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. 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 $J\pi=0^+$ 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 2012Wa38. 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 tetrahedron; 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.

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 in the reaction ^{4}He(^{8}He,^{8}Be)^{4}n. Thoennessen (2017Th03) 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)).

In addition, as reported 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.

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 modelled 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 4n 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.

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 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 resonance implying that a 4n 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 4n resonance.

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 4n resonance at 2.1 MeV

Adopted Levels (continued)

2 by one method and 2.0 MeV *10* by the other. There is no mention of the width of the resonance.

Using the no-core Gamow shell model 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. The calculated width is larger than the width reported in 2016Ki01.

Positive experimental results: (See reaction data sets).

Negative experimental results:

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

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 seem in the negative energy region which could correspond to a bound 4n but might be a background effect. The author comments that statistical uncertainties did not allow for firm conclusions.

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: 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.

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.

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.

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:

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 facilities at Argonne National Laboratory, the authors did neutron irradiation of $C_2H_4N_4$ and looked for evidence of ^{17}N decay resulting from ^{14}N(^{4}n,n)^{17}N. They also did neutron irradiation of 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 resulting from the neutron irradiation. 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.

Adopted Levels (continued)

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

1952Su10: The authors obtained fast neutrons from ^{9}Be(d,n) using 16 MeV deuterons from the University of Pittsburgh cyclotron which 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: ^{130}Te target was irradiated with 44 MeV ^{3}He beam by 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 that would indicate the existence of the tetraneutron was found.

^{4}n Levels

Cross Reference (XREF) Flags

A	^{2}H(^{8}He,^{3}Het)
B	^{4}He(^{8}He,^{8}Be)
C	C(^{14}Be,^{10}Be),C(^{8}He,^{4}He)

E(level)	J^{π}	Γ	XREF	Comments
0?	0^{+}	<2.6 MeV	ABC	XREF: A(?)C(?). E(level): from $E(^{4}n)_{rel}$=0.83±0.65(stat)±1.25(sys) MeV.

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

The authors were looking for evidence of ^{7}H states using a ^{8}He beam with an energy of 42 MeV/nucleon at the Center for Nuclear Study at the University of Tokyo. The ^{7}H spectrum is constructed from measurements of the observed ^{3}He and the ^{3}H from the decay of ^{7}H. The ^{7}H 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(Jπ=0$^+$) in the final state, while the continuum region involves both ^{8}Be(Jπ=0$^+$) and ^{8}Be(Jπ=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 $+29-18$.

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

2002Ma21: Using a ^{14}Be beam with energy 35 MeV/nucleon at GANIL undergoing breakup on a C target into ^{10}Be plus 4 neutrons, the authors obtained a few events which they interpreted as bound clusters of neutrons, most likely 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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