Adopted Levels

$Q(\beta^-)=23.06\times10^3$ *syst*; $S(n)=0.81\times10^3$ *syst* 2021Wa16

^{7}H is the nucleus with, by far, the most unbalanced neutron to proton ratio. The first experimental indication of ^{7}H being a resonant state came in 2003 from RIKEN (2003Ko11). This study argued that it is unlikely that ^{7}H exists as a bound state, but a resonant state near the ^{3}H+4n threshold with $J^\pi=1/2^+$ seems likely. It was assumed that such a state would likely decay either into five outgoing particles (^{3}H+4n) or two particles (^{3}H+^{4}n) if the tetraneutron exists.

Most recent observations (2020Be01, 2021Mu04, 2021Hu28, 2022Ca10, and 2023Ni06) indicate that ^{7}H ground state is a low-lying, narrow (due to neutron pairing) resonance 1.3 MeV *4* above the ^{3}H+4n mass with a width of $\Gamma<300$ keV (2020Be01), and with $J^\pi=1/2^+$ measured in (2022Ca10). Such a state would be consistent with an extended 4-neutron halo interacting with a ^{3}H core, which would decay by emission of a tetraneutron. The decay of the four-neutron-unbound ground state of ^{7}H via direct emission of a tetraneutron has not yet been experimentally observed. However, the ongoing analysis of (2021Hu28) seems to be suggestive of this mode of decay.

As for the excited states of ^{7}H, the first one is observed ~4 MeV above the ground state with a plausible $J^\pi=(5/2^+)$ assignment. This state is expected (2021Mu04) to decay via $^{5}\mathrm{H}_{\mathrm{g.s.}}$+2n, where $^{5}\mathrm{H}_{\mathrm{g.s.}}$, in turn, decays to ^{3}H+2n. So, the decay may be sequential. The first excited state may be part of a doublet containing another state at higher energy with $J^\pi=(3/2^+)$. A candidate state for the latter was reported in (2021Mu04) but its existence is uncertain. An even higher energy excited state was observed in (2021Mu04) at 9.7 MeV, whose structure may be indicative of the p+6n configuration.

Theory: Numerous investigations have been carried out to study the $^{7}\mathrm{H}_{\mathrm{g.s.}}$ properties. These are summarized below.

1985Po10: An early shell model calculation obtained $J^\pi=1/2^+$ for the ^{7}H ground state using two different models.

2000Fi22: Using resonating-group method, the wave function of ^{7}H as a cluster system of ^{3}H+n+n+n+n was calculated and analyzed hyperharmonically.

2002Ti05: Calculations using the 7-body hyperspherical harmonics functions with no core shell model predicted a ^{7}H binding energy of −7.61 MeV, estimated by exponential extrapolation. This estimation was about 300 keV lower than that for ^{5}H (2001Ko52), which would agree with the hypothesis of (2001Ko52) that ^{7}H may exist as a low lying resonance with the only decay channel being $^{7}\mathrm{H}\rightarrow{}^{3}$H+n+n+n+n. Later, (2004Ti02) performed the same kind of calculations after improving a Casimir operator such that the hyperharmonics had well defined symmetry when constructed within the shell model approach. This work deduced the ^{7}H resonance ~3 MeV above the ^{3}H+4n threshold. This theoretical result also favored a sequential decay of ^{7}H into ^{3}H+n+n+n+n.

2004Ao05: A coupled channels calculation treated ^{7}H as a combination of both a triton plus four neutrons and as a proton plus three dineutrons. The calculated ground state binding energy is about 1.5 MeV, which is about 7 MeV above the ^{3}H+4n threshold.

2009Ao03: This calculation used the Antisymmetrised Molecular Dynamics with generator coordinate and stochastic variational methods that included basis states with a triton and two dineutrons as well as basis states with a triton and 4 neutrons. This study obtained a ^{7}H ground state with a binding energy of 2.8 MeV, which is about 4.2 MeV above the ^{3}H+4n threshold. This work describes the ground state of ^{7}H as a ^{3}H+^{2}n+^{2}n. These two pairs of neutrons act as two bosons bound together by their interaction with the ^{3}H core in a di-neutron condensate.

2011Gr13: Simultaneous four neutron emission by ^{7}H is discussed in this work. They demonstrate, by using simplified 3-body and 5-body Hamiltonians, that few body dynamics of 2n and 4n emissions result in collective barriers that rise quickly with increasing the number of emitted particles. This translates into longer lifetimes being expected for nuclei which decay via 4n than those that decay via the emission of 2n. This work considered the $^{7}\mathrm{H}_{\mathrm{g.s.}}$ as a true 4n emitter and estimated that the ground state of ^{7}H has a narrow width of $\Gamma\leq1$ keV.

2019Sh36: Simultaneous non−sequential 4n emission is considered in a phenomenological five−body (core+4n) decay. This theoretical work assumes that the internal structure of the ground state of ^{7}H is dominated by a $0p^4_{3/2}$ configuration. The decay of ^{7}H may cause a mixing of configurations such as $0s^2_{1/2}0p^2_{3/2}$ due to Pauli focusing effect. This would result in correlations in energy, angular distribution, and phase space, which could be used as observable fingerprints of a simultaneous non-sequential 4n decay and to understand the decay dynamics.

