Resonant states in $^7$H. I. Experimental studies of the $^2$H($^8$He,$^3$He) reaction

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The extremely neutron-rich system $^7$H was studied in the direct $^2$H($^8$He,$^3$He)$^7$H transfer reaction with a 26 AMeV secondary $^8$He beam. Missing mass and center-of-mass (c.m.) angular distributions of $^7$H were reconstructed, as well as the momentum distribution of the $^7$H fragment in the $^7$H frame. In addition to the investigation reported in Ref. [1], we carried out another experiment with the same beam but a modified setup. In the second experiment the cross-check of the experimental calibration was performed by the studies of the $^2$H($^8$Be,$^3$He)$^7$Li reaction. There is a solid experimental evidence of the population of two resonant states in $^7$H at energies of 2.2(5) and 5.5(3) MeV relative to $^7$H+4$n$ threshold. Also, there are indications on the resonant states at 7.5(3) and 11.0(3) MeV. Based on the energy and angular distributions the weakly populated 2.2(5) MeV peak is assigned as the $^7$H ground state. It is highly plausible that the firmly ascertainment 5.5(3) MeV state is the $^5/2^+$ member of the $^7$H excitation doublet, built on the $^2^+$ configuration of valence neutrons. The 7.5 MeV state can be a member of this $5/2^- – 3/2^+$ doublet of excited states, which could not be resolved in Ref. [1] and which consequently appeared in [1] as a 6.5 MeV state of $^7$H.

I. INTRODUCTION

Exploration of exotic nuclei located near the neutron drip line has led to several remarkable discoveries, such as the neutron haloes and skins, shell quenching, and the appearance of new magic numbers. Going beyond the neutron drip line we enter the region where the conditions of “true” 4$n$ emission are probably valid for some nuclei, see the $^7$H example in Fig. 1. The attribute “true”, applied in particular to the 4$n$ decay, emphasizes the absence of sequential neutron emission, and that the decay is possible only via the five-body core+4$n$ simultaneous emission. The true 4$n$ decay of $^7$H, $^{28}$O, and some other nuclei with enormous neutron excess was the subject of detailed consideration in Ref. [2]. By applying the formalism based on the simplified three-body and five-body Hamiltonians, the authors showed that the few-body dynamics of the 2$n$ and 4$n$ emission leads to barriers which increase rapidly with the increase of number of emitted particles. Therefore, the prospects to detect extremely long-lived resonances open for true 4$n$ decay seem to be more promising than for 2$n$ decay. The discovery of the so far unexplored phenomenon of true 4$n$ emission is a task of fundamental importance. The $^7$H nucleus is evidently a suitable candidate for the outlined investigations.

In this work, we use the $E_T$ notation for the decay energy above the corresponding threshold, e.g., $^3$H+4$n$ for $^7$H or $^3$H+2$n$ for $^5$H. The experimentally determined missing mass (MM) energy is calibrated in the same way.

A. History of the research subject

The first theoretical estimations of Baz’ and coworkers [6] predicted that the $^7$H nucleus could be bound. However, the experiments [8] searching for $^7$H formed in the $^7$Li($\pi^-, \pi^+$) reaction gave negative results. Also, the experiment [10] aimed to detect this nucleus among the ternary fission products of $^{252}$Cf provided no evidence.

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The observation of the ground state resonance in $^5\text{H}$ revived theoretical interest to the possible existence of a low-lying $^7\text{H}$ state near the $^3\text{H}+4n$ decay threshold. Calculations using the seven-body hyperspherical functions formalism evaluated the $^7\text{H}$ g.s. energy as $E_T \approx 3$ MeV. In Ref. [10], the binding energy of the $^7\text{H}$ ground state was estimated to be $\sim 5.4$ MeV, which means that this resonance state is expected at about 3 MeV above the $^3\text{H}+4n$ decay threshold. The authors emphasized that the $^7\text{H}$ ground state should undergo the unique five-body decay into $^3\text{H}+4n$ with very small width. The phenomenological estimates in Ref. [12] pointed to $E_T \sim 1.3 - 1.8$ MeV. The calculations within antisymmetrized molecular dynamics provided $E_T \sim 7$ and $E_T \sim 4$ MeV, respectively.

The first experimental evidence of the $^7\text{H}$ g.s. resonance was furnished in the study of the $^1\text{H}(^8\text{He},2p)^7\text{H}$ reaction in Ref. [11]. The MM spectrum of $^7\text{H}$ obtained in that work showed a sharp increase starting from the $^3\text{H}+4n$ threshold. Nevertheless, this interesting observation did not allow the authors to give quantitative information about the resonance parameters because of low energy resolution (of $\sim 2$ MeV) and complicated background conditions.

A sophisticated approach was used in work [12] carried out by the ACCULINNA fragment-separator group. By bombarding a very thick (5.6 cm) liquid deuterium target with a beam of 20.6 AMeV $^8\text{He}$ projectiles, the authors searched for the quasielastic $^7\text{H}$ nucleus produced in the $^2\text{H}(^8\text{He},^3\text{He})^3\text{He}$ reaction within $0^\circ - 50^\circ$ c.m. angles and with a lifetime longer than 1 ns. No events of the $^7\text{H}$ with such a lifetime was found. This gives a very low limit for the cross section of the $^2\text{H}(^8\text{He},^7\text{H})^3\text{He}$ reaction, $\sigma < 3$ nb/sr, which is by several orders of the magnitude less than the expected value. Lifetime estimates made in Ref. [12] led to the conclusion that the obtained limit of the $^7\text{H}$ production cross section implies a lower limit of $E_T \gtrsim 50 - 100$ keV for its decay energy. This indicates that the only realistic approach to the $^7\text{H}$ problem is the search for the shorter-lived resonance states of this nucleus in the five-body $^3\text{H}+4n$ continuum.

Results obtained in the study of stopped $\pi^-$ absorption by the $^3\text{Be}$ and $^1\text{H}$ targets were reported in Ref. [13]. The count rate of the $p^+\text{He}$ products emitted in the $^{11}\text{B}(\pi^-p)^7\text{H}$ reaction was very low. The authors concluded that the question of the possible existence of $^7\text{H}$ states, both near the $^3\text{H}+4n$ threshold and in the region of higher excitation energy remains open [16].

