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Energy Levels of Light Nuclei
$A = 3$

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Abstract: An evaluation of $A = 3$ was published in *Nuclear Physics A*474 (1987), p. 1. Emphasis is on possible structure of $A = 3$ systems and final-state interactions in three-particle reactions. No excited states of ^{3}H and ^{3}He have been established, and no firm evidence for the existence of the trineutron or triproton has been obtained. This version of $A = 3$ differs from the published version in that we have corrected some errors discovered after the article went to press. Reference key numbers are in the NNDC/TUNL format.

(References closed June 1, 1987)

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Introduction

The purpose of this work is to bring together and organize the large body of research on the $A = 3$ system that has been published since the compilation of Fiarman and Hanna [1]). In this earlier work it was decided to present the material in the framework of a discussion of the energy levels of the system even though only two levels are presently known. This approach was chosen because it provided an organized method for presenting a large volume of data that had become well established for review of $A > 3$ nuclei, and because much of the earlier research had been motivated by a desire to discover and study levels and resonances of the system. While it is true that the major emphasis of the work reviewed here is on understanding the trinucleon system at a fundamental level and developing successful theoretical descriptions rather than on discovering new levels, it was nevertheless decided that the present review should adhere to the system of organization that had been utilized with great success in the Fiarman and Hanna work. As in that work the information is arranged by nuclear reactions under the $A = 3$ system that seems most appropriate.

Except in rare instances, references that were published prior to 1974 were not included since they would have appeared in the previous compilation. The present review includes material that appeared in the NNDC Nuclear Structure References through June 1, 1987.

In accordance with the approach of the previous compilation, the material is organized into four systems; ^{3}n, ^{3}H, ^{3}He, ^{3}Li. Under each system the reactions are presented such that first the target, then the bombarding particle, and finally the product particle are ordered according to the sequence: γ, e, μ, π, . . . , n, ^{1}H, and then by Z with increasing A. Following the convention of Fiarman and Hanna and earlier reviews, the β-decay process ^{3}H(β^-)^{3}He is given first.

Recent review articles relevant to the A = 3 system

H.W. Baer, K.M. Crowe, and P. Truöl, Radiative pion capture in nuclei (1977BA2A)

C. Ciofi degli Atti, Electromagnetic and hadronic interactions with the few-body systems at intermediate energies (1977CI2A)

H.W. Fearing, Pion production in nuclei: Things known and unknown (1981FE2A)

J.L. Friar, B.F. Gibson and G.L. Payne, Recent progress in understanding trinucleon properties (1984FR16)

B.F. Gibson, The three-body force in the three-nucleon system (1986GIZS)

M. Gmitrö, H.R. Kissener and P. Truöl, Basic mechanisms of radiative capture of pions (1982GM02)

A.N. Gorbunov, Nuclear photoeffect at helium isotopes (1976GO2A)

B. Höistad, Pion production in proton-nucleus collisions (1979HO2A)

G. Igo, Elastic and inelastic scattering of p, d, α, . . . on nuclei (1982IG2A)

B. Kuhn, Measurement of the neutron-neutron scattering length and the question of the charge dependence of nuclear forces (1975KU25)

H. Kumpf, J. Mosner, K. Moller and G. Schmidt, Deuteron breakup by protons and neutrons (1978KU13)

D.F. Measday and G.A. Miller, Hopes and realities for the (p, π) reaction (1979ME2A)

B.M.K. Nefkens, Meson induced reactions in the three- and two- nucleon systems (1978NE2B)

A.C. Phillips, Three-body systems in nuclear physics (1977PH2A)

E.I. Sharapov, Radiative capture of neutrons by the lightest nuclei (1981SH25)

I. Sick, Lepton scattering (1978SI2B)
J.E. Simmons, Some topics concerning n-n and n-d experiments at medium energies (1975SI2A)
I. Slaus, Quasifree processes and few-body systems (1974SL04)
I. Slaus, Neutron induced reactions on very light and light nuclei (1976SL2A)
I. Slaus, Experiments in few-body research (1978SL2A)
B. Sundqvist, Low-energy three- and four-nucleon scattering experiments (1978SU2A)
E.L. Tomusiak, Present status of photonuclear reactions in light nuclei (1979TO2A)
M.S. Weiss, Photonuclear studies in the few-nucleon system (1975WE2A)

Notation

E	bombarding energy in the laboratory system; subscripts p, d, t, π refer to protons, deuterons, tritons, pions, etc.
$E_{\rm cm}$	energy in the cm system;
$E_{\rm x}$	excitation energy;
$Q_{\rm m}$	reaction energy;
$E_{\rm b}$	separation energy;
Γ	full widths at half maximum of a resonance or level;
$E_{\rm R}$	resonance energy;
θ	angle in the labpratory or cm systems;
$\theta_{\rm cm}$	angle in cm system;
$\sigma(\theta)$	differential cross section;
$\sigma_{\rm tot}$	total cross section;
$P(\theta)$	polarization;
$A(\theta)$	analyzing power;
J^{π}	spin and parity;
μ	magnetic moment;
a	scattering length;
r	effective range;
q^2	four-momentum transfer squared (in fm^{-2}).

If not specified otherwise, energies are given in MeV.

Useful masses (MeV) [a]

μ^-	105.65916	(30) [b]
$\pi^\pm$	139.5685	(10)
π^0	134.9642	(38)
Λ	1115.60	(5)
^{1}n	8.071369	(13)
^{1}H	7.289030	(11)
^{2}H	13.135824	(22)
^{3}H	14.94991	(3)
^{3}He	14.93132	(3)
^{4}He	2.42492	(5)
^{5}He	11.390	(50)
^{6}He	17.5923	(10)
^{6}Li	14.0856	(7)
^{6}Be	18.374	(5)

[a] Non-hadronic masses are from ref. (2); atomic mass excesses are from ref. (3).
[b] The uncertainty in the last few significant figures is given in parentheses.

Acknowledgements

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References to the Introduction

1) S. Fiarman and S.S. Hanna, Nucl. Phys. **A251** (1975) 1
2) M. Aguilar-Benitet *et al.*, Phys. Lett. **170B** (1986) 1
3) A.H. Wapstra and G. Audi, Nucl. Phys. **A432** (1985) 1

^{3}n

(not illustrated)

GENERAL:

The weight of experimental evidence reviewed in the previous compilation of Fiarman and Hanna (1975FI08) is strongly against the existence of a bound state of the three-neutron system, and only controversial evidence of ^{3}n resonances was cited. Several experiments carried out more recently have strengthened the evidence against the bound trineutron and have failed to discover resonance structure that cannot be otherwise explained. The most suggestive work is the (π^-, π^+) double charge-exchange experiment of (1974SP08) (see reaction 2 below), the result of which could be interpreted as indicating a $T = \frac{3}{2}$ resonance around 12 MeV excitation. This observation was supported by more recent (π^-, π^+) measurements reported in (1986ST09).

Some of the contradictory aspects (1975FI08, 1977PH2A) of calculations on bound states of ^{3}n have been clarified. (1979LI19) showed that disagreements between Faddeev calculations (which predicted a bound trineutron) and variational calculations (which did not), arose from the potentials used in the Faddeev calculations. (1978GL07) has calculated the S-matrix pole trajectory in a three-neutron model and concluded that its pattern rules out the possibility of a low-energy resonance. In (1979OF01) a study using the Reid potential found that the interaction potential must be enhanced by ≈ 4 to bind ^{3}n near zero energy, indicating that a low energy resonance is extremely unlikely. The trineutron binding energy was calculated (1980BE22) using an interaction which reproduces ^{3}H, ^{3}He, ^{4}H, ^{4}He, and ^{4}Li ground states. The model suggests that ^{3}n is unbound. A Faddeev calculation (1980SU05) with a realistic nucleon-nucleon interaction in coordinate space indicated that ^{3}n states with $\frac{1}{2} < J < \frac{7}{2}$ of either parity are unbound for the Reid soft core potential. A method for finding the lower estimates of energies of specific states is proposed by (1981KA39). They investigate four varieties of potentials with the super-soft core and the Reid potential. The method indicates that only $T = \frac{1}{2}$ is allowed for $A = 3$ and forbids states of ^{3}n or ^{3}Li.

1. ^{3}H(π^-, γ)^{3}n — not observed

Measurements (1976BI05, 1979BI13) for π^- momentum $p = 200$ MeV/c with a high-resolution pair spectrometer gave no evidence for bound ^{3}n, but could not rule out resonance struture in the excitation region from 7 to 16 MeV. (See also the review of (1977BA2A). An improved experiment (1980MI12) gave an upper limit on the branching ratio (bound state width)/(total radiative capture width) of 4×10^{-3} and an upper limit on the branching ratio to resonances with width < 5 MeV was determined to be 2×10^{-2}. These results along with other radiative pion capture experiments are reviewed in (1982GM02).

In recent work by (1985WE04), the 1s π^- absorption width for ^{3}H(π^-, γ)^{3}n is predicted to be 2.25 ± 0.55 eV on the basis of the isospin dependence of the two-nucleon pion absorption operator.

2. ^{3}He(π^-, π^+)^{3}n — not observed

At $E_\pi = 140$ MeV and π^+ detection angle between 20° and 40° (1974SP08) measured an enhancement in the π^+ distribution near threshold which can be interpreted either as a $T = \frac{3}{2}$ three-nucleon resonance or a resonance of the nucleons in the ^{3}He nucleus. They obtain an upper limit of 0.12 μb/sr for the production cross section of a bound state of ^{3}n. A theoretical study by (1984JI01) using the method of hyperspherical functions in the coordinate representation showed that the resonance-like behavior of the differential cross section observed in the experiment is reproduced by the inclusion of the final state interaction, and therefore it is unlikely that it proves the formation of a ^{3}n resonance state. More recently a measurement of the differential cross section $\sigma(E_{\pi^-},\ E_{\pi^+},\ \theta)$ for the ^{3}He(π^-, π^+) reaction at 140, 200, and 295 MeV was reported in (1986ST09). The missing-mass plot showed a strong enhancement resembling a broad 3-nucleon resonance.

3. ^{4}He(π^-, p)^{3}n — not observed

Pion absorption studies have been carried out by several groups. Proton spectra were measured at $E_\pi = 60$, 100, 200 MeV and $\theta = 45°$ and $90°$ (1977JA15); at $E_\pi = 100$, 160, 220 MeV and θ between $30°$ and $150°$ (1981MC09); at $E_\pi = 50 - 300$ MeV and $\theta = 20°$ (1981KA41); at $E_\pi = 400$, 475 MeV and $\theta = 30°$ (1981KA43); at $E_\pi = 50$, 100, 150, 200, 250 MeV and $\theta = 20°$ and $40°$ (1983KA14). The breakup of ^{4}He by π^- was studied by (1981RAZV, 1981RAZZ). Proton energy spectra from the capture at rest of π^- by ^{4}He were measured (1981CE01). No evidence was reported for ^{3}n bound states in any of the pion absorption experiments.

4. ^{7}Li(π^-, ^{4}He)^{3}n — not observed

A search for ^{4}He recoils corresponding to ^{3}n formation was carried out (1977BA47) with ^{7}Li loaded emulsions. An upper limit for the branching ratio of ^{3}n formation to all other channels was found to be $< 1.2 \times 10^{-3}$ at the 90% confidence level.

5. ^{7}Li(^{7}Li, ^{11}C)^{3}n — not observed

Particle identification spectra were obtained (1974CE06) at a ^{7}Li bombarding energy of 79.6 MeV. The ^{11}C energy distribution was well fit by four-body phase-space predictions. An upper limit of 70 nb/sr for ^{3}n bound state production was obtained. No resonant structure was evident.

^{3}H
(not illustrated)

GENERAL:

Ground State

$$J^\pi = \frac{1}{2}^+$$
$$\mu = 2.978960 \pm 0.000001\ \text{nm}$$
$$M - A = 14.94991 \pm 0.00003\ \text{MeV}$$

The wave function for the triton bound state is calculated to be mostly S-state ($\approx 90\%$) with S′-state ($\approx 1\%$) and D-state ($\approx 9\%$) admixtures depending on the potentials used (1979SA15, 1986IS06). See also (1980HA10, 1980LO09, 1983FR19, 1984CI05, 1984CI09, 1984MU23). The measured magnetic moment for ^{3}H is $\mu = 2.978960 \pm 0.000001$ nm (1978LEZA). Calculations which include both impulse and pion exchange contributions are in fairly good agreement with the measured trinucleon magnetic moments (1985TO21). Recent calculation with a six-quark bag model (1986BH05) are also compatible with the data for ^{3}H and ^{3}He. See also (1982WO03, 1983BU07).

The rms charge and magnetic radii for ^{3}H determined from electron scattering (see reaction 8(a)) are $\gamma^{\rm c}_{\rm rms} = 1.63 \pm 0.03$ fm and $\gamma^{\rm m}_{\rm rms} = 1.72 \pm 0.06$ fm. In general two-body force calculations give values of $\gamma^{\rm c}_{\rm rms}$ which are $\approx 10\%$ too large (1986GIZS). This discrepancy has not yet been fully resolved by the addition of three-body forces although there are calculations (1986IS06) which, when extrapolated to give the correct triton binding energies, are in resonable agreement with $\gamma^{\rm c}_{\rm rms}$ (exp). (However, the form factor problem remains (1986GIZS)). See also (1985FR12, 1986SAZG) which examine the way in which the triton bound state observables scale with binding energy.

The binding energy of ^{3}H is 8.481855 ± 0.000013 MeV (1985WA02). Many calculations have been done to predict the binding energy of ^{3}H and ^{3}He (see the reviews of 1984FR16, 1986FRZU, 1986GIZS) and references given below. It is observed in (1986GIZS) that two-body force calculations with realistic forces underbind ^{3}H by ≈ 1 MeV whereas calculations with three-body forces give binding energies too large by ≈ 0.5 MeV, although it is pointed out in (1986SA2A) that three-body force calculations can give correct biding energies if the cut-off mass is taken to be 700 MeV.

Charge and magnetic form factors for ^{3}H have been determined from electron scattering experiments (see sect. 8(a)). Measurements for q^2 from 23 to 31 fm^{-2} are reported in (1985JU01). The available data indicate that the magnetic form factor is similar to that for ^{3}H which has a diffraction minimum at a higher value of q than predicted by impulse approximation calculations. The isobar model of (1983ST11) with meson-exchange currents satisfactorily accounts for the differences. (See also (1986SA07, 1986SA08).) Calculations of the charge form factor with two-body potentials are in serious disagreement with experiment for ^{3}He in that the theoretical momentum transfer at the first minimum is too high, and the height of the second maximum is too low. (See also sect. 8(a).) However it is pointed out in (1987PL2A, 1987ST09) that the ^{3}H charge form factor is well described by theory if the correct pseudoscalar vector coupling for the pion-nucleon vertex is used in the calculation of the exchange current contributions. For other recent calculations see (1985BO44, 1985MA24, 1986CI05, 1986FR15, 1986HA12, 1986KI17, 1986LI09, 1986SA07, 1986SA08). The addition of a three-body force increases the calculated value of the charge form factor in the region of the second maximum by 50%, but a factor of three is needed (1986GIZS). The very recent work of (1987BE30) reporting on measurements of ^{3}H and ^{3}He isoscalar and isovector form factors also reviews the extent of agreement between current theories and experiment.

The review of (1986FRZU) notes that calculational techniques for the trinucleon system have progressed to the point where critical examinations of three-nucleon forces, relativistic effects of nucleon motion, and explicit non-nuclear degrees of freedom such as pions, isobars, quarks etc. can be made with some confidence.

A great deal of work has been done to explore three-body force effects. See for example the conference proceedings (1984FA2A, 1986BE2A) and summaries (1986CA2A, 1986CH2C, 1986FRZU, 1986GIZS, 1986TO2A) and the review (1984FR16). See also recent calculations of (1976HA40, 1977HE22, 1979OS08, 1979YA03, 1981CA14, 1981CO2B, 1981LO08, 1982CO04, 1982DA06, 1982DA19, 1982DA20, 1982DA25, 1982GL05, 1982MU13, 1982ZA01, 1983CA10, 1983CO17, 1983ME14, 1983MU06, 1983WI05, 1984CO18, 1984IS04, 1984UE01, 1984WI12, 1985CH17, 1985CH22, 1985RO02, 1986CH13, 1986SA08, 1987NA02, 1987ST09).

Relativistic effects in the trinucleon bound state are considered in (1977BA25, 1979HA36, 1980MA22, 1981GA15, 1981KO02, 1986GL01). The effects of including tensor forces in three-body calculations are discussed in (1986OS04, 1986OS07).

