Nuclear Data Sheets for $A = 3^*$

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Abstract: Compilation of information about the structure of $A=3$ systems. This review mainly summarizes the work presented in (2010Pu04) and has updates of mass, lifetime and nuclear moment data as noted in the text.

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General Policies and Organization of Material: see <http://www.nndc.bnl.gov/nds/NDSPolicies.pdf>.

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NUCLEAR DATA SHEETS

Index for A = 3		
Nuclide	Data Type	Page
	Skeleton Scheme for A=3	4
^3nn	Adopted Levels	4
^3H	Adopted Levels	5
	$^1\text{H}(^6\text{He},\alpha)$	6
	$^2\text{H}(\text{n},\text{n})$	6
	$^2\text{H}(\text{n},\gamma)$ E=thermal	7
	$^3\text{H}(\gamma,\text{n}),(\gamma,\text{nn})$	8
	$^3\text{H}(\text{e},\text{e})$	8
^3He	Adopted Levels	9
	$^3\text{H} \beta^-$ Decay	9
	$^1\text{H}(^6\text{Li},\alpha)$	11
	$^2\text{H}(\text{p},\gamma)$	11
	$^2\text{H}(\text{p},\text{p}),(\text{p},\text{n}),^1\text{H}(\text{d},\text{d}),(\text{d},\text{n})\dots$	11
	$^3\text{He}(\gamma,\text{p}),^3\text{He}(\gamma,\text{n})$	12
	$^3\text{He}(\text{e},\text{e})$	12
^3Li	Adopted Levels	14

Skeleton Scheme for A=3

S(n).....6257.233²

S(p).....5493.477²

Ground-State and Isomeric-Level Properties				
Nuclide	Level	Jπ	T _{1/2}	Decay Modes
³ H	0.0	1/2+	12.32 y	2 %β ⁻ =100
³ He	0.0	1/2+	stable	

Adopted Levels

The experimental evidence reviewed in all three mass 3 evaluations (1975Fi08,1987Ti07,2010Pu04) is mostly against the existence of a bound state consisting of three neutrons. Some evidence of a possible three neutron resonance has been reported, but it has generally been weak and not reproducible or more likely due instead to two neutron final state interactions. See (1968Ka35) for a summary of the experimental situation concerning possible ${}^3\text{n}$ systems as of 1968. A theoretical study reported in (1996Cs02,1998Cs02) using the complex scaling method predicts a $J\pi=3/2+$ three neutron resonance at 14 MeV with a width of 13 MeV.

A listing of the reactions in which attempts were made to observe bound or resonant three neutron states follows.

${}^3\text{H}(\text{n},\text{p}){}^3\text{n}$: This reaction has been studied at several neutron energies. A possible ${}^3\text{n}$ bound state with binding energy around 1 MeV seen in the 0° proton spectrum was reported by (1965Aj03) but was not confirmed in the subsequent similar experiments reported in (1966Th10,1967Fu09,1968De03).

${}^3\text{H}({}^3\text{H}, {}^3\text{He}){}^3\text{n}$, ${}^3\text{He}({}^3\text{H}, {}^3\text{He}){}^3\text{H}$: Studies of these reactions with $E({}^3\text{H})=22.25$ MeV are reported in (1968Oh04). With the ${}^3\text{H}$ target, there was no indication of a bound ${}^3\text{n}$ system in the outgoing ${}^3\text{He}$ spectrum, but there was a suggestion of a possible broad resonance at around 1–1.5 MeV excitation in the ${}^3\text{n}$ system. With the ${}^3\text{He}$ target, there was no evidence in the outgoing ${}^3\text{He}$ spectrum of a resonance in the ${}^3\text{H}$ system corresponding to the analogue of a bound ${}^3\text{n}$ state.

${}^3\text{H}(\pi^-, \gamma){}^3\text{n}$: Studies of this reaction with stopped pions have been reported in (1976Bi05,1979Bi13,1980Mi12). There was no evidence seen in the γ spectrum of ${}^3\text{n}$ bound or resonance states. A shift in the outgoing γ spectrum possibly indicating resonant ${}^3\text{n}$ structure is adequately explained as due to pair-wise two neutron final state interaction (1980Mi12).

${}^3\text{He}(\pi^-, \pi^+){}^3\text{n}$: This double charge exchange reaction has been studied with $E(\pi^-)$ from 65–295 MeV (1970Sp05,1974Sp08,1986St09,1997Yu01,1999Gr01,1999Gr31). A resonance-like structure reported in (1970Sp05,1974Sp08,1986St09) has been explained as most likely due to the final state interaction of two outgoing neutrons (1970Ph05). As reported in (1999Gr01), a search for either bound or resonant ${}^3\text{n}$ states was unsuccessful. The primary interest of the results reported in (1997Yu01,1999Gr31) was in the double charge exchange mechanism, not on possible three neutron states.

${}^4\text{He}(\pi^-, \text{p}){}^3\text{n}$: One study of this reaction is reported in (1968Ka35) with $E(\pi^-)=140$ MeV who report a possible resonance feature in the proton spectrum at an excitation energy in the 3–neutron system of about 15 MeV. Studies of this reaction are also reported in (1970Zi05,1973Ba70,1981Ce01) with stopped pions and in (1977Ja15,1981Ka41,1981Ka43,1981Mc09,1983Ka14) with $E(\pi^-)$ ranging from 50–475 MeV. There was no mention of ${}^3\text{n}$ states being observed in any of these experiments. However, the focus of these experiments was on pion–nucleon interaction and not on possible three neutron states. A study of the reaction ${}^7\text{Li}(\pi^-, {}^4\text{He}){}^3\text{n}$ with stopped π^- is reported in (1977Ba47,1993Am09), but there is no mention of possible ${}^3\text{n}$ states.

