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PHYSICS OF ELEMENTARY PARTICLES AND ATOMIC NUCLEI. EXPERIMENT

Detector Array for the ^{7}H Nucleus Multi-Neutron Decay Study

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Abstract—Setup fitting the requirements for the detailed study of the five-body decay of the ^{7}H nucleus obtained as a result of the proton transfer from the ^{8}He projectiles to the deuterium target nuclei is being built at the radioactive beam line of ACCULINNA-2 separator in the G.N. Flerov Laboratory of Nuclear Reactions. Described here is the assembly of 100 BC-404 plastic scintillators, intended for neutron detection, the annular Si detector telescope for the ^{3}He recoils, and the detector array providing the ΔE–E-TOF registration of ^{3}H nuclei emitted at the ^{7}H decay. Results obtained by the Monte Carlo simulations made for the energy values and flight passes of all these particles are given together with the luminosity expected for the discussed experiments.

Keywords: five-body decay, neutron detection, multi-neutron emission, array of plastic scintillators

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1. SETUP WITH THE 75 mm THICK BC-404 SCINTILLATORS

Presented is the modification of the detector array intended for the study of nuclei undergoing decay with the multi-neutron emission. The front view of this Neutron Wall (NW) is approximated as an annular active area with the outer and inner dimensions outlined in Fig. 1. The modification assumes the use of the assembly of 100 BC-404 plastic scintillators which are at the disposal of the ACCULINNA group. Each 75 mm thick scintillator has a hexagonal cross section, which can be embedded into a 100-mm circle of a single scintillator is shown in Fig. 1. In its cross-section, the 75 mm thick plastic is the hexagon insertable into a circle with diameter 100 mm. Each scintillator is enclosed in a 1 mm thick Al frame with light reflector. Consequently, 95.5% active area of this compact assembly will be covered by the BC-404 scintillators.

The NW arrangement, shown in Fig. 1, will be the central part of the setup being created to satisfy the requirements becoming apparent as a result of study made on the decay spectra of ^{7}H and ^{6}H nuclei [1–3]. The setup composition is given in Fig. 2.

Assembly of 100 plastic scintillators shown in Fig. 1 covers a surface approximated by a circle with diameter 93 cm. Its empty central part opens way for the ^{8}He nuclei to fly free to the beam stopper placed at a 0.5 m distance behind the NW without making background distorting the detection of multiple-neutron events.

Detection probability $\varepsilon_n \approx 0.28$ is estimated for single neutrons with energy 20–30 MeV hitting the array. This estimate is based on the known [4, 5] cross section values of the elastic ^{1}H(n,p) scattering and ^{12}C(n,n,3α), ^{12}C(n,α)^{9}Be, ^{12}C(n,np)^{11}B, ^{12}C(n,p)^{12}B, ^{12}C(n,$n\gamma$) reactions induced by neutrons bombarding the hydrogen and carbon nuclei making the BC-404 plastic composition in amounts 5.23×10^{22} and 4.74×10^{22} cm^{-3}, respectively.

The depletion rate of neutron flux in the BC-404 plastic is calculated by the use of the depletion constant λ. The value of this constant is obtained as the sum of contributions made to the decrease of the neutron flux due to the neutron elastic scattering on the hydrogen nuclei and neutron reactions with carbon nuclei giving rise to the charged-particle emission.

