Adopted Levels

In the following discussion, the notation ^{4}n will be used to represent a possible bound or resonant state of four neutrons and will be called a tetraneutron. A thorough review on the quest for discovering ^{3}n and ^{4}n systems is found in 2021Ma23. The A=4 evaluations (1968Me03,1973Fi04,1992Ti02) all contain some discussion of ^{4}n. See also 2004Gr03. It is expected that the ground state of the tetraneutron, either bound or resonant, would have J^π=0$^+$ and T=2; see (1980Be22,2003Pi09,2016Hi03), for example. Calculations reported in 2003Pi09 suggest that the tetraneutron might look "...like two widely separated dineutrons." Clustering into two dineutrons seems to be expected; see (Lashko and Filippov, Phys Atomic Nuclei 71, 209 (2008)) and references therein. Also see 2003Be46, 2005La27, and figures 3 and 4 and discussion in 2017Ga10.

The fact that the decay ^{8}He→^{4}He+^{4}n does not occur requires that the binding energy of ^{4}n be no more than 3.1 MeV, using the mass table 2021Wa16. See references in 1992Ti02. An argument is presented in (Vlasov and Samoilov, Atomic Energy 17, 687 (1964)) that, because the binding energy of the proton always increases when two neutrons are added to a nucleus, it is impossible to have a ^{4}n bound state. This argument is referenced in 2003Be06.

As shown in the experimental articles cited below, most searches for evidence of ^{4}n states, using a variety of different methods, have yielded negative results. However, in 2002Ma21, studying the decay of ^{14}Be to ^{10}Be plus four neutrons, six events were observed that were interpreted as evidence of the emission of a bound tetraneutron. Referring to 2002Ma21, the author of 2003Ti03 writes, "...the breakup ^{14}Be→^{10}Be+^{4}n represents one of the best possible tools to search for a tetraneutron." This is because ^{14}Be consists of four loosely bound valence neutrons and a ^{10}Be core. A similar argument can be made about ^{8}He as a ^{4}He core plus a tetraneutron; see (2005Ma97,2016Sh35). A theoretical study of proton-tetraneutron elastic scattering reported in 2004Sh09 cast doubt on the tetraneutron interpretation of results reported in 2002Ma21.

In 2010Ni10, the ^{7}H spectrum from the reaction ^{2}H(^{8}He,^{3}He)^{7}H was measured by observing the ^{3}He and the ^{3}H from the decay of ^{7}H. It was found that the curve that best fit the observed ^{7}H spectrum was that of a two body decay – ^{3}H+^{4}n – thus giving indirect evidence of the existence of the tetraneutron.

As reported in 2016Ki01, evidence of a resonant ^{4}n state at about 0.8 MeV above the four free-neutron energy with a width not more than 2.6 MeV was observed in the missing mass spectrum of the ^{4}He(^{8}He,^{8}Be)^{4}n reaction. In 2017Th03, Thoennessen considers this to be the experiment in which the 4n resonance is first observed. For more on this result, see (Bertulani and Kajino, Nature 532, 448 (2016)). A set of follow-up measurements is underway to confirm the 2016Ki01 observations.

The first new result in 2022Du08, reports an E_{rel}(4n)=2.4 MeV *6* resonance with Γ≈1.75 MeV, in fair agreement with 2016Ki01. The experiment from RIKEN used the ^{1}H(^{8}He,pα) reaction to obtain the ^{4}n system missing mass spectrum, but with improved statistical significance. The progress report for a second RIKEN experiment using the ^{1}H(^{8}He,2p)^{7}H→t+^{4}n reaction is found in 2021Hu28.

An additional result from 2022Fa01 suggests a bound ^{4}n state produced in the ^{7}Li(^{7}Li,^{10}C*(3354))^{4}n reaction. The interpretation of a peak located between the ground- and first-excited states of ^{10}C on the spectrograph focal plane is novel, but a number of systematic questions prevent adoption of this bound ^{4}n level without additional support. See also 2020Yu05.

Theory:

In 1963Ar06, the authors discuss possible T=2 states in A=4 nuclei, including ^{4}n; see also (1963Sc35,1964Go25) and (von Hippel and Divakaran, Phys Rev Lett 12, 128 (1964)) for similar discussions.