Others: The following reactions using heavy ions were studied in unsuccessful attempts to observe ${}^3\text{n}$ states:

${}^{14}\text{N}(\pi^-, {}^3\text{n}){}^8\text{B}+{}^3\text{H}$ with stopped π^- (1972Ag01).

${}^7\text{Li}(\text{n}, {}^3\text{n}){}^5\text{Li}$, $E(\text{n})=14$ – 19 MeV (1968Fu06,1970Ko24).

${}^2\text{H}({}^{14}\text{C}, {}^{13}\text{N}){}^3\text{n}$, $E({}^{14}\text{C})=336$ MeV (1995Bo10).

${}^3\text{H}({}^7\text{Li}, {}^7\text{Be}){}^3\text{n}$ and ${}^7\text{Li}({}^7\text{Li}, {}^{11}\text{C}){}^3\text{n}$, $E({}^7\text{Li})=65$ – 82 MeV (1974Ce06,1987Al10,2005Al15).

${}^7\text{Li}({}^{11}\text{B}, {}^{15}\text{O}){}^3\text{n}$, $E({}^{11}\text{B})=52$ – 88 MeV (1986Be44,1986Be54,1987Bo40,1988Be02).

A study of the breakup of ${}^{14}\text{Be}$ by a carbon target, $E({}^{14}\text{Be})=490$ MeV, in which attempts to produce and detect neutron clusters is reported in (2002Ma21,2005Ma97). No ${}^3\text{n}$ clusters were observed, but there was a possible hint of a few ${}^4\text{n}$ clusters.

On the theoretical side, an early study of the ${}^3\text{n}$ system using Faddeev methods is reported in (1979Li19) and a shell model type calculation is reported in (1980Be22). These articles also reference earlier ${}^3\text{n}$ system calculations. A calculation reported in (1996Cs02) using the complex scaling method obtained a resonance in the ${}^3\text{n}$ system with $J\pi=3/2+$ and an energy of 14 MeV and a width of 13 MeV. A study is reported in (1997So27) using the hyperspherical method with simplified two particle interactions of $J\pi=1/2-$ ${}^3\text{n}$ states, which they consider to be the most likely spin-and-parity value of such states.

Three recent studies looking for possible bound or resonant ${}^3\text{n}$ states are reported in (1999Wi08,2002He25,2005La11). As expressed in (2005La11), modern nucleon–nucleon interactions and calculational techniques do not predict any observable ${}^3\text{n}$ bound states or resonances.

Adopted Levels

$Q(\beta^-)=18.5906\ 32$; $S(n)=6257.233\ 2$ 2012Wa38.

The discovery of hydrogen isotope ${}^3\text{H}$ with an estimate of its mass was reported in 1934; see (2012Th01) for a historical review. In (1947B131,1947B132) it is shown that the spin of ${}^3\text{H}$ is $1/2$ and the ratio of the magnetic moment of ${}^3\text{H}$ to that of the proton is found to be $1.067\ 1$. For the ${}^3\text{H}$ spin, see also (1949Di31).

Calculations show that the ground state wave functions of ${}^3\text{H}$ and ${}^3\text{He}$ consist of a spatially symmetric S state ($\approx 90\%$), a D state ($\approx 9\%$), a mixed symmetry S' state ($\approx 1\%$) and a small P state ($< 0.1\%$). See (1979Sa15,1986Is01,1987Er07,1993Wu08,2002Ho09).

The ratio η_t of the asymptotic D state to S state of ${}^3\text{H}$ is $-0.0418\ 31$. This value is the inverse square of the uncertainty weighted average of the two most recent measurements (1993Ge04,1994Ko29). The following table lists references reporting values for η_t :

Reference	η_t	Comments
1981Bo04	-0.048 7	${}^2\text{H}(\text{pol d,p}){}^3\text{H}$, $E_d=13\ \text{MeV}$
1982Bo06	-0.051 5	${}^2\text{H}(\text{pol d,p}){}^3\text{H}$, $E_d=7-13\ \text{MeV}$
1989Vu01	-0.050 6	${}^4\text{He}(\text{pol d},{}^3\text{He}){}^3\text{H}$, $E_d=32-50\ \text{MeV}$
1992Da01	-0.043 2	DWBA analysis of sub-Coulomb (pol d,t) reactions; also see (1992Ge05), who argue that the uncertainty should be 0.004, not 0.002
1993Ge04	-0.0431 25	DWBA analysis of sub-Coulomb (pol d,t) reactions
1994Ko29	-0.0411 18	DWBA analysis of sub-Coulomb (pol d,t) reactions

Also see (1988Fr01) where it was noted that there is a strong correlation between the triton and deuteron asymptotic ratios. Using several models, they obtained $\eta_t/\eta_d=1.68\ 4$. Using this ratio value and $\eta_d=0.0256\ 4$ from (1990Ro02) gives $\eta_t=-0.0430\ 12$.

