

Energy Levels of Light Nuclei

$A = 4$

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Abstract: A compilation of information on $A = 4$ was published in *Nuclear Physics A541* (1992), p. 1. Information relating to unbound states in ${}^4\text{H}$, ${}^4\text{He}$, and ${}^4\text{Li}$ is presented and discussed. No firm evidence for bound states of ${}^4\text{n}$, ${}^4\text{H}$, or ${}^4\text{Li}$ has been obtained. This version of $A = 4$ differs from the published version in that we have corrected some errors discovered after the article went to press. The introduction and introductory tables have been omitted from this version. Reference key numbers have been changed to the NNDC/TUNL format.

(References closed June 1, 1991)

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^4n

GENERAL

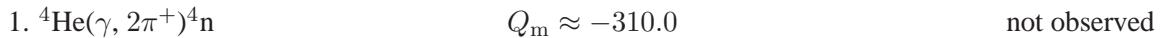
The stability of ${}^8\text{He}$ ([1968BA48](#), [1968ME03](#), [1973FI04](#), [1988AJ01](#)) sets an upper limit to the total binding energy of ${}^4\text{n}$, because the decay ${}^8\text{He} \rightarrow {}^4\text{He} + {}^4\text{n}$ does not occur ([1964GO1B](#), [1964GO25](#)). The most precisely determined mass excess of ${}^8\text{He}$ ([1988WA18](#)) yields $B({}^4\text{n}) \leq 3.1$ MeV. Noting that in all known nuclei the proton binding energy increases when two neutrons are added, ([1964VL1A](#)) show that $B({}^4\text{n}) < -Q$, where Q is the decay energy for ${}^5\text{H} \rightarrow {}^3\text{H} + 2\text{n}$. Since $Q > 0$ ([1988AJ01](#)), ${}^4\text{n}$ must be unbound.

If bound ${}^4\text{n}$ exists, a $T = 2$ state should be found in ${}^4\text{He}$ (see [1968ME03](#), [1973FI04](#)) at $26 < E_x < 29$ MeV. Also a $T = 2$ resonance should occur in $\text{n} + {}^3\text{H}$ at $6 < E_{\text{cm}} < 9$ MeV. Resonances have been found in $\text{n} + {}^3\text{H}$ (see ${}^4\text{H}$), but there is no evidence to support a suggestion ([1963AR06](#)) of $T = 2$. No low-lying $T = 2$ states of ${}^4\text{He}$ have been found (see ${}^4\text{He}$); systematics give $E_x(T = 2) \approx 34$ MeV ([1963FR14](#)), ≥ 32 MeV (Kurath, quoted in [1963SC35](#)) and $E_x > 50$ MeV based on shell-model calculations by ([1966KR06](#), [1970SZ03](#), [1972SZ07](#)). All experimental searches for ${}^4\text{n}$ have failed [see ([1965BA1A](#)) and recent work on reaction 2 below].

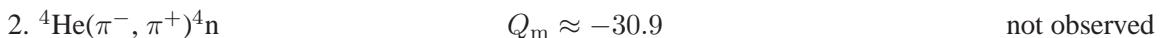
Variational calculations of the energy of the ${}^4\text{n}$ system, in which the trial wave function assumes a relative s-wave motion of two di-neutron clusters fail to produce either a bound state or a low-lying resonance ([1965TA14](#), [1970TH12](#)), although a similar theoretical technique successfully reproduces the binding energies of ${}^3\text{H}$, ${}^3\text{He}$ and ${}^4\text{He}$ ([1965TA15](#)) and the ${}^2\text{H}(\text{d}, \text{d}){}^2\text{H}$ differential cross section ([1970TH12](#)). A K -harmonic approach also finds that the ${}^4\text{n}$ state is absent ([1968BA20](#)). A hyperspherical-basis study of $A = 3 - 8$ multineutron systems ([1989GO18](#)) indicates that these systems have no bound states. However, a similar theoretical study ([1989GU16](#)) reports that ${}^4\text{n}$ has a resonance state because of the existence of a kinematical barrier.

Arguments based on pairing-energy systematics ([1960GO36](#), [1960ZE03](#)) would require the stability of ${}^4\text{n}$, if ${}^3\text{n}$ is stable ([1965TA14](#)), but see ([1968KA35](#)). Suspicion of the stability of ${}^3\text{n}$ ([1965AJ03](#)) has not been confirmed (see [1968KA35](#) and [1968ME03](#), [1975FI08](#), [1987TI07](#)).

In the following reactions, Q -values have been computed assuming $B({}^4\text{n})=0$.

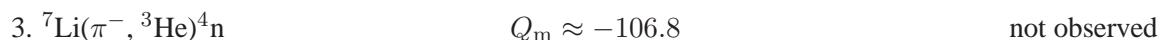


The previous compilation ([1973FI04](#)) notes one experimental search for neutrons from the above reaction with negative results: $\sigma \leq 1.7 \mu\text{b}$.

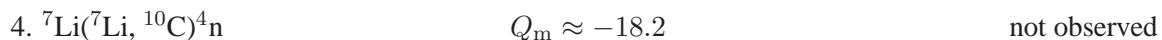


Measurements of the ${}^4\text{He}(\pi^-, \pi^+){}^4\text{n}$ reaction carried out in search of evidence for ${}^4\text{n}$ and extending from $E_{\pi^-} = 100 - 215$ MeV are summarized in the previous compilation ([1973FI04](#)). Neither bound nor unbound ${}^4\text{n}$ was detected in this early work. More recently, the 0° momentum spectrum from the double-charge-exchange reaction at $E_{\pi^-} = 165$ MeV was measured ([1984UN02](#)) in a search for ${}^4\text{n}$, and an upper limit of 22 nb/sr was set for the cross section. Note, however, that the theoretical study of ([1986KE20](#))

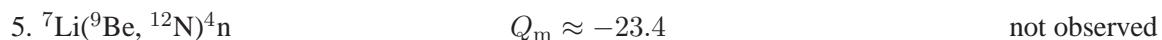
reports that the final-state interaction in the four-neutron system is so strong that the tetraneutron could not have been observed in the kinematic region explored in (1984UN02). Pion spectra were also measured (1986KI20) for incident pion energies of 180 and 240 MeV and found to be qualitatively consistent with two sequential single-charge-exchange processes. No evidence for ${}^4\text{n}$ was obtained. Total cross sections for pion double-charge exchange at 180 and 240 MeV were measured and compared with a phenomenological model in which successive charge-exchange processes complete with quasi-free scattering were included. A very recent search for the tetraneutron was carried out at $E_{\pi^-} = 80$ MeV and $\theta_{\pi^+}(\text{lab}) = 50^\circ - 100^\circ$ (1989GO17) and set an upper limit $\sigma(\theta) \leq 13$ nb/sr. Several theoretical studies of pion double-charge exchange on ${}^4\text{He}$ have been reported. In (1977GI04) cross sections were calculated for $E = 0 - 500$ MeV in a model in which two single pn charge-exchange scatterings occur. In the work of (1980JI03, 1981JI02) the reaction was studied in the framework of a four-body hyperspherical basis method.



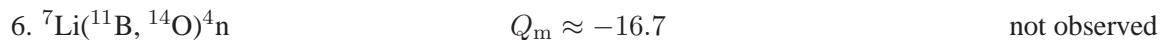
The previous compilation (1973FI04) includes only two experiments involving this reaction and no indication of the formation of ${}^4\text{n}$. Since that time the only investigation reported (1977BA47) utilized a nuclear emulsion loaded with ${}^7\text{Li}$. An upper limit of 1.2×10^{-3} was determined for the relative probability of forming ${}^3\text{n}$ and ${}^4\text{n}$ compared to all other $\pi^- + {}^7\text{Li}$ reactions.



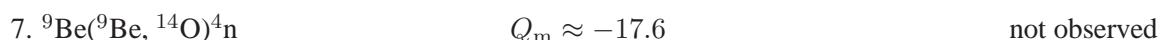
A measurement (1988AL11) carried out at $\theta_{\text{lab}} = 10^\circ$ for 82 MeV ${}^7\text{Li}$ ions found no ${}^4\text{n}$ resonances. An upper limit of 4 nb/sr for the cross section was determined.



A measurement (1988BE02) of the spectrum of outgoing nuclei for incident ${}^7\text{Li}$ energies of 72–90 MeV found no evidence of a bound state of the four-neutron system, but an upper limit was reported.



Incident ${}^7\text{Li}$ energies of 48 – 71 MeV were used (1988BE02) to study this reaction. No evidence of ${}^4\text{n}$ was observed. See also (1986BE44, 1987BO40).



This reaction was studied ([1988BE02](#)) for incident ${}^9\text{Be}$ energies of 72–90 MeV. No evidence for bound or quasi-stationary states of ${}^4\text{n}$ was obtained.

${}^4\text{H}$

GENERAL

The stability of the first excited state of ${}^8\text{Li}$ against decay into ${}^4\text{He} + {}^4\text{H}$ ([1988AJ01](#)) sets an upper limit for $B({}^4\text{H}) \leq 3.53$ MeV ([1965BA1A](#)). This also sets a lower limit to the β^- decay energy ${}^4\text{H} \rightarrow {}^4\text{He}$ of 17.06 MeV. The upper limit of the β^- decay energy would be 20.60 MeV, if ${}^4\text{H}$ is stable against decay into ${}^3\text{H} + \text{n}$. ([1965BA1A](#)) give estimates for the expected half-life of the beta decay: if $J^\pi({}^4\text{H}) = 0^-, 1^-, 2^-, \tau_{1/2} \geq 10$ min; if $J^\pi({}^4\text{H}) = 0^+, 1^+, \tau_{1/2} \geq 0.03$ sec. Experimentally there is no evidence for any β^- decay of ${}^4\text{H}$ (see reaction 1), nor has particle-stable ${}^4\text{H}$ been observed (see reactions 2–19). Evidence for a particle-unstable state of ${}^4\text{H}$ has been obtained in ${}^7\text{Li}(\pi^-, t){}^3\text{H} + \text{n}$ (see reaction 16) at 8 ± 3 MeV above the unbound ${}^3\text{H} + \text{n}$ mass with a width $\Gamma < 4$ MeV. See also reaction 17. For other theoretical work see ([1976JA24](#), [1983VA31](#), [1985BA39](#), [1989GO24](#)).

The level structure of ${}^4\text{H}$ presented here is obtained from a charge-symmetric reflection of the R -matrix parameters for ${}^4\text{Li}$ (see ${}^4\text{Li}$, GENERAL) after shifting all the $\text{p}-{}^3\text{He}$ E_λ 's by the internal Coulomb energy difference $\Delta E_C = -0.86$ MeV. The parameters then account well for measurements of the $\text{n}-{}^3\text{H}$ total cross section ([1980PH01](#)) and coherent scattering length ([1985RA32](#)), as is reported in ([1990HA23](#)). The BW resonance parameters from that analysis for channel radius $a_{\text{nt}} = 4.9$ fm are given in Table 4.1 and are shown in Fig. 1. The levels are located substantially lower in energy than they were in the previous compilation ([1973FI04](#)), as will be true for all the $T = 1$ levels of the $A = 4$ systems. The ${}^4\text{Li}$ analysis unambiguously determined the lower 1^- level to be predominantly ${}^3\text{P}_1$ and the upper one to be mainly ${}^1\text{P}_1$; that order is preserved, of course, in the ${}^4\text{H}$ levels. In addition to the levels given in Table 4.1, the analysis predicts very broad positive-parity states at excitation energies in the range 14–22 MeV, having $\Gamma \gg E_x$, as well as antibound P-wave states approximately 13 MeV below the 2^- ground state. Parameters were not given for these states in the table because there is no clear evidence for them in the data.

The structure given by the S -matrix poles is quite different, however. The P-wave resonances occur in a different order, and the positive-parity levels (especially for 0^+ and 1^+) are much narrower and lower in energy. It is possible that these differences in the S -matrix and K_R -matrix pole structures, which are not yet fully understood, could explain the puzzling differences that occur when these resonances are observed in the spectra of multi-body final states (see ${}^4\text{Li}$, GENERAL).

Fig. 1: The energy levels of ${}^4\text{H}$ are plotted on a vertical scale giving the c.m. energy, in MeV, relative to the mass of ${}^3\text{H} + \text{n}$. Horizontal lines representing the levels are labeled by the level energies and values of total angular momentum and parity (J^π). Other horizontal lines mark the threshold energies of the indicated multi-particle subsystems. A typical thin-target excitation function for $\text{n}-{}^3\text{H}$ scattering is shown at the right side of the figure, labeled along the vertical axis by laboratory energy (but plotted at the corresponding c.m. values). Numbers at the tops of the vertical arrows indicate laboratory energies (usually the highest) at which the reaction leading to formation of an $A = 4$ nucleus has been studied.

Table 4.1 contains further information on the levels illustrated, including total widths.

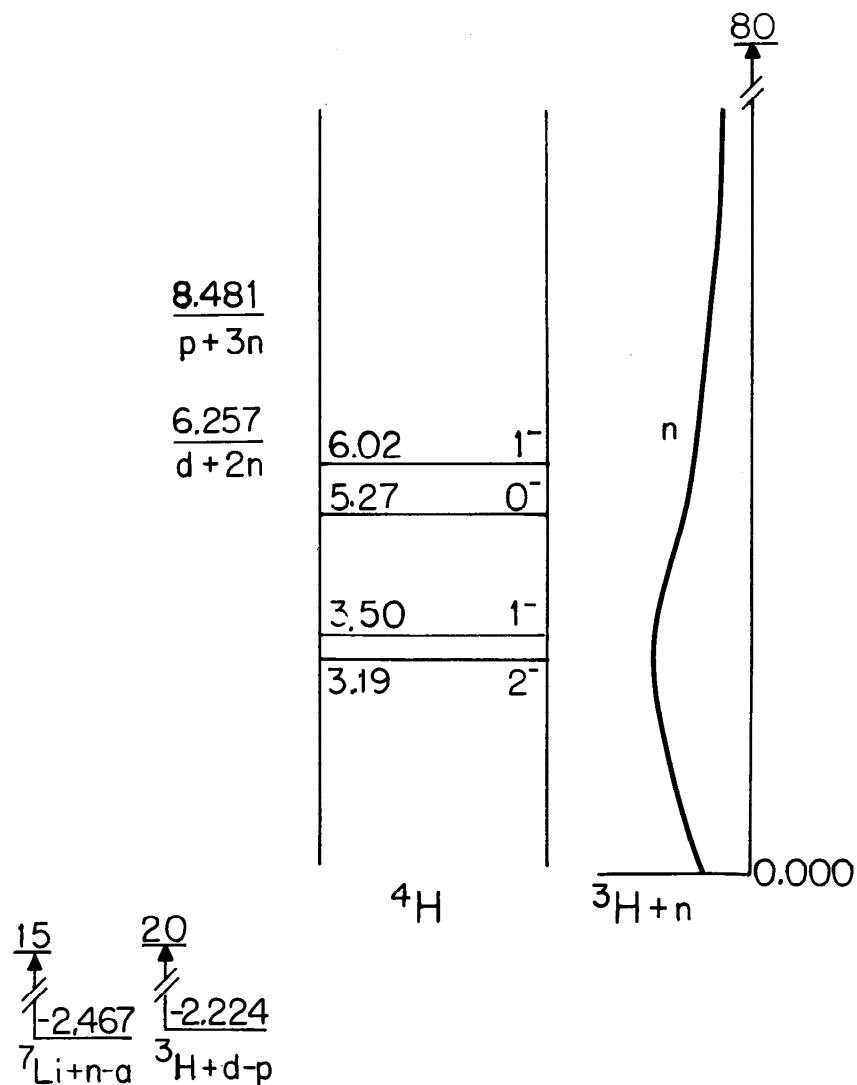


Table 4.1: Energy levels of ${}^4\text{H}$ defined for channel radius $a_n = 4.9$ fm.
All energies and widths are in the cm system.

E_x (MeV)	J^π	T	Γ (MeV)	Decay	Reactions
g.s. ^a	2^-	1	5.42	$n, {}^3\text{H}$	1, 11
0.31	1^-	1	6.73 ^b	$n, {}^3\text{H}$	11, 12
2.08	0^-	1	8.92	$n, {}^3\text{H}$	
2.83	1^-	1	12.99 ^c	$n, {}^3\text{H}$	11, 12

^a 3.19 MeV above the $n + {}^3\text{H}$ mass.

^b Primarily ${}^3\text{P}_1$.

^c Primarily ${}^1\text{P}_1$.

$$1. {}^4\text{H}(\beta^-){}^4\text{He} \quad Q_m \approx 20.6 \quad \text{not observed}$$

As noted in the previous compilation (1973FI04), all searches for the beta decay of ${}^4\text{H}$ have yielded negative results. No new work has been reported.

$$2. {}^3\text{H}(n, \gamma){}^4\text{H} \quad Q_m \approx 0 \quad \text{not observed}$$

The previous compilation (1973FI04) notes that this reaction has not been observed, but cites some work yielding upper limits for the cross section. No new work has been reported.

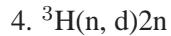
$$3. {}^3\text{H}(n, n){}^3\text{H}$$

Measurements of cross sections, polarization, and analyzing power for ${}^3\text{H}(n, n){}^3\text{H}$ are summarized in Table 4.2. Earlier work is reviewed in the previous compilation (1973FI04). See also (1972SE23) for a summary of early data on this reaction.

A review of progress in four-body scattering and breakup reaction calculations in the integral equation approach is presented in (1987FI03). Calculations of ${}^3\text{H}(n, n)$ scattering carried out in this approach are described in (1976FO13, 1976KH01, 1976TJ01, 1978KR01, 1983LE22, 1986FO07). An R -matrix prediction of $n-{}^3\text{H}$ cross sections and scattering lengths from $p-{}^3\text{He}$ scattering data is described in (1990HA23). A microscopic calculation for the ${}^4\text{H}$ and ${}^4\text{Li}$ continuum in which structure and reactions were treated on an equal footing was done by (1977BE40). ${}^4\text{H}$ and ${}^4\text{Li}$ level positions and widths were calculated. In (1979FO08) a soluble model of the four-nucleon system was developed using a nonrelativistic field theoretic formalism. A four-body calculation of the 4N system was carried out (1984FO08) to describe low energy phase shifts and cross sections. The pseudostate method in the resonating group formulation was used (1986SH12) to study distortion effects of the three-nucleon cluster in $n + t$ and $p + {}^3\text{He}$. See also (1989PO23).

Table 4.2: Measurements and summaries (S) of cross sections $\sigma(\theta)$, analyzing power $A(\theta)$ and polarizations $P(\theta)$, for the ${}^3\text{H}(\text{n}, \text{n}){}^3\text{H}$ reaction

E_{n} (MeV)	Measurement	θ_{cm} (deg)	Description	Refs.
6.0, 9.0, 18.0, 19.5, 21.0, 23.0	$\sigma(E, \theta), P_{\text{n}}$	32 – 149	Liquid ${}^3\text{H}$ target.	1972SE23(S)
14 – 15	$\sigma(E, \theta)$	0, 1, 67, 96	Reviewed, compared existing data. Measured σ in energy interval to study anomaly.	1976PA23(S)
14.1	$\sigma(E, \theta)$	4 – 40	Measured absolute cross sections. Optical model and Faddeev calculations.	1976SH20
0.06 – 80	$\sigma(E)$		Gas target. Compared with $\text{p} + {}^3\text{He}$ data.	1980PH01
0.06 – 1.2	$\sigma(E)$		Measured $\sigma(E)$ at low energy, extrapolated to zero energy. Inferred scattering lengths.	1980SE02
Low energy	bound scattering length b_c		Used neutron interferometer. Deduced singlet and triplet scattering lengths σ_s, σ_t .	1981HA36
Low energy	bound scattering length b_c		Remeasured b_c with skew-symmetric neutron-interferometer. Deduced σ_s, σ_t .	1985RA32

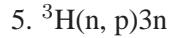


$$Q_m = -6.257$$

The previous compilation ([1973FI04](#)) lists several measurements of the $^3\text{H}(\text{n}, \text{d})2\text{n}$ reaction and notes that forward-angle deuteron spectra are sharply peaked at high energy indicating a strong final-state interaction between two neutrons.

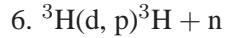
More recently only one additional measurement has been reported. Differential cross section measurements at $E_n = 14.1$ MeV were carried out ([1976SH20](#)) for deuteron angles $4^\circ, 10^\circ, 20^\circ, 30^\circ$, and 40° . The measured energy spectra were represented satisfactorily by a Faddeev calculation which took into account the nn final-state interaction.

A soluble model involving four interacting particles and utilizing a field theoretic formalism was discussed in ([1976FO13](#)). Total cross sections for $^3\text{H}(\text{n}, \text{d})2\text{n}$ were calculated. A calculation described in ([1982WU03](#)) considered quasi-free scattering and d + n cluster structure, and deduced reaction kinematics and cutoff radius effects.



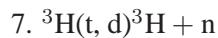
$$Q_m = -8.482$$

Measurements of proton energy spectra are summarized in the previous compilation ([1973FI04](#)). In the only measurement reported since, polarized thermal neutrons were used ([1980BOZH](#)), and the measured asymmetry was used to determine the upper limit of the P -odd asymmetry coefficient. See also the review of resonances in three-particle nuclei ([1989MO24](#)).



$$Q_m = -2.225$$

A summary of early measurements of the $^3\text{H}(\text{d}, \text{p})$ reaction is given in the previous compilation ([1973FI04](#)). Proton spectra show no evidence of formation of ^4H . Observed structure in the proton spectra is attributed to final-state interactions in the $^3\text{H} + \text{n}$ system. Upper limits for a bound state are discussed. However the recent work of ([1990BL14](#)) on a kinematically-complete measurement of the equivalent $^2\text{H}(\text{t}, \text{tp})\text{n}$ reaction for $E_t = 35$ MeV finds evidence for a ^3H ground state with $E_{\text{res}} = 3.1$ MeV, $\gamma^2 = 2.3$ MeV. This work includes a review of ^4He ground-state parameters from recent experiments. See also ([1973SL03](#), [1977WE03](#), [1981SE11](#), [1982SE08](#), [1985FR01](#), [1986BE35](#), [1987GO25](#), [1989GR22](#), [1990AM04](#), [1990BL14](#), [1990BR14](#), [1990BR17](#)). Since the previous compilation ([1973FI04](#)), measurements of vector and tensor analyzing power at $E_d = 3 - 6$ MeV and an R -matrix analysis were reported ([1980CL1A](#), [1980DE1A](#)). At $T \approx 300$ K, thermonuclear reaction rates for $^3\text{H}(\text{d}, \text{p})$ and several other reactions of interest to astrophysics were calculated ([1989SC25](#)). The distribution of relative velocities between particles was described by the Maxwell-Boltzmann distribution. Results were compared with published experimental results.



$$Q_m = -6.257$$

The previous compilation ([1973FI04](#)) cites measurements in which structure was observed in the deuteron spectra from the ${}^3\text{H}(\text{t}, \text{d})$ reaction, but the structure was attributed to final-state interactions in the ${}^3\text{He} + \text{n}$ system. Other experiments noted in ([1973FI04](#)) have determined upper limits for the cross section. No new measurements on this reaction have been reported.

8. (a) ${}^4\text{He}(\gamma, \pi^+) {}^3\text{H} + \text{n}$	$Q_m = -160.7$
(b) ${}^4\text{He}(\gamma, \pi^0) {}^3\text{H} + \text{p}$	$Q_m = -154.8$
(c) ${}^4\text{He}(\gamma, \text{p}) {}^3\text{H}$	$Q_m = -19.81$

Measurements of reaction (a) cited in the previous compilation ([1973FI04](#)) show some evidence for a ${}^3\text{H} + \text{n}$ final-state interaction, but other explanations are possible. No new work has been reported. Angular distribution measurements ([1989GL06](#)) of reaction (b) were analyzed in terms of quasi-free, exchange, and quasi-elastic reaction mechanisms. Measurements of the asymmetry in angular distributions for reaction (c) induced by polarized photons of energies 40 MeV and 120–125 MeV were reported in ([1988GA29](#), [1989VI05](#)). A theoretical investigation of structure effects in the E3 cross section for reaction (c) is described in ([1989BE07](#)). See also the analysis of ([1988TE04](#), [1989VO01](#)).

9. ${}^4\text{He}(\text{e}^-, \nu) {}^3\text{H} + \text{n}$	$Q_m = -20.596$
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The previous compilation ([1973FI04](#)) cites one calculation, but no measurements on this reaction. No new work has been reported.

10. ${}^4\text{He}(\pi^+) {}^3\text{H} + \text{n}$	$Q_m = 118.460$
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The previous compilation ([1973FI04](#)) cites one measurement, but no evidence for a ${}^3\text{H} + \text{n}$ final-state interaction. No new work has been reported.

11. (a) ${}^4\text{He}(\pi^-, \gamma) {}^4\text{H}^*$	$Q_m = 115.6$
(b) ${}^4\text{He}(\pi^-, \pi^- \pi^+) {}^4\text{H}^*$	$Q_m = -163.5$
(c) ${}^4\text{He}(\pi^-, \text{n}) {}^3\text{H}$	$Q_m = 118.5$
(d) ${}^4\text{He}(\pi^-, 2\text{n}) {}^2\text{H}$	$Q_m = 112.2$
(e) ${}^4\text{He}(\pi^-, 3\text{n}) {}^1\text{H}$	$Q_m = 110.0$

The previous compilation ([1973FI04](#)) discusses measurements ([1972BI09](#)) of the energy spectrum of γ -rays from π^- capture which show structure attributed to capture to a $J^\pi = 2^-$, $E_x = 3.4$ MeV state (apparent g.s. of ${}^4\text{H}$) and two strongly mixed 1^- levels at $E_x = 5.1$ and 7.5 MeV. No new ${}^4\text{He}(\pi^-, \gamma) {}^4\text{H}^*$

measurements have been reported. A review of recent data significant in determining the characteristics of the (π^-, γ) reaction on light nuclei was presented in (1982GM02). A calculation of the total radiative capture rate from ${}^4\text{He}$ pionic atoms is described in (1988WE01).

Early experimental and theoretical work on reaction (c) is summarized in (1973FI04). More recently, measurements of differential cross sections were reported at $E_\pi = 100, 200, 290$ MeV (1978KA01), and at $E_\pi = 285, 428, 525, 575$ MeV (1981OR01, 1982OR06). The π^- absorption was found to proceed by a two-nucleon mechanism with an energy dependence consistent with formation of a $J = \frac{1}{2}$ resonance in the intermediate state. Measurements of the energy spectra of single neutrons, protons, and deuterons following absorption of stopped π^- in ${}^4\text{He}$ were reported in (1981CE01). An analysis of the ${}^4\text{He}(\pi^-, \gamma){}^4\text{H}$ reaction at 290 MeV utilizing the effective channel approach was presented in (1981RE01). The reaction was studied in the resonance region within the framework of a Δ -hole model (1983HI11).

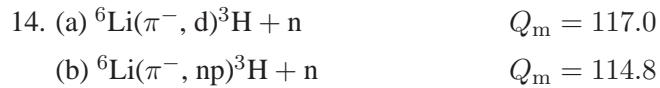
No new measurements of reactions (d) or (e) have been reported. However, a cluster-model study of ${}^4\text{He}(\pi^-, 2n){}^2\text{H}$ was reported in (1986GE08), and in (1987GE06) it was suggested that measurements carried out for pionic capture at rest could yield information on the D-state of ${}^4\text{He}$.



Experimental work cited in the previous compilation (1973FI04) showed structure in the proton spectra from the ${}^4\text{He}(n, p){}^3\text{H} + n$ reaction that was interpreted as indicating an excitation of the giant resonance 1^- states in ${}^4\text{H}$. It was noted that the 2^- ground state of ${}^4\text{H}$ does not appear to be populated appreciably. No new work on this reaction has been reported.



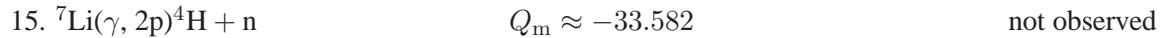
The previous compilation (1973FI04) cites no reported measurements, but notes upper limits for the production cross section of ${}^4\text{H}$ in earlier reviews. No new work has been reported.



Measurements of coincident charged-particle spectra discussed in the previous compilation (1973FI04) show structure which has been interpreted either in terms of a final-state interaction in ${}^3\text{H} + n$ or in terms of levels in ${}^4\text{H}$. The yield for reaction (a) is stated to be $(1.0 \pm 0.5) \times 10^{-4}$ of all possible $\pi^- + {}^6\text{Li}$ reactions. Early measurements of neutron-proton energy-summed coincident spectra and n-p angular distributions from reaction (b) are also cited in (1973FI04). More recently, measurements of energy spectra versus angle for reactions (a) and (b) were carried out (1983HE17) for stopped pions. The quasi-deuteron mechanism was found to be the dominant process in the reaction. Other measurements for reactions (a) and (b) with stopped pions were reported in (1985DO19) and the results discussed in terms of sequential reaction mechanisms as well as cluster absorption. Angular correlations of the cross section for reaction (b) were measured

(1986YO06) at $E_\pi = 70$ MeV, and the components of the two-nucleon absorption cross section were extracted. See also (1987KO47).

A calculation of the energy spectra and angular correlations of single and correlated spectra for absorption of stopped pions was described in (1981CH03).



The previous compilation (1973FI04) lists no observations of the ${}^7\text{Li}(\gamma, 2\text{p}) {}^4\text{H} + \text{n}$ reaction, but cites experimental work in which upper limits for the production cross section of ${}^4\text{He}$ were set as revealed by its beta decay. No new measurements have been reported.



The previous compilation (1973FI04) states that no evidence for a particle-stable state of ${}^4\text{H}$ has been found, but notes that charged-particle spectra for π^- capture at rest indicate structure which is interpreted as a ${}^3\text{H} + \text{n}$ final-state interaction. Other measurements are cited, and proposed states in the unbound ${}^3\text{H} + \text{n}$ system are discussed. More recently the charged particles from the breakup of ${}^7\text{Li}$ following π^- capture have been identified in coincidence (1979ME13), and strong evidence for a particle-unstable ${}^4\text{H}$ state is obtained. The energy of the resonance was found to be 8 ± 3 MeV above the unbound ${}^3\text{H} + \text{n}$ mass with a width $\Gamma < 4$ MeV. A review of previous experimental searches for particle-unstable ${}^4\text{H}$ is included.