A variational calculation of ^{4}n as a pair of ^{2}n with semi-realistic NN interaction was reported in 1965Ta14. It was found that no bound or resonant ^{4}n state is produced. A similar calculation using the resonating group approach was reported in 1970Th12 with the same result. In 2003Be46, ^{4}n was modeled as a molecule of a pair of weakly bound ^{2}n. A variational calculation concluded that it is unlikely to have a bound state. No search was made for a resonance. Somewhat along the same line, the study reported in (Lashko and Filippov, Phys of Atomic Nuclei, 71, 209 (2008)) of the two clusters 2n+2n and 3n+n has the potential of giving a ^{4}n resonance.

Shell model calculations reported in 1980Be22, using interactions that reproduce the binding energies of ^{3}H, ^{3}H and ^{4}He, predict ^{4}n to be a 0$^+$ state that is unbound by about 18 MeV.

In 1981Ji02, a four-body hyperspherical basis approach was used to investigate the $\pi^\mp$+^{4}He→$\pi^\pm$ + 4n(4p) reactions; the four nucleons were found to have total orbital momentum L=0, and the final state interactions were described as significant. In 2003Ti03, the author used the hyperspherical function method and realistic NN interactions and found that a bound ^{4}n state doesn't exist.

Studies of 3n and 4n systems using Jost functions in the complex momentum plane were reported in 1997So27. For physically reasonable two-body interactions, no true bound states or resonances were found, but the authors report finding a subthreshold

Adopted Levels (continued)

resonance implying that a ^{4}n resonance could occur inside a nucleus, for example. The location of the subthreshold resonance depends strongly on the interaction used. A somewhat similar but more detailed study is reported in 2005La27, using Faddeev-Yakubovsky equations with similar results. In a later study, the same group (2016Hi03 and Carbonell et al, Few-Boby Syst 58, 67 (2017)) added a T=3/2 NNN into the 4n system and found that such an interaction would have to be unphysically strong to produce a narrow ^{4}n resonance. Following the report of a resonance in 2016Ki01, the parameters of the 2016Hi03 model were adjusted by 2017La11 in an attempt to reproduce the results; no physically plausable solution was found leading to the conclusion, "any enhancement of the reaction cross section involving 4n in the final state should have an alternative dynamical explanation".

A four-body complex scaling method was utilized by 2003Ar18 in a study of ^{4}N, ^{5}H and ^{6}He. No realistic NN force leading to a bound or resonant ^{4}n state could be found.

Green's Function Monte Carlo calculations are reported in 2003Pi09 with realistic NN and NNN interactions, but did not produce a bound ^{4}n. The author also found that modifications in NN interactions that might lead to a bound ^{4}n would have major effects on models of other nuclei, thus adding more evidence against the existence of a ^{4}n bound state.

In 2006Si33, the ^{4}n system was explored by developing a four-fermion system with short-range pairwise potentials. A bound system could be found using unrealistic potentials, while a barely-unbound system was slightly less problematic.

The authors of 2016Sh35, using a modified no core shell model with the JISP16 NN interaction (see Shirokov, et al., Phys Lett B 644, 33(2007)), obtained a 4n resonance near 0.8 MeV with a width of about 1.4 MeV.

In 2017Ga10, the authors report studies of two, three and four neutron systems using quantum Monte Carlo methods with N^{2}LO effective field theory interactions to look for resonances. Using two different approaches, they obtained a ^{4}n resonance at 2.1 MeV *2* by one method and 2.0 MeV *10* by the other. There is no mention of the width of the resonance. Their model predicts the resonance energy for a trineutron state is lower than that of the tetraneutron.

Using the no-core Gamow shell model (NCGSM) and a density matrix group approach with continuum states in both models and a variety of realistic two-body interactions, the authors of 2017Fo13 obtained resonance energies around 7.3 MeV and widths about 3.7 MeV. A later NCGSM study in 2019Li50 using a larger model space took both internucleon correlations and continuum coupling into account and found a resonance energy around 2.64 MeV and width near 2.38 MeV. Their model predicts the resonance energy for a trineutron state is lower than that of the tetraneutron.

An approach using exact-continuum equations for transition operators, initially developed by (Grassberger snd Sandhas, Nucl. Phys. B 2 (1967) 181), was utilized in 2018De24, 2019De27 to investigate the dependence on *nn* force strength. No resonant behavior was found for reasonable strength.