The charge and magnetic rms radii for ${}^3\text{H}$ are $r_c=1.755\ \text{fm}\ 86$ and $r_m=1.840\ \text{fm}\ 181$ (1994Am07). See (2005Go26) for electric and magnetic form factors for ${}^3\text{H}$ and ${}^3\text{He}$ as well as isoscalar and isovector versions and comparison with theory. Also see the reaction ${}^3\text{H}(e,e){}^3\text{H}$ below for more details.

Triton magnetic moment, $\mu_t=+2.978962467\ 26\ \mu_N$. This value is obtained from a measurement of the ratio of the triton to proton magnetic moments $\mu_t/\mu_p=1.0666399151\ 30$ (2011Ne15) and the value of the proton magnetic moment $\mu_p=+2.792847356\ 23\ \mu_N$ reported in (2014Ol01). Also see Table XLI of (2012Mo42) which gives $\mu_t=2.978962448\ 38$.

${}^3\text{H}$ Levels

Cross Reference (XREF) Flags

- A ${}^1\text{H}({}^6\text{He},\alpha)$
- B ${}^2\text{H}(n,\gamma)\ E=\text{thermal}$
- C ${}^2\text{H}(n,n)$
- D ${}^3\text{H}(\gamma,n),(\gamma,nn)$
- E ${}^3\text{H}(e,e)$

E(level)	$J\pi$	XREF	$T_{1/2}$	Comments
0.0	$1/2^+$	AB	12.32 y 2	<p>$\beta^-=100$.</p> <p>$\mu=+2.978962467\ 26$.</p> <p>μ: from $\mu_t/\mu_p=1.0666399151\ 30$ (2011Ne15) and $\mu_p=+2.792847356\ 23\ \mu_N$ (2014Ol01).</p> <p>${}^3\text{H}$ mass excess: 14949.8061 keV 22 (2012Wa38).</p> <p>${}^3\text{H}$ binding energy: 8481.7986 keV 24; $S(n)=6257.2327\ \text{keV}\ 22$ using mass excess values from (2012Wa38).</p> <p>$T_{1/2}$: 12.32 y 2=4500 d 8=3.888$\times 10^8$ s 7.</p> <p>$T_{1/2}$: The half-life value given here comes from (2000Ch01,2000Lu17). (2000Ch01) analyzed 16 measurements between 1940 and 1991 of ${}^3\text{H}$ half-life, rejected 3 and averaged the rest that ranged from 12.1 y to 12.58 y. They obtained a half-life of 12.32 y 2. The authors of (2000Lu17) recommend using the day as the time unit since it is exactly defined in terms of the second. The same data were reanalyzed using a different method as reported in (2006Ma57) resulting in $T_{1/2}=4497\ \text{d}\ 4$ or 12.31 y 1.</p>

${}^1\text{H}({}^6\text{He},\alpha)$ 1994Al54,2003Ro13

Studies of this reaction have been reported in (1994Al54: $E({}^6\text{He})=19.3$ MeV), and (2003Ro13: $E({}^6\text{He})=23.9$ MeV). The outgoing α spectra in both studies had peaks corresponding the ground state of ${}^3\text{H}$ as well as resonance-like structures that would correspond to an excited state in ${}^3\text{H}$ at about 7 MeV with a width less than 1 MeV. It seems likely that the higher energy structure does not corresponds to a true ${}^3\text{H}$ resonance. It does not show up in n-d scattering, for example. Also, analogous structure in ${}^3\text{He}$ was not seen in the reaction ${}^1\text{H}({}^6\text{Li},\alpha){}^3\text{He}$, $E({}^6\text{Li})=30$ MeV, (1994Al54). Alternative interpretations of the resonance-like structure at 7 MeV are given in (2003Ro13).

 ${}^3\text{H}$ Levels

E(level)	$J\pi$
0.0	$1/2+$

 ${}^2\text{H}(\text{n},\text{n})$

Total cross section:

Fig. 1 in (1972St32) and Fig. 2 in (1973St35) show the measured total n- ${}^2\text{H}$ cross section below $E_n=1$ MeV. From a peak value of about 3.4 b at zero energy (reported to be 3.390 b 12 in (1971Di15), it falls monotonically to about 2.9 b at 1 MeV. As Figs. 4, 5 and 6 in (1972Cl04) show, the total n- ${}^2\text{H}$ cross section continues to fall monotonically as the neutron energy increases, dropping to about 1 b at 10 MeV and 0.6 b at 20 MeV. A summary of total n- ${}^2\text{H}$ total cross sections for $E_n=1$ to 17 MeV is given in (1971Da07). Table 2.3.1a in (1975Fi08) lists more than 50 references related to total n- ${}^2\text{H}$ cross sections for energies from thermal to near 300 GeV. Two additional references are given in (1987Ti07). Cross sections for thermal neutrons are reported in (1975Ca30) and from near zero to 20 MeV in (1980Ph01), along with total cross sections for neutrons on H and ${}^3\text{H}$.

