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Experimental study of ^4n with ^{8}He(p,2p) reaction

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Abstract. The tetraneutron has attracted the attention of nuclear physicists during the past decades, but there is still no unambiguous confirmation of its existence or non-existence. A new experiment based on $^{8}\mathrm{He}(p,2p)^{7}\mathrm{H}\{t+^{4}n\}$ reaction, with direct detection of the four neutrons, has been carried out at RIBF, which can hopefully help to draw a definite conclusion on the tetraneutron system.

1. Introduction

Many-neutron systems made of the chargeless neutrons, especially the tetraneutron(^{4}n), have attracted a lot of attention of the nuclear physics community in recent years. Their existence, whether as bound or resonant states, is of fundamental importance in nuclear physics, serving as a sensitive probe to investigate the nuclear force free from the Coulomb interaction. Their properties are also crucial for a deeper understanding of neutron stars [1,2].

Many experimental trials have been made in search of the very exotic ^4n state in the past decades. However, all these attempts failed to draw a firm conclusion due to the extremely low statistics. In 2002, Marqués *et al*. [3] reported the possible existence of a bound or low-lying resonant ^4n state observed in the breakup reaction of ^{14}Be → ^{10}Be + ^4n channel. Another experiment using the ^{4}He(^{8}He, ^{8}Be)^4n reaction found the candidate resonant state with an energy $E_R = 0.83 \pm 0.65(\text{stat}) \pm 1.25(\text{syst})$ MeV above the $4n$ threshold and a width $\Gamma \leq 2.6$ MeV [4].

Motivated by the experimental hints, many theoretical calculations were performed to study the tetraneutron system [5-11]. All of them agree that a bound state is ruled out based on standard nuclear forces but the existence of a tetraneutron as a low-lying resonant state is still under debate. It is supported by some theoretical models including Quantum Monte Carlo (QMC) [12] and No-Core Shell Model (NCSM) calculations [13] while some other *ab-initio* calculations exclude such a resonant ^4n state [8,9] since large (unrealistic) modifications of the three-body force would be necessary in order to reproduce the ^4n resonance reported in [4].

Here, we report a new experiment on ^4n by using the ^{8}He(p,$2p$)^{7}H{t+^4n} reaction at the RIKEN Radioactive Isotope Beam Factory (RIBF) facility.

2. Experimental Methods

The ^{8}He(p,$2p$)^{7}H{t+^4n} experiment was carried out in inverse kinematics at RIBF in 2017. The ^{8}He secondary beam with an energy of 150 MeV/nucleon was produced through the projectile fragmentation reaction from the ^{18}O primary beam bombarding on a ^{9}Be primary target, and then purified and transported through the BigRIPS fragment separator [14]. The incident beam can be identified by TOF-ΔE method on an event-by-event basis. The trajectories of beam particles can be reconstructed from two multi-wire drift chambers (BDC1, BDC2) located upstream of the target. The ^{8}He beam with an intensity of 10^5 pps impinged onto the 150 mm-thick liquid hydrogen target MINOS [15] which can offer high luminosity and ^{7}H was then produced by the (p,$2p$) reaction.

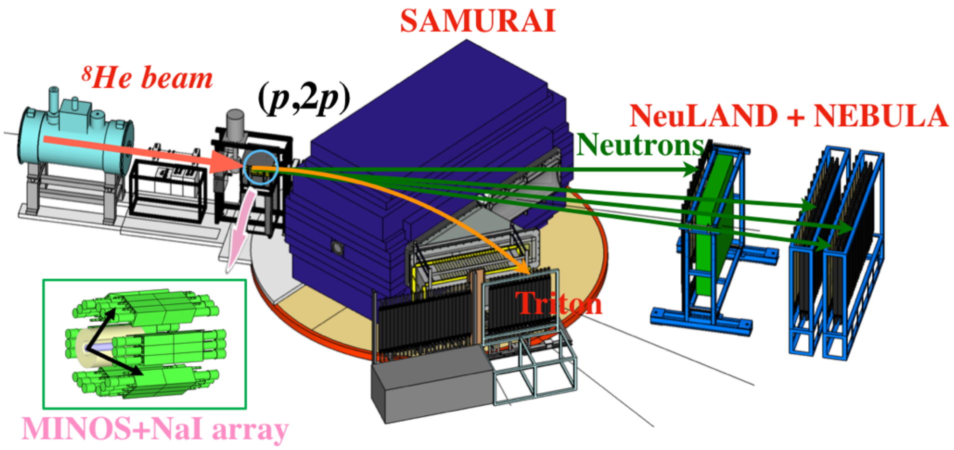

Figure 1. Schematic view of the experimental setup.

