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# Can Four Neutrons Form a Stable Nucleus?

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**Abstract:** The existence of a stable 4-neutron (4n) nucleus has been investigated theoretically and experimentally for more than five decades. Several experimental approaches were adopted in the previous century with the aim of observing 4n nuclei yielded negative results. However, in this century, the GANEL experiment has supported the existence of a tetraneutron (4n) nucleus as a long-lived nucleus by detecting 6 events of 4n nuclei. This experimental result, however, has not been confirmed by subsequent studies. Moreover, in the most recent experiment RIKEN 2016, 4 events of a tetraneutron system were obtained in a resonant state and supported by a subsequent theoretical calculation. However, both findings from GANEL and RIKEN experiments indicate that 4n nuclei are unstable, as they decayed after a short time. The detection of such nuclei is significant to investigate properties of the nuclear forces needed to fuse the 4n together as chargeless nuclei. Although the existence of a stable tetraneutron nucleus has not been confirmed yet, it is still an open and fascinating question. Future studies aim to be built on the previous experiments by maximizing the beam energy of a projectile as well as optimizing a thick target.
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## 1. Introduction

The existence of a stable neutral nucleus such as a 4-neutron nucleus has been a long-standing question in nuclear physics. This might be because of the atomic nucleus of any element usually consists of protons and neutrons that are held together by the strong nuclear force. The balanced ratio between the neutrons (n) and protons (p) within the nucleus can express its stability. Therefore, if this neutron-proton ratio (n/p) exceeds 1.5, the nucleus tends to be unstable and then undergo decay after a certain time as a result of occupying excess energy [1]. However, the investigation of stable 4n nuclei composed of only neutrons could have far- reaching implication in nuclear physics. This is because it could be a promising avenue to explore the characteristics of the nuclear forces that can hold them together [2]. Hence, it would imply the discovery of the existence of other numbers of neutrons that can form a stable nucleus. Furthermore, the existence of tetraneutron nuclei might also help to describe the properties of the nuclear forces in neutron stars, which are the only known stable multineutron systems [3]. This paper aims to discuss the possibility of the existence of stable tetraneutron nuclei and the approaches adopted to observe them in the previous century, as well as recently.

## 2. Brief History of Tetraneutron

The study of the stability tetraneutron nuclei has at- tracted considerable attention in nuclear research since a theoretical study was performed in 1963 to prove the existence of a stable 4n nucleus. In this study, a stable particle system of 4n was expected to be produced by converting a stable helium nucleus ($^4He$) to 4n nuclei. This was based on targeting $^4He$ by gamma ray to reveal 4n and two pions ($\pi^+$) by utilizing the next reaction [4]:

$$\gamma + {}^4He \rightarrow 2\pi^+ + 4n \qquad (1)$$

However, this claim has been contradicted by the Shell Model theory based on the Pauli exclusion principle. This principle specifies that identical particles in the same system cannot be in the same quantum state. Consequently, in the case of a 4n nucleus, only two neutrons can be in a ground state having opposite spins, forcing the other two into the excited state. Hence, forming an unstable nucleus which has an excess energy [5]. Furthermore, a neutron in its alone is unstable and lives for approximately 15 minutes before decaying to a proton, an electron together with an antineutrino:

$$n \rightarrow p + e^{-1} + \bar{\nu} \qquad (2)$$

This adds another objection against the existence of a stable 4n nucleus. However, numerous approaches of nuclear reactions have been studied to prove the possibility of 4n clusters (4n nuclei) as a stable particle [6].

### 2.1. Previous Studies

#### 2.1.1. Experimental Observations

During the previous century, several experimentally attempts have been conducted for investigating the existence of a stable tetraneutron system. In 1965, an at- tempt was made to prove its existence utilizing the uranium fission interaction, since such fission normally produces two neutrons or more. In this reaction the evidence for the production of tetraneutrons was investigated following the bombardment of natural uranium ($^{238}U$) with deuterons ($D_2$). Consequently, no indication for a tetraneutron was observed [7,8].