Scattering lengths:

Frequently quoted experimental values for the low energy doublet and quartet n+d scattering lengths are (1971Di15,1975Fi08,1987Ti07,1990Fr18,2003Wi08): ${}^2a_{\text{nd}}=0.65$ fm 4 and ${}^4a_{\text{nd}}=6.35$ fm 2. Calculations related to n+d scattering and ${}^3\text{H}$ structure with various interactions, as noted in (2003Sc12), have resulted in a scattering of values of ${}^2a_{\text{nd}}$. In contrast, the values obtained for ${}^4a_{\text{nd}}$ tend to be nearly constant at around 6.34 fm. These authors used an average calculated value ${}^4a_{\text{nd}}=6.346$ fm 7 to deduce a value ${}^2a_{\text{nd}}=0.645\pm0.003(\text{exp})\pm0.007(\text{theory})$ fm. This value of ${}^2a_{\text{nd}}$ has been used as input in calculations using three-body interactions; see (2006Pl09,2010Ki05).

Elastic scattering:

In Tables 2.3.1 b and 2.3.1 c of the first A=3 review (1975Fi08), there are over 60 publications reporting results from n+d elastic scattering, about 1/3 of which reported using polarized neutrons. Neutron energies ranged from less than 0.1 eV to over 150 MeV. Similarly, in the second A=3 review (1987Ti07), about 20 publications reported n+d elastic scattering results for neutron energies from 2 to 800 MeV, about 2/3 of which used polarized neutrons. In Table 3.2 of the third A=3 review, close to 40 publications are referenced that report n+d elastic scattering results. Most used polarized neutrons and some also used polarized targets. The neutron energies ranged from 11 MeV to 250 MeV.

Elastic n+d scattering phase shifts for energies up to 24 MeV are shown in Fig. 14 of (1972Se23). However, see comments in (1975Fi08) as well as in (1987Ti07) on this subject.

A major issue in n+d scattering is the so-called analyzing power puzzle in which the calculated and measured values for the analyzing power A_y do not agree. This effect is also seen in p+d scattering as well. See (2008To20) for a discussion of the puzzle.

The following are publications dealing with n+d elastic scattering since the third A=3 review:

2010We01: Table 1 lists references studying n-d analyzing power for n-d scattering for neutron energies from 1.2 to 30 MeV with a gap between 16 and 30 MeV. Fig. 8 gives $A_y(\theta)$ results of this experiment plus calculation. The analyzing power puzzle is still present.

2011Fr11: Reports differential cross sections for both n+ ${}^2\text{H}$ and n+ ${}^3\text{H}$ elastic scattering at $E_n=14.1$ MeV.

2013Er02: Reports study of n+d elastic scattering for $E_n=135-250$ MeV.

2014We04: Reports measurements of analyzing power for n+d scattering at $E_n=22.5$ MeV. Results shown in Fig. 4 and corresponding discussion show that the analyzing power puzzle is still present.

2014Na25: Studied n+d scattering, $E_n=0.1-2$ MeV.

${}^2\text{H}(\text{n},\gamma)$ E=thermal 1982Ju01

Target $J\pi=1+$.

The value for the cross section for thermal neutron capture by ${}^2\text{H}$ recommended in (2006MuZX) is $\sigma(E_{\text{thermal}},\gamma)=0.508$ mb 15. However, note that the value recommended in (2011Fi11) is $\sigma(E_{\text{thermal}},\gamma)=0.549$ mb 10.

Articles containing measurements of neutron capture by ${}^2\text{H}$:

Reference	Comments
1947Sa33	Measured thermal neutron capture cross section, 0.46 mb 11
1952Ka47	Measured thermal neutron capture cross section, 0.57 mb 1
1968Me26	Measured thermal neutron capture cross section, 0.521 mb 9
1973Is08	Measured thermal neutron capture cross section, 0.55 mb 1; note—this reference also includes other thermal cross section measurements from the 1960's not readily available today
1980Al31	Measured effective thermal neutron capture cross section
1982Ju01	Measured thermal neutron capture cross section, 0.508 mb 15
1988Ab04, 1988Ko07	Studied capture of polarized thermal neutrons; obtained photon polarization parameter $R=-0.42$ 3
1988Al29	Slow, polarized neutrons, study of parity violation
1998Na15	Measured capture cross section to be 2.12 μb 35 at $E_n=30.5$ keV and 2.04 μb 3 at 54.2 keV
2006Na35	Measured capture cross section to be 2.23 μb 34 at $E_n=30.5$ keV, 1.99 μb 25 at 54.2 keV, 3.76 μb 41 at 531 keV

 ${}^3\text{H}$ Levels

$E(\text{level})^\dagger$	$J\pi^\dagger$	$T_{1/2}^\dagger$	Comments
0.0 (6257.2482 24)	1/2+ 1/2+, 3/2+	12.32 y 2	$J\pi$: from s-wave neutron capture.

† From Adopted Levels.

 $\gamma({}^3\text{H})$

E_γ	$E(\text{level})$	$I_\gamma^{\dagger\dagger}$	Comments
6250.258 3	(6257.2482)	100	E_γ : from level-energies difference.

† Intensity per 100 neutron captures.

†† Absolute intensity per 100 neutron captures.

Level Scheme

Intensity: relative I_γ

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

The earliest reported studies of the ${}^3\text{H}$ photodisintegration cross section are (1965Bo43) and (1966Ko04). A summary of the experimental cross sections for the photodisintegration of ${}^3\text{H}$ up to 1981 is given in (1981Fa03). Fig. 10 in this reference gives the cross section for ${}^3\text{H}(\gamma, n){}^2\text{H}$ from threshold (6.25 MeV) to about 28 MeV. The cross section has a peak value of about 0.9 mb at 12 MeV and falls slowly at higher energies. Fig. 11 in the same reference gives the cross section for ${}^3\text{H}(\gamma, 2n){}^1\text{H}$ from threshold (8.48 MeV) to about 28 MeV. It reaches a peak of about 0.9 m at about 15 MeV then falls slowly. The total cross section is shown in Fig. 13. A measurement of the total ${}^3\text{H}$ photodisintegration cross section for energies from 15 MeV to 36 MeV is reported in (1981Sk02).