No evidence for a particle-stable state had been obtained at the time of the previous compilation (1973FI04). Upper limits ($\sigma \leq 2.2$ mb) were quoted. A recent measurement (1986KN06) of the ${}^4\text{He}$ production cross section for an average neutron energy of 14.95 MeV gave $\sigma = (0.336 \pm 0.016)$ b. Measurements of coincident energy spectra of alpha particles were reported in (1986MI11, 1986MI14) for $E_n = 14.6$ MeV, and it was suggested that the observed structure might be attributed to states of ${}^4\text{H}$. See also the measurements of (1986SH33).



The previous compilation (1973FI04) notes one particle-identification measurement on this reaction with no ${}^4\text{H}$ particle groups detected. No new work has been reported.



The previous compilation (1973FI04) cites one measurement which determines an upper limit on the cross section and concludes that $B({}^4\text{H}) \leq 0.16$ MeV. No new work has been reported.

^4He

GENERAL

Ground state. Due to non-central forces, the wave function for the $J^\pi = 0^+$ ground state of ^4He can be a positive-parity mixture of three $^1\text{S}_0$, six $^3\text{P}_0$, and five $^5\text{D}_0$ orthogonal states (1967BE74). Of course, the symmetric S-wave component is the dominant part of the wavefunction, with significant D-wave and almost negligible P-wave contributions. Since the D-state admixture can be inferred from measurements such as the tensor analyzing powers for $^2\text{H}(\text{d}, \gamma)^4\text{He}$ (reaction 1), it has been the subject of much experimental and theoretical attention since the previous compilation (1973FI04), despite confusion stemming from the fact that in some cases the results refer to only part of the full D-state probability as calculated in (1988CA19, 1990CH06, 1991AR01).

Recent variational and Green function Monte Carlo (GFMC) calculations [(1988CA19), (1991CA35)] using realistic nucleon-nucleon potentials have been highly successful in reproducing the ground-state properties of light nuclei. These calculations for ^4He give D-state probabilities ranging from 15–17.5%, depending on the potential model (including three-body forces) used, and P-wave probabilities that are much smaller ($\approx 1\%$). Other theoretical and experimental estimates of the D-state percentage are considerably lower, but these inferences can be complicated by the presence of more than one multipole and other D-state effects (see the discussion for reaction 1).

The latest GFMC calculation (1991CA35), using a truncated version of the Argonne V14 NN interaction (1984WI05), overbinds ^4He by 0.9 MeV, whereas most variational calculations underbind it by more than 1 MeV. In both cases, three-body forces contribute at least 3 MeV to the binding energy. When the GFMC calculation is corrected perturbatively for the terms in the NN interaction (1984WI05) that could not be included, the binding energy decreases by almost exactly enough to agree with the experimental value, 28.296 MeV. This energy results from a cancellation of large kinetic-energy and two-nucleon potential-energy terms, so that the three-body forces, though small in comparison to the two-body forces, make a significant contribution to the binding energy. Since the nuclear forces are assumed to be charge-independent, the small amount of repulsive Coulomb energy (0.75 MeV) implies high isotopic purity of the $T = 0$ ground state.

Recent calculations (1991CA35) of the charge density give form factors that are in reasonable agreement with electron-scattering experiments. For momentum transfers greater than about 4.5 fm^{-1} , the variational calculation follows the data somewhat better than does the GFMC calculation. The Fourier transforms of the proton-pair distributions have also been calculated and compared with measurements of the Coulomb sum. The comparison is quite good for both variational and GFMC calculations when the experiments are corrected for the finite energy range of the measured sums.

Excited states:

The unbound excited-state level structure presented here is based on the comprehensive, Coulomb-corrected, charge-independent R -matrix analysis of (1989HA2A). This analysis takes its isospin-1 parameters from an analysis of p– ${}^3\text{He}$ scattering data (see ${}^4\text{Li}$, GENERAL), but with the eigenenergies shifted by the internal Coulomb energy difference $\Delta E_C = -0.64 \text{ MeV}$ and the p– ${}^3\text{H}$ and n– ${}^3\text{He}$ reduced-width amplitudes scaled by the isospin Clebsch-Gordan coefficient $\sqrt{\frac{1}{2}}$. The isospin-0 parameters are then varied to fit the experimental data for the reactions among the two-body channels p+ ${}^3\text{H}$, n+ ${}^3\text{He}$, and d+ ${}^2\text{H}$, at energies corresponding to excitations in ${}^4\text{He}$ below approximately 29 MeV. In this fit, the $T = 0$ nucleon-trinucleon reduced-width amplitudes are constrained by the isospin relation

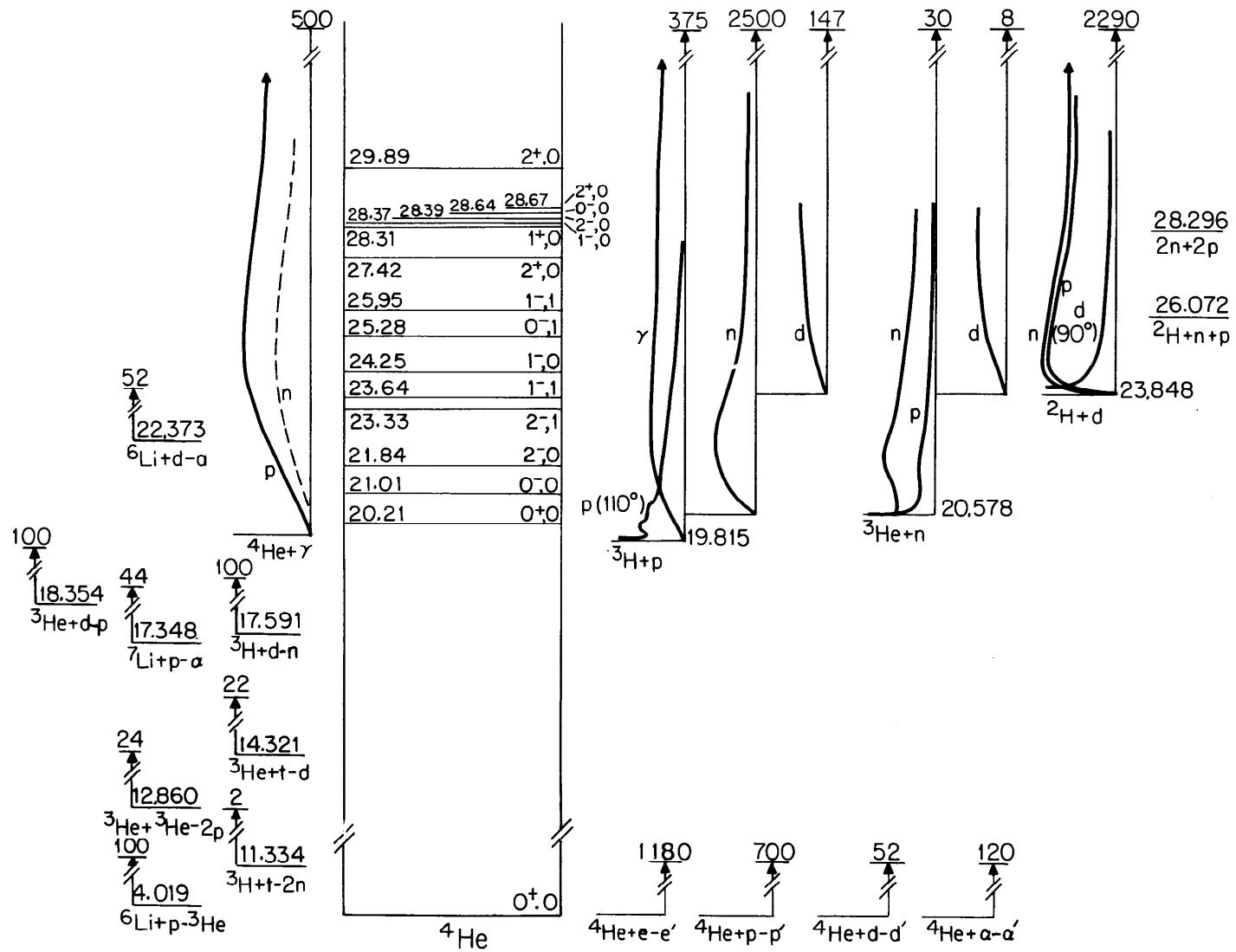


Fig. 2: The energy levels of ${}^4\text{He}$ are plotted on a vertical scale giving the c.m. energy, in MeV, relative to its ground state. Horizontal lines representing the levels are labeled by the level energies and values of total angular momentum, parity, and isospin (J^π, T). Also shown are threshold energies and typical thin-target excitation functions for some of the reactions in the ${}^4\text{He}$ system. See Fig. 1 for further details about notation and Table 4.3 for more information about the levels, including partial and total widths.

$$\gamma_{n^3He}^{(T=0)} = -\gamma_{p^3H}^{(T=0)}$$

and a small amount of internal Coulomb isospin mixing is introduced by allowing

$$\gamma_{dd}^{(T=1)} \neq 0,$$

which is necessary to reproduce the differences between the two branches of the d + d reaction (reactions 3 and 4).

Although the 4He analysis is not yet complete, the predicted levels are sufficiently stable that we feel it is worthwhile to report them as preliminary results. The BW resonance parameters at channel radii $a_{pt} = a_{n^3He} = 4.9$ fm and $a_{dd} = 7.0$ fm are given in Table 4.3, and are shown in Fig. 2. These states have relatively pure isospin, except in the cases noted below. As the previous compilation (1973FI04) pointed out, the general features of the level structure at excitation energies below 30 MeV can be understood in terms of Wigner's supermultiplet theory in which the degenerate [1] states are lowered and the [15] states are raised by an attractive particle-hole interaction. The P-wave [15] levels having $T = 1$ and $T = 0$ are much more interspersed in the present scheme than in the previous compilations, however, leading to significant isospin mixing in those states. In addition, several new $T = 0$ levels that have essentially d + d character appear, some of which were anticipated by a prediction of Sergeyev (1972SE02).

The first three $T = 0$ excited states ($0^+, 0^-, 2^-$) of Table 4.3 are in reasonable agreement with those of Table 3.0.2 (which were fairly well established) in (1973FI04). Above about 22 MeV excitation energy, differences begin to occur. There is no evidence in the analysis of the 4He -system reactions for a separate 0^+ or 1^+ , $T = 0$ level at $E_x = 25.5$ MeV as has been seen in the $\alpha + {}^4He^*$ final states of reactions 28 and 32. It is possible that the anomaly seen in these reactions is due to a shadow pole associated with the 0^+ excited state at $E_x = 20.21$ MeV, or that the true position of the 0^+ state is several MeV higher, as is indicated by the position of the S -matrix pole (see discussion below).

Nestled among a series of four negative-parity, $T = 1$ levels in the range $E_x = 23 - 26$ MeV (which were at least 3 MeV higher in (1973FI04)) is a new $1^-, T = 0$ level at $E_x = 24.25$ MeV that has important effects on the d + d reactions at low energies. Isospin mixing between this state and the 3P_1 , $T = 1$ level at $E_x = 23.64$ MeV causes significant differences in the p-wave part of the d + d reactions, as have been observed in muon-catalyzed (1984BA1W) and polarized (1981AD07) d + d fusion experiments. The $1^-, T = 0$ level was seen by (1981GR16) in their ${}^2H(d, p){}^3H$ analyzing-power data, but no evidence of their proposed 4^+ level at $E_x = 24.6$ MeV was found by (1989HA2A) in fitting their measurements.

The remaining $T = 0$ levels at $E_x = 27 - 30$ MeV are primarily d + d states, except for the 1^+ level at $E_x = 28.31$ MeV. The 5S_2 level at $E_x = 27.42$ MeV is interesting on two accounts: it marks the first appearance of a state from the [20] representation, and it probably corresponds to a resonance that had been seen by (1966LE1A) in ${}^6Li(d, \alpha){}^4He^*$ spectra, but was later withdrawn by (1968BA20) when they failed to see it in d + d elastic scattering measurements. The effect of the broad resonance can be seen in d + d elastic scattering excitation functions measured by (1969WI01), however. Because of its width, this state causes the 5S_2 transitions of the d + d reactions to be important even near the d + d threshold, in contradiction to the earlier theoretical picture that only the 1S_0 transitions were important due to Pauli exclusion of the quintet d + d S-waves.

The series of 3P_J levels concentrated near $E_x = 28.5$ MeV are clearly the ones from the [15] representation predicted by (1972SE02). These broad levels are not apparent in the data, but they are required primarily by the cross-section and analyzing-power measurements for d + d elastic scattering. The 1^- level in this sequence has been seen in the decay of ${}^4He^*$ in the final states of reactions 25, 28, and 32. The 1D_2

Table 4.3: Energy levels of ${}^4\text{He}$ defined for channel radii $a_p = a_n = 4.9$ fm, $a_d = 7.0$ fm. All energies and widths are in the c.m. system.

E_x (MeV)	J^π	T	Γ_p (MeV)	Γ_n (MeV)	Γ_d (MeV)	Γ (MeV)	Decay	Reactions
g.s.	0^+	0						
20.21	0^+	0	0.50	0.00	0.00	0.50	p	16, 22, 24, 28, 31
21.01	0^-	0	0.64	0.20	0.00	0.84	p, n	24
21.84	2^-	0	1.26	0.75	0.00	2.01	p, n	24, 29
23.33	2^-	1	2.64	2.37	0.00	5.01	p, n	
23.64	1^-	1	3.44 ^a	2.76 ^a	0.00	6.20	p, n, (γ)	
24.25	1^-	0	3.08 ^a	2.87 ^a	0.15	6.10	p, n, d	3, 4
25.28	0^-	1	4.12	3.85	0.00	7.97	p, n	
25.95	1^-	1	6.52 ^b	6.14 ^b	0.00	12.66	p, n, γ	7
27.42	2^+	0	0.25	0.23	8.21 ^c	8.69	p, n, d	6, 28, 32
28.31	1^+	0	4.72	4.66	0.51	9.89	p, n, d	
28.37	1^-	0	0.07	0.08	3.77	3.92	(p, n), d	(3, 4), 6, 28
28.39	2^-	0	0.02	0.02	8.71	8.75	(p, n), d	(3, 4), 6
28.64	0^-	0	0.00	0.00	4.89	4.89	d	6
28.67	2^+	0	0.00	0.00	3.78 ^d	3.78	d, γ	6, 21
29.89	2^+	0	0.04	0.04	9.64 ^e	9.72	(p, n), d	28

^a Primarily ${}^3\text{P}_1$.

^b Primarily ${}^1\text{P}_1$.

^c Primarily ${}^5\text{S}_2$.

^d Primarily ${}^1\text{D}_2$.

^e Primarily ${}^5\text{D}_2$.

resonance that was previously thought to be at 33 MeV is at $E_x = 28.67$ MeV, and another 2^+ resonance, primarily in the 5D_2 d + d channel, gives a second [20] state at $E_x = 29.89$ MeV.

Estimated uncertainties on the parameters given for 4He in Table 4.3 are as follows: At excitation energies below 26 MeV, the positions are uncertain by 20 keV or less, except for the $(1^-, T = 0)$ level at 24.25 MeV, which is uncertain by 150 keV. At excitation energies between 26 and 30 MeV, the uncertainties in the positions are generally less than 90 keV, with that of the $(1^-, T = 0)$ level at 28.37 MeV less than 10 keV. The widths of the levels (partial and total) are generally known to about 10%.

The uncertainties in the BW resonance parameters are usually far less than the changes that occur when the resonance parameters are derived from the poles of the S -matrix. A significant difference between these parameters and the BW parameters of Table 4.3 is in the position of the 0^+ state. The S -matrix poles are located at least 3 MeV higher in excitation energy than is the pole of K_R , meaning that the 0^+ state is no longer the first excited state of 4He . This might explain the great difficulty shell-model calculations (1977BE02, 1988CE05) have in obtaining the excitation energy of the 0^+ state as low as the “traditional” position it has occupied between the p- 3H and n- 3He thresholds. Other differences involve the ordering of the P-wave levels, and the appearance of low-lying, positive-parity, $T = 1$ levels.

Experimental work not discussed explicitly: (1973AN26, 1973AY02, 1973BR20, 1973DE17, 1973EL04, 1973GA17, 1973GO38, 1973HE06, 1973HE26, 1973JA21, 1973KA08, 1973MI20, 1973NO07, 1973SO08, 1973TO06, 1973TR04, 1974BA94, 1974GE10, 1974GO15, 1974GR02, 1974HE17, 1974LI10, 1974MI10, 1974RU06, 1974TO03, 1975BI08, 1975GE12, 1975GL08, 1975KA05, 1975SC31, 1976AR11, 1976BA57, 1976BO05, 1976BU19, 1976DA24, 1976HA17, 1976JA17, 1976OH02, 1976SC26, 1976SH23, 1976SK02, 1976SU06, 1976TA11, 1976WA12, 1976ZA11, 1977BO22, 1977CA05, 1977GO16, 1977KA02, 1977KA10, 1977LA13, 1977LE02, 1977MI13, 1977NO10, 1977RO18, 1978AR05, 1978AR21, 1978BA75, 1978CO16, 1978FA06, 1978GE12, 1978HA42, 1978LU05, 1978ZA06, 1979AB14, 1979BA27, 1979BA33, 1979BA66, 1979DR10, 1979EG01, 1979HO04, 1979JU02, 1979KA03, 1979SK05, 1979SU14, 1979WA02, 1980BA17, 1980GO21, 1980KA17, 1980MA20, 1980NE11, 1980OR05, 1980RO03, 1980WA10, 1981EG03, 1981FA02, 1981FA07, 1981GO03, 1981LA07, 1981NE08, 1981SM04, 1981VA05, 1981WA15, 1981WI11, 1981YU01, 1982BA16, 1982ER06, 1982IS06, 1982KE10, 1982LA09, 1982LA11, 1982LA20, 1983AN02, 1983AR05, 1983CO09, 1983RI01, 1983WA09, 1983YO01, 1984AR17, 1984FO18, 1984GM01, 1984HO01, 1984KA33, 1984KR12, 1984KR23, 1984LA19, 1984LA32, 1984MA71, 1984TS01, 1984TU02, 1984VO05, 1984WA18, 1985BE63, 1985BL05, 1985CE13, 1985CE16, 1985CH37, 1985TA13, 1985TA18, 1986BA68, 1986BU05, 1986CA29, 1986EN05, 1986FA13, 1986HE16, 1986KE01, 1986KL04, 1986LA26, 1986SM04, 1986SO03, 1986WA11, 1986WH01, 1987AL09, 1987BA69, 1987HU13, 1987LA25, 1987ME01, 1987ME18, 1987QA01, 1987WA25, 1987ZA07, 1988AR20, 1988DY01, 1988LA11, 1988ME11, 1988RA31, 1988SI14, 1988ST06, 1989AB10, 1989AR08, 1989AR16, 1989AR20, 1989BA23, 1989CL01, 1989CO14, 1989CR05, 1989DM02, 1989GL03, 1989SH17, 1989SZ02, 1989TA19, 1989YO03, 1990AB11, 1990BA58, 1990GE12, 1990LU10, 1990NI01, 1990SM04, 1990YA11, 1991DE02, 1991SC05, 1991WE06).

Level calculations not discussed: (1973CA16, 1973GE11, 1973KU02, 1973MA48, 1973NA19, 1973PE05, 1974LE30, 1974NA05, 1974NA18, 1974SA05, 1974SI05, 1974YA11, 1976BE01, 1977HI09, 1977SC18, 1977VE09, 1978AT01, 1978DE16, 1979BE15, 1979BE42, 1979TA23, 1981CE02, 1981SA32, 1981SC09, 1981VA23, 1982AZ01, 1982AZ02, 1982BE39, 1983BE52, 1983GE13, 1983GR24, 1983HO22, 1983KU20, 1983MA44, 1983VA08, 1983ZE06, 1984BA41, 1984KU13, 1984LI01, 1984MA03, 1984SU07, 1984VA06, 1985BE61, 1985CA40, 1985CE06, 1985DO20, 1985DU05, 1985LI09, 1985PO22, 1986AY01, 1986BE51,

1986DA04, 1986DU10, 1986KA02, 1986KN08, 1986RO03, 1986ST13, 1987BL18, 1987CA10, 1987CE01, 1987HO07, 1987KR07, 1987RE04, 1988ZH03, 1988ZH05, 1988ZH07, 1990CE06, 1990KH01, 1990OK03, 1990VA14, 1990WO09, 1990ZH10).

Table 4.4: Measurements and summaries (S) of cross sections and analyzing powers for the reaction ${}^2\text{H}(\text{d}, \gamma){}^4\text{He}$

E_{d} (MeV)	Measurement	θ_{γ} (deg)	Description	Refs.
4 – 12.5	$\sigma(\theta)$	0 – 132	Fit to $\sigma(\theta)$ indicated E2 transition ${}^1\text{D}_2 \rightarrow {}^1\text{S}_0$	1973PO01
0.163	$\sigma(E_{\gamma})$		Compared with plasma thermal distribution calculations.	1984CE03
376	$\sigma(\theta)$	73, 91	Compared to ${}^4\text{He}(\gamma, \text{d})$ measurements.	1984SI01
9.7	$\sigma(\theta), T_{20}$	45 – 140	Measured T_{20} as ${}^4\text{He}$ D-state signature.	1984WE14
0.05 – 0.160	Γ_{γ}/Γ_p	0 – 180	Compared with direct-capture calculations.	1985WI08
10	$\sigma(\theta), A_y, A_{yy}$	25 – 155	Found evidence for non-E2 radiation.	1986ME02
10	$\sigma(\theta), iT_{11}, T_{20}, T_{21}, T_{22}$	25 – 155	Model-independent analysis, extracted specific T -matrix elements.	1986ME16
0.7 – 14.9	$\sigma(E, \theta)$	40 – 140	Looked for D-state effects in (d, γ) at low energies.	1986WE07
0.05 – 0.500	$\sigma(\theta), \sigma(E)$	0 – 90	Determined $S(E)$, and implied evidence for ${}^5\text{S}_2 \rightarrow {}^5\text{D}_0$ amplitude.	1987BA58
1.2	$\sigma(\theta), A_y, A_{yy}$	55 – 140	Model calculation used to study evidence for E2, E1, M2 radiation.	1988LA14
2.5	$\sigma(\theta), iT_{11}, T_{20}, T_{22}$	25 – 155	Studied role of odd-parity multipoles interfering with E2.	1987MEZV
0.3 – 30	A_y, A_{yy}	130	Compared data to result of resonating group calculations.	1988WE15
95	$\sigma(\theta), A_y, A_{yy}$	55 – 149	Results indicate reaction dominated by $\langle {}^1\text{D}_2 \text{E}2 {}^1\text{S}_0 \rangle$ transition to ${}^4\text{He}$ S-state.	1989PI06
1.2, 14.7, $E_{\text{d}} \leq 0.8$	$\sigma(\theta), A_y, A_{yy}, T_{20}$	30 – 14	Transition matrix analysis. Compared to MCRGM.	1990LA16
5.4 – 14.7	A_y, A_{yy}	130	Studied ${}^4\text{He}$ D-state.	1990LA16

Other theoretical work: (1973AV03, 1973BO34, 1973BU01, 1973DE19, 1973DU10, 1973IO01, 1973KO26, 1973KU03, 1973LE24, 1973LI14, 1973MA10, 1973MA20, 1973NA26, 1973PA17, 1973PA19, 1973RA27, 1973WE14, 1973ZA03, 1973ZA11, 1974BE15, 1974DE41, 1974DH03, 1974DO10, 1974DZ03, 1974FI04,

1974FI13, 1974GR03, 1974KA35, 1974KH02, 1974KO03, 1974MA21, 1974PA11, 1974SA18, 1974SA29, 1974SA30, 1974SA31, 1974SO13, 1974ST14, 1974TE05, 1974TO08, 1974WE09, 1974WO06, 1974ZA01, 1974ZA07, 1974ZA08, 1975BA68, 1975BA76, 1975BO47, 1975CH22, 1975DO04, 1975FL02, 1975GO04, 1975KU01, 1975LA15, 1975LA19, 1975LI05, 1975SO07, 1975TJ01, 1975VI08, 1975WA30, 1976BA51, 1976CE01, 1976CO10, 1976FL09, 1976GA24, 1976GI06, 1976GI09, 1976HE01, 1976KI01, 1976KI16, 1976LA07, 1976LI20, 1976NA10, 1976TO07, 1976UL02, 1976UL04, 1977AV06, 1977BA74, 1977BE61, 1977BH04, 1977BL11, 1977BO24, 1977CR01, 1977DU01, 1977FR16, 1977HA02, 1977HE15, 1977HI11, 1977KI10, 1977KO25, 1977LA06, 1977LE13, 1977LE20, 1977LI11, 1977LI18, 1977LO18, 1977OS06, 1977SO05, 1977SO12, 1977TO03, 1978BE41, 1978BE57, 1978BI14, 1978CA04, 1978FA07, 1978FE08, 1978FR17, 1978FU12, 1978GI10, 1978HO07, 1978KI04, 1978LA08, 1978LI08, 1978LO16, 1978MC04, 1978OS05, 1978SI15, 1978SM02, 1978TJ02, 1978UL02, 1978WA13, 1978ZA05, 1979AY02, 1979BL05, 1979BL06, 1979FI01, 1979GH01, 1979GU16, 1979HE16, 1979HU02, 1979JA09, 1979KA06, 1979KA43, 1979MA07, 1979MO07, 1979OS09, 1979PE06, 1979RA30, 1979RI16, 1979RU09, 1979SA13, 1979SH07, 1979ST02, 1979UE02, 1979WA13, 1979WA14, 1979YA06, 1980BE17, 1980CH37, 1980DE01, 1980DU06, 1980FO14, 1980FU05, 1980GR01, 1980HA54, 1980KA18, 1980KH01, 1980KO04, 1980LA20, 1980LI09, 1980MA30, 1980ME07, 1980SA16, 1980TO11, 1980ZN01, 1981BA41, 1981BE01, 1981BE24, 1981BE39, 1981BE63, 1981BL06, 1981CA14, 1981CH03, 1981DE27, 1981DE34, 1981DO01, 1981DO02, 1981DR11, 1981DU08, 1981DU19, 1981DZ01, 1981FO01, 1981FO11, 1981FR20, 1981GO09, 1981GU10, 1981JA07, 1981JE01, 1981JI05, 1981KA12, 1981KA39, 1981KO37, 1981LE22, 1981LO08, 1981NA04, 1981NI05, 1981NO04, 1981PA16, 1981PL03, 1981SA14, 1981SH07, 1981ST19, 1981ZA01, 1981ZA02, 1981ZA05, 1982AT01, 1982AV08, 1982BA73, 1982BL05, 1982BO08, 1982DA03, 1982DA19, 1982DE12, 1982DE35, 1982DE51, 1982FR11, 1982FR14, 1982GR18, 1982HU11, 1982KA06, 1982KA11, 1982KH01, 1982KH05, 1982LA07, 1982LA16, 1982LA19, 1982MU13, 1982NI02, 1982SH08, 1982SI13, 1982SO07, 1982VA15, 1982VE12, 1982WA07, 1982WE09, 1982ZA01, 1983AR17, 1983BA43, 1983CA10, 1983CH59, 1983DM01, 1983DR16, 1983EI01, 1983FR20, 1983GE12, 1983GO04, 1983KH01, 1983MA31, 1983ME06, 1983NE08, 1983NE12, 1983NI06, 1983RI07, 1983TE05, 1983TH06, 1983WI05, 1984BA06, 1984BE17, 1984BO08, 1984CA24, 1984GA26, 1984GA34, 1984GO01, 1984GO19, 1984HE21, 1984HU04, 1984KR10, 1984LA05, 1984LI08, 1984LO09, 1984MA04, 1984MA11, 1984MO24, 1984OR01, 1984PR09, 1984RE09, 1984SH07, 1985AL12, 1985AN11, 1985AR05, 1985BA45, 1985BO02, 1985BU02, 1985BU06, 1985CH01, 1985DE37, 1985FA02, 1985FR09, 1985HE19, 1985KA30, 1985KO03, 1985KR12, 1985KW02, 1985MA30, 1985PA10, 1985PR02, 1985SA32, 1985SO06, 1985SP05, 1985TH04, 1985TI08, 1985TO19, 1985TR03, 1986AB02, 1986AN08, 1986AN09, 1986AN35, 1986BA15, 1986BA69, 1986BI01, 1986CA28, 1986DE11, 1986DU06, 1986GR02, 1986HA45, 1986HO33, 1986JI01, 1986KE07, 1986KH02, 1986KH06, 1986KU11, 1986LE22, 1986NA05, 1986PA08, 1986PA15, 1986RA21, 1986SA02, 1986TA07, 1987AR11, 1987BA49, 1987BI22, 1987BO09, 1987BU02, 1987BU04, 1987CA13, 1987CA17, 1987CA27, 1987CA29, 1987GI01, 1987GM02, 1987GM04, 1987KO31, 1987KU03, 1987KU12, 1987LI34, 1987MA61, 1987MO33, 1987NE08, 1987PA13, 1987QI01, 1987SA15, 1987SC25, 1987SH09, 1987SO04, 1987TA06, 1987TA27, 1987TR07, 1987VA05, 1987VA29, 1987VA36, 1987ZO01, 1988AL12, 1988AN18, 1988BA63, 1988BA74, 1988BO04, 1988BO40, 1988CH16, 1988CO15, 1988DI10, 1988DO17, 1988DU04, 1988FO08, 1988FR02, 1988GO10, 1988GU07, 1988KA23, 1988KO32, 1988MA33, 1988MA56, 1988MO21, 1988MU11, 1988VA27, 1988WO04, 1988YA02, 1989AK01, 1989AL08, 1989AN10, 1989BA31, 1989BO29, 1989CH49, 1989CI05, 1989CU05, 1989DU05, 1989DZ02, 1989FO12, 1989GR15, 1989JI07, 1989KH06, 1989KR08, 1989KU06, 1989KU21, 1989LA05, 1989LE24, 1989MA06, 1989NA18, 1989RA14, 1989SA17, 1989SA32, 1989SC15, 1989SC19, 1989SC22, 1989TE04, 1989UC02, 1989US01, 1989VA06, 1989ZA07, 1990AN23, 1990AS06, 1990BE14, 1990BI01, 1990BI05, 1990BR09, 1990BU29, 1990CA12, 1990CI01, 1990CI04, 1990CO12, 1990FA08, 1990GE04,

1990GO09, 1990GO30, 1990GU23, 1990HA07, 1990HE13, 1990JO01, 1990KA06, 1990KA07, 1990KA42, 1990LE24, 1990LO10, 1990LO20, 1990MA63, 1990MO17, 1990MO25, 1990NI13, 1990OE01, 1990SA47, 1990SC01, 1990SC20, 1990SC32, 1990SH11, 1990ST17, 1990SZ07, 1990VA01, 1990YU02, 1991BA16, 1991CA05, 1991DE08, 1991OE01, 1991SC12, 1991US01, 1991WI05).

$$1. \ ^2\text{H}(\text{d}, \gamma)^4\text{He} \quad Q_{\text{m}} = 23.847 \quad E_{\text{b}} = 23.847$$

The previous compilation (1973FI04) reported measurements of the $^2\text{H}(\text{d}, \gamma)^4\text{He}$ reaction from $E_{\text{d}} = 0.8 - 482$ MeV. Measurements and summaries since 1973 are presented in Table 4.4.

