Energy Levels of Light Nuclei
$A = 3$

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Abstract: A compilation of experimental and theoretical information is presented on the mass 3 systems ^{3}n, ^{3}H, ^{3}He and ^{3}p. Emphasis is on advances since the previous evaluation (1987TI07) such as, (1) detailed calculations of the vector and tensor analyzing powers for neutron and proton scattering by deuterium which led to the discovery of the still unresolved analyzing power puzzle, (2) the wide spread use of polarized ^{3}He targets which allowed for the experimental study of sum rules among other things and (3) the ability to include the Coulomb interaction in three-body calculations. As stated in the 1987 evaluation and is still the case, there is no firm evidence for either excited states of ^{3}H or ^{3}He nuclei or for the existence of the trineutron or triproton. This version of $A = 3$ differs from the published version (*Nuclear Physics A*848 (2010), p. 1) 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 December 31, 2009)

The work is supported by the US Department of Energy, Office of Nuclear Physics, under: Grant No. DE-FG02-97ER41042(North Carolina State University); Grant Nos. DE-FG02-97ER41033 and DE-FG02-03ER41231 (Duke University).

Table of Contents for $A = 3$

Below is a list of links for items found within the PDF document or on this website.

Introduction

The present evaluation summarizes the research that has been published on the $A = 3$ systems since the previous evaluations (1975FI08, 1987TI07). There are four $A = 3$ systems to consider: ^{3}n, ^{3}H, ^{3}He and ^{3}Li. Of these, only ^{3}H and ^{3}He are known with certainty to possess bound states. Studies of the reaction ^{1}H(^{6}He, α)^{3}H reported in (1994AL54, 2003RO13) have suggested the possibility of a resonance in ^{3}H at about 7 MeV above the ground state; see ^{3}H reaction 2. In the two previous evaluations, the material was presented in the framework of a discussion of the energy levels of the $A = 3$ systems. This same approach has proven to be a useful means of presenting large amounts of data for $A > 3$ systems. Also, the desire to discover and study resonances has motivated both experimental and theoretical research in the $A = 3$ systems. The same approach is followed in this review.

Except in rare instances, references to papers published prior to and included in either the 1975 or the 1987 evaluation are not included here. The present review includes material that appeared in the National Nuclear Data Center (NNDC) Nuclear Science References (NSR) database through December 31, 2009. In a few instances, references to articles not appearing in the Nuclear Science References are included. A few references with a 2010 publication date have been included; however, systematic searches later than 2009 have not been performed.

As in earlier reviews for $A = 3$, data tabulations and/or graphs of scattering and reaction cross sections have not been included in this evaluation. The database EXFOR/CSISRS contains a vast collection of experimental reaction data for incident neutrons, charged particles and photons.

The material is separated into the four systems: ^{3}n, ^{3}H, ^{3}He, ^{3}Li. The ordering of the reactions follows that of the previous evaluations, for the most part. For historical reasons associated with Evaluated Nuclear Structure Data File (ENSDF), in the ^{3}He section, the beta decay process ^{3}H(β^-)^{3}He is given first.

Theoretical topics relevant to the A = 3 systems

1) Basic issues:

(a) The Gerasimov-Drell-Hearn (GDH) sum rule relates an energy weighted integral over the spin-dependent photoabsorption cross sections of a particle to its ground state anomalous magnetic moment; see the reviews (2004DR12, 2008DR1A). It is derived using basic principles of invariance, causality and unitarity and relates a static property of a particle's ground state with aspects of its dynamical spectrum. The GDH sum rule was first tested experimentally for protons (2000TH04, 2001AH03, 2004DU17). However, by using polarized ^{3}He targets, it has become possible to test this sum rule - as well as a generalized form that allows for virtual photons - for ^{3}He and the neutron (2001GI06, 2001WE07, 2002AM08). See the ^{3}He section for more on the GDH sum rule, anomalous magnetic moments and polarized ^{3}He targets. Related to the GDH sum rule is the forward spin polarizability, γ_0. In this case, however, the integrand contains the photon energy to the inverse third power rather than to the inverse first power as in the GDH sum rule; see (2009WE1A) and references therein. Calculations of both the GDH sum rule and γ_0 for ^{2}H are reported in (2004CH58, 2004JI03).

(b) Charge symmetry breaking (CSB), or isospin violation, as currently understood, is due to the down quark having a slightly greater mass than the up quark and to electromagnetic effects; see Tables 1.1 and 1.2 in (1990MI1D) as well as (2006MI33) and references therein. Recent advances in effective field theory have been used to include CSB into NN and NNN interactions; see (2000VA26, 2003FR20, 2005FR02, 2006MI33). More references on effective field theory are given below. CSB shows up in the binding energy difference of ^{3}H and ^{3}He; the binding energy of ^{3}H is greater than that of ^{3}He by almost 764 keV of which about 85% is due to the effect of the Coulomb interaction between the two protons in ^{3}He. See (2005FR02, 2006MI33) and the introduction of the ^{3}He section for more details on the origins of the remaining 15%. CSB has also been studied in the context of elastic scattering of π^+ and π^- from ^{3}H and ^{3}He; see (2002BR49, 2002KU36) and references therein. Details on these reactions are discussed in ^{3}H reaction 10 and ^{3}He reaction 13. More general than charge symmetry and charge symmetry breaking is the subject of charge independence and charge independence breaking (CIB). A study of CIB and the role of mixing of $T = \frac{3}{2}$ states with $T = \frac{1}{2}$ states in ^{3}H and related reactions is reported in (1991WI06).

2) Realistic NN potentials:

Several phenomenological NN interactions have been developed that include the correct long range one pion exchange tail, yield essentially perfect descriptions of pp and np phase shifts and the properties of the deuteron and in some cases include charge dependent aspects. Some that are frequently used in $A = 3$ applications are: AV$_{14}$ (1984WI05), NijmI, NijmII, Reid93 (all three are presented in (1994ST08)), AV$_{18}$ (1995WI02) and CD-Bonn (1996MA09, 2001MA07). Details of various NN interactions along with comparisons of calculated results can be found in (1998CA29). Calculations using these potentials for $A = 3$ systems are in (1993FR11, 2000VI05, 2003NO01, 2004KU12). However, when the binding energy of ^{3}H and ^{3}He are calculated using these NN interactions, it is found that the predictions underbind these nuclei by about 10%. This result has been known for some time and is illustrated in (2002GL1F). However, this discrepancy is not as bad as it first sounds. Since the binding energy of ^{3}H or ^{3}He is the sum of the kinetic energy of around 40 MeV and a negative potential energy of about -48 MeV, an error of only 1 or 2 % in the potential energies can give an error of 10% in the binding energies.

3) Partially non-local NN potential:

Both many-body and relativistic effects can introduce non-local aspects into NN interactions, especially at short distances. There have been several studies which treat the long range part of the NN interaction as local and the short range part as non-local. The CD-Bonn interaction mentioned above falls into this category to a certain extent. In addition, see (1996MA09, 1998DO13, 1999DO35, 2000DO23, 2003DO05, 2004DO05, 2008DO06).

4) Non-local, separable potential from inverse scattering methods:

Using J-matrix inverse scattering techniques, a separable, non-local nucleon-nucleon interaction, called JISP, has been obtained and used in calculations related to the structure of light nuclei, including mass 3; see (2004SH41, 2009MA02, 2009SH02) and references therein. Note: The reference (2004SH41) was reproduced and updated in (2008AL1C). Calculations of the binding energies of ^{3}H and ^{3}He using various interactions, including JISP, are compared in (2005SH33). See also (2007SH27, 2009MA02). The JISP interaction was used in (2006BA57) to calculate the photoabsorption cross sections of ^{2}H, ^{3}H, ^{3}He and ^{4}He.

5) Dressed bag model of the NN interaction:

This approach treats the short and intermediate parts of the NN interaction as a six-quark bag surrounded by one or more meson fields; see (2001KU14, 2001KU16). For applications to scattering phase shifts and deuteron properties, see (2002KU14) and for an application to n-p radiative capture, see (2003KA56).

6) NNN potentials:

Three-body forces have been studied for decades. A brief discussion of the physical origin of these interactions is given in (1998CA29). The reference (1999FR02) contains a listing of several of these forces with original references. Two of these NNN interactions that have continued to be used in recent calculations - sometimes in modified form - are Urbana IX (1995PU05, 2003NO01) and Tucson-Melbourne (1995ST12, 2001CO13). The ^{3}H and ^{3}He binding energy discrepancy referred to above can be resolved by including a three-body force. This is illustrated in (2003NO01) where the binding energies of ^{3}H and ^{3}He are calculated using the AV$_{18}$ two-body interaction and the Urbana IX three-body interaction. A three-body force has also been obtained in the dressed-bag model; see (2004KU05). For a discussion of the three nucleon force in the context of neutron-deuteron and proton-deuteron scattering, see (2007SA38, 2007SA59). Section 1 of (2008KI08) contains a discussion and extensive list of references on nucleon interactions in general and the three nucleon interaction in particular from a historical perspective. A comparative study of three different NNN interactions combined with the AV$_{18}$ NN interaction is reported in (2010KI05).

7) Effective field theory:

This topic also goes by the names chiral effective field theory and chiral perturbation theory (ChPT). A brief history of this theory along with relevant references is given in (2003EN09). Work reported in this reference shows that calculations of the properties of the deuteron using an NN interaction obtained from fourth order ChPT compare favorably with those using AV$_{18}$ and CD-Bonn NN interactions and with experiment. Third order ChPT has been used to produce an NNN interaction (2002EP03, 2007NA30). A brief introduction to this topic can be found in (1998VA04). A comprehensive review of the theory can be found in (2002BE90). See also (1995BE72). Some references in which ChPT has been applied to $A = 3$ systems are (2002EP02, 2002EP03, 2004GL05, 2006PL09, 2007HA42). The reference (2007NA16) contains a useful introduction to ChPT and uses the binding energies of ^{3}H and ^{3}He to constrain low energy constants. Low energy constants for the ChPT formulation of the NNN interaction are also obtained in (2009GA23), using ^{3}H and ^{3}He binding energies and the ft value for the beta decay of ^{3}H. Chiral symmetry and ChPT also demonstrated that the Tucson-Melbourne three-body interaction needed to be modified; see (1999FR02, 2001CO13, 2001KA34). See also (2006RA33) for a study of parity violation using effective field theory. See also (2004CH58, 2004JI03) for calculations of the GDH sum rule and spin-dependent polarizabilities using effective field theory.

See (2009EP1A) for a review of the application of effective field theory to the interaction of nucleons based on quantum chromodynamics.

8) Renormalization group methods:

Techniques using the Renormalization Group in general and the Similarity Renormalization Group in particular have been used to separate lower momentum, longer range components of the NN interaction from the higher momentum, shorter range components; see (2003BO28, 2005SC13, 2007BO20, 2007JE02, 2008BO07) and references therein. The review (2007JE02) has a discussion of the role of the Renormalization Group in effective field theory applications. The reference (2008BO07) reports on shell model calculations of light nuclei, including ^{3}H, using an NN interaction produced from effective field theory modified by the Similarity Renormalization Group. See also (2008DE04).

9) Dynamical and structural calculations:

Several methods have been used to calculate bound and continuum states in $A = 3$ systems. Some of the best know are described next.

(a) The Faddeev approach has a long history as discussed in (1993WU08, 1996GL05). Both coordinate space and momentum space Faddeev methods are outlined in (1998CA29). Both methods are used and results compared in (1990FR13) where $\mathrm{n} + \mathrm{d}$ scattering is studied and in (1995FR11) where $\mathrm{n} + \mathrm{d}$ breakup amplitudes are calculated. In (1993FR11), the ground state of ^{3}H was studied using the coordinate Faddeev approach and several realistic NN interactions. In another Faddeev approach to ^{3}H and ^{3}He ground states, the interacting pair is treated in coordinate space and the spectator particle is treated in momentum space; see (1981SA04, 1993WU08). Equivalent to the continuum Faddeev approach is the Alt-Grassberger-Sandhas (AGS) method; see (2008DE1D, 2009DE02) and references therein. See (2001CA44) for an application of the AGS approach to neutron-deuteron scattering. Using the AGS approach, the Coulomb interaction can be taken into account by using a screening technique. See (2006DE26, 2009DE47) for an application of the AGS method to proton-deuteron scattering. New formulations of the Faddeev equations which contain applications to $A = 3$ processes are presented in (2008WI10, 2010GL04).

(b) The hyperspherical harmonic basis method (1993KI02, 1994KI14, 1995KI10, 1998CA29, 2004KI16) comes in several different forms. It can treat the Coulomb force exactly, produces results in agreement with Faddeev calculations (2003NO01) and has been extended to the $A = 4$ systems (2005VI02, 2005VI05). For a detailed discussion of the hyperspherical harmonic method including an application to the bound and zero energy scattering states of three and four nucleon systems, see (2008KI08). See also (2009LE1D) for a discussion of the method and some applications to three body systems.

(c) The Green's function Monte Carlo method has been applied mostly to systems with $A > 3$. The method is described in (1998CA29) where the results of a binding energy calculation of ^{3}H, both with and without a three-body force, are quoted. See also (1998WI10), where calculations of the ground state properties of ^{3}H are included along with several other light nuclei. In (2008MA50), the method is applied to calculations of the magnetic moments of ^{3}H and ^{3}He as well as the isoscalar and isovector combinations of these nuclei and to magnetic moments and M1 transitions of other light nuclei.

(d) The no-core shell model approach has been applied to systems with $A \geq 3$. A summary of the method is given in (2002BA65) along with results of binding energy calculations of ^{3}H and ^{3}He. A calculation of the binding energy of ^{3}H (and ^{4}He) using this method with a three-body interaction from effective field theory is reported in (2007NA30). Recent developments and applications of the method are reviewed in (2009NA13). A variation of the no-core shell model method is discussed in (2004ZH11) where a calculation of the binding energy of ^{3}H is used as a test case. Related to the no-core shell model is the no-core full configuration method; see (2009MA02) which includes calculations of ^{3}H and ^{3}He binding energies.

(e) A variational approach using the dressed-bag model NN and NNN interactions as well as Coulomb and charge symmetry breaking effects has been applied to calculations of the ground states of ^{3}H and ^{3}He; see (2004KU05, 2004KU06).

(f) A totally different approach, called the Lorentz Integral Transform (LIT) method, has been developed that enables matrix elements involving unbound states to be calculated without calculating the continuum wave functions. See (2007EF1A) for a review of the method and ^{3}He reaction 10 for more details. See (2000EF03) for calculations of the photodisintegration of ^{3}H and ^{3}He and (2006GA39) for the photodisintegration of ^{4}He using the LIT method.

(g) Additional theoretical studies that use ^{3}H and ^{3}He as test cases are an improved variational wave function method (2009US02) and a global vector representation of the angular motion method (1998VA1P, 2008SU1B).

Reviews relevant to the $A = 3$ systems

(See (1987TI07) for reviews dated prior to 1987.)

1988GI03 B.F. Gibson and B.H.J. McKeller, The three-body force in the trinucleons

1988WE20 H.R. Weller and D.R. Lehman, Manifestations of the D state in light nuclei

1990EI01 A.M. Eiro and F.D. Santos, Non-spherical components of light nuclei

1990LE24 D.R. Lehman, Evidence for and explication of the D state in few-nucleon systems

1990MI1D G.A. Miller, B.M.K. Nefkens and I. Slaus, Charge symmetry, quarks and mesons

1992GI04 B.F. Gibson, The trinucleons: physical observables and model properties

1993FR11 J.L. Friar et al., Triton calculations with the new Nijmegan potentials

1993FR18 J.L. Friar, Three-nucleon forces and the three-nucleon systems

1993WU08 Y. Wu, S. Ishikawa and T. Sasakawa, Three-nucleon bound states: detailed calculations of ^{3}H and ^{3}He

1996FR1E J.L. Friar and G.L. Payne, Proton-deuteron scattering and reactions, Chapter 2 in *Coulomb Interactions in Nuclear and Atomic Few-Body Collisions*, edited by Frank S. Levin and David A. Micha, 1996

1996GL05 W. Glockle et al., The three-nucleon continuum: achievements, challenges and applications

1998CA29 J. Carlson and R. Schiavilla, Structure and dynamics of few-nucleon systems

2000BE39 P.F. Bedaque, H.-W. Hammer and U. van Kolck, Effective theory of the triton

2000FR1C J.L. Friar, Twenty-five years of progress in the three-nucleon problem

2001SI39 I. Sick, Elastic electron scattering from light nuclei

2002BA15 B.R. Barrett et al., Ab initio large-basis no-core shell model and its application to light nuclei

2002BA65 B.R. Barrett, P. Navratil and J.P. Vary, Large-basis no-core shell model

2002FR21 J.L. Friar, The structure of light nuclei and its effect on precise atomic measurements

2002GL1F W. Glockle, Three-nucleon scattering

2004GL08 W. Glockle et al., Electron scattering on ^{3}He - A playground to test nuclear dynamics

2005VI05 M. Viviani et al., New developments in the study of few-nucleon systems

2006HE17 K. Helbing, The Gerasimov-Drell-Hearn sum rule

2006MI33 G.A. Miller, A.K. Opper and E.J. Stephenson, Charge Symmetry Breaking and QCD

2006WE03 C. Weinheimer, Neutrino mass from triton decay

2007EF1A V.D. Efros, et al., The Lorentz Integral Transform (LIT) method and its applications to perturbation-induced reactions

2007SA59 H. Sakai, Three-nucleon forces studied by nucleon-deuteron scattering

2008DE1D A. Deltuva, A.C. Fonseca, and P.U. Sauer, Nuclear many-body scattering calculations with the Coulomb interaction

2008KI08 A. Kievsky et al., A high-precision variational approach to three- and four-nucleon bound and zero-energy scattering states

2008OT03 E.W. Otten and C. Weinheimer, Neutrino mass limit from tritium β decay

2009EP1A E. Epelbaum, H.-W. Hammer and Ulf-G. MeiBner, Modern theory of nuclear forces

2009LE1D W. Leidemann, Few-nucleon physics

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;
$Q_{\rm m}$	reaction energy;
$S_{\rm n}(S_{\rm p})$	neutron(proton) separation energy;
$\sigma(\theta)$	differential cross section;
$\sigma_{\rm tot}$	total cross section;
$P(\theta)$	polarization;
$A_{\rm y}(\theta)$	vector analyzing power; VAP;
TAP	tensor analyzing power;
J^{π}	spin and parity;
μ	magnetic moment;
$\mu_{\rm N}$	nuclear magneton;
a_{nn}	neutron-neutron scattering length;
a_{pn}	proton-neutron scattering length;
a_{nd}	neutron-deutron scattering length;

a_{pd}	proton-deutron scattering length;
r_{ch}	rms charge radius;
r_{m}	rms magnetic radius;
DWBA	Distorted Wave Born Approximation;
FSI	final state interaction;
QFS	quasifree scattering.

If not specified otherwise, energies are given in MeV.

Useful masses (MeV) [a]

	actual masses	
μ^-	105.658367	(4) [b]
$\pi^\pm$	139.57018	(35)
π^0	134.9766	(6)
η	547.853	(24)
Λ	1115.683	(6)
	mass excesses	
^{1}n	8.07131710	(53)
^{1}H	7.28897050	(11)
^{2}H	13.13572158	(35)
^{3}H	14.94980600	(231)
^{3}He	14.93121475	(242)
^{4}He	2.42491565	(6)

[a] Non-hadronic masses are from (2008AM05); atomic mass excesses are from (2003AU03).
[b] The uncertainty in the last few significant figures is given in parentheses.

^{3}n

General

There is no experimental evidence for either bound states or narrow resonances of the three neutron system. Theoretical studies in the ^{3}n system using the Faddeev method and fairly realistic two-body interactions have been carried out for complex energies looking for evidence of resonances; see (1999WI08, 2002HE25). The conclusion in each case is that such resonances probably do not exist close to the physical region. However, a similar study reported in (1996CS02) concluded that a resonance exists in the $J^{\pi} = \frac{3}{2}^{+}$ channel with an energy of 14 MeV and a width of 13 MeV. A study of a $J^{\pi} = \frac{1}{2}^{-}$ subthreshold state in the ^{3}n system using the hyperspherical method with simplified NN interactions is reported in (1997SO27).

To date, there have been two types of experimental approaches that have been used to look for bound or resonant ^{3}n states. One approach is to use negative pions either in the capture reaction ^{3}H(π^{-}, γ)^{3}n, in the double charge exchange reaction ^{3}He(π^{-}, π^{+})^{3}n, or in knockout reactions such as ^{4}He(π^{-}, p)^{3}n and ^{7}Li(π^{-}, ^{4}He)^{3}n. The second approach makes use of heavy ion reactions such as ^{7}Li(^{7}Li, ^{11}C)^{3}n and ^{2}H(^{14}C, ^{13}N)^{3}n.

1. ^{2}H(^{14}C, ^{13}N)^{3}n $\qquad Q_{\rm m} = -13.4038$

In a series of experiments reported in (1995BO10) with $E(^{14}\mathrm{C}) = 336$ MeV, this reaction was used to look for ^{3}n states. None were found.

2. ^{3}H(π^{-}, γ)^{3}n $\qquad Q_{\rm m} = 130.3060$

There have been no reports of radiative pion capture experiments on ^{3}H since the previous evaluation. Earlier references for this reaction are (1979BI13, 1980MI12, 1982GM02).

A theoretical estimate of the total width of the 1s level in the ^{3}H pionic atom is 2.2 ± 0.4 eV (1988WE01). However, the measured total width of the 1s level in the ^{3}H pionic atom is reported to be 28 ± 7 eV; see (1984SC09, 1995DA16).

3. ^{3}H(^{7}Li, ^{7}Be)^{3}n $\qquad Q_{\rm m} = -10.1264$

This reaction was studied at $E(^{7}\mathrm{Li}) = 65$ and 78 MeV (1987AL10). No evidence of ^{3}n states was found.

4. ^{3}He(π^-, π^+)^{3}n $\qquad Q_{\rm m} = -9.2827$

This pionic double charge exchange reaction on ^{3}He has been studied with $E_\pi = 65$-295 MeV. For $E_{\pi^-} = 5$, 75, 120 MeV, see (1999GR01); see also (1999GR31) for seven energies between 65 and 120 MeV. For $E_{\pi^-} = 120$, 180, 210, 240 MeV, see (1997YU01). For $E_{\pi^-} = 140$, 200, 295 MeV, see (1986ST09). In the missing mass spectra, enhancements resembling resonances have been seen at forward angles. However, it appears that the best explanation for these enhancements is that they are due to final state interactions and not due to true resonances of the ^{3}n system; see (1986ST09, 1997YU01). The authors of (1999GR01) conclude that there is no evidence for either a bound state or a resonance in the ^{3}n system. A discussion of previous pion double charge exchange work on ^{3}He (and ^{4}He) is included in (1997YU01) along with comparisons of experimental results with model calculations.

A theoretical study of this reaction using the Faddeev method for $E_{\pi^-} = 140$ MeV is reported in (1988OS03). A similar study is reported in (1989MO24).

5. ^{4}He(π^-, p)^{3}n $\qquad Q_{\rm m} = 110.4922$

No studies of this specific reaction have been reported since the previous evaluation. Studies of absorption of zero energy negative pions in gaseous ^{4}He leading to emission of nn, np, nd and nt pairs are reported in (1995DA16).

6. ^{7}Li(π^-, ^{4}He)^{3}n $\qquad Q_{\rm m} = 127.8391$

A study of ^{4}He emission after π^- capture by ^{7}Li is reported in (1993MO09), but there is no mention of possible production of ^{3}n states. See also (1977BA47).

7. ^{7}Li(^{7}Li, ^{11}C)^{3}n $\qquad Q_{\rm m} = -5.0486$

This reaction was studied at $E(^7\text{Li}) = 79.6$ MeV and no evidence for either a bound or resonance state was found (1974CE06). Studies of this reaction have been reported in (1987AL10, 2005AL15); in both reports, ^{7}Li ions with $E(^7\text{Li}) = 82$ MeV were used to look for evidence of ^{3}n states, but none were found.

8. ^{7}Li(^{11}B, ^{15}O)^{3}n $\qquad Q_{\rm m} = -3.4938$

This reaction has been studied at $E(^{11}\text{B}) = 88$ MeV (1986BE44, 1986BE54, 1987BO40) and at $E(^{11}\text{B}) = 52$-76 MeV (1988BE02). No evidence of ^{3}n states was found.

^{3}H

Ground State

$$
\begin{aligned}
J^\pi &= \frac{1}{2}^+ \\
\mu &= 2.978960 \pm 0.000001\ \mu_{\rm N} \\
\text{Mass Excess, } M - A &= 14.9498060 \pm 0.0000023\ \text{MeV} \\
T_{\frac{1}{2}} &= 12.32 \pm 0.02\ \text{y} = 4500 \pm 8\ \text{days} \\
\text{Decay Mode} &: \ \beta^- \text{ decay} \\
\text{Binding Energy, } E_{\rm B} &= 8.481798 \pm 0.000002\ \text{MeV} \\
\text{Neutron Separation Energy, } S_{\rm n} &= 6.257233 \pm 0.000002\ \text{MeV}
\end{aligned}
$$

General

The ground state wave functions for ^{3}H and ^{3}He consist mainly of a spatially symmetric S state (about 90%), a mixed symmetry S$'$ state (about 1%), a D state (about 9%) and a small P state (less than 0.1%). Some references that illustrate this are (1986IS01, 1987ER07, 1993WU08, 2002HO09) in addition to those given in (1987TI07). Note: The P state results from two nucleons each having one unit of orbital angular momentum coupling to a total of one unit of angular momentum and positive parity.

The energy of the ground state of ^{3}H, -8.482 MeV, results from the difference between two much larger numbers. For example, Table 2 in (1993FR18) has $< T > = 45.7$ MeV and $< V > = -53.4$ MeV, using the AV$_{14}$ NN interaction and $< T > = 41.6$ MeV and $< V > = -49.3$ MeV, using the NIJM NN interaction. When a three-body interaction is included, the following values are obtained using the AV$_{14}$ NN interaction and the Tucson-Melbourne NNN interaction (1997NO10): $< T > = 49.3$ MeV, $< V_{\rm NN} > = -56.5$ MeV, $< V_{\rm NNN} > = -1.3$ MeV.