The $^7\text{H}$ existence was investigated by the authors of Refs. [17, 18] in the transfer reaction $^{12}\text{C}(^8\text{He},^{13}\text{N})^7\text{H}$. Although in this work only seven events could be attributed to the desired reaction channel, a very narrow $^7\text{H}$ resonance was announced, with $E_T = 0.57^{+0.42}_{-0.21}$ MeV. It should be pointed out that no actual channel identification was possible in this experiment. The interpretation is essentially based on the assumption that only the $^7\text{H}$ g.s. is populated in this reaction. In reality, the population of $^7\text{H}$ is also possible in this experiment. In addition, the reactions $^{12}\text{C}(^8\text{He},^{14}\text{N})^9\text{H}$ and $^{12}\text{C}(^8\text{He},^{15}\text{N})^{10}\text{H}$ may mock up the detection of $^7\text{H}$.

The authors of Ref. [19] investigated the $^2\text{H}(^6\text{He},^3\text{He})^7\text{H}$ reaction. They concluded that there was some indication of a $^7\text{H}$ resonance state in the measured MM spectrum at $E_T \sim 2$ MeV. It is notable, however, that their experimental energy acceptance covered only $E_T \lesssim 5$ MeV in the $^7\text{H}$ excitation spectrum. Within this narrow energy window, the $^7\text{H}$ spectrum from the $^2\text{H}(^8\text{He},^3\text{He})^7\text{H}$ reaction looks very similar to the spectrum of the carbon-induced background from the CD$_2$ target, which made the authors cautious about their observations.

The next attempt to discover $^7\text{H}$ using the $^2\text{H}(^8\text{He},^3\text{He})^7\text{H}$ reaction was made in Ref. [20] at RIKEN. No indication on the resonance peak was revealed in the measured $^7\text{H}$ MM spectrum. However, some peculiarity was found in this spectrum at $\sim 2$ MeV above the $^3\text{H}+4n$ decay threshold. The authors reported a value of about $30 \mu$b/sr in c.m. for the cross-section of the reaction populating the low-energy part in the $^7\text{H}$ spectrum. In addition, they noted that the $^7\text{H}$ spectrum demonstrates a peculiarity at about 10.5 MeV that could be a manifestation of a $^7\text{H}$ continuum excitation.

**B. Presented experimental results**

One may conclude, that the best approach to studies of the unstable $^7\text{H}$ nucleus suggests the use of the $^2\text{H}(^8\text{He},^3\text{He})^7\text{H}$ reaction. But the low intensity of the $^8\text{He}$ beam produced at the ACCULINNA separator allowed us only to put a limit of the cross section of the $^2\text{H}(^8\text{He},^3\text{He})^7\text{H}$ reaction near the $^3\text{H}+4n$ de-
The new radioactive-beam separator ACCULINNA-2 commissioned at FLNR in 2017 provides the $^8\text{He}$ beam with intensity up to $\sim 10^5$ pps, which is sufficient for the challenging experiments aimed at $^7\text{H}$.

The first results of our studies of the $^7\text{H}$ spectrum were published as a Letter [1]. We confidently observed the resonant structure at $E_T = 6.5(5)$ MeV interpreted as an overlapping doublet of $3/2^+$ and $5/2^+$ states (this is the $2^+$ excitation of the valence nucleons coupled with the $1/2^+$ spin-parity of the $^3\text{He}$ core). There was a group of events at $\sim 2$ MeV which was considered as a candidate for the $^7\text{H}$ $1/2^+$ ground state with $E_T = 1.8(5)$ MeV. However, due to the low statistics (5 events), there was no complete confidence in such an interpretation. The estimated cross section of the reaction channel populating this possible state appeared to be quite low. The value $d\sigma/d\Omega \sim 25$ mb/sr was derived from the five $^7\text{H}$ g.s. counts detected in the c.m. angular range $19^\circ - 27^\circ$. The bump in the spectrum at $E_T > 10$ MeV was fitted by assuming a resonance contribution at $E_T = 12$ MeV with $\Gamma = 4$ MeV. Such an interpretation was quite cautious since this bump is close to the experimental cutoff of the measured $^7\text{H}$ MM spectrum.

In the present work we further elaborate the data analysis of [1] (“experiment 1”). We also present the data of a new experiment (“experiment 2”) performed with the same beam, but with an improved setup. We present new data inferring more information about the excited resonant state in $^7\text{H}$ [1] and to get clear results that would reliably characterize the $^7\text{H}$ ground state. In particular, we extend the measured spectrum to the smaller c.m. angular range. The accumulated number of $^7\text{H}$ events in the new dataset is more than three times larger, than in the first run. The calibration of the $^7\text{H}$ missing mass spectrum is independently verified by the $^4\text{He}(^{10}\text{Be},^{3}\text{He})^7\text{Li}$ reaction carried out in a dedicated experiment with $^{10}\text{Be}$ beam. The new data nicely confirms the spectrum reported in Ref. [1]. Based on the theoretical estimates and Monte-Carlo (MC) simulations, provided in this and in the forthcoming work [22], we provide a solid experimental evidence of the population of resonant states in $^7\text{H}$ at $2.2(5)$ and $5.5(3)$ MeV. There is also some evidence of the resonance states at $7.5(3)$ and $11.0(3)$ MeV.

II. EXPERIMENTAL SETUP

The experiments were carried out at the Flerov Laboratory of Nuclear Reactions (FLNR), JINR, with the use of Radioactive Ion Beam (RIB) produced by the ACCULINNA-2 fragment separator. The primary beam of $^{11}\text{B}$ ($\sim 1$ µA, 33.4 AMeV) or $^{15}\text{N}$ ($\sim 0.5$ µA, 49.7 AMeV) ions accelerated by the U-400M cyclotron bombarded a 1 mm thick beryllium production target installed at the initial focal plane of the separator. As a result of fragmentation and subsequent separation, the $^{8}\text{He}$ and $^{10}\text{Be}$ RIB’s were obtained with intensity $\sim 10^6$ ppspps, and their energies in the middle of $D_2$ target spread within $\pm 7\%$ and $\pm 2.5\%$ around the most probable values of 26 and 42 AMeV, respectively.

The sketch of the setup is shown in Fig. 2. The energy values of individual RIB projectiles were determined with precision of $\sim 0.2\%$ by means of the Time-of-Flight (ToF) detector. The two BC404 plastic scintillators placed at a ToF base of 12.3 meters allowed for identification of the RIB projectiles by the $\Delta E$-ToF method [24]. Both RIB’s, $^8\text{He}$ and $^{10}\text{Be}$, were well separated with purities better than 90% and 80%, respectively.