The early measurements of (1973PO01) at $E_{\text{d}} = 6.05, 8.96$, and 11.67 MeV gave $\sigma(\theta) \approx \sin^2 2\theta$, and it was concluded that the process proceeded through an E2 transition by ${}^1\text{D}_2 \rightarrow {}^1\text{S}_0$. Measurements at 376 MeV (1984SI01), however, corroborate deviations reported in the inverse reaction by (1976AR05) from the $\sin^2 2\theta$ angular dependence. The cross section results are consistent with time-reversal invariance.

A measurement (1984WE14) of tensor analyzing power T_{20} at $E_{\text{d}} = 9.7$ MeV gave a non-zero isotropic result which was used in connection with a heuristic model calculation assuming E2 radiation to imply a 4.8% D-state admixture in the two-deuteron wave function of ${}^4\text{He}$. Earlier evidence for the ${}^4\text{He}$ D-state was provided in a study (1975PL01) of phase shifts for $\text{p} + {}^4\text{He}$ elastic scattering. Calculations reported in (1985SA04) examined the $^2\text{H}(\text{d}, \gamma)^4\text{He}$ analyzing powers for $E_{\text{d}} < 20$ MeV, and led to the conclusion that the tensor analyzing powers depend linearly on the asymptotic D/S ratio ρ . Using wave functions with phase shifts obtained from resonating group calculations, they found good agreement with the T_{20} data of (1984WE14) for $-0.5 < \rho < -0.4$. These large values of ρ were superseded by later, more detailed calculations (see below). Measurements of vector and tensor analyzing powers at $E_{\text{d}} = 10$ MeV reported in (1986ME02, 1986ME16) indicated the presence of multipoles other than E2, and arguments are presented that the reaction cannot be used to determine the D-state admixture in ${}^4\text{He}$ unless the deuteron D-state and other tensor force effects in the entrance channel are taken into account. Calculations of (1986TO11) considered M1, E1, M2, and E2 transitions and obtained agreement with the results of (1986ME02, 1986ME16) using ${}^4\text{He}$ wave functions which were obtained from variational calculations (1986SC03) and which indicated a value for the ${}^4\text{He}$ D-state parameter (1986TO11) $D_2 \approx 0.2$ fm 2 . The energy dependence of vector and tensor analyzing powers at 130° from 0.3 to 50 MeV (1988WE15) indicates that $A_{yy}(130^\circ)$ is sensitive to ${}^4\text{He}$ D-state components and has its maximum value near $E_{\text{d}} = 30$ MeV. Some of these results are reviewed in (1987GR08).

A recent measurement (1989PI06) of cross sections and analyzing powers at intermediate energy ($E_{\text{d}} = 95$ MeV) indicated the dominance of the $\langle {}^1\text{D}_2 | \text{E}2 | {}^1\text{S}_0 \rangle$ transition involving the S-state component of ${}^4\text{He}$.

Experiments on the $^2\text{H}(\text{d}, \gamma)^4\text{He}$ reactions at low bombarding energies (50 – 150 keV) relevant to astrophysical processes were reported in (1985WI08). (This reaction had been proposed earlier (1984CE03) as a temperature diagnostic for plasmas). The Γ_γ/Γ_p ratio was measured, and it was noted that a D-state component in the ${}^4\text{He}$ wave function is a possible explanation for the result obtained. The measured cross section for E_{d} between 0.7 and 4.5 MeV and angular distributions of cross sections at $E_{\text{d}} = 1.38, 2.05, 9.6$ and 15 MeV (1986WE07) were interpreted to indicate that the ${}^4\text{He}$ D-state has large effects on the energy and angle dependence of the low-energy capture cross sections. In particular it was shown that the ratio $\sigma(90^\circ)/\sigma(135^\circ)$ increased at low energies in such a way as to imply an asymptotic D- to S-state ratio $\rho = -0.2 \pm 0.05$. Measurements of $\sigma(E)$ and $\sigma(\theta)$ for $E_{\text{c.m.}} = 50 - 500$ keV (1987BA58) were interpreted to indicate that the ${}^5\text{S}_2 \rightarrow {}^5\text{D}_0$ amplitude is dominant for $E_{\text{c.m.}} < 200$ keV. The indicated astrophysical

S-factor ([1984FO1A](#)) is 32 times larger than previously estimated and may affect inhomogeneous big-bang nucleosynthesis models.

Theoretical studies ([1987AS03](#)) of the $^2\text{H}(\text{d}, \gamma)^4\text{He}$ reaction based on a microscopic description of the nuclear wave function reproduce the data for $E_{\text{d}} < 3$ MeV and indicate a 5–7% D-state admixture in the ^4He ground state. The study reported in ([1987BL12](#)) finds that conclusions about D-state components based on simple potential model analysis of experimental data are very sensitive to the parametrization of the nucleus-nucleus potential and may be misleading. The phenomenological study of $^2\text{H}(\text{d}, \gamma)^4\text{He}$ ([1987PI08](#)) allows for the D-state component of the colliding deuterons and concludes that it is important in estimating the effects of D-state components in ^4He . However, a more detailed calculation including these same effects ([1988AR11](#)) has shown that the value of $\rho \approx -0.4$ suggested in ([1987PI08](#)) is too large and should be -0.2 as proposed in ([1986WE07](#)). The difficulty of extracting D-state properties in ^4He is demonstrated in the work of ([1988WA02](#)), using a microscopic multi-channel resonating-group model. This model was used by ([1988LA14](#), [1990LA16](#)) in the analysis of measurements of cross sections and vector and tensor analyzing powers at $E_{\text{d}} = 1.2$ MeV to conclude that the cross section consists of nearly equal contributions of E2, E1, and M2 radiation, and that the tensor analyzing power is primarily due to the large E1/M2 strength. The results of this calculation are compared with experimental data on A_y and A_{yy} for $E_{\text{d}}(\text{lab}) = 0.3 – 50$ MeV. Good agreement was obtained with A_{yy} , but A_y was overpredicted at low energies (1 – 2 MeV). See also ([1990WE03](#)). This model predicts a D-state probability of 2.2% in ^4He , but this is only the two-deuteron part of the D-state.

An extensive review of the manifestations of the D-State in ^4He and other light nuclei is presented in ([1988WE20](#)). It is worth noting that the most recent calculations of ([1988CA19](#)), which use the Green function Monte Carlo method, indicate a *total* D-state probability in ^4He ranging from 12 to 17.5%, depending on the details of the NN interaction assumed. A variational Monte Carlo calculation ([1991AR01](#)) of the reaction for $E_{\text{d}} \leq 500$ keV indicated that at these energies the reaction proceeds through the D-states in the deuteron and the alpha particle, and that the contribution of the ^2H or ^4He D-states can either add to produce a large cross section or cancel. A recent review of non-spherical components of ^4He and other light nuclei is presented in ([1990EI01](#)).

2. (a) $^2\text{H}(\text{d}, \pi^0)^4\text{He}$	$Q_{\text{m}} = -111.1$
(b) $^2\text{H}(\text{d}, 2\pi^0)^4\text{He}$	$Q_{\text{m}} = -246.1$
(c) $^2\text{H}(\text{d}, \pi^+\pi^-)^4\text{He}$	$Q_{\text{m}} = -255.3$

Measurements of the charge-symmetry-breaking reaction (a) reported in ([1987BA15](#)) established an upper limit of $\sigma(\theta) \approx 0.8 \times 10^{-6} \mu\text{b}/\text{sr}$ at $E_{\text{d}} = 0.8$ GeV, $\theta_{\text{c.m.}} \approx 100^\circ$. An historical synopsis of experiments and theoretical estimates of reaction (a) is also presented. An earlier measurement reported in ([1974BA2H](#)) gave an upper limit $\sigma(\theta) \approx 1.9 \times 10^{-5} \mu\text{b}/\text{sr}$ at $E_{\text{d}} = 1.89$ GeV, $\theta_{\text{c.m.}} \approx 79^\circ$. See also ([1981EG03](#)). A theoretical calculation ([1982CH27](#)) assuming various charge-symmetry-breaking mechanisms gave $0.1 \times 10^{-6} \mu\text{b}/\text{sr}$ for $\sigma(\theta)$ at 0° in the region of the $\Delta(3, 3)$ resonance. More recently $\sigma(\theta)$ at 0° was estimated ([1986CO01](#)) to be $\approx 0.8 \times 10^{-6} \mu\text{b}/\text{sr}$ at $E_{\text{d}} = 1.95$ GeV assuming virtual η and η' production and $\pi^0\eta$ and $\pi^0\eta'$ mixing. See also ([1976BA1A](#), [1985BA1X](#)). For references to earlier work see ([1973FI04](#)).

3. ${}^2\text{H}(\text{d}, \text{n}){}^3\text{He}$

$Q_m = 3.269$

$E_b = 23.847$

Measurements and summaries of cross sections, polarizations, analyzing powers, and polarization transfer coefficients are presented in Table 4.5. Summaries and discussions of earlier works are given in the previous compilation (1973FI04). Several experiments which have a bearing on possible excited states in ${}^4\text{He}$ have been reported. Measurements of $\sigma(E, \theta)$ at 70 – 150 keV (1975PO04) indicate no evidence for a resonance near the dd threshold in ${}^4\text{He}$. Measurements of $\sigma(\theta)$ made at lab energies of 300 – 700 keV (1973YI01) were expanded in even powers of $\cos\theta$ and indicate some evidence for a state in ${}^4\text{He}$ at 23.9 MeV, but do not differentiate between suggested assignments of 2^+ or 1^- . A measurement of $P_n(\theta)$ (1976TO03) is discussed in relation to possible f-wave admixtures on the 2^+ state in ${}^4\text{He}$ at 22.1 MeV. Measurements of $\sigma(E, \theta)$ between 18 and 26 MeV (1980JO07) and Legendre polynomial fits provide no evidence of a proposed level in ${}^4\text{He}$ near 30 MeV.

Several measurements of the ${}^2\text{H}(\text{d}, \text{n}){}^3\text{He}$ cross section have been made at low energies ($E_d < 1$ MeV) that are relevant to plasma physics or astrophysics. (See Table 4.5). Recent work reported in (1987KR18) with windowless gas targets at $E_{\text{c.m.}} = 2.98 - 162.5$ keV extend into the plasma fusion region and deduce the astrophysical factor $S(E)$ and present polynomial fits. Another measurement of $S(E)$ at 125 keV is reported in (1986BR20).

Several experimental studies related to the use of the reaction for a source of monoenergetic neutrons have been carried out and are included in Table 4.5. See especially the work reported in (1978DR08), which establishes an absolute scale for $\sigma(\theta)$ for $E_d = 6 - 17$ MeV. Extensive tables of cross sections and Legendre coefficients are presented. See also (1972DI05, 1973SA20, 1973WE19, 1981PA26). Analyzing power measurements are reported in (1972DU02, 1972GR28, 1972HA49, 1972SM04, 1972SP05, 1974SA07, 1975GA07, 1976TO03, 1983GU03). Polarization transfer measurements are described in (1973SA20, 1974SA07, 1975LI08, 1984KL05). See also the recent review (1990DR10) of accelerator-based monoenergetic neutron source reactions, including ${}^2\text{H}(\text{d}, \text{n})$, for fusion-related applications.

Measurements of observables for the mirror reactions ${}^2\text{H}(\text{d}, \text{n}){}^3\text{He}$ and ${}^2\text{H}(\text{d}, \text{p}){}^3\text{H}$ and the implications of possible differences on the question of charge-symmetry violations are described in (1972GR28, 1973YI01, 1975PO04, 1978KO06, 1979DR01, 1979KO23, 1980BI08, 1981AD04). See also the compilations of (1987FI03, 1987GR08).

Theoretical work described in (1972SE02, 1972SE25) concludes that the different anisotropy observed for the (d, n) and (d, p) angular distributions at low energies can be explained by new negative-parity $T = 0$ levels with small nucleon and single-particle deuteron widths. Analysis (1987KO21) of polarization data for the (d, p) and (d, n) reactions indicates no evidence for a $J^\pi = 1^-$ level in ${}^4\text{He}$ at 24.1 MeV.

Analyzing powers and polarizations for ${}^2\text{H}(\text{d}, \text{n}){}^3\text{He}$ and ${}^2\text{H}(\text{d}, \text{p}){}^3\text{H}$ were calculated (1980BE21) in a generalized R -matrix methodology framework, and the differences predicted were an order of magnitude smaller than those reported by (1979DR01). The (d, p) and (d, n) reactions were also studied (1973FI10) at energies below 200 keV, and the relationship between an “ R -matrix approach” and a “direct approach” to the reaction were discussed. Soluble four-body models have been used (1976FO13, 1979FO08, 1983OS05) to predict the (d, n) cross section. A four-nucleon K -matrix approach is discussed in (1985SO07). See also (1976SA02). The parameterization of polarization observables in terms of matrix elements for ${}^2\text{H} + \text{d}$ reactions is given in (1982AD04). The mirror reactions ${}^2\text{H}(\text{d}, \text{n}){}^3\text{He}$ and ${}^2\text{H}(\text{d}, \text{p}){}^3\text{H}$ were studied (1990VA04) in a multichannel resonating group framework, and the parameters of $J^\pi = 0^+, 0^-, 1^-, 2^-$ resonances in ${}^4\text{He}$ are established. An analysis of all available data on these mirror fusion reactions was carried out (1990LE23) to extract reaction matrix elements for $E_d \leq 500$ keV. The effect of the ${}^2\text{H}(\text{d}, \text{n})$ reaction rate on predicted abundances of light isotopes from primordial nucleosynthesis is investigated in (1991RI03).

Table 4.5: Measurements and summaries (S) of cross sections $\sigma(\theta)$ and analyzing powers $A(\theta)$ for $^2\text{H}(\text{d}, \text{n})^3\text{He}$

E_{d} (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg)	Description	Refs.
11.4	iT_{11}	10 – 140	Compared with $^2\text{H}(\text{d}, \text{p})^3\text{H}$ to check charge symmetry.	1972BL02
12, 14, 16, 18	$\sigma(\theta), \sigma(E_{\text{n}}, 0^\circ)$	0 – 65	Looked for evidence of resonances in ^4He .	1972DI05
10.8	P_{n}	35 – 60		1972DU02
10.0, 11.5	$iT_{11}, T_{20}, T_{21}, T_{22}$	95 – 156	Looked for excited states in ^4He .	1972GR28
16, 18, 20, 22	P_{n}	45	Discussed usefulness of reaction for polarized n source.	1972HA49
1.96 – 6.2	$\sigma(E, \theta)$	0 – 15, 0 – 180	$^2\text{H}(\text{d}, \text{n})^3\text{He}$, t.o.f. Measured $^2\text{H}(\text{d}, ^3\text{He})\text{n}$.	1972SC28
0.87 – 5.00	P_{n}	10 – 150	Compared with $^2\text{H}(\text{d}, \text{p})^3\text{H}$.	1972SM04
6, 8, 10, 12, 14	P_{n}	10 – 90		1972SP05
0.3 – 0.9	P_{n}	46	Studied polarimeter errors.	1973DA15
3.3 – 14.9	K_z^z	0	Studied use of $^2\text{H}(\vec{\text{d}}, \vec{\text{n}})$ as reaction source.	1973SA20
18.6	$\sigma(E_{\text{d}}, E_{\text{n}})$	3.5 – 32	Studied use of reaction as high intensity n source.	1973WE19
0.3 – 0.7	$\sigma(E, E_{^3\text{He}}, \theta)$	20 – 160	Measured relative $^2\text{H}(\text{d}, \text{n}), ^2\text{H}(\text{d}, \text{p})$ cross sections.	1973YI01
13.9 – 15.25	$\sigma(E_{\text{d}}, E_{\text{n}}, \theta)$	0 – 130		1975AZ02
1.1 – 5.45	P_{n}	27 – 105		1975GA07
1 – 15	$K_y^{y'}, A_{zz}$	0	Provided observables needed for use of $^2\text{H}(\vec{\text{d}}, \vec{\text{n}})$ as source reaction.	1975LI08
0.07 – 0.15	$\sigma(E, \theta)$	15 – 165	No evidence for resonance near dd threshold.	1975PO04
0.052 – 0.692	P_{n}	52 – 53	Used new type of He recoil polarimeter.	1975SI16
2.44	P_{n}	45, 55	Agreed with (1975GA07).	1976TO03
0.035 – 0.275	P_{n}	45	No evidence for resonance at 100 keV.	1977AL08
50 – 85	$\sigma(\theta)$	12.5 – 45	Measured $^2\text{H}(\text{d}, \text{n})$ and $^2\text{H}(\text{d}, \text{p})$.	1978AL26
6 – 17	$\sigma(\theta)$	$\approx 0 – 180$	Established absolute scale for $\sigma(\theta)$ by calibrated t.o.f. system.	1978DR08(S)
2.5 – 11.5	$iT_{11}, T_{20}, T_{21}, T_{22}$	20 – 160	Measured for $^2\text{H}(\text{d}, \text{n}), ^2\text{H}(\text{d}, \text{p})$. Reported differences.	1978KO06

Table 4.5: Measurements and summaries (S) of cross sections $\sigma(\theta)$ and analyzing powers $A(\theta)$ for ${}^2\text{H}(\text{d}, \text{n}){}^3\text{He}$ (continued)

E_{d} (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg)	Description	Refs.
15.5, 17.0	$A_y, A_{xx}, A_{yy}, A_{xz}$	70 – 130	Measured ${}^2\text{H}(\text{d}, \text{n})$ and ${}^2\text{H}(\text{d}, \text{p})$.	1979BR18
0.5 – 5.5	$A_{zz}, A_y, A_{zz}, A_{xz}, A_{xx-yy}$	0, 0 – 160	Compared with ${}^2\text{H}(\text{d}, \text{p})$. Found differences.	1979DR01
0.100 – 0.500	P_n	45 – 130	Used improved small angle Mott-Schwinger scattering Polarimeter.	1979GA05
13.6, 24.3	$\sigma(\theta)$	0	Used gas target proton recoil telescope.	1979GO21
4 – 13	$iT_{11}, T_{20}, T_{21}, T_{22}$	wide range	Measured for ${}^2\text{H}(\text{d}, \text{n}), {}^2\text{H}(\text{d}, \text{p})$. Report evidence for CS violation.	1979KO23
300 – 1250	$\sigma(E_{\text{d}}, \theta)$	0 – 60	Phenomenological analysis of baryonic exchange mechanism.	1980BI08
10	$K_y^y, K_x^x, K_z^z, K_z^x, K_z^y, K_y^{y'}, A_y, A_{xx}, A_{yy}, A_{zz}$	0 – 180		1974SA07
0.290 – 0.460	P_n	24.5 – 90		1980GA03
18 – 26	$\sigma(E_{\text{d}}, \theta)$	20 – 90	Detected recoils.	1980JO07
0.06 – 0.485	$A_y, A_{zz}, A_{xz}, A_{xx-yy}$	20 – 150	Detected recoils. Studied ${}^2\text{H}(\text{d}, \text{n})$ and ${}^2\text{H}(\text{d}, \text{p})$.	1981AD04
3 – 6	$\sigma(\theta)$	0	Used Proton recoil telescope.	1981PA26
8.0	P_n	0 – 20	Measured $P_n(\theta)$ at small angles to explore properties of reaction for source of polarized neutrons.	1981TO15
6.4, 8.03	$\sigma(\theta)$	0	Reported technique to correct for background from breakup neutrons.	1982GR26
5.5 – 11.5	A_y	0 – 150		1983GU03
0.14	$\sigma(E_{\text{d}}, E_{\text{n}})$		Used high pressure ${}^3\text{He}$ ion chamber to measure n spectra from ${}^2\text{H}$ plasma.	1984FI04
52	$P_n, A_y, K_y^{y'}$	60 – 160		1984KL05
11	$\sigma(E_{\text{d}}, E_{\text{n}})$		Used NE213 and t.o.f. simultaneously.	1986AN32
0.125	$S(E), \text{ anisotropy versus } E$			1986BR20
18	P_n	0 – 85.4	Used liquid ${}^4\text{He}$ as scintillator in n polarimeter for $E_{\text{n}} = 3 – 18$ MeV.	1987IE02
0.0298 – 0.1625	$\sigma(E, \theta)$		Used windowless gas target. Deduced $S(E)$.	1987KR18

Table 4.5: Measurements and summaries (S) of cross sections $\sigma(\theta)$ and analyzing powers $A(\theta)$ for ${}^2\text{H}(\text{d}, \text{n}){}^3\text{He}$ (continued)

E_{d} (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg)	Description	Refs.
0.001 – 19	$\sigma(E_{\text{n}}, \theta)$	0, 90	Studied background problems.	1989BO41
0.02 – 0.117	$\sigma(E, \theta)$	20 – 130	2.0% accuracy. R -matrix analysis.	1990BR04
18	P_{n}	15 – 75		

The ${}^2\text{H}(\text{d}, \text{n}){}^3\text{He}$ reaction at very low energies ($E_{\text{d}}(\text{c.m.}) < 55$ keV) is calculated in a one-step reaction model and discussed in ([1988AB03](#)). An extended elastic model is applied in ([1989SC25](#), [1989SC36](#)) to calculate reaction rates for very low energies ($T \approx 300$ K). Branching ratios in (d, n) and (d, p) reactions at low energies are estimated in a second-order DWBA calculation in ([1990KO26](#)). The fusion of polarized deuterons is considered in ([1984HO10](#)) and it is argued that a “neutron lean” $\text{d}-{}^3\text{H}$ fusion reactor is unlikely to actually be so. On the other hand, the DWBA calculation of ([1986ZH05](#)) indicates that such a reactor may be feasible.

$$4. {}^2\text{H}(\text{d}, \text{p}){}^3\text{H} \quad Q_{\text{m}} = 4.033 \quad E_{\text{b}} = 23.847$$

Measurements and summaries of cross sections, polarizations, analyzing powers, and polarization transfer coefficients are given in Table 4.6. Earlier work is reviewed in the previous compilation ([1973FI04](#)). For a review of recent measurements of polarization observables for the ${}^2\text{H}(\text{d}, \text{p}){}^3\text{H}$ reaction and a comparison with model calculations, see ([1987GR08](#)).

Recent measurements at low energies ([1987KR18](#)) have provided more accurate determinations of the astrophysical factor $S(E)$. See also ([1985JA16](#), [1986BR20](#)).

A considerable number of experiments have examined the cross section and polarization observables for differences between the charge-symmetric reactions ${}^2\text{H}(\text{d}, \text{p}){}^3\text{H}$ and ${}^2\text{H}(\text{d}, \text{n}){}^3\text{He}$. Measurements of vector polarization at 1 MeV ([1987KO22](#)) for both reactions give differences outside of the experimental uncertainties. Analyzing power measurements for both reactions for deuteron energies between 60 and 485 keV ([1981AD04](#)) are presented in contour plots which are very similar for the two reactions. Differential cross sections measured for (d, p) and (d, n) at 13.2 MeV ([1979OK01](#)) coincide closely. Precision polarization transfer measurements at 10 MeV ([1974GR30](#)) and for energies between 6 and 15 MeV ([1973CL05](#)) are compared with (d, n) values and show little or no differences within uncertainties. On the other hand, measurements of vector and tensor analyzing powers for $E_{\text{d}} = 1.5 - 15.5$ MeV are interpreted ([1979KO23](#)) to indicate strong evidence for charge-symmetry violation. Measurements of these observables at $E_{\text{d}} < 5.5$ MeV ([1979DR01](#)) and at $E_{\text{d}} = 2.5 - 11.5$ MeV ([1978KO06](#), [1978KO26](#)) show significant differences between the two reactions, while measurements at 13.39 and 17.00 MeV ([1979BR18](#)) indicate smaller differences at these higher energies.

Polarization measurements below 1 MeV ([1985KO20](#)) indicate that $P^{y'}(\theta)$ is a slowly varying function of E_{d} , and that the $l = 1$ barrier penetration factor is sufficient to describe the energy dependence. Cross section measurements between 70 – 150 keV ([1975PO04](#)) indicate no evidence for a resonance near the $\text{d} + \text{d}$ threshold. Tensor analyzing power data measured in the same region are discussed along with other available data and fail to provide conclusive evidence for a resonance. Cross section data measured between

300 – 400 keV ([1973YI01](#)) indicate the need for a state in ${}^4\text{He}$ at 23.9 MeV but do not distinguish between 2^+ and 1^- . Measurements ([1981GR16](#)) of the cross section and tensor analyzing power for $E_d = 1 - 13$ MeV are fitted with Legendre polynomials and give clear evidence ([1987GR08](#)) for a 1^- level at 24.1 MeV and strong indications of a 4^+ level at 24.6 MeV.

Table 4.6: Measurements and summaries (S) of cross sections, polarizations, and polarization transfers for ${}^2\text{H}(\text{d}, \text{p}){}^3\text{H}$

E_p (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg)	Description	Refs.
7.1, 9.8	$A_y^y, A_{xz}^y, A_{zz}^0$	0	Studied reaction mechanism.	1972DU18
3.0 – 11.5	$\sigma(\theta), iT_{11}, T_{20}, T_{21}, T_{22}$	7.5 – 160	Looked for ${}^4\text{He}$ resonance.	1972GR28
1.96 – 6.20	$\sigma(E, \theta)$	10 – 150	Sought improved accuracy, absolute σ .	1972SC28
6 – 15	$K_y^{y'}, K_{yz}^{x'}$	0	Compared with (d, n) (six energies).	1973CL05
0.3 – 0.7	$\sigma(E, E_p, \theta), \sigma(E, {}^3\text{He}, \theta)$	20 – 160	Detected all charged particles. Compared with (d, n), looked for ${}^4\text{He}$ state.	1973YI01
10	$P_y^y, K_x^{x'}, K_y^{y'}, K_z^{x'}, K_{xx}^y, K_{yy}^{y'}, K_{zz}^{y'}, K_{xz}^{y'}$	21 – 82	Cooled ${}^2\text{H}$ target; He polarimeter.	1974GR30
0.09 – 0.190	Tensor analyzing power versus E_d		Explored anomaly near $E_d = 100$ keV.	1974GU22
13.6	$\sigma(E_d, \theta)$	20.9 – 146	Accurate to <1% error.	1974JA15
12	$A_y(E_d, \theta)$		Polynomial fits. Explored possible resonance in ${}^4\text{He}$.	1974NE13
12.6	$A_y(\theta)$		Compared A_y, P_y .	1974ZA06
0.7 – 0.150	$\sigma(E_d, \theta)$	15 – 160	Measured (d, p), (d, n). Looked for ${}^4\text{He}$ state.	1975PO04
50 – 85	$\sigma(E_d, \theta)$	12.5 – 45 (lab)	PWBA analysis.	1978AL26
2.5 – 11.5	$iT_{11}, T_{20}, T_{21}, T_{22}$	20 – 160	Compared (d, p), (d, n). Possible CSB.	1978KO06
13.39, 15.50, 17.00	$A_y, A_{xx}, A_{yy}, A_{zx}$	20 – 150	Explored asymmetry about 90°. Measured, compared (d, p), (d, n).	1979BR18
0.5 – 5.5	A_{zz}	0	Compared (d, p), (d, n). Explored possible CSB.	1979DR01
4.0 – 13	$iT_{11}, T_{20}, T_{21}, T_{22}$	5 – 160	Compared (d, p), (d, n). Possible CSB.	1979KO23

Table 4.6: Measurements and summaries (S) of cross sections, polarizations, and polarization transfers for ${}^2\text{H}(\text{d}, \text{p}){}^3\text{H}$ (continued)

E_{p} (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg)	Description	Refs.
13.2	$\sigma(\theta)$	12 – 90	DWBA analysis, compared (d, p), (d, n).	1979OK01
300 – 1250	${}^4\text{He}$	0 – 60	Baryon exchange interpretation.	1980BI08
0.120 – 0.5	$\sigma(E_{\text{d}}, E_{\text{p}})$	90, 135	Information for ion-beam analysis.	1980MO03
0.6 – 0.485	$A_y, A_{zz}, A_{xz}, A_{xx-yy}$	20 – 150 (lab)	Compared (d, p), (d, n). Extrapolated to low E .	1981AD04
1 – 13	$\sigma(E_{\text{d}}, \theta), iT_{11}$	5 – 160 (lab)	Found evidence for levels in ${}^4\text{He}$.	1981GR16
0.02 – 0.117	$\sigma(E_{\text{d}}, \theta)$		Extracted $S(E)$.	1985JA16
0.250 – 0.975	$P^{y'}$	15 – 85 (lab)	Analyzed in term of barrier penetration parameters.	1985KO20
0.125	$S(E)$		Measured $S(E)$, studied H fusion reactions.	1986BR20
1 – 24	$\sigma(E_{\text{d}}, \theta), T(\theta), A(\theta)$		Reviewed new pol. observables, evidence for levels in ${}^4\text{He}$.	1987GR08(S)
0.975	$P^{y'}$	15 – 100	Precision measurements. Compared with (d, n) to examine CSB.	1987KO22
0.0298 – 0.1625	$\sigma(E_{\text{d}}, \theta)$		Windowless gas target. Deduced $S(E)$.	1987KR18
0.02 – 0.117	$\sigma(E, \theta)$	20 – 130	2.0% accuracy. R -matrix analysis.	1990BR04

A review of recent progress in theoretical studies of four-body scattering and breakup including the (d, p) and (d, n) reactions focusing on the integral-equation approach is presented in ([1987FI03](#)). Calculations of this type are reported in ([1977BA46](#), [1977PE13](#), [1982BL15](#), [1983OS05](#), [1984BA17](#), [1984FO08](#), [1985SO07](#), [1986FO07](#), [1989FO13](#), [1990FO02](#)).

