Experimental Evidence for the Existence of ^{7}H and for a Specific Structure of ^{8}He

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Experimental search for the superheavy ^{7}H isotope was performed in the reaction $p(^8\mathrm{He}, pp)^7\mathrm{H}$ with the ^{8}He beam at 61.3A MeV. The evidence for existence of the ^{7}H state near the $t + 4n$ threshold was obtained. In the same experiment, the $p(^8\mathrm{He}, t)$ reaction populating the ground and excited 2^+ state of ^{6}He was investigated. The obtained results argue on a specific structure of the ^{8}He ground state containing the ^{6}He subsystem in the excited 2^+ state with a large weight.

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Progress in experimental technique including usage of secondary beams of short-lived radioactive nuclei has enabled studies of exotic nuclear systems in the vicinity of and beyond the neutron drip line. Recently, experimental studies of ^{5}H were performed in the reactions $p(^6\mathrm{He}, ^2\mathrm{He})^5\mathrm{H}$ [1], $t(t, p)^5\mathrm{H}$ [2], and $d(^6\mathrm{He}, ^3\mathrm{He})^5\mathrm{H}$ [2]. These three measurements show a peak of ^{5}H at $\sim$1.8 MeV above the $t + 2n$ threshold. Note that two other recent experiments [3,4] devoted to ^{5}H show a ^{5}H peak at somewhat higher energy. Because of the known systematics for helium isotopes, where ^{8}He having two more neutrons than ^{6}He is more bound relative to the separation of two neutrons than ^{6}He as well as ^{7}He is less unbound than ^{5}He, the results for ^{5}H allow us to speculate that ^{7}H may exist as a state in a vicinity of the $t + 4n$ threshold.

Hardly ^{7}H exists as a bound state. During the years, in numerous measurements performed using the ΔE-E method, the region of hydrogen and helium isotopes was studied in detail and no hyperbole of the bound ^{7}H in ΔE-E plots was observed. However, ^{7}H may exist as an unstable state. Being close to the threshold, ^{7}H could be an especially interesting system. It should undergo the unique five particle decay into $t + 4n$ and its width may be very narrow. An extreme fraction of neutrons in ^{7}H, $N/Z = 6$, is comparable with that in neutron stars.

Experimental search for unstable ^{7}H presents a difficult task, and this resonance has never been observed. Recent calculation of ^{7}H within the seven-body hyperspherical functions method suggests that ^{7}H can be unbound with respect to the $t + 4n$ decay by 840 keV [5].

We made an additional attempt to estimate the energy range for ^{7}H to be measured. In Ref. [5], the binding energy of ^{7}H has been obtained by exponential extrapolation of energies calculated up to $K = K_{\mathrm{min}} + 6$. Such an extrapolation can give only a rough evaluation of the converged binding energy. In the present work, we study proton separation energy for ^{8}He, $S_p(^8\mathrm{He})$, rather than total ^{7}H energy. Calculating proton separation energy in ^{6}He also, we have revealed that, unlike the total binding energy, S_p is only slightly sensitive to the increase of the model space. The reason for this lies in the well-pronounced cluster structure of ^{6,8}He and ^{5,7}H for which the binding energies of the cores ^{4}He and ^{3}H converge rapidly.

In the present calculations, we used all variants of the Volkov NN potential [6], trying to find a case which reproduces the binding energies of ^{3,5}H and

^{4,6,8}He simultaneously. The best results have been obtained with potential V6 modified as follows: $V_{31}^{\rm mod} = \alpha V_{31}$, $V_{13}^{\rm mod} = (2-\alpha)V_{13}$, $V_{11}^{\rm mod} = (1-2M)V_{31}^{\rm mod}$, and $V_{33}^{\rm mod} = (1-2M)V_{13}^{\rm mod}$ with $\alpha = 1.15$ and standard Majorana parameter $M = 0.6$. The results for $S_p(^6\mathrm{He})$ and $S_p(^8\mathrm{He})$ obtained with this potential are shown in Fig. 1 together with those obtained with potential V1 [6]. The $S_p(^6\mathrm{He})$ values are reasonably close to the experimental value [1] also shown in Fig. 1. One can see that the proton separation energy for ^{8}He is about 26 MeV for both potentials. Since the experimental ^{8}He binding energy is 31.4 MeV, we can expect the ^{7}H seven-body binding energy to be ~5.4 MeV which is about 3 MeV above the $t + 4n$ threshold. Because of the remnant convergence over K, which is seen in Fig. 1 for ^{6}He, the estimated energy of ^{7}H can be regarded as an upper limit for the potentials used.