The beam tracking was arranged by a pair of the Multi-Wire Proportional Chambers (MWPC) placed at distances of 28 and 81 cm upstream of the gaseous target. This allowed for determination of the RIB interaction points in the target plane with a 1.8 mm precision. Also, using this beam-tracking installation we determined the inclination angles of individual RIB projectiles to the ion optical axis with an accuracy of $\sim 0.15$ degrees.

The 4 mm thick target cell, equipped with the 6 µm thick and 24 mm diameter stainless-steel entrance and exit windows, was cooled down to 27 K and filled with the deuterium gas up to a pressure at which the target thickness was $\sim 3.7 \times 10^2$ cm$^{-2}$. The cell was concealed in a screened volume having a pair of 3.5 µm thick aluminum-backed Mylar windows and kept cooled to the same temperature to ensure thermal protection. The entrance/exit target windows, deformed by the gas pressure, took the near-lenticular form, so that the maximum target thickness turned out to be 6 mm.

The part of the experimental setup described above was common for both experiments investigating the $^7\text{H}$ MM spectrum populated in the $^2\text{H}(^{8}\text{He},^{3}\text{He})^7\text{H}$ reaction. The features of the setups employed in individual experiments will be described in subsections below. The main contribution to the $^7\text{H}$ MM energy resolution is the accuracy of the recoil $^{3}\text{He}$ energy determination, mainly caused by the uncertainty of the interaction point $Z$-coordinate in the target volume. For the purposes of the data analysis, it was assumed that the interaction...
point was in the middle plane of the target. To ensure a homogeneous thickness of the target, only events when the RIB hit a central part of the target with a circular shape of the diameter of 17 mm were taken into account. This selection ensured also the rejection of the reactions with the material of the target frame.

A. Experiment 1

Two identical $\Delta E$-E-E single-sided silicon-detector telescopes provided the measurement of the $^3$He recoil nuclei emitted from the target between $8^\circ$ and $26^\circ$ in laboratory system, see Fig. 3. The telescopes located 166 mm downstream the target consisted of three layers of silicon strip detectors (SSD). The 20-micron-thick SSD with a sensitive area of $50 \times 50$ mm$^2$ was divided into 16 strips, the second and the third layers were created by the two identical 1-mm thick SSDs ($60 \times 60$ mm$^2$ with 16 strips).

The central telescope was installed at the beam line at the distance of 280 mm behind the target. It was intended to detect tritons emitted with high energies at the angles $< 9^\circ$ in the laboratory system as a result of the $^7$H decay. The telescope consisted of one 1.5 mm thick double-sided SSD ($64 \times 64$ mm$^2$, with 32 strips on each side) followed by a square array of 16 CsI(Tl) crystals. The crystals had a cross section of $16.5 \times 16.5$ mm$^2$ and thickness 50 mm each, which allowed to stop all charged particles in the sensitive volume of the telescope. Each crystal was covered with a 3.5 $\mu$m-thick aluminized Mylar on its entrance and was coupled with its Hamamatsu R9880U-20 photomultiplier tube (PMT) by the optical grease. In order to increase the collection of light and to avoid light cross-talks, each crystal was wrapped in a 100 $\mu$m-thick VM-2000 reflector.

The $^7$H MM spectrum was reconstructed from energies and angles of the $^3$He recoil particles detected in coincidence with the $^3$H fragments. The $^7$H MM spectrum was obtained from 119 $^3$H-$^3$He coincidence events. The 1.1 MeV energy resolution of the $^7$H MM spectrum was much better as compared to the previous works

B. Experiment 2

The most important task of the new experiment, studying the same $^2$H($^4$He,$^3$He)$^3$H reaction, was to increase the statistics obtained in the experiment 1 and to expand the measured angular range of the $^3$He recoils to lower values in the laboratory system. For this purpose, the detector setup was modified, see Fig. 4. The new $^3$He telescope assembly was installed at a distance of 179 mm from the target. It consisted of four identical $\Delta E$-E-E telescopes made of the same SSD’s as described in Section II A. The angular range covered by these telescopes for the $^3$He recoil nuclei was extended up to the range from $\sim 6^\circ$ to $\sim 24^\circ$ in the laboratory system.

The tritons originating from the $^7$H were emitted in the experiment 2 within more narrow cone in comparison with the experiment 1. Therefore, the central telescope, the same as in the experiment 1, was placed at a distance of 323 mm from the target. As a result of these modifications, we could expect that the $^7$H yield is increased by a factor of $\sim 2.5$. Based on the results of the first experiment, we expected that $\sim 300$ of $^7$H events should be collected in our experiment taking into account the expected larger cross section for the $^7$H population at smaller angles. This estimate corresponds well to the actually collected statistics of 378 events.

The setup of experiment 2 also included the neutron spectrometer, made of 48 organic scintillator modules. The spectrometer detects neutrons by measuring the light produced by the interaction of the recoil charged particles (mainly protons) within the scintillator. It was located at zero angle in approximately 2 meters behind the reaction chamber. The distance between the neighboring modules was approximately 12 cm, which allowed to cover most of the forward angles, see Fig. 2. The sensitive part of each module was cylinder made of stilbene crystal, C$_{14}$H$_{12}$. Each cylinder had 8 cm diameter and 5 cm thickness and was oriented by its axis to the target. Each crystal, covered with reflective MgO powder, was inserted into the 0.5 mm thick aluminum housing and connected to the PMT by the glass window and
optical grease. Two types of PMT were used: Philips Photonis XP 4312 and ET-Enterprise 9822B. In order to decrease the background signals produced by charged particles or $\gamma$-rays, PMT-crystal systems were put into the steel tubes with 0.5 mm entrance windows.

C. Reliability of channel identification and background conditions

The background reduction and unambiguous reaction channel identification were the primary objectives of the experiment 1 because of the low statistics obtained in the experiment 1 (5 ground state candidate events for the 1.8 MeV state and $\sim$ 25 events for the 6.5 MeV state). The most of the discussions of this work are based on the double-coincidence $^3$He-$^3$H events. The quality of $^3$H and $^3$He identification is illustrated in Figs. 5 and 6, respectively.

Operation of the central $^3$H telescope is fairly standard, and the provided particle identification is extremely reliable. In contrast, a sophisticated analysis procedure was developed for side telescopes. A very thin 20 $\mu$m $\Delta E$ detector is needed for the $^3$He identification, since its energy can be as small as 7 – 8 MeV. Because of fabrication inhomogeneity, inherent for such a thin silicon plates, the calibration thickness maps were determined for each of these thin detectors. Fig. 9 illustrates the particle identification, which was actually implemented for each strip separately, but even in this presentation it looks quite convincing.