Calculations ([1980BE21](#)) within the framework of a generalized R -matrix methodology compare the analyzing powers and polarizations for the (d, p) and (d, n) reactions. See also ([1977BE02](#)). A number of theoretical studies and analyses related to possible states in ${}^4\text{He}$ were carried out. Microscopic multi-channel calculations reported in ([1981HO04](#)) propose an additional low-lying $1^- T = 0$ level, but rule out a d + d threshold level and find no evidence for a 1^+ level around 25.5 MeV. A calculation reported in ([1990VA04](#)) for (d, n) and (d, p) establishes the parameters of resonances in ${}^4\text{He}$ with $J^\pi = 0^+, 0^-, 1^-, 2^-$. An R -matrix approach ([1987KO21](#)) used to analyze (d, p) and (d, n) polarization data finds no evidence for a 1^- level at 24.1 MeV. Theoretical arguments ([1972SE02](#)) are used to suggest $T = 0$ states in ${}^4\text{He}$. Criteria for analysis of polarized deuteron reactions, and signatures of excited states and level parameters are derived in ([1975SE07](#)). See also ([1974NE13](#), [1982AD04](#)). A method for empirical continuation of polarization observables for ${}^2\text{H}(\text{d}, \text{p})$ is presented in ([1989BO32](#)). See also the study of three-body Coulomb effects in one-particle transfer reactions ([1990KA17](#)). Calculations related to the (d, p) and (d, n) reaction

at low energies include (1987AS05), which examines the effect of electron screening at fusion energies. An elastic model for subbarrier fusion for the $^2\text{H}(\text{d}, \text{n})$ and $^2\text{H}(\text{d}, \text{p})$ reactions is applied at very low energies in (1989SC25, 1989SC36). Branching ratios for these reactions at very low energies are estimated in second order DWBA in (1990KO26). See also (1973FI10, 1981AD07). An analysis of all available data on these mirror fusion reactions was carried out (1990LE23) to extract reaction matrix elements for $E_{\text{d}} \leq 500$ keV. The effect of the $^2\text{H}(\text{d}, \text{n})$ reaction rate on predicted abundances of light isotopes from primordial nucleosynthesis is investigated in (1991RI03).

5. (a) $^2\text{H}(\text{d}, \text{npd})$	$Q_{\text{m}} = -2.225$	$E_{\text{b}} = 23.847$
(b) $^2\text{H}(\text{d}, 2\text{n}2\text{p})$	$Q_{\text{m}} = -4.449$	$E_{\text{b}} = 23.847$

Measurements and summaries of particle spectra from the breakup reactions (a) and (b) reported since 1973 are presented in Table 4.7. Earlier work is reviewed in (1973FI04).

The dp and dn spectra obtained for $E_{\text{d}} = 6 - 13$ MeV and reported in (1972VA04, 1972VA05) are dominated by a broad peak associated with d-nucleon quasi-free scattering (QFS). A simple quasi-free scattering model predicts general behavior, but not the magnitude of the cross section. Spatial localization effects were considered in (1973VO06) in a phenomenological explanation of the peaks in some coincidence spectra. Quasi-free scattering was analyzed (1976DJ01) in terms of the modified single-impulse approximation (MSIA). The final-state interaction (FSI) coincidence spectra agreed with the triplet np enhancement factor. See also (1972BU03). Work reported in (1972AN02) indicates a ratio of peak cross sections for nd and pd quasi-free scattering that is constant and close to one. Energy spectra at $E_{\text{d}} = 12$ MeV are explained (1982JE04) with a superposition of triplet np FSI and QFS. It is reported in (1978KL07) that the angular distribution of np pairs with zero relative energy can be predicted absolutely from dd elastic scattering. No evidence of isospin non-conservation is found. The measured nd and pd angular distributions are identical. FSI studies reported in (1973CH05) give no indication of any contribution from the (isospin forbidden) ${}^1\text{S}_0$ pn final state. Proton-deuteron coincidence spectra were used in (1972VO13) to test the Trieman-Yang criterion. The results indicate that the one-pole graph is not sufficient to describe the reaction. Three-body breakup energy spectra for $E_{\text{d}} = 60$ MeV (1982FU10) show large forward-angle enhancements and can be reproduced by calculations in the single-scattering four-body model.

Absolute cross sections for the four-body breakup reaction (b) were measured (1975WA09), and evidence for a double final-state interaction was obtained. Plane-wave analysis of measurements made at $E_{\text{d}} = 34.7$ MeV (1978AL21) under the two-spectator condition gave an experiment/theory ratio of about 0.14. At 80 MeV (1978LE01) analysis indicated that, in addition to the double-spectator process, the process of double spin-flip excitation is important. (See also (1985KO01)). However, good fits to these same data were obtained (1981WA29) by assuming final-state interactions between both final np pairs and ignoring the double-spectator process. Measurements at 15.7 MeV are reported in (1987ZH11) and interpreted to indicate evidence for a ${}^2\text{He}$ resonant state with a breakup energy of 0.45 MeV.

A review of quasi-free processes in few-body systems is presented in (1974SL04). See also (1973SL04) for a critical analysis of models. Off-energy-shell corrections to nucleon-deuteron scattering amplitudes are explored in (1972DU12). Absolute magnitudes and shapes for QFS processes in reaction (a) are correctly predicted by the use of Eckart cluster-model wave functions. A possible explanation of the colinearity effect involving rescattering is examined in (1976RE08). Calculation of the three-body breakup cross section in the Alt, Grassberger and Sandhas (AGS) formalism reported in (1986MD02) gives good agreement at low

energies for the shapes but not the magnitudes. Agreement with the magnitudes improves at higher energies. Coulomb effects in quasi-free scattering are explored ([1987BA27](#)) by the use of exact three-body scattering theory for Coulomb-like potentials. Four-body AGS calculations for reaction (a) are extended ([1988MD01](#)) to regions where final state interactions are important.

Table 4.7: Measurements and summaries (S) of particle spectra from the ${}^2\text{H} + {}^2\text{H}$ reaction

E_d (MeV)	Particle detected	θ (deg)	Description	Refs.
12.5	dp, dn coin.	$\theta_n = -\theta_d$	Compared QFS in d + d, p + d processes.	1972AN02
27.5	dn coin.	3 angular conditions	Studied quasi-free processes, MSIA analysis.	1972BU03
11.3 (pol)	n	0 – 60° (lab)	Searched for spin dependent effects in 3-body final state.	1972PO02
10	pn	$\theta_n = 0$	QFS model analysis. Compared with p + d process.	1972VA04
6 – 13	np, nd, pd coin.	$\theta_1 = -\theta_2$	Studied dominance of Nd QFS processes.	1972VA05
20	pd coin.		Conditions chosen to enhance nd QFS, test Trieman-Yang criterion.	1972VO13
27.5	pn coin.	$\theta_p = \theta_n$	Conditions chosen to enhance np FSI.	1973CH05
23.15	pp coin.	small pp	Absolute σ , looked for double FSI, nn, pp relative energy spectra.	1975WA09
50 – 85	pd coin.	2 angle pairs	Angles chosen to study both QFS and FSI.	1976DJ01
34.7	pp coin.	symmetric angle pairs $\theta_p = 34.8^\circ$	Studied two-spectrum quasi-free processes.	1978AL21
52	pd, nd coin.		Studied angular dependence of np FSI, pd and nd QFS.	1978KL07
80	pp coin.	symmetric angle pairs θ_p	Geometry chosen to emphasize double spectator processes.	1978LE01
60	d, p energy spectra	forward angles	Compared with single scattering 4-body model.	1982FU10
12	dp coin.	3 dp angle pairs	Compared with triplet np FSI and 4-body model.	1982JE04
108	pp, pn, coin.	correlated np pairs	Studied two-spectator QFS processes.	1985KO01
50	pp, pd coin.	several angle pairs	Studied use of QFS to measure effective radius r_{nn} .	1987GO13
15.7	pp coin.	24.1, 49.7, 19.9, 52.2, 17.8, 53.7, 15.2, 56.3, 12.8	Measured resonant-particle spectrum. Deduced resonant spectrum of intermediate state.	1987ZH11
60			Measured A_y .	1989FU12
5.3 – 13.3	n		Measured neutron yield.	1990CA36
12	n		Measured $\sigma(\theta, E)$.	1990FEZZ

Measurements and summaries (S) of cross sections and analyzing powers are presented in Table 4.8. Summaries and discussions of earlier work can be found in the previous compilation ([1973FI04](#)). As noted there, the cross section has no pronounced structure below $E_d = 40$ MeV ($E_x = 24 - 44$ MeV in ${}^4\text{He}$). In the very low energy region, $E_d = 80 - 360$ keV, measurements of the cross section ([1975MA43](#), [1975NI06](#)) provided no evidence for a resonance near the d + d threshold. Similarly, the cross section measured at $E_d = 9.8 - 36$ MeV ([1985NE04](#)) showed a smooth pattern with no indications of resonances. Measurements of vector and tensor analyzing powers at $E_d = 6 - 11.5$ MeV ([1972GR29](#)) show a vector component which is small but non-zero and changes sign between 6.0 and 10.0 MeV, and tensor components which increase monotonically with energy. No resonance-like behavior is observed, but arguments are made that the sign change of iT_{11} suggests a broad resonance near $E_x = 28$ MeV in ${}^4\text{He}$. (See also ([1972ME20](#))). At $E_d = 50$ MeV the vector analyzing power maximum is 0.32 at about $\theta_{\text{c.m.}} = 60^\circ$.

Since the earlier compilation on the $A = 4$ system, a considerable amount of theoretical work on ${}^2\text{H}(\text{d}, \text{d}){}^2\text{H}$ elastic scattering has been done. A number of these calculations involved resonating group methodologies. A resonating group method (RGM) with imaginary potential was applied ([1972CH20](#)) to d + d scattering. Comparison to experiments at 6.9 – 19.9 MeV gave good agreement with cross section data. Calculations ([1975ME25](#)) of d + d near threshold with the RGM using exact deuteron wave functions evaluated with a Malfliet-Tjon two-nucleon potential were found to predict no resonance, in agreement with experiment ([1975MA43](#)). Microscopic multichannel calculations for $A = 4$ from the first breakup threshold to $E_{\text{c.m.}} = 10$ MeV carried out ([1981HO04](#)) in the framework of a refined resonating-group model gave agreement with the well-established resonance structure, but ruled out a dd threshold resonance. An additional low-lying broad $1^- T = 0$ resonance was proposed. The work reported in ([1985XU01](#)) used single-channel RGM with a central-force NN potential having a soft repulsive core. The calculated (d, d) scattering phase shifts and cross sections for $E_d < 20$ MeV agree very well with experiment. The ground and even-parity excited states and the scattering problems for the ${}^4\text{He}$ system were examined ([1986KA21](#)) within the framework of the multichannel resonating group method and good agreement with experiment was obtained. See also the partial amplitude calculations with resonating group methods of ([1987IS06](#)).

A study of d + d elastic scattering in the helicity formalism for polarized beam is reported in ([1972LI01](#)) and includes a phase-shift analysis. A study for the case of non-conservation of channel spin is reported in ([1972PH07](#)). Expressions for σ and P are given in terms of phase shifts. The work of ([1976FO13](#)) applies a solvable model involving four identical particles to $A = 4$ scattering and reactions. A microscopic K -matrix approach is applied to the four-nucleon problem ([1977BA46](#)), and satisfactory agreement with experiment is obtained for all reactions except ${}^2\text{H}(\text{d}, \text{d})$. Work reported in ([1979FO08](#)) uses a nonrelativistic field theoretic formalism to develop a solvable model of the four-nucleon system and predicts the correct shape for the (d, d) cross section, but the magnitude is much too small. The work of ([1983OS05](#)) uses a four-body solvable model involving intermediate quasiparticle states and calculates cross sections for E_d between 6.1 and 51.5 MeV for (d, p), (d, n), and (d, d). Good agreement with experiment is obtained. In ([1984FO08](#)) a two-body separable T -matrix between pairs is used to solve the four-body equations and one-parameter models are developed to describe low- E phase shifts and cross sections for reactions and scattering. The four-body equations of Alt, Grassberger, and Sandhas (AGS) are solved ([1986FO07](#)), and contributions of p-wave (3 + 1) subamplitudes to the ${}^4\text{He}$ binding energy and scattering observables below the four-body breakup threshold are studied. See also the calculation of tensor analyzing powers in ([1989FO13](#)). A review of progress in four-body scattering and breakup in the integral equation approach is presented in ([1987FI03](#)). Calculations of (d, d) cross sections with a three-body formalism including Coulomb interactions are reported in ([1986AG03](#)).

Table 4.8: Measurements and summaries (S) of cross sections $\sigma(\theta)$ and analyzing powers $A(\theta)$ for $^2\text{H}(\text{d}, \text{d})^2\text{H}$

E_{d} (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg)	Description	Refs.
6.0, 8.0, 10.0, 11.5	$iT_{11}, T_{20}, T_{21}, T_{22}$	20 – 62.5 (lab)	Studied results for resonances in ^4He .	1972GR29
10.0	$iT_{11}, T_{20}, T_{21}T_{22}$	25 – 100	Measured recoils in coin.	1972ME20
1.96 – 6.2	$\sigma(E, \theta)$	10 – 150	Accuracy 1.7 – 3.4%. Polynomial fits.	1972SC28
1690	$\sigma(\theta)$	small angles	Obtained dd scattering amplitude. Deduced f_{dd} .	1974DU04
12.305	$\sigma(\theta)$	10 – 100 (lab)	$\Delta\sigma = 0.5 – 1.0\%$.	1974JA15
0.08 – 0.36	$\sigma(E)$	90	Searched for resonance in ^4He near dd threshold.	1975MA43
0.045 – 0.300	$\sigma(E, \theta)$	68, 90	Searched for resonance in ^4He near dd threshold.	1975NI06
52	iT_{11}	30 – 150	Measured (d, d), (d, p).	1977BE44
50 – 85	$\sigma(E, \theta)$	12.5 – 45, 2.5° steps	PWBA analysis.	1978AL26
13.2	$\sigma(E, \theta)$	12 – 90	Optical-model analysis with Majorana exchange term.	1979OK01
$p_{\text{d}} = 2.38 – 12 \text{ GeV}/c$	A_y	75 – 120	Momentum transfer $-t = 0.005 – 0.054 (\text{GeV}/c)^2$.	1989AV02
1650, 2000, 2290	$\sigma(E, \theta)$	small angles	Measured missing-mass spectra. Searched for dibaryonic resonances.	1984CO29
9.8 – 36	$\sigma(E, \theta)$	20 – 90	Compared with resonating group calculation.	1985NE04
191, 395	iT_{11}, T_{20}, T_{22}	30 – 150	Discussed applications to intermediate-energy deuteron polarimeters.	1986GA18

In (1977BE02) a new model for ${}^4\text{He}$ which treats structure and reaction aspects on an equal footing in a dynamical R -matrix methodology is presented. Results are given for the spectrum of resonances obtained within the model and for (d, d) elastic scattering. See also (1980BE18) which presents detailed results obtained with this model. Comparisons are made with data and resonating group and field theoretic approaches, noting that none of these models provides a complete description. A potential description of dd scattering is presented in (1990DU05).

Table 4.9: Measurements and summaries (S) of cross sections $\sigma(\theta)$ and analyzing powers $A(\theta)$ for ${}^3\text{H}(\text{p}, \gamma){}^4\text{He}$

E_{p} (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg)	Description	Refs.
6 – 16 (pol)	$\sigma(E, \theta), A$	45 – 135	Determined singlet and triplet E1, E2 amplitudes.	1978KIZQ
0.46, 0.50, 0.62,	$\sigma(E, \theta),$	0 – 135 (lab)	Analyzed in terms of E1, M1, E2.	1980DE32
0.77, 0.93	$P_{\gamma}(90^\circ)$			
17 – 31	Fore-aft asymmetry	55, 125	Fitted with expression including 2^+ resonance.	1980MC06
8 – 30	$\sigma(E, \theta)$	21 – 144	Tabulated σ , Legendre expansion coefficients.	1982MC03
8.34, 13.6	$\sigma(E, 90^\circ)$	90	Compared with other ${}^3\text{H}(\text{p}, \gamma), {}^4\text{He}(\gamma, \text{p}), {}^4\text{He}(\gamma, \text{n})$ data.	1983CA14
0.045 – 146	$\Gamma_{\gamma}^0/\Gamma_{\alpha}$		Compared with cluster model calculations.	1984CE08
9.0 (pol)	$\sigma(\theta), A$	30 – 150	E1, E2 analysis. Studied ${}^3\text{D}_2$ amplitude.	1985WA28
227, 300, 375	$\sigma(\theta), A$	54 – 118	Compared with (γ, p) inverse reaction to search for TRI violation.	1986TH05
2 – 15	$\sigma(90^\circ)$ absolute	90	Examined $\sigma(\gamma, \text{p})/\sigma(\gamma, \text{n})$. Found ratio ≈ 1.1 .	1990FE06

The work of (1985KU19) applies nuclear collision theory (including many-body correlations induced by the short-range repulsion and medium-range attraction of the NN interaction) to (d, d) elastic scattering. Phase shifts are calculated and compared to RGM results. In (1988BE06) it is shown that the polarizability of the deuteron has a negligible effect on the total inelastic cross section at very low energies. Collective excitation of ${}^4\text{He}$ in d + d scattering at energies ≈ 30 MeV is studied in (1990FI06). An analysis of (d, d) scattering data at 1.65, 2.00, and 2.29 GeV in the framework of a Glauber NN multiple-scattering model is described in (1984BA68). See also (1989ET04). An integral formula for calculating Glauber multiple-scattering amplitudes is derived in (1990TA27). A geometric model is applied to high-energy d+d collisions

(1990HU09).

$$7. \ ^3\text{H}(\text{p}, \gamma)^4\text{He} \quad Q_m = 19.814 \quad E_p = 19.814$$

Measurements of cross sections and analyzing powers are summarized in Table 4.9. Summaries and discussions of earlier work can be found in the previous compilation (1973FI04). As noted there, the total cross section is mostly E1 and has a broad peak near $E_p \approx 4$ MeV, but no fine structure in the measured energy range. The broad peak is attributed to the presence of two $1^-, T = 1$ levels in ${}^4\text{He}$. The determination (1978KIZQ) of the singlet E1 strength distribution indicates that the lower of the two levels (at 27.4 MeV) contains the larger fraction of the singlet E1 strength. Measurements (1980MC06) of the fore-aft asymmetry in the angular distribution were interpreted as providing evidence for a 2^+ level at 40 MeV in ${}^4\text{He}$ with $\Gamma_{c.m.} = 3.5$ MeV. An E1, E2 analysis of the differential cross section and analyzing power measurements of (1978KIZQ) confirmed the dominant singlet E1 character of the outgoing radiation, but also indicated an anomalously large 3D_2 contribution to the E2 strength. See also (1980DE32, 1985WA28). However, measurements of (1989WA03) showed that the inclusion of a small M1 strength (0.5 – 1% of the total capture cross section) in the analysis gave better fits and eliminated the need for a large 3D_2 contribution. The absolute cross section for ${}^3\text{H}(\text{p}, \gamma)$ has been studied extensively along with that of the mirror reaction ${}^3\text{He}(\text{n}, \gamma)$ to test isospin mixing, and there are many discrepancies in the published results. Accurate measurements of the ${}^3\text{H}(\text{p}, \gamma){}^4\text{He}$ cross section at 8.34 and 13.6 MeV are reported in (1983CA14) and earlier published results are reviewed. However, a new result (1990FE06) gives considerably lower cross sections in agreement with the recent monoenergetic ${}^4\text{He}(\gamma, \text{p}){}^3\text{H}$ results of (1988BE38). These new results bring the (γ, p) -to- (γ, n) ratio for ${}^4\text{He}$ into agreement with standard model predictions. [See sects. 14 and 21.] *The whole range of experimental and theoretical evidence bearing on the $\sigma(\gamma, \text{p})/\sigma(\gamma, \text{n})$ ratio is summarized in a separate discussion at the end of sect. 21.* Measurements of the cross section and analyzing power at intermediate energies 227, 300, and 375 MeV were carried out (1986TH05) and compared with the inverse photodisintegration reaction, and no violation of time-reversal invariance was found. Analysis of these results with DWIA methods indicated that meson exchange currents are important at these energies. See also the review of capture on light nuclei of (1985CA42).

Theoretical calculations of (1981HA10, 1983HA21) done within the framework of recoil corrected continuum shell model (RCCSM) determine $\sigma(\gamma, \text{p})/\sigma(\gamma, \text{n})$, and it is concluded that the value near 2 that was indicated by some experiments cannot be obtained within standard theoretical assumptions. However, the authors of (1988WA20) conclude that calculations done within the framework of a microscopic multichannel resonating group model demonstrated that all types of experimental data except for the integrated (n, γ) cross section can be reproduced. Calculations of the ${}^3\text{H}(\text{p}, \gamma)$ cross section at intermediate energies were done at 156 MeV by (1973BA27) within the framework of a direct reaction peripheral model. Calculations for $\sigma(\theta)$ at 30 – 100 MeV described in (1978GA13) are discussed in terms of information about the effects of meson exchange currents and NN correlations at forward and backward angles. Calculations at 40 and 140 MeV are presented in (1976HE12).

$$8. \ ^3\text{H}(\text{p}, \text{n}){}^3\text{He} \quad Q_m = -0.764 \quad E_p = 19.814$$

Measurements of cross sections and analyzing powers are summarized in Table 4.10. Summaries and discussions of earlier work can be found in the previous compilation (1973FI04). Legendre polynomial

Table 4.10: Measurements and summaries (S) of cross sections $\sigma(\theta)$, analyzing powers $A(\theta)$, polarizations $P(\theta)$, and polarization transfers $K(\theta)$ for the ${}^3\text{H}(\text{p}, \text{n}){}^3\text{He}$ reaction

E_{p} (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg)	Description	Refs.
1.5 – 12 (pol)	A	45	Compared with $P(E, \theta)$.	1972HA33
8.94, 13.55	$K_y^y, K_x^{x'}, K_z^x, P$	15 – 120	Compared with R -matrix calculations.	1972HA36
6 – 16	$\sigma(\theta)$	0 – 140	Determined relative and absolute $\sigma(\theta)$.	1972MC23
2.238	$\sigma(E_{\text{n}})$	$\theta({}^3\text{He}) = 10^\circ$	Measured neutron flux for $E_{\text{n}} = 250$ keV.	1972PA41
1.5 – 5.0	P_{n}	5 – 110 (lab)	Legendre polynomial expansion, contour map.	1972SM03
1.3 – 2.9	A	30 – 140	Legendre polynomial expansion, contour map.	1974BR09
4 – 15	$K_z^{z'}$	0, 15 – 100	Compared with R -matrix calculations.	1974JA03
6.00, 9.96, 13.55	A	0.3 – 130	Compared with $P(\theta)$ and R -matrix calculations.	1974JA06
5.97, 9.9	$K_x^{x'}, K_z^{x'}, K_y^y P_{\text{n}}$	0 – 100	Compared with R -matrix calculations.	1974JA20
9.5	$\sigma(E, \theta)$	15 – 135	Measured relative yield.	1975MO36
1.7 – 3.9	A_y, P^y	10 – 60	Compared A_y, P^y . Checked CSB.	1976DO07
6 – 17	$\sigma(\theta)$	$\approx 0 – 180$	Established absolute scale for $\sigma(\theta)$ by calibrated t.o.f. system.	1978DR08(S)
1245, 1800	$\sigma(\theta)$	$0.003 < t < 0.493 (\text{GeV}/c)^2$	Glauber-model analysis.	1980BI02
1.75 – 4.0	A_y	45, 20 – 150	Compared with $P(E, \theta)$ R -matrix calculations. Established ${}^4\text{He}$ level order.	1981DO10(S)
2.0 – 3.8	P^y	45, 15, 50	Compared with $A(E, \theta)$. Charge symmetry interpretation.	1981TO12(S)
318	$d\sigma/dt$	$0.01 < t < 0.06 (\text{GeV}/c)^2$	Compared with multiple scattering theory.	1982BL23
9.77 – 14.77	$d^2\sigma/d\Omega dE$	0	Studied ${}^3\text{H}$ breakup contributions.	1982TH07
0.4 – 15.5	$\sigma(E)$	20 – 140	Described technique for calibrating t.o.f. spectrometer.	1985HO12
1.125	$E_{\text{n}}, \phi_{\text{n}}$	0	Used ${}^3\text{He}(\text{p}, \text{n})$ as neutron source to study ${}^{26}\text{Al}(\text{n}, \text{p})$.	1986TR02
2.05, 3.37	$\sigma(E_{\text{p}}, E_{\text{n}})$	0, 90	Studied neutron background.	1989BO41

expansions of $\sigma(\theta)$ and $P(\theta)$ are given for $E_p = 1.5 - 5.0$ MeV in (1972SM03) and for $E_p = 1.3 - 2.9$ MeV in (1974BR09). Contour maps of $P(\theta)$ are presented. A number of measurements relating to the use of ${}^3\text{H}(\text{p}, \text{n})$ as a source of polarized and unpolarized neutrons have been made. See especially (1978DR08) in which an absolute scale for $\sigma(\theta)$ is established. Relative and absolute differential cross sections for $E_p = 6 - 16$ MeV are given in (1972MC23). See also (1972PA41) for measurements of flux density for $E_n = 250$ keV, and (1982TH07, 1989BO41) for measurements of tritium breakup contributions. Practical aspects of accelerator-based neutron source reactions including ${}^2\text{H}(\text{p}, \text{n})$ are reviewed in (1990DR10). Neutron polarizations and polarization transfer coefficients have been measured over a wide range of angles and energies (1972HA36, 1972SM03, 1974JA03, 1974JA20, 1976DO07, 1981TO12).

The analyzing power measurements of (1972HA33, 1974JA06) were compared with neutron polarization data, and it was found that above 4 MeV the two quantities were essentially equal, but below 4 MeV the observed differences in the magnitudes exceeded those predicted by charge-independent R -matrix calculations based on the level parameters of (1968WE14). Similar conclusions were drawn from the polarization-transfer coefficient measurements presented in (1972HA36, 1974JA20). However, remeasurement of P^y , and further measurements of A_y between 2 and 4 MeV resolved the discrepancies (1981DO10, 1981TO12), and it was concluded that there are no anomalously large differences between P and A outside the uncertainties of predictions of present models. A review of existing data and discussions of charge-independent R -matrix calculations is included in (1981DO10). The calculations establish the order of the lowest p-wave $T = 0$ levels in ${}^4\text{He}$ as $J^\pi = 0^-, 2^-, 1^-$.

The reported differences between polarization and analyzing power were investigated in (1974AR01) and related to ${}^3\text{P}_2 \longleftrightarrow {}^3\text{F}_2$ transitions enhanced in the region of the 2^- state. They were also calculated (1977BE28) within the framework of a generalized R -matrix method. See also the recoil-corrected continuum shell-model calculations of (1983HA21). Microscopic calculations of the ${}^4\text{He}$ continuum were carried out by a coupled-channels method (1975RA31, 1976RA13, 1977DO03, 1980RA17), by a K -matrix approach (1977BA46), and within the framework (1980BE18) of a dynamical R -matrix formalism. Excited states of ${}^4\text{He}$ are discussed as are comparisons with ${}^3\text{H}(\text{p}, \text{n})$ and other reaction data. See also the [3N + N] cluster-model study of (1981FU08). Calculations of elastic scattering and charge exchange at intermediate energies using Glauber multiple scattering theory are reported for $E_p = 156$ MeV (1973NA06) and for 415 and 600 MeV (1981BI08). A microscopic, momentum space optical potential is used in the calculations of (1986LA02). The results are compared with data at 415 and 600 MeV, and the sensitivity to the removal of meson exchange currents from nuclear densities is discussed. A generalized potential description of the $\text{p} + {}^3\text{H}$ interaction is described in (1990DU11).

9. ${}^3\text{H}(\text{p}, \text{p}){}^3\text{H}$

$$E_b = 19.814$$

Measurements of cross sections and analyzing powers for ${}^3\text{H}(\text{p}, \text{p}){}^3\text{H}$ are summarized in Table 4.11. Summaries and discussions of earlier work including a discussion of the general behavior of the cross section and analyzing power as a function of energy can be found in the previous compilation (1973FI04).