Considering the experimental search for ^{7}H, we took into account the following. It is reasonable to suppose that neutrons in the ground state of ^{7}H occupy the same orbitals as in ^{8}He. Hence, by pickup of one proton from ^{8}He, we should get a good chance to populate the ground state $1/2^+$ of ^{7}H. Consequently, we have chosen the reaction $p(^8\mathrm{He}, pp)^7\mathrm{H}$ for experimental search for ^{7}H.

The experiment was performed in RIKEN (Japan) using a secondary beam of ^{8}He produced by the fragment separator RIPS from fragmentation of a primary beam of ^{18}O. The obtained ^{8}He beam had a very high intensity of ~300 000 particles per second and an energy of 61.3A MeV with an energy spread of 2.6A MeV.

As a proton target, we used a cryogenic target from GANIL (France), which was filled with hydrogen gas at a temperature of 35 °K and pressure of 10 atm. The target thickness was 6×10^{21} protons/cm^2.

The experimental setup is shown in Fig. 2. Two plastic scintillators were used for the identification of each particle of the secondary beam and for the measurement of its energy by time of flight. The trajectories of individual ^{8}He ions were measured by a pair of two-dimensional multiwire proportional chambers (MWPCs). The two protons originating from the reaction $p(^8\mathrm{He}, pp)^7\mathrm{H}$ were detected in coincidence by the RIKEN telescope which is a stack of Si strip detectors. This telescope allows one to detect several particles in coincidence, to identify each particle, and to measure its energy and angles. The beam passed through the central hole in the annular strip detectors. Using this telescope, we detected the two protons at small angles in the laboratory system. Note that it differs from geometry used in studies of quasifree pp scattering, where two protons are measured with an angle of 90° between them, whereas the geometry used in the present experiment corresponds to our expectation that the two protons from the reaction $p(^8\mathrm{He}, pp)^7\mathrm{H}$ can undergo final state interaction being emitted as a virtual singlet state ^{2}He. This method was used in the study of ^{5}H in the reaction $p(^6\mathrm{He}, pp)^5\mathrm{H}$ [1]. When detecting the two protons by the RIKEN telescope, we obtain kinematically complete information about these two protons and, due to energy and momentum conservation in the reaction $p(^8\mathrm{He}, pp)^7\mathrm{H}$, we can unambiguously reconstruct a mass of the residual system ^{7}H. Also, we detected tritons and neutrons from the breakup of ^{7}H using a downstream detection system consisting of a dipole magnet and plastic scintillators. This part of setup was the same as in our previous experiment described in Ref. [7].

Experimental results obtained in the pp coincidences are shown in Fig. 3. Spectra measured in coincidences with triton and neutron emitted downstream have a very similar character, but lower statistics. In Fig. 3, spectra are shown as a function of the ^{7}H energy, $E_{^7\mathrm{H}}$, relative to the $t + 4n$ decay threshold. The solid histogram shows the result obtained with the proton target. The cutoff at ~20 MeV reflects the detection limit due to the RIKEN telescope. The dashed histogram presents a background obtained with an empty-target and normalized according to the ^{8}He beam integral. The shift of the background with and without hydrogen gas in the target is smaller than the size of the bin in the shown spectra. This background accounts for events at negative energies, where ^{7}H would be bound. At positive energies, a definite effect from the reaction on the proton target is observed: The solid histogram exceeds the dashed histogram. At the same time, a high contribution from the empty-target background puts obstacles in a detailed analysis of the ^{7}H spectrum. However, one very interesting feature can be seen in the obtained results. This is a very rapid increase of the ^{7}H spectrum near the $t + 4n$ threshold.