2021Li62: The energies and neutron-emission widths of the unbound hydrogen isotopes were computed using the no core Gamow shell model. The ground state of ^{7}H was considered as a rigid ^{3}H core and 4 valence neutrons (coupled to J=0), which immediately gives $J^\pi(^{7}\mathrm{H}_{\mathrm{g.s.}})=1/2^+$. The many body basis of the Gamow shell model for the $^{7}\mathrm{H}_{\mathrm{g.s.}}$ was generated from natural orbitals. The resonance energy of ^{7}H was deduced. The results vary between 1-3 MeV with an uncertainty of 400-600 keV, depending on the different phenomenological NN interactions used. These results are more or less in agreement with the previous experimental results. A width of $\Gamma\approx0.1$ MeV was deduced for the $^{7}\mathrm{H}_{\mathrm{g.s.}}$, and it was recommended that the ground state of ^{7}H is a very narrow resonance due to the $0p_{3/2}$ being a closed sub neutron shell in ^{7}H.

2022Hi06: The ground state of ^{7}H was considered as a five-body consisting of a solid ^{3}H core interacting with 4 valence neutrons.

Adopted Levels (continued)

The properties of the $^{7}H_{g.s.}$ were computed in the 5-body cluster approximation (^{3}H-n-n-n-n), which is considered to be the dominant decay channel for a low energy resonant state. A n-^{3}H local interaction was constructed without any tensor component and adjusted in order to reproduce the n-^{3}H phase shifts. These were calculated by solving the ab-initio four-nucleon scattering problem. The Gaussian Expansion Method was used to solve the five-body Schrödinger equation for the ^{3}H-n-n-n-n system. The Stabilization Method was used to estimate the complex energies of the ^{7}H resonant state. As a result, instead of a narrow ^{7}H resonant state in the vicinity of the ^{3}H+4n threshold, a resonance was found at 9.5 MeV with a width of Γ=3.5 MeV. This result is in agreement with that of (2004Ao05), but it is in sharp contrast with the result of (2021Li62). The authors of (2022Hi06) argue that the Gamow shell model used in (2021Li62) underestimates the width. The results of (2022Hi06) are also inconsistent with the recent experimental results for the $^{7}H_{g.s.}$ (2003Ko11, 2007Ca28, 2010Ni10, 2020Be01). Thus, it was mentioned in (2022Hi06) that the deduced wide resonance at 9.5 MeV may be linked to the experimental results of (2020Be01), where a resonance was found at E=6.5 MeV *5* with a width of Γ=2.0 MeV *5*. It should be noted that the 6.5 MeV state measured in (2020Be01) is an unresolved doublet consisting of the first excited state and a candidate for the second excited state of ^{7}H.

In the following reactions, excitation and resonance energies in ^{7}H are given relative to the ^{3}H+4n threshold.

^{7}H Levels

Cross Reference (XREF) Flags

A	^{252}Cf SF decay	E	^{9}Be(π^{-},pp)
B	^{1}H(^{8}He,pp)	F	^{11}B(π^{-},p^{3}He)
C	^{2}H(^{8}He,^{3}He)	G	^{12}C(^{8}He,^{13}N)
D	^{7}Li(π^{-},π^{+})	H	^{19}F(^{8}He,^{20}Ne)

E(level)‡	J$^{\pi}$	Γ(MeV)	E$_{res}$(^{3}H+4n)(MeV)	XREF	Comments
0	1/2^{+}	<300@ keV	1.3 *4*	BC FGH	E$_{res}$(^{3}H+4n)=1.3 MeV *4* is the weighted average of 0.73 MeV *+58−47* (2022Ca10), 0.57 MeV *+42−21* (2008Ca22), 1.8 MeV *5* (2020Be01), and 2.2 MeV *5* (2021Mu04). E(level): The missing mass spectra of (2020Be01, 2021Mu04) are more easily understood than those of (2007Ca47, 2008Ca22, 2022Ca10). The former spectra show clear evidence of the ground and excited states of ^{7}H, which are accounted for in the analysis of (2020Be01, 2021Mu04). However, the missing mass spectrum displayed on Fig. 3 of (2022Ca10) shows two wide peaks corresponding to the production of ^{7}H from the (^{8}He,^{3}He) reactions on ^{19}F and ^{12}C targets. These two peaks are ~5 MeV wide at FWHM (for the case of ^{19}F(^{8}He,^{3}He)) and several MeV wide at FWHM (related to the ^{12}C contribution). Such a wide range may already include at least the first excited state of ^{7}H. So, it is unclear (a) why (2022Ca10) did not consider any excited states, and (b) how the interplay between the production of the $^{7}H_{g.s.}$ and potential excited states were deconstructed from the detector response function. Therefore, even though the E$_{res}$(^{3}H+4n) is computed from the weighted average of the results of (2020Be01, 2021Mu04, 2008Ca22, 2022Ca10), the evaluator has a preference for the analysis and results of (2020Be01, 2021Mu04). E(level): Using E$_{res}$=1.3 MeV *4* and assuming the observed resonance is the ^{7}H ground state, the ^{7}H mass excess is ΔM=48.5 MeV *4*; this compares with ΔM=49.135 MeV *1004* given in 2021Wa16.