 ${}^3\text{H}(e, e)$

The following table lists references for electron scattering from ${}^3\text{H}$:

Reference	Q^2 (fm $^{-2}$)	Comments
1965Co08	1-8	$r_c=1.70$ fm 5, $r_m=1.70$ fm 5
1982Be10	0.29-1.0	$r_c=1.67$ fm 6
1984Be46	0.0477-2.96	$r_c=1.68$ fm 3, $r_m=1.72$ fm 6
1985Ju01	0.3-31.3	Measured charge and magnetic form factors; $r_c=1.76$ fm 4, $r_m=1.72$ fm 4
1987Be30	0.09-8.26	Measured isoscalar and isovector form factors

In (1994Am07), the three experiments reported in (1982Ca15, 1985Ju01, 1992Am04) for electron scattering from ${}^3\text{H}$ and ${}^3\text{He}$ are described and a complete set of cross sections, electric and magnetic form factors are obtained. Also, $T=0$, 1 form factors are obtained and compared with $A=2$, 4 form factors. See (2005Go26) for electric and magnetic form factors for ${}^3\text{H}$ and ${}^3\text{He}$ as well as $T=0$, 1 form factors and comparison with theory.

 ${}^3\text{H}$ Levels

E(level)	$J\pi$
0.0	1/2+

Adopted Levels

S(p)=5493.477 2 2012Wa38.

The isotope ${}^3\text{He}$ was probably first observed in 1933–34. See (2012Th01) and references therein. That ${}^3\text{He}$ has spin 1/2 is reported in (1949Do24,1950Di11).

Calculations show that the ground state wave functions of ${}^3\text{H}$ and ${}^3\text{He}$ consist of a spatially symmetric S state ($\approx 90\%$), a D state ($\approx 9\%$), a mixed symmetry S' state ($\approx 1\%$) and a small P state ($< 0.1\%$). See (1979Sa15,1986Is01,1987Er07,1993Wu08,2002Ho09).

The ratio η_t of the asymptotic D state to S state of ${}^3\text{He}$ is $-0.0389\ 42$. This value is the inverse square of the uncertainty weighted average of the two most recent measurements (1995Ay03,1997Ri07,1997Sc31).

The charge and magnetic rms radii for ${}^3\text{He}$ are $r_c=1.959\ \text{fm}\ 30$ and $r_m=1.965\ \text{fm}\ 153$ (1994Am07). See (2005Go26) for electric and magnetic form factors for ${}^3\text{H}$ and ${}^3\text{He}$ as well as $T=0$, 1 form factors and comparison with theory. See the reaction ${}^3\text{He}(e,e){}^3\text{He}$ below for more details.

The magnetic moment, $\mu=-2.127625306\ 25$, is from Table XLI of (2012Mo42).

 ${}^3\text{He}$ Levels**Cross Reference (XREF) Flags**

A ${}^1\text{H}({}^6\text{Li},\alpha)$

B ${}^2\text{H}(p,\gamma)$

C ${}^2\text{H}(p,p),(p,n),{}^1\text{H}(d,d),(d,n)\dots$

D ${}^3\text{H}\ \beta^-$ Decay

E ${}^3\text{He}(\gamma,p),{}^3\text{He}(\gamma,n)$

F ${}^3\text{He}(e,e)$

E(level)	J π	XREF	T _{1/2}	Comments
0.0	1/2+	AB D F	stable	$\mu=-2.127625306\ 25$ (2012Mo42). ${}^3\text{He}$ Mass excess: 14931.2155 keV 23 (2012Wa38). ${}^3\text{He}$ binding energy: 7718.0428 keV 23; S(p)=5493.4768 keV 23 using mass excess values from (2012Wa38).

 ${}^3\text{H}\ \beta^-$ Decay

Parent ${}^3\text{H}$: E=0.0; J π =1/2+; T_{1/2}=12.32 y 2; Q(g.s.)=18.5906 32; % β^- decay=100.

Measurements of the β^- -decay spectrum of tritium in solid tritiated valine by (1981Lu06,1985Bo34) indicated a nonzero electron antineutrino mass within the limits from 20 eV to 45 eV.

 ${}^3\text{He}$ Levels

E(level)	J π	T _{1/2}
0.0	1/2+	stable

 β^- radiations

The Q value for this decay process is given in (2012Wa38) to be 18.591 keV 1. The β^- decay of ${}^3\text{H}$ is 100% to the ground state of ${}^3\text{He}$. As stated earlier, the half-life of ${}^3\text{H}$ is 12.32 y 2. This gives $\log ft=3.0524\ 7$ and the average $E_{\beta}=5.68\ \text{keV}$.

Measurements of ${}^3\text{H}\ \beta^-$ -decay end point energy (EPE) or ${}^3\text{H}-{}^3\text{He}$ mass difference (MD): [Note: Table VII in (1950Ho80) lists eight measurements of EPE prior to 1950 ranging from 12 keV 5 to 18.9 keV 5.].

