

Interfering reaction channels observed in the ${}^2\text{H}({}^8\text{He}, {}^4\text{He}){}^6\text{H}$ reaction studies

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Abstract. In the recent work [Nikolskii et al., Phys. Rev. C **105**, 064605 (2022)] the ${}^2\text{H}({}^8\text{He}, {}^4\text{He}){}^6\text{H}$ reaction was used for the study of the extreme neutron-rich ${}^6\text{H}$ isotope. A broad bump was observed in the measured ${}^6\text{H}$ spectrum interpreted as the broad overlapping ground and some low-lying states of this nuclide. There could be certain doubts in the interpretation of this work: in conditions of the limited phase space it is not impossible that the structure in the missing mass spectrum of ${}^6\text{H}$ is actually induced by the resonant states populated by some other channels opened in the ${}^8\text{He}+{}^2\text{H}$ interaction. This work provides a body of the evidence for the correct channel identification and for the absence of the ${}^6\text{H}$ resonances at energy $E_T = 0 - 3.5$ MeV above the ${}^3\text{H}+3n$ decay threshold. In addition the first strong experimental evidence is given that the ${}^6\text{H} \rightarrow {}^5\text{H}^* + n \rightarrow {}^3\text{H}+3n$ sequential decay is the dominating ${}^6\text{H}$ decay channel.

1 Introduction

So far there is no answer to a fundamental question about the limits of the nuclear structure defined by the border between the unbound nuclei, still showing their resonance states, and the nuclear systems exhibiting only the continuous spectra. The search for the new isotopes beyond the driplines is a main experimental tool to find out where such limit is located. Not long ago a series of experiments were performed in order to obtain the superheavy hydrogen isotopes ${}^7\text{H}$ and ${}^6\text{H}$ [1–5]. The recently reported results [6, 7] shed light on the spectroscopy of these nuclei and decay mechanisms of their ground and excited states. However, the missing mass (MM) spectrum of ${}^6\text{H}$ reported in work [7] is characterized by the absence of any distinct narrow peak, and the observed resonance state is relatively wide and implicit. The latter leads to the question of whether the obtained structure could be formed by the final-state interaction appearing in some other reaction channels which are not so exotic and may occur with higher probabilities.

This work is dedicated to the analysis of the diverse reaction channels occurring in the ${}^8\text{He}+{}^2\text{H}$ interaction characterized by the detection of the same products as those

which were used in Ref. [7] to identify the ${}^6\text{H}$ population. Such analysis allows one to elucidate the ${}^6\text{H}$ decay channels and its spectrum nature reported in [7].

2 Experiment

The experiment was performed at the ACCULINNA-2 facility, FLNR, JINR, producing 26 A MeV ${}^8\text{He}$ beam and focusing it on the cryogenic deuterium target. The detection system was intended to identify the products of the ${}^2\text{H}({}^8\text{He}, {}^4\text{He}){}^6\text{H}$ reaction and the further ${}^6\text{H} \rightarrow {}^3\text{H}+3n$ decay. The employed detector system is described in Ref. [7].

For the identification of beam nuclei two plastic scintillators were used, which allowed to measure the energy of the projectile from its time-of-flight (ToF) and identify the isotope by the dE-ToF method. The trajectories of the beam projectiles were tracked by the two pairs of multi-wire proportional chambers. The cryogenic target was filled with deuterium gas at atmospheric pressure and cooled to 27 K. For the detection of the charged reaction products two types of ΔE - E telescopes were used: the side assembly of the three (20 μm , 1 mm and 1 mm thick) silicon strip detector (SSD) telescopes, and the front tele-

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scope made of the 1.5 mm double side SSD coupled to the CsI(Tl) scintillator array. The thin, 20 μm detectors in the side telescopes allowed one to reliably identify and reconstruct the low-energy particles (the recoil ^4He nuclei with energy ≥ 5 MeV) emitted from the target in the laboratory angular range between 8° and 26° , see Ref. [8]. The front telescope covered the lab angles $\leq 9^\circ$. It was used to measure the high-energy particles (tritons with energy up to 160 MeV) stopping in the CsI(Tl) crystal. The neutron detection was realized by the ToF stilbene modules [9].