Several multichannel resonating group calculations have been carried out (1981FU08, 1981HO04, 1982HO05, 1983FI14, 1986KA21). The [3N + 1] cluster model is found (1981FU08) to explain the general properties of the ${}^4\text{He}$ excited states. Using microscopic multichannel calculations, the investigation of (1981HO04) finds the well-established resonance structure, rules out the dd threshold resonance, and predicts a low-lying $J^\pi = 1^-, T = 0$ resonance. However, no evidence for a 0^- or 1^+ state near $E_x = 25.5$ MeV is found. This

same work identifies the observed differences in ${}^2\text{H}(\text{d}, \vec{\text{p}}){}^3\text{H}$ and ${}^2\text{H}(\text{d}, \vec{\text{n}}){}^3\text{He}$ as resulting from Coulomb effects alone, and explains the differences between the ${}^3\text{H}(\text{p}, \vec{\text{p}}){}^3\text{H}$ polarization data of (1976KA12) and the ${}^1\text{H}(\text{t}, \vec{\text{t}}){}^1\text{H}$ data of (1978HA38) as resulting from the odd spin-orbit component of the nucleon-nucleon force. Microscopic calculations of the resonance states in ${}^4\text{He}$ were carried out by (1984CA20) using a modified R -matrix method and a variational approach, and by (1980BE18) within the framework of a dynamical R -matrix methodology. See also (1977BE53). Momentum distributions of single nucleon, two-nucleon cluster relative motion, etc. were reported in (1988MO09). Scattering and reactions in the $A = 4$ systems within a K -matrix formalism were studied (1980BA55). A coupled channels treatment was applied to interpret the positive- (1980RA17) and negative-parity (1975RA31) resonances in ${}^4\text{He}$. See also (1978RA01). The Amado model was used (1977AA01) to investigate D-phase anomalies in ${}^3\text{H}(\text{p}, \text{p}){}^3\text{H}$ for $E_{\text{p}} = 4 - 12$ MeV. All possible couplings of $\text{p}-{}^3\text{H}$ and $\text{n}-{}^3\text{He}$ were considered in a calculation of S -matrix elements by (1972HE15). A two-dimensional integral equation solution of the $A = 4$ system was used (1978KR01) to calculate the ${}^4\text{He}$ binding energy and $\text{n}-{}^3\text{He}$ and $\text{p}-{}^3\text{H}$ phase shifts. See also (1977PE13) and the review (1987FI03) of four-body scattering in the integral equation approach. Cross sections for intermediate energies were calculated by diffraction multiple-scattering theory by (1978PE20, 1976LE32), and by the Glauber formalism (1973NA06, 1976FR12, 1979ME08, 1981BI08). A generalized potential description of the $\text{p}-{}^3\text{H}$ interaction is presented in (1990DU11). Collective excitations of ${}^4\text{He}$ are included in a study (1990FI06) of the structure of the continuum spectra in $\text{p} + {}^3\text{H}$ scattering at ≈ 30 MeV.

$$10. \quad {}^3\text{H}(\text{p}, \text{d}){}^2\text{H} \quad Q_{\text{m}} = -4.033 \quad E_{\text{b}} = 19.814$$

Measurements of the ${}^3\text{H}(\text{p}, \text{d}){}^2\text{H}$ reaction published prior to 1972 are reported in the previous compilation (1973FI04), and some possible evidence of time-reversal invariance violation is discussed. More recently, measurements of angular distributions of the analyzing power for ${}^3\text{H}(\vec{\text{p}}, \text{d}){}^2\text{H}$ at eight energies from 6.7 to 14.7 MeV were reported in (1972HA14, 1972HA50). It is noted that by reciprocity these analyzing powers are the same as proton polarizations of the ${}^2\text{H}(\text{d}, \vec{\text{p}}){}^3\text{H}$ reaction. Comparisons were made with the mirror reaction ${}^2\text{H}(\text{d}, \vec{\text{n}}){}^3\text{He}$, and good agreement is found when the reactions are compared at the same exit-channel energies. It is concluded that these results give no evidence for violations of charge symmetry. One additional measurement for the ${}^3\text{H}(\text{p}, \text{d}){}^2\text{H}$ reaction was reported in (1974JA15). Differential cross sections for $E_{\text{p}} = 13.600$ MeV for $\theta_{\text{lab}} = 15 - 55^\circ$ were measured with an accuracy better than 1%.

Calculations of differential cross sections for the ${}^3\text{H}(\text{p}, \text{d}){}^2\text{H}$ reaction were carried out (1986KA21) in a multichannel resonating group approximation, and good agreement with experiment was obtained.

$$\begin{array}{lll} 11. \quad \text{(a)} \quad {}^3\text{H}(\text{d}, \text{n}){}^4\text{He} & Q_{\text{m}} = 17.589 & E_{\text{b}} = 16.696 \\ \text{(b)} \quad {}^3\text{H}(\text{d}, \text{n}){}^3\text{He} + \text{n} & Q_{\text{m}} = -2.988 & \\ \text{(c)} \quad {}^3\text{H}(\text{d}, \text{n}){}^3\text{H} + {}^1\text{H} & Q_{\text{m}} = -2.225 & \end{array}$$

Measurements of cross sections and analyzing powers for ${}^3\text{H}(\text{d}, \text{n})$ reactions are summarized in Table 4.12. Earlier work is reviewed and discussed in the previous compilation (1973FI04). As noted there, the neutron spectrum from reaction (a) indicates no excited states in ${}^4\text{He}$ between 1 and 13 MeV excitation. The properties of the neutron distributions from reactions (b) and (c) are also described.

Table 4.11: Measurements and summaries (S) of cross sections $\sigma(\theta)$, analyzing powers $A(\theta)$, and polarizations $P(\theta)$, for the ${}^3\text{H}(\text{p}, \text{p}){}^3\text{H}$ reaction

E_{p} (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg)	Description	Refs.
19 – 57	$\sigma(\theta), P(\theta)$			1972DA08
19, 30	$\sigma(\theta), A(E, \theta)$	20 – 160	Deduced phase shifts. Compared with $\text{p} + {}^3\text{He}$.	1972DA10
9.4 – 10.7, 12.0 13.4, 14.7	A	25 – 160	Uncertainties ≈ 0.005 . Parametrized in terms of phase shifts.	1972HA51
6.7, 7.4, 8.0	A	110 – 160	Uncertainties ≈ 0.005 . Parametrized in terms of phase shifts.	1972HA51
13.6	$\sigma(\theta)$	12 – 50	Uncertainties $< 1\%$.	1974JA15
600	$\sigma(\theta)$	$0.08 < t < 0.45(\text{GeV}/c)^2$	Deduced reaction mechanism.	1976FA09
4.15 – 12.00	$\sigma(\theta), A$	$\approx 30 – 160$	Phase-shift analysis. Contour plots. Related to ${}^4\text{He}$ levels.	1976KA12
1.245	$\sigma(\theta)$	$0.045 < t < 0.686(\text{GeV}/c)^2$	Glauber model interpretation.	1980BI02
318 ($E_{\text{t}} = 2.5$ GeV)	$\sigma(\theta)$	$0.02 < t < 0.15(\text{GeV}/c)^2$	Compared to multiple-scattering theory.	1982BL23

Table 4.12: Measurements and summaries (S) of cross sections $\sigma(\theta)$, analyzing powers $A(\theta)$, and polarizations $P(\theta)$, for ${}^3\text{H}(\text{d}, \text{n})$ reactions

E_{d} (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg)	Description	Refs.
32	P_{n}	30	Measured with He gas scatterer.	1972RY01
1 – 5	P_{n}	10 – 110	Legendre polynomial expansion of σP , Contour map.	1972SM05
5 – 15.7	$\sigma(\theta)$	0	Obtained absolute $\sigma(\theta)$. Improved accuracy.	1973MC05
5.5 – 13	$\sigma(E_{\text{p}})$ for ${}^3\text{He}(\text{d}, \text{p})\text{pt}$	60	Studied states in $A = 5$ involving coupling to 0^+ state in ${}^4\text{He}$.	1974SC04
8 – 16	$\sigma(\theta, E_{\text{d}})$	0 – 145 (lab)	Polynomial expansion. Compared with cluster model.	1975MA28
3.5 – 12.8	A_{zz}	0	Calculated $P_{z'}$ from A_{zz} for use of ${}^3\text{H}(\text{d}, \vec{\text{n}})$ as $\vec{\text{n}}$ source reaction.	1976LI15
0.7	P_{n}	0 – 50 (lab)	Used liquid He polarimeter.	1978CA13
7 – 16.5	$\sigma(\theta)$	0	Established absolute scale. Analyzed new data along with previous data.	1978DR08
0.24 – 6.75	A_{zz}	0	Measured ${}^3\text{H}(\text{d}, \text{n})$ along with ${}^3\text{He}(\text{d}, \text{p})$. Studied charge symmetry.	1980DR01
0.333	${}^4\text{He}$ yield	90	Used Si detector to measure ${}^4\text{He}$ to obtain neutron yield.	1980GA25
3 – 10	$\sigma(\theta)$ evaluated	0, 180	Improved evaluation of $\sigma(0)$, $\sigma(180)$ by including ${}^4\text{He}$ particle excitation functions.	1981DR05(S)
37.1	P_{n} (inferred from A_y for ${}^4\text{He}(\vec{\text{n}}, \text{d})$)	38.6	Studied TRI and charge symmetry.	1982SA05
0.02 – 0.05	$E_{\text{n}}, \sigma(E_{\text{n}})$	0	Measured ${}^2\text{H}$ energy loss in solid Ti-T target.	1984TS09
3.0	$\sigma(E_{\text{n}})$	85 – 150	Presented calibration procedure for fast neutron t.o.f. spectrometer.	1985HO12
0 – 0.275	$\sigma(\text{d}, \gamma)/\sigma(\text{d}, \text{n})$	0	Measured branching ratio. Integrated over resonance 0 – 275 keV.	1986MO05
1, 1.5, 2	$\sigma(\theta, E_{\text{d}})$	0 – 150 (lab)	Presented Legendre polynomial fits.	1987LI07

Table 4.12: Measurements and summaries (S) of cross sections $\sigma(\theta)$, analyzing powers $A(\theta)$, and polarizations $P(\theta)$, for ${}^3\text{H}(\text{d}, \text{n})$ reactions (continued)

E_{d} (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg)	Description	Refs.
100 – 200	$\sigma(E_{\text{d}})$		Studied reaction as neutron source.	1989GA21

Experiments bearing on the question of possible charge-symmetry breaking include the ${}^3\text{H}(\text{d}, \vec{n}){}^4\text{He}$ polarization measurements of (1972SM05) and the ${}^3\text{H}(\vec{d}, \text{n}){}^4\text{He}$ and ${}^3\text{He}(\vec{d}, \text{p}){}^4\text{He}$ analyzing power measurements of (1980DR01). In the latter work the authors note large differences for the two reactions for E_{d} below 1.65 and above 4 MeV. Comparisons of the analyzing powers for the inverse reactions ${}^4\text{He}(\vec{n}, \text{d}){}^3\text{H}$ and ${}^4\text{He}(\vec{p}, \text{d}){}^3\text{He}$ are reported in (1982SA05) to be consistent with charge symmetry.

A review of accelerator-based neutron source reactions including ${}^3\text{H}(\text{d}, \text{n})$ is presented in (1990DR10). See also (1984MA71, 1984TS01, 1989CO14, 1989CR05, 1989SH17).

Relatively few calculations for reaction (a) have been carried out. For early work see the previous compilation (1973FI04). More recently, the work described in (1972SE09, 1975SE07, 1977SE09) derives criteria for a simplified analysis of measurements with polarized deuterons involving $A_{yy}(\theta)$ in the vicinity of isolated resonances. See also the multichannel resonating group calculations of (1990BL08). A nondynamical calculation of polarization observables for E_{d} below 1 MeV in terms of (l, s, j) matrix elements is described in (1986KO21). A new method for determination of the nuclear vertex constants from charged particle-transfer reactions is used to analyze $\sigma(\theta)$ for reaction (a) at $E_{\text{d}} = 15$ MeV. See also (1990KA22). Analytical approximations to the cross section for the purpose of calculation of resonant thermonuclear reaction rates are discussed in (1987GU25). See also the $T \approx 300$ K reaction rate calculations of (1989SC25) and those of (1989AB21).

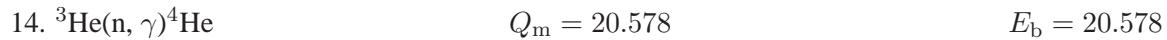
$$12. \begin{array}{lll} \text{(a)} {}^3\text{H}(\text{t}, \text{n}){}^5\text{He} & Q_m = 10.438 & E_b = 12.306 \\ \text{(b)} {}^3\text{H}(\text{t}, 2\text{n}){}^4\text{He} & Q_m = 11.332 & \end{array}$$

These reactions are reviewed by (1988AJ01). Early measurements of neutron spectra are noted in the previous compilation (1973FI04). No new work has been reported on reaction (a). A measurement of the 0° differential cross section for ${}^3\text{H}(\text{t}, 2\text{n}){}^4\text{He}$ at $E_{\text{t}} = 160$ keV and angular distributions at $55 - 80$ keV were reported in (1977SE11). A resonating group method was used to calculate the energy dependence for the cross section and astrophysical factor in (1989VA20).

$$13. \begin{array}{lll} \text{(a)} {}^4_{\Lambda}\text{H}(\pi^-){}^3\text{H} + {}^1\text{H} & Q_m = 35.744 & \\ \text{(b)} {}^4_{\Lambda}\text{H}(\pi^-){}^4\text{He} & Q_m = 34.981 & \\ \text{(c)} {}^4_{\Lambda}\text{H}(\pi^+){}^3\text{He} + \text{n} & Q_m = 55.559 & \end{array}$$

Early work on three-body decays (a) and (c) was summarized in the previous compilation (1973FI04). More recently, extensive reviews of experimental and theoretical work on hypernuclei were presented in

(1975GA1A, 1978PO1A, 1990CO1D, 1990OS1A). A theoretical study (1985LY1A) found that the polarization of the protons and tritons in reaction (a) is largely determined by the strong interaction in the p– ${}^3\text{H}$ system. The two-body decay (b) was used (1988TA29, 1989TA16, 1989TA19) in measurements of the formation probability of ${}^4_{\Lambda}\text{H}$ from K^- absorption at rest on light nuclei. Theoretical studies of ${}^4_{\Lambda}\text{H}$ production, structure, and decay are reported in (1982KO13, 1984CO1E, 1986DZ1B, 1987YA1M, 1988MA09, 1989TA17, 1989WA25). Calculations of Coulomb effects and charge-symmetry breaking for $A = 4$ hypernuclei are described in (1985BO17). A four-body calculation of the $0^+ - 1^+$ binding energy difference is reported in (1988GI1F). Non-mesonic decays are discussed in (1985TA1E, 1986SZ1A, 1990LY1B). Evidence for the existence of a Σ -nucleus bound state formed in a (K^- , π^-) reaction on ${}^4\text{He}$ was reported in (1989HA39). See also (1990HA08, 1990HA11). The possibility of forming doubly strange Ξ hypernuclei is considered in (1983DO1B).



Measurements for the ${}^3\text{He}(n, \gamma){}^4\text{He}$ reaction made since the previous compilation (1973FI04) are listed in Table 4.13. Measurements of the thermal neutron capture cross section were reported in (1973BO34, 1979SU05, 1980AL05, 1989WO10, 1991WE06). The results are listed in Table 4.14 below. Experimental and theoretical results for neutron radiative capture on light nuclei including ${}^3\text{He}$ are reviewed in (1981SH25). Calculations (1981TO03) including meson-exchange currents were able to account satisfactorily for the thermal neutron cross section. A recent Monte Carlo variational calculation in which the scattering-length dependence was deduced was reported in (1990CA28). The results indicate that the cross section is almost entirely due to exchange currents.

Shell model calculations including two-body meson exchange currents are reported for both ${}^3\text{He}(n, \gamma){}^4\text{He}$ reaction and the weak ${}^3\text{He}(p, e^+, \nu e)$ reaction (1991WE06).

Doubly radiative neutron capture cross sections were calculated and reported in (1976LE27). Cross sections in the 0 – 70 keV region are reported in (1979AL25), and are shown to be in general agreement with an E1 direct capture calculation. At higher energies ($E_n = 6.0 - 17$ MeV) the detailed-balanced cross sections of (1981WA18) confirmed the reported ${}^4\text{He}(\gamma, n)$ cross section (see the section on the ${}^4\text{He}(\gamma, n)$ reaction) which, when combined with the previously reported ${}^4\text{He}(\gamma, p)$ cross section, implied a (γ, p)-to-(γ, n) ratio of 1.6 to 1.9 in the 23 – 33 MeV excitation region of ${}^4\text{H}$. Additional information on the capture process in this energy region is provided by the polarized neutron capture cross sections and analyzing powers of (1982WE05). Calculations carried out within the framework of the recoil-corrected continuum shell model (1981HA10, 1983HA21) indicated that standard theoretical assumptions were unlikely to account for the reported large (γ, p)-to-(γ, n) ratio. On the other hand, the microscopic multichannel resonating group model calculations of (1988WA20) imply that the effect of the Coulomb force on thresholds for the two mirror channels can account for the observed differences in measured observables in the 23–33 MeV excitation region of ${}^4\text{H}$, excluding the “anomalous” (γ, p)-to-(γ, n) ratio. For additional related information see sect. 7 on ${}^3\text{H}(p, \gamma)$ and sect. 21 on ${}^4\text{He}(\gamma, n)$, ${}^4\text{He}(\gamma, p)$. *The whole range of experimental and theoretical evidence bearing on the $\sigma(\gamma, p)/\sigma(\gamma, n)$ ratio is summarized in a separate discussion at the end of sect. 21.*

The measured values for the thermal neutron capture cross section of the ${}^3\text{He}(n, \gamma){}^4\text{He}$ reaction are listed in Table 4.14.

The two latest measurements (1989WO10, 1991WE06) are in excellent agreement, but disagree with the result of (1980AL05). It should be noted, however, that the results of (1989WO10) rely heavily upon

Table 4.13: Measurements and summaries (S) of cross sections $\sigma(\theta)$, analyzing powers $A(\theta)$, and polarizations $P(\theta)$, for ${}^3\text{He}(\text{n}, \gamma){}^4\text{He}$ reaction

E_{n} (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg)	Description	Refs.
Thermal energies 0.001 – 0.070	$\sigma_{\text{n}\gamma}$ $\sigma(E_{\text{n}})$	45	Compared with direct E1 calculation. Measured $(\text{n}, \gamma\gamma)/(\text{n}, \gamma)$ ratio.	1973BO34 1976LE27 1979SU05
Thermal energies 6.0 – 17.0	$\sigma(\text{n}, \gamma)$ $\sigma(E_{\text{n}}, \theta)$	90 30 – 140	Used pulsed reactor, t.o.f. Estimated admixture of ${}^4\text{He}$ “mixed-symmetry” state. Compared detailed-balanced results to existing ${}^4\text{He}(\gamma, \text{n})$ and ${}^4\text{He}(\gamma, \text{p})$ cross sections.	1980AL05 1981WA18
9.0	$\sigma(\theta), A_y$	30 – 140	Deduced b_k coefficients, compared with continuum shell model.	1982WE05
24.5	$\sigma_{\text{n}\gamma}$		Activation measurement.	1989WE07
Thermal energies Thermal, 0.0245	$\sigma_{\text{n}\gamma}$		Deduced astrophysical factor. Carried out shell-model calculations. Discussed Solar HEP-neutrino implications.	1989WO10 1991WE06

Table 4.14: Measured values for the thermal neutron capture cross section for the ${}^3\text{H}(\text{n}, \gamma){}^4\text{He}$ reaction

Refs.	$\sigma_{\text{n}\gamma}^{(\text{th})}$ (μb)
1973BO34	60 ± 30
1979SU05	60 ± 12
1980AL05	27 ± 9
1989WO10	54 ± 6
1991WE06	55 ± 3

the ${}^3\text{H}(\text{p}, \gamma){}^4\text{He}$ cross section at $E_{\text{p}} = 3.82$ MeV ([1970ME07](#)). If the lower value reported for this cross section in ([1990FE06](#)) is used, the $\sigma_{n\gamma}^{(\text{th})}$ cross section becomes $40 \pm 4 \mu\text{b}$, which agrees (within error) with that of ([1980AL05](#)).

A neutron-capture cross section at 24.5 keV was measured by ([1991WE06](#)) to be $\sigma_{n\gamma}$ (24.5 keV) = $9.1 \pm 0.8 \mu\text{b}$. The thermal-neutron-capture cross section has been used to estimate the astrophysical S -factor for the ${}^3\text{He}(\text{p}, e^+\gamma){}^4\text{He}$ reaction ([1989WO10](#), [1991WE06](#)). The results indicate that about 10% of the solar-neutrino flux in the Davis experiment can be ascribed to the high-energy ${}^3\text{He} + \text{p}$ neutrinos. The double photon decay cross sections are also given in ([1980AL05](#)) and ([1979SU05](#)).



Measurements of cross sections, polarizations and analyzing powers for the ${}^3\text{He}(\text{n}, \text{n}){}^3\text{He}$ reaction are summarized in Table [4.15](#). Earlier work is reviewed in the previous compilation ([1973FI04](#)). More recent experiments are reviewed in ([1978SU1A](#), [1981GR1A](#)). See also the discussions in ([1983HA20](#), [1985KL03](#), [1988JA06](#)) of the experimental and theoretical developments relating to ${}^3\text{He}(\text{n}, \text{n}){}^3\text{He}$ and the $A = 4$ system.

A variety of theoretical approaches have been used to describe $\text{n}-{}^3\text{He}$ scattering. At thermal energies, the complex incoherent scattering length for ${}^3\text{He}$ was estimated ([1975SE06](#)) on the basis of effective range theory and a Breit-Wigner analysis. Low-energy $\text{n}-{}^3\text{He}$ scattering was studied in the integral equation approach ([1976KH01](#), [1976TJ01](#)) and scattering lengths were calculated. Higher energy observables for nucleon reaction channels in ${}^4\text{He}$ were calculated by recoil-corrected continuum shell model techniques ([1979HA22](#)), and excellent agreement with experiment was reported. Proton and neutron polarization differences in ${}^3\text{He}(\vec{\text{n}}, \text{n}){}^3\text{He}$ and ${}^3\text{H}(\vec{\text{p}}, \text{p}){}^3\text{H}$ were analyzed ([1977BE53](#)) in the framework of a dynamical R -matrix model methodology, and quantitative agreement with experiment was obtained. Several resonances are predicted in the vicinity of a narrow resonance near $E_x = 37$ MeV suggested by the phase-shift analysis of ([1976LI03](#)). The R -matrix methodology is used to construct a detailed theoretical model of ${}^4\text{He}$ ([1980BE18](#)). Scattering results and phase-shift calculations are presented and discussed and are also compared with resonating group and field-theoretic models. Cluster-model calculations of ${}^4\text{He}$ excited states based on (trinucleon + nucleon) ([1976IO01](#), [1981FU08](#)) as well as (trinucleon + nucleon) and d + d clusters ([1983FI14](#)) have been carried out. Collective and cluster degrees of freedom are included in a study ([1990FI06](#)) of the structure of the continuum spectra of ${}^4\text{He}$ in the ≈ 30 MeV region. The ground and even-parity states were examined within the framework of a multichannel resonating group model approach ([1986KA21](#)), and agreement with the elastic scattering and polarization observables was reported. Multichannel resonating group calculations for $A = 4$ from the first breakup threshold to 10 MeV are presented ([1981HO04](#)), and reported to predict the established resonance structure and provide evidence bearing on other possible states. Multichannel resonating-group calculations, which include distortion effects due to the coupled deuteron cluster, were used ([1986KA21](#)) to examine the ground and even-parity excited states and the scattering problem of the ${}^4\text{He}$ system.

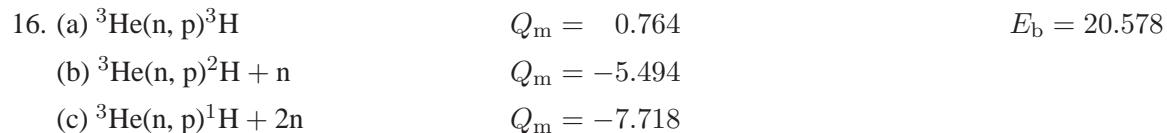


Table 4.15: Measurements and summaries (S) of cross sections $\sigma(\theta)$, analyzing powers $A(\theta)$, and polarizations $P(\theta)$, for the ${}^3\text{He}(\text{n}, \text{n}){}^3\text{He}$ reaction

E_{n} (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg)	Description	Refs.
3.0	P_{n}	40 – 120	Measured asymmetry, differential polarization.	1972HO04
7.9, 12.0, 13.6, 14.4, 23.7	$\sigma(E, \theta)$	26 – 139	Deduced σ_{el} , limits for σ_{tot} , $\sigma_{\text{n},2\text{n}} + \sigma_{\text{n},\text{pn}}$. Compared with charge-symmetric reaction.	1974DR01
8.0, 12.0, 17.1	P_{n}	47 – 148	Compared with ${}^3\text{H}(\vec{\text{p}}, \text{p})$. Phase-shift analysis for ${}^3\text{He}(\text{n}, \text{n})$ for $1 < E < 23.7$ MeV.	1976LI03
2.43, 3.00	$A_y(\theta)$			1977DR05
0.001 – 0.200	$\sigma_{\text{total}}, \sigma_{\text{n},\text{n}}$		Obtained singlet and triplet scattering lengths.	1981AL09
1.67, 2.43, 3.0, 3.4, 7.8	$A_y(\theta)$			1982DR09
1.5 – 40	$\sigma(E)$		Compared with predictions of R -matrix analysis.	1983HA20
3.7 – 10.0, 15.3, 22.0	$A_y(E, \theta)$	26 – 161	Compared with ${}^3\text{H}(\text{n}, \text{n}), {}^3\text{He}(\text{p}, \text{p})$.	1985KL03(S)
15 – 50	$A_y(E, \theta)$		Phase-shift analysis.	1986KL04(S)
0.95 – 2.0	$A_y(E, \theta)$	50 – 160	Improved precision, phase-shift analysis.	1988JA06(S)

Early work on reaction (a) is summarized in the previous compilation ([1973FI04](#)). It is noted there that the reaction proceeds almost 100% through the ${}^1\text{S}_0$ resonance at $E_{\text{n}} = -0.25$ to -1.0 MeV, and that the proton spectra from reactions (b) and (c) reveal no clear indication of an n-d, three-nucleon or two-nucleon final-state interaction.

A more recent measurement ([1975WI04](#)) of the ${}^3\text{He}(\text{n}, \text{p}){}^3\text{H}$ total cross section at $E_{\text{n}} = 3.5$ MeV gives $\sigma_{\text{total}} = 422 \pm 58$ mb. The cross section was measured ([1982BO19](#)) in the energy range $E_{\text{n}} = 0.15 – 150$ keV with an accuracy of 2–3%, and the departure from the $1/v$ law was investigated. Measurements of the P -odd asymmetry in ${}^3\text{He}(\text{n}, \text{p}){}^3\text{H}$ were made ([1981VE08](#)), and an upper limit was obtained. Little theoretical work on reaction (a) has been reported since the previous compilation ([1973FI04](#)). A resonating-group model calculation was carried out ([1976IO01](#)) involving the groupings $\text{n} + {}^3\text{He}$ and $\text{p} + {}^3\text{H}$. Total cross sections were calculated and compared with experiment at 1, 3, 5, 6, and 14.4 MeV. The contribution of the triangle diagram for the ${}^3\text{He}(\text{n}, \text{p})$ reaction was investigated in a K -Matrix scattering calculation reported in ([1984BA17](#)).

17. (a) ${}^3\text{He}(\text{n}, \text{d}){}^2\text{H}$	$Q_m = -3.27$	$E_b = 20.578$
(b) ${}^3\text{He}(\text{n}, \text{d}){}^1\text{H} + \text{n}$	$Q_m = -5.494$	
(c) ${}^3\text{He}(\text{n}, 2\text{n}2\text{p})$	$Q_m = -7.718$	

Reactions (a), (b), and (c) are reviewed in the previous compilation ([1973FI04](#)). No new work has been reported.

