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Estimates of the ^{7}H width and lower decay energy limit

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Abstract

The ^{7}H nucleus most likely possesses an unique decay dynamics: the four-neutron emission (or 5-body decay). We estimated theoretically the ^{7}H width as a function of its decay energy. Uncertainty inherent to the estimated decay energy leaves a room for a possible very small width of ^{7}H. In an attempt to observe a long living quasi stable ^{7}H nucleus, produced in the reaction ^{2}H(^{8}He, ^{7}H)^{3}He, we set an upper limit of 3 nb/sr for the reaction cross section. We utilized a 20.5 MeV/amu ^{8}He beam bombarding a 5.6 cm thick liquid deuterium target, and searched for ^{7}H within 0°–50° CM angles. The obtained cross section limit corresponds to a ^{7}H lifetime less than 1 ns, which allows us to estimate a lower limit of 50–100 keV for the ^{7}H energy above the $^3\mathrm{H} + 4n$ breakup threshold.

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1. Introduction

In the recent years the knowledge about nuclear systems near (and beyond) the drip lines has been improved significantly. Exotic phenomena observed here (haloes, skins, two-proton decays) may have features making their dynamics qualitatively different from the dynamics we have got used to in the close-to-stability region. One of such exotics are unstable systems, which can decay only via the few particle (few cluster) emission. This happens when the particles cannot be emitted sequentially because, due to the separation energy conditions, none of the (quasi)stationary intermediate systems can be formed. This is a pure quantum mechanical phenomenon which has no analogue in classical physics. In his famous paper on the two-proton radioactivity [1] Goldansky has pointed at

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important qualitative features of such decay. The necessity to emit several particles simultaneously significantly reduces the width, so, for such systems, the width systematics should be different from that expected for the ordinary, two-body decays.

The tree-body ground state decay is quite a typical phenomenon in the investigated dripline regions. The ground states of ^{5}H [2–4], ^{10}He [5], ^{6}Be [6], ^{12}O [7], and ^{16}Ne [8,9] are known to decay this way. For many heavier systems the dripline is simply not investigated yet. There is the first evidence for the $2p$ decay of ^{45}Fe [10,11]. Active searches for the $2p$ decay in other systems, such as ^{19}Mg, ^{48}Ni, and ^{54}Zn, are in progress.

Early theoretical estimates predicted that even such an exotic system as ^{7}H has a chance to be stable [12]. The single experiment [13] in which the search for ^{7}H was made using the $^7\mathrm{Li}(\pi^-, \pi^+)$ reaction yielded no indication that such a metastable nucleus exists. The authors of Ref. [14] tried to detect directly ^{7}H nuclei emitted in the ternary fission of ^{252}Cf and gave only an upper limit of 10^{-4} for the ^{7}H yield defined with respect to the yield of ^{3}H. However, the lack of at least an approximate comprehension about the yields of $Z = 1$ nuclei, known for ternary fission (see review papers [15–17]), prevents us from saying that this limit is incompatible with the existence of a low-lying, narrow resonance state in ^{7}H. There still remains a possibility that directly detectable ^{7}H nuclei will be found among the products of some appropriate reactions.

Progress achieved within the last years in experimental techniques gives a new impact to the activity in this direction. Radioactive beams available now present new possibilities to create such exotic systems in some simple transfer or knock-out reactions. An experiment [2] where $^1\mathrm{H}(^6\mathrm{He}, ^2\mathrm{He})$ reaction was used to investigate the ^{5}H system gave a very promising result. Recently the first evidence for a low-lying ground state of ^{7}H was reported in Ref. [18]. The authors demonstrated an abnormal behaviour of the ^{7}H missing mass spectrum just above the $t + 4n$ threshold. This result, however, does not give quantitative information how low the ^{7}H ground state is actually located.

Most likely the ^{7}H nucleus has an exotic decay path—the four-neutron emission (5-body decay).[1] This is a light nuclear system with (at most) p-wave centrifugal barriers. However, estimates given below show that, due to the necessity to emit all particles simultaneously, the system should be quite narrow, if its decay energy is less than 2–3 MeV. Below 50–300 keV the width of the resonance may be as small as 10^{-12} MeV. The corresponding lifetime (about 10^{-9} s) will give a chance to the ^{7}H nuclei produced in a reaction to fly out of the target and to be detected by a detector array. To check this extraordinary possibility we chose the $^2\mathrm{H}(^8\mathrm{He}, ^7\mathrm{H})^3\mathrm{He}$ reaction.