Furthermore, the measurement of pion ($\pi^-$) double charge exchange DCX $^4He$ ($\pi^-$, $\pi^+$) 4n reaction was also an at- tractive reaction. This is because it was assumed to pro- duce a stable tetraneutron undergoing the next reaction:

$$\pi^- + p \rightarrow \pi^+ + n \qquad (3)$$

Therefore, converting the two protons in the $^4$He nuclei to two neutrons before forming a tetraneutron as shown in Figure 1.

$$\pi^- + {}^4H \rightarrow \pi^+ + 4\,n \qquad (4)$$

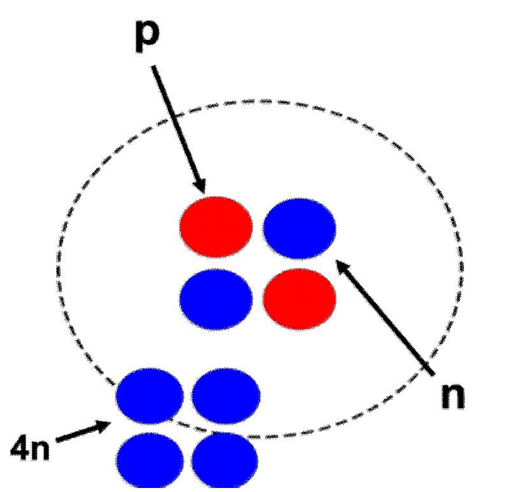


Figure 1: Represents the DXC reaction that converts helium 4 to a 4n nucleus.

However, in this experiment, instead of obtaining a four-neutron system, the reaction produced 4 separate neutrons observed in the pion spectrum. Thus, providing negative evidence opposed to the possibility of obtaining tetraneutron systems [9].

## 3. Current Experimental Observations

### 3.1. The GANIL-2002 Experiment

In 2002, the possibility of producing and detecting a bound 4n cluster was performed experimentally utilizing a very rich neutron isotope beryllium-14 ($^{14}Be$). The importance of such an isotope stems from consisting of a nuclear halo composed of 4 clustered neutrons which is weakly bound to $^{14}Be$. Therefore, exciting them above their particle emission thresholds can lead to neutrons appearing as a tetraneutron-like configuration [10].

#### 3.1.1. Experimental Setup

The technique was based on the breakup reaction of the fragmentation of a high energetic beam of $^{14}$Be (35MeV/n) in order to release the four- neutron halo. This was performed in $^{14}Be + {}^{12}C \rightarrow 10Be + 4n$ reaction in which a carbon target bombarded by a beam of $^{14}$Be nuclei. The resulting production of $^{10}Be$ was subsequently absorbed by a silicon detector, while because the 4n are chargeless, they penetrated the detector without any interaction as shown in Figure 2.

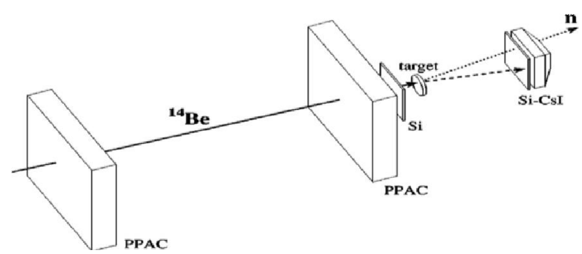


Figure 2: Shows the experimental setup of $^{14}Be + {}^{12}C \rightarrow 10Be + 4n$ reaction. From left to right the beam tracking detectors, the ($^{12}C$) target and a silicon detector for the detection of charged fragments ($^{10}Be$) [12].

Thus, liquid $^4$He detectors, which are rich in protons were utilized to observe the 4n [11]. The detection in a liquid scintillator is accomplished via neutron-proton scattering, in which the recoiling proton can take energy ($E_p$) up to that of the incident neutron ($E_n$). In such interaction, the neutron usually does not lose all its energy and might escape from the liquid detectors. For any ideal detector and single incident neutron, the ratio $E_p/E_n \leq 1$. However, for a real detector such as the one used in this experiment, this ratio could reach 1.4, taking the background ($\gamma$ cosmic rays) and the resolution of the detector into account. Thus, the possibility of measuring multineutron events could be associated with the value $E_p/E_n$>1.4[12].

