussed by (1956FE1A). See also (1956AB1A, 1956LE1C, 1958HO1B).

Polarization of the scattered protons is discussed by (1949CR1A, 1952AD09, 1952DO30, 1952HE15, 1955SC1A, 1956BR1D, 1956JU10, 1957RO1A, 1957SC1B, 1957SE40, 1958BR24, 1958SC1A, 1958SC27) and others.

For α-scattering in hydrogen: see (1954JU1B, 1954RU1A, 1957RO1A). See also (1956EI05, 1957TY27).

7. (a) ^{4}He(p, d)^{3}He $\quad Q_{\rm m} = -18.351 \quad E_{\rm b} = -1.796$

(b) ^{4}He(p, pn)^{3}He $\quad Q_{\rm m} = -20.577$

Angular distributions are reported at $E_{\rm p} = 27.9$ MeV (1957WI22), 31.6 MeV (1952BE1A) and 95 MeV (1955TE1A) for reaction (a). The cross section at $E_{\rm p} = 40$ MeV, $\theta = 30°$, is 10 ± 1 mb/sr (1956EI05). For reaction (b), see (1957WI22) and (1956EI05).

8. ^{4}He(p, 2p)^{3}H $\quad Q_{\rm m} = -19.812 \quad E_{\rm b} = -1.796$

See (1957WI22) and (1956EI05).

9. ^{4}He(d, n)^{5}Li $\quad Q_{\rm m} = -4.023$

At $E_{\rm d} = 13$ MeV, a broad, asymmetric neutron group corresponding to the ground state is observed. There is no evidence for structure corresponding to the $P_{1/2}$ excited state (1956BO1F, 1956BO43).

10. ^{6}Li(γ, n)^{5}Li $\quad Q_{\rm m} = -5.494$

Table 5.4: Phase shifts in $^{4}He(p, p)^{4}He$ [a]

E_p (lab) (MeV)	$S_{1/2}$ (deg)	$P_{1/2}$ (deg)	$P_{3/2}$ (deg)	$D_{3/2}$ (deg)	$D_{5/2}$ (deg)	References
0.95	−12.0	3.3	3.3	0	0	(1949CR1A, 1949FR20)
1.49	−18.1	4.1	20.4			(1949CR1A, 1949FR20)
1.70	−17.6	4.2	31.1			(1949CR1A, 1949FR20)
2.02	−24.6	8.1	47.8			(1949CR1A, 1949FR20)
2.22	−26.7	9.4	60.6			(1949CR1A, 1949FR20)
2.53	−28.2	13.1	78.8			(1949CR1A, 1949FR20)
3.03	−27.3	10.3	99.3	0.7	0.1	(1958MI93)
3.04	−32.0	15.7	96.6			(1949CR1A, 1949FR20)
3.51	−30.9	18.8	107.6	1.3	−1.1	(1958MI93)
3.58	−35.2	20.3	105.4			(1949CR1A, 1949FR20)
4.02	−32.9	23.6	112.4	2.1	−1.7	(1958MI93)
4.50	−43.1	29.1	111.6	−3.1	−0.5	(1958MI93)
5.00	−51.8	35.5	109.9	−4.7	0.1	(1958MI93)
5.1	(no analysis)					(1951BR93)
5.78	−47.9	38.7	112.9	−1.3	−0.49	(1952DO30, 1954KR1B, 1955LU60)
7.50	−57.95	52.51	112.1	−1.87	+0.44	(1956PU41)
9.48	−65.36	54.72	109.2	−5.73	−3.21	(1952PU1A, 1956PU41)
9.55	(optical model)					(1954FR22, 1957GI14: see (1955WI26, 1957HO1C))
9.76	(no analysis)					(1955WI26)
9.8	(no analysis)					(1954CO69)
12.0	−66.9	60.1	108.7			(1957BR28) [b]
14.0	−76.7	50.2	92.7			(1957BR28) [b]
16.0	−81.1	49.1	89.5			(1957BR28) [b]
17.0 [c]				(−14)	(−17)	(1954AL28)
17.45	−85.7	53.2	94.8			(1956BR29, 1957BR28)
18	−85.8	46.4	85.4			(1956BR29, 1957BR28)
19.4	(no analysis)					(1956VA1B, 1957VA1B)
27.9	(no analysis)					(1957WI22)
31.6	(no analysis)					(1953CO62)
39.85	(optical model)					(1957BR24)
95	(no analysis)					(1955TE1A)

[a] Phase shifts for $E_{\rm p} = 1$ to 18 MeV are plotted by (1958MI93); extrapolated values from 10 to 40 MeV are tabulated by (1958GA13).
[b] (1957BR28) also tabulates values for $E_{\rm p} = 13$, 15 and 17 MeV; D-wave $< 8°$.
[c] From ^{4}He(n, n)^{4}He.

The photoneutron threshold is 5.4 ± 0.2 MeV (1951TI06), 5.35 ± 0.2 MeV (1951SH63), 5.6 ± 0.1 MeV (1955TI1A), 5.73 ± 0.05 MeV (1958RY77). An earlier reported higher state is not confirmed (1955TI1A).

11. ^{6}Li(p, d)^{5}Li $\quad Q_{\rm m} = -3.267$

$Q_0 = -3.0 \pm 0.15$ (1955LI09).

At $E_{\rm p} = 18.6$ MeV, the ground-state group appears as a broad, asymmetric peak ($\Gamma = 1.8$ MeV) which tails off to a low continuum at lower energies. The angular distribution of the ground-state group has a maximum at $15°$ (c.m.) and, at small angles, conforms with stripping theory ($l_{\rm n} = 1$) (1955LI09).

12. ^{6}Li(d, t)^{5}Li $\quad Q_{\rm m} = 0.765$

$Q_0 = 0.80 \pm 0.15$ (1958FR52).

At $E_{\rm d} = 1$ MeV a broad ground-state triton group is observed ($\Gamma_{\rm c.m.} = 1.5$ MeV). The distribution of protons from the ^{5}Li breakup indicates a pronounced forward distribution (1958FR52). Se also ^{8}Be.

13. ^{6}Li(^{3}He, α)^{5}Li $\quad Q_{\rm m} = 15.084$

See (1955AL57) and (1953KU24).

14. ^{7}Li(p, t)^{5}Li $\quad Q_{\rm m} = -4.262$

This reaction has been observed at $E_{\rm p} = 17.5$ MeV (1957MA04).

References

(Closed December 01, 1958)

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