Extremely strong background cleaning and channel identification for $^7$H is provided by additional coincidences with neutrons. Statistics of these measurements is extremely low, and they can be used in Fig. 10 (c) just to demonstrate the compatibility of these data with a suggested interpretation.

Measurements with the empty target are standard approach to demonstrate directly the background conditions of the experiment, see Figs. 7 (a,b) and 10 (b). The measured empty target beam-integral values made $\sim$ 10% and $\sim$ 15% of the total beam-integral in the experiments 1 and 2, respectively. In the experiment 1 only 3 empty target events were recorded, which allows to evaluate the total background contribution in this experiment as $\sim$ 15%. In the experiment 2 this type of background is evaluated to be considerably smaller, i.e. $\sim$ 8%. In the distribution of empty target events, see Fig. 7(a), a “dangerous region” can be spotted with $7.5 < E_T < 10.5$ MeV. Fortunately, these events are all concentrated on a certain angular range $18^\circ < \theta_{nm} < 35^\circ$, see Fig. 7 (b). Concentration of empty target events in the narrow “dangerous region” can hardly be explained by statistical fluctuations, see the distribution of the complete data in Fig. 7 (c). This situation motivates us to avoid the “dangerous region” in the interpretation of the data and enhance the confidence in the rest of the data.

Here we should remind briefly the situation with the reaction-channel identification and background conditions in the previous experiments on proton removal from $^8$He. In experiment 11 only the missing mass of $^7$H was available, and background conditions were very poor: the MM spectrum extended into negative energy region down to $-20$ MeV, and more than 90% of the data were related to the background in the analysis. In experiment 19 also only the missing mass of $^7$H was available, and background conditions were poor: the MM spectrum extended into the negative energy region down to $-3$ MeV, and $\sim$ 75% of the data were related to the background reactions originated from the carbon component of the CD$_2$ target. In experiment 20 the missing mass spectrum...
of $^7$H was augmented by the requirement of the $^3$He-$^3$H coincidence, which drastically improved the background conditions. Still, some evidence of the background is visible, since the MM spectrum extends into the negative region beyond the values implied by the energy resolution of the experiment. In our experiments, the coincidence with $^3$H and reconstruction of the $^3$H momentum allow for using the “kinematical triangle” as a selection gate, which reduces significantly the MM background, see Fig. 10 (a,d).

D. Experimental resolution

The complete Monte-Carlo simulations of the experimental setup were performed and extensively used in the interpretation of the data. Here we address the question of experimental resolution. The Fig. 8 shows MC simulations for the angular $\theta_{cm}$ vs. energy $E_T$ distributions defined by the product of $\delta$-functions at the corresponding energy and angle. The projections of the plotted structures either on the energy or the angle axis reflect the respective distributions at a certain place of the kinematical plane, see Table III. It is possible to find out that at $\theta_{cm} \rightarrow 0$ the energy resolution is defined mainly by the target thickness. The relative importance of this factor decreases with increase of the $^7$H MM energy: the energy resolution is changing from $\sim$ 800 keV at $E_T = 2.2$ MeV to $\sim$ 250 keV at $E_T = 14$ MeV. The angular resolution at $\theta_{cm} \rightarrow 0$ is defined by the beam tracking precision and granularity of the $^3$He telescopes. It is clear from Fig. 8 that for large $\theta_{cm}$ the MC “spots” are tilted and, thus, both the energy and the angular resolutions aggregate the two mentioned factors. Consequently, the best resolution for the $^7$H g.s. MM energy is obtained for small center-of-mass reaction angles, and for the larger angles it considerably degrades.

E. Calibration $^2$H($^6$Be,$^3$He)$^3$Li reaction

The proton pick-up reaction ($d$, $^3$He) was studied with a 42 AMev $^{10}$Be secondary beam in order to test the reliability of the obtained experimental data on $^7$H system, to control calibration parameters, and to get an experimental estimate of the $^7$H MM resolution. These measurements were performed just after the experiment 1 and all conditions were kept the same. The excitation

FIG. 7. Empty target correlated spectra $E_{3H}$ vs. $E_T$ for $^7$H (a) and $\theta_{cm}$ vs. $E_T$ (b) for $^7$H in the experiment 2. The vertical gray dotted lines indicate assumed positions of the $^3$H resonant states, see Fig. 10. Panel (c) shows all the data of experiment 2 in the plane $\theta_{cm}$ vs. $E_T$. In all panels the red dots show the distribution for the events within the “kinematical triangle”, see Fig. 10; additional black dots show the rest of the data. The vertical gray dotted lines indicate assumed positions of the $^3$H resonant states. The vertical hatched area contains events either from “asymmetric” 5.5 MeV state or from the 5.5 – 7.5 MeV doublet. The line $E_{3H} < 2/7E_T$ in panel (a) is discussed in Section III B 2.
FIG. 9. Excitation spectrum of $^9$Li measured in the $^2$H($^{10}$Be,$^3$He)$^9$Li reaction. The insert shows the part of the $^9$Li spectrum near the ground state. The red curve represents the Monte-Carlo calculation of the $^9$Li(g.s.) taking the parameters of the experimental setup.

The solid histogram in Fig. 9 shows a well-pronounced peak corresponding to the ground state of $^9$Li populated in the $^2$H($^{10}$Be,$^3$He)$^9$Li(g.s.) reaction. On the right slope of this peak the population of not well-resolved first excited state of $^9$Li ($E^* = 2.69$ MeV) is also observed. The insert in Fig. 9 shows the part of $^9$Li spectrum near the ground state. Red curve demonstrates the Monte-Carlo calculation for the $^9$Li(g.s.) using parameters of the experimental setup.

It is clearly seen that the MC simulation reproduces quite well the shape of the $^9$Li(g.s.) peak demonstrating the resolution of $\sim 2.2$ MeV (FWHM). The corresponding calculations of the missing mass resolution of $^7$H at energy near 2 MeV gave FWHM $\sim 1.1$ MeV (see discussion in Section III). The reason for this $\sim 2$ times better resolution in $^7$H experiment is caused by the larger energies of $^3$He recoils, as compared to the $^2$H($^{10}$Be,$^3$He)$^9$Li reaction, and, therefore, the smaller energy losses in the target. It is also a demonstration that the target thickness makes the main contribution to the energy resolution in this energy range. The cross-section values of $^9$Li derived from the data of the $^{10}$Be run is shown in Figure 9.