2. Lifetime estimates

2.1. General notes

Here we make simple estimates for the ^{7}H decay energy in a way very similar to the speculations made in Ref. [12]. The two neutron threshold energy E_{2n} in ^{6}He is about -0.9 MeV. This roughly consists of the single particle energies E_{sp} (for the ^{5}He ground state $E_{\mathrm{sp}} = 0.9$ MeV) and the pairing energy

$$E_{2n} = 2E_{\mathrm{sp}} + E_{\mathrm{p}}.$$

Pairing energy can be thus estimated as $E_{\mathrm{p}} = -2.7$ MeV. The same estimate for ^{8}He

$$E_{4n} = 4E_{\mathrm{sp}} + E_{\mathrm{q}}$$

with the threshold energy $E_{4n} = -3.1$ MeV gives the "quadrupling" energy $E_{\mathrm{q}} = -6.7$ MeV. Let us assume that the ratio $R_{\mathrm{qp}} = E_{\mathrm{q}}/E_{\mathrm{p}} \approx 2.5$ should be the same in corresponding helium and hydrogen isotopes.

When we try to apply this procedure to estimate E_{4n} for ^{7}H we face a problem with recent contradictory experimental results on ^{5}H. They give either $E_{2n}(^5\mathrm{H}) \sim 1.7$ MeV [2,3,19] or $E_{2n}(^5\mathrm{H}) \sim 3$ MeV [4]. The single particle energy (the ^{4}H ground state) is also not well-known $E_{\mathrm{sp}} \sim 2.5$–3.3 MeV. A formula trivially extrapolating the behaviour of He isotopes to heavy hydrogens is

$$E_{4n}\big(^7\mathrm{H}\big) = (4 - 2R_{\mathrm{qp}})E_{\mathrm{sp}} + R_{\mathrm{qp}}E_{2n}\big(^5\mathrm{H}\big), \tag{1}$$

giving $E_{4n}(^7\mathrm{H}) = 1.3$–$1.8$ MeV for $E_{2n}(^5\mathrm{H}) = 1.7$ MeV and $E_{4n}(^7\mathrm{H}) = 4.5$–$5.0$ MeV for $E_{2n}(^5\mathrm{H}) =$

[1] This is a conditional statement as it depends on the g.s. energy of ^{5}H, which is not known well, and on the energy of ^{7}H itself, which is not known at all. However, we will see below that this situation is quite likely.

3 MeV. It should be noted that in the first case the sequential decay via the ^{5}H ground state is impossible. In the second case the ^{5}H ground state should be very broad and it should not change dynamics much. It is interesting that the calculations performed in [18] in the A-body hyperspherical approach with Volkov potential fit well in the simple systematics of Eq. (1): $E_{4n}(^7\mathrm{H}) \sim 3$ MeV for $E_{2n}(^5\mathrm{H}) \sim 2.3$ MeV. What we want to emphasize here is the large uncertainty of the estimated values and the strong sensitivity of the extrapolation to the decay energy of ^{5}H. This makes not impossible a very low decay energy of ^{7}H.

A value of 5.5 MeV was reported in Ref. [20] for the ^{5}H ground state energy. Such energy of ^{5}H probably leaves no place for a low-lying, narrow ^{7}H. However, no spin identification is possible in [20], and the reaction mechanism do not suggest a preferable population for low-spin states (which was an important feature of the other experiments [2–4]). It is possible that the ^{5}H ground state is simply poorly populated in the reaction employed in Ref. [20].