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Adopted Levels (continued)

^{7}H Levels (continued)

E(level)[‡]	J$^{\pi}$	Γ(MeV)	$E_{res}(^{3}H+4n)$(MeV)	XREF	Comments
					Γ: See also the Γ=0.18 MeV *+47−16* measured in (2022Ca10), Γ=0.09 MeV *+94−6* measured in (2007Ca47, 2008Ca22), theoretical estimation of $\Gamma \leq 1$ keV in (2011Gr13), and theoretical estimation of $\Gamma \approx 0.1$ MeV in (2021Li62). J$^{\pi}$: From L=0 in a DWBA fit to the measured angular distribution of the $^{19}F(^{8}He,^{20}Ne)^{7}H$ transfer reaction data from (2022Ca10). The L=0 is inferred since the best fit for the DWBA calculation assumes that ^{20}Ne is in its ground state, and that the proton is removed from the ground state of ^{8}He (2022Ca10). The decay mode is most likely to $^{3}H+^{4}n$, but the direct emission of a tetraneutron from the $^{7}H_{g.s.}$ is not yet experimentally observed. The preliminary analysis of (2021Hu28) seems to be suggestive of this decay mode.
4.2×10^{3} *5*	(5/2^{+})[&]	0.75[#] MeV	5.45[†] *3*	C	E(level): This state was unresolved in (2020Be01) and identified at $E_{res}(^{3}H+4n)$=6.5 MeV *5* with a width of Γ=2.0 MeV *5*. This state is expected (2021Mu04) to decay via $^{5}H_{g.s.}$+2n, where $^{5}H_{g.s.}$, in turn, decays to ^{3}H+2n. So, the decay may be sequential.
6.3×10^{3}? *5*	(3/2^{+})[&]	0.9[#] MeV	7.6[†] *3*	C	E(level): This state was unresolved in (2020Be01) and identified at $E_{res}(^{3}H+4n)$=6.5 MeV *5* with a width of Γ=2.0 MeV *5*. E(level): the existence of this state is uncertain (2021Mu04, 2023Ni06). Γ: A width of Γ=2.7 MeV can also provide a reasonable fit but the statistical arguments made by (2021Mu04) favors Γ=0.9 MeV. Moreover, there is no mention of Γ=2.7 MeV fit in (2023Ni06).
9.7×10^{3} *5*			11.0[†] *3*	C	This state may have a structure of dissolved core, where ^{3}H breaks into p+n+n resulting in a p+6n configuration. But no experimental evidence exists.

[†] From (2021Mu04).

[‡] E_x is deduced using $E_{res}(^{3}H+4n)$=1.3 MeV *4*.

[#] from Fig. 15 in (2021Mu04) and Fig. 4 in (2023Ni06).

[@] from (2020Be01).

[&] from L=0 in a DWBA (using FRESCO) fit to the measured (2020Be01, 2021Mu04) efficiency corrected angular distributions of the $^{2}H(^{8}He,^{3}He)^{7}H$ reaction. The L=0 is inferred by the evaluator based on the J$^{\pi}$ assignments of the nuclei involved and the fact that the FRESCO calculation for the J$^{\pi}$=3/2^{+} and 5/2^{+} excited states were performed in (2020Be01, 2021Mu04) assuming that the populations of these states occur, due to the collective excitation, via the proton transfers from the $^{8}He(2^{+})$ state with β_2=0.45.

^{252}Cf SF decay 1982Al33,1982AlZK

1982Al33, 1982AlZK: ^{7}H is searched for among the ternary products of the ^{252}Cf spontaneous fission. An upper limit to the ^{7}H yield is established: 10^{-3} times lower than the very small yield (few counts) of tritons observed in (1982Al33). This upper limit is consistent with no ^{7}H production. It was concluded that ^{7}H is unstable with respect to decay into nucleons.

^{1}**H(**^{8}**He,pp)** **2003Ko11,2003Ko68**

2003Ko11, 2003Ko68: The experiment was performed in RIKEN using a ^{8}He beam produced from the fragmentation of a primary ^{18}O beam at the RIPS fragment separator. The ^{8}He beam bombarded a cryogenic hydrogen gas target filled with 10 atm of hydrogen at 35 K. The outgoing protons were detected by a stack of Si strip detectors and the tritons and neutrons from the breakup of ^{7}H were detected in a downstream detection system consisting of a dipole magnet and plastic scintillators. A kinematic reconstruction of the 2p momenta permitted a reconstruction of the ^{7}H excitation spectrum. A resonant state was found ~3 MeV above the ^{3}H+4n threshold (binding energy of ~5.4 MeV) superimposed over a large background. However poor center-of-mass energy resolution and the large statistical error bars did not allow to extract accurate information on the resonance energy and width. This is the first report of a resonant state in ^{7}H.

2020PoZY, 2021Hu28: A p(^{8}He, 2p)^{7}H(^{3}H+4n) experiment was performed at the RIBF facility of RIKEN. A 150 MeV/nucleon ^{8}He beam was produced via projectile fragmentation of a ^{18}O primary beam bombarding a ^{9}Be target. BigRIPS fragment separator was used to purify the ^{8}He beam (10^{5} pps). This beam impinged on MINOS, a 150 mm think liquid hydrogen target. The outgoing protons from the p(^{8}He, 2p) reaction were tracked by the Time Projection Chamber surrounding MINOS and were detected in coincidence by an array of 36 NaI crystals arranged in two symmetric rings around MINOS. The energy resolution of these scintillators was 1% (FWHM) at E_{p}=80 MeV. The tritons from the decay of ^{7}H were momentum analyzed by the SAMURAI dipole magnet. Its associated focal plane detectors measured the energy loss and time-of-flight of the tritons. Neutrons′ time-of-flight and positions were detected by two plastic scintillator arrays: the NeuLAND demonstrator from GSI and the NEBULA array, placed downstream of SAMURAI at θ=0°. These arrays together provide the highest 4n detection efficiency (~0.6% at decay energy of 1 MeV).

