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Experimental study of ^4n by directly detecting the decay neutrons

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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.

Keywords Tetraneutron · Direct detection

1 Introduction

Few-neutron systems, especially the tetraneutron (^{4}n), have been at the focus of interest in recent years. They will not only serve as a sensitive probe to investigate the nuclear force, in particular the isospin dependence of many-body nuclear forces, and also help to understand how the structure of nuclei located around the neutron drip line and the properties of neutron-rich nuclear matter and neutron stars emerge from the underlying nuclear force and correlations [1–3].

While it is a general consensus that ^{4}n cannot be a bound state, the possibility for ^{4}n existing as a low-lying resonant state still remains elusive despite many experimental and theoretical efforts (for

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details see recent review [3]). A candidate ^4n resonance with a decay energy $E_R = 0.83 \pm 0.65(\text{stat}) \pm 1.25(\text{syst})$ MeV and a width $\Gamma \leq 2.6$ MeV was recently reported in a double-charge-exchange reaction ^{4}He(^{8}He, ^{8}Be)^4n performed at RIKEN [4]. While the measurement is basically background-clean because of the SHARAQ spectrometer and the highly selective reaction channel, the result suffered from the low statistics—only four events indicative of a ^4n resonant state. Another notable experiment claiming the possible observation of a ^4n resonance was made by Marqués *et al.* in 2002, where several events observed in the breakup of the neutron-rich nucleus ^{14}Be were found consistent with a low-lying ^4n resonant state [5,6].

Competing *ab initio* theoretical methods using well-established nuclear interactions, either realistic interactions like Argonne and JISP16 or interactions derived from the chiral effective field theory, have been employed to investigate the four-neutron system [3,7–17]. The existence of a ^4n resonance is supported by some theoretical models including Quantum Monte Carlo (QMC) [7,8], No-Core Shell Model (NCSM) [9], and No-Core Gamow Shell Model (NCGSM) [10,11], but is incompatible with some other calculations using the Faddeev-Yakubovsky (FY) or Alt-Grassberger-Sandhas (AGS) formalisms [12–14], the variational Gaussian Expansion Method [15], and the adiabatic hyper-spherical approach [16,17]. It is of great interest and also of urgent importance to understand and resolve the obvious discrepancy between these state-of-the-art theoretical calculations. But the only available experimental data mentioned above are insufficient to draw a conclusion on the possible existence of a ^4n resonance, particularly because of the extremely low statistics [4–6].

We have carried out a new experimental study of ^4n by using the ^{8}He$(p,2p)^7$H$\{t+^4n\}$ reaction in inverse kinematics. We populated the four-neutron-unbound nucleus ^{7}H by removing one proton from ^{8}He, which subsequently decayed via direct emission of four neutrons since the sequential decay through intermediate ^{4,5,6}H should be energetically forbidden [18–21]. Our study concerns a kinematically complete measurement of all the reaction products including the four decay neutrons.