3 “Background” reaction channels for ^6H

The first question to be solved is whether the low-energy part of the ^6H MM spectrum, see the E_T spectrum in Fig. 1 (a), can be caused by some other reaction mechanism. The ^6H events were identified by the detection of the ^4He recoil, emerging from the $^2\text{H}(^8\text{He}, ^4\text{He})^6\text{H}$ reaction, and the ^3H decay product of the ^6H decay (also the neutron coincidence information can be used on demand). How can we be sure that these nuclei were produced solely in the channel populating the ^6H states, but not in some different reaction channels, where they appear in the $^3\text{H}+n+n+n+^4\text{He}$ group? In reality the final state products of the $^8\text{He}+^2\text{H}$ interaction can be partitioned also as $\{^3\text{H}+n+n\} + \{^4\text{He}+n\}$, $\{^3\text{H}+n\} + \{^4\text{He}+n+n\}$ or $\{^3\text{H}\} + \{^4\text{He}+n+n+n\}$. These outcomes correspond to the reactions $^2\text{H}(^8\text{He}, ^5\text{He})^5\text{H}$, $^2\text{H}(^8\text{He}, ^6\text{He}^*)^4\text{H}$, and $^2\text{H}(^8\text{He}, ^7\text{He}^*)^3\text{H}$. In this section, we provide data for the two of these reaction channels and study the correlations of these reaction channels with the obtained low-energy part of the ^6H spectrum.

The ^7He system was reconstructed assuming that ^3H is the nucleus formed immediately in the $^2\text{H}(^8\text{He}, ^7\text{He}^*)^3\text{H}$ reaction. The ^4He nucleus, detected in the side telescope, was used as the selection gate allowing one to reduce significantly the MM background conditions. Effective method was the so-called “kinematical triangle” selection used in works [6, 7, 10]. This allowed us to localize the background events in the correlation pattern of the kinetic energy of the emitted particles, taken in the center-of-mass frame (CMS) of the decaying system, with the MM energy of the decaying system (in this case it is the correlation of the ^4He kinetic energy in the ^7He CMS with the ^7He MM energy).

To study the correlations with the $^7\text{He}^*$ MM spectrum we selected the low-energy part of the ^6H MM spectrum derived from the $^2\text{H}(^8\text{He}, ^4\text{He})^6\text{H}$ reaction data, see the green colored part in Fig. 1 (a). The $^7\text{He}^*$ MM spectrum is presented in Fig. 1 (b) by the black histogram, while the green-line histogram corresponds to the low energy events in the ^6H MM spectrum. One may see that the low-energy events of ^6H are spread in the high-energy region of ^7He and do not form any pronounced peak. Thus, we conclude that the analyzed range of ^6H spectrum is very weakly affected by the final state interactions connected with the possible population of ^7He states in the $^2\text{H}(^8\text{He}, ^7\text{He}^*)^3\text{H}$ reaction.

The other possible “background” reaction $^2\text{H}(^8\text{He}, ^5\text{He})^5\text{H}$ is the result of a triton transfer from

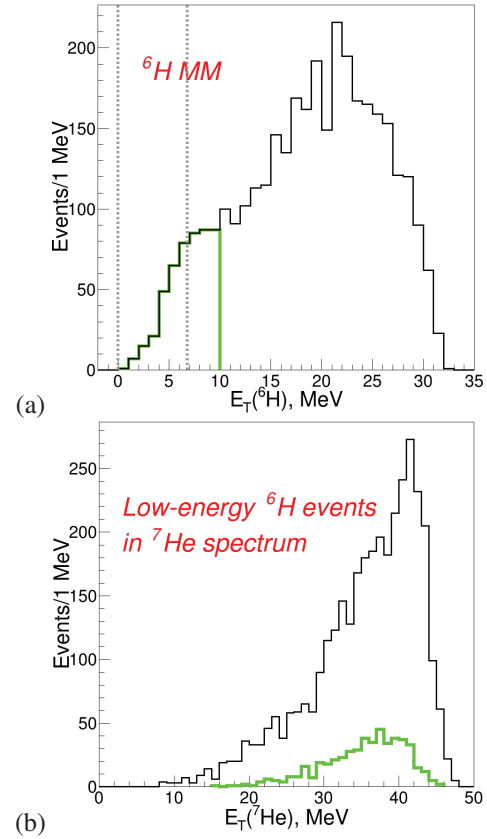


Figure 1. (a) The ^6H MM spectrum; the part of this spectrum at $E_T < 10$ MeV is indicated by green color. The vertical gray dotted lines show the $^3\text{H}+3n$ threshold and $E_T(^6\text{H})=6.8$ MeV. (b) The ^7He MM spectrum built with respect to the $^4\text{He}+3n$ threshold (black histogram). The green histogram in (b) corresponds to the low-lying events with $E_T < 10$ MeV in the spectrum of ^6H .