The survey of the $^7$H spectra obtained by using the missing mass method in this work, as well as in Refs. [1, 20], is given in Fig. 10. From these spectra we assign the ground state at 2.2(3) MeV, the first excited state at 5.5(3) MeV, and the higher-energy resonances at 7.5(3) and 11.0(5) MeV.

At first glance, the resonance features in the $^7$H MM spectrum in Fig. 10(b) are not very pronounced. For that reason we provide first a general note about the observation of resonant states in a spectrum either containing broad overlapping states or having important continuous background contribution, and then turn to a detailed inspection of our data.

A. General note on resonant states observations

Let us consider one selected spectrum from Fig. 10. Is it possible to interpret it without assumption about the population of resonant states? To answer this question in the first approximation, different representations of the $^7$H MM spectrum are shown in Fig. 11 with own binning factors and bin offsets. The $^7$H decay events with $\theta_{cm} < 18^\circ$ were selected, see Fig. 11(c), and we accordingly split the data in two parts in Fig. 11. One motivation for $\theta_{cm} = 18^\circ$ selection is illustrated in Fig. 5: the best energy resolution of the $^7$H spectrum is obtained for the small center-of-mass reaction angles, and it considerably deteriorates at larger angles. The selected $\theta_{cm} < 18^\circ$ range is also consistent with the cutoff needed for elimination of a “dangerous background region”, specified in the experiment with empty target, see Fig. 7(c). For $\theta_{cm} < 18^\circ$ the three resonant structures at 2.2, 5.5, and 11 MeV are well identified in all representations in Fig. 11. Evidence of the 7.5 MeV peak may be statistically insignificant in some representations, but it is typically present. So, the assumed resonant structures are at least not artefacts of the histogram arrangement. The spectra with the $\theta_{cm} > 18^\circ$ selection gate are dominated by a smooth “phase volume”-like contribution. Only the 5.5 MeV peak can be clearly seen on the top of the smooth component. Some resonance contributions can be suspected at energies $E_T > 10$ MeV, but their manifestation on the top of the large smooth component is statistically insignificant.

### TABLE I. Experimental resolution in the second experiment as a function of $^7$H MM energy and center-of-mass angle $\theta_{cm}$ based on the MC simulations Fig. 5.

| $E_T$ (MeV) | 2.2 | 5.5 | 11 | 14 |
|-------------|-----|-----|----|----|
| $\theta = 10^\circ$ | 0.95 | 2.2 | 0.73 | 2.3 | 0.48 | 2.5 | 0.38 | 2.8 |
| $\theta = 20^\circ$ | 1.10 | 1.6 | 0.93 | 1.8 | 0.64 | 2.2 | 0.52 | 2.6 |
| $\theta = 30^\circ$ | 1.13 | 1.2 | 0.99 | 1.3 | 0.77 | 1.8 | 0.69 | 2.0 |

$\sim 7-10$ mb/sr at forward angles in the c.m. system were deduced from these data for the reaction populating the $^9$Li ground state.

Thus, the data obtained with the $^{10}$Be beam provide an independent cross-check of the MM spectrum calibration in the experiment 2 and validation for the developed MC simulation framework. This is an important support of the data and interpretation of experiment 2, which was not available for experiment 1.
Then we turn to statistical analysis. It shows that the description of each spectrum in Fig. 10 merely by some smooth underlying continuum is possible with values of root-mean-square deviation (RMSD) for the spectrum in Fig. 10(f) with RMSD ∼ 1, for the spectrum in Fig. 10(e) with RMSD ∼ 1 − 2, and for the spectra in Figs. 10(b,c) with RMSD ∼ 2 − 3. These are statistically tolerable values of the mismatch, which does not exclude a “smooth scenario”. However, the following general points should be clarified.

If the real spectrum of $^7$H is smooth, then, due to the small-statistics data, a purely random mockup of several peaks is possible. In such a case data with very large statistics (e.g. $10^3 − 10^4$ events) are required in order to exclude such accidental “resonances” with a high confidence level. In contrast, if the real $^7$H spectrum contains narrow resonant peaks, then reliable identification of these resonant states becomes possible even with few measured decay events. We assume that the $1/2^+$ g.s. of $^7$H and the lowest excitations, such as $5/2^+–3/2^+$ doublet are located at $E_T < 10$ MeV. The width estimates for such $^7$H states provided in the related article [23] show that the widths are likely to be quite small with the expected values of $\Gamma \lesssim 1$ MeV. So, the narrow resonant-state scenario seems to be physically reasonable and even unavoidable at least for $E_T < 10$ MeV.

One can see in Fig. 10 that the same peaks may are spotted in all three experimental datasets of the $^2$H($^6$He,$^3$He)$^7$H reaction. The individual statistics of the datasets of the order 100 − 400 events can not exclude a pure statistical origin of these peaks in each case. However, it is extremely improbable that the same statistical artefacts could arise in the three different, totally independent experiments. This is a strong general argument supporting the data interpretation of this work. Below we provide an in-depth view in different aspects inherent to each structure and also demonstrate that all these aspects can be interpreted in a consistent way.

B. Group of events at 2.2 MeV

The events with $E_T < 3.2$ MeV were selected as candidates to represent the $^7$H ground state. There are 9 such events with the mean energy value of 2.2 MeV and the dispersion of 0.6 MeV. These values agree well with the results of experiment 1 reported in Ref. [1], where the $^7$H g.s. energy $E_T = 1.8(5)$ MeV was obtained. The events are well separated (there is ∼ 0.5 MeV gap) from nearest event connected with the higher $^7$H excitation. There are 4 possible reasons to get these events here: (i) background events, (ii) “contamination” by events from higher excitations of $^7$H, (iii) some smooth phase-space distribution, (iv) narrow resonant state. We insist on option (iv), but we have to comment on the other points as well.

(i) Possible background contribution in the $E_T$ region of interest can be estimated based on the empty target
measurements. No background events were observed in proximity, see Fig. 11 (a,b). Another way is to estimate it from the density of background counts beyond the kinematical triangle in Fig. 11 (a). Here we can expect ~1 background event in the 2.2 MeV group.