The quark structure of the trinucleon and the effect of quark clusters onits ground state properties have been studied by (1983BE08, 1983NE08, 1983NE12, 1984GR18, 1984SU03, 1985FA01, 1985KO02, 1985MA30, 1985MA24, 1985MA67, 1985VE15, 1986AB02, 1986BH05, 1986CH22, 1986GU12, 1986KI17, 1986OE02, 1986SA02).

Trinucleon asymptotic normalization constants have been calculated by (1976LE01, 1979GI2B, 1979KI03, 1980HA03, 1980SA23, 1982BO22, 1982FR07, 1984FR16, 1986IS01).

Binding energy calculations in addition to those mentioned above have been carried out by (1975HE11, 1976DZ01, 1976SH16, 1977EL05, 1977GL07, 1977HE16, 1977NU2A, 1978BI02, 1978CH21, 1978EF01, 1978GI10, 1978KI14, 1979HA27, 1979OS02, 1979SA15, 1980BA21, 1980GO10, 1980MI19, 1980PA12, 1981HA41, 1982BA58, 1982DA24, 1983HA19, 1983OR06, 1984GI01, 1984JI05, 1984OR02, 1985AB12, 1985EF01, 1985OR03, 1985OR05, 1985OR06, 1985OR08, 1985RU04, 1986BE25, 1986HA10, 1986HA36, 1986KE07, 1986NA10, 1986PE08, 1987TO04).

Theoretical papers not mentioned elsewhere are (1975AF01, 1975GO04, 1975MC17, 1977AF02, 1977BA20, 1977BE61, 1977BL11, 1977EM01, 1977SO05, 1978HY01, 1978ST28, 1979BE09, 1979DE13, 1979PE06, 1980ZN01, 1981KO37, 1981LE22, 1981PA05, 1981SA27, 1982AT01, 1983GR24, 1983ME06, 1985BO17).

1. ^{3}H(β^-)^{3}He $\qquad Q_\mathrm{m} = 18.594$ keV

Early measurements of the half-life are reviewed in (1975FI08). A recent evaluation of available experimental data was carried out by (1984HO2A). The recommended value is $T_{1/2}$ is 12.3 ± 0.1 years. The standard deviation on the recommended value is based on the disagreement between the evaluated measurements. A very recent measurement reported in (1987SI01) gave $T_{1/2}$=12.32 ± 0.03 years. The Q-value adopted by (1985WA02) is 18.594 ± 0.008 keV. A recent measurement by (1985SI07) with a tritium implanted Si(Li) detector gave 18.577 ± 0.007 KeV for the ^{3}H end point energy. See also the related mass-difference measurements of (1981SM02, 1984LI24, 1984NI16, 1985LI02).

Using the evaluated data for the half life and end-point beta-decay energy, (1978RA2A) obtained a value for the Gamow-Teller matrix element, $\langle \sigma \cdot \tau \rangle = \sqrt{3}(0.975 \pm 0.007)$. This was based on a value of the ratio of axial-vector to polar-vector coupling constants $|G_{\rm A}/G_{\rm V'}| = 1.237 \pm 0.008$. On the basis of more recent data, (1982BA20) has suggested using $|G_{\rm A}/G_{\rm V'}| = 1.259 \pm 0.009$. This results in a value for the Gamow-Teller matrix element of $\langle\sigma\cdot\tau\rangle = \sqrt{3}(0.958\pm0.008)$ which (1982BA20) compares with calculated values in various approximations. The value calculated using π^- and ρ^- exchange with point couplings agrees with this modified value. A calculation of $\langle\sigma\cdot\tau\rangle$ including axial meson exchange current effects (1984CI01) gave agreement with experiment. An experiment to measure $\langle\sigma\cdot\tau\rangle$ in a model-independent way is discussed in (1985BUZZ). The effect of the atomic and molecular environment on the value of $\langle\sigma\cdot\tau\rangle$ deduced from experiment was studied by (1983BU13) and found to be significant, and could imply a higher probability of finding delta isobars in the triton. An analysis by (1984BO03) of experimental results which included ^{3}H beta decay placed limits on unusual coupling constants.

Measurements of the ^{3}H beta spectrum to determine the antineutrino mass were carried out by (1981SI18, 1983DE47) who determined $m_\nu < 65$ eV and $m_\nu < 50$ eV, respectively. The experiment of (1980KO2A, 1980LU2A, 1981LU07) on the ^{3}H beta spectrum in the valine molecule indicated a finite antineutrino mass, $14 < m_\nu < 46$ eV. The effects of molecular structure on the ^{3}H beta spectrum shape were studied by (1982KA1X, 1983KA33) who determined that the lower limit of 14 eV should be replaced by a higher value. See also (1985KA21). However, the experiments of (1980KO2A, 1980LU2A, 1981LU07) were re-evaluated by (1984SI2B) and (1985BE01) who found that there is no conclusive evidence for $m_\nu > 0$. More recent studies by (1985BO34, 1985BO53) with improved apparatus and techniques found $m_\nu > 20$ eV. Very recently an analysis (1987BO07) of ^{3}H decay in valine gave a neutrino mass of 30.3^{+2}_{-8} eV while measurements of free molecular tritium decay reported in (1987WI07) gave an upper limit of 27 eV for m_ν. In other work bearing on the antineutrino mass measurements it was found that the effects of Coulomb corrections (1983WU01) and radiative-spectrum corrections (1983RE13) could prove important in the determination of the neutrino mass from the ^{3}H beta spectrum. The effects of atomic final state interactions on the neutrino mass-determination problem were studied by (1983WI02) and found to be negligible. Two-step processes were examined by (1984ST09) and found to be unimportant. See also the recent work of (1986EM01, 1986LI08, 1987DR03). An experiment utilizing free atomic and molecular tritium is described in (1985KNZX). The beta spectrum of the tritium molecule is computed by (1985FA05), and it is shown that molecular effects are crucial in determinations of the neutrino mass. See also the recent work of (1986AR07, 1986AR18, 1986AR19, 1987SZ01). Electron energy losses were studied in (1986GE03) for the effect on neutrino mass determinations. A method for determining the neutrino mass by means of the photon spectrum from radiative beta capture in ^{3}H is discussed by (1985PA25) which also contains a review of neutrino mass determinations. A study of the effects of a possible neutrino mass on ^{3}H longitudinal polarization etc. was reported in (1986KE08). The possibility of an influence by intense electromagnetic waves on the beta decay of polarized (1983TE04, 1983TE06, 1984TE02, 1984TE03) or unpolarized (1983TE03) ^{3}H has been studied. An experimental test of laser enhancement of ^{3}H beta decay (1985BE26) found no effect. The possibility of observing recoilless resonant neutrino absorption in ^{3}H beta decay was pointed out (1983KE07). Other calculations are found in (1975BE49).

2. ^{2}H(n, γ)^{3}H $\qquad$ $Q_{\rm m} = 6.257$ $\qquad$ $E_{\rm b} = 6.257$

Measurements of the cross section cited in the previous review (1975FI08) included a measurement at 0.01 eV, six measurements at thermal energies, one at 2.4 MeV and one at 14.4 MeV. No information on gamma angular distributions had been obtained. More recent measurements made at thermal energies (1973IS08, 1979ALZL, 1982JU01) are listed in Table 3.1.

Table 3.1: ^{2}H(n, γ)^{3}H measurements with thermal neutron [a]

σ(n, γ) (mb)	Refs.	Method
0.55 ± 0.01	1973IS08	activation
0.487 ± 0.024	1979ALZL	relative to Cl(n, γ)
		$\sigma = 33.2 \pm 0.5$ mb
0.476 ± 0.020	1980AL31	direct Ge(Li)
0.508 ± 0.015	1982JU01	direct Ge(Li)

[a] The value quoted in the neutron cross section compilation of (1981MUZQ) is $\sigma(\mathrm{n_{th}},\ \gamma) = 0.519 \pm 0.007$ mb.

As noted in (1975FI08) the calculation of (1973HA30) which included meson exchange currents gave a thermal neutron capture cross section of 0.52 ± 0.05 mb in good agreement with experiment. See also (1981SH25) for a review of experimental and theoretical results for this reaction. A recent calculation (1983TO12) investigated the role of meson currents along with the use of wave functions obtained from the Faddeev equations using realistic NN forces as well as the effects of three-nucleon forces. The capture of thermal neutrons by deuterons proceeds predominantly via a magnetic dipole transition into the S′ state of mixed spatial symmetry in ^{3}H (1975FI08). The effects of S′ and D state admixtures in ^{3}H are discussed by (1973HA30, 1981SH25, 1983TO12).

Measurements of doubly radiative thermal neutron capture have been made by (1977MC05) who found an upper limit $\sigma(2\gamma) = 8 \pm 15$ μb for 700 keV $< E_\gamma <$ 5550 keV. See also (1979WU05). Calculations with a single-particle direct capture model (1976LE27) gave $\sigma(2\gamma) = 21$ nb, while a detailed three-particle calculation (1977MC05) gave $\sigma(2\gamma) = 26$ nb.

An analysis (1974MC06) of parity non-conserving amplitudes in ^{2}H(n, γ)^{3}H indicates that gamma circular polarization and asymmetry depends on isoscalar and isovector parity non-conserving interactions respectively. See also (1986DE24, 1986DU14). The asymmetry of the photons from polarized thermal neutron capture was measured by (1984AV2A) to be $(7.8 \pm 3.4) \times 10^{-6}$. A very recent measurement is reported in (1986AV04). Values of the weak coupling constants from the implied parity violations are discussed by (1985DO02, 1985MI10).

At higher neutron energies, measurements of differential cross sections $\sigma(\theta)$ and analyzing powers $A(\theta)$ have been made by (1986MI17) and are listed in Table 3.2.

Absolute values for the angle-integrated cross section after detailed balancing are in good agreement with the inverse reaction (see section on ^{3}H(γ, n)). The fore-aft asymmetry, defined by

$$a_\mathrm{s} = [\sigma(\mathrm{f}) - \sigma(\mathrm{a})]/[\sigma(\mathrm{f}) + \sigma(\mathrm{a})],$$

where the fore and aft angles are the zeros of $P_2(\theta)$ (approximately $55°$ and $125°$), indicates an anomalously large E2 strength in the ^{2}H(n, γ) reaction. By using the (p, γ) asymmetries from (1984KI06), the ratio $a_\mathrm{s}(\mathrm{n},\gamma)/a_\mathrm{s}(\mathrm{p},\gamma)$ is determined to be ≈ -0.5 in disagreement with the factor of -0.2 expected from effective charge arguments. This result is consistent with the result obtained from the inverse reaction measurements of (1981SK02).

Table 3.2: ^{2}H(n, γ)^{3}H differential cross section and analyzing power measurements by (1986MI17)

$E_{\rm n}$ (MeV)	$E_{\rm x}$ (MeV)	$\theta_{\rm lab}$ (deg)	Measurement
6.85	10.8	87.7	$\sigma(\theta)$
9.0	12.3	$53-135$	$\sigma(\theta)$, $A(\theta)$
10.8	13.5	$53-135$	$\sigma(\theta)$
14.0	15.6	65, 125	$\sigma(\theta)$

3. ^{2}H(n, n)^{2}H $\qquad E_{\rm b} = 6.257$

Measurements of total cross sections up to 270 GeV, differential scattering cross sections up to 152 MeV, and polarizations and analyzing powers upt to 35 MeV have been reviewed in (1975FI08). More recently total cross-section measurements were made at 4.2 MeV by (1975CA30) and from 0.07 to 20 MeV by (1980PH01). References for differential scattering, polarization and analyzing power measurements reported since (1975FI08) are listed in Tables 3.3 and 3.4.

The values cited in the neutron cross-section compilation of (1981MUZQ) for the two scattering lengths (^{2S+1}a) for low energy nd scattering (S is the channel spin) are $^{4}a = 6.34 \pm 0.02$ fm and $^{2}a = 0.65 \pm 0.03$ fm. (Note however the measurement of (1975CA30) which is in disagreement.) These values are consistent with theoretical calculations cited in (1975FI08) and are well reproduced by the calculation of (1982PA21) based on a formulation using zero-energy Faddeev-type equations and the s-wave interaction model of Malfliet and Tjon (1969MA2A). Other calculations of ^{4}a and ^{2}a were made by (1975BA2B, 1975WH02, 1978AL22, 1980HA40, 1981BE18, 1983PE18, and 1983ZA06, 1986PE08). The possible effect of the three-nucleon force on ^{2}a has been studied by (1984DE20). For discussions of the correlation between the nd scattering lengths and the triton binding energy, see the ^{3}H General section of this compilation.

Phase-shift analyses for cross sections and polarization data have been carried out at 2.45 MeV (1974BO04 and 1978BO28), and at $15-50$ MeV (1986KL04).Theoretical predictions of nd phase shifts for energies below 45 MeV were made by (1974LA16, 1975AL07, 1975WH02, 1978FU01, 1978ST06, 1980HA40, 1982DU20, 1983KU08, 1987TO04). A phase shift calculation near the deuteron-breakup threshold was done by (1983PO04).

Calculations of elastic scattering cross sections for $E_{\rm n}$ below 50 MeV have been made by (1975AL07, 1975MO17, 1975ST11, 1976BE19, 1977OR01, 1978AL22, 1978ST06, 1980HA40, 1981ZA06, 1982DU20, 1983KU08, 1986HA36).

Theoretical predictions of polarizations and analyzing powers in nd scattering below 50 MeV have been made by (1974DO2A, 1975ST11, 1976BE19, 1978ST06, and 1981ZA06, 1986HA36). See also (1981ZH02, 1983MO24). A calculation of differential cross section and deuteron tensor analyzing power for incident energies 0.3 to 1 GeV taking into account the contributions of tribaryon resonances has been done by (1981KO09). Variational methods with separable potentials were used by (1974BR01, 1979ST17) for calculating off-shell amplitudes for ^{2}H(n, n).

Most of the aforementioned calculations of three-nucleon observables involved solution of some version of the Faddeev equtions or application of various approximation methods in the framework of the Faddeev equations. (See the general discussion on ^{3}H for more details.)

Table 3.3: Measurements of differential cross sections for ^{2}H(n, n)^{2}H

E_n (MeV)(lab)	θ (deg)(cm)	Refs.
2.016	$104 - 180$	1981WE17
2.48, 3.28	$47 - 180$	1978CH20, 1979CH13
$2.5 - 30$	$45 - 180$	1983SC15
26.5	$90 - 166$	1974WA13
$200 - 800$	180	1977BO25
794	$139 - 179$	1978BO04

Table 3.4: Measurements and summaries (S) of polarization and analyzing powers for ^{2}H(n, n)^{2}H

E_n (MeV)(lab)	θ (deg)(cm)	Refs.
2.2, 3.4, 7.8	120	1974MA29 (S)
2.45	$45 - 100$	1978BO28
10	$30 - 145$	1982TO06
12	$45 - 146$	1978TO03 (S)
14.1	$44.5 - 161.6$	1982BR14
14.1	$30 - 153$	1983TO06
14.2	$50 - 152$	1976PR04
14.3	$44.5 - 145.0$	1977FI05
$15 - 50$	[a]	1986KL04
16.8, 21.2	$46 - 146$	1974MO07
30	$45 - 140$	1978DO10
50	$37 - 92$	1982WA09
50	$90 - 150$	1982RO03

[a] Information unavailable at time of review.

Table 3.5: Measurements and summaries (S) of cross sections for ^{2}H(n, p)n1n2

E_n (MeV)	Particles detected	Geometry	Description	Refs.
14.2	n_1, n_2, p (coinc)	coplanar	Measured nn correlation spectra. Deduced nn scattering length.	1974BR08 (S)
18.4	n_1, n_2, p [a] (coinc)	non-coplanar	Geometry chosen to study nn and pp FSI. Deduced nn scattering length and effective range.	1974ZE03
14.1	n_1, n_2	coplanar symmetric angles	Studied QFS.	1975BO15
14.1	n, p [a] (coinc)	$\theta_{n1} = 0$	Geometry chosen to obtain data over large fraction of phase space, including FSI region. Deduced a_{nn} and γ_{nn}.	1975KE10
$8.2 - 22$	p [a], d [a]	integrated spectrum of p and d pulses from target scintillator	Measured total cross section for breakup by observing ratio of breakup to elastic scattering.	1975PA21
13.98	p	$\theta_p = 16°$	Used high-resolution magnetic spectrometer. Analyzed nn FSI. Deduced nn scattering length.	1977HA20
14.3, 29.6	n_1, p [a] (coinc)	$\theta_n = 40 - 150$	Measured analyzing power versus neutron angle $A(\theta_n)$ for n2-p rel energy < 1 MeV.	1978FI2A
120	n_1, n_2, p [a] (coinc)	coplanar	Collinear neutron geometry chosen to enhance nn FSI. Deduced nn scattering length.	1978ON02
21.5	n_1, n_2 (coinc)	coplanar	Measured at several quasifree angles. Deduced nn scattering length and effective range.	1979SO02
$17 - 27$	n, p (coinc)	coplanar	Geometry chosen to give symmetric nn and np FSI enhancements together with np QFS in spectrum. Deduced nn scattering length.	1979VO07
25	n_1, n_2 (coinc)	coplanar	Kinematic conditions for nn QFS. Deduced nn scattering length and effective range.	1980GU11
24	n_1, n_2 (coinc), n, p (coinc)	coplanar	Compared relative cross section for nn and np QFS. Deduced nn effective range.	1980VO06

Table 3.5: Measurements and summaries (S) of cross sections for ^{2}H(n, p)n1n2 (continued)

E_n (MeV)	Particles detected	Geometry	Description	Refs.
11, 25	p	θ_p=0	Used mag. spectrometer. Observed proton spectra. Deduced nn scattering length.	1981KU12

[a] Measured particle recoil energy in target scintillator.