2 Experimental Methods

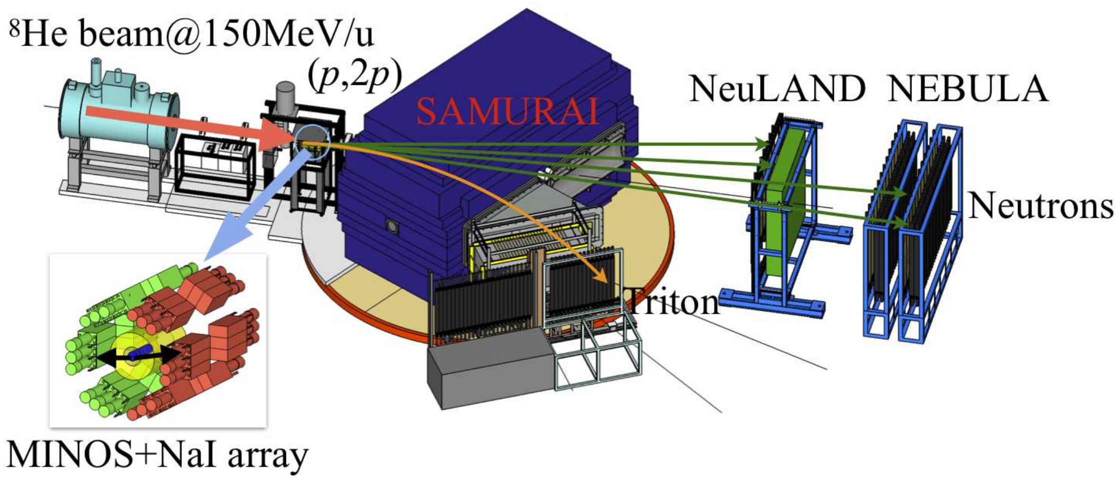

Fig. 1 Schematic view of the experimental setup.

The ^{8}He$(p,2p)^7$H$\{t+^4n\}$ experiment was carried out at the radioactive isotope beam factory (RIBF) operated by the RIKEN Nishina Center and the Center for Nuclear Study of the university of Tokyo. Fig. 1 shows the schematic view of the experimental setup. The secondary beam of ^{8}He with an energy of 150 MeV/nucleon was produced through the fragmentation of the ^{18}O primary beam, and then purified and transported through the BigRIPS fragment separator [22]. The secondary beam particles were identified on an event-by-event basis. Using two multi-wire drift chambers (BDC1, BDC2), the ^{8}He beam with an intensity of 10^5 pps was tracked onto the 150 mm-thick liquid hydrogen target MINOS [23] and ^{7}H was then produced by the $(p,2p)$ reaction.

The key ingredient of our experiment is the kinematically complete measurement of all the reaction products. The recoil protons were detected by an array of 36 NaI crystals (part of DALI2 [24]), arranged in two symmetric rings, providing an energy resolution of 1% (FWHM) for 80 MeV protons. Energy calibration was performed by measuring the *p*-*p* elastic scattering at 175 MeV with the same setup.

The particle identification (PID) and momentum analysis of the charged fragments were achieved using the SAMURAI spectrometer and the associated detectors [25,26]—two drift chambers (FDC0, FDC2), located at the entrance and exit of the dipole magnet, measuring the trajectory and the HODO plastic scintillator array measuring the energy loss and the time of flight (TOF). Light fragments including triton, ^{4}He and ^{6}He can be clearly identified with the TOF-ΔE method [27]. Beam-velocity neutrons were detected by two plastic scintillator arrays placed at 0°, the NeuLAND demonstrator from GSI [28] and the existing NEBULA array [29], which can together provide the highest $4n$ detection efficiency at present. The momenta of neutrons were determined from the measured hitting positions and TOF.

3 Preliminary results

We first analyzed the ^{6}He+n channel, populated in the (p, pn) reaction of ^{8}He, to validate the momentum analysis of fragments and neutrons. The relative-energy (E_{rel}) spectrum of ^{7}He reconstructed from the momenta of ^{6}He and the coincident neutron is shown in Fig. 2a, exhibiting a prominent peak at around 0.4 MeV which corresponds to the well-known ground state of ^{7}He [30,31]. A tentative fitting (red solid line in Fig. 2a) shows that the E_{rel} spectrum of ^{7}He can be nicely described by a single *p*-wave Breit-Wigner function ($E_{\mathrm{rel}} = 0.38$ MeV, $\Gamma = 0.14$ MeV) convoluted by the detector response function obtained from the simulation taking into account the experimental resolution (~160 keV (FWHM) at $E_{\mathrm{rel}} = 1$ MeV) and acceptance, in agreement with previous reports [30,31].

We also checked the distribution of the polar angle θ defined as the angle between the ^{7}He momentum and ^{6}He-n relative momentum in the projectile rest frame. As shown in the inset of Fig. 2a, the $cos(\theta)$ spectrum is anisotropic but symmetric with respect to 90°, consistent with previous work [31].

We then checked the consistency of the full detector calibrations by further combining the proton detection of NaI crystals. For the ^{8}He$(p, pn)^7$He channel, we can reconstruct the momentum of the recoil neutron from momentum conservation although it is not detected in our experiment [32]. The energy conservation of all involved reaction particles shown in Fig. 2b clearly indicates the correct calibrations of all the detectors including the beamline detectors and NaI crystals.