(ii) The observed width of the 2.2 MeV event group is assumed to be entirely defined by the energy resolution of the experiment. This is true even if the intrinsic width of this state is larger by a factor 100 − 500 as compared to the theory estimate giving $\Gamma \lesssim 1$ keV for the $^7$H g.s. [23].

The discussion of the energy profiles of the $^7$H first excited state is provided in the next Section and in Ref. [23]. Various theoretical estimates agree that there should be an empty “window” between the ground state and the first excited state from $E_T \sim 3$ MeV to $E_T \sim 4.0 − 4.5$ MeV. Any events emerging in this energy range should be connected with backgrounds or/and the poor missing mass resolution. The MC simulations of the $^7$H MM spectrum are shown in Fig. 11. They confirm that even the poorly populated $^7$H g.s. can be reliably separated from the “tail” of the first excited state, and that such a separation is the best at small c.m. angles of $^7$H.

(iii) The phase space for the true core+4n decay at $\sim 2.2$ MeV is

$$dW/dE_T \sim E_T^2.$$  \hspace{1cm} (1)

The ordinarily expected five body phase space is $\sim E^5$, but antisymmetrization requirement among four neutrons modifies it to the formula [11], see [2]. At about $2.5 − 3$ MeV a turnover may occur from the true 4n emission to sequential emission via the $^5$H ground state (located at about $1.8$ MeV above the $^3$H+n+n breakup threshold [3, 16]). After that the dependence

$$dW/dE_T \sim E_T^2,$$  \hspace{1cm} (2)

is expected. In any case, the “phase space” behavior that can be expected for $^7$H is a strongly growing function of energy, not something smoothly rising from the threshold.

An additional support for the interpretation of the group of events at 2.2 MeV as a resonant state is provided by three types of distributions, which were analyzed for the events of the 2.2 MeV group: (i) $^7$H center-of-mass angular distribution, (ii) $^3$H energy distribution in the $^7$H frame, and (iii) $^3$H lab system angular distribution relative to the $^7$H flight direction. Statistics, which we have for the ground-state candidate events is very small. However, all the mentioned distributions demonstrate correlated character, expected for the $^7$H g.s. decay, in contrast with the casual behavior expected for background events.

1. $^7$H center-of-mass angular distribution

The center-of-mass angular distributions for the $^2$H($^8$He,$^3$He)$^7$H reaction are further discussed in Section III. Here we comment on the distribution of the 2.2 MeV event group.

In the $^7$H g.s. case, there is a gap between events from $9.5^\circ$ to $15.5^\circ$, see Fig. 12 (a). This feature is consistent with the observations of Ref. [1], where 5 g.s. candidate events were localized in the range $18^\circ < \theta_{cm} < 27^\circ$. Such observed angular distributions can be problematic from the point of view of theoretically predicted angular distributions because theory typically predicts the diffraction minimum at $\theta_{cm} \sim 16^\circ − 18^\circ$. Considerably lower values $\theta_{cm} \sim 13^\circ − 14^\circ$ are suggested by the data. If the latter is true, then the observed angular distribution provides important tip for the following problems.

(i) There was a problem pointed out in Ref. [1]: the g.s. angular acceptance of experiment 1 was high enough for $\theta_{cm} > 8^\circ$ [see black dotted curve in Fig. 12 (a)] to ensure the registration of few events in the angu-
lar range $\theta_{cm} \sim 8^\circ - 14^\circ$ (assuming diffraction minimum at $\theta_{cm} \sim 16^\circ - 18^\circ$). One may explain this fact if the diffraction minimum actually covers a range of $10^\circ < \theta_{cm} < 18^\circ$.

(ii) the DWBA/FRESCO calculations with standard parameters fail to provide the diffraction minimum at $\theta_{cm} \sim 13^\circ - 14^\circ$. Such an angle of the minimum might provide an evidence of the extreme peripheral character of the $^7$H g.s. population in the $^7$H($^6$He,$^3$He)$^7$H reaction. Such an extreme peripheral character of the reaction gives a natural explanation of the extremely low cross section observed for the $^7$H g.s. population ($\sim 25 \mu b$/sr within the angular range $\theta_{cm} \sim 17^\circ - 27^\circ$ [21]). See also Ref. [23] for extended discussion of this point.

How statistically significant is the $\theta_{cm} \sim 9.5^\circ - 15.5^\circ$ gap in the g.s. angular distribution? Let’s make a simple estimate: assume that the actual angular distribution is homogeneous, and experimental efficiency is constant and nonzero in the ranges $\theta_{cm} \sim 8^\circ - 26^\circ$ and $\theta_{cm} \sim 6^\circ - 24^\circ$ in the experiments 1 and 2, respectively. Then the estimated probability of non-population of the $\theta_{cm} \sim 9.5^\circ - 15.5^\circ$ range in both the experiments simultaneously is $\sim 0.5 - 1\%$. So, it is very unlikely that the experimentally observed patterns are generated by some featureless distribution because of statistical fluctuations. The interpretation by assigning the diffraction minimum at $\theta_{cm} \sim 13^\circ - 14^\circ$ is, thus, quite natural.

The best energy resolution of the $^7$H g.s. can be expected for the small-angle events from the first diffraction maximum. Indeed, by selecting 4 events with $\theta_{cm} < 10^\circ$ we obtain a bit different mean energy $E_T = 2.1$ MeV and dispersion of 0.55 MeV (compared to results with the complete data). The dispersions of the g.s. events for the small $\theta_{cm}$ ($0.55$ MeV) and for the complete data ($0.6$ MeV) are consistent with the MC estimated energy resolutions, see Table I.

2. $^3$H energy distribution in the $^7$H rest frame

The emission dynamics of the true 4n nuclear decay is still a completely unexplored phenomenon. Our data for the first time provide access to this type of information. The commonly expected energy distribution of the $^3$H fragments emitted at the $^7$H g.s. decay, has the shape of a 5-body “phase space”

\[
\frac{dW}{d\varepsilon} = \sqrt{\varepsilon(1-\varepsilon)^2}, \quad \varepsilon = \frac{E_{3H}}{4E_T},
\]

where $E_{3H}$ is the energy of $^3$H in the $^7$H rest frame. This distribution suggests that $\sim 92\%$ of events are located below $\varepsilon = 1/2$ and the mean $^3$H energy value $\langle \varepsilon \rangle = 1/4$. Moreover, a realistic energy distribution obtained in the 5-body calculations of Ref. [27] has even more correlated character, with $\langle \varepsilon \rangle \sim 0.21 - 0.22$ for $E_T \sim 2 - 3$, see Fig. [27] This happens because in the decay via emission of 4 neutrons, at least 2 additional excitation quanta in the “neutron part” of the WF are needed to enable the anti-symmetrization of the WF. In this distribution $\sim 95\%$ of events are located below $\varepsilon = 1/2$. The regions where the absolute majority of the “physical” events should residue
according to the above “phase space” argument are separated by the $E_{3\text{H}} = 2/7E_T$ lines in Figs. 7(a) and 10(a, d).

