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Candidate Resonant Tetraneutron State Populated by the ^{4}He(^{8}He,^{8}Be) Reaction

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A candidate resonant tetraneutron state is found in the missing-mass spectrum obtained in the double-charge-exchange reaction ^{4}He(^{8}He, ^{8}Be) at 186 MeV/u. The energy of the state is $0.83 \pm 0.65(\text{stat}) \pm 1.25(\text{syst})$ MeV above the threshold of four-neutron decay with a significance level of 4.9σ. Utilizing the large positive Q value of the (^{8}He, ^{8}Be) reaction, an almost recoilless condition of the four-neutron system was achieved so as to obtain a weakly interacting four-neutron system efficiently.

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Multineutron systems have attracted considerable attention in nuclear physics [1]. Few-body systems comprising chargeless nucleons such as the tetraneutron system have long fascinated nuclear physicists and have motivated investigations of pure neutron-neutron interactions possible for these systems. These systems are located beyond the neutron drip line and can serve as a unique test case for understanding nuclear structure at the limit of nuclear stability [2]. They are also closely related to the structure of neutron-rich hypernuclei [3]. Information on multineutron forces obtained in studies of multineutron systems is a critical input into theories of neutron stars [4,5]. Possible testing of universality in many fermion systems is another interesting application of these studies. The weakly coupled many-neutron systems can provide an opportunity to investigate the universality in systems governed by a strong interaction; the BCS-BEC crossover found in cold atoms is a good example [6,7].

Several attempts have been made to find a bound tetraneutron system by using a uranium fission reaction [1,8], a pion double-charge-exchange (DCX) reaction ^{4}He(π^-, π^+) [9–11], and several transfer reactions [12,13]. The existence of the bound tetraneutron system was also discussed in theoretical studies [14–16]. Previously, no evidence was reported for the existence of either a bound tetraneutron system or resonant tetraneutron state. However, Marqués *et al.* [17] reported the possible existence of a bound tetraneutron observed in a breakup reaction of the $^{14}\text{Be} \rightarrow {}^{10}\text{Be} + 4n$ channel. Following this experimental result, several theoretical studies were performed to confirm this result, but all results from these studies were negative [18–20].

The possibility of the tetraneutron system forming a resonant state remains an open and fascinating question. *Ab initio* calculations incorporating realistic nuclear interactions [20] suggest that a broad resonance of a tetraneutron state may exist at 2 MeV above the threshold based on the extrapolation of the calculated energy with an external potential well. An investigation of a resonant state by solving the Faddeev-Yakubovsky equations with a complex energy plane shows that a resonant state can be generated only in the presence of a strong four-body force, which is incompatible with the current understanding of nuclear interactions [21]. A calculation assuming a compound system with coexisting $^3n + n$ and $^2n + {}^2n$ coupled cluster configurations suggested the possibility of an attractive interaction to ensure the existence of a resonant state [22]. According to these calculations, the observation of a resonant tetraneutron state can significantly impact our understanding of nuclear few-body systems and nucleon-nucleon interactions.

In this study, the DCX reaction ^{4}He(^{8}He, ^{8}Be) at a forward angle was used to populate a tetraneutron state near the threshold. This particular reaction is efficient in producing the tetraneutron system at an almost recoilless condition that is crucial for populating very weakly bound systems. The condition can be fulfilled by the DCX reaction with a large positive Q value where the transferred energy is converted from the large internal energy in the unstable ^{8}He nucleus. This feature makes the DCX reaction ^{4}He(^{8}He, ^{8}Be) a highly suitable probe for tetraneutron systems, especially at low excitation energies.