Also shown in (1997NO10) are graphs of the two nucleon correlation function for ^{3}H for various NN interactions. This function gives the probability that a pair of nucleons is separated by a distance r. The calculated correlation functions all peak at separations of about $r = 1$ fm and drop to a tenth of the peak value at about $r = 3$ fm. When the NNN interaction is included, the effect on the correlation function is to increase its value near the peak. The NN interactions that are more repulsive at short range have smaller correlation values for $r < 1$ fm, for the NN interactions that are less repulsive at short range, the correlation values are larger for small r. In turn, the strength of the NNN interaction required to give the correct ^{3}H binding depends on correlation values for small r in that the NN interactions that are less repulsive for small r require smaller NNN strength factors; see Table 3 and Fig. 2 in (1997NO10). These authors also calculated the probability of a nucleon being a distance r from the center of mass with and without the NNN interaction. They found that the addition of the NNN interaction increased the probability slightly for $r < 1$, especially around $r = 0.5$ fm.

In an asymptotic sense, the ground state of ^{3}H can be considered to be composed of a spin 1 deuteron and a spin $\frac{1}{2}$ neutron bound with an energy of -6.257 MeV. The total spin and relative angular momentum of these two clusters could be either $S = \frac{1}{2}$, $L = 0$, or $S = \frac{3}{2}$, $L = 2$ and still form $J^\pi = \frac{1}{2}^+$. These two states are referred to as asymptotic S and D states, respectively. Given that the energy and angular momenta of these states are known, the mathematical forms of the asymptotic radial functions are known. The only unknowns are the normalization constants of the asymptotic S and D states, $C_{\rm S}$ and $C_{\rm D}$. The ratio $C_{\rm D}/C_{\rm S}$ is called the triton asymptotic ratio, $\eta_{\rm t}$. There are several ways by which $\eta_{\rm t}$ can be experimentally determined. One such method is illustrated in (1992DA01, 1993GE04, 1994KO29). In these works, neutron pick-up reactions using polarized deuterons at sub-Coulomb energies are performed on medium weight nuclei; an example from (1992DA01) is ^{119}Sn($\vec{\rm d}$, t)^{118}Sn$_{\rm g.s.}$ with $E_{\rm d} = 6$ MeV, which is 33% below the Coulomb barrier. Differential cross sections and TAP's were measured and analyzed using finite range DWBA. The calculated analyzing powers are quite sensitive to changes in $\eta_{\rm t}$, which makes it possible to obtain reasonably accurate values of $\eta_{\rm t}$. The weighted average of the results for $\eta_{\rm t}$ from (1993GE04) who obtained $\eta_{\rm t} = -0.0431 \pm 0.0025$ and from (1994KO29) who obtained $\eta_{\rm t} = -0.0411 \pm 0.0018$ is $\eta_{\rm t}$(ave.) $= -0.0418 \pm 0.0015$; the weights used were the inverse of the squares of the errors. Earlier experimental values for $\eta_{\rm t}$ including values obtained by different techniques are given in (1988WE20, 1990EI01, 1993GE04). An early calculation of this ratio for several models using the Faddeev method is reported in (1993WU08). See also (1997KI17). The analogous case in ^{2}H has $\eta_{\rm d} = 0.0256$; see Table I in (1998CA29). In (1990EI01), the authors discuss the physical origin of the opposite signs of $\eta_{\rm d}$ and $\eta_{\rm t}$. They also discuss the possible presence of an additional phase factor which gives $\eta_{\rm t}$ a positive sign in some formalisms.

For the relationship between $\eta_{\rm t}$ and the analogous quantity in ^{3}He, see the section on the ground state properties of ^{3}He.

See reaction 2 where evidence of an excited state in ^{3}H at about 7 MeV excitation energy is reported.

A theoretical study of virtual $J^\pi = \frac{1}{2}^+$ states in ^{3}H and ^{3}He is reported in (1999CS02). The authors obtain such states at $E = -1.62$ MeV in ^{3}H relative to the d + n threshold and $E = (-0.43 \pm i0.56)$ MeV in ^{3}He relative to the d + p threshold. The authors also report an unpublished preliminary analysis of scattering data with approximately the same results.

1. ^{3}H(β^-)^{3}He $\qquad Q_{\rm m} = 18.5912$ keV

Half-life measurements for the decay of ^{3}H are reviewed in (1975FI08, 1978RA2A, 1990HO28, 1991BU13, 2000CH01, 2000LU17). The half-life value reported in (2000LU17) is 4500 ± 8 days or 12.32 ± 0.02 years. The latter value is chosen by Audi, et al. (2003AU02). The authors of (2000LU17) recommend expressing the tritium half-life as 4500 ± 8 days since the day unit is exactly defined in terms of the second. The value reported in (2000LU17) is the average of about a dozen measurements using different techniques.

The Q value for this decay as given in (2003AU03) is 18.591 ± 0.001 keV. In reference (1993VA04), the ^{3}H-^{3}He mass difference is given as 18.5901 ± 0.0017 keV as measured using the Penning trap mass spectrometer. This is the value used by the Mainz Neutrino project from which the endpoint energy of the β^- spectrum is obtained; see (2005KR03). Table II in reference

(1993VA04) contains results of measurements of the ^{3}H-^{3}He mass difference with references and measurement methods. For more on the Q value of ^{3}H decay and the measurement of neutrino masses, see (2006OT02).

It was during the time period covered by this evaluation that the question of the existence of an electron anti-neutrino with a mass of 17 keV arose. The β-decay of ^{3}H played a major role in these studies. It is now generally considered that no such anti-neutrino exists, but many useful experimental and theoretical studies came about as a result of the question being raised. The complete story is told in (1995FR27).

On-going precision studies of the endpoint region of the β^- spectrum from ^{3}H decay have been carried out with the goal of either measuring the mass of the electron anti-neutrino or at least setting upper limits on the mass. The review (1988RO21) gives an overview of the status of these experiments as of 1988. The value of the upper limit of the electron anti-neutrino mass continues to get smaller as the experimental techniques undergo greater refinement. For example, the Los Alamos group, who used gaseous molecular tritium, lowered the upper limit from 27 eV in 1987 to 9.3 eV in 1991; see (1987WI07, 1991RO07). Two experimental groups that have continued to pursue these studies are the Mainz Neutrino project and the Troitsk nu-mass experiment. The Mainz project uses a cold, thin film of molecular tritium; the Troitsk experiment uses tritium gas. For details about the Mainz experiment, see (2005KR03) and references therein and, for the Troitsk experiment, see (2002LO11, 2003LO10) and references therein. Recent values of the upper limit of this mass from both groups are just over 2 eV; see (2003LO10, 2005KR03, 2008CA1C).

The reference (2005KR03) gives a brief historical account of laboratory studies of neutrino masses and mass differences of neutrino flavors obtained from studies of neutrino oscillations. The same reference also refers to a study using cosmological data that suggests that the actual mass of neutrinos is around 0.2 eV. The Mainz and Troitsk experiments are not able to reach this level of sensitivity. In the references (2003LO10, 2005KR03), a planned ^{3}H(β^-) decay experiment called KATRIN is described which is expected to be sensitive enough to explore this mass range for the electron anti-neutrino. For more on neutrino masses in general and the KATRIN experiment in particular, see (2006BI13, 2008OT03).

Two different approaches to determining the mass of the anti-electron neutrino emitted in the beta decay of ^{3}H have been proposed in (2010JE1A). In one case, they consider the two-body decay in which the emitted electron is captured in a bound state of the ^{3}He$^+$ ion and the anti-neutrino mass is determined from a measurement of the speed of the recoiling ^{3}He atom. In a second method using ultra-cold tritium, they propose measuring the momenta of the outgoing electron and ^{3}He$^+$ ion from which the mass of the anti-neutrino can be determined. The authors consider the second method to be the most promising.

Over the years, there have been several studies addressing the question of the extent to which the environment affects the ^{3}H(β^-) decay spectrum. The fact that the Q-value for ^{3}H decay is only 18.6 keV causes this to be of particular concern; the typical β-decay Q-value is larger than this by a factor of 40 to 100 or more. (A counter example is the β-decay of ^{187}Re, the Q value for which is 2.47 keV.) The usual treatment of ^{3}H(β^-) decay has the electron and the anti-electron neutrino both produced in continuum states and the residual ^{3}He nucleus recoiling with a maximum kinetic energy of about 3.4 eV. However, it is possible that, instead of being in a continuum state, the electron might be bound by the Coulomb field of the ^{3}He nucleus. For more details see (1993HA1U, 2004AK06, 2004AK16, 2005AK04) and references therein.

The ratio of the axial-vector to the vector weak interaction coupling constants, G_A/G_V, can be obtained from half-life measurements. Fig. 1 in reference (2004AK06) shows a historical summary of values obtained for this ratio along with the value obtained by these authors, $G_A/G_V = -1.2646 \pm 0.0035$. See also (2005AK04) where the same G_A/G_V ratio is obtained along with the comparative half-life value $ft = 1129.6 \pm 3.0$ s which gives $\log ft = 3.053 \pm 0.001$. This ft value is used in (2009GA23) along with binding energies of ^{3}H and ^{3}He, to determine values for low energy constants in the chiral perturbation theory formulation of the NNN interaction.

2. ^{1}H(^{6}He, α)^{3}H $\qquad Q_{\rm m} = 7.5093$

With the advent of ^{6}He beams in the 1990s, it became possible to study two-neutron transfer reactions (^{6}He, α) with select targets, including ^{1}H. Mostly such experiments were done with the intent of studying the cluster structure of ^{6}He; see (2005GI07), for example. However, by observing the outgoing α spectrum, it becomes possible to study possible structure in ^{3}H using this reaction. Two such studies have been reported: E(^{6}He) $= 19.3$ MeV (1994AL54) and E(^{6}He) $= 23.9$ MeV (2003RO13). The authors of (1994AL54) reported a peak in the α spectrum corresponding to the ^{3}H ground state and a resonance-like structure that would correspond to a ^{3}H state at 7.0 ± 0.3 MeV excitation energy with a width of 0.6 ± 0.3 MeV. The authors of (1994AL54) suggest that this ^{3}H state might be a proton plus di-neutron system in analogy to ^{6}He being an α plus di-neutron system. A theoretical study of such a model was reported in (1995BB09), in which it was suggested that the observed ^{3}H state at 7 MeV is a $\frac{1}{2}^+$ state. In a similar experiment reported in (2003RO13), a resonance-like peak was observed at about 6.8 MeV excitation energy in ^{3}H with a width no larger than 1 MeV. Since ^{3}H has a neutron separation energy of 6.25 MeV, such a resonance would be about 0.8 MeV above the neutron-deuteron separation threshold. Thus, it would likely be observed in n-d scattering, but no such resonance has been seen. The authors of (2003RO13) suggest that the observed structure in the α spectrum might be a di-neutron state of ^{3}H or that it might be due to three-body final state effects.

It was also reported in (1994AL54) that the reaction ^{1}H(^{6}Li, α)^{3}He was studied with E(^{6}Li) $=$ 30 MeV. A peak corresponding to the ground state of ^{3}He was observed, but there was no higher-lying peak analogous to the peak seen in this reaction.

A theoretical study of excited states in ^{3}H and ^{3}He is reported in (1999CS02).

3. ^{2}H(n, γ)^{3}H $\qquad Q_{\rm m} = 6.2572$

An early review of experimental and theoretical aspects of this reaction can be found in (1981SH25). Table 3.1 in (1987TI07) lists pre-1987 references for this reaction. Table 3.1 in this publication lists references since 1987. A compilation of neutron capture reactions throughout the periodic table is given in (2006MUZX). The value of the cross section for thermal neutron capture by ^{2}H as

Table 3.1: References for ^{2}H(n, γ)^{3}H since 1987

References	E_n (keV)	Comments
(1988AL29)	Slow	$\vec{n}$ beam; studied asymmetry and parity violation
(1988KO07)	Thermal	$\vec{n}$ beam; measured γ-ray polarization, obtained evidence of meson exchange currents
(1988AB04)	Thermal	Somewhat expanded version of (1988KO07); includes ^{3}He(n, γ)^{4}He
(2008FIZZ)	Thermal	Measured neutron capture cross section for large number of isotopes; compared with earlier measurements
(1998NA15, 2006NA25)	30.5, 54.2, 531	Measured capture cross section; evaluated astrophysical aspects

recommended in (2006MUZX) is $\sigma(E_{\text{thermal}}, \gamma) = 0.508 \pm 0.015$ mb. See also (2011FI11) which contains a list of measurements of the cross section for neutron capture by ^{2}H and which gives an adopted value of 0.549 ± 0.010 mb. Cross sections for ^{2}H(n, γ)^{3}H and ^{3}H(γ, n)^{2}H are related by detailed balance, as is illustrated in (1986MI17). See also ^{3}H reaction 8.

The importance of this reaction in astrophysical studies has been discussed in (1998NA15, 2002NA32, 2006NA25).

It is interesting to compare the cross sections for thermal neutron capture by ^{1}H and ^{2}H, as done in (2008PA37). As reported in (2006MUZX), these cross sections are 332.6 ± 0.7 mb and 0.508 ± 0.015 mb, respectively. Capture of thermal s-wave neutrons by both nuclei proceeds primarily by M1 transitions. Because of the orthogonality of the radial component of the scattering state in the ^{2}H + n system with the dominant S component of the ^{3}H ground state, neutron capture takes place through the small S$'$ component of the ^{3}H ground state which results in the small capture cross section value. In contrast, for the ^{1}H + n system, as shown in (2008PA37), the radial parts of the scattering ^{1}H + n state and the ^{2}H ground state are essentially identical which results in a large capture cross section. See section IX.C.1 of (1998CA29) for a discussion of this point with relevant references.

Meson exchange currents (MEC's) play a significant role in the theory of neutron capture by light nuclei; see (1990FR19), for example. Indeed, MEC's were introduced by Riska and Brown (1972RI02) to explain the 10% difference between the calculated and experimental cross sections for the reaction ^{1}H(n, γ)^{2}H. A modern calculation demonstrating this can be found in (2005MA54). The effect of including MEC's is even more dramatic in the reaction ^{2}H(n, γ)^{3}H. Table II in (1983TO12) shows that the capture cross section is approximately doubled when MEC's are included. Essentially the same result is shown in Table IV in (2005MA54) using more modern interactions. In the reaction ^{2}H(n, γ)^{3}H at low energies where only s-waves need be considered, there are two channels to consider: $\frac{1}{2}^+$ and $\frac{3}{2}^+$. It is shown in (1983TO12, 1988KO07, 2005MA54) that the MEC's have their major effect in the $\frac{1}{2}^+$ channel and a relatively small effect in the $\frac{3}{2}^+$

channel.

Because of the Coulomb interaction, the mechanism for low energy proton capture ^{2}H(p, γ)^{3}He is different from that of the low energy neutron capture ^{2}H(n, γ)^{3}H. See ^{3}He reaction 3 for more details.

Capture cross sections have also been measured for $E_{\rm n} = 30.5$, 54.2 and 531 keV and astrophysical aspects discussed in (1998NA15, 2006NA25). As reported in (1986MI17) and (1987TI07), neutron capture cross sections have also been measured for $E_{\rm n} = 6.85$-14 MeV. The data in (1986MI17) are analyzed by assuming that capture at these energies occurs by E1 and E2 transitions although anomalies are found in forward-backward asymmetry values when compared to proton capture by ^{2}H which may be due to a larger than expected E2 component in the capture cross section. As shown in (1986MI17), cross section data are consistent with comparable photodisintegration measurements.

Calculations of capture cross sections using effective field theory for $E_{\rm n} = 20$-200 keV are reported in (2005SA28). This reference also contains a short history of the study of n + d radiative capture with references. See also (2006SA1N). Additional calculations of the reaction ^{2}H(n, γ)^{3}H are reported in (2001SC16). It is pointed out in both (2005MA54) and (2006NA25) that calculated values of the n + d capture cross sections exceed the experimental values by about 10%. The reason for the difference is uncertain, but may have to do with Δ excitation currents.

Parity violation in polarized neutron capture is reviewed in (1994KR20).

See also ^{3}H reaction 8 and ^{3}He reaction 3.

4. ^{2}H(n, n)^{2}H

Earlier references relating to this reaction are given in Tables 2.3.1a, b, c in (1975FI08) and Tables 3.3 and 3.4 in (1987TI07). References since 1987 or not included in (1987TI07) are given in Table 3.2.

Important parameters for describing low energy n + d scattering are the doublet and quartet scattering lengths, $^2a_{nd}$ and $^4a_{nd}$. Frequently quoted experimental values are $^2a_{nd} = 0.65 \pm 0.04$ fm and $^4a_{nd} = 6.35 \pm 0.02$ fm; see (1971DI15, 1987TI07, 2003WI08). A related quantity is the coherent scattering length, b_{nd}. See Eq. (1) in (2003BL07) or Eq. (8) in (2003WI08) for the relationship between these quantities. A measurement of $b_{nd} = 6.6649 \pm 0.0040$ fm has been reported in (2003BL07, 2003SC12) using neutron interferometry techniques. These reference also gives a world average of measured values of this quantity as $b_{nd} = 6.6683 \pm 0.0030$ fm. See also (2006HU16).

It has been known for many years that calculated values of $^2a_{nd}$ are correlated with calculated values of the ^{3}H binding energy. This nearly straight line correlation is known as the Phillips line; see (2003WI08) for references. Using the Faddeev approach with a variety of NN and NNN interactions, a number of calculated values of $^2a_{nd}$, $^4a_{nd}$, b_{nd} and the ^{3}H binding energy are reported in Table I of (2003WI08). A striking feature of this table is that, although the values of $^2a_{nd}$ and the binding energy values have considerable scatter, $^4a_{nd}$ is nearly constant at around 6.34 fm. A similar observation is discussed in (2003SC12). In this reference, an average calculated value of

$^4a_{nd} = 6.346 \pm 0.007$ fm was used together with their measured value of $b_{nd} = 6.6649 \pm 0.0040$ fm to deduce the value $^2a_{nd} = 0.645 \pm 0.003$ (exp.) ± 0.007 (theor.) fm. This value of $^2a_{nd}$ was used as an input parameter to calculate the binding energy of ^{3}H using effective field theory; see (2006PL09). This value of $^2a_{nd}$ was also used in (2010KI05) in their study of various NNN interactions. There is a proposed experiment reported in (2004VA13) for which it is expected that a measurement of $^2a_{nd}$ with improved accuracy will be achieved. See also (2007VAZW). A study of $^2a_{nd}$ and $^4a_{nd}$ using Faddeev methods and several interaction models is reported in (1991CH16). Agreement between theory and experiment is reasonably good. The corresponding calculated values for the p-d scattering lengths $^2a_{pd}$ and $^4a_{pd}$ also reported in (1991CH16) differed significantly from the experimental values. For more details, see ^{3}He reaction 7.

Table 3.2: References for ^{2}H(n, n)^{2}H since 1987 or not included in (1987TI07)

References	$E_{\rm n}$ (MeV)	Comments
(2003BL07, 2003SC12, 2006HU16)	11.1 meV	Measured coherent neutron scattering lengths; deduced $^2a_{nd}$ and $^4a_{nd}$; compared with theory
(2006FO04)	1.18, 5.0, 6.88, 9.0	$\vec{\rm n}$ beam, $\vec{\rm d}$ target; deduced spin dependence of $\sigma_{\rm tot}$; compared with theory
(2003NE01)	1.2, 1.9	$\vec{\rm n}$ beam; measured $A_{\rm y}(\theta)$; compared with p + d; compared with theory; studied role of magnetic moment interaction with Coulomb field
(2001GO17)	2.0	$\vec{\rm n}$ beam; measured $A_{\rm y}(\theta)$; compared with p + d and with theory; studied charge-symmetry breaking
(1993MC08)	3	$\vec{\rm n}$ beam; measured $A_{\rm y}(\theta)$; compared with rigorous calculation using realistic NN interactions; differences found; modification of ^{3}P$_{\rm j}$ components of NN interaction improves fit [see (1991TO05, 1991WI10)]
(1994MC05)	3	$\vec{\rm n}$ beam; measured $A_{\rm y}(\theta)$; compared with Faddeev calculations where differences are seen; compared n + d with p + d scattering
(1991TO05)	5, 6.5, 8.5	$\vec{\rm n}$ beam; measured $A_{\rm y}(\theta)$; compared with Faddeev calculations using realistic NN interactions where large differences are found
(1985MA68)	6.5	$\vec{\rm n}$ beam; measured $A_{\rm y}(\theta)$
(1987BA05)	7.9, 22.4	Measured $\sigma(\theta)$

Table 3.2: References for ^{2}H(n, n)^{2}H since 1987 or not included in (1987TI07) (continued)

References	$E_{\rm n}$ (MeV)	Comments
(1994HO34)	8-14	Studied $\sigma(\theta)$ at back angles
(1988TO05)	8.5	Measured $A_{\rm y}(\theta)$; calculated peak in $A_{\rm y}$ not in agreement with experiment
(1986TA20)	8.6	Measured $\sigma(\theta)$; compared with Faddeev calculations
(1987HO09)	10-14	Measured $A_{\rm y}(\theta)$; compared with theory
(1989TO06)	10, 14.1	$\vec{\rm n}$ beam; measured $A_{\rm y}(\theta)$; compared data with calculations using NN and NNN interactions
(1987KL01)	10-50	Review of neutron scattering experiments
(1991HO26)	12	Review of several n + d scattering experiments and comparisons with state-of-the-art calculations
(1988HO14)	12	$\vec{\rm n}$ beam; measured $A_{\rm y}(\theta)$; compared with Faddeev calculation using realistic NN interaction
(1998NI02)	12	$\vec{\rm n}$ beam; measured $A_{\rm y}(\theta)$; compared p + d with n + d
(1989CU09)	13	$\vec{\rm n}$ beam; measured $A_{\rm y}(\theta)$; compared with Faddeev calculation
(1990SH35)	13.6, 15.23	Measured $\sigma(\theta)$; compared with Faddeev calculation
(1998HE04)	15, 17, 19, 25.8	$\vec{\rm n}$ beam; measured polarization transfer coefficient at $\theta_{\rm lab} = 50°, 80°$; compared with Faddeev calculations using NN and NNN interactions
(2002BO61)	16.2	$\vec{\rm n}$ beam; $\vec{\rm d}$ target; measured polarization observables
(1986DO09)	18-50	$\vec{\rm n}$ beam; measured $\sigma(\theta)$ and $A_{\rm y}(\theta)$; compared with Faddeev calculation
(2007TO16)	19, 21, 22.7	$\vec{\rm n}$ beam; measured $A_{\rm y}(\theta)$; compared with existing data and theory
(1985CH30)	31, 61, 76	Measured $\sigma(\theta)$

Table 3.2: References for ^{2}H(n, n)^{2}H since 1987 or not included in (1987TI07) (continued)

References	E_n (MeV)	Comments
(1990BR29)	67	$\vec{n}$ beam; measured $A_y(\theta)$; compared with Faddeev calculations using realistic NN interactions
(1991RU04)	67	$\vec{n}$ beam; measured $A_y(\theta)$; compared with Faddeev calculations using realistic NN interactions with good agreement
(1995BA05)	67	Measured $\sigma(\theta)$; compared with Faddeev calculations with good agreement
(2004ME14, 2006ME26, 2008MEZW)	95	Measured $\sigma(\theta)$; compared with n + p and Faddeev calculations; observe NNN effects
(2000AN10)	189	$\vec{n}$ beam; measured $A_y(\theta)$; compared with p + d data and with Faddeev calculations with and without NNN interaction
(2001SA33, 2007MA46, 2007MA61)	248, 250	$\vec{n}$ beam; measured $\sigma(\theta)$, $A_y(\theta)$; compared with Faddeev calculations using NN and NNN interaction which is low in back angles; studied relativistic effects; compared with p + d scattering

A common method for describing low energy elastic scattering is effective range theory in which the quantity kcot($\delta(E)$) is expressed in terms of the scattering length and a few other parameters. Here, k is the wave number in the center of mass system and $\delta(E)$ is the scattering phase shift. Effective range studies of doublet n-d scattering are reported in (2000BB05, 2006OR03) and references therein. Figs. 1 and 2 in (2006OR03) and the figure in (2000BB05) show experimental values of the quantity kcot($\delta(E)$) and graphs of parameterizations and theoretically derived curves. Emerging from such studies as these is the notion of a virtual doublet state in ^{3}H at an energy of about -0.48 MeV; see Fig. 4 in (2006OR03), with $^2a_{nd} = 0.65$ fm. An early discussion of such a state is given in (1979GI1F). Also emerging from effective range studies are values of asymptotic normalization parameters (ANP's). Values of ANP's for the ^{3}H ground state and the virtual ^{3}H state are obtained in (2000BB05).

Table 3.2 indicates that most measurements of this reaction since the previous evaluation have made use of polarized neutron beams. Such beams have enabled detailed measurements to be made not only of the differential cross section but also of the analyzing power, A_y, as functions of the scattering angle. As NN, NNN interactions and three-body calculations have gotten more sophisticated, it was discovered that the three-body models gave differential cross sections in good agreement with experiment, but resulted in a serious discrepancy between the calculated and experimental values of the analyzing powers. This effect has become known as the A_{y} puzzle or as the analyzing power puzzle. The analyzing power puzzle also shows up in p + d scattering both as a discrepancy in A_{y} for polarized protons and in the VAP iT_{11} for polarized deuterons and in p + ^{3}He scattering. See ^{3}He reaction 7 and (2006FI06) and references therein. The reference (1996GL05) contains a number of examples of the effect for both n + d and p + d scattering, as does (1998TO07). The reference (2007MI26) contains a discussion of the puzzle and of some attempts to explain its origin. These authors also study relativistic effects that may play a role in the explaining the puzzle. In reference (2003NE01), it is shown that the difference between the calculated and measured A_{y} values is essentially independent of the incident neutron energy for $E_{\mathrm{n}} =$ 2-16 MeV. Calculations reported in (2001CA44) show that the discrepancy has disappeared when E_{n} reaches 30 MeV. See (2008TO12) for more on the energy dependence of the A_{y} puzzle. These authors attribute the puzzle as being due to a new type of NNN interaction. Higher orders of chiral perturbation theory provide NNN interactions that may provide a solution to the A_{y} puzzle; see (2002EP03, 2006EP01). However, in a recent calculation using the hyperspherical harmonic method with the next-to-next-to leading order NNN interaction, the A_{y} puzzle is still evident; see (2009MA53) and references therein. See (2008TO20) for a discussion of the history of the analyzing power puzzle. See ^{3}He reaction 7 for more on the analyzing power puzzle in the context of proton-deuteron scattering.