4. ^{2}H(n, p)^{2}n $\quad Q_m = -2.225 \quad E_b = 6.257$

Measurements and summaries (S) of deuteron breakup by neutrons published from 1974 to the present are listed in Table 3.5. Earlier work is reviewed in (1975FI08). In a three-particle reaction, five kinematic variables must be measured to make the experiment kinematically complete (e.g. E_{ni}, θ_{n1}, E_{n2}, θ_{n2}, E_p). Table 3.5 indicates the particles detected and the coincidence requirements. Detector angles are not given explicitly, but the type of geometry, the main emphasis of each experiment and the region of phase space explored is indicated.

Some of the experimental difficulties associated with measurements of the breakup process are discussed in (1974TH2A). A system designed for detecting two neutrons is presented, and various ways to reduce the background are discussed. Measuremants of neutron analyzing power in the n + d breakup reaction have been made at incident neutron energies of 14.3 and 29.6 MeV by (1978FI2A) (see Table 3.5). No others have been reported. References to several early reviews of experimental and theoretical wrok on the three-body breakup reactions are given in (1975FI08) along with a brief discussion of the general features of the cross section and particle spectra. For more recent reviews see (1976SL2A, 1978KU13, 1978SL2A).

The total cross section for n + d breakup measured by (1975PA21) and others (see reviews (1976SL2A, 1978KU13)) increases almost linearly from zero at threshold (3.34 MeV) to a maximum of $\approx$ 180 mb at 12.2 MeV and then decreases slowly to $\approx$ 100 mb at 47 MeV. The peaks or enhancements in the proton energy distribution observed in nd breakup are assiciated (1975FI08) with the np and nn final state interactions (FSI) and the nn and np quasifree scattering (QFS). See (1975KU25, 1976SL2A, 1978KU13) for extensive discussions of these features including the kinematics of the processes. Calculations based on Faddeev formalism and simple NN interactions correctly predict both shapes and magnitudes of the breakup spectra (1976SL2A, 1978KU13). Experimental and theoretical investigations of the QFS portion of the proton spectra are reviewed and discussed in (1976SL2A and 1978KU13). See also (1975BO15, 1977FU05, 1978CA2A, 1979SO02, 1980GU11, 1980VO06).

Many measurements of the ^{2}H(n, p)^{2}n reaction have been carried out for the purpose of extracting the nn scattering length a_{nn} and the effective range γ_{nn}. Early work is reviewed in (1975FI08). For more recent work see references of Table 3.5 and the reviews mentioned above. An exhaustive review of experimental and theoretical methods of determining a_{nn} including discussions of possible charge-symmetry breaking and violations of charge independence implied by the results is given in (1975KU25). The review of (1976SL2A) discusses all aspects of the n + d breakup reaction with emphasis on experimental data and the relative accuracy of various methods for extracting $a_{\rm nn}$. It is apparent in these reviews that the values quoted vary slightly depending on the classes and subclasses of experiments that are included in the averages and the type of analysis. An average value of $a_{\rm nn} = -16.3 \pm 0.6$ fm is obtained (1976SL2A) from kinematically complete ^{2}H(n, p)^{2}n experiments using Faddeev theory (see also 1978SL2A). For the nn effective range $\gamma_{\rm nn}$, the value obtained by (1985SL2A) is $\gamma_{\rm nn} = 2.76 \pm 0.11$ fm. It is concluded (1975KU25) that the difference between $a_{\rm nn}$ and the neutron proton scattering length $a_{\rm np}$ provides clearcut evidence for charge independence violation, but a discrepancy between $a_{\rm nn}$ and the proton-proton scattering length $a_{\rm pp}$ (after Coulomb correction) may not necessarily imply breaking of charge symmetry because of the dependence of the extracted value of $a_{\rm pp}$ on off-energy-shell deuteron breakup by protons as well as neutrons.

The effect of three-nucleon forces (i.e. forces which depend in an irreducible way on the simultaneous coordinates of three nucleons when only nucleon degrees of freedom are taken into account) on the nd breakup process is investigated by (1984ME03), and it is determined that such a force could produce noticeable effects. In (1982SL2A) it is suggested that the difference between the accepted value of $a_{\rm nn}$ $(-16.3 \pm 0.6$ fm) and the value obtained from the ^{2}H(π^-, p)^{2}n reaction $(-18.6 \pm 0.48$ fm) can be explained by a three-body force and that the effects of this force are different for neutron pickup and proton knock-on processes in the ^{2}H(n, p)2n reaction. This suggestion is examined in the review of trinucleon properties by (1984FR16), and it is concluded here that evidence for significant three-nucleon force effects is largely circumstantial, but nontrivial. See also the reviews of (1986GIZS, 1986TO2A). It is shown in work reported in (1984SL02) that corrections arising from the magnetic dipole interactions are relevant to the discrepancy in scattering parameters deduced from defferent reactions.

It is suggested (1982SV01, 1984FR16) that the triple differential cross sections for ^{2}H(n, p)2n could be used to test for the presence of tensor force effects. See also the calculations of (1977ST16, 1979ST05) which show significant differences in the predictions of breakup reaction observables by different potential models.

5. ^{2}H(p, π^+)^{3}H $\qquad$ $Q_{\rm m} = -134.6$ $\qquad$ $E_{\rm b} = 5.494$

Many new experimental and theoretical studies of the ^{2}H(p, π^+)^{3}H reaction have been made in the past few years. Measurements and summaries of differential cross sections and analyzing powers obtained with polarized proton beams published since the previous compilation (1975FI08) are listed in Table 3.6.

A survey of experimental and theoretical work on (p, π^+) reactions, including reaction 5, can be found in (1981FE2A). See also the reviews of (1979HO2A, 1979ME2A).

The differential cross section for the reaction is forward peaked. For example at 5°(lab) (1977AS06) has reported $\sigma(\theta) = 47$, 28, 8 μb/sr at $E_{\rm p} = 410$, 605 and 809 MeV respectively, while at back angles $110^\circ < \theta({\rm cm}) < 160^\circ$ the cross section is nearly flat and within the range 0.9 to 1.25 μb/sr at $E_{\rm p} = 425$, 450, 475, 500 MeV (1984AB2A). Analyzing power angular distributions are characterized (1984LO08, 1982LO17) by a gradual change in shape from a negtive maximum near 100° at 277 MeV to a large positive maximum near 90° at 500 MeV (1981CA08). Recent data at 650 and 800 MeV (1984KI2D) show unexpected energy and back-angle structure in both differential cross section and analyzing power at 800 MeV, and the authors speculate that the anomaly is related to the delta-delta component in the deuterion ground state. Also, large structure were seen in the 0.6–1.5 GeV back angle data of (1985BE46), who suggest possible baryonic delta excitations in the intermediate state.

Table 3.6: Measurements and summaries (S) of cross section $\sigma(\theta)$ and analyzing powers $A(\theta)$ for ^{2}H(p, π^{+})^{3}H

E_p (MeV)	Measurement	θ (deg)(cm)	Refs.
277	$A(\theta)$	$70 - 130$	1984LO08 (S)
500		137.5, 148.9	
305	$A(\theta)$	$68 - 145.5$	1982LO17
330			
375			
400			
400	$\sigma(\theta)$, $A(\theta)$	$120 - 160$ (lab)	1980AU07
425		$\Delta\theta = 10$	
443			
470			
410	$\sigma(\theta)$	5, 15, 25, 43 (lab)	1977AS06
605		5, 15, 25, 32, 45, 65 (lab)	
809		5, 10.7, 19 (lab)	
425	$\sigma(\theta)$, $A(\theta)$	$110 - 160$	1984AB2A
450			
475			
500			
470	$\sigma(\theta)$	$10 - 160$	
500	$\sigma(\theta)$	$10 - 160$	1981CA08
500	$A(\theta)$	$70 - 152$	
470	$\sigma(\theta)$	$37 - 160$	1973DO17
590			
500	$\sigma(\theta)$ [a]	$\approx 48, 98$	1985SI21
585	$\sigma(E_\pi, \theta)$	$22.5 - 135$ (lab)	1980CR03
	$P(E_\pi, \theta)$ [b]	45 (lab)	
$600 - 1500$	$\sigma(\theta)$	≈ 180	1985BE46
650, 800	$\sigma(\theta)$, $A(\theta)$	$\approx 10 - 170$	1984KI2D
900, 100, 1000	$A(\theta)$	$\approx 10 - 170$	1986MA59

[a] Also measured ^{2}H(p, π_0)^{3}He and formed ratio to compare with isospin invariance predictions.

[b] Asymmetry parameter, $P = (\sigma(\text{up}) - \sigma(\text{dn}))/(\sigma(\text{up}) + \sigma(\text{dn}))$ for proton beam polarized perpendicular to pion production plane.

Experimental and theoretical interest in the (p, π^+) reaction on light nuclei was originally stimulated by the prospect that the reaction would provide a probe of nuclear structure at high momentum transfer, but problems with understanding the reaction mechanism have proved to be a barrier to this objective. Various theoretical approaches to the problem (DWBA single-nucleon mechanisms, other single-nucleon mechanisms, and two-nucleon models) are reviewed in (1979HO2A, 1979ME2A, 1981FE2A). The theoretical situation for ^{2}H(p, π^+)^{3}H is unsatisfactory. No detailed calculations have been sucessful in describing both differential cross sections and analyzing powers (1984LO08). Work in development since the previous review includes the microscopic two-nucleon model calculations of (1982IQ2A) and (1982DI2A) and the isobar-doorway model work of (1984KE02). Various wave function effects within the coupled channels delta-isobar model were investigated by (1982SA25). A recent calculation of all helicity amplitudes for ^{2}H(p, π^+) in the GeV region with the relativistic model is reported in (1986LO02). For other recent theoretical work see (1977GI06, 1978IS06, 1979LA02, 1979GR03, 1979GR12, 1979GR19, 1981BL12, 1981KO04).

6. ^{3}H(γ, π^-)^{3}He $\qquad$ $Q_{\rm m} = -139.039$

Only one measurement for this reaction has been reported since the pervious compilation (1975FI08). Measurements of neutral and charged pion photoproduction in ^{3}H and ^{3}He by bremsstrahlung photons with $E_{\rm max} = 500$ MeV were reported in (1984BE08). See also ^{3}He reactions 6 and 7 for related information.

7. (a) ^{3}H(γ, n)^{2}H $\qquad$ $Q_{\rm m} = -6.257$

(b) ^{3}H(γ, p)2n $\qquad$ $Q_{\rm m} = -8.482$

Only a few measurements of the photodisintegration of ^{3}H had been done prior to 1974, and they are listed in the previous compilation (1975FI08). More recently, both the two-body reaction (a) and the three-body reaction (b) photodisintegration cross sections were measured simultaneously from threshold to ≈ 25–32 MeV (1980FA03, 1981FA03). Monoenergetic photons were used and neutrons were detected. (See also (1981FA03) for a thorough review of experimental work.) For reaction (a) the cross section rises sharply from threshold to maximum of ≈ 0.9 mb at 12 MeV, then decreases only slightly to 0.8 mb at 19 MeV. For reaction (b) the cross section rises sharply from threshold to a maximum of ≈ 0.9 mb at 14 MeV and then falls smoothly to ≈ 0.4 mb at 26 MeV. The experiments of (1981FA03) included measurements of the ^{3}He(γ, n)2p reaction by the same techniques used for reactions (a) and (b). Detailed comparisons of the three reactions measured and of previous ^{3}He(γ, p)^{2}H data (1973TI05, 1975FI08) were made. The results were (a) the two-body breakup cross sections for ^{3}H and ^{3}He have nearly the same shape but the^{3}He cross section is lower in magnitude, (b) the three-body breakup cross section for ^{3}He is higher in magnitude, broader in the peak region, and rises less sharply from threshold than for ^{3}H, and (c) the differences between the cross sections for the breakup modes largely compensate in their sum so that the total photon absorption cross section is nearly the same for ^{3}H and ^{3}He. The integrated cross sections and their first and second moments (1981FA03) are listed in Table 3.7.

Measurements of differential cross sections for reaction (a) at angles from $45°$–$135°$ at photon energies of 6.7, 7.6, and 9.0 MeV, and at $90°$ over the energy range from 18–31 MeV were listed in (1975FI08).

Table 3.7: Integrated cross sections and moments from [a] (1981FA03)

Reaction	E_γ max (MeV)	$\sigma_{\rm int}$ [b] (MeV · mb)	σ_{-1} [b] (mb)	σ_{-2} [b] (mb/MeV)
^{3}He(γ, n)	30.0	16.4 ± 2.0	0.917 ± 0.092	0.056 ± 0.004
^{3}H(γ, n)	30.0	15.4 ± 1.8	0.986 ± 0.099	0.072 ± 0.006
^{3}H(γ, p)	30.0	13.6 ± 1.6	0.767 ± 0.077	0.047 ± 0.004

[a] Obtained (1981FA03) by integrating measurements and extrapolating up to 30 MeV.
[b] $\sigma_{\rm int} = \int_0^{E_\gamma \text{ max}} \sigma(E_\gamma) {\rm d}E_\gamma,\ \ \sigma_{-1} = \int_0^{E_\gamma \text{ max}} \sigma(E_\gamma) E_\gamma^{-1} {\rm d}E_\gamma,\ \ \sigma_{-2} = \int_0^{E_\gamma \text{ max}} \sigma(E_\gamma) E_\gamma^{-2} {\rm d}E_\gamma.$

More recently (1981SK02) measured the cross section at $55°$, $90°$, and $125°$ over the energy range from 15–36 MeV by detecting the deuterons. From these data and published data for ^{3}He(γ, p) (see section on ^{3}He(γ, p)) the ^{3}H fore-aft asymmetry (see section on ^{2}H(n, γ)) is found not to be $-\frac{1}{5}$ that for ^{3}He as predicted by simple effective charge arguments, but (although negative) it is only about half the magnitude of that of ^{3}He(γ, p), and has approximately the same energy dependence. This is consistent with the results obtained from the inverse reaction (1986MI17) (see section on ^{3}H(n, γ)).

For reaction (b) measurements of the differential cross section for angles $45°$–$135°$ made at a photon energy of 10.8 MeV, and at $90°$ for photon energies 18–31 MeV are listed in (1975FI08), No new measurements of the ^{3}H(γ, p)2n differential cross section have been reported.

Many theoretical treatments of the trinucleon photoeffect do not distinguish between ^{3}H and ^{3}He. Thus the section on ^{3}He should be consulted in addition to the work listed here. The previous compilation (1975FI08) includes references to a number of calculations of the excitation function for ^{3}H(γ, n) as well as calculations of the integrated and bremsstrahlung-weighted cross sections and discussions of sum rules for $A = 3$ photodisintegrations. See also the review of (1977CI2A) and see (1981FA03) which contains an extensive summary of theoretical work for trinucleon photodisintergration. A calculation by (1975GI01) using a separable-potential Faddeev mode explored the charge dependence and asymmetry effects in ^{3}H(γ, n) and ^{3}He(γ, p). Agreement with the two-body photodisintegration (reaction a) data of (1981FA03) is fair, but some details are incorrectly predicted, e.g. the ^{3}H(γ, n) cross section is underestimated at energies below the peak. Electric dipole transitions are calculated by (1977MY01, 1979MA03) and comparisons with sum rules are discussed. A recent calculation by (1977VO11, 1981VO07) for ^{3}H(γ, n) and ^{3}H(γ, p) total cross sections used realistic NN potentials and the method of hyperspherical functions with an interpolation approach. The energy range considered was 10–8 MeV and the agreement with experiment was satisfactory over this range, but see (1981FA03) for a detailed comparison.