The experiment was performed at the RI Beam Factory [23] at RIKEN using the SHARAQ spectrometer [24] with a liquid helium target system [25]. A primary beam of ^{18}O at 230 MeV/u was bombarded onto a 20-mm-thick beryllium target at BigRIPS [26]. The secondary beam of ^{8}He at 186 MeV/u was transported to a liquid helium target with a thickness of 136 mg/cm^2 at SHARAQ-S0. A schematic view of the experimental setup for the downstream of F6 is shown in the left panel of Fig. 1. The ^{8}He beam intensity was 2×10^6 counts/s with a bunch structure synchronized with the cyclotron radio frequency of 13.7 MHz. The purity of the ^{8}He beam was 99.3%.

To obtain the missing-mass spectrum of the tetraneutron system with approximately 1 MeV resolution, the SHARAQ spectrometer was used at 0° to measure the momenta of two α particles that are decay products of ^{8}Be. The SHARAQ spectrometer was designed for use in high-resolution spectroscopy in combination with the rare isotope beams. The momentum spread of the secondary beam was approximately $\pm 1\%$, which is considerable larger than the resolution of the SHARAQ spectrometer. Therefore, we measured the momentum of the beam particle on an event-by-event basis. A high-resolution achromatic transport [27] was employed at the BigRIPS and high-resolution beam line. The momentum of ^{8}He was measured using a multiwire drift chamber (MWDC) [28] at F6, which is the dispersive focal plane in BigRIPS. For the reaction products, the SHARAQ spectrometer was operated in a large-momentum acceptance mode. This ion-optical transport covered an effective solid angle of 4.3 msr for the ground state of ^{8}Be(0^+) and the momentum resolution, resulting in a missing-mass resolution of approximately 1 MeV. To cover the maximum size of the spatial spread of the two α particles and to obtain a detection efficiency that is as high as possible for the two particles with the small spatial spread, cathode-readout drift chambers (CRDCs) were used [29] at the final focal plane S2 of the SHARAQ spectrometer. Using CRDCs, the two particles were successfully identified in events where the two particles were separated by more than 5 mm in the vertical direction or 10 mm in the horizontal direction. The efficiency of the present two-particle identification is estimated to be 93% for two α particles from ^{8}Be(0^+).

The good signal-to-noise ratio achieved by performing the coincidence detection of the two α particles at the final focal plane of the SHARAQ spectrometer is advantageous for the study of tetraneutron systems. The angular spread of two α particles from the ground state of ^{8}Be(0^+) with the incident ^{8}He beam energy of 186 MeV/u is at most 8 mrad; this is smaller than the acceptance of the SHARAQ spectrometer.

The candidate events were selected by imposing the requirements as follows: (1) time of flight between the S0 and S2 plastic scintillators and energy loss at the S2 plastic scintillators; (2) rejection of events that include more than two beam particles (multiparticle) in one bunch; (3) identification of two α particles in coincidence at the final focal plane; (4) confirmation of the hitting position at the target. Under the high-rate conditions of the secondary beam with 2×10^6 counts/s, 15% of the triggered bunches include more than two particles. The multiparticle events in the triggered bunches were excluded from the analysis of the MWDC at F6. The right panel of Fig. 1 shows the momentum correlation between the ^{8}He beam ($P_{^8\mathrm{He}}$) and the ^{8}Be ejectile ($P_{^8\mathrm{Be}}$) for the candidate events. A reasonable difference in the number of events between the regions separated by the threshold was obtained.

For calibration of the missing-mass of the tetraneutron system, the reaction ^{1}H(^{8}He, ^{8}Li(1^+))n on hydrogen in a plastic scintillator at the target area was measured by changing the magnetic field of the SHARAQ spectrometer. The missing mass of the DCX reaction was then calibrated from the ^{8}Li peak position and the ratio of the magnetic field strengths measured with a NMR probe, after