Additional studies of relativistic effects in n + d scattering are reported in (2005WI13, 2008WI02). Firstly, in (2005WI13), n + d differential cross sections and analyzing powers were calculated for $E_{\mathrm{n}} = 28$, 65, 135 and 250 MeV. It was found that relativistic effects were of increasing importance as the energy increased and were seen mostly in the differential cross sections for angles larger than 160 degrees. Relativistic effects on the analyzing powers were found to be small. Secondly, in (2008WI02), calculations are reported of A_{y} values for n + d scattering for several neutron energies ≤ 65 MeV. The relativistic effect of primary interest in this study was the Wigner spin rotations. It was found that the effect on A_{y} became larger as the E_{n} decreased. The net result is that by including the Wigner rotations the A_{y} discrepancy is increased compared to the nonrelativistic calculations. The authors observe that this effect is due to the sensitivity of A_{y} to changes in the $^{3}\mathrm{P}_{j}$ components of the NN interaction. On this same point, see (1998TO07, 2008DO06).

5. (a) ^{2}H(n, p)nn $\qquad Q_{\mathrm{m}} = -2.2246$

(b) ^{2}H(n, nn)^{1}H $\qquad Q_{\mathrm{m}} = -2.2246$

Table 2.4.1 in (1975FI08) and Table 3.5 in (1987TI07) give extensive lists of references of studies of deuteron breakup by neutrons. Table 3.3 gives references for these reactions since 1987. For details about the analogous process of deuteron breakup by protons see ^{3}He reaction 6.

In (1996GL05), Fig. 32 gives the total n + d breakup cross section as a function of the lab energy of the neutron. The quoted experiments are from the 1960s and 70s. The cross section rises from zero at threshold ($E_{\mathrm{n}}(\mathrm{lab}) = 3.3$ MeV) to about 175 mb at 18 MeV and declines to 100 mb at $E(\mathrm{lab}) = 60$ MeV and continues to fall, according to calculations. Faddeev calculations with realistic NN interactions give a fairly good description of the total breakup cross section.

In kinematically complete three-body breakup experiments in which the two neutrons are observed, a commonly used way of viewing the coincidence spectrum of the two neutrons makes use of a three-body kinematical curve. If the observed neutrons are arbitrarily labeled n_1 and n_2, then the energy and emission angle of the unobserved proton can be determined from energy and momentum conservation if the neutron energies E_1 and E_2 , their polar angles θ_1 and θ_2 and the relative azimuthal angle ϕ_{12} are measured. For any given set of values of the laboratory angles θ_1, θ_2 and ϕ_{12} - determined by the locations of the detectors - the allowed values of E_1 and E_2 lie along a curve in E_1-E_2 space calculated using energy conservation. This curve is called the three-body kinematical curve; the arc length along this curve is called S and has units of energy. S is set equal to zero where E_2 equals zero. Any pair of (E_1, E_2) values for coincidence neutrons corresponds to a point in this space on or near the kinematical curve. By dividing the S curve into bins, one can obtain differential cross sections $d^5\sigma/d\Omega_1 d\Omega_2 dS$ as functions of S. Several such curves can be seen in (2005SE05), for example, for different values of θ_1, θ_2 and ϕ_{12}.

Table 3.3: References for deuteron breakup reactions ^{2}H(n, p)nn and ^{2}H(n, nn)^{1}H

References	E_n (MeV)	Comments
(2002BO52)	thermal	Detected p; search for evidence of di-neutron
(1993GE05)	10.3	Detected p, n_1, n_2; used FSI configuration for n's; compared with theory; determined a_{nn}
(1988HO14)	12	Detected p and n in FSI and QFS configurations; measured A_y; compared with theory
(1990HO14)	12	$\vec{n}$ beam; detected n and p in several configurations; measured n spectrum and A_y
(1988ST15, 1989ST15)	13	Detected p, n_1, n_2 in 22 configurations including np FSI, nn collinear, coplanar and space star; compared with theory; space-star anomaly observed
(1996SE14)	13.0	Detected n_1, n_2 in collinear, coplanar-star, space-star configurations; measured cross sections; compared other n + d and p + d data and theory including NNN interaction; space-star anomaly confirmed
(1998HO08)	13.0	Detected n_1, n_2 in six configurations; compared with previous data and theory including NNN; space-star anomaly confirmed
(1998TO06)	13.0	Detected n_1, n_2 and p in FSI configurations at four different angles; determined a_{nn} and a_{np}; compared with other data and theory; no NNN effects observed

Table 3.3: References for deuteron breakup reactions ^{2}H(n, p)nn and ^{2}H(n, nn)^{1}H (continued)

References	$E_{\rm n}$ (MeV)	Comments
(1999GO22)	13.0	Detected n_1, n_2 and p; used FSI configurations; determined a_{nn} and a_{pn}; compared with previous measurements and theory including NNN
(2005SE05)	13.0	Detected n_1, n_2; measured differential cross sections at seven configurations; compared with theory including NNN interaction; space-star anomaly confirmed
(2006GO11)	13.0	Expanded version of (1999GO22); kinematically complete study of n-d breakup reaction; determined a_{nn}; compared with other experiments; no evidence of NNN effects
(2001HU01)	16.6, 25.3	Kinematically complete study of n-d breakup reaction; detection angles chosen to allow model independent determination of a_{nn} and a_{np}; compared with other experiments
(2001ZH09)	25	Detected n_1, n_2 in space-star configuration; compared with theory; studied energy dependence of space-star anomaly
(2002DE50)	25	Detected n, p; deduced n-p scattering length
(2007RU11)	25	Measured n-n scattering cross section in QFS configuration for n-d breakup; compared with theory
(2000HU11, 2001HU10, 2002SI06)	25.3, 26	Detected n, p and n_1, n_2 pairs in QFS configurations; compared with Monte Carlo simulations; determined a_{nn}, a_{pn}
(1991MA51)	58	Measured p spectrum; compared with impulse approximation calculation
(1989KO24)	63	Detected p; measured high resolution proton spectrum
(1992KI19)	67	$\vec{\rm n}$ beam; detected n and p in both QFS and FSI configurations; measured $A_{\rm y}$; compared with theory
(1995BA05)	67	Detected n, p in five QFS configurations with $20^\circ \leq \theta_{\rm n} \leq 60^\circ$; compared with theory

Some detector configurations have received special attention. They are referred to as collinear, coplanar-star, space-star, FSI (final state interaction) and QFS (quasifree scattering) configurations.

If the angle ϕ_{12} is set to $180°$ (thus detecting neutrons scattered in opposite directions) and θ_1 and θ_2 are both set to $60°$, then when $E_1 = E_2$, the proton will be at rest in the center of mass system. This point in E_1-E_2 space is called the collinear point. Since the neutrons are identical and the scattering angles are equal, the differential cross section will be symmetrical around the collinear point. For other values of θ_1 and θ_2 with $\phi_{12} = 180°$, there will also be points at which the proton is at rest. However, the differential cross sections are not symmetrical around the collinear point in those cases. Such configurations which allow for the possibility of the proton being at rest in the center of mass system are called collinearity configurations. Examples are shown in (2005SE05) where differential cross sections are shown as functions of the arc length S and the collinearity points are labeled. See also Fig. 40 in (1996GL05).

The star configurations are ones in which the three nucleons, in the center of mass system, are emitted with equal momenta separated by $120°$; thus the three momentum vectors form an equilateral triangle. Any configuration allowing for this condition to occur at some point on the S curve is called a star configuration. The plane containing the equilateral momentum triangle is called the star plane. By a suitable arrangement of detectors, this plane can have any orientation, but two orientations are of particular interest. When the star plane lies in the same plane as the beam, the configuration is referred to as a coplanar-star configuration. When the star plane is perpendicular to the beam, the configuration is called the space-star configuration. Differential cross sections for each of these configurations can be seen in (2005SE05), for example. This reference also contains a histogram in E_1-E_2 space, Fig. 8, for the space-star configuration.

The QFS configuration allows for one of the three nucleons in the final state to remain at rest in the lab system, as if it were a spectator to the scattering process. See (2002SI06) for an example in which three-body breakup is used to study n + p and n + n scattering.

The FSI configuration allows for two nucleons to be emitted with approximately equal momenta and only a small relative momentum. In this case, the interaction of the two co-moving nucleons will be emphasized. In n + d breakup reactions, this configuration has made the study of the interaction of two neutrons possible. See (2000HU11) and (2001HU01) as examples of where studies using the FSI configuration are reported.

In connection with the space-star configuration, it has been found that the calculated differential cross section using realistic NN and NNN interactions is in disagreement with experimental results. This discrepancy is called the space-star anomaly. See (1988ST15, 1989ST15, 1996SE14, 1998HO08, 2001ZH09, 2005SE05). The origin of this anomaly isn't completely understood, but the authors of (2005SE05) suggest that some aspect of the three-body force may still be missing in the calculations.

Kinematically complete neutron-deuteron breakup reactions have been used to measure the neutron-neutron scattering length, a_{nn}; see (1996WI22) for a theoretical discussion of such reactions. Experiments were performed at two laboratories to obtain a_{nn}; see (2001HU01, 2006GO11) and references therein. The resulting values of a_{nn} obtained from the two laboratories were inconsistent. The reason for the inconsistency remains unclear. See (2009GA1D) for an extensive discussion of these matters.

Table 3.4: References for ^{2}H(p, π^+)^{3}H

References	E_p (MeV)	Comments
(2000KL11)	263, 295, 328	Simultaneous measurement of ^{2}H(p, π^+)^{3}H and ^{2}H(p, π^0)^{3}He reactions; measured $\sigma(\theta)$, σ_tot
(2001MB03, 2003AB16)	263-470	Summary of (2001BE35) and (2003AB02)
(2000BE15, 2001BE35)	263, 295, 328	Simultaneous measurement of ^{2}H(p, π^+)^{3}H and ^{2}H(p, π^0)^{3}He reactions; measured $\sigma(\theta)$; studied isospin symmetry
(2003AB02, 2003AB30)	362, 397, 433, 470	Continuation of (2001BE35) to Δ excitation region
(1989AB04)	425, 450, 475, 500	$\vec{\mathrm{p}}$ beam; measured analyzing powers and angular distributions of outgoing π^+ at backward angles; compared with theory
(2003AB20, 2006RO27)	882-1003	Simultaneous measurement of ^{2}H(p, π^+)^{3}H and ^{2}H(p, π^0)^{3}He reactions; measured $\sigma(\theta)$; studied isospin symmetry breaking effects

6. ^{2}H(p, π^+)^{3}H $\qquad Q_\mathrm{m} = -134.0953$

References for this reaction are listed in Table 3.4. This reaction is often studied in conjunction with the reaction ^{2}H(p, π^0)^{3}He. See ^{3}He reaction 5 for additional discussion. There are no reports of the reaction ^{1}H(d, π^+)^{3}H where the target and projectile are reversed.

7. ^{3}H(γ, π^-)^{3}He $\qquad Q_\mathrm{m} = -139.5516$

There are four pion photoproduction reactions relating ^{3}H and ^{3}He, namely ^{3}H(γ, π^-)^{3}He, ^{3}He(γ, π^+)^{3}H, ^{3}H(γ, π^0)^{3}H and ^{3}He(γ, π^0)^{3}He. References for the first of these are listed here. References for the second are listed in ^{3}He reaction 9. References for the third and fourth are listed in ^{3}He reaction 8.

Only two references for this reaction have appeared since the previous evaluation (1987TI07). For $E_\gamma = 250$-450 MeV, studies of the two reactions ^{3}H(γ, π^-)^{3}He and ^{3}He(γ, π^+)^{3}H were reported in (1987BE27). They measured the differential cross section for a range of energies and for several different values of the square of the momentum transfer. Comparison with theory showed poor agreement. Another paper by the same group (1988BE61) shows some new data for this reaction as well as the data from reference (1987BE27) in the context of the development of a solid state detector.

Calculations of polarization observables in the photoproduction of π^- particles from ^{3}H (and from ^{13}C and ^{15}N, as well) are reported in (1993CH26).

8. (a) ^{3}H(γ, n)^{2}H $\qquad Q_{\rm m} = -6.2572$
   (b) ^{3}H(γ, d)n $\qquad Q_{\rm m} = -6.2572$
   (c) ^{3}H(γ, p)2n $\qquad Q_{\rm m} = -8.4818$
   (d) ^{3}H(γ, 2n)^{1}H $\qquad Q_{\rm m} = -8.4818$

Reactions (a) and (b) are two-body photodisintegration reactions listed separately to indicate which outgoing particle is observed, the neutron in (a) and the deuteron in (b). Similarly, reactions (c) and (d) are three-body photodisintegration reactions in which either the proton or the two neutrons are observed .

There are no reports of measurements related to reactions (a), (b), (c) or (d) since the previous evaluation.

In the past, experimental and theoretical studies of the photodisintegration of ^{3}H have often been carried out in conjunction with the photodisintegration of ^{3}He and of neutron and proton capture by ^{2}H. Hence, ^{3}H reaction 3 and ^{3}He reactions 3 and 10 should be consulted for additional information regarding these processes.

A few measurements of reactions (a) and (c) are reviewed in (1975FI08). Also, reference (1981FA03) contains a summary of the experimental results up to 1981 for the photoneutron reactions (a) and (d). Figs. 10, 11 and 13 of that reference show cross sections for reactions (a) and (d) and their sum for E_γ from threshold to about 28 MeV. For the two-body disintegration, reaction (a), the cross section climbs rapidly from threshold, reaches its peak value of around 0.9 mb at about 12 MeV and drops slowly to around 0.2 mb at 26 MeV. The three-body disintegration, reaction (d), rises moderately rapidly from threshold to a peak value of around 0.9 mb at about 15 MeV and falls to about 0.4 mb at 26 MeV. As discussed in (1975GI01) and (1987LE04), for E_γ from threshold to around 40 MeV, two-body photodisintegration of ^{3}H (or ^{3}He) takes place by an E1 transition from the spatially symmetric component of the ground state to the p-wave state with a deuteron plus a neutron (or proton). The reference (1981FA03) also contains a useful overview of the theoretical work on the photodisintegration of ^{3}H and ^{3}He prior to 1981. A review of low energy photonuclear reactions on ^{3}H and ^{3}He is presented in (1987LE04).

A calculation of the photodisintegration of ^{3}H (as well as ^{3}He) using the Lorentz Integral Transform method with realistic NN and NNN interactions is reported in (2000EF03). For more on this approach, see the Introduction and reaction 10 in the ^{3}He section. A theoretical study of reaction (d) and the analogous reaction ^{3}He(γ, d)^{1}H using the Faddeev approach with modern interactions is reported in (2003SK02). Comparisons are made with experimental results and references for the data are given. The role of 3N interactions is studied as are different approaches that include meson exchange currents. A similar study is reported in (1998SA14). In both of these studies, it is observed that there is a correlation between the peak heights of the photodisintegration cross section and the binding energy of ^{3}H; see Fig. 9 in (1998SA14). A study of photonuclear reactions on

^{3}H and ^{3}He up to the pion threshold that includes Δ isobar excitation is presented in (2002YU02, 2004DE11).

Integrated moments for the reactions (a), (c) and ^{3}He(γ, n) are quoted in (1981FA03, 1987TI07).

9. (a) ^{3}H(e, e)^{3}H
   (b) ^{3}H(e, e′n)^{2}H $Q_m = -6.2572$
   (c) ^{3}H(e, e′p)2n $Q_m = -8.4818$

There are no reports of new measurements of reaction (a) since the previous evaluation. See below for a report of inclusive inelastic scattering of electrons by ^{3}H.

A brief history of experimental studies of electron scattering by ^{3}H and ^{3}He is given in the Introduction section of (1994AM07). This reference summarizes results from three previous reports, namely (1982CA15, 1985JU01, 1992AM04). Of the three reports, only (1985JU01) deals with reaction (a), a discussion of which was included in the previous evaluation (1987TI07). The authors of (1994AM07) combined their data with the world data to obtain charge and magnetic form factors for ^{3}H and ^{3}He for q^2 up to 30 fm^{-2} and compared with theory and with ^{2}H and ^{4}He form factors.

It has proven to be of value to study the charge and magnetic form factors, F_c and F_m, that can be obtained from the electron elastic scattering cross sections. See (1985JU01), for example, in the context of obtaining the form factors for ^{3}H. These quantities are expressed as functions of q^2, the square of the momentum transferred to the target in the scattering process. Two different units are used in the literature for q^2, namely fm^{-2} and (GeV/c)^2. The conversion factor is 1 (GeV/c)^2 corresponds to 25.6 fm^{-2} or 1 fm^{-2} corresponds to 0.0391 (GeV/c)^2. It should be noted that as a unit for q^2, (GeV/c)^2 is sometimes written as just (GeV)^2, as in (2007PE21) and (2007AR1B). The form factors are defined in such a way that both F_c and F_m equal 1 at q^2 equal to zero. Fig. 1 in (1985JU01) shows both form factors for ^{3}H for q^2 from 0 to about 23 fm^{-2} and 31 fm^{-2} for F_c and F_m respectively. The form factors drop rapidly with increasing q^2 and each has a minimum at about 13 fm^{-2} for F_c and at about 23 fm^{-2} for F_m. Figs. 6 and 7 in (1994AM07) show the charge and magnetic form factors for both ^{3}H and ^{3}He. Similar graphs are shown in Figs. 6-9 in (2009LE1D). The ^{3}He form factors are qualitatively similar to those for ^{3}H; the minima occur at slightly different values of q^2. Since ^{3}H and ^{3}He form an isospin doublet, it is useful to consider the isoscalar and isovector combinations of the form factors of ^{3}H and ^{3}He; see (1992AM04, 1994AM07) for the relationship between the standard form factors and the isoscalar and isovector form factors. As discussed in (1992AM04), meson exchange currents are expected to make a larger contribution to the isovector form factors than to the isoscalar ones. The isoscalar and isovector form factors are shown in Figs. 12 and 13 of (1994AM07).

Charge and magnetic rms radii values have been obtained from form factors; see (1988KI10), for example. This reference discusses the methods and difficulties in deducing rms radii values from form factors and quotes a range of values for the charge radii obtained for ^{3}H and ^{3}He. The slopes of the charge and magnetic form factor curves at $q^2 = 0$ are related to the mean square radii; see Eq. (9) of (1988KI10), for example. Using data from earlier experiments, the charge and magnetic rms radii of ^{3}H are obtained from slopes of form factor curves and reported in (1994AM07) to have the values $r_{\rm ch} = 1.755 \pm 0.086$ fm and $r_{\rm m} = 1.840 \pm 0.181$ fm. The reference (1994AM07) also reported the corresponding values for ^{3}He to be $r_{\rm ch} = 1.959 \pm 0.030$ fm and $r_{\rm m} = 1.965 \pm 0.153$ fm.

A theoretical study of the correlation between the ^{3}H binding energy and the charge radius is reported in (2006PL02), following an earlier calculation reported in (1985FR12). Averaging two calculations with different choices of input data, the authors obtained a charge radius of 2.1 ± 0.6 fm.

With regard to reactions (b) and (c), there have been no reports of any experiments since the previous evaluation.

There is a study of inclusive inelastic electron scattering from ^{3}H (and ^{3}He) for low excitation energies reported in (1994RE04). Longitudinal and transverse response functions were obtained for six values of the momentum transfer between 0.88 fm^{-1} and 2.87 fm^{-1} for excitation energies less than 18 MeV. The experimental results for the response functions were compared with values calculated using several different techniques. The agreement was better for smaller values of the momentum transfer and excitation energy than for larger values. It is observed that the longitudinal response function near threshold is somewhat larger for ^{3}He than for ^{3}H. This effect has been observed in earlier experiments and has been attributed to a Coulomb monopole transition; see references in (1994RE04). Inclusive inelastic electron scattering measurements for ^{3}H and ^{3}He are reported in (1988DO13). Longitudinal response functions were measured for momentum transfers from 200 MeV/c (1.0 fm^{-1}) to 550 MeV/c (2.78 fm^{-1}). (Note: Two different units are used for momentum transfer values, namely fm^{-1} and MeV/c. The conversions between the two are 100 MeV/c corresponds to 0.506 fm^{-1} and 1 fm^{-1} corresponds to 198 MeV/c.) Calculations of the longitudinal response function with the Lorentz Integral Transform method using realistic NN and NNN interactions and comparing theory with the experimental data of (1988DO13, 1994RE04) are reported in (2004EF01).

For more details on inclusive inelastic electron scattering in the quasi-elastic region for ^{3}H and ^{3}He, see ^{3}He reaction 11.

10. (a) ^{3}H($\pi^{\pm}$, $\pi^{\pm}$)^{3}H
    (b) ^{3}H(π^{+}, π^{0})^{3}He $Q_{\rm m} = 4.6122$
    (c) ^{3}H(π^{+}, γ)^{3}He $Q_{\rm m} = 139.5888$

With respect to reaction (a), the reference (2002BR49) is the last of a series of reports measuring elastic scattering of π^+ and π^- from ^{3}H and ^{3}He at $E_\pi = 142$, 180, 220 and 256 MeV. A major focus of these studies is charge symmetry breaking (CSB). The accompanying theoretical report is (2002KU36); the earlier experimental reports are referenced in (2002BR49), in the charge symmetry review (1990MI1D) and in ^{3}He reaction 13. See also (1999CO08) for an analysis of this data. The theory report (2002KU36) contains figures showing experimental and theoretical angular distributions for the four cases $\pi^+ + {}^3$He, $\pi^+ + {}^3$H, $\pi^- + {}^3$He, $\pi^- + {}^3$H at the four energies mentioned above. In each case, the diffraction pattern has a minimum at a scattering angle of about 80° and is fairly flat at larger angles. Ratios of cross section pairs were defined such that - if charge symmetry held - they would each equal unity at all angles and energies. Fig. 1 in (2002BR49) summarizes a number of experiments that measure these ratios. For each ratio and each energy, there are significant deviations from unity, especially near the 80° scattering angle. Corresponding figures in (2002KU36) compare calculations which take into account CSB effects with the data. Except for the 142 MeV data, the theoretical results agree well with the data.

One source of CSB between ^{3}H and ^{3}He is the repulsive charge of the protons in ^{3}He compared to the neutrons in ^{3}H. This effect leads to slightly different distributions and rms radii of the neutrons and protons in the two nuclei. The authors of (1991GI02) conclude that the neutron rms radius in ^{3}He is larger than the proton radius in ^{3}H by 0.035 ± 0.007 fm and that the rms proton radius in ^{3}He is larger than the rms neutron radius in ^{3}H by 0.030 ± 0.008 fm. This result was also discussed in (2002KU36, 2007KR1B) in a more general context of determining neutron and proton distributions using pion scattering.

For additional theoretical references related to reaction (a), see (1987KI24, 1989BR02, 1991BR33, 1995BR35, 1995CH04, 2001BR33).

The only report of a study of the charge exchange reaction (b) is (1995DO06) in which a 142 MeV π^+ beam was used and the recoiling ^{3}He nucleus was observed. The momentum distribution and differential cross section of the outgoing ^{3}He nuclei were measured and compared to theory and previous measurements. Of interest in the experiment was the comparison of the spin-flip and the non-spin-flip contributions to the cross section.

There were no reports of reaction (c) for the time period of this evaluation.

11. (a) $^3_\Lambda$H(π^-)^{3}He $\qquad Q_\mathrm{m} = 42.6936$

(b) $^3_\Lambda$H(π^-)^{2}H^{1}H $\qquad Q_\mathrm{m} = 37.2001$

(c) $^3_\Lambda$H(π^-)^{1}H^{1}Hn $\qquad Q_\mathrm{m} = 34.9756$

Studies of hypernuclei in general and the decay of the hypertriton in particular have been fruitful to both nuclear and particle physics. General references and reviews are listed below.

For completeness, some properties of the Λ and Σ hyperons are listed from the Particle Data Group publication. The Λ particle has zero charge, strangeness -1, isospin 0, $J^\pi = \frac{1}{2}^+$, mass $= 1115.683 \pm 0.006$ MeV and mean lifetime $= (2.632 \pm 0.020) \times 10^{-10}$ s which corresponds to a decay width of about 2.50×10^{-6} eV. The major decay modes are (p $+ \pi^-$) at 64% with an energy release of about 38 MeV and (n $+ \pi^0$) at 36% with an energy release of 41 MeV.

Closely related to the Λ hyperons are the Σ hyperons with strangeness -1, isospin 1 and $J^\pi = \frac{1}{2}^+$. The neutral member of the three Σ's is Σ^0 with a mass of 1192.642 ± 0.024 MeV which is about 77 MeV more massive than the Λ. Its basic quark structure is the same as that of Λ. It decays almost 100% into $\Lambda + \gamma$. It has a mean lifetime of $(7.4 \pm 0.7) \times 10^{-20}$ s, which corresponds to a decay width of about 8.9 keV.

In the early days of hypernuclear physics studies, the hypertriton was produced by capturing a stopped K$^-$ meson. For example, in (1973KE2A), the reaction ^{4}He(K$^-$, π^-p)$^3_\Lambda$H was used to produce hypertritons. More recently, the reaction ^{3}He(e, e$'$K^{+})$^{3}_{\Lambda}$H, with $E_{e} = 3.245$ GeV, has been used; see (2001RE09, 2001ZE06, 2004DO16). The reaction (π^{+}, K^{+}) with π^{+} energy of 1.05 GeV has been used to produced heavier hypernuclei; see (1996HA05, 1998BH05) and references therein.