The experimenters estimate that 20% of the neutrons detected may come from multiple hits produced by the background neutrons. Ongoing analysis indicates that this experiment has access to the complete 7−body kinematics of the final state (2p+^{3}H+4n). Their preliminary analysis seems to suggest that ^{7}H decays via direct emission of a tetraneutron since the sequential decay through intermediate ^{4,5,6}H is energetically forbidden. The results of this experiment are not yet published.

^{7}H Levels

E(level)	J$^{\pi}$	Comments
0	(1/2^{+})	Γ=broad. J$^{\pi}$: from (2003Ko11, 2003Ko68).

^{2}H(^{8}He,^{3}He) 2004Go26,2023Ni06

2004Go26: Deduced that the lower limit for the ^{7}H breakup energy is 50-100 keV above the ^{3}H+4n threshold. They estimated that the lifetime of ^{7}H is τ<1 ns. This limit was deduced based on an upper limit of 3 nb/sr for the ^{7}H production cross section.

2007Te12: Structure in missing mass spectrum includes possible ^{7}H state in 0-3 MeV range. Low statistics only allows for a limit to be placed on the cross section of the d(^{8}He, ^{3}He) reaction near the ^{3}H+4n threshold: cross section is below 0.02 mb/sr in $\theta_{c.m.}=9°-21°$.

2007GoZY: No clear evidence for ^{7}H resonances is seen.

2007FoZY, 2007FoZX, D. Baumel *et al.*, International Symposium on Physics of Unstable Nuclei, ISPUN07, July 2007, Hoi An, Vietnam, ISBN 9789814472487, 2007, pp. 18-25: A 15.3 MeV/nucleon ^{8}He beam is produced, at the GANIL-SPIRAL facility, by fragmentation of a ^{13}C bombarding a thick carbon target. The ^{8}He beam impinged on an isotopically enriched deuterated polypropylene target. The missing mass spectrum of ^{7}H is deduced from kinetic energies and emission angles of the ^{3}He ejectiles detected by the Silicon array MUST. The earlier analysis of these data by (2007FoZY, 2007FoZX) indicated that a broad structure was observed at ~2 MeV above the ^{3}H+4n emission threshold, which was proposed to be the ground state of ^{7}H. Two months later, Baumel *et al*. reported a candidate resonance observed at 1.56 MeV *27* above the ^{3}H+4n mass with a width of Γ=1.74 MeV *72*. These results have not been published in a peer-reviewed journal. Also, unlike more modern measurements, these inclusive ^{2}H(^{8}He,^{3}He) results did not require an exclusive triton coincidence with the ^{3}He reaction products, which would select the correct ^{7}H decay channel (^{3}H+4n). Therefore, these results were excluded from the Adopted Levels of ^{7}H presented in this evaluation.

2010Ni10, 2010NiZT: The missing mass spectrum exhibits a shoulder at around 2 MeV as well as a maximum around 10.5 MeV, relative to the ^{3}H+4n threshold. The maximum at 10.5 MeV could be an indication of a ^{7}H continuum excitation. They estimate the cross section of ~30 μb/sr in the center of mass frame at $\theta_{c.m.}=6°-14°$ for the reaction populating the low energy part of the ^{7}H spectrum.

The above experiments did not show conclusive evidences. The first quantitative results from studying the ^{2}H(^{8}He, ^{3}He) reaction comes from the (2020Be01) measurement.

2020Be01: A 26 MeV/nucleon ^{8}He beam is produced using the ACCULINNA-2 fragment separator at the Flerov Laboratory of Nuclear Reactions (JINR) to study the ^{2}H(^{8}He, ^{3}He)^{7}H reaction. The ^{3}He reaction products and the tritons from the decay of ^{7}H are momentum analyzed by a set of position sensitive ΔE-E-E telescopes covering an angular range of $\theta=8°-26°$, and a position sensitive silicon detector backed by a set of CsI(Tl) crystals coupled to PMTs positioned at $\theta=0°$, respectively. A total of 105 [later changed to 119 in (2021Mu04)] ^{3}He-^{3}H events are measured in coincidence mode.