### 3.1.2. Results

The expectation was to observe four separate neutrons resulting from the collision in the region $E_p/E_n \leq 1$. However, the neutrons liberated from this reaction were detected as six events, in which the values of $E_p/E_n$ were in the region ranging between 1.4 and 2.2 (see Figure 3). Therefore, as the 4n of each event reach the detector material in one specific position, and even at the same time, these events have tentatively been interpreted as a configuration of the tetraneutron in a bound state. Theses 4n clusters remained for approximately 100 ns before decaying to 4 individual neutrons, which indicates that they are unstable [10,13].

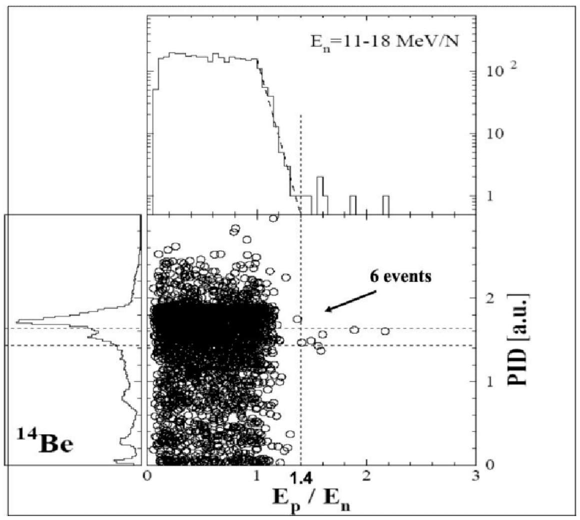


Figure 3: Displays the six events of the 4 neutrons produced in the $^{14}Be + ^{12}C \rightarrow 10Be + 4n$ reaction, where the horizontal band (dotted line) corresponds to $E_p/E_n$=1.4 [12].

Following this experimental result, several experimental approaches and theoretical studies were per- formed to verify this result, but no evidence was re- ported for the existence of tetraneutron nuclei. They indicated that the obtained number of events is statistically weak to confirm the existence of a 4-neutron system [14]. However, these negative outcomes have not prevented the researchers from continuing to search for such clusters as a staple particle.

### 3.2. The RIKEN-2016 Experiment

The existence of tetraneutron was revived again in 2016, following an experiment performed in a Japanese RIKEN Institute. In this recent experiment, a new re- action was exploited utilizing a high energy beam of $^{8}He$, the most neutron-rich helium isotope. This $^{8}He$ isotope is also a halo nucleus that consists of a particle ($^{4}He$) and 4 loosely bound neutrons. Therefore, the $^{8}He+^{4}He$ collision seems to be a promising reaction for the isolation of these 4 clustered neutrons [15].

#### 3.2.1. Experimental Technique

The mechanism of this experiment concentrated on the $^{8}He+^{4}He \rightarrow ^{8}Be+4n$ reaction. This reaction was based on a beam of 186 MeV/nucleon $^{8}$He ions, which is relatively high energetic, produced by the fragmentation of an $^{18}O$ beam in an $^{8}Be$ target at the RIKEN accelerator. Thus, this $^{8}He$ beam collided with a 136 mg/cm$^{2}$ liquid helium ($^{4}He$) target as shown in Figure 4.

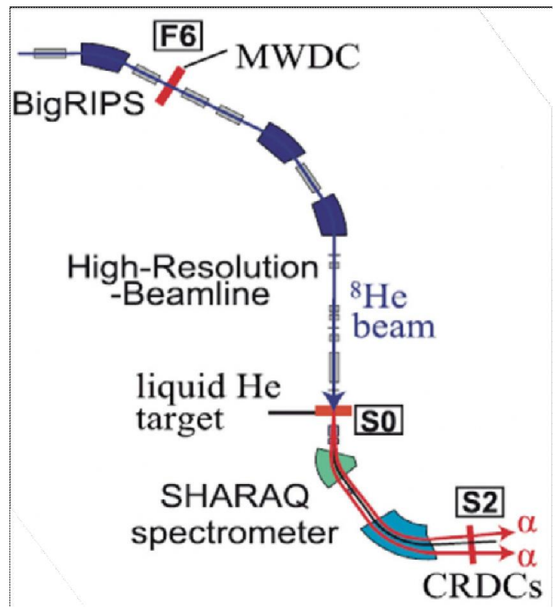


Figure 4: Shows The schematic of the experimental set up is based on three steps. Starting with the production of $^{8}He$, which then collides with $^{4}He$ and the reaction products are then detected in the spectrometer [16].