No bound states of $A = 2$ hypernuclei, such as $^{2}_{\Lambda}$H, have ever been observed, nor have other $A = 3$ hypernuclei such as $^{3}_{\Lambda}$He. For $A = 4$ hypernuclei, two bound systems are known, namely $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He. It has been pointed out in (1989AF1A) and (1995GI16) that, as the lightest bound hypernucleus, the hypertriton plays a similar role in hypernuclear physics to that which the deuteron plays in ordinary nuclear physics. Analogous to the way in which the bound state properties of the deuteron are used to put constraints on models of the nucleon-nucleon interaction, the bound state properties of the hypertriton can be used to constrain the hyperon-nucleon interaction.

The hypertriton consists primarily of a weakly bound system of a deuteron and a Λ particle. Because of the strong coupling between the Λ and the Σ hyperons, the hypertriton has a small probability of being a deuteron and a Σ particle. A recent calculation gives that percentage as 0.15% and 0.23% for two different interactions that give approximately the current Λ binding energy; see (2002NE11). An earlier calculation (1973DA2A) gives the Σ component to be 0.36%. However, in the calculation reported in (1973DA2A), the $\frac{1}{2}^{+}$ state is more deeply bound than measurement gives and an unobserved bound $\frac{3}{2}^{+}$ state is predicted. A Faddeev calculation of the hypertriton using realistic interactions reported in (1995MI12, 1998GL01) gives 0.5% as the Σ component probability.

The hypertriton has $J^{\pi} = \frac{1}{2}^{+}$, isospin 0 and the Λ separation energy $= 0.13 \pm 0.05$ MeV; see Appendix IV in Nuclear Wallet Cards (2005TUZX) and (1995GI16) and references therein. A simplified model of the hypertriton as a deuteron plus Λ is discussed in (1992CO1A). The deuteron is treated as a free deuteron and a Λ-deuteron potential is developed. The experimental Λ separation energy is used as an input to calculate the Λ part of the hypertriton wave function. The resulting wave function is used to calculate the hypertriton lifetime and the branching ratio, R, defined below. The calculated results agree with experiment within experimental error, as will be discussed below.

In addition to the π^{-} decay processes listed in reactions (a), (b) and (c), the corresponding π^{0} processes are also possible: $^{3}_{\Lambda}$H(π^{0})^{3}H, $^{3}_{\Lambda}$H(π^{0})^{2}Hn, $^{3}_{\Lambda}$H(π^{0})^{1}Hnn. All of these π^{-} and π^{0} processes are referred to as mesonic decay modes. In addition, the following non-mesonic decay modes are possible in principle: $^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + \mathrm{n}$ and $^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{1}\mathrm{H} + \mathrm{n} + \mathrm{n}$.

The reference (1973KE2A) gives a measured value of $(2.46^{+0.62}_{-0.41}) \times 10^{-10}$ s for the lifetime of the hypertriton. This is the latest (1973) of several measurements. Table 1 in (1990CO1D) contains a list of measured values of lifetimes of light hypernuclei, including the hypertriton. Although the uncertainty in the measurement of the hypertriton lifetime is quite large, it appears that it is comparable to and possibly somewhat smaller than that of the free Λ particle. In the simplified model of the hypertriton in (1992CO1A) referred to above, the calculated value of this lifetime is 12% smaller than that of the free Λ. In the study reported in (1998KA12), the calculated value of the hypertriton lifetime is 3% larger than the free Λ lifetime. Since the hypertriton is primarily a loosely bound Λ state, it isn't surprising that its lifetime is comparable to the free Λ. In heavier hypernuclei where the Λ binding energy is greater, the measured and calculated lifetimes tend to be lower than the free Λ; see (1998BH05).

In hypernuclei heavier than the hypertriton, the major decay mode is the non-mesonic decay because the mesonic decay modes are suppressed by the Pauli principle. To see why this occurs, recall that when the Λ decays into a nucleon and a pion, the energy released is about 40 MeV. Most of this energy goes to the pion, leaving only a small amount of energy and momentum for the nucleon. However, in nuclei heavier than the triton most of the low energy and momentum states are full, thus inhibiting this decay mode. For example, in ${}^{12}_{\Lambda}$C the ratio of the π^- decay rate to the non-mesonic decay rate is found experimentally to be 0.045 ± 0.04; see (1989GI10) and references therein. In the hypertriton, there are empty states available at low energy and the mesonic decay mode is the active decay mode. Using numbers from Table I in (1998KA12), the calculated value of this ratio for ${}^{3}_{\Lambda}$H is 15.2.

Reaction (a) is a two-body π^- decay while (b) and (c) are three- and four-body π^- decays. The branching ratio $R = \Gamma({}^{3}_{\Lambda}\text{H} \rightarrow \pi^- + {}^{3}\text{He})/\Gamma({}^{3}_{\Lambda}\text{H} \rightarrow \text{all } \pi^- \text{ modes})$ has been measured several times; Γ is the decay rate. Table 4 in (1992CO1A) collects the measured values (with references) and gives an average value for the ratio to be $R = 0.35 \pm 0.04$. In the simplified model of the hypertriton in (1992CO1A) referred to above, the calculated value of this ratio is $R = 0.33 \pm 0.02$, where the theoretical uncertainty results from an uncertainty in a parameter of the model. Using numbers from Table I in (1998KA12), the calculated value of this ratio for ${}^{3}_{\Lambda}$H is $R = 0.379$; see also (1998GL01).

In studies of the decay of hyperons and hypernuclei, an empirical observation called the $\Delta I = \frac{1}{2}$ rule has received considerable attention. This rule can be illustrated in the two-body mesonic decay of ${}^{3}_{\Lambda}$H, reaction (a). Before decay, the isospin is zero for the Λ and zero for the deuteron. After decay into an isospin $\frac{1}{2}$ triton and an isospin 1 pion, the final isospin could be either $\frac{1}{2}$ or $\frac{3}{2}$. Thus the change in isospin in the decay process is either $\frac{1}{2}$ or $\frac{3}{2}$. In (1989GI10), it is reported that, experimentally, "...one finds the $\Delta I = \frac{1}{2}$ amplitude to be enhanced by an order of magnitude over the $\Delta I = \frac{3}{2}$ amplitude." See (1989GI10) for a discussion of the $\Delta I = \frac{1}{2}$ rule, including examples and references. This rule was used explicitly in (1998KA12) in the calculation of the decay rates of the hypertriton. See also (2000AL27) for a study of the $\Delta I = \frac{1}{2}$ rule in hypernuclei. See also (2005SA16) for a possible violation of the $\Delta I = \frac{1}{2}$ rule in hypernuclei.

Additional theoretical studies of the hypertriton can be found in (1989AF1A, 1990AF02, 1992BE02, 1993MI21, 1995DO01, 1995MI06, 1995MI12, 1997GO04, 1998BL17, 1998GL10, 1998GO06, 1999GO19). General reviews of hypernuclear physics can be found at (1989GA15, 1995GI16) and various measurements in $Nuclear\ Physics\ A$ 639 (1998) which result from the 1997 Symposium on Hypernuclear and Strange Particle Physics.

^{3}He

Ground State

$$
\begin{aligned}
J^{\pi} &= \frac{1}{2}^{+} \\
\mu &= -2.127497718 \pm 0.000000025\ \mu_{\mathrm{N}} \\
\text{Mass Excess, } M-A &= 14.93121475 \pm 0.00000242 \text{ MeV} \\
\text{Decay Mode} &: \text{ stable} \\
\text{Binding Energy, } E_{\mathrm{B}} &= 7.718043 \pm 0.000002 \text{ MeV} \\
\text{Proton Separation Energy, } S_{\mathrm{p}} &= 5.493478 \pm 0.000002 \text{ MeV}
\end{aligned}
$$

General

A topic of interest in connection with the mass 3 nuclei is the difference in binding energies of ^{3}H and ^{3}He and the relationship of this difference to charge symmetry breaking (CSB). The binding energy of ^{3}H is larger than that of ^{3}He by a little less than 764 keV. There are several reasons for this difference; see (1990MI1D, 2005FR02, 2006MI33) and references therein. The two most obvious differences between ^{3}H and ^{3}He are the presence of the two protons and their associated Coulomb interaction in ^{3}He and the larger masses of the two neutrons in ^{3}H. According to results presented in Table I in (2005FR02), the Coulomb interaction accounts for about 85% of the binding energy difference and the larger neutron masses produces about a 2% effect on the binding energy difference due to the different kinetic energies. Additional relativistic and electro-magnetic (EM) effects contribute a little less than 4%. Using chiral perturbation theory and Faddeev methods, two- and three-body interactions with CSB aspects included are found to contribute the remaining approximately 9% of the binding energy difference. The up-down quark mass difference and EM effects at the quark level are the sources of the CSB in the strong interactions (2005FR02).

In addition to having an effect on the ^{3}H-^{3}He binding energy difference, CSB should also be seen in differences of the distributions of neutrons and protons in these nuclei. If charge symmetry were exact, the rms radius of the neutron in ^{3}He should be the same as that of the proton in ^{3}H and similarly for the rms radii of two protons in ^{3}He and two neutrons in ^{3}H. By analyzing the results of π^{+} and π^{-} elastic scattering from ^{3}H and ^{3}He, it is reported in (1991GI02) and discussed in (2007KR1B) that the rms radius of the neutron in ^{3}He is larger than that of the proton in ^{3}H by 0.035 ± 0.007 fm. Similarly; it was found that the rms radius of the protons in ^{3}He is larger than that of the neutrons in ^{3}H by 0.030 ± 0.008 fm.

For more on charge symmetry and charge symmetry breaking, especially as it relates to differences in the scattering lengths a_{pp} and a_{nn}, and how that relates to the difference in binding energies of ^{3}H and ^{3}He, see (2009GA1D) and references therein.

In the discussion of the ground state of ^{3}H, it was mentioned that - in an asymptotic sense - ^{3}H can be considered to be a deuteron and a neutron in a mixture of an S and a D state with an asymptotic ratio $C_{\mathrm{D}}/C_{\mathrm{S}} = \eta_{\mathrm{t}}$(ave.) equal to -0.0418 ± 0.0015. For the analogous case in ^{3}He, the asymptotic form of the ground state can be considered to be a mixture of a deuteron and a proton in a mixture of S and D states. By studying TAP's for proton pickup reactions by polarized deuterons from ^{93}Nb, ^{63}Cu and ^{89}Y targets with energies below the Coulomb barrier, a value for the D state to S state asymptotic ratio $\eta_{^3\mathrm{He}} = -0.0386 \pm 0.0046 \pm 0.0012$ was reported; see (1995AY03). In addition, in a study of the TAP for capture of low energy polarized deuterons by protons, a value of $\eta_{^3\mathrm{He}} = -0.0399 \pm 0.0091$ is reported in (1997RI07, 1997SC31). An inverse square error weighted average of these two values is $\eta_{^3\mathrm{He}}$(ave.) $= -0.0389 \pm 0.0042$. See (1989VU01) for a detailed comparison of measured and calculated values of η_t and $\eta_{^3\mathrm{He}}$.

By measurements of isotope shifts in helium, determinations of the nuclear rms charge radius of ^{3}He are reported to be 1.9506 ± 0.0014 fm (1995SH12) and to be 1.9642 ± 0.0011 fm (2006MO08). Electron scattering results reported in (1994AM07) give $r_\mathrm{ch} = 1.959 \pm 0.030$ fm.

The magnetic dipole moment of ^{3}He is $-2.12749772 \pm 0.00000003$ nuclear magnetons; see (1993FL1B, 2000MO36).

A theoretical study of the electric dipole moment of the ^{3}He nucleus is reported in (2008ST14).

An important experimental advance that has occurred since the previous evaluation is the widespread availability of polarized ^{3}He targets. The techniques for producing polarized ^{3}He targets are discussed in detail in the review article (1997WA39) and in (2002GO44) as well as in the context of scattering of polarized electrons from polarized ^{3}He targets in (1993AN12, 1996AN25). Two methods have been used for producing polarized ^{3}He targets. See section 4 of (2002GO44) for details.

An important theoretical advance is the ability to include the Coulomb interaction in scattering and break-up reactions such as occur in proton-deuteron scattering. In the hyperspherical harmonic approach, see (2009MA53) and references therein. In the Faddeev method, see (2009IS04, 2009WI16, 2009WI17) and references therein. In the momentum space Alt-Grassberger-Sandas method, see (2008DE1D, 2009DE47) and references therein.

As was mentioned in the Introduction, the Gerasimov-Drell-Hearn (GDH) sum rule relates the anomalous magnetic moment of a system to an energy weighted integral of the photoabsorption spin asymmetry. References to the original papers in which the sum rule is obtained can be found in (2008SL01), for example. This sum rule has been tested for protons (2004DR12, 2008DR1A). It is under investigation for the neutron and the deuteron; see (2009FI06) and (2004AR26, 2009WE1A) and references therein. The existence of polarized ^{3}He targets allows this sum rule to be tested in this case as well.

The following comment, relevant to the standard notation related to the GDH sum rule, is a private communication from Dr. A.M. Sandorfi, JLab (2009):

The Gerasimov-Drell-Hearn-Hosoda-Yamamoto sum rule relates an energy-weighted integral of the total photo-reaction cross sections with photon and target spins parallel and anti-parallel to the anomalous magnetic moment of the target, $\int \mathrm{d}\omega(\sigma_\mathrm{P} - \sigma_\mathrm{A})/\omega = 4S\pi^2\alpha(\kappa/M)^2$. In the literature, helicity designations have sometimes been used for the parallel and anti-parallel cross sections, and this has created some level of confusion. The helicity of a particle or photon is defined as the dot product of spin and a unit vector in the direction of the momentum, $S \cdot \mathrm{p}/|\mathrm{p}|$. The total helicity is only usefully defined in the center of momentum (CM) frame, since the target is stationary in the laboratory. In the CM frame, the photon and target momenta are opposed, so that when their spins are parallel, their helicities have opposite signs. Thus for $\gamma + {}^3$He reactions, the parallel-spin cross section is associated with a total channel helicity of $\frac{1}{2}$ and similarly anti-parallel spins correspond to total helicity $\frac{3}{2}$.

In Sandorfi's comment, the limits on the integral are the threshold energy for photoabsorption at the low limit and infinity at the upper limit. The mass of the target is M and must be expressed in units of inverse length to match the cross section units on the left-hand side of the integral. Note that all masses in this discussion are nuclear masses, not atomic masses. The ratio of the nuclear magnetic moment to the nuclear magneton can be written as $\mu/\mu_{\rm N} = 2(M_{\rm p}/M)(Q/{\rm e}+\kappa)S$, where κ is the anomalous magnetic moment. For ^{3}He, the measured value for μ is -2.1275 $\mu_{\rm N}$, which leads to a value of $\kappa = -8.3678$.

A second sum rule involving the same photoabsorption cross sections is the forward spin polarizability, $\gamma_0 = (-\frac{1}{8}\pi^2)\int {\rm d}\omega(\sigma_{\rm P} - \sigma_{\rm A})/\omega^3$. The limits on the integral are the same here as in the GDH integral. See (2008AH01, 2009WE1A) for studies of the GDH and γ_0 sum rules where indirect methods were used to obtain experimental values for the integrals for ^{2}H. No experimental results have been reported for γ_0 for ^{3}He.

For ^{3}He, using the value of κ presented above, the value of the GDH integral is 497.94 μb. For the neutron, the value of the GDH integral is 233.15 μb. One would expect that, above the pion threshold, most of the contribution to the ^{3}He GDH integral would come from the neutron, since the polarization properties of ^{3}He are primarily due to the neutron in ^{3}He. Thus, much of the difference of about 265 μb between the neutron and ^{3}He values of the GDH integral must come from the energy region between the ^{3}He photoabsorption threshold, 5.49 MeV, and pion emission threshold, about 135 MeV. Studies of the contribution to the GDH integral near the ^{3}He photoabsorption threshold using the capture processes ^{2}H($\vec{\rm p}$, γ)^{3}He and ^{1}H($\vec{\rm d}$, γ) are reported in (2000WU02, 2001WE07).

Generalizations of the GDH sum rule which make use of virtual photons have been obtained; see (2000KO1Q, 2001DR1A, 2001JI02, 2008SL01). See ^{3}He reaction 11 for studies related to these generalized GDH sum rule.

1. ^{3}H(β^-)^{3}He $\qquad Q_{\rm m} = 18.5912$ keV

The decay is to the ground state of ^{3}He. The half-life is 12.32 ± 0.02 years or 4500 ± 8 days. The $\log ft$ value is 3.053 ± 0.001. See ^{3}H reaction 1.

2. ^{1}H(^{6}Li, α)^{3}He $\qquad Q_{\rm m} = 4.0196$

A study of this reaction at $E({}^6{\rm Li}) = 30$ MeV is reported in (1994AL54). A peak in the α spectrum was observed corresponding to the ^{3}He ground state, but no other structure was seen to indicate the presence of any excited states in ^{3}He. See ^{3}H reaction 2 for an analogous study with a ^{6}He beam and ^{3}H final state.

3. (a) ^{2}H(p, γ)^{3}He $Q_m = 5.4935$
(b) ^{2}H(p, e$^+$e$^-$)^{3}He $Q_m = 4.4715$
(c) ^{2}H(p, p$'\gamma_{brem}$)^{2}H
(d) ^{1}H(d, d$'\gamma_{brem}$)^{1}H

Shown in Table 3.2.1 of (1975FI08) are references for reaction (a) at $E_p = 24$ keV-197 MeV available in 1975. Table 3.10 in (1987TI07) lists references for the period between 1975 and 1986 for $E_p = 6$-550 MeV. Table 3.5 of the present work contains a list of the experimental papers for this reaction that have appeared since (1987TI07). For E_p between about 0.1 MeV and 50 MeV, the angular distribution of the gamma rays shows a $\sin^2\theta$ pattern suggesting a predominant E1 capture process. At higher energies, it has been necessary to include additionally M1, E2 and M2 multipoles to obtain reasonable fits.

Table 3.5: Experimental references for ^{2}H(p, γ)^{3}He and ^{1}H(d, γ)^{3}He

References	E_p, E_d or E_{cm} (MeV)	Comments
(2005BY05)	$E_{cm} = 2.7$-16.7 keV	Deduced astrophysical S-factor
(2002CA28)	$E_p = 4$-32 keV	Deduced astrophysical S-factor
(2010BY01)	$E_p = 12.1$, 13.9, 14.8 keV	Deduced astrophysical S-factor
(1996SC14)	$E_{cm} = 26.6$ keV	$\vec{p}$, $\vec{d}$ beams; measured VAP and TAP; compared with three-body calculations to observe effects of MEC's and tensor interaction; evaluated astrophysical S-factor
(2000WU02)	$E_{cm} = 26.6$ keV	$\vec{p}$, $\vec{d}$ beams; obtained low energy contribution to the GDH sum rule
(1997RI15)	$E_{cm} = 27$, 54 keV	Measured differential cross section, VAP and TAP at 27 keV and photon polarization at 54 keV; obtained doublet and quartet M1 capture cross sections
(1997MA08)	$E_{cm} = 40$-210 keV, 75, 108, 133, 173 keV	Measured VAP and TAP in 40-210 keV range; obtained σ_{tot}'s and S-factors for 75-173 keV range; compared S-factors with other measurements and with theory
(1995SC40)	$E_p = 80$ keV	$\vec{p}$ beam; deduced astrophysical S-factor
(1997RI07)	$E_p = 80$ keV	D/S asymptotic states ratio deduced

Table 3.5: Experimental references for ^{2}H(p, γ)^{3}He and ^{1}H(d, γ)^{3}He (continued)

References	E_p, E_d or E_{cm} (MeV)	Comments
(1997SC31, 1998WE06)	$E_{p,d} = 80$ keV	$\vec{p}$, $\vec{d}$ beams; measured A_y, T_{20}, polarization of γ-rays; obtained D/S asymptotic ratio; compared with three-body calculations; studied MEC effects
(1999SM06)	$E_{cm} = 2$	$\vec{p}$, $\vec{d}$ beams; measured cross sections, VAP and TAP
(1988VE07)	$E_p = 3$; $E_d = 6$	$\vec{p}$, $\vec{d}$ beams; measured VAP; studied E1, E2 and M1 capture strengths
(1992GO04)	$E_{cm} = 5, 10$	Measured VAP and TAP; deduced γ-ray multipolarity
(1996BR24)	$E_d = 5.25$	Measured $T_{20}(90°)$
(2001AK08)	$E_d = 17.5$	Measured analyzing powers
(2006KL03)	$E_d = 29, 45$	Follow-up of (1998AN12); measured VAP and TAP; increased angular range; each energy expected to emphasize different dynamics
(1998AN12)	$E_d = 45$	$\vec{d}$ beam; measured TAP A_{yy} in range $50°$ to $160°$; compared with theory
(1998JO15)	$E_p = 98, 176$	See Table 3.7
(1988PI01)	$E_d = 95$	Measured cross section, VAP and TAP; deduced asymptotic D/S ratio
(2005ME09)	$E_d = 110, 133, 180$	Measured VAP and TAP; compared with theory and with (2003YA23)
(2003YA23)	$E_d = 200$	Measured cross section, A_y, A_{xx}, A_{yy}; studied energy dependence of A_{xx} and A_{yy} at $90°$; compared with theory
(2000ME16)	$E_p = 190$	Possible role of Δ resonance
(2001VO06, 2002BA41)	$E_p = 190$	$\vec{p}$ beam; measured cross section; compared with theory
(1988AD01)	$E_p = 800$	Measured VAP's

As will be discussed further below, in the limit as the center of mass energy approaches zero, the reaction ^{2}H(p, γ)^{3}He proceeds by roughly comparable s-wave and p-wave components of the three-body continuum wave function. To a large extent, this is to due an aspect of the Coulomb interaction which gives rise to a non-zero p-wave amplitude in the limit as the energy approaches zero. By contrast, the reaction ^{2}H(n, γ)^{3}H is 100% s-wave capture in the same energy limit since the p-wave amplitude goes to zero in this energy limit in the absence of the Coulomb interaction. Also note that the M1 multipole arises from s-wave capture and the E1 multipole comes from the p-wave capture.

The low energy behavior of the cross section for the reaction ^{2}H(p, γ)^{3}He has important astrophysical implications. This reaction is an essential part of the deuterium burning phase of protostellar evolution. At higher stellar temperatures, it is step two in the proton-proton chain for burning hydrogen into helium. For more details and further references, see (1997SC31, 2002CA28, 2005DE46). A compilation and R-matrix analysis of nuclear reaction rates involved in Big Bang nucleosynthesis was reported in (2004DE48, 2005DE46). Graph 1a, page 232, in (2004DE48) shows the astrophysical S-factor for the reaction ^{2}H(p, γ)^{3}He for $E_{\rm cm}$ from near zero up to 10 MeV, compiled from data sets stretching over forty years. The R-matrix analysis has the M1 multipole slightly larger than the E1 multipole for $E_{\rm cm}$ less than 10 keV and E1 being dominant for energies above 10 keV. The M1 contribution to $S(E)$ is nearly flat from zero energy to around 100 keV. Specifically, as shown in Table 3 of (2004DE48), $S(0)$ is found to be 0.223 ± 0.010 eV $\cdot$ b of which 60% (0.134 ± 0.006 eV $\cdot$ b) comes from the M1 contribution and 40% (0.089 ± 0.004 eV $\cdot$ b) from the E1 contribution. Table III and Fig. 16 in (1997SC31) show the percent M1 contribution of the capture cross section dropping from about 54% at zero energy to about 16% at 75 keV. The NACRE collaboration (1999AN35) used a polynomial fit to existing data and obtained $S(0)$ to be 0.20 ± 0.07 eV $\cdot$ b. The LUNA collaboration (2002CA28) obtained cross sections and S-factors for energies below about 20 keV. The results are shown in Fig. 7 of that reference and the value of $S(0)$ is given as 0.216 ± 0.006 eV $\cdot$ b. However, in (1997SC31) the value of $S(0)$ is reported to be 0.166 ± 0.005 eV $\cdot$ b. An analysis of existing data reported in (2009AR02) results in a value of 0.162 ± 0.019 eV $\cdot$ b for $S(0)$. Fig. 2 in (2000NE09) shows the S-factor for $E_{\rm cm}$ from near zero up to 10 MeV. This figure was obtained by combining the results of (1997SC31) up to 57 keV and the world data given in (1999AN35) for higher energies. Proton capture reaction rates calculated over the same energy range are given in Table 1 of (2000NE09). Low energy cross sections, S-factors and thermonuclear reaction rates are reported in (1997MA08) and compared to other measurements and theory. A weighted average of the two most recent measurements (1997SC31, 2002CA28) gives an $S(0)$ value of 0.19 ± 0.03 eV $\cdot$ b where the uncertainty has been adjusted to represent the spread in the reported values. Note that this value agrees with that reported in (1997MA08). This reference gives $S(0)$ to be 0.191 eV $\cdot$ b. In a study of the electromagnetic properties of $A = 2$ and 3 nuclei (2005MA54), the pair-correlated hyperspherical harmonics method was used with modern two- and three-body interactions and currents to calculate among other things the S-factor for low energy p + d capture. The results were in agreement with the LUNA data as well as some older data; the quoted value of $S(0)$ is 0.219 eV $\cdot$ b. A calculation of the M1 contribution to $S(0)$ is reported to be 0.108 ± 0.004 eV $\cdot$ b (1991FR03), where the given uncertainty is somewhat subjective.

A summary of experimental vales of the astrophysical S-factor for the reaction ^{2}H(p, γ)^{3}He is given in Table 3.6.

Table 3.6: Experimental values of astrophysical S-factor for the reaction ^{2}H(p, γ)^{3}He at zero energy, $S(0)$, by various methods.

References	$S(0)$ (eV · b)	Comments
(1997SC31) [a]	0.166 ± 0.006	Extrapolated from data with $E_{\rm p} = 16$ to 76 keV
(1999AN35)	0.20 ± 0.07	Polynomial fit to existing data
(2002CA28)	0.216 ± 0.006	Extrapolated from data with $E_{\rm p} = 2.5$ to 20 keV
(2004DE48) [b]	0.223 ± 0.010	R-matrix analysis of existing data
(2009AR02)	0.162 ± 0.019	Analysis of existing data
	0.19 ± 0.03	Average of most recent measurements; see text

[a] Obtained M1 percentage of $S(0)$ to be 54 ± 4 % or 0.090 ± 0.007 eV · b.