A discussion of the integrated cross sections and moments of Table 3.7 and comparison with calculated sum rules is given in (1981FA03). As noted there the value for the ^{3}He integrated total photodisintegration cross section σ(int) is 28.2 ± 2.8 MeV mb at 30 MeV (obtained by combining data in Table 3.7 with published data for ^{3}He(γ, p) (1975FI08)). This comparable to the corredponding ^{3}H value of 29.0 ± 3.0 MeV mb.These values are about 40% of the strength predicted by (1978DR02) for the entire three-body photodisintegration cross section integrated up to the pion threshold. Agreement of the moments σ_{-1} and σ_{-2} with sum rules is poor (1981FA03) and raises questions about the adequacy of the calculations and the principle of charge symmetry.

Table 3.8: Measurements of cross section of ^{3}H(e, e)^{3}H

q^2 (fm^{-2})	E_e (MeV)	θ_e (deg)	$\theta_{^3H}$ (deg)	Refs.
$0.0477 - 2.96$	$29.85 - 350$	$60 - 160$		1984BE46
$0.29 - 1.00$	$77 - 147$		45 (lab)	1982BE10
$0.3 - 31.3$	$190 - 685$	$25 - 104, 155$		1985JU01
unspecified	$200 - 600$	unspecified		1984MEZZ
$0.09 - 8.4$		54, 134.5		1987BE30

Table 3.9: Measurements of cross section of ^{3}H(e, e′) ^{3}H

E_e(MeV)	θ_e(deg) $\theta_{^3H}$(deg)	Refs.
$100 - 400$	(information not available at time of review)	1986BA17

8. (a) ^{3}H(e, e)^{3}H
   (b) ^{3}H(e, e′n)^{2}H $\quad Q_m = -6.257$
   (c) ^{3}H(e, e′p)2n $\quad Q_m = -8.482$

Measurements of elastic and inelastic electron scattering cross sections up to q^2 (four-momentum squared) of 8 fm^{-2} are summarized by (1975FI08). More recent measurements are listed in Tables 3.8 and 3.9. The ^{3}H charge form factor was measured in the range $0.29 < q^2 < 1$ fm^{-2} by (1982BE10). Both the charge and magnetic form factors were measured in the range $0.0477 < q^2 < 2.96$ fm^{-2} by (1984BE46). Measurements of the charge form factor for $0.3 > q^2 > 22.9$ fm^{-2} and the magnetic form factor for $3.1 > q^2 > 31.3$ fm^{-2} were reported in (1985JU01). A very recent measurement of the isoscalar and isovector form factors for ^{3}H and ^{3}He for momentum transfer $0.09 > q^2 > 8.4$ is reported in (1987BE30). Charge and magnetic radii are quoted by (1984BE46) as $r^c_{rms} = 1.63 \pm 0.03$ fm and $r^m_{rms} = 1.72 \pm 0.06$ fm; by (1985JU01) as $r^c_{rms} = 1.76 \pm 0.04$ fm and $r^m_{rms} = 1.72 \pm 0.02$ fm; and by (1986MA2A) as $r^c_{rms} = 1.81 \pm 0.05$ fm and $r^m_{rms} = 1.80 \pm 0.09$ fm.

Theoretical calculations for thr charge form factor of ^{3}H and ^{3}He were reviewed in (1977CI2A), who came to the conclusion that it is inadequate to use nonrelativistic wave functions resulting from conventional models of the two-body potentials, and to include only nucleon degrees of freedom in the electron-nucleus interaction Hamiltonian. A variational calculation with correlated basis functions was carried out for ^{3}H and compared with the results of other methods by (1985CI04).

The effect of many-body exchange currents on tri-nucleon charge form factors is to increase the height of the second maximum hence reducing the discrepancy between calculated and empirical values (1977RI15). The effects of the experimental uncertainty of the neutron charge form factor on the charge form factors of ^{3}H and ^{3}He have been investigated and are seen to be sizable (1975BR22). Analysis of parity-violating asymmetries in elastic electron-nucleus scattering was made by (1981FI05). The effect of meson exchange currents on the charge and magnetic form factors of ^{3}H was investigated by (1975BA08, 1976HA33, 1976KL02, 1977HA03, 1977RI15, 1979GI08, 1981FR15, 1982HA09, 1983BE08, 1983DR12, 1983HA04, 1984MA26). Inclusion of meson exchange currents considerably improves the impulse approximation fits to the experimental data. See also the work of (1985TO21) on the calculation of trinucleon magnetic moments. The effect on the charge and magnetic form factors of clustering in the ^{3}H nucleus was investigated by (1976TA06). Recent calculations reported in (1987ST09) include single-Δ isobar admixtures in the three-nucleon wave function. A discussion of electromagnetic form factors of ^{3}H is included in the review of trinucleon properties by (1984FR16) and in the very recent experimental paper of (1987BE30). The upper limit of the probability of the interior six-quark compound states in ^{3}H and ^{3}He was calculated from the electron scattering data by (1985KO02), and the effect of such states on magnetic moments was investigated by (1984KA25). However (1985KI12) find the method used to be unreliable and conclude that the meson-exchange current efects dominate those of the six-quark compound states.

No new experimental data have been published on reactions (b) since the compilation of (1975FI08), though a preliminary experiment has been reported by (1984FR2B), however, recent data on reaction (c) at 500, 560 MeV is reported in (1986BA17). A calculation of threshold two-body electrodisintegration of ^{3}H and ^{3}He within the context of exact three-body theory is reported in (1977HE22). A theory for calculating spectral functions and angular distrobutions for electrodisintegration processes on ^{3}H and ^{3}He has been proposed by (1978CI2A, 1979CI2A). In (1979CI2A) a calculation was made of the quasi-elastic peak of ^{3}H and ^{3}He obtained by incoherently summing the cross sections for the two-body and three-body electrodisintegration processes, after integrating over the energy and the direction of the ejected nucleon. A variational three-body wave function is used in the calculations. The importance of final state interactions is pointed out.

9. (a) ^{3}H($\pi^\pm$, $\pi^\pm$)^{3}H

(b) ^{3}H(π^+, π^0)^{3}He $\quad Q_{\rm m} = 4.623$

(c) ^{3}H(π^+, γ)^{3}He $\quad Q_{\rm m} = 139.587$

Only a few experiments involving pions on tritium targets have been performed. See the review of (1978NE2B) which notes elastic scattering measurements at incident energies 132–187 MeV at angles $75°$–$135°$, $25°$–$60°$. Measurements of the charge exchange reaction (b) at $E_\pi = 132$–148 MeV and angles $100°$–$150°$ and of the capture reaction (c) at 132–148 MeV and angles $105°$–$130°$ are also listed. More recent measurements of pion charge exchange on tritium were carried out by (1980GL01) at incident pion momenta of 232 and 252 MeV/c and compared to theoretical predictions. Charge-independence bounds were determined from elastic scattering cross sections.

10. (a) $^3_\Lambda$H(π^-)^{3}He $\quad Q_{\rm m} = 43.12$

(b) $^3_\Lambda$H(π^-)^{2}H, ^{1}H $\quad Q_{\rm m} = 37.62$

(c) $^3_\Lambda$H(π^-)2^{1}H, n $\quad Q_{\rm m} = 35.40$

Recent reviews of light hypernuclei are found in (1984BO2B, 1984SH07, 1986BO1E, 1986GI2B, 1987SH1H). For earlier work see the review of (1975GA2A), and see (1973JU2A, 1977RO04) and references listed in (1975FI08).

Little new experimental information on ${}^{3}_{\Lambda}$H has been published since the previous compilation (1975FI08), As noted there the ground state spin is $J = \frac{1}{2}$, and some evidence exists for a $J = \frac{3}{2}$ excited state. The binding energy of ${}^{3}_{\Lambda}$H was measured (1973JU2A) to be 0.13 ± 0.05 MeV. Results of several measurements of the lifetime of ${}^{3}_{\Lambda}$H are given in (1975FI08). A more recent measurement described in (1973KE2A) gives $\tau({}^{3}_{\Lambda}\mathrm{H}) = (2.47 + 0.62, \ -0.41) \times 10^{-10}$ s for the mean lifetime.

Theoretical calculations of the ${}^{3}_{\Lambda}$H binding energy are discussed in (1973DA2A, 1974BH2A, 1974GI2A, 1977KO2A, 1977RO04, 1980GE1X, 1980GI2A, 1980OG2A, 1980VE2B, 1981KO2D, 1981TO2B, 1982VE2A, 1983HA2B, 1984BO2B, 1984SH07, 1984SU2B, 1986BO1E, 1986GI2B, 1987SH1H). Calculations of the lifetime and two-body decay mode branching ratios are presented in (1979MA2B). Polarization effects are discussed in (1985LY2A), and a method of calculating the ${}^{3}_{\Lambda}$H magnetic moment is presented in (1985NA2A). Considerations of charge-symmetry breaking are discussed in (1977GI2B, 1977RO2B).

^{3}He

GENERAL

Ground State

$$J^\pi = \frac{1}{2}^+$$
$$\mu = -2.127624 \pm 0.0000011 \text{ nm}$$
$$M - A = 14.93132 \pm 0.00003 \text{ MeV}$$

General properties of the ground state of the $A = 3$ system are under ^{3}H above. The wave function is predominantly S-state ($\approx 90\%$) with S′-state (1–2%) and D-state ($\approx 9\%$) admixtures (1975FI08, 1980PA12, 1984CI05, 1984CI09).

For ^{3}He the measured magnetic moment is $\mu = -2.127624 \pm 0.0000011$ nm (1978LEZA, 1978NE12). Calculations which include both impulse and pion exchange contributions (1985TO21) are adequate to explain magnetic moments of ^{3}He and ^{3}H. Results obtained with a six-quark bag model are also compatible with the data according to (1986BH05) which includes a discussion of other published calculations. Exchange current contributions to the ^{3}He magnetic properties are calculated by (1983ST11). See also sect. 9(a).

The rms charge and magnetic radii of ^{3}He determined from electron scattering (see sect. 9(a)) are $\gamma^{\rm c}_{\rm rms} = 1.976 \pm 0.015$ fm and $\gamma^{\rm m}_{\rm rms} = 1.99 \pm 0.06$ fm. See the discussion under ^{3}H for comparisons with theory.

The binding energy of ^{3}He is 7.718109 ± 0.000010 MeV (1985WA02). Calculations of the binding energy tend to underestimate the experimental results as is also true for ^{3}H. See references under ^{3}H above. Many calculations have been performed in an attempt to account for the ^{3}H–^{3}He binding energy differences (≈ 0.76 MeV) and various methods are reviewed in (1986FRZU). Most two-body force calculations with realistic forces underestimate this difference, giving ≈ 0.64 MeV for the Coulomb energy of ^{3}He and the problem is not resolved by three-body force calculations (1986GIZS).

Charge and magnetic form factors for ^{3}He have been determined in electron scattering experiments (see sect. 9(a)). The ^{3}He magnetic form factor has a diffraction minimum at a higher value of q than predicted by impulse approximation calculations (1984FR16) but the isobar model of (1983ST11) satisfactorily accounts for the difference. The ^{3}He charge form factor has a diffraction minimum at $q^2 \approx 11$ fm^{-2} and a very large secondary maximum. The charge densities derived from the data indicate a deep "hole" near the origin which remains a problem for theorists (1986FRZU). Impulse approximation calculations significantly underestimate the secondary maximum, and three-body force calculations have improved the predictions but have not solved the problem (1986GIZS).

References not mentioned above or under the ^{3}H discussion, relating to the ^{3}H–^{3}He binding energy difference and other charge asymmetry effects include (1975GI06, 1975ZA03, 1976ZA04, 1978BR03, 1978FR09, 1978FR07, 1978FR17, 1978SI15, 1980PA13, 1981SA04, 1981YA03, 1982BA41, 1982YA01, 1983SA17, 1983SH10, 1985BA24, 1985BA70, 1985BE57, 1985DE56, 1986BE39, 1986CH16, 1986FR23, 1986OS04, 1986SA02, 1986SC03, 1987DR04).

1. ^{3}H(β^-)^{3}He $\qquad Q_{\rm m} = 18.651$ keV

Table 3.10: Measurements and summaries (S) of cross sections and analyzing powers for ^{2}H(p, γ)^{3}He

E_p (MeV), E_d (MeV) or E_x	θ_γ(deg) (cm)	Quantity measured	Method	Refs.
$E_x \approx 7 - 15$ [a]	90 (lab)	$\sigma(90)$	[b]	1979SK01 (S)
$E_x = 8.83, 9.83$	$30 - 140$	$\sigma(\theta)$		
10.83		$A(\theta)$		
$E_x = 6.0$ [a] ^{2}H(p, γ)	$35 - 150$	$A(\theta)$	[b]	1984KI14
$E_x = 6.0$ [a] ^{1}H(d, γ)	$50 - 135$	$A(\theta)$		
$E_p = 6.3 - 7.1$ [c]	d, p bremsstrahlung cross section			1986BR15
$E_p = 6.5 - 16.0$	$30 - 150$	$\sigma(\theta)$	[b]	1983KI11
$E_x = 9.83 - 16.12$ [a]	$30 - 150$	$\sigma(\theta)$	[b]	1984KI06
$E_x = 10.83, 16.12$		$A(\theta)$		
$E_p = 16$	$32 - 152$	$\sigma(\theta)$	[d]	1974MA18 (S)
$E_x = 21, 24.1, 26.8,$	$34 - 135$	$\sigma(\theta)$	[b]	1983AN16
29.5, 32.1 [a]				1983AN17
$E_p = 18 - 43$				
$E_d = 19.8$ [c]	$\approx 20 - 160$	T_{20}	[d]	1985VE02
$E_d = 29.2, 45.3$ [c]	90(lab)	A_{yy}	[b]	1985JO05, 1986JO06
$E_p = 99.1, 150.3,$	$\approx 20 - 155$	$\sigma(\theta)$	[e]	1987PI01
200.7		$A(\theta)$		
$E_p = 200 - 500$	60, 90	$\sigma(\theta)$	[e]	1982AB09
$E_p = 200 - 500$	$15.5 - 15$	$\sigma(\theta)$	[e]	1984CA23, 1985CA42
		$A(\theta)$		
$E_p = 377, 576$	90	$\sigma(\theta)$	[e]	1976HE2A
462	$45 - 135$			
$E_p = 300, 350, 400$	$\approx 60 - 90$	$\sigma(\theta)$	[e]	1985BR23
425, 450, 470, 500				
$E_d = 376$ [c]	84, 98, 113			
$E_d = 600$	96, 105			
$E_p = 450, 550$	$52 - 92$	$\sigma(\theta)$	[e]	1980NE03

[a] Authors specified excitation energy in ^{3}He.
[b] Detected gammas.
[c] Deuteron bombarding energy used in ^{1}H(d, γ) reaction.
[d] Detected ^{3}He recoils.
[e] Detected gamma-^{3}He coincidences.

See reaction 1 under ^{3}H.

2. ^{2}H(p, γ)^{3}He $\quad Q_{\rm m} = 5.494 \quad E_{\rm b} = 5.494$

Measurements of differential cross sections and analyzing powers carried out since the previous compilation (1975FI08) are listed in Table 3.10.