18. (a) ${}^3\text{He}(\text{d}, \text{p}){}^4\text{He}$	$Q_m = 18.353$	$E_b = 16.387$
(b) ${}^3\text{He}(\text{d}, \text{np}){}^3\text{He}$	$Q_m = -2.225$	
(c) ${}^3\text{He}(\text{d}, 2\text{pt})$	$Q_m = -1.461$	
(d) ${}^3\text{He}(\text{d}, \text{p}2\text{d})$	$Q_m = -5.494$	

Table 4.16: Measurements and summaries (S) of cross sections $\sigma(\theta)$, analyzing powers $A(\theta)$, polarizations $P(\theta)$, and transfer coefficients for ${}^3\text{He}(\text{d}, \text{p}){}^4\text{He}$

E_d (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg)	Description	Refs.
11.99, 2.81, 3.94, 6.0	P	5.7 – 148.5	Legendre polynomial fits. Contour map.	1973CL13
4 – 14	$K_y^{y'}, K_{yz}^{x'}$	0	Compared with ${}^3\text{H}(\text{d}, \text{n})$ results and R -matrix parameterization.	1973HA51
8.0	$P^{y'}, K_x^{x'}, K_y^{y'}, K_z^{z'}, K_{xx}^{y'}, K_{yy}^{y'}, K_{zz}^{y'}, K_{xz}^{y'}$	15, 30, 45, 60	Compared with ${}^3\text{H}(\text{d}, \text{n})$ results and R -matrix parameterization.	1973HA51
12	Left-right asymmetry	20 – 130	Polarized ${}^3\text{He}$ target.	1974BE67
0.344, 0.065, 0.727	$iT_{11}, T_{20}, T_{21}, T_{22}$	25 – 160	Polynomial fit. Tabulates coefficients.	1974GA21
10.0	$\sigma(\theta)$	120 – 168 (lab)	Accuracy < 1%.	1974JA15
6.6 – 15.8	A_{zz}	0	Studied reaction as \vec{d} polarization analyzer.	1974TR02
0.34 – 11.60	T_{20}	0	Absolute calibration.	1976SC15
9.28	A_{yy}	23.6	Found maximum $A_{yy} = 1$.	1976GR08
8.5 – 10.5	A_y, A_{yy}	12 – 32	Found maximum $A_{yy} = 1$.	1976GR10
6.44	iT_{11}	29	Presented absolute standard for d induced vector analyzing powers.	1977ST06
0.24 – 6.75	A_{zz}	0	Compared A_{zz} for ${}^3\text{He}(\text{d}, \text{p}), {}^3\text{H}(\text{d}, \text{n})$.	1980DR01
3 – 6.75	T_{20}	0	Discussed consistency of absolute calibration data below 6.75 MeV.	1980GR14
15 – 40	$\sigma(\theta), iT_{11}$	15 – 165	Polynomial expansion, DWBA analysis.	1981RO13
4 – 12	P_z, P_{zz}		Described design, calibration and performance of \vec{d} polarimeter.	1982GR25

Table 4.16: Measurements and summaries (S) of cross sections $\sigma(\theta)$, analyzing powers $A(\theta)$, polarizations $P(\theta)$, and transfers coefficients for ${}^3\text{He}(\text{d}, \text{p}){}^4\text{He}$ (continued)

E_{d} (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg)	Description	Refs.
1 – 30	$\sigma(E_{\text{d}}, \theta)$, $iT_{11}, T_{20}, T_{21}, T_{22}, A_y, A_{yy}, A_{xx}$		Reviewed polarization measurements $A = 4 - 6$.	1987GR08(S)
15 – 100	$iT_{11}, T_{20}, T_{21}, T_{22}$		Discussed design construction and calibration of high efficiency \vec{d} polarimeter.	1987GR30
0.0695 – 0.1418	$\sigma(E_{\text{d}}, \theta)$		Windowless gas target, deduced $S(E)$.	1987KR18
0.0059 – 0.0416	$\sigma(E_{\text{d}})$		Measured ${}^3\text{He}(\text{d}, \text{p})$ and ${}^2\text{H}({}^3\text{He}, \text{p})$, studied effects of electron screening.	1988EN03
9.25 – 19.0	Polarimeter analyzing power		Developed polarimeter based on ${}^3\text{He}(\text{d}, \text{p})$.	1988SA40
10 – 16	$A_y, A_{yy}, A_{xz}, A_{zz}$	0, 25	Described polarimeter based on ${}^3\text{He}(\text{d}, \text{p})$.	1989AB17
0.006 – 0.042	$\sigma(E_{\text{d}})$		Studied effect of electron screening.	1989SC10
1 – 13	$iT_{11}, T_{20}, T_{21}, T_{22}$	10 – 170	High-precision measurement.	1990BI13

Reactions (a) to (c) are reviewed by ([1988AJ01](#)). Early measurements of single and coincident charged-particle spectra are summarized in ([1973FI04](#)) and a discussion of evidence bearing on excited states of ${}^4\text{He}$ is presented. Measurements of cross sections, analyzing powers, polarizations, and polarization transfer coefficients are summarized in Table 4.16. See also ([1986HE16](#)). Polarization observables for the ${}^3\text{He}(\text{d}, \text{p}){}^4\text{He}$ reaction and other reactions relating to $A = 4 - 6$ were reviewed in ([1987GR08](#)). A considerable number of measurements of vector and tensor analyzing powers have demonstrated the suitability of reaction (a) as an analyzer of deuteron polarization ([1973HA51](#), [1973KA08](#), [1974GA21](#), [1974TR02](#), [1976GR08](#), [1976GR10](#), [1976SC15](#), [1977ST06](#), [1980DR01](#), [1980GR14](#), [1981RO13](#), [1988SA40](#), [1989AB17](#)). See also the related theoretical work ([1976SE03](#), [1977SE09](#), [1978SE01](#)). Design and calibration of polarimeters based on reaction (a) have been presented in ([1980ST1A](#), [1982GR25](#), [1987GR30](#)).

Distorted-wave calculations for reaction (a) are presented and discussed in ([1975NE11](#)). See also ([1989BO22](#)). Off-diagonal interaction spin dependence is discussed in ([1975YA12](#)). An estimate of cross sections for reaction (a) at intermediate energies in terms of the (p, π^+) cross section is discussed in ([1980WI02](#)). The single-resonance contribution to the cross section and reaction rate at thermonuclear energies is studied ([1987GU25](#)), and the effect of electron screening on low-energy fusion cross sections is discussed in ([1987AS05](#)).

Measurements of the breakup reactions (b), (c), and (d) are summarized in Table 4.17. A discussion of these reactions is included in the review of quasi-free processes and few-body systems of ([1974SL04](#)). Calculations for reaction (c) in the region of small proton-tritium relative energies are presented in ([1984DU10](#)).

19. (a) ${}^3\text{He}(\text{t}, \text{d}){}^4\text{He}$	$Q_m = 14.320$	$E_b = 15.796$
(b) ${}^3\text{He}(\text{t}, \text{d}){}^3\text{He} + \text{n}$	$Q_m = -6.257$	
(c) ${}^3\text{He}(\text{t}, \text{d}){}^3\text{H} + {}^1\text{H}$	$Q_m = -5.494$	
(d) ${}^3\text{He}(\text{t}, \text{d}){}^2\text{H}$	$Q_m = -9.526$	

Table 4.17: Measurements and summaries (S) of particle spectra from ${}^3\text{He} + \text{d}$ breakup reactions

E_{d} (MeV)	Particles detected	θ (deg)	Description	Refs.
10.92	p, ${}^3\text{He}$ (coin.), p, ${}^3\text{H}$ (coin.)	$\theta_{\text{p}} = 60, \theta({}^3\text{He}) = 30$	Studied FSI, discussed effects of ${}^4\text{He}$ states.	1972NI02
27.5	p, n (coin.)	$10 - 35$ (lab), $\theta_{\text{n}} = \theta_{\text{p}}$	Studied pn FSI.	1973CH05
23.5 c.m.	${}^3\text{H}$	$10 - 180$	Measured absolute energy spectra. Deduced ${}^3\text{He}$ range parameter.	1975RU04
15.0	p, ${}^3\text{He}$ (coin.), p, ${}^3\text{He}$ (coin.)	± 30	Measured A_y, A_{yy}, A_{xx} .	1976ME13
$E_{\text{d}} = 22.3, 33, E({}^3\text{He}) = 30, 33.5, 52.5$	d, d (coin.), p, ${}^3\text{H}$ (coin.), p, d (coin.), p, ${}^3\text{H}$ (coin.)	$10 - 65$	Studied quasi-free scattering and quasi-free reaction processes.	1977SL04
60	d, d	$15 - 64$	Measured $\sigma(E, \theta_1, \theta_1)$ in QFS region. Studied multiple scattering effects. PWIA analysis.	1985OK03

Reactions (a) through (d) are reviewed in the previous compilation ([1973FI04](#)). For reaction (a) measurements of analyzing powers $A_y(\theta)$ for $E_t = 9.02, 12.86$, and 17.02 MeV at $\theta_{\text{c.m.}} = 16^\circ - 159^\circ$ as well as measurements of $A_y(E)$ at 90° for $E_t = 9.02 - 17.27$ MeV were reported in ([1977HA42](#)). Marked deviations from the antisymmetric shape predicted by a simple particle-transfer model incorporating charge symmetry were observed. Possible charge asymmetry effects in this reaction were also discussed in ([1978FE07](#), [1978FE08](#)). See also ([1988RA31](#)). No new work has been reported on reactions (b) through (d).

$$20. \begin{aligned} & \text{(a)} {}^3\text{He}({}^3\text{He}, 2\text{p}){}^4\text{He} & Q_m = 12.86 & E_b = 11.489 \\ & \text{(b)} {}^3\text{He}({}^3\text{He}, 2\text{p}){}^3\text{H} + {}^1\text{H} & Q_m = -6.954 \end{aligned}$$

Measurements on reaction (a) reported since the previous compilation ([1973FI04](#)) include spectra and differential cross sections at beam energies of 9.11, 7.88, and 6.9 MeV ([1972DE46](#)) and at $E_{\text{c.m.}} = 16$ MeV ([1974RO01](#)). The total cross section was measured for $E_{\text{c.m.}} = 30 - 150$ keV ([1974DW01](#)), and the astrophysical factor $S(E)$ was measured at $E_{\text{c.m.}} = 17.9 - 342.5$ keV.

Total cross section measurements for ${}^3\text{He} + {}^3\text{He}$ at 17.9, 21.7, and 24.0 MeV were reported in ([1987BR02](#)). See also ([1985SI12](#)).

Calculations to determine the NN scattering parameters from final-state interactions in reaction (a) were described in ([1974DE18](#)). Calculations of a diproton production mechanism in reaction (a) were reported in ([1976MC04](#)), and the effects of electron screening on cross sections for low-energy fusion reactions, including reaction (a), were studied in ([1987AS05](#), [1989BE08](#)). An extended elastic model was applied to calculate the reaction rate at astrophysical energies in ([1989SC25](#), [1990SC15](#)). The astrophysical S -factor is calculated with the two-channel approximation of the RGM in ([1989VA20](#)).

Triton spectra from reaction (b) are discussed in the previous compilation ([1973FI04](#)).

21. (a) ${}^4\text{He}(\gamma, \pi^0){}^4\text{He}$	$Q_m = -134.97$
(b) ${}^4\text{He}(\gamma, n){}^3\text{He}$	$Q_m = -20.578$
(c) ${}^4\text{He}(\gamma, p){}^3\text{H}$	$Q_m = -19.814$
(d) ${}^4\text{He}(\gamma, n\pi^0){}^3\text{He}$	$Q_m = -155.55$
(e) ${}^4\text{He}(\gamma, p\pi^-){}^3\text{He}$	$Q_m = -158.85$
(f) ${}^4\text{He}(\gamma, d){}^2\text{H}$	$Q_m = -23.847$
(g) ${}^4\text{He}(\gamma, np){}^2\text{H}$	$Q_m = -26.071$
(h) ${}^4\text{He}(\gamma, 2p2n)$	$Q_m = -28.296$

Measurements of photonuclear cross sections for ${}^4\text{He}$ are summarized in Table 4.18. Earlier experimental and theoretical work is summarized and discussed in the previous compilation (1973FI04). Measurements and analyses of reaction (a) for energies near threshold are reported in (1980AR06, 1981AR10, 1988AR08), and for energies near the $\Delta(1232)$ resonance in (1985AN14). Measurements at GeV energies in the region of small momentum transfers are reported in (1982AL09). See also (1978AL08). A number of calculations have been made with the Δ -isobar model (1981OS1A, 1981SA01, 1983KO02) and in the distorted wave impulse approximation (1983GI02, 1983LE12, 1985KA22, 1986LE07, 1987CH24, 1987LE13). Impulse approximation calculations in the resonance region were reported in (1978TR03, 1979GA18). Screening corrections were calculated (1978ST21). Momentum-dependent terms in the operator and a two-nucleon exchange production mechanism were discussed in (1977VE05), and calculations near threshold were reported. Rescattering corrections were calculated in (1976OS03). A discussion and comparison of the various methods of calculating the amplitudes of partial reactions are presented in (1983TR02) for energies in the nucleon resonance region.

Reactions (b) and (c) have cross sections which are similar in shape at all energies as pointed out in the previous compilation (1973FI04), but there has been considerable disagreement among the results of the measurements of each. *The whole range of experimental and theoretical evidence bearing on the $\sigma(\gamma, p)/\sigma(\gamma, n)$ ratio is summarized in a separate discussion at the end of this section.* The absolute measurement of $\sigma(\theta)$ for reaction (c) described in (1991JO04) includes useful evaluative discussions of existing experimental and theoretical work. See also (1978AR1B, 1978AR26, 1980AR20, 1984GU18). A considerable amount of theoretical work has been done on reactions (b) and (c) with a great deal of it related to the question of the $\sigma(\gamma, p)/\sigma(\gamma, n)$ ratio (1974CH50, 1974GA10, 1974GA32, 1974ST08, 1980BE42, 1981AR21, 1981HA10, 1983BE13, 1983DE31, 1983HA21, 1984BA73, 1984GU18, 1985QU01, 1986CA05). See also (1974GA32, 1974NO10, 1974RA18, 1975GU23, 1976FI11, 1976NO06, 1977DE26, 1979GU13, 1980AR04, 1980BO13, 1980RA17, 1986CH05, 1988TE04, 1989VO01). A method for estimating the polarization of final particles in reactions (b) and (c) is developed in (1990GU21).

Structure effects in the E3 cross section for reaction (c) were investigated in (1989BE07). A review of progress on four-body scattering and breakup, in the integral equation approach, is presented in (1987FI03).

Reaction (d) was studied in two investigations reported in (1982AN16, 1984AN04). The experimental results were analyzed satisfactorily by means of impulse-approximation calculations involving a reaction amplitude described by the sum of two pole diagrams with a virtual neutron and a ${}^3\text{He}$ nucleus. No recent work has been reported on reaction (e). Cross sections were measured in the energy region of the $\Delta(1236)$ resonance (1972AR23). An impulse-approximation calculation in terms of quasi-free nucleons in ${}^4\text{He}$ was reported in (1972LE24).

Only a few measurements have been done for reaction (f), and those reported since the previous compilation ([1973FI04](#)) are listed in Table 4.18. Cluster-model calculations for energies of a few MeV above threshold are reported in ([1974ST08](#)). A low-energy theorem is applied to cross section calculations in ([1981GO15](#)). See also the review presented in ([1978AR26](#)). Comparisons of the cross section data with calculations were reported in ([1980AR04](#), [1980GU25](#)) to provide evidence for a 2^+ state in ${}^4\text{He}$ at $E_\gamma = 30 - 35$ MeV.

Measurements for reaction (g) reported since the previous compilation and listed in Table 4.18 have been carried out for photon energies from $28 - 400$ MeV with cloud chambers and with combinations of magnetic spectrometers and neutron detectors. Relative cross sections for reactions (b), (c), (f), (g), and (h) were obtained ([1977BA35](#)) from threshold to $E_\gamma \approx 80$ MeV, and it was concluded that the main mechanism for reaction (g) in this energy region is two-nucleon absorption. Similar measurements at $30 - 40$ MeV ([1979BA47](#)) were used to study clustering effects, and the results suggested that the most important mechanism for reaction (h) is photoabsorption from a quasideuteron correlated with another quasi deuteron, both of which decompose. See also the review of ([1985HO27](#)). Theoretical calculations of reactions (b), (c), and (g) utilizing the quasideuteron mechanism are reported in ([1974NO10](#), [1976NO06](#), [1984CH09](#)). See also ([1982AR11](#)).

Table 4.18: Measurements and summaries (S) of photonuclear cross sections on ${}^4\text{He}$

Reaction	E_γ (MeV)	Description	Refs.
${}^4\text{He}(\gamma, \pi^0){}^4\text{He}$	1500 – 4500	Developed apparatus. Measured $\sigma(E, \sigma)$.	1978AL08
	1 – 10 (above threshold)	Measured relative yields for ${}^1\text{H}$, ${}^2\text{H}$, ${}^3\text{He}$, ${}^4\text{He}$ targets. DWBA analysis.	1980AR06
	139 – 153	Analyzed $\sigma(E, \theta)$ data, deduced yields.	1981AR10
	1500 – 4500	Measured $\sigma(\theta)$ versus momentum, deduced Ω meson trajectory.	1982AL09
	450	Measured $\sigma(\theta)$ for ${}^4\text{He}$ recoils versus recoil energy. Bremsstrahlung beam.	1982AN16
	290	Measured $\sigma(\theta)$ near $\Delta(1232)$ resonance.	1984TI04
	190 – 430	Measured $\sigma(\theta)$ near $\Delta(1232)$ resonance.	1985AN14
	138 – 155	Measured pion yields, deduced $\sigma(E)$, s-wave threshold amplitudes.	1988AR08
	179	Measured σ_{total} .	1989JA07
	< 30	Measured $\sigma(E, E_n)$ at 90° .	1972BE06
${}^4\text{He}(\gamma, n){}^3\text{He}$	30.0 – 51.8	Determined $\sigma(E)$ for (γ, n) and (γ, p) in same apparatus (mag. spectrometer).	1972DO03
	24 – 120	Determined $\sigma(E)$ for (γ, n) and (γ, p) under same physical conditions.	1973AR07
	$E_x = 22 - 37$	Measured $\sigma(E)$ at 98° . Compared results for liquid and gas targets.	1973IR02
	1 – 10 (above threshold)	Measured $\sigma(E, \theta)$. Confirmed 2^+ state at ≈ 35 MeV.	1973MA57
	20 – 120	Measured σ_{total} . Determined energy moments.	1974AR18
	35	Measured $\sigma(\gamma, n)$ versus beam intensity.	1974IR02
	270 – 400	Measured $\sigma(E)$ at $90^\circ, 120^\circ$ in region of $\Delta(1236)$ resonance.	1975AR01

Table 4.18: Measurements and summaries (S) of photonuclear cross sections on ${}^4\text{He}$ (continued)

Reaction	E_γ (MeV)	Description	Refs.
${}^4\text{He}(\gamma, \text{n}){}^3\text{He}$	27 – 30	Measured σ_{total} and $\sigma(E, \theta)$. Determined E1, E2 amplitudes, phases.	1975AR13
	22 – 32	Measured $\sigma(E, \theta)$. Determined E1, E2 contributions, obtained σ_{total} .	1975IR01
	$E_{\text{th}} – 150$	Determined E1, E2 cross sections.	1976AR17
	$< E_x = 80$	Measured σ_{total} and $\sigma(E, \theta)$ for (γ, n) and (γ, p) . Used cloud chamber.	1977BA35
	31 – 51	Measured $\sigma(\gamma, \text{p})/\sigma(\gamma, \text{n})$ ratio at 90° by detecting ${}^3\text{H}$ and ${}^3\text{He}$ recoils.	1979PH04
	21 – 47	Measured $\sigma(E)$ with gas target. Used monoenergetic photons. Compared with other measurements.	1980BE45
	22.5 – 137	Measured cross section versus E_γ . Analyzed by assuming $2^+ T = 0$ levels in ${}^4\text{He}$ at 29.6, 35.6 MeV.	1981AR23
	40	Measured asymmetry of (γ, n) and (γ, p) cross sections for linearly polarized γ -rays.	1985VI07
	100 – 360	Measured $\sigma(E, \theta)$ for (γ, n) and (γ, p) for $60^\circ, 90^\circ, 120^\circ$. Compared to calculations with MEC contributions.	1986SC01
	40	Measured asymmetry of (γ, n) and (γ, p) cross sections for linearly polarized γ -rays.	1989VI05
${}^4\text{He}(\gamma, \text{p}){}^3\text{H}$	30.0 – 51.8	Determined $\sigma(E)$ for (γ, n) and (γ, p) in same apparatus (mag. spectrometer).	1972DO03
	24 – 120	Determined $\sigma(E)$ for (γ, n) and (γ, p) under same physical conditions.	1973AR07
	180 – 320	Measured $\sigma(E, \theta)$ at $\theta_{\text{c.m.}} = 60^\circ – 120^\circ$ in spark chamber.	1973KI06
	20 – 120	Measured σ_{total} .	1974AR18
	190 – 420	Measured $\sigma(E)$ at $60^\circ, 90^\circ$ in region of $\Delta(1236)$ resonance.	1975AR01
${}^4\text{He}(\gamma, \text{p}){}^3\text{H}$	$E_{\text{th}} – 150$	Determined E1, E2 cross sections.	1976AR17
	$< E_x = 80$	Measured σ_{total} and $\sigma(E, \theta)$ for (γ, n) and (γ, p) . Used cloud chamber.	1977BA35
	200 – 450	Measured $\sigma(E, \theta)$ at $30^\circ – 150^\circ$ in $\Delta(1236)$ resonance region.	1979AR07
	31 – 51	Measured $\sigma(\gamma, \text{p})/\sigma(\gamma, \text{n})$ ratio at 90° by detecting ${}^3\text{H}$ and ${}^3\text{He}$ recoils.	1979PH04
	50 – 140	Analyzed $\sigma(E, \theta)$ data to estimate proton momentum distribution in ${}^4\text{He}$.	1982AR17
	187 – 427	Measured momentum spectrum of protons at 30° . Tagged photons. Deduced pion photo-production σ .	1984HO24

Table 4.18: Measurements and summaries (S) of photonuclear cross sections on ${}^4\text{He}$ (continued)

Reaction	E_γ (MeV)	Description	Refs.
${}^4\text{He}(\gamma, \text{p}){}^3\text{H}$	40	Measured asymmetry of (γ, n) and (γ, p) cross sections for linearly polarized γ -rays.	1985VI07
	100 – 360	Measured $\sigma(E, \theta)$ for (γ, n) and (γ, p) for $60^\circ, 90^\circ, 120^\circ$. Compared to calculations with MEC contributions.	1986SC01
	187 – 427	Measured $\sigma(E_p)$ at $\theta_p = 30^\circ, 60^\circ, 90^\circ$, and 105° in Δ -region.	1987HO17
	28.6 – 58.1	Measured absolute $\sigma(E)$ with monochromatic photon beam. Deduced $\sigma(\gamma, \text{p})/\sigma(\gamma, \text{n})$ ratio.	1988BE38
	350	Measured polarization of inclusive protons. Compared with quasideuteron mechanisms of photon absorption.	1988ZY01
	120 – 250	Measured asymmetry versus θ_p . Linearly-polarized photons.	1988GA29
	60, 140, 350	Measured asymmetry at $\theta_p = 90^\circ$. Linearly-polarized monochromatic photons.	1988GA25
	40	Measured asymmetry of (γ, n) and (γ, p) cross sections for linearly polarized γ -rays.	1989VI05
	63 – 71	Absolute measurement of $\sigma(\theta)$, quasi-monochromatic photons.	1991JO04
${}^4\text{He}(\gamma, \text{n}\pi^0){}^3\text{He}$	450	Measured σ versus θ, E of recoil ${}^3\text{He}$. Impulse approximation calculation.	1982AN16
	450	Measured σ versus $\theta_\pi, \theta_{{}^3\text{He}}, E_{{}^3\text{He}}$ -deduced pion production mechanism.	1984AN02
${}^4\text{He}(\gamma, \text{p}\pi^-){}^3\text{He}$	< 150	Measured cross section near $\Delta(1236)$.	1972AR23
	350	Measured asymmetry at 90° for linearly polarized photons.	1988GA25
	120 – 250	Measured asymmetry versus θ for linearly polarized photons.	1988GA29
${}^4\text{He}(\gamma, \text{d}){}^2\text{H}$	< 150	Measured $\sigma(\theta, E)$. Bremsstrahlung beam. Diffusion chamber.	1972AR21
	20 – 120	Measured $\sigma(E)$. Determined energy moments, E1, E2 contributions, ${}^4\text{He}$ radius.	1974AR18
	190 – 380	Measured $\sigma(E)$, dd coin.	1976AR05
	25 – 40	Measured $\sigma(E)$. Multipole expansion. Deduced level in ${}^4\text{He}$.	1978AR23
	< 80	Measured $\sigma(E, \theta)$ for $(\gamma, \text{n}), (\gamma, \text{p}), (\gamma, \text{d}), (\gamma, \text{np}), (\gamma, 2\text{n}2\text{p})$ with diffusion cloud chamber.	1977BA35
${}^4\text{He}(\gamma, \text{np}){}^2\text{H}$	28 – 150	Determined distributions in the Treiman-Yang angle.	1979AR15
	30 – 40	Measured $\sigma(E, \theta)$ for $(\gamma, \text{n}), (\gamma, \text{p}), (\gamma, \text{d}), (\gamma, \text{np}), (\gamma, 2\text{n}2\text{p})$. Deduced reaction mechanism.	1979BA47

Table 4.18: Measurements and summaries (S) of photonuclear cross sections on ${}^4\text{He}$ (continued)

Reaction	E_γ (MeV)	Description	Refs.
${}^4\text{He}(\gamma, \text{np}){}^2\text{H}$	150	Measured quasideuteron momentum distribution. Deduced quasideuteron channel radius.	1982AR17
	40 – 150	Analyzed data to determine $\sigma(E)$ off the mass shell.	1985AR22
	< 450	Analyzed particle spectra to deduce possible free superdense deuteron.	1985CH35
	200 – 400	Reviewed measurements of $\sigma(\theta, E_p)$.	1985HO27(S)
	75 – 150	Measured $\sigma(\theta, E_d)$. Deduced breakup normalization constant.	1986AR16
	not given	Measured $\sigma(E_d, E_p, E_n)$. Studied quasideuteron correlations.	1986CH15
	130 – 450	Measured $\sigma(E_d, E_p, E_n)$, spectrometer development.	1990NI11
	< 80	Measured $\sigma(E, \theta)$ for $(\gamma, \text{n}), (\gamma, \text{p}), (\gamma, \text{d}), (\gamma, \text{np}), (\gamma, 2\text{n}2\text{p})$ with diffusion cloud chamber.	1977BA35
	30 – 40	Measured $\sigma(E, \theta)$ for $(\gamma, \text{n}), (\gamma, \text{p}), (\gamma, \text{d}), (\gamma, \text{np}), (\gamma, 2\text{n}2\text{p})$. Deduced reaction mechanism.	1979BA47

Theoretical studies of the total photonuclear absorption cross sections by means of sum rules have been described in ([1974FI03](#), [1977LI12](#), [1980AR20](#), [1983EL07](#)). See also the theoretical investigations of the integrated photonuclear cross sections reported in ([1974GO13](#), [1977GR08](#), [1984KO33](#), [1985SA01](#)).

The ${}^4\text{He}(\gamma, \text{p}){}^3\text{H}$ -to- ${}^4\text{He}(\gamma, \text{n}){}^3\text{He}$ cross section ratio

The ratio of the two photonuclear cross sections, ${}^4\text{He}(\gamma, \text{p}){}^3\text{H}$ -to- ${}^4\text{He}(\gamma, \text{n}){}^3\text{He}$, below $E_x = 35$ MeV has constituted a long-standing anomaly in low-energy photonuclear physics. A review of the experimental data ([1983CA08](#)) concluded that the data indicated a (γ, p) -to- (γ, n) ratio which varied slowly from 1.7 to 1.2 in the excitation-energy range $E_x = 25 – 35$ MeV, in substantial disagreement with the ratio predicted by conventional isospin-conserving theoretical calculations. Data obtained in recent years change this picture substantially. Relevant measurements include:

${}^4\text{He}(\gamma, \text{p}){}^3\text{H}$ and ${}^3\text{H}(\text{p}, \gamma){}^4\text{He}$: ([1955PE34](#), [1962GA03](#), [1962GE04](#), [1965CL1A](#), [1967DE18](#), [1970AR24](#), [1970ME07](#), [1970WA23](#), [1982MC03](#), [1983CA14](#), [1988BE38](#), [1990FE06](#));

${}^4\text{He}(\gamma, \text{n}){}^3\text{He}$ and ${}^3\text{He}(\text{n}, \gamma){}^4\text{He}$: ([1954FE16](#), [1963ZU03](#), [1966FE07](#), [1968GO19](#), [1971BE43](#), [1972BE06](#), [1973MA57](#), [1975IR01](#), [1977BA35](#), [1978AR26](#), [1980BE45](#), [1981WA18](#));

${}^4\text{He}(\pi^\pm, \pi^{\pm'}){}^4\text{He}$: ([1986BL07](#));

${}^4\text{He}(\pi, \pi'\text{p}), {}^4\text{He}(\pi, \pi'\text{n})$: ([1990JO04](#));

${}^4\text{He}(\text{e}, \text{e}'\text{p}){}^3\text{H}, {}^4\text{He}(\text{e}, \text{e}'\text{n}){}^3\text{He}$: ([1989SP05](#));

${}^4\text{He}(\gamma, \text{p}){}^3\text{H}$ to ${}^4\text{He}(\gamma, \text{n}){}^3\text{He}$ ratio: ([1972DO03](#), [1979PH04](#)).

Theoretical work related to the question includes: ([1972GI14](#), [1972LO11](#), [1974CH50](#), [1981HA10](#), [1983HA21](#), [1984BA73](#), [1988WA20](#)).

An examination of all of the (γ , p) and (γ , n) data, including inverse reaction studies, led the authors of (1983CA08) to conclude that the (γ , p)-to-(γ , n) ratio was substantially greater than 1.0 below $E_x = 35$ MeV. However, since that time a measurement using monoenergetic photons (1988BE38) indicated that the ${}^4\text{He}(\gamma, \text{p}){}^3\text{H}$ cross section was substantially smaller below $E_x = 35$ MeV than previously thought, and was essentially in agreement with the monoenergetic-photon results for the ${}^4\text{He}(\gamma, \text{n}){}^3\text{He}$ reaction (1954FE16, 1963ZU03, 1966FE07, 1968GO19, 1971BE43, 1972BE06, 1973MA57, 1975IR01, 1977BA35, 1978AR26, 1980BE45). This (γ , p) result has received additional support from a new ${}^3\text{H}(\text{p}, \gamma){}^4\text{He}$ measurement (1990FE06) which agreed with it. The (γ , n) results of (1980BE45) are also supported by the capture measurements of (1981WA18). Thus, if we take the most recent (γ , n), (γ , p), (p, γ) and (n, γ) cross-section measurements we obtain, for $E_\gamma = 24 - 31$ MeV, a (γ , p)-to-(γ , n) ratio which is about 1.1, consistent with conventional theoretical predictions and indicating that no charge-symmetry violation is required in ${}^4\text{He}$ to explain these data.

Additional support for this result is provided by the π^+/π^- cross section ratio measurement of (1986BL07). The measured ratio of 1.05 ± 0.08 indicated little or no isospin mixing in ${}^4\text{He}$ between $E_x \approx 23 - 30$ MeV. A recent simultaneous measurement of ${}^4\text{He}(\text{e}, \text{e}'\text{p}){}^3\text{H}$ and ${}^4\text{He}(\text{e}, \text{e}'\text{n}){}^3\text{He}$ cross sections (1989SP05) gave a ratio less than 1.2, consistent with the predictions of a microscopic model which assumed a charge-symmetric nuclear hamiltonian (1988WA20). Unfortunately, previous results which disagree with this conclusion have not been accounted for. The results of (1982MC03, 1983CA14) are especially disturbing. On the theoretical side, while the “new” data produce a ratio in agreement with essentially all calculations, the lower absolute cross sections, for both (γ , p) and (γ , n), disagree with most theoretical results (see especially (1983HA21, 1988WA20)). However, a flaw has been revealed recently in the manner in which Siegert’s theorem was used in the calculations of (1988WA20). The correction brings the absolute cross sections down to the lower values, while keeping the ratio close to 1.1, in agreement with the new results. The impact of this correction on the (e, e'p) and (e, e'n) channels remains to be examined, but is expected to be small. Unfortunately, the ratio question continues to haunt many workers in the field, and it has not been unambiguously resolved.