[b] Obtained M1, E1 contributions to $S(0)$ to be 0.134 ± 0.006 eV · b and 0.089 ± 0.004 eV · b, respectively.

There have been two studies of the reaction (b); see Table 3.7. By observing the energies and angles of the outgoing electron-positron pairs, the energy and angle of the equivalent virtual photon is determined. A study reported in (1998JO15) used $E_{\rm p} = 98$ and 176 MeV. Cross sections for both ^{2}H(p, e$^+$e$^-$)^{3}He and ^{2}H(p, γ)^{3}He reactions at laboratory angles of $40°$ and $80°$ of the real and virtual photons were measured and the ratio compared to calculations. With 98 MeV protons, it was found that the experimental results for this ratio exceeded theory by 60% to 75%, depending on the angle of the outgoing real or virtual photons. However, with 176 MeV protons better agreement was obtained between theory and experiment. The same model was used for both reactions and the authors comment that the model is in reasonably good agreement with the ^{2}H(p, γ)^{3}He data. The reaction ^{2}H(p, e$^+$e$^-$)^{3}He was studied also at $E_{\rm p} = 190$ MeV at four center-of-mass angles between $80°$ and $140°$, as reported in (2000ME14). Because the available energy is close to the threshold for pion emission, it was expected that mesonic degrees of freedom and nucleon excitation might be of importance. In addition to cross section measurements, this reference reports the determination of four electromagnetic response functions. The experimental virtual photon angular distribution is in reasonable agreement with calculations based on a relativistic gauge-invariant model, but the same is not true for the response functions. The authors suggest that virtual Δ excitation may be playing an important role in the response functions. The theory used for comparison is reported in (1998KO60).

The nucleon-nucleon interaction far away from elastic scattering can be studied by proton-proton bremsstrahlung and neutron-proton bremsstrahlung with high energy outgoing (so-called "hard") photons; see, for example (2001VO06, 2004MA71, 2005LI33) and references therein. A feature of proton-proton bremsstrahlung is that symmetry conditions forbid E1 photons and first order meson exchange currents; see (1998MA44), for example. In neutron-proton bremsstrahlung, however, first order effects are dominant; see (1992CL02, 2004VO07) where references to the few existing neutron-proton bremsstrahlung experiments are given. At intermediate energies, the

Table 3.7: References for ^{2}H(p, e^+e^-)^{3}He

Reference	E_p (MeV)	Comments
(1998JO15)	98, 176	Detected outgoing e^+ and e^-; determined equivalent virtual photon; measured cross section for two virtual photon angles, $40°$ and $80°$; compared to real photon cross section at same angles; also compared with previous measurements and to theory
(2000ME14)	190	Measured cross section for four virtual photon between CM angles of $80°$ and $140°$; determined EM response functions; compared with theory

neutron-proton bremsstrahlung cross section is about an order of magnitude larger than that for proton-proton bremsstrahlung (2003VO04). Thus the study of proton-deuteron bremsstrahlung becomes important for several reasons (1992CL03). It leads to a better understanding of the neutron-proton bremsstrahlung process since that is the dominant process in proton-deuteron bremsstrahlung. Also, proton-deuteron bremsstrahlung is an intermediate process between proton-neutron bremsstrahlung and proton-nucleus bremsstrahlung and ultimately to nucleus-nucleus bremsstrahlung for which it is usually assumed that proton-neutron bremsstrahlung is the basic process; see (1992CL03) and references therein.

Experiments from the current evaluation period involving reactions (c) and (d) are listed in Table 3.8. Studies from the 1960s reporting proton-deuteron bremsstrahlung are referenced and briefly discussed in (1990PI15, 1992CL02). As shown in Table 3.8, proton-deuteron bremsstrahlung studies reported during the period of this evaluation have been performed at E_{cm} from about 97 MeV to 186 MeV. In the experiment reported in (2002GR06), the energies are above the pion production threshold. These authors conclude that most (about two thirds) of the photon production in their experiment comes from the neutron-proton interaction in the presence of a spectator proton. With this interpretation, they obtain total cross sections that slowly increase from about 9 μb at $E_{cm} = 145$ MeV to about 18 μb at $E_{cm} = 186$ MeV. The same experimental group reported deuteron-proton reactions at the same energies resulting in π^0 and π^+ production (2000GR31). Since the primary decay mode of the π^0 is into two γ-rays, it is of interest to compare the cross section for π^0 production with that of bremsstrahlung at the same energies. According to authors of (2000GR31), the cross section for π^0 production grows from about 0.6 μb at $E_{cm} = 145$ MeV to about 90 μb at $E_{cm} = 186$ MeV.

In the experiment performed at Kernfysisch Versneller Instituut (KVI) and reported in (2003VO04), a 190 MeV polarized proton beam was scattered from a deuterium target and the outgoing proton, deuteron and photon were detected in a coplanar geometry, which allows for the differential cross section and the analyzing power A_y to be measured. The results were compared with what the authors call a soft photon model, based on (1993LI1X). The model fits the data rather well. In a related KVI experiment with the same beam and target, studies of the four-body final state were reported in (2004VO07) in which the two protons, the neutron and the photon were all detected.

Table 3.8: References for ^{2}H(p, p$'\gamma_{\mathrm{brem}}$)^{2}H and ^{1}H(d, d$'\gamma_{\mathrm{brem}}$)^{1}H

References	E_p or E_d (MeV)	Comments
(1992CL02)	$E_\mathrm{p} = 145, 195$	Measured photon energy spectrum and angular distribution; compared with previous measurements and theory
(2001VO06, 2003VO04)	$E_\mathrm{p} = 190$	$\vec{\mathrm{p}}$ beam; detected outgoing p, d and γ-ray; measured differential cross section and analyzing powers in coplanar geometry; compared with theory
(2004VO07)	$E_\mathrm{p} = 190$	Continuation of (2003VO04) to deuteron breakup channels; $\vec{\mathrm{p}}$ beam; detected outgoing p_1, p_2, n and γ-ray; compared quasifree and free ppγ cross sections; measured quasifree pnγ cross sections; compared with theory
(1990PI15)	$E_\mathrm{p} = 200$	Measured photon energy spectrum and angular distribution; compared with previous measurements and theory
(2002GR06)	$E_\mathrm{d} = 437\text{-}559$	Kinematically complete experiment; measured cross sections; studied quasifree case with spectator proton

The emphasis was on the geometries in which either the neutron or one of the protons was essentially a spectator, i.e., the quasifree geometries. Phase space considerations were used to obtain equivalent three-body final states for these cases. Thus, quasifree proton-proton bremsstrahlung or quasifree proton-neutron bremsstrahlung results were obtained. As long as the spectator neutron was at low energy, the quasifree proton-proton bremsstrahlung cross sections agree in shape with the free proton-proton bremsstrahlung cross sections reasonably well, but the magnitude of the quasifree cross section was 2.5 times larger than the free cross sections. Using a similar procedure, including the same scaling factor, the authors obtained cross sections for quasifree proton-neutron bremsstrahlung; only coplanar geometry cross sections are reported in (2004VO07). These cross sections are compared with three calculations of free neutron-proton bremsstrahlung: two soft photon models based on (1993LI1X) and a microscopic two-body model (1992HE06, 1992HE18). The agreement is reasonably good, particularly with the microscopic model. A direct comparison of the quasifree proton-neutron bremsstrahlung reported in (2004VO07) with measurements of proton-neutron bremsstrahlung cross sections is reported in (2007SA14). The role of meson exchange currents in proton-neutron bremsstrahlung is studied in (2008LI14) and references therein.

One objective of the experiment reported in (1990PI15) was to settle a discrepancy in the total photon emission cross section reported in two earlier studies; see the paper for relevant references. The authors also compared their results to a calculation of free neutron-proton bremsstrahlung

(1989NA04) and they commented that agreement was found to be reasonable at lower photon energies, but failed at higher energies, possible due to the neglect of the neutron momentum in ^{2}H and/or Pauli blocking effects.

4. (a) ^{2}H(p + μ, $\gamma + \mu$)^{3}He $\quad Q_\mathrm{m} = 5.4935$
(b) ^{2}H(p + μ, μ)^{3}He $\quad Q_\mathrm{m} = 5.4935$

Muon catalyzed fusion of a proton and a deuteron is a process that has been studied for many years. The process is believed to proceed as follows (1991FR03): When a μ^- particle enters liquid hydrogen which contains a small amount of deuterium, it is captured by a proton and quickly settles into an atomic 1S state. This small, electrically neutral entity can travel fairly freely through the material. If the μ^- doesn't decay first, this muonic hydrogen-like atom can encounter a deuterium nucleus. Because of the larger mass of the deuterium and therefore the lower muonic energy levels (-2.66 keV vs. -2.53 keV; see (2003NA1F), page 72), the muon is transferred to the deuterium forming a muonic deuterium atom. The next step is the formation of a deuteron-proton-muon molecule with the proton and deuteron ultimately in a relative S state with essentially zero energy and an average p-d separation of about 500 fm (1990PO1H). Despite the large separation, the presence of the negatively charged muon can assist the fusion of the proton with the deuteron to form a ^{3}He nucleus. This can occur in two ways: In reaction (a), which is radiative muon catalyzed p-d fusion, a 5.5 MeV gamma ray is emitted and the muon is left in a bound state around the ^{3}He nucleus. In reaction (b), non-radiative muon catalyzed fusion, a ^{3}He nucleus is formed from fusion of the proton and deuteron and the muon carries away 5.3 MeV and may then start another fusion process. It was the observation of these fixed energy muons in a hydrogen bubble chamber reported in (1957AL32) that was an early experimental indication of muon catalyzed fusion. The bubble chamber photograph of this discovery is reproduced in (1992PE1F). See also (1992FR1G) which contains a review and brief history of muon catalyzed fusion and (1985BO2G) for additional early references and more details of the fusion process. Reviews of muon catalyzed fusion can be found in (1989BR1O) and (1998NAZZ). However, both of these references deal primarily with d-d and d-t fusion.

Of interest here is the spin dependence of the p-d fusion processes and the information that a detailed study of these processes can produce about the low energy p-d system and the ^{3}He bound state. The total spin of the p-d system is either $\frac{1}{2}$ (doublet) or $\frac{3}{2}$ (quartet). The radiative capture process, reaction (a), is predominantly an M1 transition. The fusion rate from the doublet state is somewhat larger than that from the quartet state. In liquid or solid mixtures of ordinary hydrogen and deuterium, it is possible to vary systematically the fusion yield from the quartet state relative to that of the doublet state by varying the concentration of deuterium and the temperature. This process is called the Wolfenstein-Gerstein effect; see (1992PE1F, 2004ES04). Using this procedure, the doublet and quartet fusion rates are found to be $(0.35 \pm 0.02) \times 10^6$ s^{-1} and $(0.11 \pm 0.01) \times 10^6$ s^{-1}, respectively (1992PE1F). Calculations using the Faddeev method with realistic NN interactions and including 3N interactions and meson currents reported in (1991FR03) give $(0.37 \pm 0.01) \times 10^6$ s^{-1} for the doublet state fusion rate and $(0.107 \pm 0.06) \times 10^6$ s^{-1} for the quartet. The uncertainty quoted in the calculated fusion rates is somewhat subjective. Note that the doublet and quartet p-d radiative capture M1 cross sections have been directly determined, as reported in (1997RI15), and found to be in reasonably good agreement with the predictions in (1991FR03).

The non-radiative fusion process, reaction (b), is essentially an internal conversion process involving primarily the E0 multipole. A calculation of this fusion rate is also reported to be $(0.062 \pm 0.002) \times 10^6$ s^{-1} (1991FR03) as compared to the experimental value of $(0.056 \pm 0.006) \times 10^6$ s^{-1}; see (1991FR03) for references. The same references also compares experimental and theoretical astrophysical S-factors for p-d fusion.

For both reactions (a) and (b), the agreement between experiment and theory is excellent. Since these zero energy fusion processes are complimentary to the usual bound state and scattering phenomena, they provide additional tests of three-body dynamics.

5. (a) ^{2}H(p, π^0)^{3}He	$Q_{\rm m} = -129.4831$
(b) ^{1}H(d, π^0)^{3}He	$Q_{\rm m} = -129.4831$
(c) ^{2}H(p, π^+)^{3}H	$Q_{\rm m} = -134.0953$
(d) ^{1}H(d, π^+)^{3}H	$Q_{\rm m} = -134.0953$
(e) ^{2}H(p, pπ^0)^{2}H	$Q_{\rm m} = -134.9766$
(f) ^{2}H(p, 2π^0)^{3}He	$Q_{\rm m} = -264.4597$
(g) ^{2}H(p, $\pi^+\pi^-$)^{3}He	$Q_{\rm m} = -273.6469$
(h) ^{2}H(p, π^-)^{1}H^{1}H^{1}H	$Q_{\rm m} = -141.0124$
(i) ^{2}H(p, ^{3}He)η	$Q_{\rm m} = -542.35952$

Reaction (c) is the same as ^{3}H reaction 6 and reaction (d) is the inverse of that reaction. They are included here because of their relationship to the other pion production reactions listed here.

After the NN $\rightarrow$ NNπ reactions, the next simplest pion production reactions involving nucleons are the reactions (a) through (d). The fact that the nuclear systems involved - ^{2}H, ^{3}H, ^{3}He - are reasonably well understood make these reactions of particular interest. It may also be possible to see at least the beginnings of the effects of the nuclear medium on the NN $\rightarrow$ NNπ reaction mechanism, effects that may show up in heavier nuclei. Table 3.9 lists references for reactions (a), (b) and (c). There are no reports of reaction (d).

An early theoretical study of the pion production reactions (a) and (c) is that of (1952RU1A), who introduced the so-called spectator or deuteron model. Refinements and developments of this model are referenced and discussed in (2005CA20). This latter reference contains calculations of the proton analyzing power $A_{\rm y}$ and differential cross sections for the reaction (a) using modern NN interactions and three-body Faddeev methods which are in rather good agreement with the data of (1987CA26) and (2003AB02). A study of the spin dependent form of the deuteron model is reported in (1994FA10, 2000FA03) in which vector and TAP's are calculated for the reactions (a) and (b) with polarized beams and comparisons with data of (1996NI06) are discussed.

Table 3.9: References for ^{2}H(p, π^0)^{3}He, ^{1}H(d, π^0)^{3}He and ^{2}H(p, π^+)^{3}H

References	E_p or E_d (MeV)	Comments
(1992PI14) [a]	E_p near 200	$\vec{p}$ beam; near threshold proton energies; measured $\sigma(\theta)$, $A_y(\theta)$, σ_{tot}
(1998GA47, 2000KL11, 2001BE35, 2001MB03) [b]	$E_p = 263$, 295, 328	Measured σ_{tot}, $\sigma(\theta)$; studied isospin symmetry
(2001MB03, 2003AB16) [b]	$E_p = 263$-470	Measured $\sigma(\theta)$ and σ_{tot} in Δ excitation region; studied isospin symmetry
(2001BE37) [a]	$E_p = 328$, 470	Measured $\sigma(\theta)$; compared with theory
(2000BE15) [b]	$E_p = 330$	Measured $\sigma(\theta)$; determined ratio σ(pd $\rightarrow$ ^{3}Hπ^+)/σ(pd $\rightarrow$ ^{3}Heπ^0)
(1987CA26) [a]	$E_p = 350$, 450, 500	$\vec{p}$ beam; measured $\sigma(\theta)$ and $A_y(\theta)$; poor agreement with theory
(2003AB02, 2003AB30) [b]	$E_p = 362$-470	Measured $\sigma(\theta)$ and σ_{tot} in Δ excitation region; analyzed reaction mechanism
(1996NI06) [c]	$E_d = 397.3$-429.7	Near π^0 threshold; $\vec{d}$ beam; measured σ_{tot}, $\sigma(\theta)$ and TAP's
(1988BO33) [c]	$E_d = 400.7$	Near π^0 threshold; $\vec{d}$ beam; measured T_{20}; analyzed production mechanism
(1989AD02) [a]	$E_p = 800$	$\vec{p}$ beam; measured $A_y(\theta)$; studied role of Δ; discrepancies with theory at back angles
(2003AB20, 2006RO27) [b]	$E_p = 882$-1004	Measured $\sigma(\theta)$; deduced isospin symmetry breaking

[a] Studied reaction ^{2}H(p, π^0)^{3}He only.
[b] Studied reactions ^{2}H(p, π^0)^{3}He and ^{2}H(p, π^+)^{3}H.
[c] Studied reaction ^{1}H(d, π^0)^{3}He only.

Table 3.10: References for ^{2}H(p, $2\pi^0$)^{3}He and ^{2}H(p, $\pi^+\pi^-$)^{3}He

References	E_p (MeV)	Comments
(1998AN36, 2000AN21, 2000AN30)	477	Measured cross section for double pion production and determined ratio $\sigma(\pi^+\pi^-; T = 1)/\sigma(\pi^+\pi^-; T = 0)$; studied pion production mechanism
(1999BE60)	546	Measured differential cross section for $\pi^+\pi^-$ reaction
(2006BA29)	893	Measured $\sigma(\theta)$ and invariant mass distributions; compared with double Δ excitation calculation

Isospin symmetry was studied in (2001BE35) by measuring simultaneously the two reactions ^{2}H(p, π^+)^{3}H and ^{2}H(p, π^0)^{3}He. The authors make the point that their experiment falls in energy between the pion threshold and the Δ excitation region. They comment that the ratio of the cross section for the π^+ channel to that for the π^0 channel should equal 2 if isospin symmetry holds. By measuring the ratio for both total and differential cross sections as well as by comparing reaction matrix elements, the authors concluded that the amount of isospin symmetry breaking was small.

Table 3.10 shows references of experimental studies in which either a $\pi^+\pi^-$ pair or two π^0's are produced in the formation of ^{3}He from the collision of a proton and a deuteron. It was found that, at energies near threshold for two pion production, a larger than expected production cross section is observed. The effect was originally observed in the 1960s by the authors Booth, Abashian and Crowe and is called the ABC effect; see the references in (2006BA29). As indicated in (2006BA29), the explanation for the effect is still unclear. Table 1 in (2000AN21) gives cross sections at incident $E_p = 477$ MeV for both $T = 0$ and $T = 1$ production of a $\pi^+\pi^-$ pair and for the production of two π^0's.

Table 3.11 lists references for reaction (e). The threshold proton energy for this reaction is 207 MeV. Total cross sections near threshold are reported in (1993RO08, 1993RO15). Fig. 3 in (1993RO08) shows a comparison of the total cross sections for the reactions (a) and (e) from (1992PI14) and ^{1}H(n, π^0)^{2}H from (1990HU01) for small values of the outgoing pion momentum. The cross section for reaction (e) is smaller than the other two by factors of 10^2 to 10^3 at the lowest energies. Table 3.11 also lists references for the related reaction, ^{1}H(d, pπ^0)^{2}H, for which the threshold deuteron energy is 414 MeV. In both (1988BO33) and (1996NI06), polarized deuterons were used to obtain $\sigma(\theta)$ and TAP's. Evidence is given in (1996NI06) for significant interference between the s- and p-wave pion production.

Reaction (e) has also been used to study quasi-free neutron-proton reactions such as ^{1}H(n, π^0)^{2}H by using configurations such that the outgoing proton is essentially a spectator; see (2000BI09, 2001BI01, 2004LE32).

Table 3.11: References for ^{2}H(p, pπ^0)^{2}H and ^{1}H(d, pπ^0)^{2}H

References	E_p or E_d (MeV)	Comments
(1993RO08, 1993RO15)	$E_p = 208.4$-294.6	Measured σ_{tot} near threshold; compared with theory
(2000BI09, 2001BI01)	$E_p = 320$	Measured spectator proton spectrum; compared with theory
(1996NI06)	$E_d = 397$-430	$\vec{d}$ beam; measured $\sigma(\theta)$, analyzing powers
(1998GR24, 2000GR31)	$E_d = 437$-559	Kinematically complete study of both ^{1}H(d, d′p)π^0 and ^{1}H(d, d′π^+)n; measured σ_{tot}
(2004LE32)	$E_p = 585$	Measured proton spectrum and missing mass

The η and π^0 mesons both have spin zero and negative parity and are uncharged. The η is more massive than the π^0, 547.85 MeV compared to 134.98 MeV. The π^0 is part of an isospin triplet while the η has isospin zero. The π^0 decays primarily into two photons with a mean lifetime of $(8.4 \pm 0.6) \times 10^{-17}$ s; the η decays primarily into either two photons, one photon and two pions or three pions with a mean lifetime of about $(5.06 \pm 0.27) \times 10^{-19}$ s. References for reaction (i) are listed in Table 3.12. The threshold energy for this reaction is 892 MeV. Also listed in the same table are references for the inverse reaction ^{1}H(d, ^{3}He)η, the threshold for which is 1783 MeV and the inelastic scattering reaction ^{2}H(p, p′d)η, the threshold for which is 902 MeV.

As shown in Fig. 4 of (2007ME11) and Fig. 1 of (2007KH18), the total cross section for reaction (e) rises rapidly from zero to about 400 nb just above threshold and remains nearly flat for the next 10 MeV or so of excess energy. Of particular interest is the interaction between the η and the remaining nucleus and whether the system forms a bound or quasi-bound state; see (1993WI04, 1995FA12, 2003KH14, 2003ST01, 2004SI30, 2004SI32, 2007UP01). Total cross sections for ^{2}H(p, ^{3}H)η and ^{2}H(d, ^{4}He)η are compared in (1997WI11, 2002BI02). Cross sections for reactions (a) and (i) are compared in (2004SI32).

6. (a) ^{2}H(p, n)^{1}H^{1}H $\qquad Q_m = -2.2246$
   (b) ^{1}H(d, n)^{1}H^{1}H $\qquad Q_m = -2.2246$
   (c) ^{1}H(d, pp)n $\qquad Q_m = -2.2246$

Tables 3.4.1 in (1975FI08) and 3.11 in (1987TI07) contain references for these reactions for the periods covered by those evaluations. In both of these earlier evaluations, the number of references and the amount of work reviewed is quite extensive. Table 3.13 lists references for these reactions since 1987.

Table 3.12: References for ^{2}H(p, ^{3}He)η, ^{1}H(d, ^{3}He)η and ^{2}H(p, p′d)η

References	E_p or E_d (MeV)	Comments
(2007ME11)	$E_\text{p} = 883$-912	Measured $\sigma(\theta)$ and σ_tot; compared with earlier data
(1996MA15)	$E_\text{p} = 892$-903	Measured σ_tot; studied reaction mechanism and FSI
(2007AD02)	$E_\text{p} = 900$-964	Measured $\sigma(\theta)$ and σ_tot; compared with theory; also see (2007KH18)
(2000HI13)	$E_\text{p} = 905$, 909	Studied ^{2}H(p, p′d)η; measured σ_tot near threshold; compared with ^{2}H(p, ^{3}He)η and theory
(2002BI02, 2004BI04)	$E_\text{p} = 930$-1100	Kinematically complete study of ^{2}H(p, p′d)η; measured $\sigma(\theta)$ and σ_tot; compared with theory
(2000BE01)	$E_\text{p} = 980$	Measured σ_tot; studied reaction mechanism
(1988BE25)	$E_\text{d} = 1783$-1855	$\vec{\text{d}}$ beam; measured $\sigma(\theta)$ and T_{20}; compared with ^{1}H(d, ^{3}He)π^0

In kinematically complete three-body breakup experiments in which the two protons are observed, a commonly used way of viewing the coincidence spectrum of the two protons makes use of a three-body kinematical curve. If the observed protons are arbitrarily labeled p_1 and p_2, then the energy and emission angle of the unobserved neutron can be determined from energy and momentum conservation if the proton energies E_1 and E_2, their polar angles θ_1 and θ_2 and the relative azimuthal angle ϕ_{12} are measured. For any given set of values of θ_1, θ_2 and ϕ_{12} - determined by the locations of the detectors - the allowed values of E_1 and E_2 lie along a curve in E_1-E_2 space energy calculated using energy conservation. This curve is called the three-body kinematical curve; the arc length along this curve is called S and has units of energy. S is set equal to zero where E_2 equals zero. Any pair of (E_1, E_2) values for coincidence protons corresponds to a point in this space on or near the kinematical curve. By dividing the S curve into bins, one can obtain differential cross sections $\text{d}^5\sigma/\text{d}\Omega_1\text{d}\Omega_2\text{dS}$ as functions of S. A number of such curves can be seen in (2005KI19), for example, for different values of θ_1, θ_2 and ϕ_{12}.

Some detector configurations have received special attention. If the angle ϕ_{12} is set to $180°$ and θ_1 and θ_2 are both set to $60°$, then when $E_1 = E_2 = \frac{1}{2}E_\text{cm}$, the neutron will be at rest in the center of mass system. For other values of θ_1 and θ_2, there will be (E_1, E_2) points at which the neutron is at rest. Such configurations which allow for the possibility of the neutron being at rest in the center of mass system are called collinearity configurations. Several examples are shown in (1994AL21) where differential cross section and A_y curves are shown as functions of the arc length S and the collinearity points are labeled.