Due to the few-body decay channels the width estimation is a complicated theoretical task. At the moment, any generally accepted recipe does not exist for this task. The first known to us work of this kind is paper [1] on two-proton radioactivity. The paper treated the problem as an "uncorrelated" decay in a sense that the two protons are emitted simultaneously, share the total available energy, but do not interact with each other. An intuitive formula for the decay width was suggested:

$$\Gamma_3 \sim \int_0^E d\varepsilon\, P_l(\varepsilon, r_{\mathrm{ch}}, Z_{\mathrm{c}}) P_l\big((E-\varepsilon), r_{\mathrm{ch}}, Z_{\mathrm{c}}\big),$$

where P_l is the standard penetrability depending on energy, r_{ch} is the channel radius, and Z_{c} is the charge of the core. Here and below Γ_A is the width to the A-body decay channel. It was shown in [1] that because of the exponential dependence of the penetrability on energy the function under the integral should have a sharp maximum at $\varepsilon = E/2$. Hence, the energy dependence of the three-body width can be well approximated as

$$\Gamma_3 \sim P_l^2(E/2, r_{\mathrm{ch}}, Z_{\mathrm{c}}). \tag{2}$$

A trivial generalization of this formula on the ^{7}H case is an assumption about the simultaneous emission of four p-wave neutrons sharing the available energy:

$$\Gamma_5 \sim P_{l=1}^4(E/4, r_{\mathrm{ch}}, Z_{\mathrm{c}} = 0). \tag{3}$$

Expressions of the kind (2) and (3) have a strong sensitivity to the channel radius r_{ch}. It is also difficult to estimate consistently the value of preexponential factor. This was discussed in Refs. [21–23], where estimates made for the two-proton emission were compared to the three-body calculations. Typical corrections for this case are of 1–2 orders of magnitude. Even larger correction factors can be expected for four-neutron emission. For that reason we developed an alternative approach, which is ideologically close to the one of Eqs. (2) and (3), but is free of the mentioned methodological difficulties.

2.2. *Emission off a Gaussian source; the two-body case*

Our approach is to study the penetration of the particles emitted simultaneously by a Gaussian source and showing no interaction with each other. First we would like to study the model in a trivial two-body case where comparison with other well-known methods is possible.

The source for A particles is taken as

$$\Phi(\mathbf{r}) = \prod_{i=1,A} \exp\big[-k_i^2 \mathbf{r}_i^2\big], \tag{4}$$

where $k_i = \sqrt{A_i}k$ and A_i is the mass number of particle i. In the two-body case this gives

$$f_2(r) = r \exp\big[-k^2 r^2\big]$$

for the radial part of the source function (again, here and below f_A is the source function for A particles). The function having an outgoing asymptotics with angular momentum l is generated using the Green's function method. Its radial part is

$$\psi_{E,l}^{(+)}(r) = \int_0^\infty G_{E,l}^{(+)}(r, r')\, f_2(r')\, dr'. \tag{5}$$

Standard expression for the radial part of the Green's function is well known:

$$G_{E,l}^{(+)}(r, r') = -\frac{1}{q} \left\{ \begin{array}{ll} \chi_l^{(+)}(qr)\chi_l(qr'), & r > r' \\ \chi_l(qr)\chi_l^{(+)}(qr'), & r \leqslant r' \end{array} \right\}, \tag{6}$$

where $E = q^2/2M$, $\chi_l(qr) = (qr)\, j_l(qr)$, and $\chi_l^{(+)}(qr) = (qr)[n_l(qr) + i\, j_l(qr)]$ are Bessel–Ricatti functions.

The width for function $\psi_{E,l}^{(+)}(r)$ can be found using the "physical" definition of a current passing through a sphere of a large radius a divided by the number of particles inside the sphere:

$$\Gamma_2 = \frac{j}{N} = \frac{1}{M}\frac{\mathrm{Im}[\psi_{E,l}^{(+)\dagger}(r)\nabla_r\psi_{E,l}^{(+)}(r)]|_{r=a}}{\int_0^a |\psi_{E,l}^{(+)}(r)|^2\, dr}. \tag{7}$$

Estimates show that a values lying between 15 and 20 fm are reasonable here and can be used also in the few-body cases.