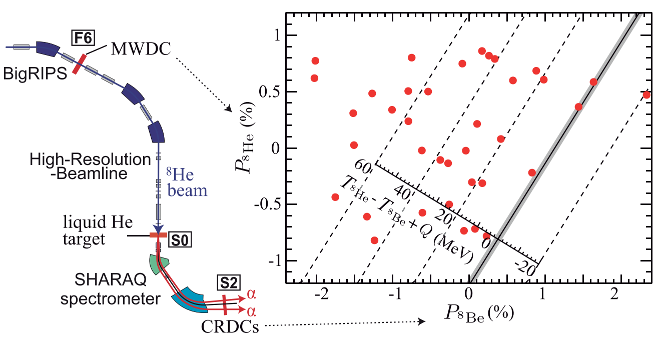

FIG. 1. Left: schematic of the experimental setup downstream of BigRIPS-F6. Right: momentum correlation between the ^{8}He beam ($P_{^8\mathrm{He}}$) at F6 and the ^{8}Be ejectile ($P_{^8\mathrm{Be}}$) at S2 for candidate events. $P_{^8\mathrm{He}} = P_{^8\mathrm{Be}} = 0\%$ corresponds to the central position of the focal plane. The shaded diagonal line shows the energy threshold of four-neutron decay. The diagonal axis is $T_{^8\mathrm{He}} - T_{^8\mathrm{Be}} + Q$, where $T_{^8\mathrm{He}}$ and $T_{^8\mathrm{Be}}$ denote the kinetic energies of ^{8}He and ^{8}Be, respectively, and Q is the Q value of the ^{4}He(^{8}He, ^{8}Be)$4n$ reaction. This axis corresponds to the sum of the missing mass and the recoil energy of the tetraneutron. The recoil energy for each event ranges from 0 to 3 MeV depending on each scattering angle, which is another degree of freedom from the magnitudes of the momenta.

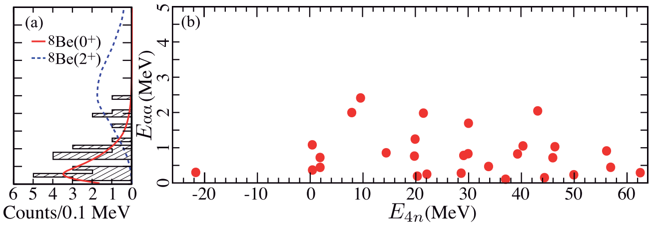

FIG. 2. A scatter plot of the missing mass of the tetraneutron vs the relative energy between two α particles, together with the projected histogram for $E_{\alpha\alpha}$. The solid (red) and dashed (blue) curves in (a) represent the response functions for ^{8}Be(0^+) and ^{8}Be(2^+), respectively. The magnitudes of the response functions are described in the text.

correction for the difference of the effective field lengths. The systematic error due to the calibration was estimated to be 1.25 MeV.

The missing mass of tetraneutron E_{4n} was calculated on an event-by-event basis from the momentum vectors of ^{8}He and the two observed α particles, where finite scattering angles were taken into account. Here, $E_{4n} = 0$ MeV corresponds to the threshold of four-neutron decay. We obtained 27 events in the $-25 < E_{4n} < 65$ MeV energy region. The overall missing-mass resolution was estimated to be 1.2 MeV (σ) using the ion-optical analysis. The relative energy between the two observed α particles, $E_{\alpha\alpha}$, was also deduced for examining the states of ^{8}Be. Figure 2 shows a scatter plot of E_{4n} vs $E_{\alpha\alpha}$, together with the projected histogram for $E_{\alpha\alpha}$. The solid (red) and dashed (blue) curves in Fig. 2(a) represent the response function for ^{8}Be(0^+) and ^{8}Be(2^+), respectively, where the acceptance and the finite resolution in angles and momenta are taken into account. The magnitude for ^{8}Be(0^+) is determined by fitting the histogram, whereas that for ^{8}Be(2^+) is arbitrary for the comparison of the shapes. The acceptance of ^{8}Be(2^+) was estimated to be 13% of that of ^{8}Be(0^+). The observed spectrum of $E_{\alpha\alpha}$ is statistically consistent with the response function of ^{8}Be(0^+). In particular, the events in $0 < E_{4n} < 2$ MeV are considered to be the contribution from ^{8}Be(0^+), while the events with large $E_{\alpha\alpha}$ in $E_{4n} > 8$ MeV, for instance, $E_{\alpha\alpha} > 1.8$ MeV, may be the possible contribution from ^{8}Be(2^+). In the following analysis, we first assume ^{8}Be(0^+) for simplicity and then discuss a possible contribution from ^{8}Be(2^+) later.