Table 3.13: References for ^{2}H(p, n)^{1}H^{1}H, ^{1}H(d, n) ^{1}H^{1}H and ^{1}H(d, pp)n since 1987

References	E_p or E_d (MeV)	Comments
(1991RA19)	$E_\mathrm{p} = 13.0$	$\vec{\mathrm{p}}$ beam; detected p_1, p_2; measured cross section and A_y in four configurations; compared with Faddeev calculations
(1999BE18)	$E_\mathrm{p} = 15.8$	Detected n's at $0°$; measured energy spectrum from thick ^{2}H target
(1994ZA10)	$E_\mathrm{p} = 22.7$	Detected p_1, p_2; measured differential cross section for several detector configurations; compared with theory
(1995QI02)	$E_\mathrm{d} = 52.1$	$\vec{\mathrm{d}}$ beam; detected p_1, p_2 in collinear and coplanar configurations; measured VAP and TAP; compared with Faddeev calculations
(1990PI09)	$E_\mathrm{p} = 54, 71$	$\vec{\mathrm{p}}$ beam; detected n's at $0°$; measured n spectrum, polarization and polarization transfer coefficient; compared with other data and impulse approximation calculation with pp $^1\mathrm{S}_0$ FSI
(1994AL21, 1996AL34, 1997ZE01)	$E_\mathrm{p} = 65$	$\vec{\mathrm{p}}$ beam; detected p_1, p_2; measured analyzing power and differential cross section; compared with theory; see also (1996AL10, 2001BI08)
(1999ZE05)	$E_\mathrm{p} = 70$	$\vec{\mathrm{p}}$ beam; detected n's; measured $0°$ polarization transfer; compared with Faddeev calculation
(2003KI21)	$E_\mathrm{d} = 130$	Observed p_1, p_2; measured differential cross sections for three-body breakup in 38 different configurations; compared with several models; observed NNN effects
(2005KI19)	$E_\mathrm{d} = 130$	Continuation of (2003KI21); measured differential cross sections for three-body breakup in 72 different configurations; compared with several models; observed NNN effects
(2006KI13)	$E_\mathrm{d} = 130$	Continuation of (2005KI19); studied effect of Coulomb force in deuteron-proton breakup
(2006BI03)	$E_\mathrm{d} = 130$	$\vec{\mathrm{d}}$ beam; observed p_1, p_2 in three configurations; measured analyzing powers; compared with theory; observed no NNN effects

Table 3.13: References for ^{2}H(p, n)^{1}H^{1}H, ^{1}H(d, n) ^{1}H^{1}H and ^{1}H(d, pp)n since 1987 (continued)

References	E_p or E_d (MeV)	Comments
(1996AN16)	$E_p = 135$	Detected n's; measured cross section for six lab angles from $0°$ to $30°$; studied FSI in pp system and QFS in np system; compared with impulse approximation and Faddeev calculations
(1987SA02)	$E_p = 160$	$\vec{p}$ beam; detected n's at $0°$; measured n spectrum, polarization and polarization transfer coefficient; compared with impulse approximation with pp $^{1}S_0$ FSI
(2004VO07)	$E_p = 190$	Studied p-n bremsstrahlung; detected p, n, γ-ray; compared with model
(2008MA52)	$E_p = 190$	$\vec{p}$ beam; measured cross section, VAP; compared with theory
(2002PR04)	$E_p = 197$	$\vec{p}$ beam; measured p $\rightarrow$ n polarization transfer observables at four lab angles in quasifree region; compared with theory
(1995PA37)	$E_p = 200$	$\vec{p}$ beam; detected p and n in coplanar configuration; measured cross section and analyzing power
(1998AN09)	$E_p = 200$	$\vec{p}$ beam in three spin states; measured n spectrum and spin transfer coefficients near QFS peak
(1999CA11, 1999CA15)	$E_p = 200$	$\vec{p}$ beam; studied QFS for both (p, 2p) and (p, np); measured cross section and analyzing power; compared with impulse approximation
(2004ME16)	$E_d = 270$	$\vec{d}$ beam and $\vec{p}$ target; detected p_1 and p_2 kinematically complete; measured analyzing power and tensor correlation coefficients; compared with Faddeev calculations; looked for NNN effects
(1994SA43)	$E_p = 300$, 400	$\vec{p}$ beam; detected n's in QFS process; compared (p, n) reaction on ^{2}H with several other targets
(1992MC06)	$E_p = 305$-788	$\vec{p}$ beam; deduced n polarization; measured spin transfer parameter
(1993ME06)	$E_p = 318$, 494	$\vec{p}$ beam; detected $\vec{n}$; measured polarization transfer coefficient

Table 3.13: References for ^{2}H(p, n)^{1}H^{1}H, ^{1}H(d, n) ^{1}H^{1}H and ^{1}H(d, pp)n since 1987 (continued)

References	E_p or E_d (MeV)	Comments
(2004WA12)	$E_p = 345$	$\vec{p}$ beam; measured polarization of outgoing n's, differential cross section and polarization parameters in quasielastic region; deduced longitudinal and transverse spin functions; compared with theory
(1998SA15, 1999WA08)	$E_p = 346$	$\vec{p}$ beam; measured n spectrum and n polarization, A_y and polarization transfer coefficients, longitudinal and transverse spin functions in quasielastic region
(1992MC09, 1993CH13, 1994TA15, 1994TA24)	$E_p = 495$	$\vec{p}$ beam; detected n's; measured polarization transfer coefficients in QFS; studied isovector spin response
(1993GL01)	$E_p = 643$, 797	$\vec{p}$ beam; detected scattered p's and either recoil p or n in QFS configuration; measured analyzing power; compared with free n + p scattering
(1994PR08)	$E_p = 795$	$\vec{p}$ beam; detected n's; measured spin observables in Δ excitation region; deduced cross sections; compared with theory
(1990AL06)	$E_p = 1$ GeV	Detected p_1 and p_2 in kinematically complete experiment; measured cross section and recoil p polarization; compared with impulse approximation
(1994AL07)	$E_p = 1$ GeV	Detected either p and n, or p and p in QES arrangement; compared with theory

7. (a) ^{2}H(p, p)^{2}H
   (b) ^{1}H(d, d)^{1}H

Table 3.14 gives references for the scattering processes ^{2}H(p, p)^{2}H and ^{1}H(d, d)^{1}H since the previous evaluation. Tables 3.5.1a and 3.5.1b in (1975FI08) and Table 3.12 in (1987TI07) list earlier references for these reactions.

Table 3.14: References for ^{2}H(p, p)^{2}H and ^{1}H(d, d) ^{1}H

References	$E_{\rm p}$, $E_{\rm d}$, or $E_{\rm c.m.}$ (MeV)	Comments
(1999KA46)	$E_{\rm cm} = 0.163$-2	$\vec{\rm p}$, $\vec{\rm d}$ beams; measured cross section, VAP and TAP; compared with theory; studied 3N force effects
(1997KI17)	$E_{\rm cm} = 0.432$	$\vec{\rm d}$ beam; measured T_{20} and T_{22}; compared with theory; obtained p-d scattering lengths and D/S asymptotic ratio
(1998BR11)	$E_{\rm cm} = 0.43$	$\vec{\rm p}$, $\vec{\rm d}$ beams; measured $A_{\rm y}$ and iT_{11}; compared with theory including 3N force; find discrepancy in both analyzing powers
(2001BR12)	$E_{\rm cm} = 0.43$-2.0	$\vec{\rm p}$, $\vec{\rm d}$ beams; measured σ, VAP and TAP, excitation function for iT_{11}; compared with theory; observe discrepancy in analyzing powers
(2001WO06, 2002WO05)	$E_{\rm cm} = 0.667$	Measured cross sections and analyzing powers for both ^{2}H(p, p) and ^{1}H(d, d) with $\vec{\rm p}$, $\vec{\rm d}$ respectively; deduced phase shifts; compared with 2N and 3N model predictions; studied $A_{\rm y}$ puzzle
(2001KI03, 2001KI22)	$E_{\rm p} = 1$, $E_{\rm d} = 1$	Measured cross section; compared with theory; studied 3N force effects
(1996KI15)	$E_{\rm p} = 1$-3, $E_{\rm d} = 5$,6	$\vec{\rm p}$, $\vec{\rm d}$ beams, determined cross section, phase shifts, VAP and TAP
(2007DE31)	$E_{\rm p} = 1.9$-3.0	Measured differential cross sections for lab angles of 151 and 167 degrees; compared results with earlier measurements
(1995SH25)	$E_{\rm p} = 2$-4, $E_{\rm d} = 5$,6	$\vec{\rm p}$, $\vec{\rm d}$ beams; measured $A_{\rm y}$, iT_{11}, T_{21}, T_{22}; compared with Faddeev calculation
(1994SA26)	$E_{\rm p} = 2$-18	Used polarized and unpolarized p's; measured energy dependence of cross section and $A_{\rm y}$; compared with Faddeev calculation

Table 3.14: References for ^{2}H(p, p)^{2}H and ^{1}H(d, d) ^{1}H (continued)

References	E_p, E_d, or E_{cm} (MeV)	Comments
(1993KN02)	$E_p = 3$; $E_d = 6$	$\vec{p}$, $\vec{d}$ beams; measured cross section, analyzing powers; deduced phase shift parameters; compared with Faddeev calculation
(1987SO05)	$E_d = 10$	$\vec{d}$ beam; measured $iT_{11}(\theta)$, $T_{20}(\theta)$, $T_{21}(\theta)$, $T_{22}(\theta)$; compared with Faddeev calculation
(1988RA43)	$E_p = 10$-16.5	$\vec{p}$ beam; measured cross sections and analyzing powers especially at forward and back angles; compared with Faddeev calculations with realistic potentials
(1993SY01, 1994SY01, 1998SY01)	$E_p = 19$	$\vec{p}$ beam; observed polarization of outgoing p's and d's; measured analyzing powers and polarization transfer coefficients; compared with Faddeev calculations with different NN forces and force components
(1989CL06, 1990CL01, 1990GR20)	$E_p = 22.7$	$\vec{p}$ beam; measured polarization transfer coefficients; deduced properties of n-p system; compared with Faddeev calculation
(2006WI09)	$E_p = 22.7$	$\vec{p}$ beam; observed polarization of outgoing p's or d's; measured polarization transfer coefficients; compared with Faddeev calculation
(1989KI03)	$E_p = 43$	$\vec{p}$ beam; deduced analyzing power; looked for parity non-conservation
(1987NA03)	$E_p = 65$	$\vec{p}$ beam; measured depolarization parameter as function of θ
(1987AR30)	$E_d = 70$	$\vec{d}$ beam; measured cross section and VAP; compared with Faddeev calculation
(1993WI25)	$E_d = 75$-187	$\vec{d}$ beam; measured analyzing powers; compared with Faddeev calculations with realistic NN interactions

Table 3.14: References for ^{2}H(p, p)^{2}H and ^{1}H(d, d) ^{1}H (continued)

References	E_p, E_d, or E_{cm} (MeV)	Comments
(2001ER01, 2001ER02)	$E_p = 108$-170	Measured VAP's; compared with theory; deduced no improvement with 3N force
(2003ER04, 2004KA28, 2005ER03, 2007KA38)	$E_p = 108$-190	$\vec{p}$ beam; measured cross section and VAP; compared with theory; deduced 3N force effects
(1991CA32)	$E_d = 120$-150	$\vec{d}$ beam; measured $iT_{11}(\theta)$, $T_{22}(\theta)$, $T_{20}(\theta)$, $T_{21}(\theta)$
(1990WI21)	$E_p = 120$, 200	$\vec{p}$ beam; measured p-d coincidence spectra; deduced analyzing power
(2003KI21, 2005KI19, 2007ST29)	$E_d = 130$	$\vec{d}$ beam; measured cross section, VAP, TAP; compared with Faddeev calculation with modern NN and 3N forces; 3N force effects seen
(2008RA17)	$E_d = 130$, $E_p = 135$	$\vec{p}$ and $\vec{d}$ beams; measured differential cross sections; VAP and TAP; compared with previous experiments
(2007MA23)	$E_d = 130$, 180	$\vec{d}$ beam; measured VAP and TAP; compared with theory; differences found
(2006PR22)	$E_p = 135$, 200	$\vec{p}$ beam and $\vec{d}$ target; detected both outgoing particles; measured cross section, analyzing powers and spin correlation coefficients; compared with Faddeev theory including 3N force
(2005SE22)	$E_p = 135$; $E_d = 270$	Studied both ^{2}H(p, p) and ^{1}H(d, d); measured cross section, compared with previous measurements and theory; deduced 3N force and relativistic effects
(2001SE09, 2002SE03)	$E_d = 140$, 200, 270	$\vec{d}$ beam; measured cross section, VAP and TAP; compared to Faddeev calculations with modern NN and 3N forces

Table 3.14: References for ^{2}H(p, p)^{2}H and ^{1}H(d, d) ^{1}H (continued)

References	E_p, E_d, or E_{cm} (MeV)	Comments
(2000BI02, 2001KA25)	$E_p = 150, 190$; $E_d = 270$	$\vec{p}$, $\vec{d}$ beams; measured VAP and TAP; compared with theory; deduced role of 3N force
(2007AM03)	$E_d = 180$	$\vec{d}$ beam; measured cross section, VAP, TAP, spin-transfer coefficients; compared with theory; deduced 3N force effects
(2001CA05, 2001KI18)	$E_p = 197$	$\vec{p}$ beam and $\vec{d}$ target, measured analyzing powers, spin correlation parameters; compared with theory; deduced 3N force effects
(1994BU11)	$E_p = 198.5$, 297.6, 456.6	Measured cross section; deduced scattering length
(1998RO12)	$E_p = 200$, 221, 235, 258, 295	Measured $\sigma(\theta)$ for center of mass angles from $11°$ to $29°$; compared with Faddeev calculations; suspect possible relativistic effects
(2002HA43, 2003HA41, 2003SH45)	$E_p = 250$	$\vec{p}$ beam; measured cross section, analyzing power, polarization transfer coefficients; compared with Faddeev calculations; deduced 3N force effects
(1996SA45)	$E_d = 270$	$\vec{d}$ beam; measured $\sigma(\theta)$, VAP and TAP; compared with Faddeev calculation
(2000SA24, 2001SA14, 2001SA33, 2003SE06, 2003SE18, 2004SE07)	$E_d = 270$	$\vec{d}$ beam; measured polarization transfer coefficient; compared with model calculations
(2003TA43)	$E_p = 392$	$\vec{p}$ beam; measured cross section, VAP; compared with model predictions
(1987RA17)	$E_p = 500$, 800	$\vec{p}$ beam; measured polarization and asymmetry of scattered p's and spin transfer observables; compared with relativistic multiple scattering model

Table 3.14: References for ^{2}H(p, p)^{2}H and ^{1}H(d, d) ^{1}H (continued)

References	E_p, E_d, or E_{cm} (MeV)	Comments
(1991GU01)	$E_p = 641.3, 792.7$	Measured cross section; compared with relativistic theory
(1989GR20)	$E_p = 695\text{-}991$	Compared p + ^{2}H and p + ^{4}He scattering
(1992GU01)	$E_p = 794$	$\vec{p}$ beam and $\vec{d}$ target; measured various spin quantities; compared with relativistic calculations
(1988AD02, 1988IG02)	$E_p = 800$	$\vec{p}$ beam and $\vec{d}$ target; measured analyzing powers and spin transfer coefficients
(2008JA07, 2008KU14)	$E_d = 880$	$\vec{d}$ beam; measured VAP and TAP; compared with theory
(1989AV02)	$E_d = 0.9\text{-}10$ GeV	$\vec{d}$ beam; measured analzing power
(1999BB21, 1999DE47)	$E_p = 1.1\text{-}2.4$ GeV	$\vec{p}$ beam and polarized and unpolarized targets; measured analyzing powers, spin correlation parameters, polarization transfer quantities; compared with other data and theory
(1987HA35)	$E_d = 1.2$, 1.8, 2.0 GeV	$\vec{d}$ beam; measured vector and tensor spin observables; compared to relativistic multiple scattering theory
(1997LA21)	$E_p = 1.25$ GeV	$\vec{p}$ beam and $\vec{d}$ target; measured spin correlation and transfer quantities
(1988DE30)	$E_d = 1.488$, 1.588 GeV	$\vec{d}$ beam and $\vec{p}$ target; measured analyzing powers and spin correlations
(1991GH01)	$E_d = 1.6$ GeV	$\vec{p}$ beam and $\vec{d}$ target; measured many vector and tensor spin observables; compared to previous experiments and to relativistic impulse approximation
(1997AZ02, 1998AZ02)	$E_d = 2.1\text{-}4.9$ GeV	$\vec{d}$ beam; measured $\sigma(\theta)$ and $T_{20}(\theta)$; studied reaction mechanism
(1989OH04)	$E_p = 3.5$ GeV	$\vec{p}$ beam; measured analyzing power; compared with Glauber theory

Low energy s-wave proton-deuteron scattering can be characterized by two quantities, the doublet scattering length, ${}^2a_{pd}$ and the quartet scattering length, ${}^4a_{pd}$. As stated in ^{3}H reaction 4, the corresponding neutron-deuteron quantities are ${}^2a_{nd}$ and ${}^4a_{nd}$, the frequently quoted values for which are 0.65 ± 0.04 fm and 6.35 ± 0.02 fm respectively. (See ^{3}H reaction 4 for references and more details.) The corresponding quantities for proton-deuteron scattering are less well known. Table 2 in (1999BL26) quotes three early experimental determinations of ${}^4a_{pd}$ that have an average value of about 11.5 ± 0.2 fm while their own analysis gives 14.7 ± 2.3 fm. In Table 1 of the same reference, three calculated values of ${}^4a_{pd}$ are quoted all near 13.8 fm. Less certain is the doublet length. The same two tables in (1999BL26) give experimental values ranging from 1.3 fm to 4.0 fm and calculated values that range from -0.1 fm to 0.257 fm. Their own data analysis gives -0.13 ± 0.04 fm. Table 1 and Fig. 1 in (2006OR07) illustrate the various values obtained for this quantity. In the opening sentence of (2006OR07), the authors state, "The problem of determining the doublet nuclear proton-deuteron scattering length ${}^2a_{pd}$ has yet to be solved conclusively." For an early discussion of these matters, see (1989CH10, 1990FR18). In these references it is discussed that the doublet effective range function has a significant curvature at low energies. This makes it difficult to extrapolate to zero energy in order to determine the scattering length. A study of ${}^2a_{pd}$ and ${}^4a_{pd}$ using Faddeev methods and several interaction models is reported in (1991CH16). These authors present a Phillips line relating calculated ${}^2a_{pd}$ values as a function of calculated ^{3}He binding energy values. Near the experimental binding energy of 7.72 MeV, the resulting ${}^2a_{pd}$ is approximately zero. Their calculated value for ${}^4a_{pd}$ for two different two- and three-body interactions are 13.76 ± 0.05 fm and 13.52 ± 0.05 fm (where the quoted errors are somewhat subjective), respectively. It appears, then, that ${}^2a_{pd}$ is approximately zero and ${}^4a_{pd}$ is approximately 14 fm, both with significant uncertainties.

Most of the experiments referenced in Table 3.14 make use of either polarized proton or polarized deuteron beams. In addition to differential cross section measurements, such beams have enabled detailed measurements to be made of the vector analyzing power, $A_{\rm y}$, with polarized proton beams and of vector and tensor analyzing powers iT_{11}, T_{20}, T_{21} and T_{22} with polarized deuteron beams. As NN and NNN interactions and three-body calculations became more sophisticated, it was discovered that the three-body models gave differential cross sections in reasonably good agreement with experiment, but resulted in a serious discrepancy between the calculated and experimental values of certain analyzing powers. This effect has become known as the $A_{\rm y}$ puzzle or more generally as the analyzing power puzzle, since the discrepancy was found to occur not only in $A_{\rm y}$ but also in iT_{11}. This puzzle occurs also in neutron-deuteron scattering as discussed in ^{3}H reaction 4. The references (1996GL05, 1998TO07, 2008TO12) contain examples of the effect for both n + d and p + d scattering. The energy dependence of the discrepancy in p + d scattering is illustrated in Fig. 5 of (2008TO12) which shows that it is essentially constant for $E_{\rm p}$ up to about 25 MeV, then starts to decrease and goes away at around 40 MeV. See ^{3}H reaction 4 for additional comments and references concerning the analyzing power puzzle, its possible origins including relativistic effects. The reference (2008TO20) has a discussion of the history of the analyzing power puzzle. The analyzing power puzzle is still an open question as is illustrated by the recent study of the effects of three-body forces reported in (2009KI1B, 2010KI05). See also (2009MA53).

In the early days of calculations of p + d scattering, the Coulomb interaction was ignored. More recent calculations that include the Coulomb interaction have shown that it is important, especially at low energies and forward angles; see (2002AL18, 2006DE26, 2008DE1D). Figs. 2 through 7 in (2002AL18) show calculations of differential cross sections and VAP's and TAP's for a number of energies with and without the Coulomb interaction.

The influence of the three-body force may be appearing in a detailed analysis of elastic p + d scattering in what is referred to as the Sagara discrepancy. In (1994SA26), it was found that a small discrepancy existed between theory and experiment at the angle where differential cross section is a minimum. In (2002AL18, 2009IS04), it is shown that including the Coulomb interaction in the calculations has an effect on the details of the Sagara discrepancy, but it does not eliminate it. In (1998WI22), studies of n + d scattering show that when the three-body interaction is taken into account, most of the discrepancy is removed.

Table 3.15: References for ^{3}He(γ, π^{+})^{3}H and ^{3}He(γ, π^{+})X; X = nd and nnp

Reference	E_{γ} (MeV)	Comments
(1993DH01)	210-450	Measured cross sections in Δ excitation region; analyzed reaction mechanism; compared with theory
(1987BE27)	250-450	Measured cross sections for reaction 9(a) and ^{3}H(γ, π^{-})^{3}He; compared with theory and earlier measurements

8. (a) ^{3}He(γ, π^{0})^{3}He $Q_{\mathrm{m}} = -134.9766$
   (b) ^{3}H(γ, π^{0})^{3}H $Q_{\mathrm{m}} = -134.9766$
   (c) ^{3}He(γ, $\pi^{+}\pi^{-}$)X $Q_{\mathrm{m}} = -279.1404$

The only reference relating to reaction (a) since the previous evaluation is (1988AR08) where previous data on the photoproduction of π^{0} on ^{2}H, ^{3}He and ^{4}He are reanalyzed using updated results for cross sections of the photoproduction of π^{0} from the proton.

There are no new references for reaction (b).

A study of reaction (c) was first reported in (1997WA09), in which photons of energies from 380 MeV to 700 MeV were used. Additional studies, some at higher energies, are reported in (1998HU10, 1998LO01, 1999KA38, 2003HU17). Of interest in these studies is the determination of the mass of the ρ meson in the nuclear medium.

9. (a) ^{3}He(γ, π^{+})^{3}H $Q_{\mathrm{m}} = -139.5888$
   (b) ^{3}He(e, e$'\pi^{+}$)^{3}H $Q_{\mathrm{m}} = -139.5888$
   (c) ^{3}He(e, e$'$K^{+})$^{3}_{\Lambda}$H $Q_{\mathrm{m}} = -675.9408$

References for reaction (a) since the previous evaluation are listed in Table 3.15.

In the introductory remarks in (1991KA32), there is a nice discussion of both experimental and theoretical aspects of reaction (a) for the period prior to 1991. These authors study final state interaction (FSI) effects in reaction (a) and find that they are considerable. They also study the two-step excitation process ^{3}He(γ, π^0)^{3}He(π^0, π^+)^{3}H and show that it is important in the higher energy region around the Δ excitation energy. Calculations of polarization observables for reaction (a) were reported in (1992KA31). Studies of the FSI effects in reaction (a) have also been reported in (1994CH15). The role of meson exchange currents near the Δ excitation peak in reaction (a) is studied in (1996GO37). This reference also reports studies of polarization observables for experiments using polarized photons.

Table 3.16: References for ^{3}He(e, e$'\pi^+$)X; X = ^{3}H, n^{2}H and nnp since the previous evaluation

References	$E_{\rm e}$ (MeV)	Comments
(1996BL20, 1997BL13, 2001KO23, 2002KO16)	555-855	Measured longitudinal and transverse cross sections; compared with theory; studied medium effects; searched for Δ's in ^{3}He ground state; compared with ^{3}He(e, e$'\pi^-$)ppp
(2000HI09)	720	$\vec{\rm e}$ beam and $^3\overrightarrow{\rm He}$ target; demonstrate possibility of detecting recoiling ^{3}He and ^{3}H from reactions ^{3}He(e, e$'^3$He)π^0 and ^{3}He(e, e$'^3$H)π^+
(2001GA63, 2001JA08, 2002GA02)	845-3245	Measured longitudinal and transverse cross sections for ^{3}He(e, e$'\pi^+$)X for X = ^{3}H, n^{2}H and nnp; compared with ^{3}He(e, e$'\pi^-$)ppp, H(e, e$'\pi^+$)n and ^{2}H(e, e$'\pi^+$)nn

Results of cross section measurements of ^{3}He(γ, π^+)X for X = ^{3}H, nd and nnp are shown in (1993DH01) for several energies near the Δ excitation region. The results show a narrow peak at the highest outgoing pion momentum corresponding to the X = ^{3}He channel and a broad peak at lower outgoing pion momenta corresponding to the X = nd and nnp channels. In the same energy region, cross sections for both ^{3}He(γ, π^+) and ^{3}H(γ, π^-) are reported in (1987BE27).

References with measurements related to reaction (b) are shown in Table 3.16.

The cross sections for the two reactions ^{3}He(e, e$'\pi^+$)X and ^{3}He(e, e$'\pi^-$)ppp as functions of the missing mass for the incident $E_{\rm e} = 555$, 600, 675 and 855 MeV are reported in (1996BL20); see also (1997BL13). The channel with X = ^{3}H is visible as a narrow peak at zero missing mass. The cross section for the breakup channels with X = nd and nnp is about a factor of two larger than that for the π^-ppp channel for most missing mass values. However, since the π^+nd channel has no equivalent in the π^-ppp cross section, there are small differences in the shape of the two cross sections at low missing mass. In the references (1996BL20, 1997BL13) just mentioned as well as follow-up studies by the same group (2001KO23, 2002KO16), parallel kinematics (i.e., pion and virtual photon have same directions) are used and cross sections measured as functions of virtual photon polarization which allows transverse and longitudinal cross sections to be determined. The polarization and flux of the virtual photons can be calculated using kinematics of the scattered electrons; see (1997BL13) and references therein.

Studies of reaction (b) and ^{3}He(e, e′π^-)ppp at $E_e = 0.845$-3.245 GeV in parallel kinematics were reported in (2001GA63, 2001JA08, 2002GA02). As in the earlier, lower E_e studies mentioned above, the π^{+3}H channel is separated from the π^+nd and π^+nnp channels. At larger values of the missing mass, the yields of the π^+ channels are almost exactly twice that of the π^- channels and the effect of the π^+nd channel at intermediate missing mass values is seen; see Fig. 2 in (2001JA08). The reaction (b) results were compared with the analogous reactions using H and ^{2}H targets in (2001GA63).