${}^3\text{H}$ β^- Decay (continued) β^- radiations (continued)

Reference	Energy (keV)	Comment
1950Je60	18.6 2	Calorimetry, measured average energy, deduced EPE
1959Po78	18.61 10	EPE, double lens spectrometer
1969Sa21	18.72 5	EPE; retarding electrostatic field
1970Le15	18.540 95	EPE, ${}^3\text{H}$ implantation
1972Be11	18.610 16	EPE, magnetic-electrostatic spectrometer
1972Be11	18.651 16	MD, magnetic-electrostatic spectrometer
1973Pi01	18.538 0	EPE, magnetic spectrometer
1974Ro08	18.648 26	EPE, magnetic spectrometer
1975Sm02	18.600 7	MD, mass spectrometer, ${}^3\text{H}$, ${}^3\text{He}$ masses measured
1976Tr07	18.575 13	EPE, magnetic spectrometer
1981Lu07	18.577 13	EPE, magnetic spectrometer
1981Si18	18.567 5	EPE, ${}^3\text{H}$ implantation
1981Sm02	18.573 7	MD, mass spectrometer; reconsider (1975Sm02) results
1982Di01	18.594 25	EPE, ion implantation reconsider
1983De47	18.562 6	EPE, thermal diffusion
1984Ni16	18.584 4	MD, ion cyclotron resonance
1985Bo34	18.5842 16	EPE, magnetic-electrostatic spectrometer
1985Li02	18.599 2	MD, ion cyclotron resonance
1985Si07	18.577 7	EPE, ${}^3\text{H}$ implantation
1985TaZK	18.582 3	MD
1986Fr09	18.5823 1	EPE, magnetic spectrometer
1987Bo07	18.5793 8	EPE, β spectrometer
1987Ka51	18.593 5	EPE, β spectrometer; also see (1988Ka12,1988Ka32)
1989Re04	18.590 8	EPE, reconsideration of earlier results
1989St05	18.5890 26	MD, β spectrometer
1991Bu12	18.595 6	MD, bremsstrahlung
1992Ho09	18.57332 18	EPE, β spectrometer
1993Va04	18.5901 17	MD, Penning trap mass spectrometer
1993We03	18.5748 6	EPE, β spectrometer, also see (1993Ba08)
1995Hi14	18.597 14	MD, magnetic spectrometer
2006Na49	18.5898 12	MD, Penning trap mass spectrometer
2015My03	18.59201 7	MD, cyclotron frequency ratio

The β spectrum end point energy differs from the ${}^3\text{H}$ - ${}^3\text{He}$ mass difference due to the recoil energy, the final state of the residual system and the mass of the emitted but not detected anti-electron neutrino. In the table above, most of the references that measured the end point energy (EPE) also put upper limits on the neutrino mass. An early history of the role that the β decay of ${}^3\text{H}$ has played in attempts to measure the neutrino mass can be found in (1988Ro21). Fig. 1 in this article is a graph of the ${}^3\text{H}$ β spectrum near the EPE for the electron neutrino masses of 0 and 30 eV. Fig. 1 in (2006We03) and Fig. 3 in (2013Dr11) show the β spectrum near the end point energy for electron neutrino masses of 0 and 1 eV. Modern refinements of these measurements have resulted in the upper limit of the electron neutrino mass being just over 2 eV; see (2005Kr03,2010Ot02,2011As10,2013Dr11).

Studies of atomic and molecular effects on the ${}^3\text{H}$ β spectrum near the end point energy are reported in (1971Sc23,2010Ot02,2015Bo02).

$E\beta^\dagger$	E(level)	$I\beta^\ddagger$	Log ft	Comments
(18.591 4)	0.0	100.0	3.0524 8	av $E\beta$: weight-average heat output 0.3233 10 W/ γ from (0.321 3 (1950Je60)), (0.321 1 (1958Gr93)), (0.312 1 (1958Po64)), (0.3240 9 (1961Pi01)), (0.3244 13 (1961Jo22)).

† A review of early work is found in (1973Pi01).

‡ Absolute intensity per 100 decays.

${}^1\text{H}({}^6\text{Li},\alpha)$ 1994A154

Reference (1994A154) reports a study of this reaction. The α spectrum showed ${}^3\text{He}$ ground state but no excited states.

 ${}^3\text{He}$ Levels

<u>E(level)</u>	<u>Jπ</u>
0.0	1/2+

 ${}^2\text{H}(\text{p},\gamma)$

The low energy cross sections, or S(E) factors, of this reaction have important astrophysical implications. Graph 1a in (2004De48) shows S(E) for E from about 2 keV up to 9 MeV. S(0) was determined to be 0.223 eV·b 10, 60.1% of which is due to M1 capture and 39.9% is E1 capture. The graph results from an R-matrix analysis of results compiled from (1962Gr39,1963Gr12,1963Wa19,1967Wo08,1970Ba68,1979Sk01,1997Ma08,1997Sc31,2002Ca28). A later determination of S(E) for this same energy range is given in (2013Xu14). Also see (2014By01). In addition to the experimental results used by (2004De48) the following articles were cited: (1967Ge05,1996Sc14,1997Ma08,2002Ca28,2008By03,1964Be45,1965Fe01,1965St07,1973Ti05). The last four references in this list actually studied the inverse reaction ${}^3\text{He}(\gamma,\text{p}){}^2\text{H}$. The value of S(0) determined by (2013Xu14) is 0.21 eV·b 4.

