Multi-neutron ^{4}n and ^{6}n states in extremely neutron-rich nuclei beyond the neutron drip line

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We performed an experiment to search for $4n$ and $6n$ cluster states, which are expected to appear on the surface of extremely neutron-rich nuclei beyond the neutron drip line, at the SAMURAI facility at the radioactive isotope beam factory (RIBF), RIKEN (NP1812-SAMURAI47). We studied the $4n$ and $6n$ cluster states in ^{10}He and the $4n$ cluster states in ^{8}He, and we attempted the production of these states via quasi-free scattering $(p, 2p)$ reactions in inverse kinematics, namely ^{11}Li$(p, 2p)^{10}$He* and ^{9}Li$(p, 2p)^8$He* reactions.

A fundamental question in nuclear physics is how neutrons are correlated in extreme conditions, such as in very neutron-rich and low-dense environments. Two neutron halo nuclei and weakly unbound nuclei are potential candidates for a strongly correlated quasi-bound neutron pair, dineutron, as predicted by Migdal[1] in the 1970s. We obtained evidence of the dineutron correlation in two neutron halo nuclei. For example, the dineutron was shown in the Coulomb breakup[2] and quasi-free proton scattering experiments.[3] The extremely weakly unbound nucleus ^{26}O at 18(5) keV with respect to ^{24}O + $2n$ observed in the earlier experiment at SAMURAI at RIBF[4] is considered a potential candidate for exhibiting dineutron correlations.[5] The SAMURAI collaboration observed a peak for the candidate tetra-neutron by the ^{8}He$(p, p\alpha)^4n$ reaction.[6] The observed energy $E_{4n} = 2.37(0.38)(0.44)$ MeV was consistent with the earlier work at SHARAQ[7] using the ^{4}He(^{8}He, ^{8}Be)^4n reaction. One of the most recent highlights given by the SAMURAI collaboration is the observation of ^{28}O,[8] the candidate doubly magic nucleus, and a possible $4n$ cluster nucleus, where ^{28}O can be described by the doubly magic ^{24}O core and correlated four neutrons.

The $6n$ and $4n$ cluster states in ^{10}He and the $4n$ cluster states in ^{8}He were searched at the SAMURAI facility[9,10] at RIBF. We used a fragmentation reaction of ^{18}O beam at 250 MeV/nucleon for producing secondary ^{11}Li and ^{9}Li beams at 200 MeV/nucleon at the BigRIPS for studying ^{10}He* and ^{8}He*, respectively. The secondary beam impinged on the 0.1-mm-thick CH_2 target surrounded by the newly introduced missing mass setup composed of a silicon strip detector array called Prototype For Advanced Detector (PFAD)[11] and a CATANA CsI (Na) detectors array.[12] This setup was used to measure the two recoil protons emitted at c.a. ±45° each with nearly 90° of opening angles.

The residue, ^{10}He* (^{8}He*), is expected to instantly decay into exit channels ^{4}He + $6n$, ^{6}He + $4n$, or ^{8}He + $2n$ (^{4}He + $2n$, ^{6}He + $4n$). ^{6}He and ^{8}He were tracked by the multi-wire drift chambers, FDC1 and FDC2, and their energy loss and time of flight were measured by the HODF24 plastic scintillator hodoscope installed at about 40° with respect to the beam axis after the bending in the SAMURAI superconducting magnet at 2.9 T. Low-rigidity ^{4}He particles were tracked using multi-wire cathode read-out drift chambers, PDC1 and PDC2, and the energy loss and and time of flight were measured by a HODP plastic scintillator hodoscope at 70°. These detectors for the residues are the SAMURAI standard detector.[9]

For neutrons, we used newly upgraded NEBULA,

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called NEBULA-plus (we call the original NEBULA array[13,14] and the newly introduced NEBULA-plus as "NEBULA-plus" as a whole). Considering the use of the thin target mentioned above, we can measure up to two neutrons in coincidence in this measurement. In the current experiment, we use the missing mass method for measuring the energy and angles of the two recoil protons as mentioned above, and the neutron measurement was performed for redundancy for the $2n$ + ^{8}He ($2n$ + ^{6}He) channels.

This experiment was performed in April 2024 as one of the SAMURAI campaign experiments, following the SAMURAI53[15] and the NEBULA-plus commissioning.[16] It was conducted as planned, and all the measurements were completed, including the calibration runs using proton, deuteron, ^{4}He, ^{6}He, and ^{8}He beams provided as secondary beams from the same ^{18}O beam. The data analysis of the experiment is in progress.

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