Table 3.17: References for ^{3}He(γ, p)^{2}H

References	E_γ (MeV)	Comments
(2006NA10)	10.2, 16.0	Measured cross sections; compared with earlier measurements and theory
(2003SH18, 2003SH27)	10.9, 16.5	Measured cross sections; compared with earlier measurements and theory
(1986BE34)	90-350	$\vec{\gamma}$ beam; measured cross section asymmetry
(1994KO11)	172, 185, 197, 208	Tagged $\vec{\gamma}$ beam; measured differential cross sections; compared with theory and other experiments; for three-body breakup study by same group, see (1996KO45) in Table 3.19
(1985GO25)	200	$\vec{\gamma}$ beam; measured polarization of outgoing protons; studied asymmetry
(1994IS05)	200-800	Used tagged photons; detected outgoing p and d; compared excitation functions with other experiments; measured differential cross sections at 30 energies; compared several with theory; for three-body breakup study by same group, see (1997AU02) in Table 3.19

In a study reported in (2000HI09), an ultra-thin polarized ^{3}He target is used to detect the recoil nuclei in the reactions $^3\overrightarrow{\mathrm{He}}(\vec{\mathrm{e}}$, e′^{3}He)$\pi^0$ and $^3\overrightarrow{\mathrm{He}}(\vec{\mathrm{e}}$, e′^{3}H)$\pi^+$.

With regard to reaction (c), studies of the production of kaons by inelastic scattering of electrons from light nuclei, including ^{3}He, has been reported in (2001RE09, 2001ZE06, 2004DO16, 2007DO1D). As discussed in ^{3}H reaction 11, $^3_\Lambda$H is the lightest hypernucleus. There is evidence for the production of this nucleus in the missing mass plots shown in these references. In all of these studies, the energy of the electron beams is 3.245 GeV. Cross sections were measured for

Table 3.18: References for ^{3}He(γ, pn)^{1}H

Reference	E_γ (MeV)	Comments
(1991KO16)	45-95	Measured cross section in a kinematically complete experiment; quasi-deuteron breakup observed; obtained ratio to deuteron breakup cross section
(1994EM01)	145-425	Used tagged photons to measure cross section in configurations in which one proton was essentially a spectator; compared with ^{2}H(γ, p)n data.
(1994TE07)	235-305	$\vec{\gamma}$ beam; measured cross section and asymmetries; compared (γ, pp) with (γ, pn) results and with theory

^{2}H, ^{3}He, ^{4}He and ^{12}C targets and compared with ^{1}H. The effective proton numbers were obtained, which turned out to be 1.76 ± 0.26 for ^{3}He.

10. (a) ^{3}He(γ, p)^{2}H $\quad Q_\mathrm{m} = -5.4935$
    (b) ^{3}He(γ, n)2^{1}H $\quad Q_\mathrm{m} = -7.7180$
    (c) ^{3}He(γ, np)^{1}H $\quad Q_\mathrm{m} = -7.7180$
    (d) ^{3}He(γ, pp)n $\quad Q_\mathrm{m} = -7.7180$
    (e) ^{3}He(γ, pπ^+)2n $\quad Q_\mathrm{m} = -148.0706$
    (f) ^{3}He(γ, pπ^-)2^{1}H $\quad Q_\mathrm{m} = -146.5059$

Reaction (a) is the only two-body breakup channel possible for the photodisintegration of ^{3}He. See Table 3.17 for references relative to reaction (a). For discussion of the three-body breakup reaction, it is convenient to indicate which outgoing particles are observed - the neutron only as indicated in (b), the neutron plus one proton as in (c) or both protons as in (d). There have been no reports of studies of reaction (b) since the previous evaluation. See (1988DI02) for a comprehensive review of photoneutron cross sections, including reaction (b). Tables 3.18 and 3.19 contain references for reactions (c) and (d), respectively. Table 3.21 lists references for reactions (e) and (f). Table 3.20 lists references for the inclusive reaction ^{3}He(γ, p)X, where only a single outgoing proton is observed.

Many experimental studies of some of these reactions were done in the 1960s and 1970s. Tables 3.8.1 and 3.8.2 in (1975FI08) contain extensive lists of references up to 1975. E_γ from 5.49 MeV to near 800 MeV were used for reaction (a) and 7.70 to 170 MeV for reaction (b). In some instances the outgoing proton or neutron was observed at a single $60°$ or $90°$ angle and sometimes angular distributions of the outgoing particles were measured. A few additional reaction (b) experiments were reported in (1987TI07). Cross sections for reaction (b) for E_γ from threshold to about 25 MeV are reported in (1981FA03), along with cross sections for the ^{3}H(γ, n)^{2}H and ^{3}H(γ, 2n)^{1}H reactions.

Table 3.19: Measurements for ^{3}He(γ, pp)n

References	E_γ (MeV)	Comments
(2003SH18, 2003SH27)	10.9, 16.5	Cross sections measured at these two energies are compared with earlier measurements and theory
(1992SA08, 1993SA03)	90-250	Observed both protons in kinematics where effects of 3N forces are expected to be maximized
(1996KO45)	161-208	Tagged $\vec{\gamma}$ beam; measured p-p angular distributions; compared with theory; for two-body breakup study by same group, see (1994KO11) in Table 3.17
(1989AU04, 1991AU03, 1993AU04)	200-474	Studied three-body photon absorption with both low and high outgoing neutron momenta; compared to (γ, np) cross section
(1998OK02)	200-480	Discussion of kinematically complete, three-body photodisintegration with tagged, polarized photons
(1994EM02)	200-500	Measured cross section for photon absorption by the two protons only; deduced cross section for photon absorption by all three particles
(1997AU02)	200-800	Detected both outgoing protons; measured three-body breakup cross section; compared with theory and other data; for two-body breakup study by same group, see (1994IS05) in Table 3.17
(1994TE07)	235-305	$\vec{\gamma}$ beam; measured cross section and asymmetries; compared (γ, pp) with (γ, np) results and with theory
(2004NI18)	350-1550	Tagged $\vec{\gamma}$ beam; detected both protons, measured cross sections in three kinematic regions; compared with other experiments and with theory

Table 3.20: References for ^{3}He(γ, p)X

Reference	E_γ (MeV)	Comments
(1989BE32)	48.6	Measured cross section with 4π proton detector
(1988GA25)	60-350	$\vec{\gamma}$ beam; measured asymmetry; also studied inclusive (γ, $\pi^{\pm}$) reactions
(1986BE34)	90-350	$\vec{\gamma}$ beam; measured asymmetry
(1994RU04)	195-304	$\vec{\gamma}$ beam; measured differential cross section and photon asymmetry; compared with theory
(1985GO25)	200	$\vec{\gamma}$ beam; measured outgoing proton polarization; deduced asymmetry parameters
(1989DH01)	208-338	Measured outgoing proton spectrum at several angles and as a function of excitation energy of undetected n-p pair; compared with theory
(1988ZY01)	350	Measured polarization of outgoing proton; studied reaction mechanism
(1995ZY01)	200-1000	Measured outgoing proton polarization for three proton momenta; compared with outgoing proton polarization from ^{2}H(γ, p)n

In the introductory section of (1992KL02), there is an extensive discussion and reference list dealing with two-body photodisintegration of ^{3}H and ^{3}He and pd-capture for the period prior to 1992. Also, in (1982BR12, 1983SO10, 1985BR23), reaction (a) and its time-reverse pd capture were compared; see (1994KO11) for additional references and commentary on this point.

Cross sections for reactions (a) and (d) and the sum of the two are shown in Fig. 12 in (2006NA10) for E_γ from thresholds up to about 30 MeV; see also Figs. 2, 3 and 4 in (2003SH18). The authors of (2006NA10) include results from earlier measurements along with their own. Most experiments have the cross section for reaction (a) rising to roughly 0.8 mb for E_γ of about 11 MeV, falling slowly to about 0.25 mb at 30 MeV and continuing to fall thereafter. There is considerable scatter in the experimental results around the peak; see Fig. 4 in (1992KL02). Note, however, that the most recent measurement reported in (2006NA10) has the two-body breakup cross section as 0.77 ± 0.05 mb at 10.2 MeV and 0.65 ± 0.05 mb at 16.0 MeV. The same reference shows that these experimental values fall below calculated values even when the calculations are performed using realistic NN and NNN interactions. For example, near the peak, the experimental cross section is smaller than theory by about 20%; see Fig. 12(b) in (2006NA10) and Fig. 2 in (2003SH18) while at 10.2 MeV the experimental cross section is less than the theoretical value by about 30%. As shown in (2007DE40), when the Coulomb interaction between the protons is included in the calculation, the theoretical value moves closer to the experimental value, but a sizable discrepancy is still present.

The cross section for reaction (d) rises to about 1 mb for E_γ of about 15 MeV and decreases from there; see Graphs 2A and 3A in (1988DI02) as well as Fig. 12(b) in (2006NA10) and Fig. 3 in (2003SH18). As in the reaction (a) case, the theoretical cross section is larger than the experimental values, especially at E_γ just above threshold, which is 7.72 MeV, and again above 25 MeV. For example, at about 10 MeV, the measured cross section is only about $\frac{1}{3}$ of the theoretical value (2006NA10). The sum of the reactions (a) and (d) cross sections has a peak value of about 2 mb and occurs at about 15 MeV. Note also that at around 320 MeV, there is a broad peak in the reaction (d) cross section of about 16 μb, up from 1 to 2 μb before and after the resonance; see (1997AU02). This peak is probably due to the excitation of the Δ isobar in the ^{3}He ground state.

Extensive theoretical studies of the photodisintegration of $A = 3$ nuclei are reported in (1987KO19, 1987KO26, 1987LE04, 1988LA29, 1988LA31, 1990KO23, 1990KO46, 1990NE14, 1991KO38, 1992KL02, 1994WI12, 1997SC04, 1999UM01, 2000EF03, 2000FO11, 2000VI05, 2001SC16, 2002GO24, 2002YU02, 2003SK02, 2003SK03, 2004DE11, 2005DE17, 2005DE56, 2005GO26, 2005SK01, 2005SK05). Frequently, in these references, two- and three-body breakup of both ^{3}H and ^{3}He are studied together as is the capture of either a neutron or a proton by ^{2}H. Thus, the relevant sections - ^{3}He reaction 3 and ^{3}H reactions 3 and 8 - should be consulted for additional information.

Several approaches have been used to calculate photodisintegration of ^{3}H and ^{3}He cross sections. In the Faddeev approach, the bound and continuum wave functions are obtained by solving the Faddeev equations and calculating the appropriate matrix elements and response functions from which the cross section is obtained. See (2003SK02, 2003SK03) and references therein where the Faddeev approach has been used in $A = 3$ photodisintegration studies. A method related to the Faddeev approach makes use of the Alt-Grassberger-Sandhas (AGS) scheme to produce three particle wave functions. See (2001SC16, 2002YU02, 2004DE11, 2005DE17, 2007DE40) and references therein for applications of the AGS method to $A = 3$ photodisintegration. The role of the Coulomb interaction between the two protons using a screening technique is studied in (2005DE17, 2007DE40).

In a totally different approach, called the Lorentz integral transform method, it is not necessary to calculate the continuum wave functions. A localized auxiliary function related to the bound state wave function is calculated from which the response function is obtained by inverting an integral transform. As currently practiced, the bound state and auxiliary functions are obtained using correlated hyperspherical harmonics. The Faddeev and Lorentz integral transform methods are shown to give identical results in the context of the photodisintegration of ^{3}H in (2002GO24). Some additional references that use the Lorentz integral transform method for photodisintegration studies are (1997EF05) and (2000EF03). For a more general discussion of the method, see (1988EF02, 2007EF1A) and references therein.

A third method for calculating photodisintegration cross sections is the Laget approach which uses diagrammatic techniques to evaluate the contributions of various photodisintegration mechanisms. There is a brief explanation of Laget's approach in the introduction of (2004NI18) which also contains a list of references. See also (2005LA03) for commentary and for references concerning the Laget approach in the context of electron scattering. Calculations of the cross section for two-body photodisintegration, reaction (a), for E_γ from threshold to 100 MeV are reported in

Table 3.21: References for ^{3}He(γ, pπ^+)2n and ^{3}He(γ, pπ^-)2^{1}H

Reference	E_γ (MeV)	Comments
(1993EM02)	380-700	Tagged $\vec{\gamma}$ beam; measured yields from both reactions simultaneously; studied Δ component in ^{3}He
(2000HU13)	800-1120	Tagged $\vec{\gamma}$ beam; measured yields from both reactions simultaneously; studied Δ component in ^{3}He

(2001SC16). Also shown in this reference are the differential cross section at $90°$ for E_γ from threshold to 40 MeV and angular distributions for $E_\gamma = 60$ and 100 MeV. Three different interaction models were used corresponding to three different ^{3}He binding energies. The authors of (2001SC16) note that peak heights of the calculated cross sections are correlated with calculated ^{3}He binding energies with the lower peak heights corresponding to the higher binding energies; see ^{3}H reaction 8 for more on this effect. The calculated cross sections generally follow the trends of the data, but much of the data - including the most recent reported in (2003SH18, 2006NA10) - lies below the calculations as can be seen in Fig. 1 in (2001SC16), Fig. 2 in (2003SH18) and Fig. 12 in (2006NA10), as mentioned above. In a calculation of the angular distribution of photons from proton capture by ^{2}H at $E_\text{p} = 10.93$ MeV, it is shown in (2001SC16) that an excellent fit to the data results from including the E2 component along with the E1 component. The calculation of the fore-aft asymmetry from threshold to about 35 MeV reported in (2001SC16) agrees well with the data, although the data has large uncertainties. Note also that the reference (2001SC16) contains an extensive set of references for experimental papers of ^{3}H and ^{3}He photodisintegration dating back into the 1960s.

Calculations are reported in (2000EF03) for both two- and three-body photodisintegration of both ^{3}H and ^{3}He for E_γ up to 140 MeV. Several interaction models were used and the role of 3N interactions was investigated. It was found that including 3N forces lowers the calculated peak height and raises the calculated cross section at E_γ above 70 MeV. Both the Faddeev method and the Lorentz integral transform method are used in (2002GO24, 2003SK03, 2005SK01) to study the two- and three-body photodisintegrations of ^{3}H and ^{3}He. Studies of the effects of retardation, meson exchange currents using the Siegert theorem and the role of multipoles other than E1 on the transitions are reported in (2002GO24). Note also that (2002GO24) contains a brief discussion of the unretarded E1 transition operator and it is shown there that, for E_γ below about 50 MeV, this approximation is quite accurate. The role of the Δ isobar excitation 3N interaction in nucleon-deuteron capture and in the two- and three-body photodisintegration of ^{3}H and ^{3}He is discussed in (2002YU02, 2004DE11). Using the AGS integral equation method and techniques for handling the Coulomb interaction developed in (2005DE17, 2005DE21, 2005DE39), along with the CD Bonn NN interaction and including the Δ isobar excitation, calculations of the differential cross section for reaction (c) are reported in (2005DE56) for $E_\gamma = 55$ and 85 MeV and compared to data from

(1991KO16). It was found that the Δ isobar excitation plays only a small role, but including the Coulomb interaction was essential in obtaining a good account of the data.

It is of interest to compare the cross sections for reactions (c) and (d). An experiment that does this is reported in (1994TE07), using polarized photons with energies from 235 MeV to 305 MeV. Fig. 2 of this reference shows that the differential cross section for pn pair emission is larger than that for pp pair emission by factors from about 2 to about 6. The authors of (1994TE07) state the following: "Two-nucleon absorption dominates the pn data, but is suppressed in the pp data. The pp data require the inclusion of three-nucleon absorption to describe the cross section and beam asymmetry over all momenta." The effect that the pn pair emission is larger than the pp pair emission is even more dramatic when the residual particle is essentially a spectator. In Fig. 3 of (1994EM02), the total cross section for pp pair emission with a spectator neutron is shown to drop from about 2 μb at $E_\gamma = 200$ MeV to about 1 μb at $E_\gamma = 400$ MeV. By contrast, in Fig. 3 of (1994EM01), the total cross section for pn pair emission with a spectator proton is shown to drop from about 60 μb at 200 MeV to about 20 μb at 400 MeV. Both of these reactions have been studied theoretically as reported in (1994WI12, 1995NI07, 1995WI16). The quasi-deuteron model is used for the np pair emission study reported in (1994WI12, 1995NI07).

The quasi-deuteron model as a feature of photodisintegration has been around for many years; see (2002LE05). The reference (1991KO16) also contains references to early evidence of the quasi-deuteron effect. This reference also contains evidence of this effect in the reaction (c) in which coincident n-p pairs are observed. The authors conclude that the quasi-deuteron model holds in the three-body photodisintegration of ^{3}He for E_γ at least as low as 55 MeV. That the Coulomb interaction plays a significant role in reaction (c) can be seen in the Fig. 14 of (2005DE56) where the calculation of the differential cross section with and without the Coulomb is compared with the data of (1991KO16). In another study of reaction (c) reported in (1994EM01) in configurations when one of the protons is essentially a spectator, it was found that the cross section scales with the ^{2}H(γ, p)n cross section, the ratio being 1.24 ± 0.26. Theoretical studies of the data in (1994EM01) using the quasi-deuteron model are reported in (1994WI12) and (1995NI07). See also (1999UM01) for an application of the quasi-deuteron model to both reactions (c) and ^{4}He(γ, pn)^{2}H.

Table 3.20 lists several references wherein a single outgoing proton is detected. Fig. 1 of (1989DH01) shows a proton spectrum observed at an angle of $23°$ for $E_\gamma = 278$ MeV. A narrow peak is seen in this spectrum at the high proton momentum end corresponding to reaction (a) and a broader peak at lower outgoing proton momentum corresponding to three-body breakup. Also seen in the results reported in (1994RU04) - in which polarized photons are used and both cross sections and cross section asymmetries are measured - is that absorption by two nucleons (the quasi-deuteron effect) is the dominant mechanism in the proton high momentum peak while absorption by three nucleons is also important in the proton momentum region below the narrow peak.

The question of the existence of Δ isobars in the ground state of nuclei in general and ^{3}He in particular has been around for years; see (1987LI1P, 1987ST09, 1993EM02, 2000HU13) and references therein. The Δ isobars are roughly 300 MeV more massive than nucleons. They have spin and isospin of $\frac{3}{2}$. Their resonance width is around 120 MeV, which means that they decay in about 5×10^{-24} s and travel no more than a few femtometers before decaying. The dominant decay mode is into a nucleon plus a pion. Two examples are: $\Delta^{++} \rightarrow \mathrm{p} + \pi^{+}$ and $\Delta^{0} \rightarrow \mathrm{p} + \pi^{-}$. Possible experimental signals indicating the presence of Δ's in the ground state of ^{3}He are discussed in (1987LI1P). One suggestion is that photons of several hundred MeV energy, in favorable kinematic conditions, would produce coincident outgoing p-π^+ pairs rather easily by knocking out a doubly charged Δ^{++} and few or no coincident outgoing p-π^- pairs due to the photon's reduced ability to eject an uncharged Δ^0. As shown in Table 3.21, two photodisintegration experiments have been carried out looking for p-π^+ and p-π^- pairs; see (1993EM02, 2000HU13). The authors of (1993EM02) conclude that the Δ component in the ground state of ^{3}He is less than 2% and the authors of (2000HU13) conclude that it is between about 1.5 ± 0.8 % and 2.6%. The authors of (2000HU13) also note that they were able to identify a kinematical region in which p-π^+ pairs were observed but no p-π^- pairs were seen, as predicted in (1987LI1P). In a study of ^{3}H and ^{3}He electromagnetic form factors (1987ST09) which includes admixtures of Δ's in the ground state wave functions, percentages of 2.33 and 2.55 were obtained for the Δ isobar component for two different models. Also shown in Fig. 5 of this reference are the momentum distributions of the Δ isobar for the two models.

The highest energy photodisintegration of ^{3}He reported so far is that of reference (2004NI18) in which photons of energies from 350 MeV to 1550 MeV were used and the three-body disintegration, reaction (d), was studied. With the energy of the tagged photon and the energies and momenta of the outgoing protons all measured, the energy and momentum of the neutron were deduced. Different kinematic regions were studied. Studied in particular were the star configuration in which the three particles in the center of mass system have equal energies and their momenta form a $120°$ triangle and the spectator neutron configuration in which the neutron has a small momentum. At these energies, the theoretical approach used by these authors is that of Laget; see (1988LA31) and other references given in (2004NI18). As discussed in (2004NI18), two-body photodisintegration is the dominant mechanism in the spectator neutron configuration up to about 600 MeV and three-body photodisintegration is dominant in the star configuration as predicted in (1988LA31).

A property of ^{3}He that is obtainable in principle from the photodisintegration cross section is the electric polarizability; α_E. By a sum rule, the electric polarizability is directly related to σ_{-2}, which is the energy integral of the photodisintegration cross section divided by the photon energy squared; see (1997EF05), for example. This result requires that the magnetic polarizability is negligible compared to the electric; see (1983FR05). Calculations of α_E for ^{3}He using the sum rule with theoretical cross sections have been reported. For example, in (2007PA1E) the value 0.153 fm^3 is obtained using a realistic model of ^{3}He and in (1997EF05) values of 0.143 fm^3 and 0.151 fm^3 are obtained for two different models of ^{3}He. Also reported in (1991GO01) are values of α_E from 0.13 fm^3 to 0.17 fm^3 obtained by evaluating σ_{-2} using different sets of data for photodisintegration cross sections. By studying deviations from Rutherford scattering of ^{3}He by ^{208}Pb (1991GO01), a value 0.250 ± 0.040 fm^3 was obtained for α_E. The reason for the difference between the experimental values for α_E is unclear; see (1997EF05).

11. (a) ^{3}He(e, e)^{3}He

(b) ^{3}He(e, e′p)^{2}H $Q_m = -5.4935$

(c) ^{3}He(e, e′n)2^{1}H $Q_m = -7.7180$

Table 3.22: References for the processes ^{3}He(e, e)^{3}He (elastic) and ^{3}He(e,e′X), *i.e.*, inclusive inelastic electron scattering

References	E_e (MeV)	Comments
(1988DO13)	unspecified [a]	Obtained longitudinal response functions for ^{3}H and ^{3}He; compared with theory
(1994RE04)	100-700	Measured inclusive inelastic cross sections for both ^{3}H and ^{3}He; obtained response functions; compared with theory
(2003HI05)	263, 506, 549	Measured inelastic scattering cross sections; compared with theory
(2001NA22)	265-822	Measured elastic scattering; deduced ^{3}He magnetic form factor; compared with model calculations and other data
(1992AM04)	315-640	Measured elastic scattering cross sections; used world data to obtain $T = 0$ and 1 charge and magnetic form factors; compared with theory
(1994GA20, 1995HA08, 1995JO17)	370	Inclusive scattering of $\vec{e}$ by $^3\overrightarrow{\mathrm{He}}$; measured asymmetry; compared with theory; obtained neutron magnetic form factor
(1987AK03, 1987AK05)	538	Measured inclusive inelastic scattering cross section; deduced ^{3}He structure functions
(1990MI26, 1990WO06, 1991JO06, 1991WO02, 1992TH03, 1993JO01)	574, 578	Inclusive scattering of $\vec{e}$ by $^3\overrightarrow{\mathrm{He}}$; measured asymmetry; compared with theory; studied neutron electric form factor
(2000DU10, 2000HA29, 2000XU07, 2001GA29, 2001XI04, 2003XU02, 2007AN08)	0.778, 1.727 GeV	Inclusive scattering of $\vec{e}$ by $^3\overrightarrow{\mathrm{He}}$; measured asymmetry; compared with theory and other data; obtained neutron magnetic form factor
(2001GI06, 2002AM08, 2002ME08, 2004AM01, 2004AM13, 2005ME03, 2008SL01)	0.862-5.058 GeV	Inclusive $\vec{e}$ by $^3\overrightarrow{\mathrm{He}}$; measured cross section and virtual photon asymmetry; deduced sum rule features, ^{3}He and n spin structure functions, GDH integral for n, generalized GDH integral for ^{3}He

Table 3.22: References for the processes ^{3}He(e, e)^{3}He (elastic) and ^{3}He(e,e′X), *i.e.*, inclusive inelastic electron scattering (continued)

References	E_e (MeV)	Comments
(1992ME08, 1993ME01)	0.9-4.3 GeV	Measured inclusive inelastic scattering cross section for both ^{3}He and ^{4}He; deduced response functions; studied Coulomb sum rule
(1992KU10)	1.211 GeV	Measured inclusive inelastic scattering cross section between quasielastic and resonant regions
(2005KR14)	3.465-5.727 GeV	Inclusive scattering of $\vec{e}$ by $^3\overrightarrow{He}$; deduced neutron spin structure functions
(2004KO68)	5.7 GeV	$\vec{e}$ beam and $^3\overrightarrow{He}$ target; measured first moments of n and p spin structure functions of n and virtual photon asymmetry; compared with theory
(2004ZH01, 2004ZH42)	5.7 GeV	$\vec{e}$ beam and $^3\overrightarrow{He}$ target; obtained neutron spin asymmetry and spin structure function ratio for large Bjorken x; compared with theory
(2003ME21)	5.7 GeV	Summary of two experiments using $\vec{e}$ beam and $^3\overrightarrow{He}$ target; measured asymmetries and spin structure functions
(2002ZO04)	5.7 GeV	$\vec{e}$ beam and $^3\overrightarrow{He}$ target; measured scattering asymmetry; deduced n spin structure function
(1993AN12, 1994PE29, 1996AN25)	19.42, 22.66, 25.51 GeV	$\vec{e}$ beam and $^3\overrightarrow{He}$ target; measured cross section; deduced neutron asymmetries and structure functions; studied sum rules
(1997AB18, 1998PE02)	48.3 GeV	$\vec{e}$ beam and $^3\overrightarrow{He}$ target; measured asymmetries; obtained structure function; tested sum rules; compared with other data and theory

[a] The energy for the accompanying elastic scattering data (1987BE30) is reported in (1987TI07) to be 54, 134.5 MeV.