In this experiment, the identification of the tetra-neutron system was not directly because the neutrons resulting from the $^{8}He+^{4}He \rightarrow ^{8}Be+4n$ reaction were expected to have low energy [16]. Alternatively, a tetraneutron state was investigated using a missing mass spectrum. In such a method, the energy of the tetraneutron ($E_{4n}$) was calculated on an event-by-event basis from the measurement of the momentum vectors and energy as follow:

$$m^2 = (\sum E_{in} - \sum E_{out})^2 - (\sum p_{in} - \sum p_{out})^2 \quad (5)$$

Where m is the mass of the missing particle (tetraneutron) $E_{in}$ is the total energy of incident particles and $E_{out}$ is the total energy of the producing particles whereas $P_{in}$ and $P_{out}$ are their momentums respectively [15,17].

**3.2.2. Results**

The resulting production of the collision between $^{8}He$ and $^{4}He$ is usually 2 alpha and 4 individual neutrons. However, the decay products of the neutrons delayed for approximately $5\times10^{-22}$ s before they appeared as 4 separate neutrons. Therefore, by utilizing the missing mass spectroscopy to measure the momentums and the energies of the total reaction searching for the missing 4n, 4 events of tetraneutron nuclei were obtained. These 4 events were observed above the tetraneutron thresh- old $E_{4n}$ in the resonant region with an energy of 0.83 ± 0.65± 1.25MeV, where the first error is statistical and the second error is systematic. Therefore, because of the relatively high errors of these events produced, they have interpreted as a candidate short-lived four neutrons in a resonant state [16,18].

These findings have been supported by a theoretical research utilizing a Monte Carlo approach based on nucleon-nucleon interaction. The theoretical results prove that the tetraneutron resonance energy is at 0.84 MeV which is significantly compatible with 0.83 MeV, which was recently obtained experimentally. However, both results indicate that tetraneutron nuclei are unstable as they appeared in an excited state (a resonant state) [19].

**4. A Future Approach**

A future study has been proposed for the production and the detection of tetraneutron utilizing the 4He ($\pi^-$, $\pi^+$) 4n reaction. Such a reaction was investigated in the previous century using an 80 MeV pion ($\pi^-$) beam. However, no evidence for 4n nuclei has been observed [9]. In this study, the technique is based on maximizing the beam energy of the pion ($\pi^-$), which is expected to reach 850 MeV. Followed by the collision with a 2.0 g/cm$^2$ thick liquid helium target ($^{4}He$) which is 20 times thicker than in the previous experiment to enhance the number of interactions. This 4He ($\pi^-$, $\pi^+$) 4n reaction was simulated before being conducted in at the accelerator facility. Therefore, it yielded 97 events of tetraneutron nuclei in a bound state which is relatively high in comparison with the previous observations. This indicates that observing such a number of events experimentally could confirm the existence of a 4n nucleus.

**5. Conclusion**

The existence of a pure stable 4 neutron has been investigated for more than five decades. Numerous dif- ferent reactions were conducted in the previous century to search for a stable tetraneutron failed to provide any evidence for a stable 4n nucleus. However, in recent observations, the GANIL approach was the first experiment that indirectly justified the existence of long lived 4n nuclei. This tentative claim, however, was not con- firmed in subsequent experiments and even theoretical calculations. Moreover, the RIKINE experiment discovered the existent of 4n as an unstable candidate in a resonant state which is unlike the results of the GANIL, it has been supported by a very recent theoretical calculation. Although the existence of a stable tetraneutron has not been proven yet, it remains a standing question for future further investigations. Future work aims to be built on the previous experiments by enhancing both the beam energy as well as the target thickness.