Analysis of the ^{7}H missing mass spectrum with a 1.1 MeV resolution (FWHM) and two binning factors (events/0.3 MeV and events/1.25 MeV) is performed. The missing mass spectrum with the events/1.25 MeV binning factor shows peaks at (i) E_T=1.8 MeV *5* (5 events) with Γ<300 keV (E_T is energy relative to the ^{3}H+4n threshold), (ii) E_T=6.5 MeV *5* with Γ=2.0 MeV *5* (27 events), and (iii) E_T=12 MeV with Γ=4 MeV. The experimenters interpret the E_T=1.8 MeV peak as the ground state of ^{7}H with an experimental cross section of ~25 μb/sr in the $\theta_{c.m.}=17°-27°$. They consider the peak at E_T=6.5 MeV to be the first excited state of ^{7}H and conclude that this state is either a $J^{\pi}=3/2^{+}$ or $5/2^{+}$ state, or an unresolved doublet encompassing both of these states built upon the 2^{+} excitation of valence neutrons. The average experimental cross section of this state is estimated to be 30 μb/sr over $\theta_{c.m.}=10°-45°$. The authors advise that the peak at E_T=12 MeV could be produced as a result of a rapid decrease in the detection efficiency combined with growing 5-body (from the decay of ^{7}H) phase space effects, which would complicate the spectrum. This study deduced theoretical differential cross sections using FRESCO for a $J^{\pi}=1/2^{+}$ for the ground state and a $J^{\pi}=3/2^{+}$ and $5/2^{+}$ for the first excited state. As a result, spectroscopic factors of ~0.08-0.12 for the ^{7}H ground state and ~1 for the population of the ^{7}H first excited state are deduced. However, due to very low statistics for both states, these results may not be reliable.

2021Mu04, 2023Ni06: These studies have an improved experimental setup in comparison with the (2020Be01) experiment. A beam of 26 MeV/nucleon ^{8}He ions, produced by fragmentation of a ^{11}B primary beam at the FLNR/JINR/ACCULINNA-2 (Dubna) fragment separator, impinged on a windowed gas target filled with 1.13 atm (thick-mode) and 0.56 atm (thin-mode) D_2 gas maintained at 27 K. It was assumed that beam interacted with the target in the middle plane of the target. The detection system was modified to increase angular coverage at lower angles. The ^{3}He reaction products and tritons from the decay of ^{7}H were detected in coincidence (378 events) using 4 ΔE-E-E (last one used as veto) telescopes consisting of single sided silicon strip detectors covering an angular range of $\theta_{lab}=6°-24°$ and a ΔE-E telescope placed at $\theta_{lab}=0°$ consisting of a double sided position sensitive silicon strip detector backed by 16 CsI(Tl) crystals coupled to PMTs, respectively. An array of 48 organic scintillator neutron detectors with 12 cm distance between each two were positioned along $\theta=0°$. This array had a 15% efficiency for single neutrons and a 2% efficiency for neutrons in coincidence with charged particles. The resolution of the array was 4.5%. The experimental resolution was deduced using Monte Carlo simulation validated by an independent reference measurement of d(^{10}Be, ^{3}He)^{9}Li using the same setup. This reference measurement was also used to calibrate the ^{7}H missing mass spectrum.

^{2}H(^{8}He,^{3}He) 2004Go26,2023Ni06 (continued)

The missing mass spectrum was deduced from momenta of ^{3}H and ^{3}He particles. Eight events were produced from the requirements of ^{3}He+^{3}H+n triple coincidences. The experimenters applied a cut on the data for $\theta_{c.m.}>18°$ because angular resolution rapidly degrades at higher angles. Moreover, data at higher angles are more affected by the background. The missing mass spectrum reported in (2023Ni06) shows two clear peaks as well as evidence for a higher energy third peak. These peaks are evident in the spectrum of (2021Mu04). Furthermore, in (2021Mu04), there is evidence of an additional higher energy peak.

The first peak – $^{7}H_{g.s.}$: It exists at E $_{T}$=2.2 MeV *5*, where E_T is decay energy above the ^{3}H+4n threshold. This peak is constructed from 9 events (2 events are from triple ^{3}He-^{3}H-n coincidences) associated to the $^{7}H_{g.s.}$ with a theoretically estimated width (2011Gr13) of $\Gamma\leq1$ keV. The measured angular distribution is consistent with a one-step FRESCO calculation assuming a $J^{\pi}=1/2^{+}$ state and an extreme peripheral transfer.

The second and third peaks fitted as one peak: The next region of interest of the missing mass spectrum is the $3.5 \leq E_T \leq 9.5$ MeV region. If the events in this region are fitted with only one peak, the result would be a peak at E_T=5.7 MeV with a width of Γ=1.5 MeV corresponding to the first excited state of ^{7}H. However, assuming that this state decays via the sequential decay of $^{5}H_{g.s.}$ + 2n, where ^{5}H decays, in turn, via ^{3}H+2n, the 1.5 MeV width of the 5.7 MeV state would be twice as large as the upper limit width of the $^{5}H_{g.s.}$ decay (Grigorenko, unpublished). Therefore, a more reasonable analysis involves fitting two peaks for the events in the $3.5 \leq E_T \leq 9.5$ MeV region of the missing mass spectrum.

The first and second excited states – the doublet: When fitting 2 peaks under the above region, the first excited state is located at E_T=5.45 MeV *3* (Γ=0.75 MeV). Two of the events from triple ^{3}He-^{3}H-n coincidences contribute to the formation of this state. For the second excited state, two equally reasonable fits were achieved both placing it at E_T=7.6 MeV *3* but with a width of Γ=0.9 MeV or Γ=2.7 MeV. Statistical arguments favor the fit with the smaller width. The authors argue that the states at E_T=5.54 MeV and 7.6 MeV could be the $5/2^{+}$ and $3/2^{+}$ observed as an unresolved doublet in (2020Be01). However, they use caution for the state at $E_T\sim$7.6 MeV since it could also originate from an asymmetric broad shoulder to the state at $E_T\sim$5.45 MeV, or from two broad overlapping states. It should be noted that only 1 ^{3}He-^{3}H-n coincident event contribute to the formation of the second excited state. But the authors point out that the observation of this state does not have reasonable statistical confidence.