Let us study this model on a simple example of a decay resulting in the emission of a p-wave neutron. A compact analytical expression can be obtained for width (7) for sufficiently small E and sufficiently large a:

$$\Gamma_2 = \frac{6\sqrt{2M}E^{3/2}/k}{(2.71 - \frac{3}{ak}) + (6 - \frac{8.83}{ak})\frac{aME}{k}}. \tag{8}$$

This expression is given in the form closely resembling the ordinary R-matrix expression for the p-wave decay in the Wigner limit

$$\Gamma_2(RM) = \frac{6\sqrt{2M}E^{3/2}r_c(1 + 2r_c^2ME)}{8(1 + r_c^2ME + (r_c^2ME)^2)}. \tag{9}$$

This is the one level formula "corrected" for the resonance shape [24]. Parameter k^{-1} plays in our model the role analogous to the role of the channel radius r_c in the R-matrix phenomenology. However, the dependencies of the width on this parameter are somewhat different in Eqs. (8) and (9).

The results of the different theoretical models are compared in Fig. 1 on the example of the ^{5}He ground state. One can see that the width associated with the Gaussian source is in a good agreement with other model calculations. In the potential model, we define the width as FWHM for the p-wave partial cross section. Calculations are done with Gaussian potentials

$$V(r) = V_0 \exp\left[-(r/r_0)^2\right] \tag{10}$$

with different radii r_0. The choice of parameters made for the calculations presented in Fig. 1 ensured the mutual consistency of the models. The geometry of the wave function $\psi^{(+)}(r)$ with $k = 0.25$ fm^{-1} is quite close to the one obtained for the potential model wave function with $r_0 = 2$. The classical outer turning point for potential (10) with $r_0 = 2$ fm is close to 4 fm. This justifies the choice of $r_c = 4$ fm for the R-matrix estimate. The same is true for the parameter set $k = 0.19$ fm^{-1}, $r_0 = 3$ fm, $r_c = 6$ fm. It should be noted that the radius typically employed for the Gaussian α–n potential in the ^{6}He calculations is 2.35 fm [25]. The values $k = 0.19$ fm^{-1} and $k = 0.25$ fm^{-1} provide us a range for the source size acceptable in the ^{5}He case. We are going to rely on this parameter range in the calculations of the few-neutron emission as well.

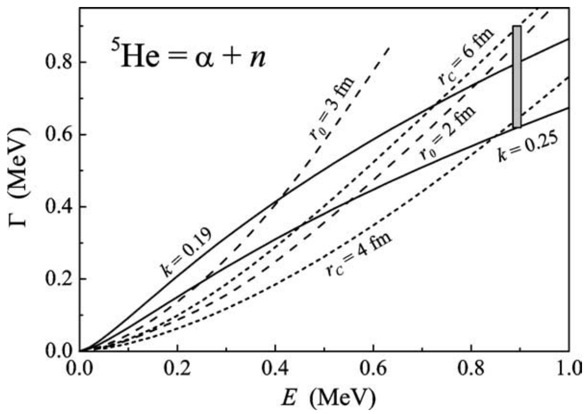

Fig. 1. The dependence of the width on the ^{5}He energy obtained in different models. The solid curves correspond to the emission off the Gaussian source (parameter $a = 16$ fm is used), the dashed curves are obtained in a potential model, and the dotted curves are standard R-matrix estimates. The gray rectangle shows the experimental width and position known for the ^{5}He ground state.

2.3. Few-particle emission

For the case of a few-particle emission we utilize the hyperspherical decomposition of the wave function. In this approach the multidimensional few-body problem is reduced to a set of coupled differential equations describing the one-dimensional motion of an "effective" particle in a complicated field. The decay aspect of the problem can be studied as penetration through a collective (hyperradial) barrier. We neglect all the coupled channels but one. This is reasonably motivated by dynamic calculations (see [23,25–27]) which show that, typically, in the cluster models of p-shell nuclei one component of the wave function is strongly dominating. In the few-body calculations this assumption is likely to lead to the underestimation of the width, because the interaction of multiple channels causes the appearance of effective long-range potentials which should reduce the barrier. This difficulty makes the few-body case different from the two-body problem.

For the emission off a source we obtain an equation closely resembling the one valid for the ordinary two-body case

$$\left[\frac{d^2}{d\rho^2} - \frac{\mathcal{L}(\mathcal{L}+1)}{\rho^2} + 2ME\right]\chi_K(\rho) = f_A(\rho),$$

where $\mathcal{L} = K + (3A-6)/2$, and K is the generalized (hyperspherical) momentum. The sources for the three and five body decays are obtained by the conversion of Eq. (4) to the hyperspherical variables

$$f_A(\rho) = \rho^{(3A-4)/2}\exp\left[-k^2\rho^2\right].$$

This is an important feature of our approach: there is no arbitrary choice of parameter k in the few-body case. Reasonable parameters are found for the two-body and three-body decays of neighbouring systems and then used for the 5-body estimates. This actually governs the choice of the Gaussian source: the function, which is Gaussian for individual nucleons, remains Gaussian in the collective variable (hyperradius).