**References**

1. Diehl R. Astrophysics with radioactive isotopes. In Astrophysics with Radioactive Isotopes 2018 (pp. 3-27). Springer, Cham.
2. Gandolfi S, Hammer HW, Klos P, Lynn JE, Schwenk A. Is a trineutron resonance lower in energy than a tetraneutron resonance?. Physical review letters. 2017 Jun 8;118(23):232501.
3. Bystritsky VM, Dudkin GN, Kuznetsov SI, Padalko VN, Syrtanov MS. A direct search for neutron nuclei in decay of 238 U. International Journal of Modern Physics E. 2017 Mar;26(03):1750004.
4. Argan PE, Piazzoli A. SOME POSSIBLE CON-SEQUENCES OF THE EXISTENCE OF THE STATES H sup 4 AND H sup 5. Phys. Letters. 1963 May 15;4.
5. Bertulani CA, Zelevinsky V. Nuclear physics: Four neutrons together momentarily. Nature. 2016 Apr;532(7600):448.
6. Kezerashvili RY. A short summary on the search of trineutron and tetraneutron. arXiv preprint arXiv:1608.00169. 2016 Jul 30.
7. Dudkin GN, Garapatskii AA, Padalko VN. Method of searching for neutron clusters. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment. 2014 Oct 1;760:73-8.
8. Bystritsky VM, Dudkin GN, Kuznetsov SI, Padalko VN, Syrtanov MS. A direct search for neutron nuclei in decay of 2 3 8 U. International Journal of Modern Physics E. 2017 Mar;26(03):1750004.
9. Fong W, Matthews JL, Dowell ML, Kinney ER, Soos T, Wang MY, Wood SA, Gram PA, Rebka Jr GA, Roberts DA. Inclusive pion double charge exchange in light p-shell nuclei. Physical Review C. 2007 Jun 8;75(6):064605.
10. Marques FM, Orr NA, Falou HA, Normand G, Clarke NM. On the possible detection of 4n events in the breakup of 14Be. arXiv preprint

nucl- ex/0504009. 2005 Apr 6.
11. Marqu´es FM. The four-neutron system. Few-Body Systems. 2008 Dec 1;44(1-4):269-71.
12. Marque˜s, F.M., Labiche, M., Orr, N.A., Ange˜lique, J.C., Axelsson, L., Benoit, B., Bergmann, U.C., Borge, M.J.G., Catford, W.N., Chappell, S.P.G. and Clarke, N.M., (2002). Detection of neutron clusters. Physical Review C, 65(4), p.044006.
13. Nan M, Bo-Lin L, Jia-Lun P. Tetraneutron in the Chiral Quark Model. Chinese Physics Letters. 2014 Jan;31(1):011201.
14. Carbonell J, Lazauskas R, Hiyama E, Kamimura M. On the Possible Existence of Four Neutron Resonances. Few-Body Systems. 2017 Mar 1;58(2):1.
15. Orr N. Can Four Neutrons Tango?. Physics. 2016 Feb 3;9:14.
16. Kisamori K, Shimoura S, Miya H, Michimasa S, Ota S, Assie M, Baba H, Baba T, Beaumel D, Dozono M, Fujii T. Candidate Resonant Tetraneutron State Populated by the He 4 (He8, Be8) Reaction. Physical review letters. 2016 Feb 3;116(5):052501.
17. Rogers WF, Garrett S, Grovom A, Anthony RE, Aulie A, Barker A, Baumann T, Brett JJ, Brown J, Christian G, De Young PA. Unbound excited states of the N= 16 closed shell nucleus O 24. Physical Review C. 2015 Sep 16;92(3):034316.
18. Deltuva A. Tetraneutron: Rigorous continuum calculation. Physics Letters B. 2018 Jul 10;782:238- 41.
19. Shirokov AM, Papadimitriou G, Mazur AI, Mazur IA, Roth R, Vary JP. Prediction for a four-neutron resonance. Physical review letters. 2016 Oct 28;117(18):182502.
20. Fujioka H, Fukuda T, Harada T, Hiyama E, Itahashi K, Kanatsuki S, Nagae T, Nanamura T, Nishi T. Search for Tetraneutron by Pion Double Charge Exchange Reaction at J-PARC. In Proceedings of the 14th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon (MENU2016) 2017 (p. 020058).

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