Third excited state: Lastly, the final peak in the missing mass spectrum is located at E_T=11.0 MeV *3* and contains 3 ^{3}He-^{3}H-n coincidence events. This state is more prominent at $\theta_{c.m.}$ between 20°−35° but in this region the background is strong. The authors argue that this state may have a structure of a dissolved core (p+6n, where the ^{3}H core disintegrates into p+n+n). A search for decay into p+6n was performed in (2021Mu04) but no evidence was found. The authors deduced cross sections of ~24 μb/sr for $\theta_{c.m.}$=5°−9° and ~7 μb/sr for $\theta_{c.m.}$=15°−19° (both for the ground state); and ~30 μb/sr for $\theta_{c.m.}$=5°−18° and ~11 μb/sr for $\theta_{c.m.}$=18°−30° (both for the first excited state).

^{7}H Levels

E(level)[†]	J^{π}[#]	Γ	E_{res}(^{3}H+4n)(MeV)	Comments
0	($1/2^{+}$)	<300 keV	2.0 *4*	E_{res}(^{3}H+4n)(MeV): the weighted average between 1.8 MeV *5* (2020Be01) and 2.2 MeV *5* from (2021Mu04). Γ: The theoretical prediction is for $\Gamma\leq1$ keV (2011Gr13) and $\Gamma\approx0.1$ MeV (2021Li62). But the observed width in (2021Mu04) is dominated by the experimental resolution, which improves with increasing the decay energy (E_T). Γ<300 keV is from (2020Be01). $d\sigma/d\Omega$=24 μb/sr between $\theta_{c.m.}$=5°−9° and ~7 μb/sr between $\theta_{c.m.}$=15°−19° from (2021Mu04); and $d\sigma/d\Omega\sim$25 μb/sr between $\theta_{c.m.}$=17°−27° from (2020Be01). The spectroscopic factors of ~0.08-0.12 are deduced in (2020Be01) for the ^{7}H ground state. However, due to very low statistics (5 events), these results may not be reliable.
3.4×10^{3}[a] *5*	($5/2^{+}$)	0.75[‡] MeV	5.45[@] *3*	$d\sigma/d\Omega$=30 μb/sr between $\theta_{c.m.}$=5°−18° and ~11 μb/sr between $\theta_{c.m.}$=18°−30° from (2021Mu04). Spectroscopic factors of ~1 for the population of the ^{7}H first excited state are deduced in (2020Be01). However, due to low statistics, these results may not be reliable. This state is expected (2021Mu04) to decay via $^{5}H_{g.s.}$+2n, where $^{5}H_{g.s.}$, in turn, decays to ^{3}H+2n. So, the decay may be sequential.

Continued on next page (footnotes at end of table)

^{2}H(^{8}He,^{3}He) 2004Go26,2023Ni06 (continued)

^{7}H Levels (continued)

E(level)[†]	J^{π}[#]	Γ	E_{res}(^{3}H+4n)(MeV)	Comments
5.6×10^{3}?[a] *5*	(3/2^{+})	0.9[‡] MeV	7.6[@] *3*	E(level): the existence of this state is uncertain (2021Mu04, 2023Ni06). Γ: width of Γ=2.7 MeV can also provide a reasonable fit but the statistical arguments made by (2021Mu04) favors Γ=0.9 MeV. Also, there is no mention of Γ=2.7 MeV fit in (2023Ni06).
9.0×10^{3} *5*			11.0[&] *3*	This state may have a structure of dissolved core, where ^{3}H breaks into p+n+n resulting in a p+6n configuration. But no experimental evidence exists.

[†] E_x is deduced using E_{res}(^{3}H+4n)=2.0 MeV *4*.
[‡] From (2021Mu04, 2023Ni06).
[#] From (2020Be01) and (2021Mu04).
[@] From Fig. 15 in (2021Mu04) and Fig. 4 in (2023Ni06).
[&] From (2021Mu04).
[a] These states were unresolved in (2020Be01) and identified at E_T=6.5 MeV *5* with a width of Γ=2.0 MeV *5* and an average cross section of 30 μb/sr over $\theta_{c.m.}$=10°−45°.

^{7}Li(π^{-},π^{+}) 1981Ev01,2007Fo05

1981Ev01: A π^{-} beam at 102 MeV (produced at the Swiss Institute for Nuclear Research, SIN) was focused onto a thick ^{7}Li target. The π^{+} reaction products were recorded in an emulsion stack (prepared at the Laboratory of Nuclear Problems at JINR) placed at 30° to the incident beam and shielded with lead bricks. In this early study of the ^{7}Li(π^{-},π^{+})^{7}H reaction, no evidence of resonances in ^{7}H was seen in the spectrum of outgoing π^{+}, but the histogram of the outgoing π^{+} favored a final state as a triton+^{4}n (tetraneutron) over a ^{3}H+4n or a proton+6n. The authors determined an upper limit of 1.0×10^{-31} cm^{2}/sr at (90% confidence limit) for the differential cross section corresponding to the production of ^{7}H.