^8He . This channel leads to the production of the target-like ^5He and beam-like ^5H . The latter moves forward and decays into $^3\text{H}+n+n$, which does not allow to measure it directly by our setup. For that reason the $^2\text{H}(^8\text{He}, ^5\text{He})^5\text{H}$ reaction examination can be performed only based on the triple $^4\text{He}-^3\text{H}-n$ coincidence events. The ^6H spectrum, stemming from the spectrum of Fig. 1 (a) by this coincidence requirement, is shown in Fig. 2 (a). For those events, the recoil ^5He invariant mass (IM) spectrum can be reconstructed from the measured ^4He and neutron, see the black histogram in Fig. 2 (b). The low-energy ^6H events with $E_T < 10$ MeV in the ^5He IM distribution are presented with the green histogram in Fig. 2 (b). One may find here the following:

- (i) The ^5He g.s. resonance is expected to be found with $E_T(^5\text{He}) \sim 0.9$ MeV. We really see a strong indication of this resonant state in the derived spectrum of ^5He .
- (ii) The ^6H low energy events are practically not correlated with the energy range of ^5He where the resonant states are known to exist. Thus, the ^6H spectrum can not be governed by the final state interactions connected with possible population of ^5He in the $^2\text{H}(^8\text{He}, ^5\text{He})^5\text{H}$ reaction.

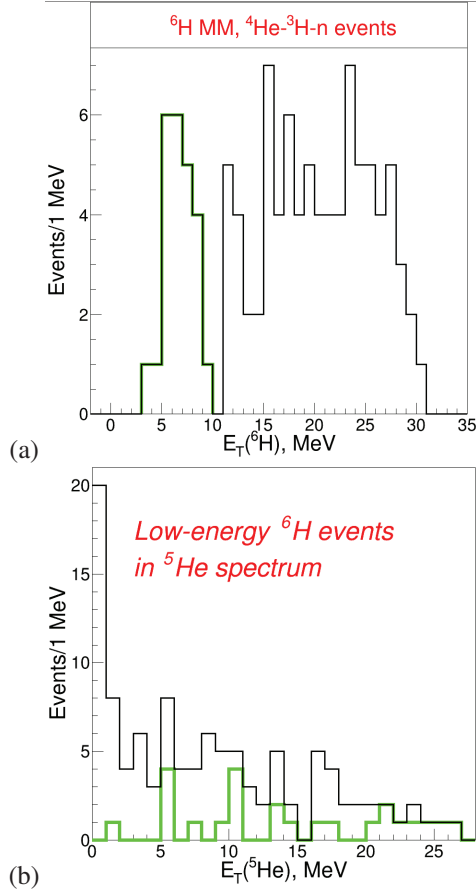


Figure 2. (a) The ${}^6\text{H}$ MM spectrum based on the ${}^4\text{He}$ - ${}^3\text{H}$ - n coincidence events; the part of this spectrum at $E_T < 10$ MeV is given in green color. (b) The ${}^5\text{He}$ invariant mass spectrum constructed from the ${}^4\text{He}$ and neutron momentum vectors in the triple ${}^4\text{He}$ - ${}^3\text{H}$ - n coincidence events.

The reconstruction of the ${}^2\text{H}({}^8\text{He}, {}^6\text{He}^*){}^4\text{H}$ reaction requires the detection of $2n$ coincidence events, which is not possible because of the low efficiency of our neutron-wall setup. However, it is quite unexpected that such reaction is important, while the populations of ${}^5\text{He}$ and ${}^7\text{He}$ are found to be negligible.

4 ${}^5\text{H}$ populated in the ${}^6\text{H}$ decay

In work [7], the authors showed that the assumption of the ${}^6\text{H} \rightarrow {}^5\text{H}(\text{g.s.}) + n \rightarrow {}^3\text{H} + 3n$ sequential decay leads to the evidence of an extremely strong “dineutron-type” correlation in the decay of the ${}^5\text{H}$ ground state. Here we apply the reaction-channel test for the decay-mechanism analysis of the ${}^6\text{H}$ spectrum obtained in this work.