One channel Green's function in hyperradius is used to generate the wave function with outgoing asymptotic. The expression is analogous to Eq. (6), but it uses other Bessel–Rikatti functions $\chi_K(q\rho)$:

$$\chi_K(q\rho) = \sqrt{\frac{\pi q\rho}{2}}\, J_{K+3A/2-5/2}(q\rho);$$

function $\chi_K^{(+)}(q\rho)$ is expressed similarly via the Hankel function of integer index $H^{(+)}$. The analytical expressions for the widths are very complicated to be shown. Their low-energy limits in the important for us $K = 2$ case can be obtained as

$$\Gamma_3 = \frac{1.36M^3E^4}{k^6}, \qquad \Gamma_5 = \frac{0.0185M^6E^7}{k^{12}}.$$

They are, respectively, 50% and 20% precise for E below 1 MeV.

We use the decay of the 2^+ state in ^{6}He to calibrate our model. The choice of $K = 2$ is unique here. For a $J^\pi = 2^+$ state the value of K cannot

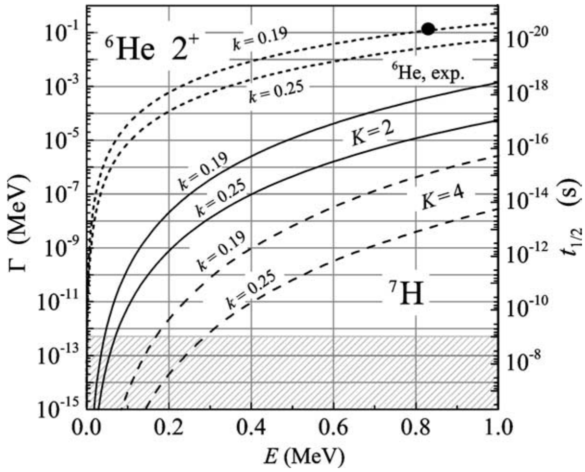

Fig. 2. Width dependencies on energy calculated for the 2^+ state in ^{6}He (dotted curve) and the ^{7}H ground state (solid and dashed curves correspond to $K = 2$ and $K = 4$ calculations). The hatched area corresponds to ^{7}H lifetimes, long enough to allow the detection of this nucleus before its decay.

be less than 2; on the other hand, we know from calculations [26] that the $K = 2$ components dominate in the structure and decay of this state. For ^{5}He the values $k = 0.19$ fm^{-1} and $k = 0.25$ fm^{-1} define the band which reproduces well the experimental width. One can see in Fig. 2 that such band is shifted downwards for ^{6}He: while the $k = 0.19$ curve exactly reproduces the experimental width of the 2^+ state ($\Gamma = 113$ keV), the $k = 0.25$ curve gives a three times lower value. As it has been mentioned already, the reason for this shift is qualitatively clear. We consider here the simultaneous few-body decay assuming no final-state interaction (FSI) between the emitted particles. In reality there exists a strong short-range FSI in each pair of particles. In the hyperradial space these interactions are translated into effective interactions, which decrease quite slowly ($\sim \rho^{-3}$ for three particles) and significantly affect the barrier. We should pay attention that the uncertainty of the width estimates connected with the source size increases drastically in the case of the two-neutron emission compared to the one-neutron emission (the relative differences between the $k = 0.19$ and $k = 0.25$ curves are about 3 and 0.3, respectively).