Figure 3(a) shows the obtained missing-mass spectrum of the tetraneutron system; the spectrometer acceptance was constant in the region of the spectrum.

The yield of the background in the missing-mass spectrum was then estimated with multiparticles in a triggered bunch considered to be a possible background source. A large fraction of these background events were rejected using the MWDC at F6. However, because the detection efficiency of the MWDC was not 100%, the multiparticle events could produce the background if one of the particles was detected while the others were not. Furthermore, the multiparticle events in the same cell of the MWDC were not identified as two particles. Other possible background sources such as the events where particles were misidentified and the events originating in the window foils of the detectors are estimated to be negligibly small. The number of integrated background events in the spectrum was estimated to be 2.2 ± 1.0. The shape of the background was reconstructed by selecting two independent single-α events identified at S2 at random, which is consistent with the missing-mass spectrum of two α particles for the events identified as multiparticles in a triggered bunch. The dashed line (blue) in Fig. 3(a) represents the estimated background magnified by 10 times for visualization.

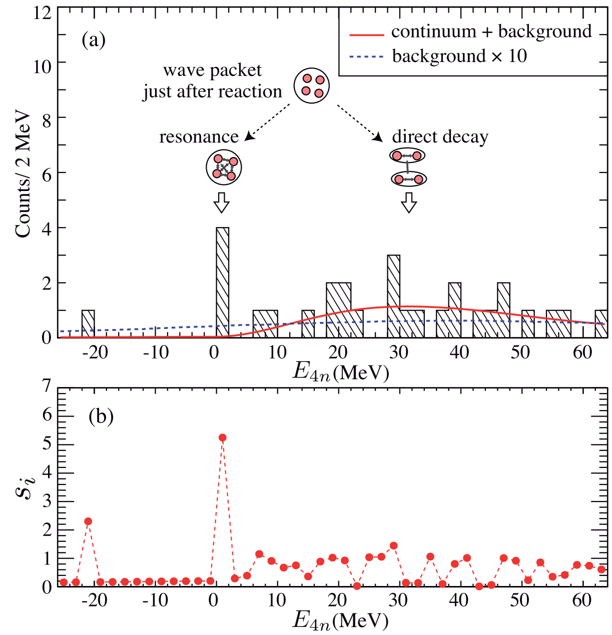

FIG. 3. (a) Missing-mass spectrum of the tetraneutron system. The solid (red) curve represents the sum of the direct decay of correlated two-neutron pairs and the estimated background. The dashed (blue) curve represents the estimated background multiplied by a factor of 10. The schematic of the decay process is discussed in the text. (b) Evaluation of the goodness of fit for each bin using the likelihood ratio test. The s_i were defined in Eq. (3).

Two components are clearly observed in this spectrum in spite of the relatively low statistics. One is the continuum in the $E_{4n} > 2$ MeV region, whereas the other is the peak at the low-energy region $0 < E_{4n} < 2$ MeV. To interpret this spectrum, we assume two different states. One is the direct decay with the final-state interaction between the two correlated neutron pairs. This direct decay contributes to the continuum in the spectrum. The other is a possible resonant or bound state of the tetraneutron system.

The shape of the continuum of the tetraneutron system produced by knockout reactions was discussed by Grigorenko *et al.* [30]. They obtained an energy spectrum assuming that the wave packet of the tetraneutron system just after the reaction is the source evolving by the four-body Hamiltonian. For the case of the knockout reaction of ^{8}He, the position of the peak in the continuum is predicted to be approximately 12 MeV (4 MeV) for the source size of 5.6 fm (8.9 fm). On the other hand, for the pion DCX reaction on ^{4}He, the peak position is expected to be 30–40 MeV because of the compact source from tightly bound ^{4}He.