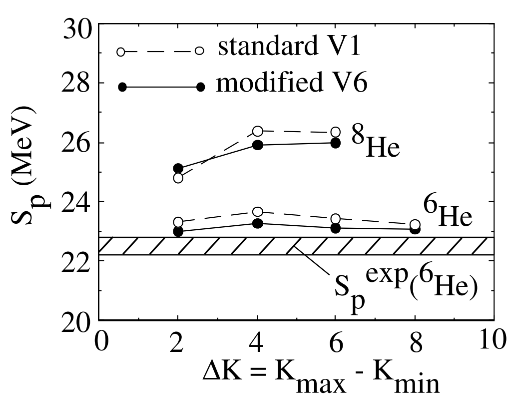

FIG. 1. Proton separation energies for ^{6}He and ^{8}He as functions of difference in maximum and minimum hypermoments.

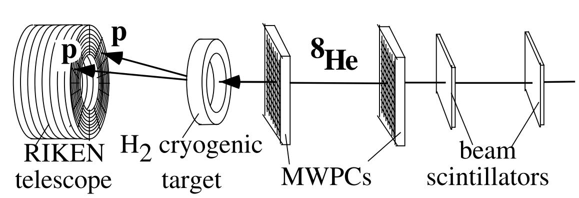

FIG. 2. Scheme of the experimental setup.

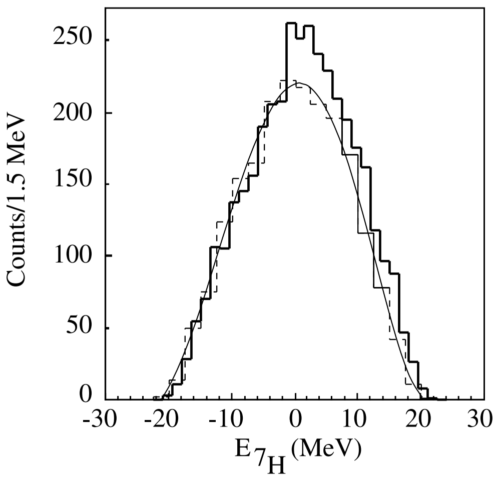

FIG. 3. Spectrum of ^{7}H from the reaction $p(^8\mathrm{He}, pp)^7\mathrm{H}$. The solid histogram was obtained with the proton target. The dashed histogram shows the empty-target background.

It is more clearly seen in Fig. 4 obtained in the following way. We fitted the empty-target background by a polynomial of the fifth order (it is shown by the thin solid curve in Fig. 3) with χ^2 per degree of freedom smaller than unity and subtracted this polynomial from the solid histogram in Fig. 3. Figure 4 shows the obtained result. Error bars present statistical errors for the solid histogram in Fig. 3. Figure 5 shows the spectrum obtained by direct subtraction of the empty-target background with error bars including statistical uncertainty of the background subtraction. Experimental resolution in these spectra was 1.9 MeV (FWHM).

In Figs. 4 and 5, the very sharp increase of the spectrum starting from the $t + 4n$ threshold is obviously seen. Such a behavior does not correspond to a nonresonant continuum, which is illustrated by curves 1–3 in Fig. 4. When calculating curve 1, we described the motion in the $t + 4n$ system by the five-body phase volume, $dN/dE_{^7\mathrm{H}} \propto E_{^7\mathrm{H}}^5$. The detection efficiency, which is shown in the inset in Fig. 5, and the experimental resolution were taken into account. Curve 2 was obtained, when the motion of $t + 4n$ was taken as the three-body phase volume, $dN/dE_{^7\mathrm{H}} \propto E_{^7\mathrm{H}}^2$. This can be considered as an extreme model for a process, when two pairs of neutrons in the $t + 4n$ system undergo final state interactions in singlet states, $t + {}^2n + {}^2n$, and when the relative motion in the both pairs of neutrons is described by delta functions for simplicity. If we use a more realistic distribution for the relative motion of two neutrons in a singlet state, curve 2 becomes less steep and more similar to curve 1. At last, curve 3 shows the most extreme case. It shows a calculation using the two-body phase volume for $t + 4n$, $dN/dE_{^7\mathrm{H}} \propto E_{^7\mathrm{H}}^{1/2}$. This can be considered as a model for a process, when each pair of neutrons is emitted in a singlet state and when the relative motion of two neutrons in each pair is described by delta function. Again, usage of more realistic distribution for the relative motion of two neutrons in singlet state makes curve 3 less steep and more similar to curve 2. Also, curve 3 can be considered as a model for the emission of a bound tetraneutron with a small binding energy.

