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 $^4\text{H}$ isotope. A broad bump was observed in the measured $^4\text{H}$ 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 $^4\text{H}$ 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 $^4\text{H}$ resonances at energy $E_F = 0 - 3.5$ MeV above the $^3\text{H}+3\text{n}$ decay threshold. In addition the first strong experimental evidence is given that the $^6\text{H} \rightarrow ^3\text{H}+n \rightarrow ^3\text{H}+3\text{n}$ 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 mechanisms of their ground and excited states. However, the detection of the same products as those of the missing mass (MM) spectrum of $^6\text{H}$ reported in work [1–5] 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 AMeV $^8\text{He}$ 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 $^6\text{H} \rightarrow ^3\text{H}+3\text{n}$ 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 $\Delta E-E$ telescopes were used: the side assembly of the three (20 $\mu$m, 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 $^4$He nuclei with energy $\geq 5$ MeV) emitted from the target in the laboratory angular range between $8^\circ$ and $26^\circ$, 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 $^6$H

The first question to be solved is whether the low-energy part of the $^6$H MM spectrum, see the $E_T$ spectrum in Fig. 1 (a), can be caused by some other reaction mechanism. The $^6$H events were identified by the detection of the $^4$He recoil, emerging from the $^2$H($^8$He,$^4$He)$^6$H reaction, and the $^3$H decay product of the $^6$H 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 $^3$H states, but not in some different reaction channels, where they appear in the $^3$H+n+n+n+$^4$He group? In reality the final state products of the of the $^3$He+$^2$H interaction can be partitioned also as $[^1H+n+n]+[^4He+n]$, $[^1H+n]+[^4He+n+n]$ or $[^1H]+[^4He+n+n+n]$. These outcomes correspond to the reactions $^2$H($^8$He,$^5$He)$^5$H, $^2$H($^8$He,$^6$He+$^3$He)$^4$H, and $^2$H($^8$He+$^3$He)$^4$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 $^6$H spectrum.

The $^7$He system was reconstructed assuming that $^3$H is the nucleus formed immediately in the $^2$H($^8$He,$^3$He)$^4$H reaction. The $^3$He 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 $^4$He kinetic energy in the $^7$He CMS with the $^7$He MM energy).

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

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

- (i) The $^3$He g.s. resonance is expected to be found with $E_T(^3$He$) \sim 0.9$ MeV. We really see a strong indication of this resonant state in the derived spectrum of $^3$He.
- (ii) The $^6$H low energy events are practically not correlated with the energy range of $^3$He where the resonant states are known to exist. Thus, the $^6$H spectrum can not be governed by the final state interactions connected with possible population of $^3$He in the $^2$H($^8$He,$^3$He)$^5$H reaction.

![Figure 1.](https://doi.org/10.1051/epjconf/202329009001)
Figure 2. (a) The $^6$H MM spectrum based on the $^4$He-$^3$H-$n$ coincidence events; the part of this spectrum at $E_T < 10$ MeV is given in green color. (b) The $^5$He invariant mass spectrum constructed from the $^4$He and neutron momentum vectors in the triple $^4$He-$^3$H-$n$ coincidence events.

The reconstruction of the $^2$H($^8$He,$^5$He)$^5$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 $^5$He and $^7$He are found to be negligible.

4 $^5$H populated in the $^6$H decay

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

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

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5 Results

In this work we investigated the ancillary reaction channels which may impede the interpretation of the $^5H(4^H,3^H)4^H$ reaction data. The obtained results confirm those reported in Ref. [7] and provide more evidence for the suggested structure and decay mechanism of both $^6H$ and $^7H$ systems.

The analysis of the possible background channels confirms the nature of the low-energy $^4H$ MM spectrum presented in Ref. [7]. For the first time the spectrum of $^5H$ produced in the $^4H$ decay was reconstructed. The obtained strong correlation between the low-energy spectra of $^6H$ and $^5H$ makes the first experimental evidence that the notion about the two-step $^6H\rightarrow^5H(\text{g.s.})+n\rightarrow^3H+3n$ decay is correct. Although, the obtained $^5H$ MM energy resolution did not allow us to resolve it into the known $^5H$ structure with the ground state at 1.8 MeV [11–13]. The presented strong correlation of the $^5H$ and $^6H$ spectra reproduces the conclusion of the absence of the $^4H$ resonances for $ET < 3.5$ MeV. The latter, in conjunction with the observation of the $^7H$ 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 $^6H$ and $^7H$ isotopes is a long-standing experimental challenge, and this work represents an important step towards the resolution of this problem.

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