 ${}^3\text{He}$ Levels

<u>E(level)</u>	<u>Jπ</u>
0.0	1/2+

 ${}^2\text{H}(\text{p},\text{p}),(\text{p},\text{n}),{}^1\text{H}(\text{d},\text{d}),(\text{d},\text{n}),(\text{d},\text{pp})$

A very large number of both experimental and theoretical studies of elastic and inelastic deuteron-proton scattering have been reported.

The total p-d cross section has a steep drop at low proton energies to a minimum of about 55 mb at 400 MeV, then rises to about 80 mb at 1500 MeV and drops slowly from there, as the following table shows. Also see Fig. 7 in reference a) below.

E_p (MeV)	σ_t (mb)	Comment
40	≈ 290	Fig. 4 of Ref. e)
77	146 7	Ref. d)
208	61.0 40	Ref. b)
315	56.8 50	Ref. b)
380	53.2 20	Ref. a), uncertainty approximate
408	55.6 30	Ref. c)
590	66.8 20	Ref. a), uncertainty approximate
810	76.0 20	Ref. a), uncertainty approximate
1060	78.3 24	Ref. a), uncertainty approximate
1260	80.3 20	Ref. a), uncertainty approximate
1480	80.8 26	Ref. a), uncertainty approximate
2000	78.7 30	Ref. a), uncertainty approximate
2600	74.2 33	Ref. a), uncertainty approximate

- a) (1956Ch79).
b) (1954De37).
c) (1958Ma69).
d) (1963Da20).
e) (1963Da21).

Table 3.4.1 in (1975Fi08) shows over 120 references of p+d break-up reactions with either proton beams with energies from 3.4 MeV to 24 GeV or deuteron beams with energies from 7.5 MeV to 190 MeV. Similarly, Table 3.11 in (1987Ti07) lists 41 references for p-d breakup reaction studies for proton energies from 3.82 MeV to 800 MeV or deuteron energies from 7.12 MeV to 7.5 MeV; some beams were polarized. Likewise, Table 3.13 in (2010Pu04) lists 37 breakup reaction references with proton energies from 13 MeV to 1 GeV or deuteron energies from 52 MeV to 270 MeV. Many of these studies used either polarized beams or, in some instances both beam and target were polarized. Vector and tensor analyzing powers as well as cross sections were measured and compared with modern theories.

Continued on next page

${}^2\text{H}(\text{p,p}),(\text{p,n}),{}^1\text{H}(\text{d,d}),(\text{d,n}),(\text{d,pp})$ (continued)

The number of references for elastic p-d scattering is also large. In Table 3.5.1b, there are about 80 references of elastic differential cross section measurements with proton energies from 0.2 MeV to 70 GeV or deuteron energies from 0.96 MeV to 433 MeV. In Table 3.12 of (1987Ti07), 35 references are listed giving differential cross sections, vector and tensor analyzing powers and other polarizations observables for proton energies from 0.4 MeV to 1 GeV or deuteron energies from 3 MeV to 5 GeV. In Table 3.14 in (2010Pu04), a list is given of about 80 studies of p-d elastic scattering with proton energies from 0.2 MeV to 3.5 GeV or deuteron energies from 0.48 MeV to 4.9 MeV, most involving polarized beams and in a few instances both beams and targets. Differential cross sections, vector and tensor analyzing powers were measured and compared to modern theories.

A brief summary of recent p-d (and n-d) scattering measurements, including polarization observables, is presented in (2013Se09). In (2011Se06,2011Se17,2014Se13), measurements are reported of elastic d-p scattering with vector and tensor polarized deuterons at 250 and 294 MeV per nucleon. Comparisons with theory with best NN and NNN forces result in large discrepancies at back angles. Studies of elastic scattering ${}^1\text{H}(\text{d,d}){}^1\text{H}$ at $E_d=500, 700$ and 880 MeV are reported in (2013Gu25). At lower energies, as reported in (2012Ci01,2013St06), it was found that NNN and Coulomb forces played only a small role in ${}^1\text{H}(\text{d,d}){}^1\text{H}$, and in ${}^1\text{H}(\text{d,pp})\text{n}$, at $E_d=100, 130$ MeV.

In contrast with neutron-deuteron low energy scattering where the doublet and quartet scattering lengths, ${}^2a_{\text{nd}}$ and ${}^4a_{\text{nd}}$ are reasonably well known, the corresponding quantities for proton-deuteron scattering are more uncertain.

This is discussed in the ${}^3\text{He}$, reaction 7 section in (2010Pu04) where the conclusion is given that ${}^2a_{\text{pd}}$ is approximately zero and ${}^4a_{\text{pd}}$ is approximately 14 fm both with significant uncertainties.

As mentioned in the ${}^2\text{H}(\text{n,n})$ section, a major issue in p+d scattering, as in n+d scattering, is the analyzing power puzzle in which the calculated and measured values of A_y and iT_{11} (vector and tensor analyzing powers) do not agree. For more on the analyzing power puzzle in p+d scattering, see (2008To12,2008To20,2014We04).