Experimental data on ^{2}H(p, γ)^{3}He and the inverse reaction prior to 1979 were reviewed in (1979BE2C, 1979TO2A). For the ^{3}He excitation energy region $E_{\rm x} < 30$ MeV the existing data and theory are reviewd in the experimental papers of (1974MA18, 1979SK01). These papers also described attempts to resolved the discrepancies in the published cross section which are subtantial, e.g. at $E_{\rm x}$ near 12 MeV the measured differential cross sections for ^{3}He(γ, p)^{2}H range from 90 to 120 μb/sr. Measurements of (1979SK01) at $E_{\rm x} = 10.83$ MeV gave 117 ± 11 μb/sr and 1.07 ± 0.11 mb respectively for the detailed balanced differential ($\theta({\rm lab}) = 90°$) and total cross section. The T-matrix analysis of the differential cross sections and analyzing power data of (1979SK01) gave an E2 cross section of $(12 \pm 5)\%$ of the total at $E_{\rm x} = 10.83$ MeV which is ≈ 10 times the theoretical estimates of (1975FI08, 1981AU02). Measurements and calculations by (1983KI11) demonstrated the sensitivity of the extracted a_2 angular distribution coefficients in the region $E_{\rm p} = 6.5$–16 MeV to the inclusion of D-state components in the ^{3}He wave function, and are consistent with 5–9% D-state probabilities. This effect was incorporated in the analysis (1984KI06) of an improved data set (relative to (1979SK01), and the results are consistent with an E2 strength of $(2 \pm 3)\%$ of the total cross section at $E_{\rm x} = 10.8$ MeV and an $s = \frac{3}{2}$ (E1) strength of $(3 \pm 5)\%$, which could arise from the D-state admixture in the ^{3}He ground state. This lower E2 strength is consistent with the electrodisintegration results of (1983SK01). Measurements of the vector analyzing power in ^{2}H(p, γ)^{3}He and ^{1}H(d, γ)^{3}He at very low excitation energies ($E_{\rm x} = 6$ MeV) (1984KI14) indicated the presence of $s = \frac{3}{2}$ capture strength and the results are consistent with an M1 strength amounting to 1–8% of the total cross section. The tensor analyzing power T_{20} in ^{1}H(d, γ) was measured (1985VE02) and compared with an effective two-body direct capture calculation which used the Faddeev-generated ground state wave functions of (1984GI01). The results were in good qualitative agreement although the calculated T_{20} was about 20% too small when ^{3}He wave functions having 5–9% D-state probabilities were assumed. The data were also analyzed to extract a D/S asymptotic ratio of 0.035 ± 0.01 in the ^{3}He wave function. This results is consistent with the range $(0.038 < \eta < 0.050)$ calculated (1984GI01) for ^{3}He D-state probabilities between 5 and 9%. The tensor analyzing power $A_{\rm yy}$ was measured (1985JO05, 1986JO06) and compared with a full Faddeev calculation using the Reid soft-core interaction as a check of the ^{3}He D-state component. The comparison shows that the calculated D-state wave function is about 20% too large (in the 2–5 fm region).

In the intermediate energy region, measurements at $E_{\rm p} = 337$ and 576 MeV were made (1976HE2A) to compare with measurements of the inverse reaction for a test of time reversal invariance. The results were consistent with no violation but the conclution was a matter of controversy (1980NE03) because of discrepancies in existing data for ^{3}He(γ, p)^{2}H. The situation is reviewed in (1981FA2B) and most recently in (1985BR23). Additional measurements were made by (1980NE03, 1982AB09, 1984CA23, 1985CA42, 1987PI01) with none reporting any evidence for time-reversal invariance violation. See also (1982BR12, 1983SO10). The most recent measurements were those of (1987PI01) and (1985BR23) which report final values which supercede the preliminary data of (1980NE03) and which are in agreement with those of (1984CA23). The data of (1984CA23, 1985CA42) were compared with several theoretical calculations showing that inclusion of meson-exchange current contributions are important in reproducing the cross sections, but the analyzing powers measured at $E_{\rm p} = 500$ MeV were not explained by microscopic models. Comparison of the data of (1985BR23) wtih calculations showed that the contribution of delta effects is undramatic but must be included. The recent measurements of $\sigma(\theta)$ and $A(\theta)$ for $E_{\rm p} = 99.1$, 150.3, 200.7 MeV (1987PI01) were well accounted for by a simple "quasideutero" model. See also (1984ME13).

Theoretical work on the ^{2}H(p, γ)^{3}He reaction and its inverse has focused in large part on the effects on the cross sections and other observables of D-state components in the ^{3}He bound state wave function. In (1973HE20) ^{3}He wave functions generated from Faddeev equations with separable Yamaguchi interactions were used in calculating cross sections, and it was concluded that the isotropic part of the cross section was unlikely to yield information on D-state components in ^{3}He and ^{2}H. Realistic bound state wave functions obtained with NN interactions given by the Reid soft-core potential were used in (1977CR01) in calculations over a wide energy region from threshold to 600 MeV. The results indicated substantial contributions of D-state to both total and differential cross sections, but gave pronounced structure in the cross sections in disagreement with experiment. The calculations of (1981AU02) used the same physical input as (1977CR01) but used different methods and found no distinct signature of D-state components in ^{3}He and ^{2}H for $E_\gamma < 35$ MeV. On the other hand the work of (1983KI11) mentioned above demonstrated the sensitivity of the differential cross section to D-state effefcts. In addition, calculations reported in (1984AR07) used the Sasakawa wave function for ^{3}He and found that the tensor analyzing powers for the ^{1}H(d, γ)^{3}He are very sensitive to D-state components in ^{3}He. The data were shown to be consistent with an asymptotic D- to S-state ratio of $\eta = -0.029$. At intermediate energies dispersion methods were used to calculate angular distributions for the ^{2}H(p, γ) reaction (1979PR12). Comparisons with data 52.5, 100, and 140 MeV gave reasonable agreement with angular and energy dependence.

3. (a) ^{2}H(p, π^0)^{3}He $\qquad Q_{\rm m} = -129.471 \qquad E_{\rm b}$=5.494

(b) ^{1}H(d, π^0)^{3}He

A measurement of differential cross section and tensor-analyzing power T_{20} at $\theta_{\rm cm} \approx 0°, 180°$ for ^{1}H(d, π^0)^{3}He was reported at 19 energies between 500 MeV and 2.2 GeV in (1986KE18).

4. ^{2}H(p, n)2^{1}H $\qquad Q_{\rm m} = -2.225 \qquad E_{\rm b} = 5.494$

Measurements of particle spectra, cross sections, and polarization observables from experiments on deuteron breakup by protons published from 1974 to the present are listed in Table 3.11. A large body of earlier work is reviewed in the previous compilation (1975FI08). A three-particle reaction is completely determined if five kinematic variables are measured. This requires that at least two particles be detected in coincidence for kinematically complete experiments, and this is specified in the table by indicating the particles detected and coincidence requirements. Detector angles are not given explicitly, but the type of geometry and the main emphasis of each experiment is indicated along with the region of phase space explored.

Table 3.11: Measurements and summaries (S) of cross sections and analyzing powers for ^{2}H(p, n)$p_1 p_2$, ^{2}H(p, pn)p, and ^{1}H(d, 2p)n

E_p (MeV)	Particles detected	Geometry	Description [a]	Refs.
3.82, 4.02, 4.49, 5.0 $E_d = 7.120$, 7.263 7.333, 7.405	p_1, p_2 (coinc)	coplanar	Measured pn correlation spectra	1981SL01
6.4, 10, 15.9, 19.9, 25.8	p_1, p_2 (coinc)	coplanar	Studied p, n FSI. Measured 9 angular combinations at each E_p. Measured σ along whole kinematic curve.	1978DO04
7, 8.5, 10	p_1, p_2 (coinc)	coplanar, non-coplanar	Measured absolute cross section.	1975KU13
$E_d = 7.2$, 7.5	p_1, p_2 (coinc)	coplanar		1986NA12
$8 - 12$ $\Delta E = 0.5$	p_1, p_2 or p, n (coinc)	coplanar	Conditions chosen for near-zero relative np energy to study np FSI.	1976PL01
8.5	p_1, p_2	coplanar	Conditions chosen for zero relative np energy. Studied FSI.	1977GU13
9.5	n	$\theta_n = 15 - 135°$ $\Delta\theta = 15°$	Measured relative neutron yield of ^{2}H(p, n), ^{3}H(pn).	1975MO36
10	p_1, p_2 (coinc)	coplanar and non-coplanar	Measured precise absolute cross sections, to check form-factor dependence.	1974EB01
10.0, 14.1	p_1, p_2 (coinc)	coplanar	Measured $\sigma(\theta)$, $A(\theta)$ Geometry chosen for FSI and collinear config. in cm. Searched for 3BF effects.	1986RA2A 1985KA08 1986PA2A
$10.6 - 15.1$	n	0°	Measured transverse	1980LI03

Table 3.11: Measurements and summaries (S) of cross sections and analyzing powers for ^{2}H(p, n)p_1p_2, ^{2}H(p, pn)p, and ^{1}H(d, 2p)n (continued)

E_p (MeV)	Particles detected	Geometry	Description [a]	Refs.
15.1 (pol)			polarization transfer coefficient $K_y^{y'}$.	
15	p_1, p_2 (coinc)	non-coplanar	Measured along a kinematical locus sensitive to type of NN interaction.	1978DU11
16 (pol d)	p	$\theta_p = 15.0° - 42.5°$ (lab)	Measured ^{1}H(d,p)pn analyzing-powers A_y, A_{xx}, A_{yy}, A_{xz} versus angle and excitation energy in residual pn system.	1981CO07
20.4 (pol)	n	$\theta_n = 18°$	Measured transverse pol. transfer coeff. $K_y^{y'}$ versus En.	1975GR24
21	p_1, p_2	$\theta(\text{lab}) = 75°$	Measured vector analyzing power.	1978SA2A
22.7 (pol)	p_1, p_2	coplanar symmetric configuration	Measured analuzing power.	1980FO10
23	p_1, p_2 (coinc)	coplanar	Measured at several quasifree angles. Enhances QFS-FSI interference.	1974PE02
23	p_1, p_2 (coinc)	coplanar	Conditions chosen for collinearity of p_1, p_2, in cm system.	1976LA01
23.0 39.5	p_1, p_2 (coinc)	non-coplanar	Measured cross sections on two types of constant-relative-energy loci.	1979BO19
25.7	p_1, p_2 (coinc)	coplanar	Chose kinematic conditions far from two-body enhancements to study sensitivity to higher partial-wave components.	1982SV01
28.6	p_1, p_2	coplanar	Made measurements in collinear and non-collinear geometry. looked for collinearity enhancement.	1979BI07
29.4,	n	0°	Measured 0° neutron production	1976RO10

Table 3.11: Measurements and summaries (S) of cross sections and analyzing powers for ^{2}H(p, n)p_1p_2, ^{2}H(p, pn)p, and ^{1}H(d, 2p)n (continued)

E_p (MeV)	Particles detected	Geometry	Description [a]	Refs.
39.2, 49.5			cross section versus neutron energy.	
39.5	p_1, p_2 (coinc)	coplanar	Measured along const NN relative energy loci.	1975MC04
44.9	p_1, p_2 (coinc)	non-coplanar	Studied dependence of cross section on kinematic variables of undetected n.	1974SH02
44.9	p_1, p_2 (coinc)	coplanar non-coplanar	Kinematic conditions included QFS region and regions far from QFS. Studied sensitivity to on-shell and off-shell aspects of potential models.	1976HA45
50	n	20°(lab)	Measured neutron polarization versus neutron energy.	1978LE10
50	p_1, p_2 (coinc)	non-coplanar	Used multidetector array to cover 85% of kinematical phase space. Studied quasi-two-body reaction mechanisms.	1981BL09
58.5	p_1, p_2 (coinc)	coplanar	Studied off energy-shell effects.	1974DU03
65 (pol)	p_1, p_2 (coinc)	coplanar	Measured analyzing power $A(\theta_1, \theta_2)$. Studied pp and pn QFS.	1982SH07
65, 85, 100	p_1, p_2 or p_1, n (coinc)	coplanar	Angles chosen to enhance pp or pn QFS or pn FSI.	1974CH30
156	p_1, p_2 or p_1, n (coinc)	coplanar	Studied genl behavior of (p, 2p), (p, pn), also pp, pn QFS and pn FSI or FSI.	1974DI09
156	p_1, p_2 or (coinc)	coplanar	Kinematic conditions for collinear p_1, p_2, in cm. Also neighboring kinematic conditions.	1977FU01

Table 3.11: Measurements and summaries (S) of cross sections and analyzing powers for ^{2}H(p, n)p_1p_2, ^{2}H(p, pn)p, and ^{1}H(d, 2p)n (continued)

E_p (MeV)	Particles detected	Geometry	Description [a]	Refs.
156	p_1, p_2 (coinc)	coplanar	Kinematic conditions chosen for collinear nucleons in cm. Also measured for neighboring kinematic conditions.	1977YU01
400	p_1, p_2 or p_1, n (coinc)	coplanar	Geometry chosen to study QFS proton and neutron knockout.	1979JA20
585	p_1, p_2 (coinc)	coplanar	Studied np FSI and QFS, ^{2}H momentum distribution.	1975WI29
585, 800	p_1, p_2, n (coinc)	coplanar	Studied (p, 2p) and (p, pn). QFS observed over spectator momentum range $0 - 350$ MeV/c.	1976FE05
585, 800	p_1, p_2 (coinc)	coplanar	Conditions chosen for small np relative momentum. Studied FSI.	1977FE06
800 (pol)	n	$0°$	Measured polarization transfer coefficient K_{NN}, K_{LL}.	1981RI06
800	n	$133°$(cm)	Measured neutron polarization to compare with n(pol) + p analyzing power. Test of time reversal invariance.	1982BH01
800	p_1, p_2; p_1, n (coinc)	coplanar	Measured p(pol) + p and p(pol) + n cross sections and analyzing power A_y versus angle.	1983BA05

[a] FSI denotes final-state interaction, QFS denotes quasifree scattering.

Reviews of three-body breakup reactions are given in (1978SU2A) which includes 3- and 4-body elastic scattering and breakup and emphasizes the precision of the measurements, and in (1978KU13) which contains an extensive discussion of three-particle kinematics, experimental techniques, and the basic theoretical equations of three-particle scattering as well as a review of existing data and theoretical work. See also (1978SL2A) which includes the ^{2}H(p, n)2p reaction in discussion of few-nucleon experiments and theory in general.

The ^{2}H(p, n) excitation curve at $0°$ rises from threshold to ≈ 50 mb/sr at $E_p = 7$ MeV (1975FI08). The total cross section for breakup rises from threshold to ≈ 180 mb at $E_p = 13$ MeV and drops off gradually to ≈ 130 mb at $E_{\rm p} = 25$ MeV. The particle spectra contain structure corresponding to pn and pp quasifree scattering (QFS) and to pn and pp final state interactions (FSI). The structure is similar to that of ^{2}H(n, p)2n.

As noted in (1975FI08), the ratio of the np to pp QFS peaks varied between 2 and 3 depending on $E_{\rm p}$ in the region between 4.5–60 MeV and is larger than that of free nucleon-nucleon cross sections especially at low energies. This topic is discussed in (1978KU13, and 1981BL09). Empirical rules for the energy behavior of this ratio are proposed in (1977FU05). Good agreement between the measured ratio with estimates based on the impulse approximation is obtained by (1979JA20). Agreement of pp and np QFS with the spectator model is obtained (1975WI29, 1976FE05) for spectator momenta up to ≈ 200 MeV/c, significant discrepancies are found at higher momenta. The measurements of (1982SH07) indicate that polarization effects on the spectator nucleon in pp QFS is quite different from that of pn QFS.

It has been established (1975FI08, 1978KU13) that deuteron breakup measurements with complete kinematics allow the determination of the two-nucleon scattering parameters with good accuracy and that the np and pp scattering lengths agree with the corresponding free scattering lengths. See also the section of this review on ^{2}H(n, p)2n and the references cited there.

Comparisons with Faddeev calculations show that both the structure and absolute value of the cross sections are described very well (1975FI08) even if the two-particle interaction is taken as a separable potential that reproduces the NN data only at low energies (1978KU13).

A major aim of pd and nd breakup studies is to obtain information about the off-shell behavior of nuclear forces and to explore the role of three-body forces. Much theoretical efforts has gone into attempting to separate the two. Numerical solutions of the integral equations of scattering theory were used by (1983ZA04) to study the effect of the form of the two-particle interaction on the breakup amplitude. The authors of (1981SL02) studied pp correlation spectra at very low kinetic energy with Faddeev calculations which included Coulomb corrections and discuss the possible role of three-body forces. Calculations of cross sections and polarization observables in the approximation of pole and triangular diagrams reported in (1980GO03) gave satisfactory agreement with experiment for $E_{\rm p} = 200$–340 MeV. Backward inelastic pd scattering for $E_{\rm p} = \approx 1$ GeV was calculated in (1978AM06) and attributed primarily to “triangle” diagrams with single-pion exchange. Observed asymmetry in the angle between the proton momentum transfer and the direction of the spectator nucleon was explored with the separable potential model (1977AL04). Calculations with several separable potentials by (1976HA38) were done to explore the short-range behavior of the nuclear force and suggest that FSI angular distributions between 20 and 50 MeV would be useful. See also (1974ST19) for potential effects. Off-shell and multiple scattering effects were explored (1975LH02) in analysis of $E_{\rm p} = 156$ MeV data. Realistic potentials were used (1975IS06) in analysis of QFS data for $E_{\rm p}$ between 60 and 160 MeV. See also (1975DU13). Differences in pp and pn QFS were stuied (1975HA03) with an energy-dependent-core model. A general discussion and review of quasifree processes in few-body systems is given in (1974SL04). See also (1974HA07, 1974HA36, 1974ME06).