Let us assume that in the process of the ${}^8\text{He} + {}^2\text{H}$ interaction the ${}^5\text{H}$ resonance is somehow populated. And moreover, we presume that all these events are characterized by the detection of the low-energy ${}^4\text{He}$ appearing in the side telescope in coincidence with the high-energy ${}^3\text{H}$ and neutron hitting the front telescope and stilbene wall, correspondingly. The only two channels satisfying these conditions are:

- The triton transfer reaction: ${}^2\text{H}({}^8\text{He}, {}^5\text{He}){}^5\text{H}$.

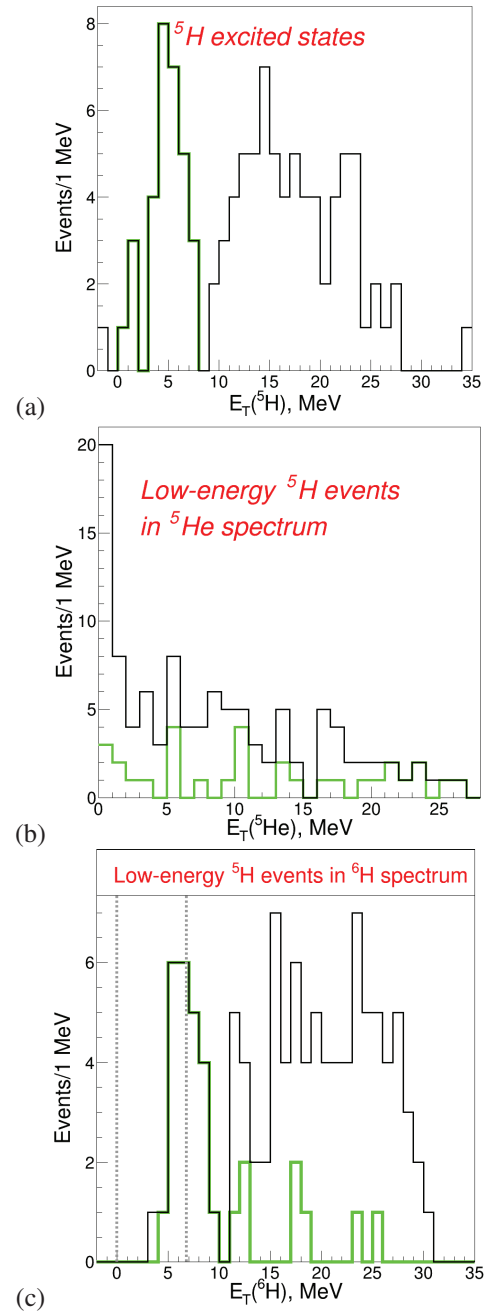


Figure 3. (a) The ${}^5\text{H}$ MM spectrum reconstructed via the IM spectrum of ${}^5\text{He}$. The green histogram corresponds to the ${}^5\text{H}$ events with $0 < E_T({}^5\text{H}) < 9$ MeV. (b) The ${}^5\text{He}$ IM spectrum. (c) The ${}^6\text{H}$ MM spectrum formed by the triple ${}^4\text{He}$ - ${}^3\text{H}$ - n coincidence events. The vertical lines show the ${}^3\text{H} + 3n$ threshold and the resonance observed at $E_T({}^6\text{H}) = 6.8$ MeV.

- The deuteron transfer reaction ${}^2\text{H}({}^8\text{He}, {}^4\text{He}){}^6\text{H}$ in the assumption of the sequential ${}^6\text{H} \rightarrow {}^5\text{H}(\text{g.s.}) + n \rightarrow {}^3\text{H} + 3n$ decay.

Both options imply that the studied ${}^5\text{H}$ can be reconstructed as a missing component from the measured ${}^4\text{He}$ and the neutron. The ${}^5\text{H}$ MM spectrum presented in Fig. 3 (a) was obtained from the analysis of the ${}^2\text{H}({}^8\text{He}, {}^4\text{He}){}^6\text{H}$ reaction data [7]. An important feature of this spectrum is the strong event concentration obtained around