2007Fo05, 2007FoZZ: These authors measured all inclusive double charge exchange by measuring the doubly differential cross sections, $d^{2}\sigma/d\Omega dE_{\pi}$, at three to five angles in the range 25°−130°, for incident pion energies between 120 and 240 MeV. Some structure in the cross section is reported, but there is no explicit mention of ^{7}H states. Cross sections are below 0.1 μb/sr in a wide $\theta_{c.m.}$=0°−50° region.

^{9}Be(π^{-},pp) 2009Gu17

1987Go25: This experiment was carried out with a low energy pion beam from the Synchrocyclotron of the Leningrad Institute of nuclear Physics. The search for ^{7}H was unsuccessful and no ^{7}H states were detected.

2000Ko46, 2005GuZZ, 2007Gu24, 2009Gu17: A beam of 30 MeV π^{-}, produced at the Los Alamos Meson Physics Facility (LAMPF) traversed a beryllium moderator and was stopped in a thin target. The experiment was performed with the aid of the double-arm semiconductor spectrometer. The charged particle reaction products were detected by two multi-layered semiconductor telescopes arranged at an angle of 180° with respect to each other. Either telescope consisted of two Si(Au) and fourteen Si(Li) semiconductor detectors. The missing mass spectrum of ^{7}H with a resolution of 1 MeV (FWHM) was constructed, which shows no resonance behavior near zero but suggests possible evidence of two broad resonances near 16 and 21 MeV, with Γ=2 and 5 MeV, respectively. Later in (2016Gu21), the authors reanalyzed the data and emphasized that no statistically significant evidence of ^{7}H states is found.

^{11}B(π^{-},p^{3}He) 2007Gu24,2009Gu17

2007Gu24, 2009Gu17, 2016Gu21: These experiments were performed using the Low Energy Pion (LEP) beamline at LAMPF, and the double arm semiconductor spectrometer. A π^{-} beam with an energy of 30 MeV passed through a beryllium degrader and stopped in a thin target. The secondary charged particles were detected by two multi-layer semiconductor devices. A feature exists in the missing mass spectrum of ^{7}H near resonance energy E_r~0. However, insufficient energy resolution and poor statistics make it impossible to analyze this structure.

^{7}H Levels

E(level)
0?

^{12}C(^{8}He,^{13}N) 2008Ca22,2022Ca10

2007Ca28, 2007Ca47, 2007CaZZ, 2008Ca22: The ^{12}C(^{8}He,^{13}N)^{7}H proton transfer reaction is studied by impinging an E(^{8}He)=15.4 MeV/nucleon beam, produced at the SPIRAL facility in GANIL, on a C_4H_{10} gas target. The ^{13}N and tritium (from ^{7}H decay) charged reaction products are detected in coincidence mode. Seven events are associated with ^{7}H. The energy of the ground state ^{7}H resonance is determined to be E_{res}=0.57 MeV *+42−21* above the ^{3}H+4n breakup threshold with a width of Γ=0.09 MeV *+94−6*. The uncertainties in E_{res} and Γ are large because of the small number of observed events. These experiments do not report on the ^{7}H spin and parity, and no reaction channel identification was possible. (2021Mu04) mentions that the results of these experiments are based on the assumption that only ${}^{7}H_{g.s.}$ was populated. This assumption however may be questionable because of the potential for the populations of ^{7}H*, as well as ^{12}C(^{8}He, ^{14}N)^{6}H, and ^{12}C(^{8}He, ^{15}N)^{5}H, which would complicate the detection of ${}^{7}H_{g.s.}$ in the absence of the reaction channel identification.

(2022Ca10): XUNDL dataset compiled by TUNL, 2023: The authors used the ^{19}F(^{8}He, ^{20}Ne) and ^{12}C(^{8}He, ^{13}N) reactions to investigate the ground state properties of ^{7}H.

A beam of ^{8}He ions with an intensity of 10^4 pps and an energy of 15.4 MeV/nucleon was produced in the SPIRAL facility at GANIL. The beam impinged on the MAYA active-target detector filled with 176 mbar of a mixture of helium and CF_4. The trajectories of the ^{20}Ne and ^{13}N recoils were measured with an angular resolution of 1.2°. The tritons from the decay of ^{7}H were detected, in coincidence with the recoils, in a ΔE-E telescope composed of 20 silicon detectors backed by 80 CsI crystals.

In comparison with the ^{19}F(^{8}He,^{20}Ne) events, the missing mass spectrum shows a less obvious peak associated to the contribution of the ^{12}C to the resonant formation of ^{7}H. This peak is in a region with a significant contribution from the lower tail of the non-resonant continuum. An upper limit of 0.2 mb/sr was estimated for the contributions other than those of the ^{7}H and its non-resonance continuum. The authors deduced the spectrum of ranges (16 mm resolution at FWHM) for those recoils whose emission angles were between θ_{lab}=45°−54°. This distribution shows a clear peak corresponding to the contribution of ^{12}C to the formation of ^{7}H. The peak was simulated with a Breit-Wigner probability distribution. The mass and width of the ^{7}H resonance were extracted from a log-likelihood minimization between the simulation and the measured range distribution. The angular distribution of the ^{7}H production with the ^{12}C target was measured. DWBA calculations were performed with the code FRESCO. The average production cross section with the ^{12}C yields 1.2 mb/sr *+5−6* between $\theta_{c.m.}$=6° and 27°. Systematic uncertainties are estimated to be ~0.7%. The measured angular distributions is rather featureless, and the DWBA fits suffered from large statistical and systematic uncertainties, which prevented a clear assignment of spin and parity.