5. (a) ^{2}H(p, p)^{2}H $\qquad E_{\rm b} = 5.494$

(b) ^{1}H(d, d)^{1}H

Measurements of differential cross sections and polarizations in ^{2}H(p, p)^{2}H and ^{1}H(d, d)^{1}H since the compilation of (1975FI08) are listed in Table 3.12. Reviews of the experimental data and theory may be found in (1975SI2A, 1978SI2B, 1981GR1A, 1982IG2A, 1983ZA01). See also (1978DU2B, 1981OH2A).

Table 3.12: Measurements and summaries (S) of differential cross sections and polarization observables in ^{2}H(p, p)^{2}H scattering

E_p (MeV) (or E_d (MeV)) [a]	θ_p(deg) (θ_d(deg)) [a]	Quantity measured	Refs.
0.4 – 1	44.5 – 149.2	$\sigma(E,\theta)$, $A_y(E,\theta)$	1983HU07 (S)
2.5 – 6.5	15 – 170	$A_y(\theta)$	1979WH01
3 – 13 [a]	22.6 – 165 [a]	$iT_{11}(\theta)$, $T_{2q}(\theta)$	1979WH01
3.14, 3.74 [b]	20 – 150	$\sigma(\theta)$	1980LA19
6.8 [b]	29.9 – 120	$\sigma(\theta)$	1977BO40
8.5 – 22.7	30 – 160	$\sigma(E,\theta)$, $A_y(E,\theta)$	1983GR05
8.5, 10, 12,	30 – 160	$\sigma(\theta)$, $A(\theta)$	1978GR23
17, 20, 24		$iT_{11}(\theta)$, $T_{20}(\theta)$, $T_{22}(\theta)$	
10	30 – 120	pol. transfer coefficients	1981SP05
10	92 – 180	pol. transfer coefficients	1982SP03
10	30 – 160	$A(\theta)$	1978GR04
11.1	15 – 160	$\sigma(E,\theta)$, $A_y(E,\theta)$	1983SA05
17 – 22 [a]	15 – 160 [a]	$iT_{11}(\theta)$, $T_{2q}(\theta)$	
14.1	30 – 150	$A_y(\theta)$	1978DU2B
17 – 45.4 [a]	30 – 160 [a]	$iT_{11}(E,\theta)$, $A_{yy}(E,\theta)$, $A_{xx}(E,\theta)$	1983GR05
20 [a]	30 – 160 [a]	$iT_{11}(\theta)$, $T_{2q}(\theta)$	1978GR04
35.0, 46.3	90 – 170	$\sigma(\theta)$	1974BR13
48.5 [b]	120 – 140	$\sigma(\theta)$	1983GR14
50	10 – 160	$A_y(\theta)$	1977KI09
60	30 – 104	pol. transfer coefficients	1980SP08
64.8	8 – 169	$\sigma(\theta)$, $A(\theta)$	1982SH13
185 [b]	4.1 – 51	$\sigma(\theta)$	1974GU25
316, 516	100 – 170	$A_y(\theta)$	1978AN06 (S)
0.4, 0.8, 1.0 GeV	155 – 175	T_{20}	1979IG02
600 [b]	$-t = 0.003 - 0.029$ [c]	$\sigma(\theta)$	1976FA09
0.6 – 2.7 GeV	158 – 180	$\sigma(E)$	1982BE30
630 [b]	80 – 158	$\sigma(\theta)$	1978MU16
0.68 – 1.53 GeV	93 – 172	$A(\theta)$	1978BI2B
796	4.53 – 13.02 [d]	$\sigma(\theta)$, $A_y(\theta)$	1983IR03
800	14.1 – 153.6	$\sigma(\theta)$, $A_y(\theta)$	1980WI07 (S)
800	22 [d]	$iT_{11}(\theta)$	1981BR21

Table 3.12: Measurements and summaries (S) of differential cross sections and polarization observables in ^{2}H(p, p)^{2}H scattering (continued)

$E_{\rm p}$ (MeV) (or $E_{\rm d}$ (MeV)) [a]	$\theta_{\rm p}$(deg) ($\theta_{\rm d}$(deg)) [a]	Quantity measured	Refs.
800	$-t = 0.006 - 0.46$ [c]	spim rotation parameters	1983WEZV
1 GeV		$P(\theta)$	1982AL18
1.6 GeV [a]	$-t = 0.032 - 1.038$ [c]	deuteron vector and	1981BL13
2 GeV [a]	$-t = 0.05 - 1.2$ [c]	tensor asymmetries	1979BL08
$P_{\rm d} = 3.4 - 6.6$ GeV/c [e]	$60 - 175$ [a]	$\sigma(\theta)$	1974DU2C
$17.4 - 26.1$ [a]	$67.1 - 121.4$	$C_{\rm xx}$, $C_{\rm yy}$, S	1975CH19

[a] Deuteron energies and angles for reaction ^{1}H(d, d)^{1}H.
[b] Unpolarized protons.
[c] $-t$ is the square of the momentum transfer, (GeV/c)^2.
[d] Laboratory angles.
[e] Incident deuteron momentum $P_{\rm d}$.

A phase-shift analysis of pd elastic scattering based on measurements of differential cross section and proton and deuteron analyzing powers for energies below the breakup threshold was performed (1983HU08), and S- and j-split P-phases including the channel-spin mixing, unsplit D- and F-phases and SD tensor coupling were determined. A phase-shift analysis at the three-body threshold using Faddeev equations in configuration space was reported in (1980LA19). Doublet phases were extracted also (1975CH20), and a phase-shift analysis of combined cross-section and spin-correlation data was performed. An analysis of σ(total), $\sigma(\theta)$, and spin correlation-parameter data for $E_{\rm p}$ = 1.1–1.7 GeV was reported in (1980HA50). Theoretical calculations of phase shifts have been done in a Faddeev formalism using different rank-one separable interactions (1975CH20), or using S-wave NN potentials in which the Coulomb interaction was incorporated (1983HU08). Doublet and quartet phase shifts for pd and nd scattering have been calculated for nucleon energies between 2 and 10 MeV using a method based on modified Faddeev differential equations in which the Coulomb interaction is included, and they are found to agree with experiment (1983KU08). Theoretical phase shifts for nd and pd scatterings in the ^{4}P, ^{2}P, ^{4}D and ^{2}D states near threshold were calculated (1977EY01) with an off-shell model with Coulomb corrections taken into account approximately.

The effective range functions calculated from this model (1977EY01) and from a simple on-shell partial wave dispersion model (1977EY02) agree well with each other. The quartet scattering length and effective range reported in (1977EY01) are $^4a_{\rm pd} = 10.9$ fm and $^4\gamma_{\rm pd} = 1.3$ fm respectively; while the corresponding quantities obtained in (1977EY02) are $^4a_{\rm pd} = 11$ fm, $^4\gamma_{\rm pd} = 1.44$ fm. The doublet scattering length is $^2a_{\rm pd} = 1.8$ fm, while the parameters of the effective range expansion for the P- and D-states are listed in a table in (1977EY01). In (1976TI02) an analytic expression is derived for the difference in nd and pd quartet scattering lengths and a value $^4a_{\rm pd} = 10.4$ fm is calculated. In (1983FR21) a value of $^4a_{\rm pd} = 14$ fm and $^2a_{\rm pd} \approx 0$ fm is calculated using a configuration space formalism of the Faddeev equations including the Coulomb interaction. This paper emphasizes the need for new low-energy pd data.

Differential cross sections and polarization data around 800 MeV incident proton energies have been analyzed by Glauber theory (1980WI07) and by non-eikonal approximations to Glauber theory and multiple scattering theory (1979BL08, 1981BL13, 1983IR03). Non-eikonal corrections are seen to be important in explaining tensor asymmetries (1980AL2C) and proton elastic scattering from polarized deuterons (1975GU17, 1979GU14). Data in the Coulomb interference region around 600 MeV are reproduced by taking into account spin effects (1981GA15) and the virtual-deuteron effect (1976GA36) in the Glauber model.

Low energy ($E_{\rm p} \approx 10$ MeV) data have been analyzed in the Faddeev formalism (1975CH19, 1978GR04, 1981SP05, 1982SP03, 1983SA05). The analysis of (1981SP05) and the three-body calculation of (1981KO39) show that the data are sensitive to the S-wave part of the deuteron wave function, and there is evidence for NN off-shell effects in nucleon-deuteron scattering. The difference in the ^{3}S-^{3}D interactions, which do not appear in the low-energy pd scattering clearly, appear distinctly at 65 MeV (1982KO34). One set of low-energy data has been analyzed in terms of Legendre polynomials (1983GR05).

Coulomb effects in pd scattering have been taken into account in the framework of multiple scattering theory by (1975FR13) and in a three-body formalism by (1976AL13, 1976TI02). See also (1983BL15). In a first attempt to include an approximation for the Coulomb effects in Faddeev calculations, the work of (1982DO07) took into account the influence of the asymptotic Coulomb phase shifts in pd and dp scattering. See Also (1981HA30). Calculations performed in (1981ZA06) at a few energies between 5 and 15 MeV predict differences between the nd and pd analyzing powers. Except for a small angle shift this was borne out by experiment (1982TO06). The effect of Coulomb distortion on the proton analyzing powers in elastic pd scattering is calculated by an effective two-body approximation that includes nd on-shell information only, in (1983ZA01). The agreement with the measured analyzing power at 10 MeV is good but only fair at 14 MeV. A rigorous approach for solving the three-body Coulomb problem in configuration space based on Faddeev differential equations is presented in (1982PO08, 1983KU08). Differential cross sections at 2 MeV and 10 MeV agree well with experiment.

Backward pd elastic scattering in the energy range 0.3–2 GeV has been extensively studied. See (1982IG2A) for a review. See also the study of (1974NO2A) who concluded no convincing evidence for N* isoscalar exchange or pion-nucleon exchange beyond the usual nucleon transfer. A phenomenological analysis made in (1974DU05) suggests a mechanism in addition to one-nucleon exchange. The cross sections are roughly reproduced by a calculation in the framework of the pole mechanism (1975KA27). Rescattering corrections to the single-nucleon exchange model were found to be important (1975LE21). Single scattering and n-exchange are shown to account for large-q^2 pd data (1976GU2A, 1979GU14, 1979GU2B). The deuteron charge form factor is predicted from the extracted two-body form factor. In (1976TE2A) a double-triangle diagram is considered, while in (1977KO48, 1979KO2A) it is found sufficient to take into account re-scattering with the delta-isobar in the intermediate and one-nucleon exchange. Calculations based on the model of resonance one-pion exchange produce cross sections which agree with experiment but depend strongly on the deuteron wace function (1977SM04). Absence of a peak in the cross section for energies greater than 1 GeV is predicted in (1979KO2A) where light-front-dynamics is applied to describe the scattering. In (1974SH2B, 1977SH17, 1980JE03) calculations are performed in the light of the Kerman-Kisslinger model using a generalized baryon-transfer mechanism on the assumption that N*s exist in the deuteron and that the backward peak is caused by their exchange. The tensor polarization of the deuteron was calculated on the basis of a triangle diagram without free parameters and found to be small in agreement with experiment (1980VE07, 1981VE15). The contribution of the intermediate delta (1236) resonance is found to dominate the cross section in the 0.3 to 1 GeV region in (1980TO10) where a two-loop diagram is evaluated. A double diagram with intermediate $\Delta(1232)$ excitation is used in (1981AN03) to reproduce cross sections at about 600 MeV. In (1981KO09, 1981KO17) it is found necessary to include tribaryon resonances in addition to quasiresonant contributions from the delta isobar, one-nucleon exchange and nucleon-deuteron single scattering to explain the data. Elastic pd backward scattering in the energy range 0.6–2.7 GeV has been measured and discussed in terms of one-nucleon exchange and one-pion exchange mechanisms (1982BE30). The experimental plateau in the $180°$ excitation function for energies > 1 GeV could be explained as excitation of the Δ(1950) in the intermediate state. Experimental data on the sensitivity to the proton polarization and to the deuteron alignment are described in (1981KA45, 1981KA29). In (1980GU16) it is shown that it is possible to explain backward pd scattering at intermediate energies in the framework of multiple scattering theory by searching for the "optimal" approximation for the formal exact solution of the problem. The analysis also permits an extraction of the deuteron two-body form factor for values of q^2 which far exceed those measured in e, d elastic data. The accuracy of the "optimal" approximation is studied for a wide range of momentum transfer in (1983LE16).

Cross sections and tensor analyzing powers in dp elastic scattering data at $E_{\rm d} = 10$ and 20 MeV were used in a pole extrapolation technique to determine a value of $\rho_{\rm D} = 0.027 \pm 0.005$ for the asymptotic D- to S-ratio of the deuteron wave function (1978AM2B). Data at 35 MeV and 45 MeV (1979CO12) gave a value $\rho_{\rm D} = 0.023 \pm 0.0013$, while an analysis by (1980GR06) of data at ten different deuteron energies between 5 and 45 MeV gave $\rho_{\rm D} = 0.0259 \pm 0.0007$. Note however that the method has been criticized in more recent work as subject to large systematic errors (1981CO2C, 1983LO03, 1984BE2B, 1985PU01). A different method of pole extrapolation was used in (1986HO07) to obtain a D/S ratio of 0.0270 with a statistical error of 2%. The dependence of $\rho_{\rm D}$ on the asymptotic S-state amplitude $A_{\rm s}$ was studied and reported in (1982AL04).

Elastic dp scattering data in conjunction with data on pp and np elastic scattering between 10–26 GeV have been used in (1973ZO05) to determine the deuteron form factor. The ratio of pd inelastic/elastic differential cross sections has been calculated using Glauber theory in (1977DU02). Polarization data at 1 GeV have been analyzed in terms of Glauber theory and the spin-orbit proton-nucleon amplitude has been determined in (1980AL09). Parity non-conserving effects in low energy pd scattering which manifest themselves as an asymmetry in the total pd cross section for longitudinally polarized protons have been examined in (1978HE2A, 1978HE2B, 1979DE27, 1983KL05). The calculations of (1979DE27) indicate an asymmetry of about -0.8×10^{-7}.

6. (a) ^{3}He(γ, π^0)^{3}He $\quad$ $Q_{\rm m} = -134.964$

(b) ^{3}H(γ, π^0)^{3}H $\quad$ $Q_{\rm m} = -134.964$

For reaction 6(a) the previous compilation (1975FI08) cited only one measurement (1969BL10). A 340 MeV bremsstrahlung beam was used, and differential cross sections for coherent π^0 photoproduction were obtained by detecting ^{3}He recoils at angles of 20, 30, 40, and $50°$. The values ranged from ≈ 2 to 84 μb/sr. Reasonable agreement with impulse-approximation calculations was obtained. More recently, measurements of π^0 photoproduction relative yields from ^{1}H, ^{2}H, ^{3}He and ^{4}He were made in the region 1–10 MeV above threshold by (1980AR06, 1981AR10). Dipole photoproduction amplitudes E_0^+ on nucleons were deduced, but were strongly dependent on the theoretical description of the process. Large rescattering effects were observed for ^{3}He. These data were included in the review (1979DE2A) of pion photoproduction experiments and theory. Measurements of differential cross sections near $\theta = 0°$ in the P_{33} resonance region were reported for ^{3}He, Li(nat) and ^{9}Be in (1981BE13). The bremsstrahlung beam from a 500 MeV synchroton was used, and the π^0 was measured by detection of the decay photons.

Measurements on both reactions 6(a) and 6(b) were carried out in a recent experiment (1984BE08, 1984BE36) in which π^0 photproduction on a ^{3}H target was observed for the first time. Bremsstrahlung radiation from a 500 MeV electron beam was used, and the ^{3}H and ^{3}He recoils were detected. The energy-averaged differential cross section in the Δ(1232) resonance region was obtained as a function of momentum transfer both for ^{3}H(γ, π^0) and ^{3}He(γ, π^0). The averaged cross section is characterized by: (i) A steep fall-off for $|t| < 5$ fm^{-2} characteristic of a coherent process. The cross section falls from ≈ 10 μb/sr at $|t| = 3$ fm^{-2} to ≈ 1.5 μb/sr at $|t| \approx 5$ fm^{-2}. (ii) A change in slope at $|t| \approx 5$ fm^{-2} attributed to the rescattering of the photoproduced pions. (iii) Equal cross sections for ^{3}He(γ, π^0)^{3}He and ^{3}H(γ, π^0)^{3}H suggesting direct production on one nucleon without final state interactions. The results are compared with an uncorrected impulse approximation calculation, and the agreement is good for $|t| \leq 5$ fm^{-2}. The experiment also shows that the charge exchange reaction ^{3}He(γ, π^+)^{3}H is down by about an order of magnitude from the π^0 production.