In 2020Hi09, 2021Hi04, the 3- and 4-neutron systems were analyzed using adiabatic hyperspherical methods to analyzed the long-range behavior of the adiabatic potentials. No support for a resonance was found; however, a ρ^{-3} dependence was found suggesting an increase in the density of low-energy continuum states that the authors suggest is a generalized consequence of Efimov physics. This phenomena is suggested as the origin of the enhancement observed by 2016Ki01.

See other studies in 1968Ba48,1977Ba47,1981Ka39,1988In04,1989Gu16,1989Go18.

Positive experimental results: (See reaction data sets).

Negative experimental results:

^{2}H(^{8}He,^{6}Li)4n:

2004Wo10,2005Bl09: ^{8}He nuclei were produced by the SPIRAL facility at GANIL by ^{13}C fragmentation and accelerated to 120 MeV and focused on a CD_2 target. The observed spectrum was fairly well represented by the three body ^{6}Li-nn-nn simulation but also showed some structure at about 2.5 MeV above the four neutron threshold. Some structure was also seen in the negative energy region which could correspond to a bound ^{4}n but might be a background effect. The author comments that statistical uncertainties did not allow for firm conclusions. See also 2003Wo13, 2004Wo10.

2007FoZY: ^{8}He nuclei were produced at the GANIL-SPIRAL facility by ^{13}C fragmentation and accelerated to 122 MeV and focused on a deuterated target. The observed 4n missing mass spectrum showed no evidence of a bound ^{4}n system, but did show evidence of correlations between the four unbound neutrons as two n-n pairs.

^{4}He(π^-,π^+)4n:

1965Gi10: E(π^-) was 176 MeV at the CERN 600 MeV synchrocyclotron. The outgoing π^+ spectrum was obtained with no evidence of tetraneutrons.

1967Ka20, 1968Ka35: E(π^-) was 140 MeV from the Lawrence Radiation Laboratory cyclotron. The outgoing π^+ spectrum was measured with no evidence of a tetraneutron. An upper bound on its production was obtained. A report in 1981PeZU found issues

Adopted Levels (continued)

with the overall cross section scale reported by 1968Ka35, but did not contradict the non-observation of a ^{4}n resonance.

1984Un02: E(π^-) was 165 MeV at Los Alamos meson physics facility. The outgoing π^+ momentum spectrum was measured at 0°. No evidence of tetraneutrons was found; phase space results favored two 2n pairs outgoing. See also 1986Ke20.

1986Ki20: The pion energies used were 180 and 240 MeV from Los Alamos meson physics facility ; no mention is made of tetraneutrons.

1989Go17: The pion energy at TRIUMF was 80 MeV and the outgoing π^+ were observed at lab angles between 50° and 130°. A search was made in the 0 to 3 MeV region where evidence of tetraneutrons might be expected, but no evidence was found.

2005Ki20: For E(π)=180, 240 MeV and scattering angles from 25° to 130°, the differential cross section was measured at Los Alamos pion facility. No evidence of tetraneutron production was seen.

^{7}Li(^{7}Li,^{10}C)4n:

1974Ce06: E(^{7}Li)=79.6 MeV at Lawrence Berkeley laboratory, the outgoing ^{10}C spectrum showed no indication of tetraneutron production.

1988Al11,2005Al15: E(^{7}Li)=82 MeV at the Russian Research Centre Kurchatov Institute, the outgoing ^{10}C energy spectrum was reproduced by a five particle phase space. There were no indications of tetraneutron production.

^{7}Li(^{11}B,^{14}O), ^{9}Be(^{9}Be,^{14}O), ^{7}Li(^{9}Be,^{12}N)4n:

1986Be44,1986Be54,1987BeYJ,1987Bo40,1988Be02: In each of these reactions using heavy ion beams from the U-300 cyclotron at Dubna, the authors compared the observed outgoing particle spectrum with a five particle phase space calculation and saw no evidence of the existence of tetraneutron states.