Thus, the events with $\varepsilon > 0.5 - 0.6$ should be connected either with some sort of background or with poor resolution for the reconstructed energy of $^3\text{H}$ in the center-of-mass of $^7\text{H}$, populated in the $^2\text{H}(^8\text{He}, ^3\text{He})$ reaction. The observed $^3\text{H}$ energy distribution for the expected $^7\text{H}$ g.s. events is shown in Fig. 13. This energy distribution is consistent with the expected correlated emission and highly inconsistent with uncorrelated situation, see the curve called “flat”. The numerical information is also provided in Table II. A more detailed discussion of the $^3\text{H}$ energy distributions is provided in Ref. 23.

3. $^3\text{H}^7\text{H}$ angular distribution in the lab frame

From theoretical point of view, this distribution is directly connected with the energy distribution of $^3\text{H}$ in the $^7\text{H}$ frame discussed in the previous Section. Moreover, it is obtained by projecting the $^3\text{H}$ momentum distribution on the transversal plane. However, from experimental point of view, this distribution is derived in methodologically different and more safe way because a reconstruction of the $^3\text{H}$ energy is not needed, only the reconstruction of $^3\text{H}$ direction. The MC evaluated resolution of this angular distribution is quite good $\Delta\theta_{3\text{H}, 7\text{H}} \lesssim 0.4^\circ$.

The $^3\text{H}$ angular distribution relative to the $^7\text{H}$ direction in the lab frame in the experiment 2 is shown in Fig. 14 together with different predicted distributions. From this figure one may conclude that the experimental distribution is clearly inconsistent with the smallest considered energy $E_T = 1.5$ MeV and with an uncorrelated distribution (“flat” curve). Finally, from information given in Table II one can find that both the energy and angular distributions of $^3\text{H}$ are consistent with the $E_T = 2.2(5)$ MeV energy inferred from the MM data.

C. Peak at 5.5 MeV and possible 7.5 MeV state

The peak in the $^7\text{H}$ MM spectrum at $\sim 6$ MeV is assumed to correspond to $5/2^+ - 3/2^+$ doublet or one of its components in Ref. 11. For the discussion of this Section, we should assume (i) the possible width of the state and (ii) the profile of the resonance peak, which is also induced by this width. The relevant theoretical estimates are provided in Ref. 23. Contrary to the $^7\text{H}$ ground state, which has a unique true $4n$ emission decay channel, the components of the $5/2^+ - 3/2^+$ doublet, located above $E_T \sim 4$ MeV, may undergo sequential emission $^7\text{H} \rightarrow ^5\text{H}(\text{g.s.}) + 2n \rightarrow ^3\text{H} + 4n$. The alternative sequential emission channel via $^6\text{H}$ is assumed to be closed, because no $^5\text{H}$ states available for the sequential decay $^7\text{H} \rightarrow ^5\text{H} + 3n$ were found in this work below the 6 MeV energy relative the $^3\text{H} + 3n$ threshold.

We start with overall “pessimistic” estimates for the resonance profile. The upper-limit width value of the sequential decay of the “$2^+$” state at 5.5 MeV via the $^5\text{H}$ g.s. is determined in Ref. 23 as $\Gamma = 0.75$ MeV. We assume a conservative value of $\Gamma = 1.5$ MeV. It can be

**TABLE II.** Mean values of the $\varepsilon$ and $\theta_{3\text{H}, 7\text{H}}$ variables for the distributions of Figs. 13 and 14

| Value | flat | 1.5 | 2.0 | 2.5 | 3.0 | Exp. |
|-------|------|-----|-----|-----|-----|-----|
| $\varepsilon$ | 0.464 | 0.337 | 0.295 | 0.272 | 0.252 | 0.306 |
| $\theta_{3\text{H}, 7\text{H}}$ | 3.38 | 2.19 | 2.49 | 2.78 | 3.02 | 2.69 |
found on the right tail of the 5.5 MeV peak at about 7.5 MeV in Fig. 11, upper row. It could be just a statistical fluctuation of the data. However, one should keep in mind that if the 5.5 MeV peak is indeed the $^{3/2}_2$ state of $^7$H, than one may expect the $3/2^+$ member of this doublet to be located $\sim 1 - 2$ MeV above it. According to statistical argument, the $3/2^+$ state population should be two times smaller than $5/2^+$ population. For $3/2^+$ state at $E_T \sim 7.5$ MeV with width smaller than $1 - 1.5$ MeV we can show that the doublet components can be resolved by the setup of experiment 2, see Fig. 15(b), red dotted curve. Otherwise, we can expect some quite broad asymmetric “triangular” profile with “shoulder” for the $5^2/2^-3/2^+$ doublet, see Fig. 16(b) orange dash-dotted curve.

So, we can not discriminate confidently between these two opportunities and contributions just from asymmetric broad right “shoulder” of the 5.5 MeV state, see Fig. 15(a). However, the idea about contribution from the $3/2^+$ doublet state is attractive, since it allows also to explain the disagreement with experiment 1. The $E_T = 6.5(5)$ MeV peak position found in a is consistent with the observation anticipated for a unresolved $5^2/2^-3/2^+$ doublet $E_T = \{5.5, 7.5\}$ MeV, as the resolution was considerably worse in experiment 1 compared to experiment 2. It can be found in Fig. 11 that a spectrum, consistent with the results of experiment 1, can be obtained for certain binning conditions, simulating deterioration of energy resolution.

D. Group of events at 11 MeV

The 11.0(5) MeV peak is well seen in all the data representations in Fig. 10(b,c) and 11(a-e). The search for this state at $\theta_{cm} > 18^\circ$ loses sense, since this energy angular range is expected to be contaminated with the background events, see Fig. 7(b).