A number of theoretical investigations of the (γ, π^0) reaction on ^{3}H and other few-body targets near threshold have been carried out. For early work see (1975FI08). It is noted in (1976KO04) that whereas charged pions are produced mainly on the nuclear surface, neutral pions can be produced coherently, and π^0 photoproduction is in principle sensitive to the entire nuclear matter distribution. In addition, the small π^0 photoproduction cross section for a single nucleon ($\approx$ an order of magnitude smaller than that of charged pions) suggests a mechanism for π^0 photoproduction in nuclei whereby a charged pion photoproduced on one nucleon can undergo charge-exchange scattering on another nucleon. This two-nucleon mechanism is found (1976KO04) to be important. For a discussion of these and other aspects of the (γ, π^0) process in ^{1}H, ^{2}H, ^{3}H, and ^{4}He see the review of (1979DE2A). Other calculations of threshold π^0 photoproduction on ^{3}He and ^{3}H are reported in (1978BO13, 1982BE25). Threshold effects in π^0 photoproduction on ^{2}H and ^{3}He are treated in (1979LA21). The case of π^0 photoproduction by linearly polarized photons on ^{3}H and ^{3}He has been treated in the impulse approximation (1979GA18) for $E_\gamma = 180$–700 MeV, and the asymmetry in the angular distrinution has been evaluated with the use of multipole amplitudes. Finally, an investigation reported in (1984DR07) included both a calculation of π^0 photoproduction for the ^{3}H/^{3}He isodoublet in terms of nucleons, and a calculation of π^0 photoproduction for nucleons in terms of constituent quarks.

7. (a) ^{3}He(γ, π^+)^{3}H $\qquad Q_{\rm m} = -140.098$

(b) ^{3}He(e, e$'\pi^+$)^{3}H $\qquad Q_{\rm m} = -140.098$

Only a few measurements for reaction (a) have been reported since the previous compilation (1975FI08). Measurements in the energy region of the Δ(1232) pion nucleon resonance were made (1973BA15, 1975BA58) by using bremsstrahlung photons from an electron beam and detecting coincidences between pions and recoil tritons. Differential cross sections were measured at fixed values of the squared four-momentum q^2 for E_γ between 227 and 453 MeV. Values for $\sigma(\theta)$ ranged from 1.55 ± 0.13 μb/sr at $E_\gamma = 282$ MeV, $q^2 = 3.1$ fm^{-2} to 0.035 ± 0.008 μb/sr at 452 MeV, $q^2 = 13$ fm^{-2}. At fixed q^2 the resonance was shifted toward low energies relative to the same process for a free nucleon. The shift increased with increasing q^2 at a fixed angle. The results are compared with several theoretical calculations, and it was concluded that pion rescattering is important (especially at large q^2) and that this effect as well as the resonance shift is very sensitive to the S-, S$'$-, and D-state percentages in the wave functions of the mass-3 nuclei and also to the relative weight of spin-flip and non spin-flip terms in the elementary process. Other measurements of coherent π^+ and π^0 photoproduction from ^{3}He in the Δ 1232 resonance region are reported in (1984BE08). The differential cross section averaged over the resonance was obtained as a function of momentum transfer. Charged and neutral pions photoproduced on ^{3}He were distinguished by detection and charge-identification of the recoil nuclei. A measurement (1979AR08) of the π^+ photoproduction cross section from ^{3}He relative to the cross section for this reaction on a free proton was carried out at incident photon energies 1–5 MeV above threshold. Positrons from the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay were detected by Čerenkov counters. The transition matrix element was extracted, and the pion-^{3}He coupling constant was determined. The results were discussed in relation to magnetic eletron scattering data and the properties of the pionic ^{3}He atom. A recent measurement of π^+ photoproduction on ^{3}He is reported in (1986ZA10). The pion-nucleon coupling constant is deduced. The status of pion production near threshold was reviewed in (1979DE2A), and both experimental and theoretical aspects of the process were discussed.

Early theoretical work on π^+ photoproduction on ^{3}He is reviewed in (1975FI08). More recently several impulse-approximation calculations (1973LA39, 1975LA12, 1980TI01, 1983BA12) for incident photon energies that included the first pion-nucleus resonance have been carried out. An estimate of rescattering terms is made in (1973LA39), and in (1975LA12) the contribution of meson exchange effects is explored. Calculations in impulse approximation of pion photoproduction near threshold have been reported in (1976OCZZ, 1981TI02, 1981TO13, 1983BA12). See also the review of (1979DE2A). The effects of pion momentum, Fermi momentum, and delta resonance terms on the cross section near threshold were studied in (1980DR05). Realistic wave functions generated from Reid soft-core potentials with the Faddeev equations were used in the claculations reported in (1981TI02, 1981TO13, 1983BA12), while in (1980TI01) account was taken of Fermi motion on the resonance structure. In (1984DR07) threshold photoproduction of pions is calculated for nucleons in terms of constituent quarks and for ^{3}H and ^{3}He, in terms of nucleons. A determination of the π-^{3}He-^{3}H coupling constant from threshold pion photoproduction data was made in (1979LE09), and discussions of various methods for determining the coupling constant are presented in (1980DU01, 1984KL02).

The related process of electroproduction of pions from ^{3}He (reaction (b)) has been studied experimentally and theoretically. In the work reported in (1978SK01) triton recoil cross sections were measured at incident electron energies and triton recoil energies corresponding to excitation energies near 20 MeV above the pion threshold. Model calculations were reported in (1977AS07). Calculations to describe coincident cross sections for coherent pion electroproduction in the impulse approximation using realistic wave functions were reported in (1981TI01).

8. (a) ^{3}He(γ, p)^{2}H $\qquad Q_{\rm m} = -5.494$
(b) ^{3}He(γ, n)2^{1}H $\qquad Q_{\rm m} = -7.718$

Photonuclear cross sections for ^{3}He measured at photon energies ranging from 5.5–800 MeV were summarized in (1975FI08). In the most recent measurements included in (1975FI08), differential cross sections for ^{3}He(γ, p)^{2}H at proton cm angles of $60°$ and $90°$ for photon energies ranging from 170–370 MeV (1975AR01) were reported. Bremsstrahlung photons were used, and protons and deuterons were detected in coincidence. As noted in (1975FI08) the total cross section rises rapidly from threshold to a peak at 1.0 mb at $E_\gamma \approx 11$ MeV and falls off smoothly to < 10 μb at $E_\gamma < 150$ MeV. The $90°$ cross section has a similar shape with a nearly flat peak value of ≈ 100 μb at $E_\gamma \approx 12$ MeV. Differential cross sections measured for ^{3}He(γ, d)^{1}H between 150 and 300 MeV at $\theta_{\rm cm} = 60°$, $98°$ were reported in (1982BR12, 1983SO10) and compared with the time-reversed reaction ^{2}H(γ, p)^{3}He. No evidence for time-reversal-invariance violation was found. The photoneutron cross section for ^{3}He (reaction (b)) was measured from threshold to ≈ 25 MeV with monoenergetic photons (1981FA03) in an experiment which included ^{3}H(γ, n), and ^{3}H(γ, 2n).

For ^{3}He(γ, n) the cross section rises from threshold at 7.72 MeV to ≈ 1 mb at ≈ 13 MeV, remains nearly flat to ≈ 17 MeV, reaches ≈ 1.1 mb at 18 MeV and drops to ≈ 0.3 mb near 30 MeV. See the section on ^{3}H(γ, n)^{2}H and (1981FA03) for results of comparison of ^{3}He and ^{3}H photodisintegration cross sections. See Table 3.7 for integrated cross sections and first and second moments.

Many excellent reviews exist in the literature on the photodisintegration of ^{3}He and ^{3}H nuclei (1979TO2A, 1979BE2C, 1977CI2A, 1975WE2A, 1976GO2A, 1975FI08). Since theoretical calculations are often made simultaneously for both nuclei, the section on ^{3}H should be consulted as well. References to the earliest theoretical calculations on the photodisintegration of ^{3}He may be found in the compilation of (1975FI08).

The two-body breakup reaction ^{3}He(γ, p)^{2}H has been investigated and reported in (1977CR01). Cross sections at intermediate energies ($E_\gamma < 600$ MeV) are calculated using realistic bound state wave functions obtained with the Reid soft-core potential, but neglecting final state interactions. In (1981AU02) an independent calculation using the same physical input as (1977CR01) is reported. Considerable differences in the results are found and discussed in detail. The importance of final state interactions and possible meson exchange effects is also discussed. Electromagnetic and pion-ecxhange contributions were studied in calculations for $E_{\rm lab} = 165$ and 330 MeV (1976FI11). For $E_\gamma < 40$ MeV, cross sections are calculated (1975GI01) for the two-body photodisintegration of ^{3}He and ^{3}H in the electric-dipole approximation. The calculations were performed within the context of exact three-body theory with the two-nucleon interactions represented by s-wave spin-dependent separable potentials. The numerical results indicate: (i) the ^{3}He and ^{3}H 90°-photodisintegration cross sections are essentially identical in shape; (ii) the ^{3}He(γ, d)p 90° differential cross section has a peak value of approximately 95 μb/sr. (See (1981FA03) for comparison with experiment where it is concluded that agreement is not notably good).

In a later work (1976GI02) the same theory applied earlier (1975GI01) for the two-body breakup for ^{3}H and ^{3}He targets was applied to the three-body breakup reaction ^{3}He(γ, n)2^{1}H. The numerical results indicate: (1) the ^{3}He(γ, n)2^{1}H cross section has a peak value of one mb; (2) the neutron spectra for ^{3}He(γ, n)2^{1}H and a proton spectrum for ^{3}He(γ, p)np peak sharply in the region of the strong pp final state interaction. In (1975FA05, 1976FA12) hyperspherical harmonics were used for continuum three-body states in the calculation of cross sections for E1 transitions in ^{3}He to final isospin-$\frac{3}{2}$ states (trinucleon photoeffect). The use of a soft-core potential gives fair agreement with calculations of (1976GI02). In (1978FA01) this work was extented by including an additional grand orbital in the final state and finding reasonable agreement with measured total cross sections. The same formalism has been used in (1978LE11) to calculate several new examples of the trinucleon photoeffect. Agreement with experiment was in general unsatisfactory. The method of hyperspherical harmonics has also been used (1977VO11) to calculate three-body photodisintegration cross sections of ^{3}He and ^{3}H, and good agreement with experiment was obtained. The suppression of the isospin-$\frac{1}{2}$ three-body photodisintegration of ^{3}He is investigated and explained in (1979LE03), in which exact three-body calculations and evaluation of isospin sum rules are also reported.

The role of mesonic and isobaric degrees of freedom for electromagnetic processes in light nuclei including ^{3}He is discussed in (1983AR21).

9. (a) ^{3}He(e, e)^{3}He
   (b) ^{3}He(e, e′p)^{2}H $\quad Q_{\rm m} = -5.494$
   (c) ^{3}He(e, e′n)2^{1}H $\quad Q_{\rm m} = -7.718$

Table 3.13: Measurements of cross section of ^{3}He(e, e)^{3}He

q^2 (fm^{-2})	E_e (MeV)	θ_e (deg)	$\theta_{^3He}$ (deg)	Refs.
0.20 – 3.7	105 – 320	30 – 135		1985OT02
0.88 – 3.2	109 – 214		28	1984RE03
0.7 – 11	85 – 350	160		1983DU01
7 – 31.6	300 – 689	155		1982CA15
20 – 100	6 – 14 GeV	8		1978AR05
0.032 – 0.34	29 – 95	75		1977SZ02
0.347 – 20	170 – 750			1977MC03
0.09 – 8.4	54, 134.5			1987BE30

Measurements of elastic and inelastic electron scattering cross sections since the compilation of (1975FI08) are summarized in Tables 3.13, 3.14, and 3.15.

The elastic charge form factor has been measured for a range of q^2 (four-momentum squared) from 0.032 fm^{-2} to 100 fm^{-2}. Extension of the data beyond $q^2 = 20$ fm^{-2} shows the charge form factor continues to fall until $q^2 = 65$ fm^{-2} and then goes up slightly (1978AR05). Recent determinations of the rms radius of the charge density distribution in ^{3}He gave $\gamma^c_{rms} = 1.976 \pm 0.015$ fm (1985OT02) and $\gamma^c_{rms} = 1.93 \pm 0.03$ fm (1985MA12). Earlier evaluations gave $\gamma^c_{rms} = 1.877 \pm 0.019$ fm (1984RE03), 1.935 ± 0.03 fm (1983DU01), 1.89 ± 0.05 fm (1977SZ02) and 1.88 ± 0.05 (1977MC03). The elastic magnetic form factor has been measured for $q^2 = 0.2$–31.6 fm^{-2}. The data of (1982CA15) define a diffraction minimum in the magnetic form factor at $q^2 = 18$ fm^{-2} and a second maximum at 25 fm^{-2}. See also the very recent measurement of the isoscalar and isovector form factors for ^{3}H and ^{3}He for momentum transfers between ≈ 0.3 and 2.9

Table 3.14: Measurements of cross section of ^{3}He(e, e′)^{3}He

E_e (MeV)	θ_e (deg)	Refs.
100 – 300	65 – 180	1984KO05
120 – 667 [a]	36, 60, 90, 145	1985MA12
16.4 – 16.5 GeV	8	1982RO16
0.1 – 4 GeV [a]		1980MC01
40 – 61	180	1979JO02
2.8 – 14.7 MeV	8	1979DA14
1211	15 – 29	1978KU11
500	60	1976MC01
60 – 110, 120	92.6, 127.7	1975KA04, 1975KA28

Table 3.15: Measurements of cross section of ^{3}He(e, e′p) ^{2}H

E_e (MeV)	θ_e (deg)	θ_p (deg)	Refs.
806, 643	31, 28	$47.5 - 72.5, 54 - 72$	1983GO01
527.9, 509.3	52.2, 36	$53 - 77, 55 - 92$	1982JA06
806, 643 [a]	31, 28	$47.5 - 72.5, 54 - 78$	1982GO06
806, 643	31, 28	$47.5 - 72.5, 54 - 78$	1981KO25
806, 643 [b]			1980GO09
1200	30	$45.5 - 72.5$	1978GO17

[a] Also measured ep coincidences for ^{3}He(e, e′p)np.

[b] A preliminary publication detailed version appears in (1982GO06).

fm^{-1} reported in (1987BE30). Values of the rms radius for ^{3}He obtained from the magnetic form factor measurements are in agreement with one another. The values for $\gamma^{\rm m}_{\rm rms}$ are 1.93 ± 0.07 fm (1985MA12), 1.99 ± 0.06 fm (1985OT02), 1.935 ± 0.04 (1983DU01) and 1.95 ± 0.11 (1977MC03).

No theory has yet been successful in reproducing the charge form factor data over the entire range of q^2. Inclusion of a six-quark admixture in the ^{3}He wave function results in better agreement with experimental data in the whole region of momentum transfer up to $q^2 = 36$ fm^{-2} as compared with pure nuclear models (1984BU24, 1984BU42). A second diffraction minimum is predicted at $q^2 = 50$ fm^{-2} (1978HA09, 1982HA09, 1984BU24). The effects on the calculated charge form factor of the nucleon polarization (1982DR01) and the pair current (1983BE08, 1983DR12) calculated in the constituent quark model have been discussed as have multi-quark clusters (1982NA09, 1984HO22, 1985KI12, 1985MA24). The dimensional-scaling quark model is discussed in (1978CH2A). Isobar currents, mesonic exchange currents and other corrections of relativistic order (1976DU05, 1976HA33, 1976KL02, 1977HA03, 1977RI15, 1978HA09, 1978SI15, 1979GI08, 1979SA39, 1981FI05, 1981HA07, 1981TO08, 1982HA09, 1983AZ01, 1983GI11, 1983HA04, 1983HA18, 1983MA58, 1983SA28) have been examined. The ^{3}He charge density determined from the charge form factor is seen to exhibit a central depression when the protons are treated as point charges (1978SI2B). This feature of the charge density is not reproduced by non-relativistic Faddeev calculations (1978SI2B), even when different potentials are used (1981FR15). A suggestion (1981NO04) based on a variational calculation using a simple trinucleon wave function, that the central depression could be attributed to a two-pion exchange three-body force, is not borne out by a more rigorous Faddeev calculation in which a two-pion exchange three-body force is added to a realistic nucleon-nucleon interaction (1981TO08). A variational method was employed (1984HU09) to calculate the trinucleon ground state properties, and it was concluded that the charge form factor is rather insensitive to the addition of different three-body forces. See also (1986SA08). Inclusion of meson exchnage currents, isobaric processes and other corrections of relativistic order is able to reproduce the central depression (1978HA09, 1982HA09). The bearing of these ingredients on current conservation is discussed in (1986LI09). Arguments based on QCD presented in (1986AB02) indicate that the central depression is due to the presence of large hidden-color components. Ambiguities in the point charge density are discussed in (1982HA30). Errors in the determination of the charge distribution are discussed in (1978BO21, 1981BO13, 1982BO08, 1984CO06).