^{14}N(^{4}n,n)^{17}N, ^{27}Al(^{4}n,^{3}H), (^{4}n,^{1}Hnn)^{28}Mg:

1963Sc35: Using fission fuel elements at Argonne National Laboratory, the authors irradiated $C_2H_4N_4$ samples and looked for evidence of ^{17}N decay resulting from ^{14}N(^{4}n,n)^{17}N. They also irradiated an Al sample and looked for evidence of ^{28}Mg decay resulting from either ^{27}Al(^{4}n,^{3}H)^{28}Mg or ^{27}Al(^{4}n,pnn)^{28}Mg. Observing either ^{17}N or ^{28}Mg decay would give evidence of the existence of ^{4}n as a fission product. No such evidence was found.

^{nat}U(d,4n)X:

1965Ci01: The reactions ^{14}N(^{4}n,n), ^{16}O(^{4}n,t), ^{26}Mg(^{4}n,2n), ^{103}Rh(^{4}n,2n), ^{209}Bi(^{4}n,n), ^{209}Bi(^{4}n,2n) were investigated following bombardment of natural uranium with 50 MeV deuterons at Karlsruhe cyclotron looking for evidence for the production of tetraneutrons. No evidence was found.

^{103}Rh(n,4n)^{100}Rh, ^{209}Bi(n,4n)^{206}Bi:

1952Su10: Using 16 MeV deuterons from the University of Pittsburgh cyclotron, the authors obtained fast neutrons from ^{9}Be(d,n) that interacted with ^{103}Rh and ^{209}Bi targets. They found no activity from ^{100}Rh or ^{206}Bi to suggest that tetraneutrons might have been produced by either ^{103}Rh(n,4n)^{100}Rh or ^{209}Bi(n,4n)^{206}Bi.

^{130}Te(^{3}He,4n)X:

1980De36: A ^{130}Te target was irradiated with a 44 MeV ^{3}He beam from the AVF cyclotron of the Free University of Amsterdam. If ^{4}n bound states were produced, then the reaction ^{130}Te(^{4}n,2n)^{132}Te should occur. No evidence of ^{132}Te production was found.

Adopted Levels (continued)

^{4}n Levels

Cross Reference (XREF) Flags

A	^{1}H(^{8}He,pα)	D	^{7}Li(^{7}Li,^{10}C)
B	^{2}H(^{8}He,^{3}Het)	E	C(^{14}Be,^{10}Be),C(^{8}He,^{4}He)
C	^{4}He(^{8}He,^{8}Be)		

E(level)	J^{π}	Γ	E_{rel}(4n) (MeV)	XREF	Comments
0	0^+	1.75 MeV *37*	2.37 *60*	ABCDE	XREF: B(?)D(?)E(?). E(level),Γ: From E_{rel}(4n)=2.37±0.38(stat)±0.44(sys) MeV (2022Du08). A result with significantly lower statistics was interpreted as $E(^{4}n)_{rel}$=0.83±0.65(stat)±1.25(sys) MeV (2016Ki01). and Γ=1.75±0.22(stat)±0.30(sys) MeV. The theoretical analysis supporting a tetraneutron state in this vicinity is somewhat uneasy; the ab initio no-core shell model approaches in 2016Sh35 and 2019Li50 and the quantum Monte Carlo approach of 2017Ga10 are the only models known to predict a tetraneutron resonance near the reported energy. However, the models of 2017Ga10 and 2019Li50 indicate trineutron resonances at even shallower energies than the tetraneutron state, which would make them observable; since there is so far no evidence for a trineutron resonance, the reliability of these models require further experimental support. Other theoretical models fail to produce a tetraneutron resonance near the reported energy region.

^{1}H(^{8}He,pα) 2022Du08

2022Du08: XUNDL dataset compiled by TUNL (2022).

The authors searched for evidence of tetraneutron resonances by analyzing the missing mass spectrum of quasi-elastic ^{8}He(p,pα)^{4}n reactions.

A 156 MeV/nucleon ^{8}He beam from the RIKEN/BigRIPS fragment separator impinged on a 5 cm thick liquid hydrogen target that was positioned at the SAMURAI spectrometer target position. Three planes of position sensitive Si detectors provided particle identification and trajectory information for scattered protons and ^{4}He ejectiles resulting from quasi-elastic knockout reactions; additional information from the SAMURAI focal plane determined the proton and ^{4}He momenta so that the missing-mass spectrum could be deduced. A relatively low yield of 422 p+^{4}He events and low efficiency for detecting neutrons prevented implimentation of a p+^{4}He+4n exclusive event coincidence requirement.