The choice of parameter K is more complicated for estimates in ^{7}H. $K = 0$ is prohibited due to Pauli principle. $K = 2$ is dynamically suppressed in the

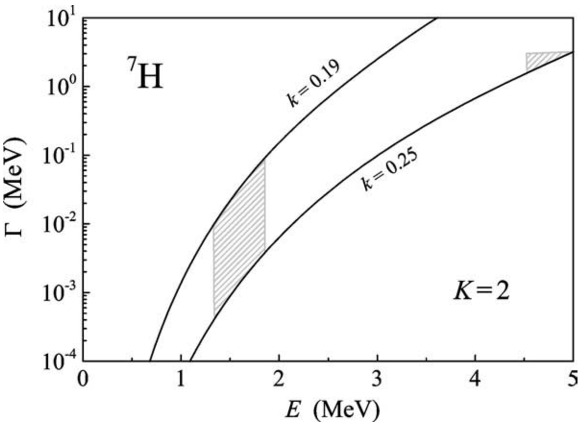

Fig. 3. The dependencies of the width on the ^{7}H decay energy. Curves are the same as in Fig. 2 but are presented in broader energy range. Hatched areas correspond to the ^{7}H energy estimates made for the two possible decay energies of ^{5}H (~ 1.7 and ~ 3 MeV) by Eq. (1).

internal region, where $K = 4$ should dominate. The s-shell is already occupied by neutrons in the triton. The four valence neutrons can approach triton only in p-waves, which counts for 4 excitation quanta and hence $K = 4$. In the sub-barrier region $K = 2$ is allowed. Penetration in $K = 2$ is suppressed by "spectroscopy" ($K = 4$ domination in the interior), but is boosted by the FSI. We think that $K = 2$ is a reliable assumption (because the two discussed trends should somehow compensate each other). Then the band given by the $k = 0.19$ and $k = 0.25$ curves represents well the realistic range of the width. The relative difference between the $k = 0.19$ and $k = 0.25$ curves is now about 30, which is much larger than in the one- and two-neutron emission cases.

The dependence of the ^{7}H lifetime on the decay energy is shown in Figs. 2 and 3. One can see that for a four-neutron separation energy below 50 keV the lifetime of ^{7}H reliably exceeds some nanoseconds. The calculations with $K = 4$ give very long lifetimes. They are provided to demonstrate the full range of the model uncertainty. We should remind that the $K = 4$ case qualitatively corresponds to the "intuitive" approach to the problem of Eq. (3). So, it is less likely, but possible, that the lifetime exceeds one nanosecond below 300 keV of the decay energy. Such lifetime means that ^{7}H nuclei formed in some nuclear reaction will have a macroscopic flight path allowing them to be detected as "stable" particles.

The regions corresponding to the lifetime estimates made for the ^{7}H decay energies obtained by Eq. (1) are shown in Fig. 3 as hatched areas. For the separation energy below 3 MeV one can expect quite a narrow state with $\Gamma \leqslant 1$ MeV. For the widths well above 1 MeV the model does not promise to give reliable results.

3. Search for ^{7}H nuclei produced in the ^{2}H(^{8}He, ^{7}H)^{3}He reaction

In Section 2 we showed that the existing experimental evidences and theoretical estimates of the ^{7}H decay energy are very uncertain. One cannot rule out that the decay energy is low (e.g., < 100 keV). At such a decay energy the ^{7}H nucleus could leave long enough (>1 ns) to be detected directly. The ^{2}H(^{8}He, ^{7}H)^{3}He reaction was selected to investigate this opportunity. To roughly estimate the chosen reaction cross section we used the results of our recent study made for the reaction ^{2}H(^{6}He, ^{5}H)^{3}He [19]. The reaction cross section deduced from the yield of the ^{5}H ground state resonance measured at 20°–50° in CM was ~ 5 μb/sr. We made DWBA calculations for the two reactions, ^{2}H(^{6}He, ^{5}H)^{3}He and ^{2}H(^{8}He,^{7}H)^{3}He, using different sets of model parameters. Though the obtained absolute cross section values varied for different parameter sets, the ratio of the cross sections calculated for the two reactions remained practically stable. Keeping in mind the destruction effect [2] produced on the two additional neutrons that are present in the ^{8}He halo we reduced the estimated cross section by a factor of 30. Thus, our expectation was that, if the assumed resonance state exists in ^{7}H, it will be produced in the ^{2}H(^{8}He, ^{7}H)^{3}He reaction with an average cross section making, at least, 100–150 nb/sr for CM angles spanning a range of 0°–50°. This estimate is valid as an average taken for the beam energy varied from 20–25 MeV/amu to 12.5 MeV/amu (the lower value, 12.5 MeV/amu, exceeds by about 10 MeV the reaction threshold).