- 22. (a) ${}^4\text{He}(\text{e}, \text{e}){}^4\text{He}$
- (b) ${}^4\text{He}(\text{e}, \text{e}'){}^3\text{He} + \text{n}$ $Q_m = -20.578$
- (c) ${}^4\text{He}(\text{e}, \text{e}'){}^3\text{H} + \text{p}$ $Q_m = -19.814$
- (d) ${}^4\text{He}(\text{e}, \text{e}'){}^2\text{H} + {}^2\text{H}$ $Q_m = -23.847$

Experiments and data analysis for elastic electron scattering on ${}^4\text{He}$ are summarized in Table 4.19. Earlier work is described in the previous compilation (1973FI04). A recent determination (1985OT02) of the r.m.s. charge radius gave $\langle r^2 \rangle^{1/2} = 1.671 \pm 0.014$ fm.

A number of theoretical calculations relating to ${}^4\text{He}(\text{e}, \text{e})$ elastic scattering have been carried out. The contribution of two-photon exchange in high-energy large-angle scattering was examined (1972BO63). The elastic scattering form factor was computed (1972CA40) in the local-density approximation and in the oscillator model with short-range correlations (1972FI10). Relativistic corrections and their effect on the diffraction minimum were examined (1973FR21). Calculations utilizing self-consistent Brueckner-Hartree-Fock wave functions (1974CI02) provided estimates of the effects of center-of-mass spuriosity. Charge form factors were calculated with many-body meson exchange operators (1977RI15). The effect of short-range three-nucleon correlations was studied (1978HE19). Elastic and inelastic form factors calculated in

Table 4.19: Measurements and analyses of cross sections for elastic electron scattering on ${}^4\text{He}$

q^2 (fm $^{-2}$)	E_e (MeV)	Description	Refs.
1 – 4.4		Used symmetrized Fermi-density distributions.	1972EL11
≈ 0.2 – 2.5	200 – 500	Obtained charge density. Model-independent analysis.	1976SI13
≤ 6.2	170 – 750	Measured charge form factor. Deduced point-nucleon distributions from model-independent analysis.	1977MC03
≤ 800		Obtained elastic structure functions.	1978AR05
0.45 – 2	105 – 320	Measured $\sigma(E, \theta)$. Obtained charge form factors. Deduced r.m.s. radii, model-independent analysis.	1985OT02

the method of hyperspherical functions were discussed in (1981BU04). A multi-quark cluster effect on the charge form factor was postulated in (1982NA09). The role of tensor and short-range correlations was investigated by (1982DE51, 1983OR05). An analytic parameterization of the charge form factor was presented in (1985AG05). The work of (1988MO32) utilized a quark model and examined symmetry of the ground-state structure of ${}^4\text{He}$. Calculations of electromagnetic form factors for ${}^4\text{He}$ based on quantum hadrodynamics is discussed in (1989LI16). The influence of short-range correlations on the charge distribution is discussed in (1989LO06). Experimental data on inclusive longitudinal and transverse response functions in the context of theoretical developments are discussed in (1989PA12). Calculations of the charge form factor using realistic variational wave functions and consistent two-body operators are reported in (1990SC01). A study of elastic and inelastic electron scattering on ${}^4\text{He}$ with the Monte Carlo method is described in (1990PA07).

Inelastic scattering experiments are summarized in Table 4.20. See also (1974GO15, 1980GO21, 1981GO03, 1988DY01). A review of the status of theoretical methods and principal results for elastic and inelastic scattering of electrons by nuclei was presented in (1974LU09). In (1974VI03) a simple model of ${}^4\text{He}$ is suggested to interpret the details of the charge distribution obtained from the electron scattering form factors for $q^2 \leq 20\text{ fm}^{-2}$. A study of the 0^+ state at 20.1 MeV in ${}^4\text{He}$ reported in (1974Z004) utilized the inelastic form factor and three-body forces in a hyperspherical description. A microscopic treatment of coupled monopole and quadrupole $T = 0$ vibrations was used in (1975AB04) to calculate transition strengths and inelastic form factors. Center-of-mass corrections for calculations related to electron scattering are studied and reported in (1980DE30). The effect of final-state interactions in inclusive electron scattering is discussed in (1980HO26). The method of hyperspherical functions is discussed in (1981BU04). Quasi-free peak parameters from calculated (e, e') cross sections are related to sum rules in (1981KO10). Data for electron scattering from ${}^2\text{H}$, ${}^3\text{He}$, and ${}^4\text{He}$ are found (1982BO30) to be unified by a nuclear scaling function. The (e, e') cross section was calculated using an interaction-time approximation for dynamic form factors (1982KO26). The existence of y -scaling for the quasi-elastic cross section was demonstrated in (1983DE13). See also the study of (1985KO19). A continuum RPA calculation with finite-range interaction was applied (1983DE39) to calculate (e, e') cross sections. The role of tensor correlations in inclusive electron scattering processes was studied and discussed in (1983OR05). The location of the quasi-elastic peak maximum in ${}^4\text{He}(e, e')$ relative to the eN scattering peak was explored (1985KU02) on the basis of ${}^4\text{He}$ properties. A calculation based on a quark description of the nuclear ground state is presented in (1986DA01). Several different NN interactions are used in a hyperspherical-harmonics calculation of the (e, e') form factor (1987SA23). The form factor for (e, e') excitation of the 0^+ resonance in

Table 4.20: Measurements and analyses of cross sections for inelastic electron scattering on ${}^4\text{He}$

q^2 (fm $^{-2}$)	E_e (MeV)	Description	Refs.
0.8 – 2.4	800 – 1200	Measured $\sigma(E, \theta)$ for $\theta = 16^\circ – 40^\circ$ near quasielastic maximum. Studied effects of center-of-mass motion.	1975DE23
	500	Measured quasielastic scattering at $\theta = 60^\circ$. Compared to static and Fermi gas models.	1976MC01
	(not given)	Measured quasielastic scattering at $\theta = 42^\circ – 140^\circ$. Used measured peak position to study NN interaction.	1984BU18
	400	Measured $\sigma(\theta, E')$ for excitation of 0^+ state at 20.1 MeV in ${}^4\text{He}$.	1983KO25
	730	Measured $\sigma(E, \theta)$ for $\theta = 37.1^\circ$ for energy transfers ≤ 550 MeV in region of Δ -resonance.	1984OC01
	808, 988, 1180	Measured $\sigma(E, E, \theta)$ in quasielastic region. Obtained scaling function. Derived momentum distribution of nucleons in ${}^4\text{He}$.	1988DE41
	130 – 200	Measured $\sigma(E)$ at 180° . Compared with RCCSM.	1988HO11
	183.4	Measured ${}^3\text{H} + \text{p}$ and ${}^3\text{He} + \text{n}$ breakup, $e' - \text{n}$, $e' - \text{p}$ coincidence. $E_x = 22 – 36$ MeV in ${}^4\text{He}$.	1989SP05
≈ 0.15	279 – 725	Measured double-differential cross section. Compared with Coulomb sum rule.	1990VO01

${}^4\text{He}$ is discussed in connection with a collective and cluster model calculation (1987VA33) and a symplectic shell model calculation (1988VA22). More recent work includes a recoil-corrected continuum shell model study of the 0^+ first excited state in (1989HA02, 1990HAZN), a $(0+2)\hbar\omega$ model-space calculation of ${}^4\text{He}$ observables in (1990WO10), an extrapolation of nucleon-momentum distributions in ${}^4\text{He}$ using asymptotic scaling analysis (1990CI03), and a Monte Carlo study (1990PA07). See also the discussion of data on longitudinal and transverse response functions (1989PA12), the relativistic model investigation of ion-ion optical potentials (1989RE07), and the microscopic study of the NN interaction (1989YA11). ${}^4\text{He}(e, e')$ data is utilized in a determination of a phenomenological Δ -nucleon potential in (1990OC01).

23. (a) ${}^4\text{He}(\pi^\pm, \pi^\pm){}^4\text{He}$
 (b) ${}^4\text{He}(\pi^\pm, \pi^{\pm'}){}^4\text{He}$
 (c) ${}^4\text{He}(\pi^\pm, \pi^{\pm'} \text{p}){}^3\text{H}$ $Q_m = -19.814$

Experiments and data analysis for pion scattering on ${}^4\text{He}$ are summarized in Table 4.21. See also (1973AN26, 1975BI08, 1976BA57, 1976BU19, 1976SH23, 1978FA06, 1980BA17, 1980KA17, 1982BA16, 1984FO18, 1984GM01, 1989AR16). These reactions were not included in the previous compilation (1973FI04).

Table 4.21: Measurements and analyses of cross sections for pion scattering on ${}^4\text{He}$

E_π (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg)	Description	Refs.
110 – 260, 67 – 285	$(\pi^-, \pi^-)\sigma(E, \theta)$, $(\pi^-, \pi'^-)\sigma(E)$	5 – 180	Phase shift analysis.	1978BI07
100, 160, 220	$(\pi^\pm, \pi^{\pm'})\sigma(E, \theta)$	30 – 150	Inclusive measurements in $\Delta(3, 3)$ region.	1981MC09
90 – 320	$(\pi^\pm, \pi^{\pm'})\sigma(E, \theta)$	30 – 135	Inclusive measurements. Isobar-hole formalism calculations.	1982BA19
120 – 320	$(\pi^\pm, \pi^{\pm'})\sigma(E, \theta)$	30 – 135	Studied quasi-free scattering.	1982BA65
120 – 320	$(\pi^\pm, \pi^{\pm'})\sigma(E, \theta)$	30 – 135	Deduced medium corrections.	1983BA24
100, 160, 220, 300	$(\pi^+, \pi^+)\sigma(E, \theta)$	30 – 146	Studied systematic properties.	1983LE12
350, 400, 475	$(\pi^\pm, \pi^{\pm'})$ momentum distribution	60, 90, 120	Studied quasi-free scattering. Impulse approximation calculations.	1985BO41
180	$(\pi^\pm, \pi^{\pm'})\sigma(E, \theta)$	20, 30, 40 (lab angles)	Studied π^+/π^- ratio in region of 1^- states of ${}^4\text{He}$ to examine CSB.	1986BL07
180	$(\pi^\pm, \pi^{\pm'}\text{p})\sigma(E, \theta)$	$\theta_\pi = 30 - 80$, $-\theta_p = 30 - 90$	Studied $\sigma(\pi^+, \pi^+\text{p})/\sigma(\pi^-, \pi^-\text{p})$ ratio, isospin characteristics of ${}^4\text{He}$.	1990JO04

Much of the work ([1978BI07](#), [1981MC09](#), [1982BA19](#), [1982BA65](#), [1983LE12](#), [1985BO41](#)) is directed toward studies of the properties of the pion-nucleon interaction and the effects of the nuclear medium. Related theoretical work includes the DWIA calculations of ([1975HE06](#)), a coupled channel method in the K -matrix approach ([1979GM01](#)), and the pole extrapolation method for separating strong and electromagnetic contributions ([1982DA15](#)). Investigation of medium effects by studying quasi-elastic scattering is discussed in ([1983SI21](#)). The question of isospin mixing in ${}^4\text{He}$ and possible charge-symmetry breaking implied by photonuclear reaction data (see sects. 7, 14, and 21 of this compilation) was studied through the π^+/π^- cross section ratio in ([1986BL07](#)) and the result implies little isospin mixing in contrast with the earlier photonuclear results. The calculations of ([1989HA03](#)) predict no significant deviation from unity of this ratio for isospin mixing at the 5% level. On the other hand, $(\pi^\pm, \pi^{\pm'}\text{p})$ measurements of ([1990JO04](#)) found dramatic differences between $(\pi^+, \pi^+\text{p})$ and $(\pi^-, \pi^-\text{p})$ in the ${}^4\text{He}$ GDR region which, although in sharp contrast to predicted values, do not provide an unambiguous indication of isospin mixing and probably arise from the interference of several reaction amplitudes.



This reaction is reviewed in ([1988AJ01](#)) under the discussion of ${}^5\text{He}$.



(b) ${}^4\text{He}(\text{p}, \text{p}') {}^3\text{He} + \text{n}$	$Q_m = -20.578$
(c) ${}^4\text{He}(\text{p}, \text{p}') {}^3\text{H} + \text{p}$	$Q_m = -19.814$
(d) ${}^4\text{He}(\text{p}, \text{p}') {}^2\text{H}^2\text{H}$	$Q_m = -23.847$
(e) ${}^4\text{He}(\text{p}, \text{d}) {}^3\text{He}$	$Q_m = -18.353$

Reaction (a) was reviewed by (1984AJ01) under the discussion of ${}^5\text{Li}$. Measurements for reactions (a)–(d) reported since the previous $A = 4$ compilation (1973FI04) are summarized in Table 4.22.

A great deal of theoretical work has been carried out to describe ${}^4\text{He}(\text{p}, \text{p}) {}^4\text{He}$ elastic scattering. Much of this work has involved optical model analyses (1973CL01, 1973SA09, 1976AR12, 1977AR01, 1977DY01, 1978LE23, 1978ME04, 1979AL12, 1979AR02, 1979DY07, 1980AR08, 1983GR20, 1985KO05, 1985KO07, 1985KO37, 1986BL02, 1986IS04, 1988FR06, 1989TA20, 1990BE53, 1990DU05, 1990LA17, 1990TA16). A distorted-wave impulse approximation calculation of the continuum analyzing power at 100 MeV is presented in (1990LA12). Glauber model multiple scattering calculations are presented in (1974BA38, 1974GU21, 1975BL04, 1975GU17, 1975NA07, 1975WA16, 1976AU04, 1977AL06, 1977YO04, 1978AU11, 1979SA09, 1980WA06, 1981AU07, 1981KH07, 1985TE02, 1986FR12, 1986SA30, 1990LO13). A multi-channel cluster model approach is discussed in (1981FE02), and a self-consistent wave function Brueckner-Hartree-Fock calculation is described in (1974CI02). A review of experimental and theoretical advances in high-energy proton scattering is presented in (1981WA1A). The effect of coupling between the ground state and the first excited state ($0^+, T = 0$) in ${}^4\text{He}$ was estimated in (1984AH03) using a breathing-mode model. Phase-shift analyses and calculations are presented in (1975CA05, 1977TH07, 1979KA17, 1979SA35, 1985SO08, 1986SA05, 1989CO11, 1991CO05), and from a study of experimental phase shifts (1975PL01) it was concluded that small D-state admixtures to the dominant S-state configurations exist in the ${}^4\text{He}$ ground state. For other theoretical studies, see (1973LA14, 1973PL02, 1973SI44, 1974BA38, 1974LY02, 1975AH07, 1975BA05, 1975GI07, 1975MA12, 1975RU07, 1976DU06, 1976LE22, 1976NA04, 1976RU04, 1977JA12, 1977PH01, 1978MA37, 1980AU09, 1981SH04, 1981ZH03, 1982PO12, 1982ZH08, 1983SA38, 1983SH12, 1984BL21, 1984FI20, 1984OK01, 1985FL04, 1985KI11, 1985KR15, 1985RO16, 1986AU05, 1986DU14, 1986KA35, 1986OK06, 1987ZH10, 1989KA39, 1990AU03, 1990HU09, 1990LO02).

Measurements of proton inelastic scattering and breakup reactions (b) and (c) showing evidence for the lowest $0^+, 0^-, 2^-, T = 0$ states in ${}^4\text{He}$ are discussed in the previous compilation (1973FI04). No recent work has been reported.

A formula to represent amplitudes for three-body breakup (reactions (b), (c), (d)) is developed and compared with data in (1987FU10).

26. (a) ${}^4\text{He}(\text{d}, \text{d}) {}^4\text{He}$	$E_b = 1.475$
(b) ${}^4\text{He}(\text{d}, \text{d}') {}^3\text{H} + \text{p}$	$Q_m = -19.814$
(c) ${}^4\text{He}(\text{d}, \text{d}') {}^2\text{H}^2\text{H}$	$Q_m = -23.847$

Reaction (a) was reviewed by (1984AJ01) under the discussion of ${}^6\text{Li}$. Measurements of reactions (a)–(c) published since the previous $A = 4$ compilation (1973FI04) are summarized in Table 4.23. See also (1973TR04, 1982IS06).

Table 4.22: Measurements and analyses of cross sections for proton scattering on ${}^4\text{He}$

E_p (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg) or $-t$ (GeV/c) 2	Description ^a	Refs.
1050	$\sigma(\theta)$	3 – 47 (lab)	Compared with various theoretical calculations.	1974BA14
85	$\sigma(\theta)$	10 – 168	Compared with various theoretical calculations.	1974VO05
580, 720	$d\sigma/dt$	$-t = 0.13 - 0.55$	Measured ${}^4\text{He}$ recoils.	1975VE09
3.47 – 8.94	A_y	$\theta \approx 90$	Determined angle for $A(E, \theta) = 0$. Phase-shift analysis.	1976BR17
2.24 – 5.90	$\sigma(\theta)$	168.8, 104.4	Determined angle for $A(E, \theta) = 0$. Phase-shift analysis.	1976BR17
600	$\sigma(\theta)$	$-t = 0.12 - 0.51$	Used Coulomb-nuclear interference to determine NN amplitudes at 600 MeV.	1976FA09
18 – 48	σ_R		Compared to various calculations.	1976SO01
350, 650, 1050, 1150	$\sigma(\theta)$	$-t = 0.02 - 0.71$	Studied first diffraction minimum. Theoretical analyses.	1977AS01
770	$\sigma(\theta)$	not given	(p, p) measurements made for DWBA analysis of (p, d) cross section.	1977BA19
11 – 14	$\sigma(\theta)$	19 – 167	R -matrix analysis for data $E = 0 - 17$ MeV.	1977DO01
11.93, 17.00	A_y	119 – 134, 37 – 157	Abs. precision ± 0.01 . Tabular presentation.	1977HA06
560 – 1730	$\sigma(\theta)$	$-t = 0.006 - 1.2$	Studied diffraction minimum. Compared with other data.	1977KL08
7.3 – 11.05	A_y	55 – 135	Tested procedure for polarimeter calibration.	1977ME06
200, 350, 500	$\sigma(\theta), A_y$	3.5 – 15	Studied dependence on momentum transfer and energy.	1977ST30
1050	$\sigma(\theta)$	≈ 180	Studied sharp backward peak.	1978BE30
1750, 2510, 4130	$d\sigma/dt$	$-t = 0.002 - 0.04$	Studied proton-nucleon amplitude.	1978DU15

Table 4.22: Measurements and analyses of cross sections for proton scattering on ${}^4\text{He}$ (continued)

E_p (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg) or $-t$ (GeV/c) 2	Description ^a	Refs.
788	$d\sigma/dt$	$-t = 0.11 - 4.19$	Evidence for backward diffraction-like structure.	1978FO33
20 – 55	$\sigma(\theta)$	10–170	Phase-shift analysis.	1978HO17
185 – 500	$\sigma(E, \theta), A_y$	144–168	Studied structure in excitation functions.	1978MC06
2680	$d\sigma/dt$	$-t = 0.15 - 0.66$	Studied shape.	1978NA13
560 – 1730	$\sigma(E, \theta), A_y$	$-t = 0.0057 - 1.21$	Compared with theory.	1979CO01
205 – 520	A_y	17, 15, 24	High-precision calibration standards.	1979GR08
45, 52, 60, 65	$\sigma(E, \theta), A_y$	15 – 160 (lab)	Obtained data for polarization analyzer.	1979IM01
100 – 700	$\sigma(E, \theta)$	180	Explored role of inelastic pion channels at large momentum transfers. ${}^4\text{He}(p, p)$ and ${}^4\text{He}(p, {}^3\text{He})$.	1979KA19
200, 350, 500	$\sigma(E, \theta), A_y$	4 – 168 (lab)	Compared with theory.	1980MO09
500	$\sigma(E, \theta), A_y$	65, 90, 120, 160	Inclusive scattering measurements. ${}^4\text{He}(p, x)$.	1981RO03
992		$-t = 0.0109 - 0.0897$	Deduced σ_{total} and diffraction cone parameter.	1982VE03
1000	$d^2\sigma/dpd\Omega$	156	Plot invariant cross section versus p^2 for (p, p') .	1983AN18
500	R	15 – 50	Measured Wolfenstein R parameter.	1983MO01
1000	$\sigma(E, \theta)$	$\approx 2 - 60$	Analyzed by Glauber-Sitenko theory.	1985AL09
46	A_z	30 – 60	Studied parity nonconservation, weak πN coupling constants.	1985LA01, 1986LA29
98.7, 149.3	$\sigma(E, \theta), A_y$	17.5 – 60	Measured continuum yields for (\vec{p}, p') and (\vec{p}, d) .	1985WE12
700 – 1000	$d\sigma/dt$	$-t = 0.0132 - 0.0799$	Deduced σ_{total} and diffraction cone parameter.	1985VE13
65	$\sigma(E_p, \theta_p), A_y$	20 – 130	Measured for (p, p') and $(p, p{}^3\text{H})$ breakup. Observed peaks for ${}^4\text{He}$ excited states.	1986FU05
71.9	$\sigma(E, \theta), A_y$	25 – 169	Phase-shift analysis of data at 71.9 and 30 – 72 MeV.	1989BU01

Table 4.22: Measurements and analyses of cross sections for proton scattering on ^4He (continued)

E_p (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg) or $-t$ (GeV/c) 2	Description ^a	Refs.
25.68	A_y	117.5 (lab)	Presented new method for precise calibration of beam polarization.	1989CL04, 1989HA28
695, 793, 890, 991	$d\sigma/dt$	$-t \approx 0.005 - 0.08$	Detected scattered particles and recoils. Phase-shift analysis.	1989GR20
25.68	A_y	117.5	Developed new method for calibration.	1989HA28, 1989CL04
14 – 18	A_y	52	Developed high-efficiency polarimeter.	1988SA41
695, 793, 890, 991	$\sigma(\theta_p, \theta_r)$	small angles	Extracted diffraction slope parameters.	1989GR20
1.5 – 2.2	A_y	87	Described design, calibration of polarimeter.	1990PR04

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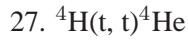
^a Elastic scattering, except as noted.

Table 4.23: Measurements and analyses of cross sections for deuteron scattering on ${}^4\text{He}$

E_d (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg) or $-t$ (GeV/c) 2	Description	Refs.
11.5 – 17	iT_{11}	51.8 – 158.9	Shows d- α scattering is a convenient analyzer for d vector polarization.	1973CH35
12, 14, 17	$\sigma(\theta), A_{xx}, A_{yy},$	30 – 145	Obtained abs. precision of ± 0.01 .	1973OH01
4.8. – 9.0	A, K	27 – 66 (lab)	Measured 4 analyzing tensors and ≈ 14 pol. transfer coefficients.	1973OH02
29.8, 32.3, 34.8, 37.8, 39.3	$\sigma(\theta, E)$	16 – 159	Avg. rel. error 2%.	1974WI13
4 – 5, 10 – 12.5	A_{yy}	20 – 180	Investigated analyzing power maxima.	1975GR10
2.38 – 13.60	iT_{11}	37.5, 45 (lab)	Absolute calibration.	1976SC15
6.04 – 7.05 (7 energies)	$\sigma(\theta), iT_{11}, T_{20}, T_{21}, T_{22}$	11 – 165	Deduced phase shifts, ${}^6\text{Li}$ resonance parameters.	1977HA34
0.870 – 1.430	$\sigma(\theta, E)$	38 – 125	Obtained resonance parameters.	1979BA30
12 – 17	$\sigma(\theta), A_y, A_{xx}$		Emphasis on backward angles. Phase-shift analysis.	1979GR13
1.8	A_y	$\theta_1 = 71^\circ 10', \theta_2 = 39^\circ 22', \theta_3 = 46^\circ 40'$	Measured left-right asymmetry for double d- ${}^4\text{He}$ scattering.	1980BA60
20	$\sigma(\theta), A_y, A_{xx}, A_{yy}, A_{xz}$	30 – 150	Optical model analysis. Needed tensor term.	1980FR01
17.0 – 42.8 (7 energies)	A_y, A_{yy}, A_{xx}	30 – 160	Compared with RGM and Faddeev calculations.	1980GR03
17 – 45 (7 energies)	$\sigma(\theta), A_y, A_{xx}$	30 – 160	Used rapid spin-flip to reduce exp. errors.	1980ST01
8, 9, 10, 11, 12, 13	$\sigma(\theta), iT_{11}, T_{20}, T_{21}, T_{22}$	$\approx 10 – 160$	Phase-shift analysis. Deduced levels in ${}^6\text{Li}$.	1983JE03
3 – 43	T_{ij}, A_{ij}		Phase-shift analysis used to investigate states of maximum polarization.	1985JE04
56	$\sigma(\theta), A_y, A_{xx}, A_{yy}, A_{xz}$	12 – 160	Deduced optical model parameters.	1985NI01
8 – 56	$\sigma(\theta), A_y, A_{xx}, A_{xz}A_{yy}, iT_{11}, T_{20}, T_{21}, T_{22}$	10 – 165	Reviewed polarization measurements, analyses.	1987GR08(S)
11.9	K	55.1	Measured six polarization transfer coefficients. Deduced scattering amplitudes.	1988EL01

Many theoretical studies of ${}^4\text{He}(\text{d}, \text{d}){}^4\text{He}$ elastic scattering have been reported since the previous compilation (1973FI04). Phase-shift analyses have been carried out by (1972SC14, 1975GR09, 1984BA19, 1985JE04, 1990KU16, 1991KR02). See also (1990KU06). Resonating group calculations are described in (1974TH05, 1976LE17, 1982KA24, 1983AO03, 1985FI01, 1985KA20), and optical model analyses in (1984FR14). Calculations based on Glauber theory (1978IN02, 1986FR12), the orthogonality-condition model (1980NI07), microscopic coupled-channel model (1983SA39), and the three-cluster coupling model (1986MI23, 1987MI06) have been carried out. Nucleon-nucleon-alpha Faddeev calculations were reported in (1987HA34, 1990BL13). Calculations utilizing a three-body formalism with Coulomb interaction were described in (1986AG03). A geometric model for dd collisions at high energies (> 6 GeV) is described in (1990HU09). Convergence properties of the pseudo-state method were investigated in (1988KA25). See also the recent work of (1990KU06, 1990KU16, 1991KR02).

Early experimental evidence for levels in ${}^4\text{He}$ from reactions (b) and (c) are discussed in (1973FI04). No new work has been reported.



$$E_b = 2.468$$

This reaction is reviewed in (1966LA04).



$$E_b = 1.588$$

This reaction is reviewed in (1988AJ01).



$$E_b = -0.091$$



Reaction (a) was reviewed by (1988AJ01) under the discussion of ${}^8\text{Be}$. The previous $A = 4$ compilation (1973FI04) reviews early work on reactions (a)–(d) giving information on excited states in ${}^4\text{He}$. More recently, the work reported in (1982FI16) studied the effects of ${}^4\text{He}$ in the first excited (0^+) state on the elastic $\alpha\alpha$ scattering. Kinematically complete experiments on reaction (d) at 119 MeV reported in (1980KA20) found structure in the coincidence energy spectra corresponding to excitations in ${}^4\text{He}$ of 25.5, 27.8, 29.7, 31.7, and 35.3 MeV. Angular correlations were used to assign $J^\pi = 2^+, 2^+(1^-)$, and 2^+ to the last three of these. An investigation (1981BA39) of the excitation spectra of ${}^4\text{He}$ near $E_x = 20$ MeV by means of an (α, α') experiment at 64 MeV used an R -matrix representation to extract level parameters $E_\lambda = 20.29 \pm 0.02$ MeV, $\Gamma_0 = 0.89 \pm 0.04$ MeV for the first excited state.

30. (a) ${}^6\text{Li}(\pi^-, 2\text{n}) {}^4\text{He}$	$Q_m = 134.57$
(b) ${}^6\text{Li}(\pi^+, 2\text{p}) {}^4\text{He}$	$Q_m = 137.16$

Reactions (a) and (b) are reviewed in the previous compilation ([1973FI04](#)) and evidence for the formation of the ground and excited states of ${}^4\text{He}$ based on the summed neutron and proton spectra from reactions (a) and (b), respectively is cited. No new evidence for ${}^4\text{He}$ levels based on reaction (a) has been reported. However, the triple-differential cross section measurements of reaction (b) described in ([1986RI01](#)) indicate strong population of the ${}^4\text{He} 2^-$ state at 22.1 MeV excitation. The energy dependence of the reaction around the $\Delta(1232)$ resonance was explored in ([1990ZHZZ](#)). See also ([1986WH01](#), [1987HU13](#)).

31. ${}^6\text{Li}(\text{n}, \text{t}) {}^4\text{He}$	$Q_m = 4.782$	$E_b = 7.250$
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This reaction was reviewed in ([1988AJ01](#)) under the discussion of ${}^7\text{Li}$. No work giving information on levels in ${}^4\text{He}$ has been reported. See, however ([1986BA68](#), [1986CA29](#), [1986FA13](#)).

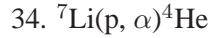
32. (a) ${}^6\text{Li}(\text{p}, {}^3\text{He}) {}^4\text{He}$	$Q_m = 4.018$	$E_b = 5.607$
(b) ${}^6\text{Li}(\text{p}, \text{pd}) {}^4\text{He}$	$Q_m = -1.475$	

These reactions are reviewed by ([1988AJ01](#)) under the discussion of ${}^7\text{Be}$. The previous compilation ([1973FI04](#)) summarizes early experimental and theoretical work on these reactions that relate to the structure of ${}^4\text{He}$. More recently, differential cross sections for reaction (a) ([1974SC24](#)) were measured and analyzed by cluster-model direct reaction formulae, and possible contributions from compound structures within the ${}^3\text{He}-{}^4\text{He}^*(0^+)$ channel involving the first excited state of ${}^4\text{He}$ at 20.1 MeV were discussed. Measurements at incident energies $E = 1 - 3$ MeV are described in ([1989ZAZX](#)). See also ([1987ZA07](#)).