^{7}H Levels

E(level)	Γ (MeV)	Comments
0	0.18 MeV *+41−12*	E(level): The resonance is at 0.64 MeV *+33−23* above the ^{3}H+4n threshold. E_{res}(^{3}H+4n)=0.64 MeV *+33−23*: the weighted average of 0.73 MeV *+58−47* from (2022Ca10) and 0.57 MeV *+42−21* from (2007Ca28, 2007Ca47, 2007CaZZ, 2008Ca22). Γ: The weighted average of 0.18 MeV *+47−16* from (2022Ca10) and 0.09 MeV *+94−6* from (2007Ca28, 2007Ca47, 2007CaZZ, 2008Ca22). $d\sigma/d\Omega$=40 μb/sr *+58−31* from (2007Ca28, 2007Ca47, 2007CaZZ, 2008Ca22), and $d\sigma/d\Omega$=1.2 μb/sr *+5−6* between $\theta_{c.m.}$=6°−27° with a systematic uncertainty of 0.7% from (2022Ca10).

^{19}F(^{8}He,^{20}Ne) 2022Ca10

(2020CaZW, 2022Ca10): XUNDL dataset compiled by TUNL, 2023: The authors describe the ^{7}H nucleus as an extended pure neutron shell around a ^{3}H core in a 1/2^{+} ground state. The neutron pairing makes the ^{7}H nucleus a long-lived and almost-bound resonance.

In this experiment, more than 200 events were assigned to $^{7}H_{g.s.}$ (from the ^{19}F(^{8}He, ^{20}Ne) and ^{12}C(^{8}He, ^{13}N) reactions measured), which is significantly higher than any other measurement. The missing mass spectrum shows a prominent peak corresponding to the resonant formation of ^{7}H with the ^{19}F target with a small contribution from the lower tail of a 3-body non-resonant continuum, as well as a less obvious peak corresponding to the ^{12}C contribution to the production of ^{7}H. The authors deduced the spectrum of ranges (with 16 mm resolution at FWHM) for those recoils whose emission angles were between θ=45°−54° in the laboratory frame. This distribution shows two clear peaks (from ^{19}F and ^{12}C contributions) and was simulated with a Breit-Wigner probability distribution. The mass and width of the ^{7}H resonance were extracted from a log-likelihood minimization between the simulation and the measured range distribution. The result describes ^{7}H as a low-lying, narrow (due to neutron pairing) resonance with a mass of 0.73 MeV *+58−47* above the ^{3}H+4n mass and a width of 0.18 MeV *+47−16*. Owing to the large number of detected ^{7}H events, most of which came from the reactions with the ^{19}F target, the angular distribution of the ^{7}H production with the ^{19}F target was measured. The average production cross-section with ^{19}F is 2.7 mb/sr *5* between $\theta_{c.m.}$=4°−18°. DWBA calculations were performed with the code FRESCO. The data obtained with the ^{19}F target are best fitted assuming the 0^{+} ground state of ^{20}Ne and a 1/2^{+} ^{7}H resonance. The scaling factor deduced from normalizing the DWBA differential cross sections to the experimental ones was observed to vary between 4.5 *28* and 12.7 *61*, depending on the nuclear density used for ^{8}He.

^{7}H Levels

E(level)	J$^{\pi}$†	Γ (MeV)	L†	Comments
0	1/2^{+}	0.18 MeV *+47−16*	0	E$_{res}$(^{3}H+4n)=0.73 MeV *+58−47* from (2022Ca10). E(level): The missing mass spectrum displayed on Fig. 3 of (2022Ca10) shows two wide peaks corresponding to the production of ^{7}H from the (^{8}He,^{3}He) reactions on the ^{19}F and ^{12}C targets. These peaks are respectively ~5 MeV and several MeV wide at FWHM and are attributed to the contributions from ^{19}F and ^{12}C, respectively. Such a wide range may already include at least the first excited state of ^{7}H, which is not considered in (2022Ca10). It is unclear how (2022Ca10) extracted the energy and width of the $^{7}H_{g.s.}$ from the detector response function, and why they did not include any potential excited states. dσ/dΩ=2.7 μb/sr *5* between $\theta_{c.m.}$=4°−18° from (2022Ca10). The spectroscopic factor deduced from normalizing the DWBA cross section to the experimental angular distribution of the ^{19}F(^{8}He, ^{20}Ne)^{7}H reaction was observed (2022Ca10) to vary between 4.5 *28* and 12.7 *61*, depending on the nuclear density used for ^{8}He in the DWBA calculation.

† From L=0 in a DWBA fit to the measured angular distribution of the ^{19}F(^{8}He,^{20}Ne)^{7}H transfer reaction data from (2022Ca10). The L=0 is inferred since the best fit for the DWBA calculation assumes that ^{20}Ne is in its ground state, and that the proton is removed from the ground state of ^{8}He (2022Ca10).

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