Question could be asked: what could be the nature of such quite a narrow states observed at such a high excitation energy? The disintegration of the $^3$H cluster into $p+n+n$ is possible above $E_T = 8.48$ MeV. Phenomenology of nuclear states suggests that the states with definite clusterization are likely to be found near the corresponding cluster disintegration thresholds (both somewhat above and somewhat below). According to this systematics the 11 MeV state can be expected to have the structure with “dissolved” $^3$H core: $p+6n$. It does not mean that such a state should be necessarily observed in the $p+6n$ decay channel. According to a penetrability argument, the $^3$H+$4n$ channel should still be a preferable decay path for such a state. Nevertheless, we performed a dedicated search for decay of this state into $p+6n$. Unfortunately, no significant concentration of such events was identified.
E. Neutron coincidence events

The neutron wall used in experiment 2 provided 4.5% energy resolution for neutron energy of $\sim 1$ MeV and the single neutron registration efficiency of $\sim 15\%$. The efficiency of the neutron registration in coincidence with $^3\text{H}$ and $^3\text{He}$ was around 2% taking into account that four neutrons are produced in each $^7\text{H}$ decay event. Such an efficiency is too low to expect statistically significant result. However, these events could be interesting as an additional consistency check of the data, see Fig. 10 (a) and (c). There are 8 triple-coincidence $^3\text{H}$-$^3\text{He}$-$n$ events. There are two events in the $E_T \sim 5.5$ MeV region, one event corresponding to $\sim 7.5$ MeV structure, and three events consistent with the $11$ MeV state. This is an encouraging result, since $\sim 75\%$ of neutron events coincide with expected regions for resonance states, while only $\sim 20\%$ of the data is concentrated on these regions.

F. $^7\text{H}$ c.m. angular distributions

The c.m. angular distributions of the direct reactions serve as one of standard tools of spin-parity identification in reaction theory. Due to the small statistics of our experiment, angular distributions can not provide a basis for reliable statements, but some conclusive remarks still can be done.

Fig. 7(c) shows the center-of-mass angle of events from the $^2\text{H}(^9\text{He},^3\text{He})^7\text{H}$ reaction versus the corresponding $^7\text{H}$ MM energy taken from the experiment 2. For $E_T > 10$ MeV the available angular range rapidly shrinks: the kinematical cut defined by the maximum energy $E = 26$ MeV of reliable identification of $^3\text{He}$ recoils can be clearly seen. The angular distributions for different energy ranges of $^7\text{H}$ are presented in Fig. 12. The efficiency-corrected angular distributions converted to cross section values are shown in the upper panels of Fig. 12.

The angular distribution for the possible $^7\text{H}$ g.s. energy range, shown in Fig. 12 (a), has already been discussed in Section III B. Here we would like to point to the deduced cross sections are $\sim 24$ mb/sr for $\theta_{\text{cm}} \sim 5^\circ - 9^\circ$ and $\sim 7$ mb/sr for $\theta_{\text{cm}} \sim 15^\circ - 19^\circ$. For the first excited state, Fig. 12 (b), the deduced cross sections are $\sim 30$ mb/sr for $\theta_{\text{cm}} \sim 5^\circ - 18^\circ$ and $\sim 11$ mb/sr for $\theta_{\text{cm}} \sim 18^\circ - 30^\circ$. The energy range $8.5 < E_T < 10.5$ MeV was excluded because of the remarkable background found in the empty target experiment, see Fig. 7 (b).

In general, we would like to comment the following. Within the available angular range and available statistics, the angular distributions of all the 4 ranges can be seen as qualitatively different. Thus, these distributions support the idea that the considered ranges contain physically different entities.

IV. CONCLUSIONS

In this work we provide extended discussion of the $^7\text{H}$ data obtained for the $^2\text{H}(^9\text{He},^3\text{He})^7\text{H}$ reaction in the experiment Ref. 11 and the new data for the same reaction but with an improved setup. The statistics collected in the last experiment (378 events) is considerably larger than in Ref. 11 (119 events) and in Ref. 20 ($\sim 100$ events). In experiment 2 four peaks are observed in the missing mass spectrum of $^7\text{H}$ at $2.2(5), 5.5(3), 7.5(3)$, and $11.0(3)$ MeV. This result is consistent with three bumps in the spectrum observed at $\sim 2 - 3, \sim 6,$ and $\sim 11$ MeV in experiments 1 and 20. For each of these three datasets, because of the limited statistics, it is not impossible that these peaks are induced by statistical fluctuations on a top of some smooth continuous spectrum starting from $E_T \sim 5$ MeV. However, it is virtually impossible for statistical fluctuations to cause peaks at the same energies in the three totally independent experiments.

The $^7\text{H}$ g.s. is extremely poorly populated in the $^2\text{H}(^9\text{He},^3\text{He})^7\text{H}$ reaction. Possible reasons for this suppression are separately discussed in the forthcoming theoretical article 23. So, our special concern in this work were the background conditions in the low-energy part of the spectrum and the energy-resolution issues, which may make possible “contamination” of the g.s. range by events from the higher-lying $^7\text{H}$ excitations. Both these aspects were found to be favorable for the $^7\text{H}$ g.s. identification even by few events. The $5^+\text{H}$ g.s. candidate events were collected in experiment 1 1] and 9 events in experiment 2. All the observed events are consistent with the $^7\text{H}$ center-of-mass angular distribution expected for the $1/2^+$ g.s. with diffraction minimum located between $\sim 10^\circ$ and $\sim 15^\circ$. They are also consistent with predicted energy distributions of the $^3\text{H}$ fragment in the $^7\text{H}$ center-of-mass system.

Summarizing, the conclusion about the observation of the $^7\text{H}$ states at $2.2(5)$ and $5.5(3)$ MeV is very reliable. The observation of the $7.5(3)$ MeV state is not statistically confident enough. Energy resolution of the experiment 2 was high enough to resolve the possible $5.5 - 7.5$ MeV doublet (while in the experiments 1 and 21 they were observed as a single structure). However, we can not exclude that the observed separation of the $5.5 - 7.5$ MeV peaks is actually a statistical fluctuation on the broad right tail of the $5.5$ MeV state. Anyway, we conclude that the firmly ascertained $5.5(3)$ MeV state is the $5/2^+$ member of the $^7\text{H}$ excitation doublet. The $11$ MeV peak is well exhibited at low center-of-mass angles $\theta_{\text{cm}} < 20^\circ$, where available statistics is limited. It is also well seen at higher center-of-mass angles $\theta_{\text{cm}} \sim 20^\circ - 35^\circ$. However, in this energy-angular range a strong background contribution is expected, so caution is needed.
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