The experiment was made at the U-400M cyclotron of FLNR JINR (Dubna). A 20.5 MeV/amu beam of ^{8}He nuclei was obtained from the fragment separator ACCULINNA. The beam intensity on the target was 2×10^4 s^{-1} in irradiations lasting for about one week. The experimental setup is shown in Fig. 4. A 5.6 cm thick cryogenic cell filled with liquid deuterium and supplied with 20 μm thick stainless steel entrance and

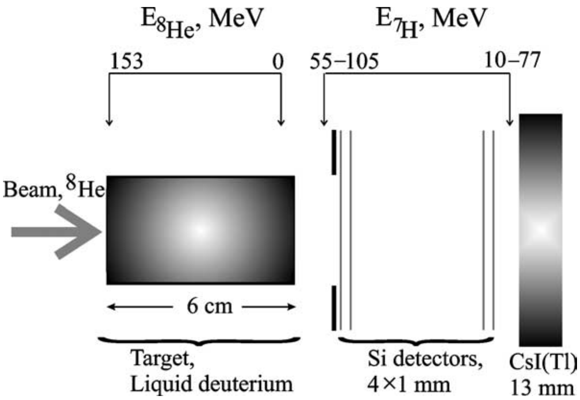

Fig. 4. Experimental setup. The energies of incoming beam ions along the beam path and the energies of searched ^{7}H product nuclei passing through the array of the ΔE detectors are indicated on the top.

exit windows was used as a target. The beam was focused in a 15 mm spot on the entrance window. The thickness of deuterium liquid was chosen counting upon the full retardation of beam nuclei. Only $Z = 1$ reaction products having high enough energy could escape from the target to the forward direction where a detector telescope was installed. Taking into account that, after passing the target window, ^{8}He ions entered liquid deuterium with energy 153 MeV and could produce ^{7}H before slowing down to ~ 100 MeV, the energy of coming ^{7}H nuclei could vary between 55 and 105 MeV at the telescope entrance. The telescope consisted of four 60×60 mm^2 Si strip detectors. These 1 mm thick detectors accomplished the four-fold measurement of energy loss $\Delta E1$–$\Delta E4$ made by each ejectile successively on its flight towards the relatively thick detector which was destined for the measurement of the energy residual E. This energy residual could vary between 10 and 77 MeV for the ^{7}H nuclei leaving the deuterium target. Measurements were performed in two parts with the use of either a 5 mm thick Si(Li) detector or a 13 mm thick CsI scintillation crystal installed at the position of the E detector.

In spite of a rather low counting rate, typical for such experiments, provisions were needed against false signals imitating the detection of hydrogen nuclei heavier than tritium. The signal detection made from 32 single strips in each ΔE detector considerably reduced the pile-up probability. Tests made for the presence of signals arriving from each of the four 1 mm detectors with properly coordinated amplitudes further reduced the single-strip pule-up effect and avoided other sources of spurious ΔE signals.

The beam identification was accomplished by two thin plastic scintillators placed on a time-of-flight base of about 8.5 m and two multiwire proportional chambers (MWPC). The plastic scintillators were used for the beam energy measurement and the $\Delta E \times$ TOF identification of beam ions. The MWPCs allowed us to know, with a 1.5 mm precision, the hitting positions of individual beam ions on the target. The integral flux of ^{8}He ions accumulated during these experiments was 3.3×10^9 particles.

Data analysis included a complete Monte Carlo simulation of the experiment. Beam nuclei hitting the target were slowed down to the reaction energy threshold at a depth of ~ 3.2 cm in liquid deuterium. Any ^{7}H nucleus emitted from the target in the forward direction had the lab energy high enough to reach the E detector and to be identified in the four $\Delta E \times E$ plots. The detection efficiency was calculated for ^{7}H nuclei emitted with a uniform angular distribution in CM system.

Fig. 5 gives an example of $\Delta E \times E$ identification plot built from the data recorded by the CsI detector in coincidence with the fourth ΔE detector. The calculated loci of protons, deuterons, tritons, ^{7}H, and ^{3}He nuclei are shown. Energy losses were calculated using the SRIM code. Single counts are seen in this plot between the loci of triton and ^{3}He. Such plots, drawn with the use of data obtained from the other three ΔE detectors, demonstrated essentially similar pictures.