As seen in Fig. 4, the experimental spectrum increases near the $t + 4n$ threshold even more sharply than the most extreme curve 3. This provides a strong indication on the possible existence of ^{7}H state near the $t + 4n$ threshold. In this region the cross section is $\sim 10^{-2}$ mb sr^{-1} MeV^{-1}. For further studies of ^{7}H, apart from the $p(^8\mathrm{He}, pp)^7\mathrm{H}$ reaction, also reactions $d(^8\mathrm{He}, {}^3\mathrm{He})^7\mathrm{H}$, and $t(^8\mathrm{He}, {}^4\mathrm{He})^7\mathrm{H}$ seem to be promising.

In the same experiment, by detecting tritons by the RIKEN telescope, we studied two-neutron transfer reactions $p(^8\mathrm{He}, t)^6\mathrm{He}_{\mathrm{g.s.}}$ and $p(^8\mathrm{He}, t)^6\mathrm{He}^*(2^+)$. The production of $^6\mathrm{He}_{\mathrm{g.s.}}$ was identified in coincidences $t + {}^6\mathrm{He}$, while $^6\mathrm{He}^*(2^+)$ was observed as a peak at $E^\star = 1.8$ MeV in $t + \alpha$ coincidences. The measured cross sections for population of the ground state and excited 2^+ state of ^{6}He are shown in Fig. 6.

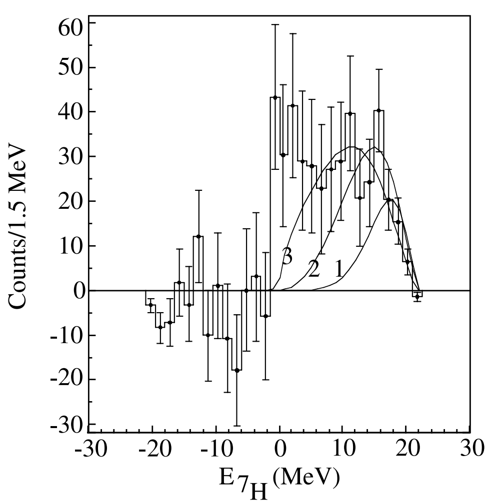

FIG. 4. Spectrum of ^{7}H after subtraction of the polynomial fit to the empty-target background. Curves show nonresonant continuums explained in the text.

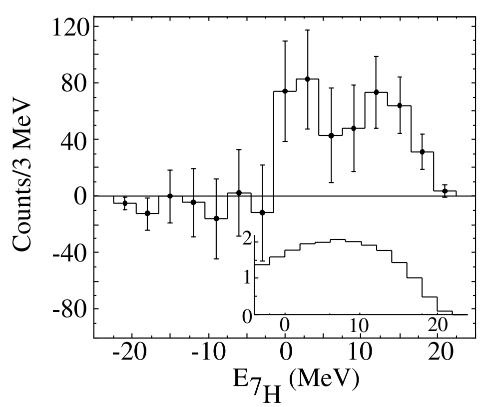

FIG. 5. Spectrum of ^{7}H after direct subtraction of the empty-target background. Inset in the lower part shows the detection efficiency in arbitrary units.

If the ground state of ^{8}He would contain subsystem ^{6}He mainly in the state 0^+, then the ^{8}He(p, t) reaction would populate preferentially ^{6}He$_{g.s.}(0^+)$, whereas the cross section for the population of ^{6}He$^*(2^+)$ would be somewhat an order of magnitude lower, because the latter would be the second order process. It requires a two-neutron peakup from ^{8}He, as in $p(^8\text{He}, t)^6\text{He}_{g.s.}$, but in addition in this case the ^{6}He(0^+) subsystem should be excited to the 2^+ state. As a result, the cross section of the $p(^8\text{He}, t)^6\text{He}^*(2^+)$ reaction would be suppressed.

Experimental data in Fig. 6 is just the contrary: The cross section of the $p(^8\text{He}, t)^6\text{He}^*(2^+)$ reaction is higher than that of $p(^8\text{He}, t)^6\text{He}_{g.s.}$. It means that the ground state of ^{8}He contains subsystem ^{6}He in the state 2^+ with a large weight.