The deduced missing mass spectrum has two dominant components. At E_{rel}(4n)=2.37±0.38(stat)±0.44(sys) MeV, a Γ=1.75±0.22(stat)±0.30(sys) MeV peak is observed that is associated with an unbound 4n resonance. At higher energies a broad 20-30 MeV group is observed that is associated with a non-resonant, direct four-body decay to the continuum. No further structure is observed in the spectrum.

The authors compared their results with a prior report of E_{rel}(4n)=0.83±0.65(stat)±1.25(sys) MeV and Γ<2.6 MeV by (2016Ki01) along with various theoretical predictions. It is perhaps surprising that the suggested observation of a 420 keV bound 4n system reported by (2022Fa01) was not mentioned; the missing mass spectrum obtained in the present quasi-elastic knockout reaction approach should be sensitive to bound and unbound states so population of such a state should be observable, but the suggested state could not be found in the present work.

^{4}n Levels

E(level)	Γ	E_{rel}(4n) (MeV)	Comments
0	1.75 MeV *37*	2.37 *60*	E(level),Γ: From E_{rel}(4n)=2.37±0.38(stat)±0.44(sys) MeV and Γ=1.75±0.22(stat)±0.30(sys) MeV.

$^{2}H(^{8}He,^{3}He t)$ 2010NiZT,2010Ni10

The authors were searching for evidence of ^{7}H states using the $^{2}H(^{8}He,^{3}He)^{7}H \rightarrow t+4n$ reaction at $E(^{8}He)=42$ MeV/nucleon at the Center for Nuclear Study at the University of Tokyo. The ^{7}H excitation spectrum was determined from kinematic analysis of the residual ^{3}He and the ^{3}H produced in the decay of ^{7}H.

The ^{7}H excitation spectrum was compared to phase space curves assuming either 5 body final state (^{3}H+4 neutrons), 3 body final state (^{3}H+2 di-neutrons) or 2 body final state (^{3}H+tetraneutron). The curve best representing the observations, especially at lower ^{7}H excitation energy, was the 2 body curve, thus giving indirect evidence for the existence of tetraneutrons.

^{4}n Levels

E(level)
0?

^{4}He(^{8}He,^{8}Be) 2016Ki01

A beam of 186 MeV/nucleon ^{8}He ions, produced by fragmentation of a ^{18}O beam in a berylium target at the RIKEN/BigRIPS facility, impinged on a 136 mg/cm^{2} liquid He target located at the SHARAQ-S0 target position. The ^{8}Be reaction products decayed into 2α particles; events within the 8 mrad acceptance (θ=0°) of the spectrometer were momentum analyzed and detected at the focal plane using cathode-readout drift chambers that resolved α projectiles separated by at least 5mm. A measurement of the Time-of-Flight through the spectrometer on an event-by-event basis permitted characterization of the reaction kinematics that permitted 1.2 MeV energy resolution in the missing mass energy resolution. There was an additional 1.25 MeV systematic uncertainty in the reconstructed energy.

The present reaction was selected since it can produce the ^{4}n system "at an almost recoilless condition that is crucial for populating very weakly bound systems (states)." Two components are observed in the missing mass spectrum: a relatively narrow peak with four counts located in the 0<E_{4n}<2 MeV region (σ=3.8 nb *+29−18*), and a broad continuum extending above E_{4n}>2 MeV. The analysis found that the lower peak appears to involve only ^{8}Be(J^{π}=0^{+}) in the final state, while the continuum region involves both ^{8}Be(J^{π}=0^{+}) and ^{8}Be(J^{π}=2^{+}). Furthermore, the analysis is consistent with 4-body decay, rather than decay to a pair of dineutrons.

^{4}n Levels

E(level)	J^{π}	Γ	Comments
0	0^{+}	<2.6 MeV	E(level): from E(^{4}n)$_{rel}$=0.83±0.65(stat)±1.25(sys) MeV. σ=3.8 nb *+29−18*.

^{7}Li(^{7}Li,^{10}C) 2022Fa01

2022Fa01: XUNDL dataset compiled by TUNL (2022).

The authors searched for evidence of the tetraneutron system using the ^{7}Li(^{7}Li,^{10}C)^{4}n 3-proton pickup reaction.