The main sources of continuous background are (i) the chance coincidences of two charged particles hitting the telescope, (ii) the pile-ups of signals produced by neutrons or gamma rays in the thick E detector with the signals from charged particles, (iii) the incomplete charge (light) collection in the E detector. We analysed the two-dimensional $\Delta E \times E$ plots obtained with the participation of each of the four ΔE detectors in combination with the each of the two E detectors (Si(Li) and CsI). The critical condition adopted for selecting the ^{7}H signature was that any event, assumed to occur due to ^{7}H, must fit within two experimental errors into the ^{7}H loci anticipated for each of the four $\Delta E \times E$ plots. None of the observed events satisfied this condition. Allowing for statistical fluctuations, we set an upper limit of 3 ^{7}H events to be used for the estimation of the attained cross section limit.

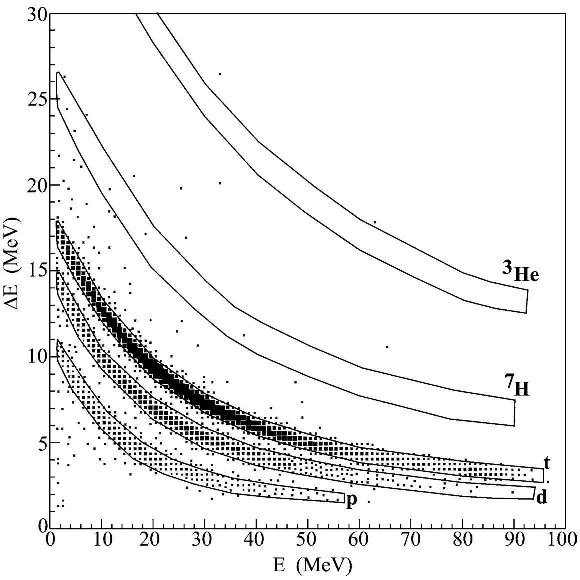

Fig. 5. Two-dimensional spectrum recorded for particles leaving the liquid deuterium target bombarded by 20.5 MeV ^{8}He nuclei. Shown in the figure is the energy loss recorded by the fourth ΔE detector vs the rest energy E deposited in the thick CsI scintillator. Contours show the calculated loci for protons, deuterons, tritons, and ^{7}H and ^{3}He nuclei. The ^{7}H locus is broadened to show the real zone where these nuclei were searched for.

Efficiency calculations showed that, in these experimental conditions, one ^{7}H event would correspond to a cross section value of 1 nb/sr estimated for the ^{2}H(^{8}He, ^{7}H)^{3}He reaction. So, we conclude that we have set a limit of 3 nb/sr for the cross section observed at forward CM angles. Since this upper limit is by 30–50 times lower than the estimated cross section value we conclude that ^{7}H nuclei were not detected in our experiments because their lifetime is too short for their survival on the path towards the detector telescope. From this we deduce that the lifetime of ^{7}H is less than 1 ns. In its turn, according to the lifetime estimates of Section 2.3, this assigns a conservative lower limit of 50–100 keV to the ^{7}H decay energy. A more relaxed lower energy limit, which, however, much stronger depends on the uncertainties of the theoretical model is about 300 keV.

4. Conclusion

The ^{7}H nucleus most likely possesses an unique decay dynamics: the four-neutron emission (or 5-body decay). We estimated theoretically the ^{7}H width as a function of its decay energy. Even for quite a large decay energy of about 3 MeV the width is predicted to be quite small—below 1 MeV. According to the estimates, a very low decay energy is not impossible for this nucleus. For a decay energy of 50–100 keV the estimated ^{7}H lifetime exceeds one nanosecond, what means that such a quasistationary state could be registered in experiments as if it is a stable nucleus.

We have made an attempt to observe ^{7}H as a long living, quasi stable nucleus produced in the reaction ^{2}H(^{8}He, ^{7}H)^{3}He. The limit of 3 nb/sr obtained for the reaction cross section allows us to estimate the lower limit for the ^{3}H + $4n$ breakup energy of ^{7}H as 50–100 keV.

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