In ([1974ZH01](#)) an estimate of the contribution of spin-flip knock-out processes in reaction (b) is presented. The distribution of effective numbers of n-p pairs in ${}^6\text{Li}$ over the excitation spectrum of ${}^4\text{He}$ is given. Quasi-elastic knockout of excited ${}^4\text{He}$ clusters by fast protons at large momentum transfers is discussed in ([1987ZH10](#)). The excitation spectrum of ${}^4\text{He}$ is calculated.

33. ${}^6\text{Li}(\text{d}, \alpha) {}^4\text{He}$	$Q_m = 22.372$	$E_b = 22.280$
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This reaction is reviewed by ([1988AJ01](#)) under the discussion of ${}^8\text{Be}$. The previous compilation ([1973FI04](#)) cites two reported experiments which provide information on excited states of ${}^4\text{He}$. More recently, an experiment ([1978FU03](#)) at $E_d = 13.6$ MeV involving $d\alpha$ angular correlations showed evidence for a 0^+ state at 25.52 MeV excitation with a width of 2.26 MeV and an odd-parity state at 27.5 MeV. See also ([1975GL08](#)). A recent experiment at $E_d = 18.2 - 36.8$ MeV is reported in ([1989BA88](#)). See also ([1973HE06](#), [1973MI20](#), [1974MI10](#), [1979WA02](#), [1981YU01](#), [1990YA11](#)). An analysis of tensor-analyzing-power data is described in ([1990SA40](#)).



$$Q_m = 17.346$$

$$E_b = 17.255$$

This reaction is reviewed by (1988AJ01) under the discussion of ^8Be . The previous compilation (1973FI04) cites two experiments which provide information on excited states of ^4He at 20.06 and 21.2 MeV. A recent measurement at incident energy $E_i = 29.1 - 44.6$ MeV is reported in (1989BA88). See also the analysis of data at thermonuclear energies in (1990RA28).

^4Li

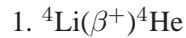
GENERAL

The stability of ^8B against particle decay (1988AJ01), in particular against decay into $^4\text{He} + ^4\text{Li}$, sets an upper limit of 1.7 MeV on the separation energy of ^4Li into $\text{p} + ^3\text{He}$ (1952SH44). The instability of ^4H against particle decay (see ^4H , GENERAL) makes the particle stability of ^4Li very unlikely, since the Coulomb energy of ^4Li is approximately 1.7 MeV larger than that of ^4H (1963WE10), and the nuclear energies should be identical because of charge symmetry. Indeed all decisive tests of the stability of ^4Li have failed. Searches for its beta decay have given negative results (see reaction 1). Indirect proof of the non-existence of ^4Li can be provided by a measurement of the solar neutrino flux which would be strongly influenced by the existence of ^4Li . See (1968ME03). For other theoretical work on ^4Li , see (1974ST14, 1979HU02, 1981KA39, 1988CO15).

The level structure of ^4Li presented here is based on an R -matrix analysis (1983HA1N) that gives a good representation of all the $\text{p} + ^3\text{He}$ scattering data at proton energies below 20 MeV. BW resonance parameters from that analysis are given in Table 4.24 and shown in Fig. 3. The spin-correlation and ^3He analyzing-power data included in the $\text{p}-^3\text{He}$ analysis determined that the lower 1^- level is primarily in the ^3P state, while the upper 1^- is primarily in the ^1P state, removing the ambiguities in the earlier phase-shift solutions, as was discussed in the previous compilation (1973FI04).

As in the case of the ^4H levels (see ^4H , GENERAL), which were based on the ^4Li parameters, all the levels are at least 1 MeV lower than they were in (1973FI04). The only significant difference between the ^4H and ^4Li levels is in the position of the ground state above the nucleon-trinucleon threshold, as would be expected from the simple model used to obtain the ^4H parameters. Again, the parameters of the analysis predict very broad, positive-parity, $T = 1$ states in the $E_x = 15 - 20$ MeV range and antibound P-wave states that cannot yet be identified in the data. The known $T = 1$ levels in the $A = 4$ nuclei are summarized in the isobar diagram of Fig. 4.

The S -matrix poles resulting from the analysis are all far from the real axis with large decay widths Γ , while their residues are relatively small, leading to small values of the strengths. Although the connection is not clear at this point, the small residues for these poles may be connected with the anomalously small widths that have been observed in recent experiments (1990BR14, 1990BR17) that detect ^4Li states in the particle spectra of breakup reactions. It may even be possible that these experiments are not detecting the 2^- and 1^- states as they assume, but positive-parity states (0^+ and 1^+) whose S -matrix poles are much lower in energy than are the K_R -matrix poles.



$$Q_m \approx 21.7$$

not observed

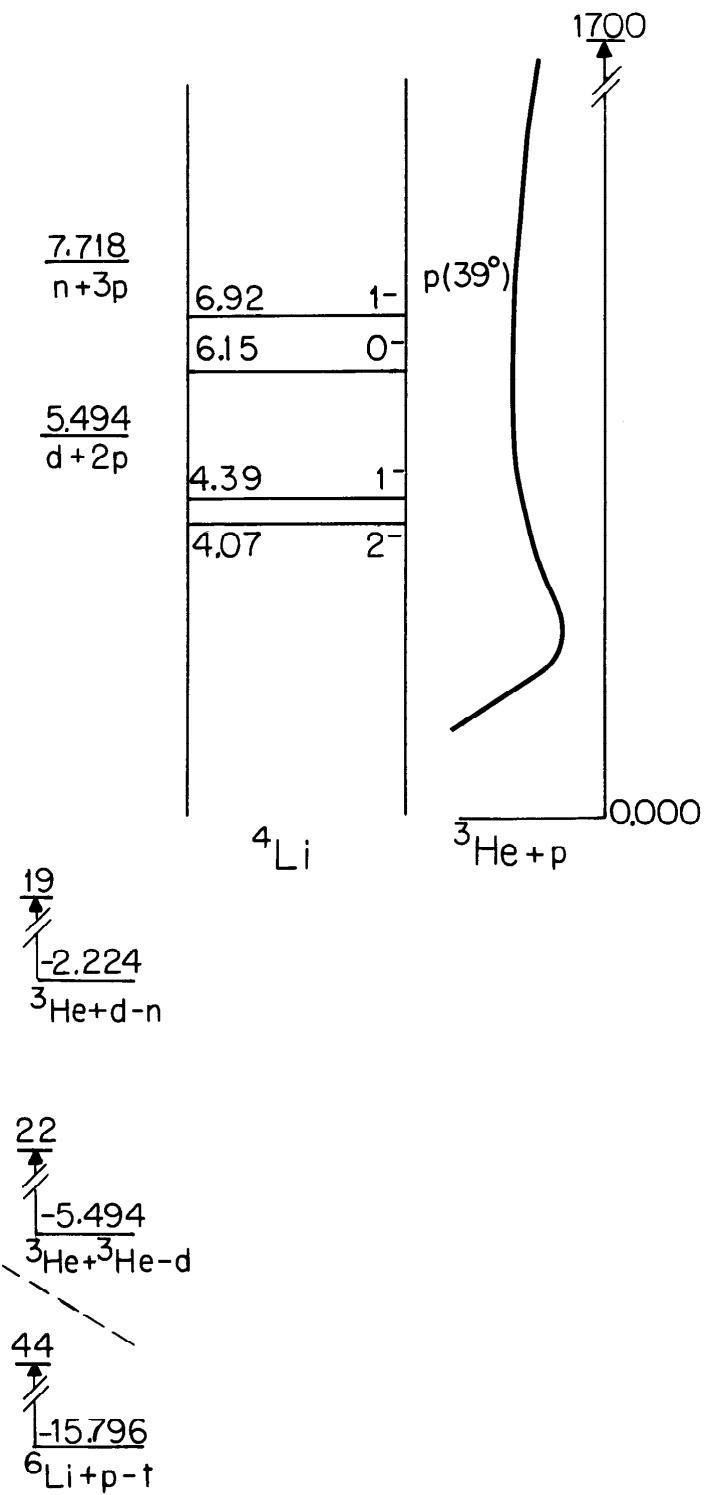


Fig. 3: The energy levels of ${}^4\text{Li}$ are plotted on a vertical scale giving the c.m. energy, in MeV, relative to the mass of ${}^3\text{He} + \text{p}$. See Fig. 1 for details about notation and Table 4.24 for more information about the levels including total widths.

Table 4.24: Energy levels of ${}^4\text{Li}$ defined for channel radius $a_p = 4.9 \text{ fm}$. All energies and widths are in the c.m. system.

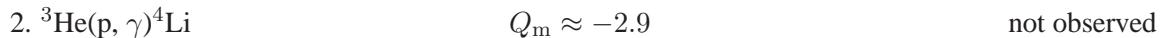
E_x (MeV)	J^π	T	Γ (MeV)	Decay	Reactions
g.s. ^a	2^-	1	6.03	p, ${}^3\text{He}$	3
0.32	1^-	1	7.35 ^b	p, ${}^3\text{He}$	3
2.08	0^-	1	9.35	p, ${}^3\text{He}$	3
2.85	1^-	1	13.51 ^c	p, ${}^3\text{He}$	3

^a 4.07 MeV above the p + ${}^3\text{He}$ mass.

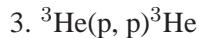
^b Primarily 3P_1 .

^c Primarily $^1\text{P}_1$.

As noted in the previous compilation (1973FI04), the positron decay of ${}^4\text{Li}$, if it were particle stable, must lie close to 20 MeV, and all searches for ${}^4\text{Li}$ beta decay with the expected energy have yielded negative results. Since the previous compilation, no evidence for this decay has been reported.



This reaction has not been observed. Upper limits have been set based on the absence of observable beta decay ([1973FI04](#)).



Measurements of cross sections, polarizations and analyzing powers reported since the previous compilation (1973FI04) are summarized in Table 4.25, and methods of analysis are indicated. No evidence for narrow levels is reported. A discussion of the general features of the earlier cross section data as it concerns possible states in ${}^4\text{Li}$ is given in (1973FI04).

Recent polarization measurements are reviewed, and analyses and comparisons with model calculations are presented in (1987GR08). Phase-shift analyses are reported in (1972BO15, 1978SZ06, 1985BE39, 1985SA22), in addition to those carried out in connection with experiments summarized in Table 4.25. A considerable amount of theoretical work bearing on ${}^3\text{He}(p, p){}^3\text{He}$ has been carried out. Microscopic calculations for the ${}^4\text{Li}$ continuum presented in (1977BE40) include ${}^3\text{He}(p, p)$ differential cross sections as well as ${}^4\text{Li}$ and ${}^4\text{H}$ level positions and widths. A cluster model study by (1979FU05) predicts the ordering of $T = 1$ negative-parity states in $A = 4$ to be 2^- , 1^- (triplet-main), 0^- , 1^- (singlet-main). In the microscopic multichannel resonating group calculations of (1981HO04) the $T = 1$ level order is predicted to be 2^- , 1^- (triplet), 1^- (singlet), 0^- .

In (1987FI03) a review of recent progress in four-body scattering and breakup reactions in the integral equation approach (IEA) is presented. Theoretical studies carried out with various formulations of (IEA) are

Table 4.25: Measurements and analyses of cross sections for proton scattering on ${}^3\text{He}$

E_p (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg) or $-t$ (GeV/c) 2	Description ^a	Refs.
13.600	A_y	15 – 165	Precision measurements. Compared with n + ${}^3\text{He}$.	1974JA16
85	$\sigma(\theta)$	10 – 168	Compared with various theoretical calculations.	1974VO05
18.0, 20.0, 22.5, 25.0, 27.5, 39.0, 35.0, 40.0, 42.7, 45.0, 48.5, 57.0	$\sigma(E, \theta)$	14 – 165	Phase-shift analysis. Compared to resonating group predictions.	1975MO15
27	$\sigma(\theta), P_3$	40 – 160	Polarized ${}^3\text{He}$ target.	1975WA08
600	$\sigma(\theta)$	$-t = 0.08 - 0.45$	Chose $-t$ range to study nuclear multiple scattering.	1976FA09
16.2	$K_x^{x'}, K_y^{y'}, K_z^{x'}$	30 – 90	R-Matrix analysis.	1976HA08
18 – 48	$\sigma_R(E)$		Beam-attenuation technique.	1976SO01
415, 600	$\sigma(\theta)$	$\theta_p = 136^\circ - 172^\circ$	Detected ${}^3\text{He}$ recoils.	1977FR05
25	A_y for ${}^3\text{He}$	46 – 156	Polarized target.	1978MU14
19.6 – 26.5	A_y	135	Phase-shift analysis.	1978MU14
2.30, 3.00, 4.47, 6.80, 8.80	A_y	$\approx 45 - 155$	Polarized ${}^3\text{He}$ target.	1978SZ05
6.82, 8.82, 10.77	$K_x^{x'}, K_y^{y'}, K_z^{x'}$	43.6, 58.9, 76.9, 93.9	Compared with calculated values from previous data analyses.	1978WE16
1000	$\sigma(\theta)$	$\approx 20 - 45$	Studied $\sigma(\theta)$ near minimum. Compared with Glauber model.	1979AL15
1.74 – 4.50	A_y	40 – 150	R-Matrix analysis. Established order of low-lying $T = 1$ ${}^4\text{Li}$ levels.	1979DE04
0.3 – 1.0	$\sigma(E, \theta), A_y$	52.4 – 173.3	Phase-shift analysis.	1980BE06

Table 4.25: Measurements and analyses of cross sections for proton scattering on ${}^3\text{He}$ (continued)

E_p (MeV)	Measurement	$\theta_{\text{c.m.}}$ (deg) or $-t (\text{GeV}/c)^2$	Description ^a	Refs.
700 – 1700	$\sigma(E, \theta)$	160 – 180	Features in $\sigma(E, \theta)$ attributed to baryonic excitation.	1981BE52
1000	$\sigma(E, E_p)$	156	Studied proton spectra.	1983AN18
21.4 – 49.6	A_y	20 – 160	Errors < 0.01. Data compared with fits from phase shift and R -matrix predictions.	1984BI05
978	$d\sigma/dt$	$-t = 0.03 - 0.15 (\text{GeV}/c)^2$	Results compared with Glauber-Sitenko theory.	1984BL07
19.5 – 47.5	$\sigma(E, \theta)$	10.1 – 173.4	Phase-shift analysis. Compared with resonating group calculation.	1984MU13
1000	$\sigma(\theta)$	$\approx 10 - 40$	Analyzed by Glauber-Sitenko theory. Obtained p, n r.m.s. radii difference.	1985AL09
25.0, 30.0, 32.5, 35.0	A_y	39.8 – 152.6	Polarized ${}^3\text{He}$ target. Statistical error ≈ 0.05 .	1985MC04
200, 300, 415, 515	$\sigma(E, \theta), A_y$	15 – 150	Analysis by Glauber multiple scattering theory.	1986HA23

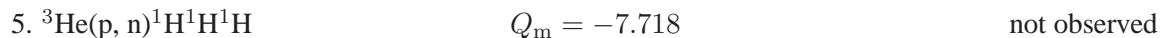
^a Elastic scattering except as noted.

(1976SA02, 1977BA46, 1985SO07, 1986FO07, 1987FI03). See also (1980BA55, 1982BL15, 1983BL15). Extensive use of the Glauber multiple scattering theory has been made to describe the scattering cross section in the intermediate energy region, for example (1973NA06, 1976FR12, 1979ME08, 1981BI08). See also (1976LE32, 1978PE20). Optical model calculations of ${}^3\text{He}(\text{p}, \text{p})$ have been reported in (1979SH06, 1984LA20, 1984PA09, 1985SA22, 1986LA02, 1990LA01). The mechanism of two-nucleon exchange in backward scattering is explored in (1989LA26). The specific distortion effect of the three-nucleon cluster in the $\text{p} + {}^3\text{He}$ system was studied in a resonating-group formulation by (1986SH12). A non-relativistic field theoretic formalism was used (1979FO08, 1984FO08) to develop a soluble four-body model and calculate scattering cross sections. Time-reversal violating effects in low-energy ${}^3\text{He}(\text{p}, \text{p})$ scattering were calculated and found to be very small (1977SI11). For other theoretical work related to ${}^3\text{He}(\text{p}, \text{p})$ ${}^3\text{He}$ see (1972KI13, 1973KI07, 1974LY02, 1975BA05, 1975KI11, 1975RU01, 1979KA19, 1983LY07, 1984LA25, 1987AB13).



Early measurements of particle spectra from the ${}^3\text{He}(\text{p}, \text{d}){}^1\text{H}{}^1\text{H}$ reaction are tabulated in the previous compilation (1973FI04), and a discussion of information obtained on pp final-state interactions (FSI) and pp and pd quasi-free scattering (QFS) processes is presented. More recent experiments on ${}^3\text{He}(\text{p}, \text{d}){}^1\text{H}{}^1\text{H}$ are summarized in Table 4.26.

Measurements of continuum cross sections and analyzing powers reported in (1985WE12) were compared with distorted-wave impulse approximation calculations based on quasi-free nucleon and deuteron knockout. Results of this comparison clearly indicated the need for including deuteron knockout. Several experiments on ${}^3\text{He}(\text{p}, \text{d})$ have been carried out to investigate the question of dibaryonic resonances. A review of experiments including ${}^3\text{He}(\text{p}, \text{d})$ and other reactions was presented in (1986GA15). Missing mass spectra reported in (1987TA17, 1987TA20) show narrow structures possibly associated with $B = 2, T = 1$ quantum numbers. The structures observed have masses and widths ($M_x = 2.240 \pm 0.005, \Gamma_{1/2} \approx 0.016 \pm 0.003$ GeV; $M_x = 2.192 \pm 0.003, \Gamma_{1/2} \approx 0.025 \pm 0.006$ GeV; $M_x = 2.121 \pm 0.003, \Gamma_{1/2} \approx 0.025 \pm 0.002$ GeV). An independent investigation reported in (1988SA33) found narrow structure in the missing-mass dependence of analyzing power that showed significant correspondence with previous reports and predictions of theory.



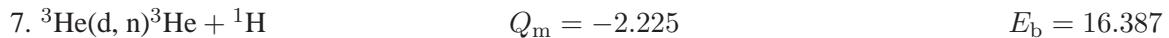
The previous compilation (1973FI04) lists a limited number of measurements of neutron spectra from ${}^3\text{He}(\text{p}, \text{n}){}^1\text{H}{}^1\text{H}{}^1\text{H}$ and notes there is no evidence for a neutron group below the four-body threshold. No recent work has been reported.



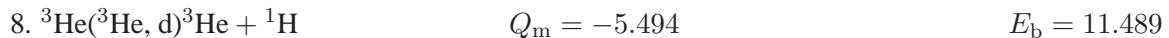
As noted in the previous compilation (1973FI04) this reaction was reviewed in (1974AJ01), and early work setting an upper limit to the cross section was cited. No new measurements have been reported. See, however, the work on primordial nucleosynthesis discussed in (1991RI03).

Table 4.26: Measurements and summaries (S) of particle spectra from the ${}^3\text{He}(\text{p}, \text{d})$ reaction

E_{d} (MeV)	Particle detected	θ (deg)	Description	Refs.
98.7, 149.3	d, p	$\theta_{\text{d}} = 17.5, 60$	Measured $\sigma(\theta)$, $A_y(\theta)$ DWIA analysis based on quasi-free d knockout.	1985WE12
750, 925	d, X	40 (lab)	Measured $\sigma(\theta, E)$, missing mass. Searched for narrow dibaryons.	1986GA15
750	d, X	6, 40 (lab)	Measured $\sigma(\theta, E)$, missing mass. Reported evidence for narrow $B = 2$ resonance.	1987TA17
750, 925	d, X	22, 32, 40 (lab), 30, 40	Measured $\sigma(\theta, E)$, missing mass. Reported evidence for narrow $B = 2, T = 1$ structure.	1987TA20
$p_{\text{p}} = 1.46 \text{ GeV}/c$	d, X	22 (lab)	Measured $\sigma(\theta)$, $A_y(\theta)$. Evidence for narrow structure.	1988SA33



This reaction was reviewed in the previous compilation ([1973FI04](#)) and by ([1974AJ01](#)). No evidence was cited for states of ${}^4\text{Li}$. No new work has been reported.



This reaction was reviewed in the previous compilation ([1973FI04](#)) and by ([1974AJ01](#)). Upper limits are quoted for the cross section. Two experiments in which the products of ${}^3\text{He}({}^3\text{He}, \text{d})$ reactions were studied have been reported since ([1973FI04](#)). The first of these ([1977DA11](#)) searched for high energy deuterons from ${}^3\text{He}({}^3\text{He}, \text{d}){}^4\text{He} + e^+ + \nu$ at $E({}^3\text{He}) = 15$ and 20 MeV in connection with the solar neutrino problem. The other experiment examined quasi-free processes in which at least two of the final-state particles were charged. Beam energies were 50, 65, and 78 MeV. The kinematic conditions that were chosen favored the dominance of d- ${}^3\text{He}$ quasi-free processes over sequential decay modes through ${}^4\text{Li}$ or ${}^5\text{Li}$. No evidence for ${}^4\text{Li}$ was observed in either of these experiments.

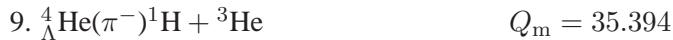


Table 4.27: Measurements and summaries (S) of $\pi^+ + {}^4\text{He}$ reactions

Reaction	E_π (MeV)	Description	Refs.
${}^4\text{He}(\pi^+, \text{p}){}^3\text{He}$	60, 100, 220	Measured $\sigma(E, \theta)$ and proton spectra at $45^\circ, 90^\circ$ (lab). Studied absorption mechanism.	1977JA15
	50 – 295	Measured $\sigma(E, \theta)$ at $20^\circ, 40^\circ$. Yields nearly proportional to number of target NN pairs.	1980KA37
	50 – 300	Measured $\sigma(E, \theta)$ at 20° . Compared $\pi^+\text{NN} \rightarrow \text{Np}$ and $\pi^+\text{d} \rightarrow \text{pp}$.	1981KA41
	400, 475	Measured yields for $\theta_p = 30^\circ$. Two-nucleon pion absorption kinematic region emphasized.	1981KA43
	100, 160, 220	Measured $\sigma(E_\pi, \theta)$ and proton spectra at $\theta_p = 30^\circ - 150^\circ$. Observed quasi-deuteron absorption mode.	1981MC09
	50 – 295	Measured $\sigma(E_\pi, E_p)$ at $\theta_p = 30^\circ, 40^\circ$. Studied pion scattering and absorption contributions.	1983KA14
	165	Measured $\sigma(\theta_{p_1}, \theta_{p_2})$. Deduced contribution of $2\text{N} + \pi \rightarrow 2\text{N}$ reactions where initial 2 nucleons are in a relative S-state.	1981AS10
${}^4\text{He}(\pi^+, 2\text{p}){}^2\text{H}$	65 – 320	Measured charged-particle multiplicity, $\sigma(\theta_1, \theta_1)$.	1990ADZY

Early work on this reaction was summarized in the previous compilation ([1973FI04](#)). More recently, extensive reviews of experimental and theoretical work on hypernuclei were presented in ([1975GA1A](#), [1978PO1A](#), [1990CO1D](#), [1990OS1A](#)). A theoretical study ([1985LY1A](#)) found that the polarization of the protons and tritons in the reaction is largely determined by the strong interaction in the p– ${}^3\text{He}$ system. Theoretical analyses of the binding energies of the ground and excited states of ${}^4\text{He}$ and ${}^4\text{H}$ are presented in ([1982KO13](#), [1987YA1M](#)). See also ([1988MA09](#)). Coulomb effects and charge symmetry breaking are discussed in ([1985BO17](#)). A four-body calculation of the $0^+ - 1^+$ binding energy difference is reported in ([1988GI1F](#)). Non-mesonic decays are discussed in ([1985TA1E](#), [1986SZ1A](#), [1990CO1D](#), [1990OS1A](#)). Evidence for the existence of a Σ -nucleus bound state formed in a (K^-, π^-) reaction on ${}^4\text{He}$ was reported in ([1989HA39](#)). See also ([1989HA30](#), [1989HA39](#), [1990HA08](#), [1990HA11](#)). The possibility of forming doubly-strange Ξ -hypernuclei is considered in ([1983DO1B](#)). Theoretical discussions of Σ -hypernuclei are given in ([1990HA1B](#), [1990HA08](#), [1990HA11](#), [1990OK03](#)).

10. (a) ${}^4\text{He}(\pi^+, \text{p}){}^3\text{He}$	$Q_m = 120.28$
(b) ${}^4\text{He}(\pi^+, 2\text{p}){}^2\text{H}$	$Q_m = 114.79$
(c) ${}^4\text{He}(\pi^+, 2\text{p})\text{N} + {}^1\text{H}$	$Q_m = 112.56$
(d) ${}^4\text{He}(\pi^+, \pi^0){}^4\text{Li}^*$	$Q_m = -14.69$

Measurements of cross sections and proton spectra from reaction (a) reported since the previous compilation ([1973FI04](#)) are summarized in Table 4.27. The emphasis in these measurements is on the study of pion scattering and absorption contributions. A review of the experimental and theoretical situation with respect to pion absorption in nuclei is presented in ([1985OH09](#)), and an isobar-hole model calculation is described for ${}^4\text{He}$ which takes into account large pion distortion effects and predicts the main features of the cross section correctly. One experimental study of reaction (b) was reported ([1981AS10](#)). The relative absorption ratio of a pion by $T = 0$ and $T = 1$ pairs was determined. Calculations of this ratio have been carried out utilizing a standard theory of Δ -isobar excitations ([1982TO18](#)) and by a unitary isobar model ([1984SI03](#)). Earlier work reported in ([1974WI19](#)) obtained amplitudes and cross sections for the $(\pi^+, 2\text{p})$ reactions in a treatment based on field theory. No new data on reaction (d) have been reported. A calculation of inelastic pion-nucleus collisions and pion absorption from the Boltzmann equation which included the (π^+, π^0) reaction is described in ([1979HU02](#)).

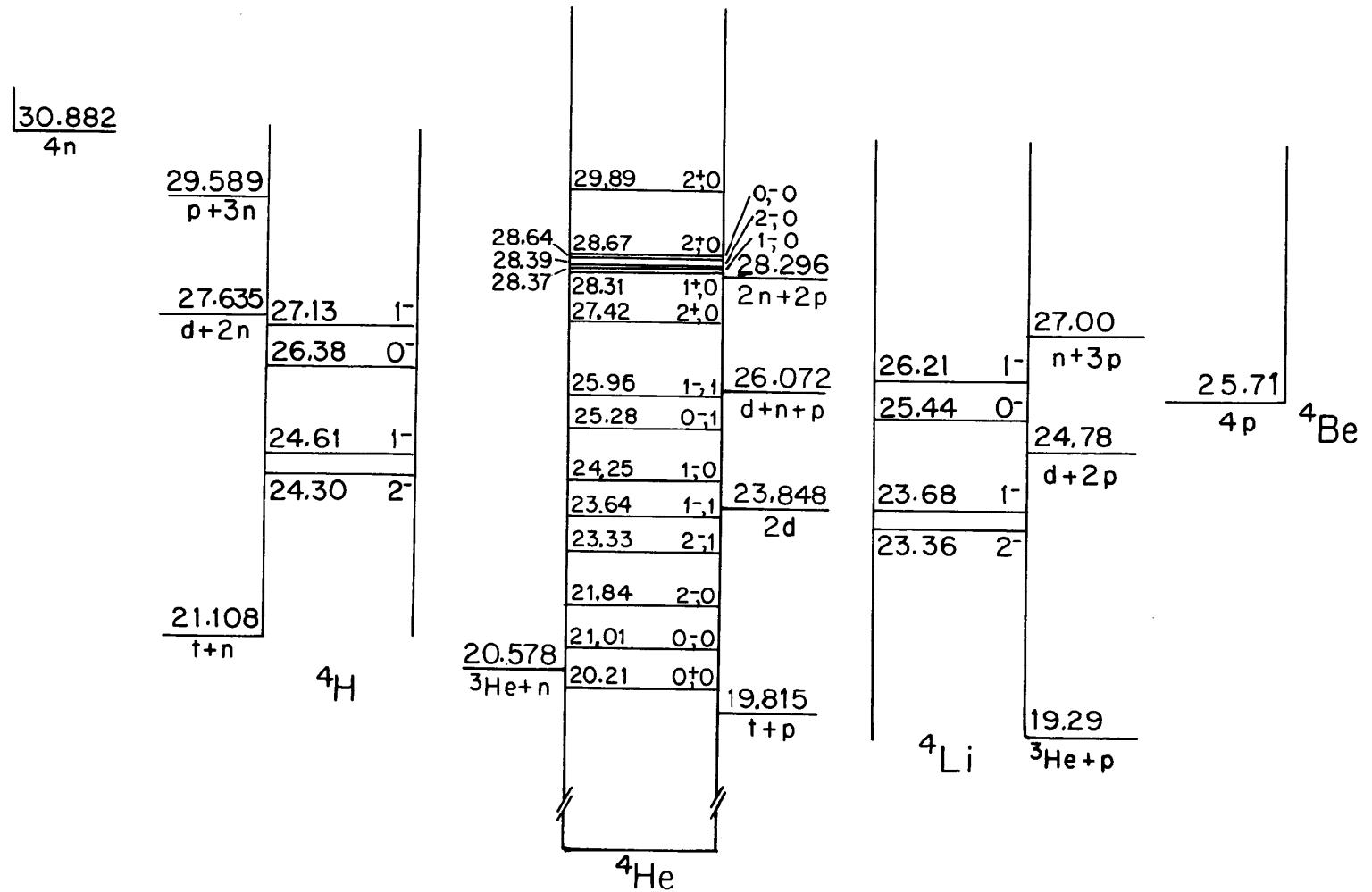


Fig. 4: Isobar diagram for $A = 4$. All energies are referred to the ground-state mass ^4He without taking into account the np mass difference or the Coulomb energy. Levels belonging to the same isospin multiplet are connected by dashed lines. For other notations, see Fig. 1.

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