Table 3.22 lists references for both elastic electron scattering and inclusive inelastic and deep inelastic scattering (DIS) by ^{3}He. Table 3.23 gives references for the two-body breakup reaction ^{3}He(e, e′p)^{2}H and for the three-body breakup reaction ^{3}He(e, e′p)n^{1}H. Table 3.24 lists references for the two-body breakup reaction in which the deuteron is observed: ^{3}He(e, e′d)^{1}H. Table 3.25 lists references in which the three-body breakup reaction is obtained.

A brief history of experimental studies of electron scattering by ^{3}H and ^{3}He is given in the Introduction section of (1994AM07). Of the two targets, ^{3}He was studied more extensively for

Table 3.23: References for the ^{3}He(e, e′p)^{2}H and ^{3}He(e,e′p)n^{1}H

References	E_e (MeV)	Comments
(1987KE07)	390	Studied both (e, e′p) and (e, e′d); measured cross sections; compared with theory
(1997LE05)	396, 670	Detected outgoing e's and p's; measured spectral functions; compared with theory
(1999FE14)	442	$\vec{\gamma}$ beam and $^3\overrightarrow{\mathrm{He}}$ target; measured spin correlation parameter for both (e, e′p) and (e, e′n) reactions; compared with theory
(2004KO51)	495, 630, 810	Measured cross section, distorted proton momentum distribution and asymmetry; compared with earlier measurements and calculations; studied FSI and MEC effects
(1987JA15)	509, 528	Detected outgoing e's and p's; measured cross section for both two- and three-body breakup; determined proton density distribution; compared with other data and theory
(1999FL02, 1999ZH42)	540, 675, 855	Detected outgoing e's and p's; measured cross section for two- and three-body breakup; determined proton momentum distribution; compared with other data and theory
(1988MA11)	560	Detected outgoing e's and p's; measured cross section for both two- and three-body breakup; determined proton density distribution; compared with other data and theory
(2005AC22)	735	$\vec{e}$ beam and $^3\overrightarrow{\mathrm{He}}$ target; detected outgoing e and p with constant energy and momentum transfer; measured asymmetries; compared with Faddeev calculations which included final state interactions and meson exchange currents
(2003CA09)	854.5	$\vec{e}$ beam and $^3\overrightarrow{\mathrm{He}}$ target; measured asymmetries; compared with theory; studied final state interaction and relativistic effects
(2002PE22)	0.845-4.800 GeV	Detected outgoing e and p in parallel kinematics; measured cross section; compared with theory
(2004HI03, 2005BE12, 2005RV01, 2005SA12)	4.806 GeV	Used fixed momentum and energy transfer; measured cross section and asymmetry; compared with theory; studied final state interactions; deduced proton momentum density for ^{3}He

Table 3.24: References for ^{3}He(e, e′d)^{1}H

References	E_e (MeV)	Comments
(1996TR04)	265.3, 382.5	Detected outgoing e and d; measured cross section; deduced structure function ratio; studied role of isospin in d production
(1998SP08, 2002SP03)	370, 576	Detected outgoing e and d; measured cross section, deduced structure functions; compared with theory; studied reaction mechanism
(1987KE07)	390	Studied both (e, e′p) and (e, e′d); measured cross sections; compared with theory

some time since it is not radioactive.

It has proven to be of value to study the charge and magnetic form factors, F_c and F_m, which can be obtained from the electron elastic scattering cross sections. See (1985JU01), for example, in the context of obtaining the form factors for ^{3}He. These quantities are expressed as functions of q^2, the square of the momentum transferred to the target in the scattering process. Two different units are used in the literature for q^2, namely fm^{-2} and (GeV/c)^2. The conversion factor is: 1 (GeV/c)^2 corresponds to 25.6 fm^{-2} or 1 fm^{-2} corresponds to 0.0391 (GeV/c)^2. It should be noted that as a unit for q^2, (GeV/c)^2 is sometimes written as just (GeV)^2, as in (2007PE21) and (2007AR1B). The form factors are defined in such a way that both F_c and F_m equal 1 at q^2 equal to zero. Figs. 6 and 7 in (1994AM07) show the charge and magnetic form factors for both ^{3}H and ^{3}He. Both form factors for ^{3}He drop rapidly from 1 as a function of q^2. The charge form factor has a minimum near $q^2 = 11$ fm^{-2} and the magnetic form factor has a minimum near $q^2 = 19$ fm^{-2}. The ^{3}H form factors are qualitatively similar to those for ^{3}He; the minima occur at slightly different values of q^2. The slopes of the form factors at $q^2 = 0$ can be used to extract charge and magnetic rms radii. Table 2 in (1994AM07) gives these values as $r_{ch} = 1.959 \pm 0.030$ fm and $r_m = 1.965 \pm 0.153$ fm. For ^{3}H, the corresponding values were similarly determined to be $r_{ch} = 1.755 \pm 0.086$ fm and $r_m = 1.840 \pm 0.181$ fm. See (1988KI10) for a discussion of the methods and difficulties in deducing rms radii values from form factors.

Since ^{3}H and ^{3}He form an isospin doublet, it is useful to consider the isoscalar and isovector combinations of the form factors of ^{3}H and ^{3}He; see (1992AM04, 1994AM07) for the relationship between the standard form factors and the isoscalar and isovector form factors. As discussed in (1992AM04), meson exchange currents are expected to make a larger contribution to the isovector form factors than to the isoscalar ones. The isoscalar and isovector form factors are shown in Figs. 12 and 13 of (1994AM07). Since both ^{2}H and ^{4}He are isoscalar nuclei, it is of value to compare the $A = 3$ isoscalar form factor with those of ^{2}H and ^{4}He, as is done in (1994AM07). For example, the position of the minimum in the three cases is about 10 fm^{-2} for ^{4}He, 12 fm^{-2} for $A = 3$ and 20 fm^{-2} for ^{2}H, which reflects the same ordering of the sizes from smaller to larger of these nuclei.

Table 3.25: References for ^{3}He(e, e′n)^{1}H^{1}H, ^{3}H(e, e′pp)n and ^{3}He(e, e′p)n^{1}H

References	E_e (MeV)	Comments
(1999FE14)	442 MeV	$\vec{e}$ beam and $^{3}\overrightarrow{He}$ target; measured spin correlation parameter for both (e, e′p) and (e, e′n) reactions; compared with theory
(2000HE10)	560-585	Detected outgoing e and both p's; measured cross section; compared with theory; studied short range correlations
(1999GR29, 1999GR37, 2001GR02)	564	Detected outgoing e and both p's; measured cross section; compared with Faddeev calculations; studied reaction mechanisms
(2000BO14)	720	$\vec{e}$ beam and $^{3}\overrightarrow{He}$ target; detected outgoing e and n; measured asymmetries; compared with theory
(1994ME09, 1997KL03, 1999BE58, 1999JO19, 1999RO19, 2000OS02, 2003BE39)	854	$\vec{e}$ beam and $^{3}\overrightarrow{He}$ target; detected outgoing e and n; measured asymmetries; deduced neutron charge form factor value; measured target analyzing power with unpolarized beam; compared with theory
(2005HO18)	1.1, 2.2, 4.4 GeV	Detected outgoing e and both p's; studied short range correlations and continuum state interactions
(2003WE10, 2004WE03)	2.2, 4.4 GeV	Detected outgoing e and back to back p's; measured cross section; studied correlated np and pp pairs; compared with theory
(2004NI01)	2.261 GeV	Detected outgoing e and both p's; measured cross sections for both pp and np pair production; compared with theory
(2004ST24)	4.46 GeV	Detected outgoing e and two p's from ^{3}He, ^{4}He, ^{12}C and ^{56}Fe targets; deduced two proton correlation functions and proton emission source sizes

A general review of quasielastic electron scattering that includes a discussion of response functions of ^{3}H and ^{3}He is reported in (2008BE09). Electron scattering by ^{3}He has been referred to as "a playground to test nuclear dynamics"; see (2004GL08, 2010SI1A). For more on the theoretical description of longitudinal and transverse response functions, including possible relativistic effects, meson exchange currents and pion production threshold effects, see (2004EF01, 2008DE15, 2010EF01) and references therein, as well as (2004GL08, 2010SI1A).

The GDH sum rule is discussed in the ^{3}He Introduction section. As originally developed, it involved the photoabsorption of real photons. Generalizations of this sum rule for virtual photons that are involved in the scattering of electrons have been developed; see (2000KO1Q, 2001DR1A, 2001JI02). Inclusive scattering cross sections of polarized electrons by a polarized ^{3}He target with $E_e = 0.862$-5.058 GeV were reported in (2002AM08, 2005ME03, 2008SL01). The generalized GDH integral and a related Burkhardt-Cottington sum rule were deduced.

12. (a) ^{3}He(μ^-, ν)^{3}H $\quad Q_m = 105.6398$

(b) ^{3}He(μ^-, ν)^{2}H + n $\quad Q_m = 99.3825$

(c) ^{3}He(μ^-, ν)^{1}H + 2n $\quad Q_m = 97.1580$

(d) ^{3}He(μ^-, $\nu\gamma$)^{3}H $\quad Q_m = 105.6398$

Muon capture in general is reviewed in (2001ME27); muon capture by ^{3}He is also fairly extensively reviewed there as well. The measured capture rate for reaction (a) is 1496.0 ± 4.0 s^{-1} (1998AC01). In two theoretical studies of this reaction reported in (2002MA66, 2003VI06), calculated values of 1484 ± 4 s^{-1} and 1486 ± 8 s^{-1} were obtained. Different structure models of ^{3}H and ^{3}He were used which gave binding energies close to experimental values. The theoretical values are in good agreement with each other and with the experimental value. A study of reaction (a) is reported in (1993CO05) in which a weighted average of early measurements of the capture rate is 1487 ± 36 s^{-1}. Calculated values of the capture rate are reported in this reference to be 1497 ± 21 s^{-1} and 1304 s^{-1} using the elementary particle method and the impulse approximation, respectively. Calculations of analyzing powers for this reaction are reported in (1993CO05, 1996CO30, 2002MA66, 2003VI06). Additional studies of reaction (a) are reported in (1996CO01, 2000GO33, 2002HO09).

A measurement of the VAP for reaction (a) using laser polarized muonic ^{3}He is reported in (1998SO08).

Of the 105.6 MeV released in reaction (a), only 1.9 MeV goes to the recoiling ^{3}H. In contrast, deuterons produced in reaction (b) and protons in (c) are found to have much higher energies; see (1992CU01, 1994KU19, 2004BY01). In (2004BY01) deuteron energies from reaction (b) are measured between 13 MeV and 31 MeV. In the same reference, measurements of the proton energy distribution from reaction (c) between 10 MeV and 49 MeV are reported. By extrapolating to the full range of energies, capture rates for reaction (b) and (c) are obtained. Two different analysis methods were used in each case. For reaction (b), capture rates of 491 ± 125 s^{-1} and 497 ± 57 s^{-1} were obtained and for reaction (c), rates of 187 ± 11 s^{-1} and 190 ± 7 s^{-1} were obtained.

Averaging, using inverse square error weighting, gives 496 ± 52 s^{-1} for the reaction (b) reaction rate and 189 ± 6 s^{-1} for the reaction (c) reaction rate. An early calculation of these reaction rates was reported in (1975PH2A) as 414 s^{-1} and 209 s^{-1}, respectively. A calculation of the sum of these two reaction rates is reported in (1994CO05) as 650 s^{-1}. This compares with the theoretical value of 623 s^{-1} from (1975PH2A) and 685 ± 52 s^{-1} obtained by adding the averaged experimental values from (2004BY01).

A study of reaction (b) using the Faddeev equations and realistic NN interactions is reported in (1999SK03).

A theoretical study of reaction (d) is reported in (2002HO09) in which two approaches are compared. In the elementary particle method, ^{3}He and ^{3}H are treated as elementary particles whose internal structures are contained in experimental form factors. In the impulse approximation method, ^{3}He and ^{3}H are treated microscopically. The photon spectrum obtained from both methods is roughly Gaussian shaped, peaked at around 40 MeV. When summed over all photon energies, the calculated capture rate for reaction (d) is of the order of 1 s^{-1} which is much smaller than the capture rates for reactions (a), (b) and (c).

Adding the capture rates quoted above (1998AC01, 2004BY01) for reactions (a), (b) and (c) and neglecting reaction (d) gives 2181 ± 52 s^{-1} for the total muon capture rate. Of this total, reaction (a) is 68.6 ± 1.6 %, reaction (b) is 22.7 ± 2.4 % and reaction (c) is 8.7 ± 0.3 %. It is of interest to note that, from calculations reported in (1975PH2A), the corresponding values for these percentages are approximately 70%, 20% and 10%, respectively. These older values, which are quoted in more recent publications (1998AC01, 1999VO23, 2001ME27, 2002MA66, 2003VI06, 2004BY01) are quite consistent with current experimental results.

Another aspect of interest in muon capture by ^{3}He concerns the hyperfine effects. For muonic ^{3}He, the total spin is 0 or 1. It is reported in (1998AC01) that the transition rate between the higher energy spin 0 state and the lower energy spin 1 state is negligibly small. Hence, when the muonic ^{3}He atom is formed, $\frac{1}{4}$ have spin 0 and $\frac{3}{4}$ have spin 1. A study of the capture rate from each spin state is reported in (1994CO05). Considering reactions (a), (b) and (c), it was found that about 60% comes from the spin 0 state and 40% from the spin 1 state. Since the ^{3}He and ^{3}H wave functions used were fairly simplistic, these results should probably be considered only as estimates.

Additionally, reaction (a) has been used to obtain a value for the pseudoscalar coupling constant, g_p. See (1996BO54, 1996JO22, 1998AC01, 1999VO23, 2000GO33, 2001BE16, 2002MA66, 2003TR06).

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

(b) ^{3}He(π^-, π^0)^{3}H	$Q_m = 4.5750$
(c) ^{3}He(π^+, p)^{1}H^{1}H	$Q_m = 132.6345$
(d) ^{3}He(π^-, p)2n	$Q_m = 131.0698$
(e) ^{3}He(π^-, n)^{2}H	$Q_m = 133.2944$
(f) ^{3}He(π^-, π^+)3n	$Q_m = -9.2827$

A review of pion reactions with ^{3}He and ^{4}He and other nuclei can be found in (2002LE39).

Table 3.26 gives references related to reaction (a) as well as some related inelastic reactions for the current evaluation period.

In a series of reports, charge symmetry breaking in pion elastic scattering on ^{3}H and ^{3}He was studied by measuring ratios of cross sections - ratios which would equal unity if charge symmetry held; see (1988PI09, 1990NE02, 1991PI03, 1993BR03, 1995BE04, 1995MA32, 1996DH01, 2002BR49). See ^{3}H reaction 10 for more discussion of these results.

Table 3.26: References for ^{3}He($\pi^{\pm}$, $\pi^{\pm}$) and related reactions

References	E_π (MeV)	Comments
(1991LA09, 1994LA09)	100	Measured cross section and asymmetry in π^+ scattered from polarized target; obtained large A_y values near diffraction minimum; compared with other data and theory
(1997YU01)	120, 180, 240	Measured inclusive inelastic scattering cross section for π^+ and π^-; compared with theory; studied double charge exchange
(1988PI09, 1990NE02, 1991PI03, 1993BR03, 1995BE04, 1995MA32, 1996DH01, 2002BR49)	142, 180, 220, 256	Measured cross section ratios for π^+ and π^- elastically scattered from ^{3}H and ^{3}He; studied charge symmetry breaking
(1996ES04, 1997ES05)	142, 180, 256	Measured A_y for π^+ scattering at three energies and π^- at 180 MeV from polarized target; compared with theory; studied role of Δ(1232) resonance
(1987KL03, 1987KL06)	170, 220, 270, 320	Measured cross sections for inclusive inelastic $\pi^{\pm}$ cross sections and exclusive (π, π'p) cross sections for both π^+ and π^-; compared with theory
(1987BO09)	300, 350, 375, 400, 475	Measured cross sections for elastic scattering of π^+ and π^- from ^{3}He and ^{4}He

When polarized ^{3}He targets became available, asymmetry (A_y) measurements in elastic scattering of pions from polarized ^{3}He were made as reported in (1991LA09, 1994LA09, 1996ES04, 1997ES05). Best agreement between theory and experiment is obtained when the pion-nucleon resonance Δ(1232) is included in the reaction model. Calculations of differential cross sections and analyzing powers for elastic scattering of both π^+ and π^- by ^{3}He for $E_\pi = 100$, 142, 180 and 256 MeV are reported in (1999ZH14). This reference also displays graphs of differential cross sections and asymmetries collected from several experiments. The agreement with experiment is generally good, except for backward angles. For the asymmetry calculations, it was found that including a D state in the ^{3}He wave function was important for π^+ scattering but not for π^- scattering.

The spectra of both π^+ and π^- inelastically scattered by ^{3}He shows a large peak near the quasi-elastic nucleon knock-out energy broadened by nucleon Fermi motion; see Figs. 3 through 9 in (1987KL06). Distorted wave impulse approximation (DWIA) calculations that assume a single pion-nucleon interaction are only in qualitative agreement with data. These authors also studied the reactions ^{3}He(π^+, $\pi^{+\prime}$p) and ^{3}He(π^-, $\pi^{-\prime}$p) and found that the DWIA calculations agree much better with the data.

A study of reaction (b) is reported in (1999ZH22). The energy of the π^- beam was 200 MeV; the ^{3}He target was polarized. The outgoing π^0 was detected indirectly by measuring the energies and angles of the two photons into which the π^0 decays. The recoiling ^{3}H nucleus was detected in coincidence with the π^0. The scattering asymmetry, $A_{\rm y}$, was determined for $\theta_{\rm cm} = 60°$-$105°$ and found to be large and negative near $60°$ and large and positive near $80°$. Comparisons are made with calculations with only qualitative agreement.

Studies of the inelastic processes ^{3}He(π^+, π^0), ^{3}He(π^+, π^0p), ^{3}He(π^-, π^0), ^{3}He(π^-, π^0p) are reported in (1995DO07). The pion beam energy was 245 MeV. The outgoing π^0 was detected as discussed above. The results suggest that the ^{3}He(π^+, π^0p) reaction occurs primarily by a quasi-free pion- nucleon process, but the ^{3}He(π^-, π^0p) involves more than a single nucleon.

The absorption of π^+ by various nuclei, reaction (c), has been a subject of study for some time; see (1993IN01), section 5 of the review in (2002LE39) and references therein. At least two nucleons must be involved in the absorption process since a single free nucleon cannot absorb a pion and conserve energy and momentum. As discussed in (2002LE39), in the early days of pion absorption studies, it was expected that this process would be a way of studying NN correlations. However, the absorption process turned out to involve more than two nucleons to a significant degree. Studies of π^+ absorption by ^{3}He have been carried out to separate the two and three nucleon absorption processes; see (1986AN11, 1991WE14, 1996HA04), for example. References for π^+ absorption by ^{3}He are given in Table 3.27.

The total π^+ absorption cross section for ^{2}H has a broad resonance with a peak value of about 12 mb for E_π of about 150 MeV; see Fig. 5 in (1993AR11), or Fig. 4(a) in (1998KA17). The same resonance feature shows up in the total π^+ absorption cross section of other nuclei as well; for example, for ^{3}He, see Fig. 4(b) in (1998KA17) and for ^{12}C, see Fig. 2 of (2002LE39) and references therein. Presumably, the resonance is due to the formation of a Δ; $\pi + {\rm N} \rightarrow \Delta$; see (1991GR09), for example. The cross section at the peak in ^{3}He is about 30 mb and for ^{12}C the peak cross section is nearly 200 mb. There is a monotonic increase in the absorption cross section with increasing mass number; see Fig. 3 in (2002LE39) and references therein.

In most of the references in Table 3.27, the primary concern has been to separate the two nucleon absorption mechanism from that involving three nucleons. See (1989SM03), for example, in which it is shown that the three nucleon absorption percentage of the total cross section increases from about 30% at an incident $E_\pi = 37$ MeV to nearly 50% at $E_\pi = 500$ MeV. Similar results are

Table 3.27: References for ^{3}He(π^+, p)^{1}H^{1}H and related reactions

References	E_{π^+} (MeV)	Comments
(1996HA04)	37	Determined differential cross sections for two nucleon and three nucleon absorption and studied final state interaction effects
(1986AN11)	62.5, 82.8	Compared two nucleon and three nucleon absorption cross sections
(1989WE10, 1991WE14)	64, 119, 162, 206	Measured angular distributions; determined separate cross sections for two- and three-body absorption
(1997LE08)	70, 118, 162, 239, 330	Compared ^{3}He(π^+, 3p) and ^{4}He(π^+, 3p)n cross sections; separated two- and three-body absorption effects
(1994AL28, 1996BA32)	118, 162, 239	Measured proton distributions; analyzed role of initial and final state interactions; measured total absorption cross section and separated two- and three-body components
(1992MA17)	120, 250	Measured polarization of protons emitted by pion absorption; compared to π^+ absorption in ^{2}H
(1991MU01)	165	Kinematically complete experiment; measured differential cross section for two-body absorption; obtained three-body absorption cross section
(1985BA59)	260 (p $= 220$ MeV/c)	Determined cross sections for three nucleon absorption for different counter configurations
(1989SM03)	350, 500	Kinematically complete experiment for the reaction ^{3}He(π^+, 2p)^{1}H; separated two and three nucleon absorption cross sections

Table 3.28: References for ^{3}He(π^-, p)2n and ^{3}He(π^-, n)^{2}H

References	E_{π^-} (MeV)	Comments
(1995GO03)	0	Studied absorption of stopped π^- by ^{3}He; measured ratio of nnp to nd channels
(1996HA04)	37.0	See Table 3.27
(1986AN11)	62.5, 82.8	See Table 3.27
(1989WE10, 1991WE14)	64, 119, 162, 206	See Table 3.27
(1994AL28, 1996BA32)	118, 162, 239	See Table 3.27
(1985BA59)	260 (p $= 220$ MeV/c)	See Table 3.27
(1991MU01)	165	See Table 3.27

shown in Fig. 11 in (1991MU01) and in Fig. 10 in (1996HA04).

A measurement of the polarization of the proton emitted in π^+ absorption by ^{3}He is reported in (1992MA17). The outgoing protons were selected by kinematical constraints to be those resulting from two nucleon absorption. The results were compared with the theory of (1987NI09) and with proton polarization from π^+ absorption by ^{2}H. At 120 MeV, the ^{3}He and ^{2}H results are similar, but not at 250 MeV. The results differ from theory at both energies. See (1993AC01) for a comparison of experimental polarization results for π^+ absorption by ^{2}H, ^{3}He and ^{4}He with each other and with theory. Theoretical work related to angular distributions and polarizations of outgoing protons following pion absorption is reported in (2003SC11), which also includes references to earlier work. In both (1993AC01) and (2003SC11), it was found that the polarization data were not well described by a two nucleon absorption mechanism.

The absorption of π^- by ^{3}He, reactions (d) and (e), can be studied using either stopped pions or in-flight pions. See Table 3.28 for references. Results from an experiment with stopped pions in cold, gaseous ^{3}He are reported in (1995GO03). These authors concluded that absorption by two nucleons coupled to zero isospin is the dominant mechanism. The value 4.2 ± 0.6 was obtained for the ratio of the three-body final state decay rate, reaction (d), to the two-body final state, reaction (e). An earlier value for this ratio is 3.6 ± 0.6; see (1995GO03) for references. These authors also concluded that final state interactions play a major role in the decay process.

Table 3.28 shows that experiments with in-flight pions often have used both π^+ and π^- beams. Fig. 10 and Table IX in (1996HA04) shows that both the two nucleon and the three nucleon π^- absorption cross sections are essentially constant as a function of $E_{\pi^-} =$ 37-350 MeV in contrast to π^+ absorption which has a resonance feature around 150 MeV. These authors also determined that, for π^- absorption, the three nucleon absorption cross section is larger than the two nucleon by an essentially constant factor of about four.

See ^{3}n reaction 4 for more on reaction (f).

^{3}Li

General

The previous $A = 3$ evaluations (1975FI08, 1987TI07) identified reactions 1 through 4 below as possible candidates for the observation of a bound or resonant state of three protons. An additional possibility would be the double charge exchange reaction ^{3}H(π^+, π^-)^{3}Li. There is a report of this reaction (2001PA47), but the pion energy was high, 500 MeV, and the focus of the experiment was on the role of the Δ component in the ^{3}H ground state, not on the possible presence of a resonant three proton state.

A calculation reported in (1996CS02) suggests a three proton resonance with $J^\pi = \frac{3}{2}^+$ at an energy of 15 MeV with a width of 14 MeV.

1. ^{2}H(p, π^-)^{3}Li $\qquad Q_m = -147.8155$

A study of the reaction $\vec{\mathrm{p}} + \mathrm{d} \rightarrow \pi^- + \mathrm{X}$ with $E_\mathrm{p} = 1.45$, 2.10 and 2.70 GeV was reported in (1991AS03). No narrow structure was observed in either the analyzing power or cross section that could be interpreted as a three-body resonance. Other references reporting similar studies are: (1988AB05: $E_\mathrm{p} = 1$ GeV), (1990BA35: $E_\mathrm{p} = 400$ MeV) and (1998DU07, 1999HA06: $E_\mathrm{p} = 353$, 403, 440 MeV). There were no reports of observation of resonant ^{3}Li states.

2. ^{3}He(p, n)^{3}Li $\qquad Q_m = -14.5211$

A study of this reaction was reported in (1998PA22) with 200 MeV polarized protons. Cross sections and analyzing powers were measured. Comparisons were made with distorted wave impulse approximation calculations. No evidence of ^{3}Li resonances was seen in the neutron spectrum. Similar studies are reported at the following energies and references: (1993BR05: $E_\mathrm{p} = 220$ MeV), (1996MI11, 2002PR04: $E_\mathrm{p} = 197$ MeV) and (1998SO09: $E_\mathrm{p} = 100$ MeV). None reported evidence of ^{3}Li resonances.

3. ^{3}He(^{3}He, t)^{3}Li $\qquad Q_m = -13.7574$

No studies are reported on this reaction.

4. ^{6}Li(^{3}He, ^{6}He)^{3}Li $\qquad Q_m = -17.2471$

No studies are reported on this reaction.

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(Closed December 31, 2009)

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 in the 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.

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