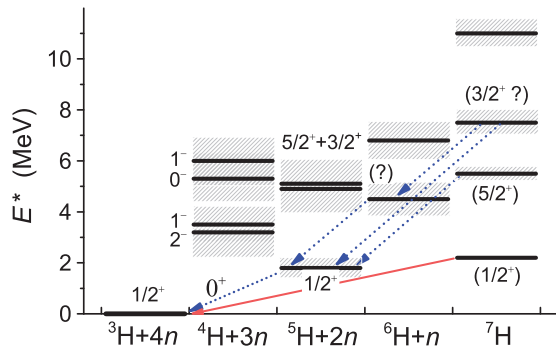


Figure 4. The level schemes of ${}^6\text{H}$ and the known neighboring ${}^4\text{H}$, ${}^5\text{H}$ [11–13] and ${}^7\text{H}$ [6, 9] systems. The solid red arrow illustrates the decay mechanism of the ground state of ${}^7\text{H}$ which is expected to be the “true” $4n$ emission. The dotted blue arrows illustrate the decay mechanism of the higher excitations in ${}^7\text{H}$, and the suggested in this work sequential decay of ${}^6\text{H} \rightarrow {}^5\text{H}(\text{g.s.}) + n \rightarrow {}^3\text{H} + 3n$.

$E_T \sim 5$ MeV — the energy attributed in Ref. [13] to the $3/2^+ - 5/2^+$ doublet of the first excited states in ${}^5\text{H}$. The expected $1/2^+$ ${}^5\text{H}$ g.s. with $E_T \sim 1.8$ MeV is practically not populated. This situation is quite consistent with the simplistic expectation of the ${}^6\text{H}$ structure as a proton hole in ${}^7\text{He}$ — the excited ${}^6\text{He}(2^+)$ configuration is known to dominate the ${}^7\text{He}$ g.s. structure.

The green line histograms in all three panels of Fig. 3 are formed by the low-energy ${}^5\text{H}$ events with $E_T({}^5\text{H}) < 9$ MeV. It can be found from Fig. 3 (b) that the ${}^5\text{H}$ peak population do not show strong correlation with the population of the low-lying resonant states of ${}^5\text{He}$. So, the hypothesis about the ${}^2\text{H}({}^8\text{He}, {}^5\text{He}){}^5\text{H}$ triton transfer reaction contribution can be rejected. In contrast, it can be found from Fig. 3 (c) that the correlation of the low-lying ${}^5\text{H}$ peak with the low-lying ${}^6\text{H}$ peak is unexpectedly strong: the higher excitations of ${}^6\text{H}$ practically do not populate the low-lying ${}^5\text{H}$ states. Thus, we conclude that the events of low-energy part of the ${}^5\text{H}$ MM spectrum are connected with the deuteron transfer reaction ${}^2\text{H}({}^8\text{He}, {}^4\text{He}){}^6\text{H}$ and the subsequent ${}^6\text{H} \rightarrow {}^5\text{H}(\text{g.s.}) + n \rightarrow {}^3\text{H} + 3n$ decay.

5 Results

In this work we investigated the ancillary reaction channels which may impede the interpretation of the ${}^2\text{H}({}^8\text{He}, {}^4\text{He}){}^6\text{H}$ reaction data. The obtained results confirm those reported in Ref. [7] and provide more evidence for the suggested structure and decay mechanism of both ${}^6\text{H}$ and ${}^7\text{H}$ systems.

The analysis of the possible background channels confirms the nature of the low-energy ${}^6\text{H}$ MM spectrum presented in Ref. [7]. For the first time the spectrum of ${}^5\text{H}$ produced in the ${}^6\text{H}$ decay was reconstructed. The obtained strong correlation between the low-energy spectra of ${}^6\text{H}$ and ${}^5\text{H}$ makes the first experimental evidence that

the notion about the two-step ${}^6\text{H} \rightarrow {}^5\text{H}(\text{g.s.}) + n \rightarrow {}^3\text{H} + 3n$ decay is correct. Although, the obtained ${}^5\text{H}$ MM energy resolution did not allow us to resolve it into the known ${}^5\text{H}$ structure with the ground state at 1.8 MeV [11–13]. The presented strong correlation of the ${}^5\text{H}$ and ${}^6\text{H}$ spectra reproduces the conclusion of the absence of the ${}^6\text{H}$ resonances for $E_T < 3.5$ MeV. The latter, in conjunction with the observation of the ${}^7\text{H}$ g.s. at 2.2(5) MeV, increases the reliability of the level data presented in work [7] for the heavy hydrogen isotopes, see Fig. 4.

The reliable determination of the decay schemes for the superheavy ${}^6\text{H}$ and ${}^7\text{H}$ isotopes is a long-standing experimental challenge, and this work represents an important step towards the resolution of this problem.

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