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Project Information	Project Number : 24H00006	Project Period (FY) : 2024-2028
	Keywords : Multi-neutron systems, Unstable Nuclei, Neutron Star, Neutron Detector Array	

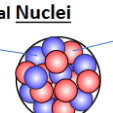
Purpose and Background of the Research

● Outline of the Research

Can neutral nuclei composed exclusively of neutrons exist? This project is dedicated to investigating “neutral nuclei”, focusing on  ${}^2n$ ,  ${}^4n$ , and  ${}^6n$ , existence of which has been a subject of controversy or remains unknown, by introducing a novel neutron detector.

**Neutral Nuclei (Nuclei made purely of neutrons) exist?** *Fundamental long-standing quest*

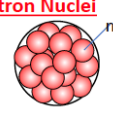
**Normal Nuclei**



proton (p)    neutron (n)

- ✓ Made of **neutrons and protons**
- ✓ **Nuclear Force + Coulomb force (protons)**
- ✓ Neutron number/Proton number  $\sim 1$

**Neutron Nuclei**



neutron (n)

- ✓ Made of **neutrons only**
- ✓ **Electrically neutral**
- ✓ **Nuclear force**
- ✓ **Neutron number/proton number =  $\infty$**

**Unique quantum systems**  
**Existence: Still Elusive**  
 (Experimental observation of candidate  $4n$  systems in 2016 and 2022)

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**Our Research Project: First full-scale Spectroscopic Experiments of neutral nuclei on  ${}^2n$ ,  ${}^4n$ ,  ${}^6n$**

${}^2n$

**Dineutron**

No bound/resonance state  
Dineutron inside nuclei?

${}^4n$

**Tetra-neutron**

t~several hundreds s?  
or  $10^{-21}$  s?

${}^6n$

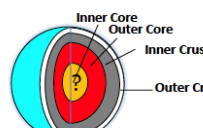
**Hexa-neutron**

No experiments so far  
“6” Semi-magic?

${}^An$

**A-neutron system**

Island of Stability?  
New magic number?

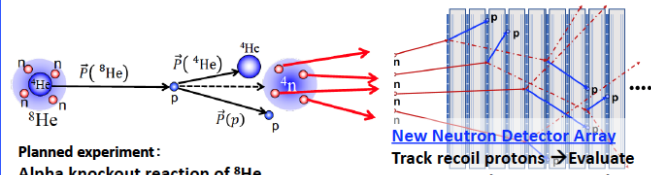


**Neutron Star - mysterious Gigantic Nuclei**  
 R:  $10^{11}$ km Not yet fixed  
 M:  $1\sim 2$  Solar mass  
 Maximum mass: unknown)  
 Inner Structure : Not yet fixed

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**Subjects of Our Research Project**

**New neutron detector array  $\rightarrow$  Detect 4-6 neutrons  $\rightarrow$  Observe  ${}^4n, {}^6n$**



Planned experiment:  
Alpha knockout reaction of  ${}^8\text{He}$

**Impact of Our Project**

- Existence of Neutral Nuclei
- Find new quantum systems
- Clarify unestablished multi-neutron forces
- Benchmark for QCD and ab-initio calculations
- Neutron star structure
- Hierarchical structure of matter

Figure 1. Outline of the Project

● **Background and Purposes of the Project** : The quest for neutron nuclei dates back to the 1960s, yet evidence such as the existence of  ${}^4n$ , has only recently been obtained (e.g. Our collaboration (SAMURAI collaboration) Nature 606, 678 (2022)). However, theoretical/experimental inconsistencies remain regarding the existence of  ${}^4n$ , necessitating further investigations. Moreover, the intriguing  ${}^6n$ , potentially linked to a semi-magic number (6) remains unexplored experimentally. This project aim to address this subject by simultaneously detecting emitted 4(6) neutrons, crucial for elucidating the states and decay scheme of  ${}^4n({}^6n)$  nuclei. To achieve this, we propose the utilization of a novel neutron detector array employing a tracking technique for recoil protons.