A beam of 46 MeV $^{7}Li^{+3}$ ions from the Garching Tandem accelerator impinged on 99% enriched 100 μg/cm^2 $^{7}Li_2O$ vapor deposition layer targets that were formed on 20 μg/cm^2 carbon foil backings. The ^{10}C reaction products were momentum analyzed using a Q3D magnetic spectrograph that was positioned at θ=7.0°, covered an angular range of 6.0° to 9.5° and had an acceptance of ≈9 msr. The spectrograph focal plane detectors utilized a single-wire proportional counter and an array of 10 mm wide and 30 mm high PIN Si detectors to obtain ^{10}C particle-identification and focal plane position information.

Due to the hygroscopic character of Li_2O deposits, non-negligible amounts of H_2O and CO_2 were expected in the targets; in fact effective thicknesses near 200 μg/cm^2 were measured indicating the presence of target contamination. The kinematics for ^{6}Li(^{7}Li,^{10}C)3n(phase-space), ^{7}Li(^{7}Li,^{10}C)4n(phase-space), ^{7}Li(^{7}Li,^{10}C)^{4}n, ^{12}C(^{7}Li,^{10}C)^{9}Li, ^{16}O(^{7}Li,^{10}C)^{13}B and ^{17}O(^{7}Li,^{10}C)^{14}B were considered in analyzing the focal plane data.

The measured ^{10}C energy spectrum included two prominent groups at 20.84 MeV *10* and 22.84 MeV *5*. The widths are reported as σ=0.24 MeV *9* and 0.39 MeV *5* for the E(^{10}C)= 20.84 and 22.84 MeV groups, respectively, and these values are consistent with the systematic energy spread induced by reactions at different depths in the target. While the 22.84 MeV peak corresponds to the expected location of ^{16}O(^{7}Li,^{10}C)^{13}B events, the 20.84 MeV group could only be associated with the ^{7}Li(^{7}Li,^{10}C)^{4}n reaction, but the description is complex.

The 20.84 MeV group corresponds to an excitation energy of 2.93 MeV above the 4-neutron+$^{10}C_{g.s.}$ threshold; it also falls below the 4-neutron+^{10}C*(3354 keV) first excited state threshold. The authors deduced Γ(FWHM)<0.24 MeV for the 20.84 MeV group, and they argue that such a narrow width is unreasonable for a ^{4}n state that is unbound by 2.93 MeV. The authors explain their observations as a ^{4}n state bound by 0.42 MeV produced with the ^{10}C*(3354 keV) first excited state.

To test their results, they repeated the measurement with the QCD spectrograph set to θ=5°. The reaction kinematics at this angle moved the two groups closer, as expected, and supported the interpretation involving a bound tetraneutron.

Lastly they compare their results with the previous ^{7}Li(^{7}Li,^{10}C) studies of (1974Ce06: E(^{7}Li=79.6 MeV)) and (2005Al15: E(^{7}Li=79.6 MeV)), which reported no evidence for tetraneutron observation. They suggest that the low energy utilized in the present study, E(^{7}Li=46 MeV)), was key to the increased production.

^{4}n Levels

E(level)	Γ	E_{rel}(4n) (MeV)	Comments
0?	<0.24 MeV	−0.42 *16*	E(level): The negative relative energy implies a bound ^{4}n system. Decay mode not specified.

C(^{14}Be,^{10}Be),C(^{8}He,^{4}He) 2002Ma21,2003Or05,2005MaZZ

2002Ma21: The ^{10}Be plus 4 neutron breakup events, resulting from E(^{14}Be)=35 MeV/nucleon bombardement of a C target at GANIL, were were analyzed in 2002Ma21. The authors obtained a few events which could be interpreted as bound tetraneutrons with a lifetime of at least 100 ns.

2003Or05,2005MaZZ: Additional discussion is presented of the results reported in 2002Ma21.

Bouchat, PhD Thesis, 2005, Universite Libre de Bruxelles: A similar experiment was done using a 15 MeV/nucleon ^{8}He beam. Preliminary results were that 18 events of possible tetraneutron production were observed.

Marques, Few Body Syst 44, 269 (2008): The author presents additional discussion of the experiments discussed in 2002Ma21 and (Bouchat, PhD Thesis, 2005, Universite Libre de Bruxelles).

^{4}n Levels

E(level)
0?

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