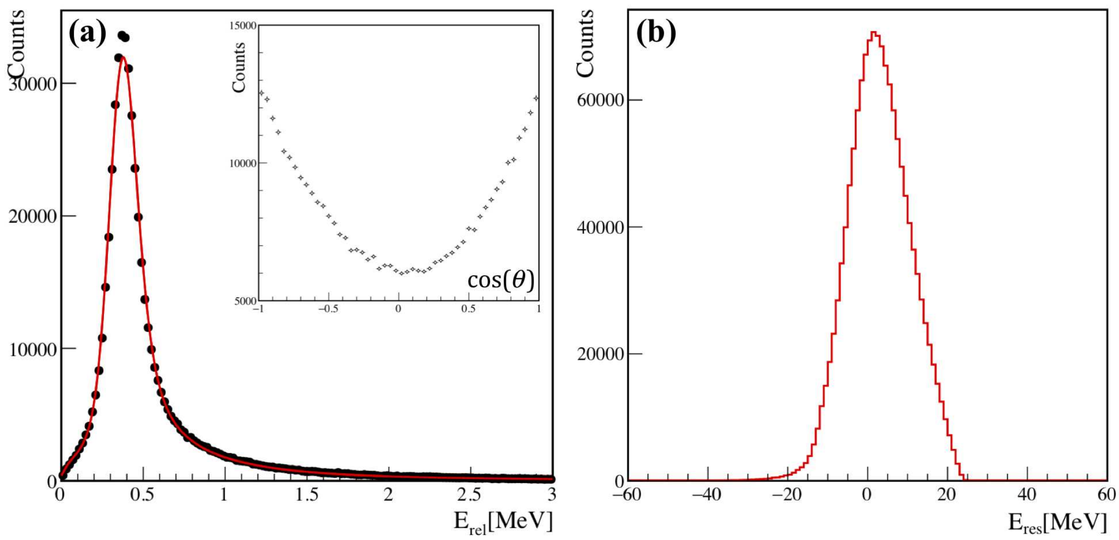

Fig. 2 (a)Relative-energy spectrum of ^{7}He. The black points with statistical error bars correspond to the experimental data. The red solid line shows the fitting result. The inset shows the polar angular distribution for ^{7}He decaying into ^{6}He+n. (b)The energy conservation distribution from the reconstruction method (explained in the text).

To analyze multi-neutron reaction channels, it's crucial to distinguish true neutrons from the crosstalk background. It is well-known that a single incoming neutron can induce multiple hit signals (so-called crosstalks) in plastic scintillators either due to the emission of secondary particles (mainly protons), which are concentrated in the close proximity of the first hit, or due to the scattering of the incoming neutron into another scintillator. The crosstalk rejection algorithm [29,33] well-established for the three-wall configuration consisting of NeuLAND and NEBULA is adopted in our analysis.

We started the crosstalk analysis by checking the time-space separation of all the recorded hits. Two hits were grouped into a same cluster if the following condition was satisfied: $\sqrt{(\frac{dr-dr_0}{R})^2+(\frac{dt-dt_0}{T})^2}<1$, where dr and dt are position and time differences of the two hits and others are adjustable parameters that are generally optimized using Geant4 simulations [29,33]. In our preliminary analysis, we adopted $dr_0 = 15$ cm, $R = 15$ cm, $dt_0 = 0.5$ ns, $T = 2.5$ ns for NeuLAND and $dr_0 = 15$ cm, $R = 15$ cm, $dt_0 = 0.5$ ns, $T = 3.5$ ns for NEBULA. For each cluster, only the fastest (first) hit was kept and in this way crosstalks in neighboring scintillators (termed as "same-wall crosstalks" in [29,33]) were eliminated.