The magnetic form factor data are not theoretically reproduced over the entire range of q^2. Inclusion of meson exchange currents in the ^{3}He wave function is essential to explain the diffraction minimum (1980RI04, 1982CA15, 1984MA26). The importance of the D-state of the trinucleon and the short-range behavior of the S- and D-state wave functions in determining the magnetic form factors of the three-body system is shown in (1975BA08). The role of the nine-quark state is discussed in (1985AN13). Parity violating asymmetries in elastic electron-nucleus scattering are considered in (1981FI05). The effect of clustering on the electromagnetic form factors of ^{3}He and ^{3}H is studied in (1976TA06). A brief review of theories on elastic electron scattering by ^{3}He and ^{3}H is contained in the talks reported in (1977CI2A, 1978SI2B). See also (1977NE2A, 1984FR16, 1985BO44) for a discussion of ^{3}He electromagnetic form factors. Pionic contributions to very-forward elastic scattering are discussed in (1986KA01). An analysis of inclusive quasielastic electron scattering data which can be interpreted to imply an increase in the nucleon radius in ^{3}He compared to the free nucleon radius is presented in (1986MC03). For other elastic scattering work see also (1974AR09, 1977DI10, 1977DU01, 1982TO08, 1986KI10).

In inelastic electron scattering experiments, a 2S–2S monopole transition has been observed (1975KA04, 1975KA28) and a possible excited state at 10 MeV has been discussed (1979JO02). The first experimental separation of the transverse and longitudinal response functions has been carried out and reported in (1980MC01). The structure function has been derived from experimental data (1982RO16), while longitudinal and transverse form factors were derived from data in (1984KO05). The inelastic electron scattering data cover a momentum transfer range $0.09 < q^2 < 1$ fm^{-2} (1975KA28), $q^2 = 5$ fm^{-2} (1976MC01), $2.5 < q^2 < 7.1$ fm^{-2} (1978KU11), $4 < q^2 < 4.9$ fm^{-2} (1979DA14), $20 < q^2 < 128$ fm^{-2} (1982RO16) and $1 < q^2 < 2.5$ fm^{-2} (1984KO05).

Theoretical fits to the data are made mainly using the impulse approximation (1981BI01) with wave functions calculated by the Faddeev technique (see (1976DI09) and the experimental papers). The spectral function is derived (1983ME03) in the plane wave impulse approximation. Contributions of meson-exchange currents and final state interactions to the longitudinal and transverse response functions of ^{3}He are estimated in (1985LA04).The effect on inelastic electron scattering from ^{3}He of meson exchange currents (1983BI05) and quark clusters (1981PI04, 1981PI2B) has been studied. Theoretical descriptions of y-scaling effects in inclusive electron scattering are discussed in (1982BO30, 1983CI11, 1983CI14, 1986GU10). The question of loose quarks in nuclei was raised (1986OE02) in connection with structure function calculations. The use of quasi-elastic scattering of polarized electrons on polarized ^{3}He as a probe of the subdominant components of the ^{3}He wave function has been explored in (1982WO05, 1984BL02).

The channels associated with two- and three-particle electrodisintegrations of ^{3}He have been separated using ^{3}He(e, e$'$p)^{2}H reactions (1981KO25, 1982GO06, 1982JA06, 1983GO01). The proton momentum distribution of ^{3}He (1982GO06, 1982JA06, 1983GO01) and spectral function (1980GO09, 1982JA06) have been determined and fitted with various theoretical models for the ^{3}He wave function and nucleon-nucleon potential. A theoretical calculation in the framework of the Faddeev fromalism in which a one-term s-wave spin-dependent separable interaction fitted to the two-nucleon scattering data is used, is found capable of explaining two-body electrodisintegration of ^{3}He near threshold and possibly at higher excitation energies (1977HE03, 1977HE22). High resolution (e, e$'$p) experiments are reviewed in (1985DE56) where it is concluded that (e, e$'$d) data of (1985KE05) constitute evidence for direct coupling of the virtual photon with correlated nucleon pairs.

Sum rules for electron scattering are discussed in (1979JO02, 1980MC01, 1981TO11) and in other references cited in (1975FI08). A recent calculation (1986EF01) involving sum rules in analysis of longitudinal (e, e$'$) spectra gave agreememt with traditional descriptions involving only nucleon degrees of freedom. For other work see also (1978CI2A, 1979CI2A, 1982BO30, 1983CI14).

10. (a) ^{3}He(μ^-, ν)^{3}H $Q_m = 105.130$

(b) ^{3}He(μ^-, ν)^{2}H, n $Q_m = 98.872$

(c) ^{3}He(μ^-, ν)^{1}H, 2n $Q_m = 96.648$

(d) ^{3}He(μ^-, $\nu\gamma$)^{3}H $Q_m = 105.130$

No experiments on the above reactions have been reported since the compilation of (1975FI08). Theoretically estimated values of the total capture rate for ^{3}He + μ^- are 2253 s^{-1} (1978TO01) and 1391–2408 s^{-1} (1980HA46). Partial capture rates calculated for reaction (a) are 1264 s^{-1} (1978TO01), 1500 s^{-1} (1978HW01), 1433 ± 60 s^{-1} (1975PH2A), 1476 s^{-1} (1975KI2A), and 1375–1537 s^{-1} (1976SA06). Calculations were also made and reported in (1986CO13). Polarizations and asymmetry parameters for reaction (a) treating the nuclei as elementary particles are calculated as well in (1976SA06). The elementary particle method and impulse approximation method are compared in (1975PH2A) where a capture rate of 414 s^{-1} for reaction (b) and 209 s^{-1} for reaction (c) is calculated. The total capture rate is calculated (1978RA25) for the reaction ^{3}He + μ^- and for reaction (a) as a function of the ratio of the induced pseudoscalar and axial vector coupling constant (g_p/g_A). The extracted values for g_p/g_A lie between 10 and 18.

The photon spectrum for the radiative capture reaction (d) has been calculated (1981KL03, 1984KL02) using the impulse approximation with a realistic function and the elementary particle method. A relativistic calculation made in (1980FE02) disagrees with the calculations of (1978HW2B) which are based on current conservation and a special linearity hypothesis. In (1976BE04, 1980GO2D, 1981GM01) the elementary particle method is employed to analyze reaction (d).

A review of muon capture by ^{3}He is contained in (1977PH2A).

11. (a) ^{3}He($\pi^\pm$, $\pi^\pm$)^{3}He

(b) ^{3}He(π^-, π^0)^{3}H $Q_m = 4.075$

(c) ^{3}He(π^+, p)2p $Q_m = 125.855$

(d) ^{3}He(π^-, p)2n $Q_m = 130.557$

(e) ^{3}He(π^-, n)^{2}H $Q_m = 132.782$

(f) ^{3}He(π^-, π^+)3n $Q_m = -10.305$

Measurements of the pion elastic scattering reaction (a), charge exchange reaction (b) and pion absorption reactions (c)–(e) on ^{3}He since the compilation of (1975FI08) are listed in Tables 3.16, 3.17, 3.18 and 3.19 respectively.

The angular distributions for $\pi^\pm$ scattering by ^{3}He at energies between 260–310 MeV comfirm the fixed angle ($\theta \approx 75^\circ$) minimum seen at lower energies and show a deep minimum at $\theta \approx 110^\circ$ (1980KA17). The data of (1976SH2B, 1978FA06, 1980FA12, 1981KA17, 1984FO18) for reaction (a) are not reproduced at all energies by optical model calculations. A value of 1.95 fm for the magnetic radius of ^{3}He is extracted by the authors of (1980FA12) from their data. Estimates of the π^-^{3}He-^{3}H coupling constant are made in (1976SH2B, 1978FA06), and a theoretical value obtained in (1979LE09, 1984KL01). The observation of the violation of charge symmetry in $\pi^\pm$ scattering on ^{3}H and ^{3}He in (1984NE01, 1984NEZY) is questioned by the authors of (1984KI13) who comment that the experimental results can be explained as the manifestation of multiquark resonances in interacting hadronic systems. See also (1986KI08). A theoretical model

Table 3.16: Measurements of cross sections of ^{3}He($\pi^{\pm}$, $\pi^{\pm}$)^{3}He

E_{π} (MeV)	θ_{π} (MeV)	Refs.
30 – 65	40 – 145	1984FO18
50 – 200	20 – 120	1981KA17
68 [a]	25 – 165	1978FA06
68 – 156 [b]	25 – 165	1976SH2B
98 – 208 [a]	25 – 165	1976SH2B
143		1984NEZY
180	44 – 96	1984NE01
145 – 195 [a]		1980FA12
260 – 310 [b]		1980KA17
295 [a]		1980KA17
350, 400, 475 [c]	60, 90, 120	1985BO41

Table 3.17: Measurements of cross sections of ^{3}He(π^{-}, π^{0})^{3}H

$E_{\pi^{-}}$ (MeV)	$\theta_{\pi^{0}}$ (deg)	Refs.
0 [a]		1986BA06
200 [b]	0 – 90	1982CO01
200	0 – 84	1980BO03
200 – 290	80 – 150	1979KA02
285 – 525	60 – 140	1982OR06
285 – 525	70 – 140	1982KA02

[a] Measured ratio ^{3}He(π^{-}, π^{0})/^{3}He(π^{-}, n) for pions at rest.

[b] Also measured continuum angular distributions.

Table 3.18: Measurements of cross sections of ^{3}He($\pi^{\pm}$, p)

E_π (MeV)	θ_p (deg)	Refs.
$50-250, 295$	20, 40	1983KA14
$50-295$ [a]		1980KA37
65 [b]	$20-120$ [b]	1984MO03
120	117, 140	1986WE02
165 [c]	55	1981AS10
400, 475	30	1981KA43

[a] ^{3}He(π^+, p) only.
[b] ^{3}He(π^+, 2p)p and ^{3}He(π^-, pn)n reactions studied; $\theta_p = \mathrm{cm}$ angle.
[c] Measured relative cross sections for the ^{3}He(π^+, 2p)p, ^{3}He(π^-, pn)n reactions.

Table 3.19: Measurements of cross sections of ^{3}He(π^-, n)^{2}H

E_π (MeV)	θ_n (deg)	Refs.
0 [a]		1982GO04
0 [b]		1986BA06
$50-295$	$20-150$	1981KA26
$100-290$	$20-150$	1978KA01
120	40, 117	1986WE02
$285-575$	$18-134$	1982OR06
$285-575$	$20-120$	1981OR01

[a] Reactions $\pi^-{}^3$He $\rightarrow$ nnp and π^- ^{3}He$\rightarrow$ nd measured with stopped pions.
[b] Measured ratio $^3\mathrm{He}(\pi^-,\ \pi^0)/^3$He($\pi^-$, n) for pions at rest.

for the distribution of matter in the ^{3}He-^{3}H system (1985BA24) is, however, able to explain the observed charge-symmetry violating effects. Off-shell effects in pion ^{3}He scattering are examined in (1980MU16, 1984GM01). A theoretical optical potential including spin is used in (1975LA15, 1975LA19) to analyze π^--^{3}He data and it is proposed that π^--^{3}He scattering can provide information on the magnetic form factor of ^{3}He. A Glauber theory calculation reported in (1975GO29) examines the effects on π^--^{3}He scattering of the details of the nuclear wave function and of a repulsive core. A model based on the use of a simple pion-nucleus potential proposed in (1981NI05) has been used to determine the value of the nuclear mass radius of ^{3}He in the region of the Δ_{33} resonance. Scattering length for π-^{3}He are calculated in work reported in (1978LO16, 1978TH2A, 1979BE13, 1979BE2C, 1981BE63, 1982MU13, 1983GE12, 1985BE56).

In references reported here all experimental data for reaction (b) are analyzed using Glauber theory which gives good to fair fits. The authors of (1979KA02, 1982OR06) have performed optical model calculations as well and get an unsatisfactory fit to their data by both methods. Dominance of spin-flip contributions is suggested by the data (1980BO03, 1982CO01, 1982KA02). The effective number of nucleons and Pauli blocking effects are deduced in (1982CO01) from measurements reported there of the continuum angular distributions. Pauli principle effects were also studied in (1986NA05). Optical model calculations (1982MA26) and Glauber model calculations (1980GE06) are used to show that the differential cross sections are insensitive to the magnetic form factor of ^{3}He. The importance of spin-flip contributions first pointed out in (1975SP06) in a Glauber calculation was later confirmed in (1977LO13). Both reactions (a) and (b) are investigated theorectically using coupled Schrödinger equations (1982AV2A), four-particle equations (1979BE13, 1980BE55) modified in the spirit of the impulse approximation (1981BE46), and optical potentials (1976MA11, 1977LA06, 1980WA09). The effect of center-of-mass correlations and intermediate states of π-^{3}He scattering can be ignored (1981ME14). A review of these relations is contained in (1978NE2B).

Proton spectra for the reactions (c) and (d) with emphasis on the kinematic region of two-nucleon pion absorption have been measured and reported in (1980KA37, 1981KA41, 1981KA43) and (1983KA14) which reports measurements of quasifree scattering as well. The isospin dependence of pion absorption by nucleon pairs has been studied experimentally in work reported in (1981AS10, 1984MO03). The strong suppression of pion absorption by nucleon pairs having isospin equal to one, in the resonance region, is explained by theories based on the delta-isobar intermediate excitations (1982LE18, 1982TO18, 1984SI03). See also (1985OH09, 1986MA21). The same suppression of absorption on isospin-one nucleon pairs for low energy s-wave pions has been used to relate the 1s absorption width in the pionic atom ^{3}H to that of ^{3}He (1985WE04). See also (1980SC24).

Reactions (d) and (e) with stopped pions have been measured (1982GO04) and branching ratios deduced for all observed final states. Theories for pion absorption on ^{3}He at threshold have been proposed in work (1978JA02) based on the two-nucleon absorption model, and in (1980AV2A) in which coupled Schrödinger equations are solved. The energy dependence of the cross sections for reaction (e) measured for pion energies between 50–575 MeV suggests the formation of an isospin equal to $\frac{1}{2}\pi$N resonance in the intermediate state (1981KA26, 1981OR01, 1982OR06).

The photon spectrum from radiative and charge exchange capture of pions in ^{3}He was measured (1974TR2A) and a value of the Panofsky ratio $P_3 = 2.68 \pm 0.13$ was obtained. An impulse approximation calculation gives $P_3 = 2.82$ (1978GI13). The Panofsky ratio and photopion production crosss section at threshold on ^{3}He are investigated in a soft-pion approach to the ^{3}He-^{3}H weak axial-vector form factor reported in (1978GO11, 1980GO2D). See (1977BA2A) for a review on radiative pion capture reactions.

Information about the interaction between pions and nuclei at low relative momenta has been extracted from measurements of X-rays from pionic ^{3}He and reported in (1977AB2A, 1978MA12, 1980MA20, 1982BA43, 1983BA39, 1984SC09).

For a discussion of reaction (f) see ^{3}n reaction 2.

^{3}Li

GENERAL :

The previous compilation (1975FI08) listed a small number of references reporting on the four reactions discussed below. Only one of the experiments cited contained any evidence for a 3p resonance, and the discussion suggested that the observed enhancement in ^{3}He(p, n) was more likely a final state interaction. In the work reported since (1975FI08) and listed below, only (1974POZN) contains any mention of the tri-proton, and no evidence for its existence was observed.

1. ^{2}H(p, π^-)^{3}Li — not observed

This reaction was studied at $E_\pi = 24$–254 MeV (1979DA19) and $E_\pi = 585$ MeV (1980CR03). No evidence for a 3p resonance was reported.

2. ^{3}He(p, n)^{3}Li — not observed

Spectra obtained at $E_\pi = 22$ and 25 MeV at $\theta_n = 3.5°$–$40°$ (1974POZN) showed no structure indicative of formation of the tri-proton.

3. ^{3}He(^{3}He, t)^{3}Li — not observed

No work was reported on reaction 3.

4. ^{6}Li(^{3}He, ^{6}He)^{3}Li — not observed

No work was reported on reaction 4.

References

(Closed 1987)

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

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