We applied this approach to the DCX reaction of the present study. The initial structure of the target nuclei, reaction mechanism, few-body effects, and final-state interaction in the studies of unbound states for analyzing the present data were all incorporated in the calculation. The initial state of the wave function of ^{4}He was assumed to be $\Phi[(0s)^4]$. After the DCX reaction, the four-neutron wave packet with angular momentum $J = 0$ is assumed to be $\Phi[(0s)^2(0p)^2]$. Here, we considered the double-dipole nature in the DCX reaction due to the Pauli blocking effect. The final-state interactions between the two neutrons in the $^1S_0$ neutron pair (dineutron) and between the two dineutrons were also considered. The broad experimentally observed distribution centered at approximately 30 MeV was well reproduced by the calculation. The spectral shape near the threshold ($E_{4n} < 4$ MeV) is approximately proportional to E^α ($\alpha \sim 3$) similar to the index $\alpha = 7/2$ for the simple four-body phase space. The important bottom line of this argument is that contributions from the nonresonant direct decay to dineutron pairs are very small near the threshold.

To demonstrate the significance of the yields near the threshold, we fitted the experimental data with a trial function assuming the absence of the resonant and bound states and estimated the goodness of fit with a statistical analysis. The trial function is defined as

$$a f_{\mathrm{cont}}(E_{4n}) + f_{\mathrm{BG}}(E_{4n}), \tag{1}$$

where $f_{\mathrm{cont}}(E_{4n})$ is the continuum obtained by the theoretical calculation described above, $f_{\mathrm{BG}}(E_{4n})$ is the estimated experimental background, and a is the parameter for a factor of the continuum. We fitted the data such that the likelihood ratio test χ^2_λ [31] was minimized. The χ^2_λ are quantities following general χ^2 statistics and are defined as

$$\begin{aligned} \chi^2_\lambda &= -2\ln\,[L(\boldsymbol{y};\boldsymbol{n})/L(\boldsymbol{n};\boldsymbol{n})] \\ &= 2\sum_i [y_i - n_i + n_i \ln\,(n_i/y_i)], \end{aligned} \tag{2}$$

where L is the likelihood function for the Poisson distribution, $\boldsymbol{n} = \{n_1, n_2, \ldots, n_i\}$ is the number of events in the ith bin, and $\boldsymbol{y} = \{y_1, y_2, \ldots, y_i\}$ is the number of events predicted by the trial function in the ith bin. The trial function for the best fit is shown by the solid (red) line in Fig. 3(a). χ^2_λ for $E_{4n} > 0$ MeV is 45 with 31 degrees of freedom. If we perform the fitting for $E_{4n} > 2$ MeV, an almost identical function is obtained with $\chi^2_\lambda = 17$, indicating a good prediction by f_{cont} for $E_{4n} > 2$ MeV.

Figure 3(b) shows the bin-by-bin goodness of fit s_i defined as

$$s_i = \sqrt{2[y_i - n_i + n_i \ln\,(n_i/y_i)]}, \tag{3}$$

the square of which corresponds to each term in Eq. (2). A large value of the goodness of fit s_i means a poor fit. An enhancement of $s_i = 5.2$ at $0 < E_{4n} < 2$ MeV can be clearly observed. This clear disagreement between the fitted curve and the experimental data means that events at $0 < E_{4n} < 2$ MeV can hardly be explained by the direct decay to dineutron pairs and can be a candidate for the state of the tetraneutron system because the fitted curve assumes neither the resonant nor the bound state. Except for the $0 < E_{4n} < 2$ MeV region, s_i is consistent with the statistical distribution. The event at $E_{4n} < -20$ MeV is considered to be the contribution from the experimental background because the upper limit of the binding energy is 3.1 MeV, provided by the particle stability of ^{8}He, which does not decay into $\alpha + {}^4n$. It appears that the bin of $s_i = 2.3$ for the above mentioned event is reasonable because the probability of the emergence of such bins corresponds to 1.3 bins in this 45-bin histogram.