Figure 1 shows the schematic view of the experimental setup. The key ingredient of our experiment is the kinematically complete measurement of all the reaction products. The recoil protons were tracked by the TPC surrounding the liquid hydrogen target and then detected in coincidence by an array of 36 NaI crystals [16], arranged in two symmetric rings. The energy resolution of the NaI scintillators was around 1% (FWHM) for 80 MeV protons. Energy calibration was performed by measuring the proton-proton elastic scattering at 175 MeV with the same setup. The trajectories of two protons are essential to reconstruct the reaction vertex in such experiments with a thick target.

Charged fragments were deflected in the SAMURAI [17] dipole magnet from the path of the neutrons. They passed through two drift chambers (FDC1, FDC2) located at the entrance and exit of the dipole magnet and finally detected by the HODO plastic scintillator array. The multiple neutron detection is crucial but extremely challenging in this kind of multi-neutron studies. The neutrons were detected by two plastic scintillator arrays, the NeuLAND demonstrator from GSI and the existing NEBULA array, placed downstream of the dipole magnet, which can together provide the highest $4n$ detection efficiency (ε_{4n} ~1%) at present. In addition, since we have access to the complete 7-body kinematics of the final state ($2p$+t+$4n$), we can also obtain the invariant mass of ^{7}H and ^4n by measuring only 3 of the 4 neutrons. The statistics can be enhanced markedly by this so-called "Missing-Invariant-Mass method" since the detection efficiency close to the threshold for $3n$ can be 10 times or more higher than that for $4n$.

3. Preliminary results

As shown in figure 2(a), tritons and ^{6}He can be separated clearly using the TOF-ΔE method. Figure 2(b) shows the polar-angle correlation for the two recoil protons in coincidence with triton fragments.

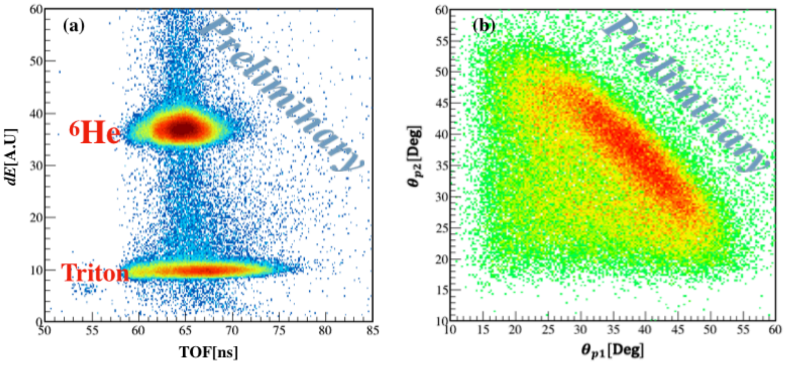

Figure 2. (a) PID of fragments identified by HODO. (b) p-p polar-angle correlation.

We first analyzed the ^{6}He+n channel, populated in the (p,pn) reaction, to validate the momentum analysis of fragments and neutrons. As shown in figure 3(a), the relative-energy spectrum of ^{7}He reconstructed from ^{6}He and one neutron exhibits a clear peak at around 0.4 MeV, in good agreement with previous works [18,19]. We also reconstructed the angular distribution of the polar angle ψ defined as the angle between the ^{7}He momentum $\boldsymbol{p}_{^7\mathrm{He}}$ and ^{6}He-n relative momentum $\boldsymbol{p}_{^6\mathrm{He}-n}$ [20]. As shown in figure 3(b), it is anisotropic but symmetric with respect to 90°, consistent with previous work [19,21].