Next, we examined the causality condition for all the remaining hits to eliminate secondary hits arising from the scattered neutron. For each pair of hits (1 for the earlier hit and 2 for the latter hit), the causality condition was defined as $\frac{\beta_{01}}{\beta_{12}} > 1$, where β_{01} is the velocity from target to the earlier hit and β_{12} is the intermediate velocity between the two hits. The causality condition works because of the energy loss of the neutron at the earlier hit, resulting in $\beta_{01} > \beta_{12}$. Once the causality condition was satisfied, the latter hit would be considered as a crosstalk and thus be rejected. This procedure was repeated successively for all combinations of hits following the timing sequence. After the crosstalk analysis, the surviving hits are considered as real incoming neutrons from the target. In the practical analysis we have also used the energy loss signals to improve the crosstalk rejection following the procedure in [33].

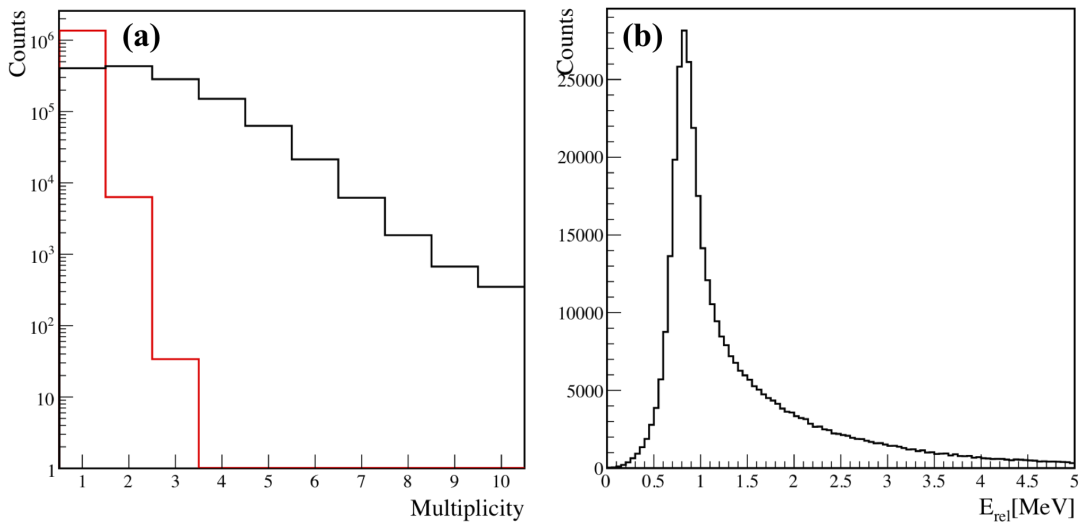

Fig. 3 (a) Experimental neutron multiplicity distribution for the ^{6}He+n channel before (black) and after (red) crosstalk elimination. (b) Relative-energy spectrum of ^{6}He decaying into ^{4}He+2n.

Fig. 3a represents the experimental distribution of neutron multiplicity, defined as the number of neutron hits, before (black) and after (red) the crosstalk rejection for the ^{6}He+n channel. Here, we requested the coincidence of ^{6}He and recoil proton to exclusively select the one-neutron decay channel ^{7}He$\to^6$He+n, so any event with multiplicity$\geq$2 must be a crosstalk. The observed ratio of the remaining crosstalk events to the total events is $\sim$0.5%, which is quite small for the multiple neutron detection and comparable with previous results [33].

The two-neutron decay channel ^{6}He$\to^4$He+2n is then analyzed using the same crosstalk filter. Fig. 3b reports the $E_{\rm rel}$ spectrum of ^{6}He reconstructed from the momenta of ^{4}He and two coincident neutrons. The low-lying narrow peak at $\sim$0.8 MeV corresponds to the first excited 2^+ state of ^{6}He, in good agreement with previous measurements [34].

We are now incorporating the crosstalk filter into the analysis of the ^{7}H$\to t$+4n channel. From the simulation of ^{7}H$\to t$+4n assuming the phase-space decay, the detection efficiency for 4 neutrons is $\sim$0.6% at a decay energy of 1 MeV, and we have also estimated that the crosstalk contamination in this four-neutron channel is within 20%. Tentative analysis also shows that for the identified ^{8}He$(p,2p)^7$H$\{t+^4n\}$ events the energy conservation of all involved particles including two recoil protons and four decay neutrons is well kept, validating the performance of the full detector setup and the extremely challenging four-neutron analysis.

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