Qualitatively it is consistent with a consideration of ^{8}He in a simple model of Ref. [8], where a five-body ($\alpha + 4n$) wave function of ^{8}He was constructed with the four antisymmetrized neutrons in the $P_{3/2}$ states relative to the α core. Under these assumptions, one can strictly investigate the spin parity of the ^{6}He subsystem in ^{8}He. The obtained weights for various J^π in the ^{6}He subsystem are the following: $P(0^+) = \frac{1}{6}$, $P(1^+) = 0$, $P(2^+) = \frac{5}{6}$, $P(3^+) = 0$. That is, the excited 2^+ state of ^{6}He is predominant in the ^{8}He ground state wave function.

Now we can roughly estimate a ratio of spectroscopic factors for the reactions $p(^8\text{He}, t)^6\text{He}_{g.s.}$ and $p(^8\text{He}, t)^6\text{He}^*(2^+)$. Assuming that in the (p, t) reaction a dineutron cluster in a singlet state is transferred from ^{8}He to proton, apart from the obtained weights of $\frac{1}{6}$ and $\frac{5}{6}$, we need to take into account squares of product of 9J symbol and Talmi-Moshinski coefficient: $\frac{2}{3} \times \frac{1}{2}$ and $\frac{1}{3} \times \frac{1}{2}$ for ^{6}He(0^+) and ^{6}He(2^+), respectively. At last, unlike the ground state ^{6}He(0^+), which contains valence neutrons mainly in the $P_{3/2}$ states as it was found in microscopic calculations (e.g., see [9]), in the excited state ^{6}He$^*(2^+)$ the $P_{3/2}$ configuration has a weight of 33% according to microscopic calculations of Ref. [10]. It gives for the ^{6}He$^*(2^+)$ channel an additional factor of $\frac{1}{3}$. Combining all mentioned coefficients, we obtain the ratio of the spectroscopic factors close to 1.

We have performed calculations in the distorted-wave Born approximation using several optical potentials taken from literature. Values of the spectroscopic factors required for agreement with the experimental cross sections depend on the choice of potentials, but the ratio of spectroscopic factors is rather stable. A typical result of the calculations is shown by curves in Fig. 6. In this case, the spectroscopic factors have been taken equal to each other. The calculations are in satisfactory agreement with the experimental data.

Further detailed theoretical analyses will require a ^{8}He model going beyond the simple jj coupling, microscopic calculations of the spectroscopic factors, and an inclusion of two-step mechanism of the (p, t) reaction.

Recently in Dubna (Russia), the (p, t) reaction was investigated at lower energy of the ^{8}He beam, 26A MeV,

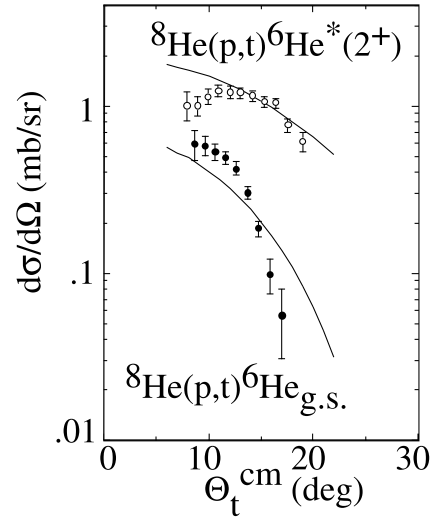

FIG. 6. Cross sections of the reactions ^{8}He$(p, t)^6$He$_{g.s.}$ and ^{8}He$(p, t)^6$He$^*(2^+)$.

and also higher cross section for the ^{6}He$^*(2^+)$ channel than that for ^{6}He$_{g.s.}$ was observed [11]. Indications on the ^{6}He$(2^+) + 2n$ configuration in the ground state of ^{8}He were previously obtained in Refs. [12,13].

In summary, we have performed the experimental search for ^{7}H in the $p(^8\text{He}, pp)^7$H reaction. The evidence for existence of the ^{7}H state near the $t + 4n$ decay threshold was obtained. In the same experiment, the $p(^8\text{He}, t)$ reaction populating the ground and excited 2^+ state of ^{6}He was investigated. The obtained results argue on a specific structure of the ground state of ^{8}He containing subsystem ^{6}He in the state 2^+ with a large weight.

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