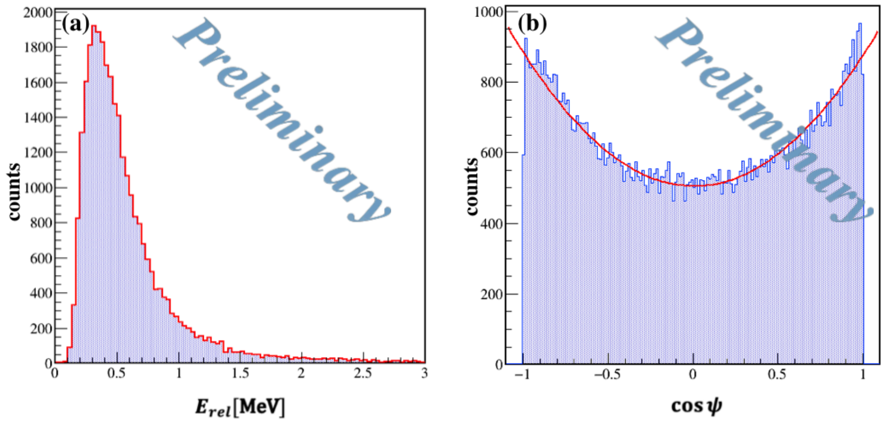

Figure 3. (a) Relative-energy spectrum of ^{7}He. (b) Polar angular distribution for ^{7}He decaying into ^{6}He+*n*.

The multi-neutron analysis is now in progress, for which rejection of crosstalk is essential. A crosstalk rejection algorithm based on the time-space separation and the energy deposition of the recorded hitting signals has been well established [22] and will be optimized in the current measurement according to the real experimental setup.

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References

[1] Demorest P B, Pennucci T, Ransom S M, Roberts M S E and Hessels J W T 2010 *Nature* **467** 1081-3
[2] Brown B A 2000 *Phys. Rev.* L **85** 5296
[3] Marqués F M *et al*. 2002 *Phys. Rev.* C **65** 044006
[4] Kisamori K *et al*. 2016 *Phys. Rev.* L **116** 052501
[5] Bertulani C A and Zelevinsky V 2003 *J. Phys.* G **29** 2431
[6] Timofeyuk N K 2003 *J. Phys.* G **29** L9
[7] Sofianos S A, Rakityansky S A and Vermaak G P 1997 *J. Phys.* G **23** 1619
[8] Lazauskas R and Carbonell J 2005 *Phys. Rev.* C **72** 034003
[9] Hiyama E, Lazauskas R, Carbonell J and Kamimura M 2016 *Phys. Rev.* C **93** 044004
[10] Grigorenko L V, Timofeyuk N K and Zhukov M V 2004 *Eur. Phys. J.* A **19** 187
[11] Yu. A. Lashko and G. F. Filippov 2008 *Phys. At. Nucl* **71** 209
[12] Pieper S C 2003 *Phys. Rev.* L **90** 252501
[13] Shirokov A M *et al*. 2016 *Phys. Rev.* L **117** 182502

[14] Kusada K *et al*. 2004 *IEEE Trans. Appl. Supercond* **14** 310
[15] Obertelli A *et al*. 2014 *Eur. Phys. J.* A **50** 8
[16] Takeuchi S *et al*. 2014 *Nucl. Instrum. Methods* A **763** 596
[17] Kobayashi T *et al*. 2013 *Nucl. Instrum. Methods* B **317** 294-304
[18] Cao Z X *et al*. 2012 *Phys. Lett.* B **707** 46-51
[19] Markenroth K *et al*. 2001 *Nuclear Physics* A **679** 462–80
[20] Simon H *et al*. 1999 *Phys. Rev.* L **83** 496-9
[21] Chulkov L V *et al*. 1997 *Phys. Rev.* L **79** 201
[22] Nakamura T and Kondo Y 2016 *Nucl. Instrum. Methods* B **376** 156-61