● **Novel Neutron Detector Array** We develop and construct a novel neutron detector array that can distinguish and measure multiple neutrons (up to six) with high accuracy. With such measurements one can determine precisely the mass (invariant-mass) and decay scheme of the  $4n$  and  $6n$  states. However, the detection of more than two neutrons have so far been nearly impossible due to the

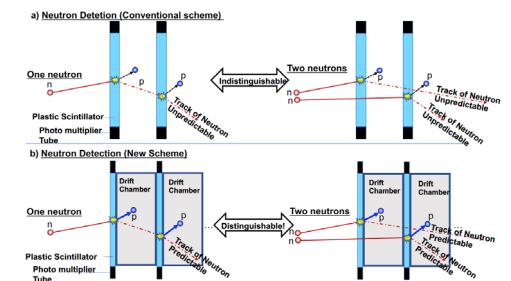


Figure 2. Neutron detection schemes: a) conventional; b) new

cross-talks as shown in Figure 2 a). A neutron in the detector (plastic scintillator) can be scattered which may cause the second signal, mimicing the “two neutron” event. In our new detection scheme, we track the recoil protons from the scintillator, with which one can evaluate the direction of the scattered neutron. Accordingly one can measure multiple neutrons.

Expected Research Achievements

● **Research Goals and Our Competitiveness**

Our objective is to pioneer full-scale spectroscopic experiments on neutral nuclei, such as  ${}^2n$ ,  ${}^4n$ , and  ${}^6n$ , for the first time in the world. Our key mile-stones encompass the confirmation of  ${}^4n$  with precise mass measurement and decay scheme, and the first observation of the  ${}^6n$  system. The point is that we use the invariant mass method which has advantages in having higher mass resolution and capability of measuring decay scheme compared to the missing mass method used previously for studying  ${}^4n$ . To achieve our objectives, we develop and construct a cutting-edge neutron detector array (see Fig.3) tailored to discern and measure multiple neutrons with exceptional precision at the Radioactive Isotope Beam Factory (RIBF) at RIKEN, a world-leading research center for unstable nuclei (Fig.4). Leveraging this detector array, we anticipate achieving resolutions of 30-70 keV (kilo-electron-volt) in measuring  ${}^4n$  and  ${}^6n$  with unprecedented accuracy. Moreover, our system enables positional detection with a remarkable 2mm accuracy, a significant improvement over conventional detectors which typically offer only centi-meter level precision. This breakthrough opens avenues for neutron imaging applications, with potential applications in medical diagnostics and engineering.

We have some advantages over competing facilities such as FRIB and FAIR, given that our neutron detection scheme remains at the forefront. While the construction of FAIR and the large-acceptance spectrometer (HRS) at FRIB is ongoing, our method offers immediate benefits, positioning us a leaders in this frontier of nuclear research.

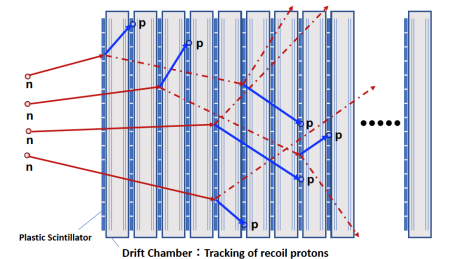


Figure 3. Schematic Figure of our new neutron detector array

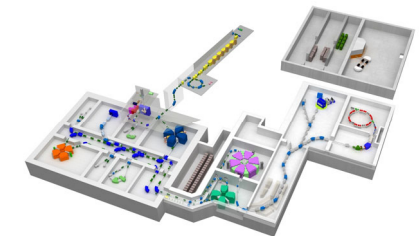


Figure 4. RIBF at RIKEN

Homepage Address, etc.

The web-site of this project is under construction. Publication list of PI (Prof. Takashi Nakamura, google scholar ) is seen at