To estimate the significance of the peak at $0 < E_{4n} < 2$ MeV more carefully, we considered the "look elsewhere effect" [32]. The significance of observing a local excess of events must be obtained by considering the probability that such an excess originated from fluctuations of the continuum elsewhere in the region. The "trial factor" was defined as the ratio between the probability of observing the excess at some fixed point and the probability of observing it anywhere in the region of interest. The region of interest is defined as $-2 < E_{4n} < 10$ MeV. If there is a resonant state at a region of $E_{4n} > 10$ MeV, the width is expected to be very large such that the resonant state cannot be distinguished from the continuum. According to this evaluation, the significance of the peak at low energies was 4.9σ, indicating that a contribution other than the continuum and experimental background is needed.

In the above statistical analysis, ^{8}Be(0^+) is assumed for all the events, while there may be possible contributions from ^{8}Be(2^+) with a large $E_{\alpha\alpha}$, as seen in Fig. 2. A more strict cut to exclude contributions from ^{8}Be(2^+), for instance, $0 < E_{\alpha\alpha} < 1.8$ MeV, eliminates events only for the continuum, which would make the significance of the $0 < E_{4n} < 2$ MeV peak larger than 4.9σ.

In conclusion, the four events in the $0 < E_{4n} < 2$ MeV region are candidates for a resonant state of the tetraneutron system. Because of the small contribution of the continuum and experimental background, the significance level of the peak is 4.9σ compared with the continuum that assumes no resonant state. The mean energy of the events is evaluated to be 0.83 ± 0.65 MeV with an additional systematic uncertainty of 1.25 MeV due to the missing mass calibration. These results suggest a possible resonant state of the tetraneutron system, although the possibility of a bound state is not experimentally excluded. The upper limit of the width of the peak is estimated to be 2.6 MeV (FWHM), which is mainly determined by the experimental missing-mass resolution. Note that the rather narrow width may be understood by considering a small phase space for the four-body decay. The cross section of the peak at low energy is estimated to be $3.8^{+2.9}_{-1.8}$ nb for integration up to $\theta_{CM} < 5.4°$, where θ_{CM} is the scattering angle in the center-of-mass system of the DCX reaction. This is compatible with a simple estimation of the two-step process assuming the Gamow-Teller and the spin-dipole transition for the projectile and the target system, respectively. It is noted that the presently observed energy is compatible with a possible resonance in a reanalysis of the $^{14}\mathrm{Be} \rightarrow {}^{10}\mathrm{Be} + 4n$ experiment by its original authors [33].

The result indicating the resonant state may suggest the necessity of strong many-body forces such as an isospin $T = 3/2$ three-body force and/or a $T = 2$ four-body force, which are incompatible with the present understanding of nuclear interactions [21]. Another possibility of forming a resonant state is the influence of the attractive interaction due to forming a compound system, where ${}^3n + n$ and ${}^2n + {}^2n$ coupled cluster configurations coexist, as discussed in Ref. [22]. Our result should serve as a basis for further investigations.

In summary, we performed missing-mass spectroscopy of the tetraneutron system via the DCX reaction $^4\mathrm{He}(^8\mathrm{He}, {}^8\mathrm{Be})$ at 186 MeV/u with the SHARAQ spectrometer at the RI Beam Factory. Through an analysis to eliminate multiparticle events, the missing-mass spectrum of the tetraneutron system containing 27 events was obtained with almost absent background signals. The spectrum has a clear peak with a 4.9σ significance level near the threshold of four-neutron decay in comparison with the theoretical curve assuming direct decay to the two correlated dineutron pairs. The mean of the peak is $0.83 \pm 0.65(\mathrm{stat}) \pm 1.25(\mathrm{syst})$ MeV and the upper limit of the width is 2.6 MeV (FWHM). This result suggests a possible resonant state of the tetraneutron system.

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