 ${}^3\text{He}(\gamma,\text{p}),{}^3\text{He}(\gamma,\text{n})$

Table 3.8.1 in (1975Fi08) lists over 20 articles for the two-body breakup reaction ${}^3\text{H}(\gamma,\text{p}){}^2\text{H}$ for $E_\gamma=\text{threshold}$ (5.49 MeV) to 800 MeV. In Fig. 2 of (1965Fe01) for example, the total cross section for this reaction is shown to rise from threshold to a maximum of about 1 mb at around 12 MeV and drops slowly from there. Also, studies of this reaction are reported in (1982Br12,1983So10) for E_γ from 150–350 MeV. The reaction ${}^2\text{H}(\text{p},\gamma){}^3\text{He}$ was also studied and no evidence of time reversal invariance was found. In the third mass 3 evaluation, (2010Pu04), there are seven additional articles reporting measurements of two-body photodisintegration for E_γ from 10.2 MeV to 800 MeV.

Table 3.8.2 in (1975Fi08) lists 9 articles dealing with the three-body breakup reaction ${}^3\text{He}(\gamma,\text{n})\text{pp}$ for γ energies from threshold (7.7 MeV) to 170 MeV. The reference (1988Di02) is an atlas of photoneutron cross sections for a number of nuclei. For the ${}^3\text{He}$ reaction ${}^3\text{He}(\gamma,\text{n})\text{pp}$, the authors of (1988Di02) quote results from (1974Be64) and (1981Fa03). Additional articles reporting three-body photodisintegration are listed in (2010Pu04) for E_γ from 10 MeV to 1,550 MeV. The reference (2014La04) reports the results of a study of the reaction ${}^3\text{He}(\gamma,\text{n})\text{pp}$ at $E_\gamma=12.8, 14.7$ MeV. Fig. 12 of this reference shows their own results plus a collection of all prior results of this reaction for E_γ from threshold to 30 MeV: The total cross section starts from zero at threshold, grows to about 1 mb at 16 MeV and drops slowly from there. Two additional articles reporting studies of the three-body breakup reaction with similar energies are (2011Pe08,2013La14).

 ${}^3\text{He}(\text{e,e})$

The following table lists references for electron scattering from ${}^3\text{He}$:

Reference	Q^2 (fm $^{-2}$)	Comments
1965Co08	1–8	$r_c=1.87$ fm 5, $r_m=1.79$ fm 10
1970Mc20,	≤ 20	Measured charge and magnetic form factors;
1977Mc03		$r_c=1.88$ fm 5, $r_m=1.95$ fm 11
1972Be65	8.8–15.6	Measured charge and magnetic form factors
1977Sz02	0.032–0.34	$r_c=1.89$ fm 5
1978Ar05	18–77	Measured structure function
1982Ca15	7.3–31.7	Measured magnetic form factor
1983Du01	0.7–11	$r_c=1.935$ fm 30, $r_m=1.935$ fm 40
1985Ot02	0.2–3.7	$r_c=1.976$ fm 15, $r_m=1.99$ fm 6
1987Be30	0.09–8.26	Measured isoscalar, isovector form factors
1992Am04	1.0–25.6	Measured charge and magnetic form factors

In (1994Am07), the three experiments reported in (1982Ca15,1985Ju01,1992Am04) for electron scattering from ${}^3\text{H}$ and ${}^3\text{He}$ are described and a complete set of cross sections, electric and magnetic form factors are obtained. Also, $T=0$, 1 form factors are obtained and compared with $A=2$, 4 form factors. Also see (2005Go26) for electric and magnetic form factors for ${}^3\text{H}$ and ${}^3\text{He}$ as well as $T=0$, 1 form factors and comparison with theory.

 ${}^3\text{He}(\text{e},\text{e})$ (continued)

 ${}^3\text{He}$ Levels

<u>E(level)</u>	<u>Jπ</u>
0 . 0	1 / 2 +

Adopted Levels

Similarly to the three neutron case, there is no firm evidence for a three proton state. A theoretical study reported in (1996Cs02,1998Cs02) using the complex scaling method predicts a $3/2^+$ three proton resonance at 15 MeV with a width of 14 MeV.

A listing of reactions in which attempts were made to observe bound or resonant three proton states follows:

${}^2\text{H}(\text{p},\pi^-){}^3\text{Li}$: Studies of this reaction are reported in (1969Br38,1979Da19,1980Cr03,1988Ab05,1990Ba35,1998Du07,1999Ha06) for proton energies from 353 MeV to 2.7 GeV. There were no reports of three proton resonant states.

${}^3\text{He}(\text{p},\text{n}){}^3\text{Li}$: Studies of this reaction are reported in (1965An03,1966Co22,1969Ba29,1969Wi13,1974PoZN,1993Br05,1996Mi11,1998Pa22,2002Pr04,2008Ih01,2008Wa10) for proton energies from 13.1 MeV to 346 MeV. Possible evidence for a three proton resonance was reported in (1969Wi13,2008Wa10), but the observed enhancement in the cross section has been interpreted as the probable result of final state interactions (1970Ph05), not a true resonance.

${}^3\text{He}({}^3\text{He},\text{t}){}^3\text{Li}$: Studies of this reaction at $E({}^3\text{He})=44$ MeV (1968To01) and $E({}^3\text{He})=53$ MeV reported no evidences of a three proton resonance.

${}^6\text{Li}({}^3\text{He},{}^6\text{He}){}^3\text{Li}$: A study of this reaction is reported in (1970Ba41), $E({}^3\text{He})=53$ MeV. No evidence of a three proton state was observed.

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