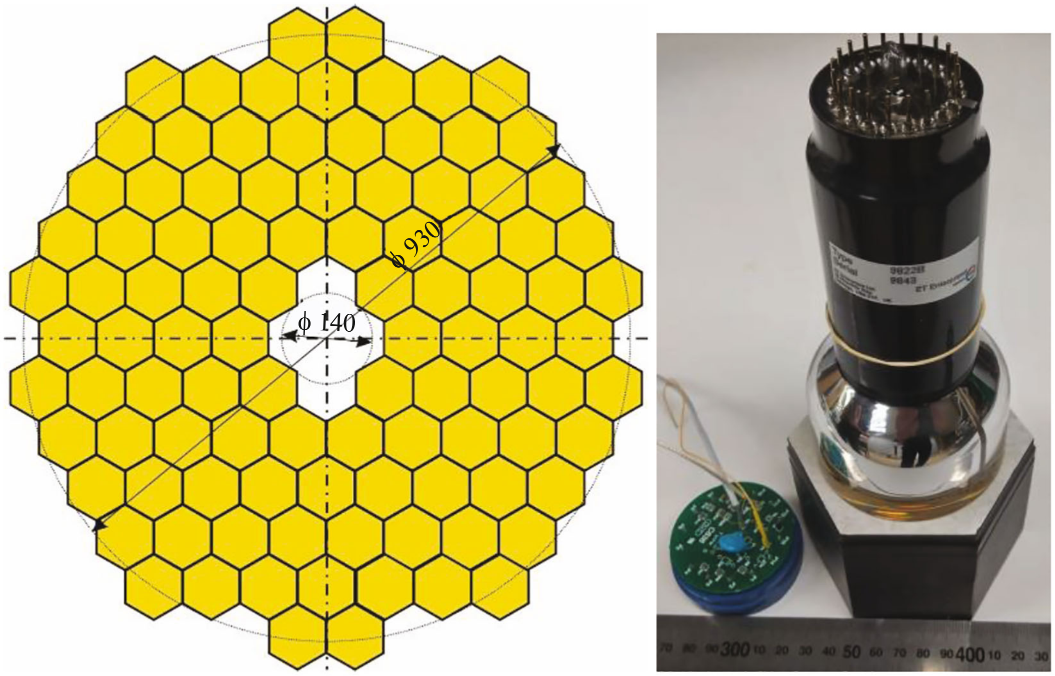

Fig. 1. Assembly of 100 BC-404 plastic scintillators suggested for the detection of nuclear decay events with multiple neutron emission (left) and photo of the detector structure (right).

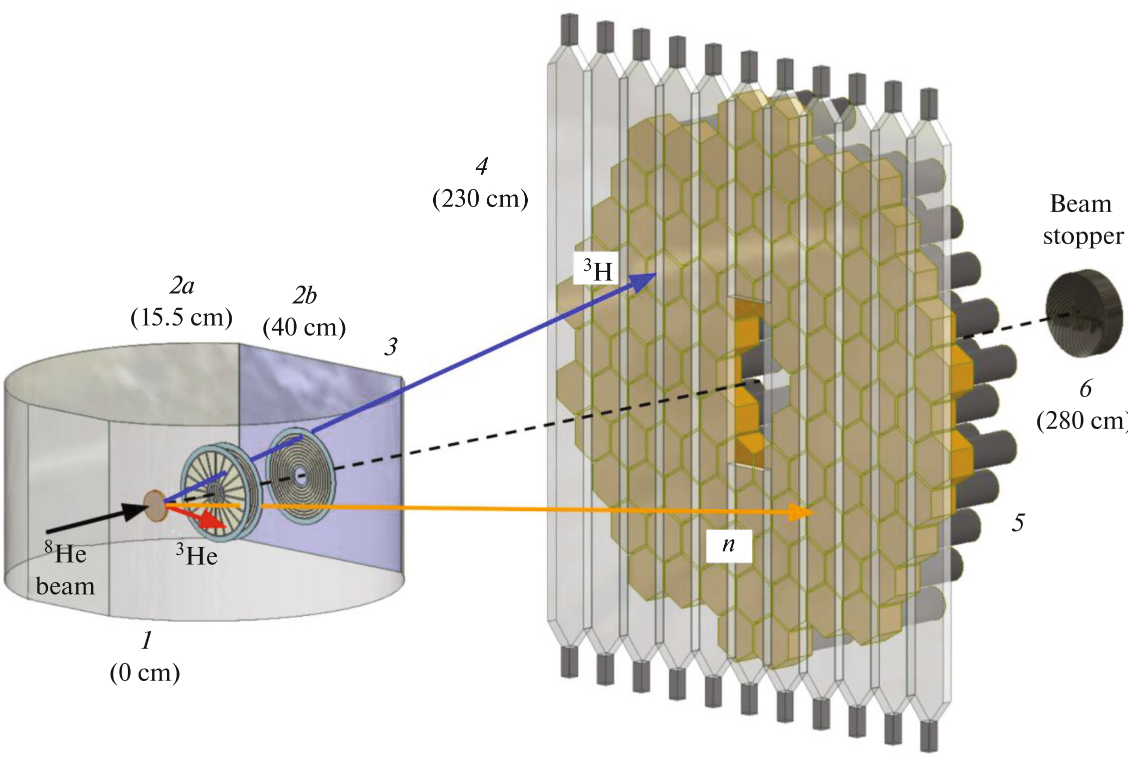

Fig. 2. Setup for the study of the ^{7}H decay events: (*1*) cryogenic deuterium target; (*2a*) 0.140 mm thick annular Si detector backed with the 1 mm thick annular Si detector; (*2b*) 1.5 mm thick annular Si-detector; (*3*) 0.18 mm thick stainless-steel vacuum window; (*4*) plastic-scintillator array stopping the ^{7}H-decay tritons; (*5*) Neutron Wall (NW); (*6*) beam stopper. The distances from the target to the items enumerated in this Figure are given under the sequence numbers. Helium bag filling the whole space between (*3*) and (*4*) is not shown in this drawing.

The values of this depletion constant obtained for neutrons with the five different energy values are given in Table 1.

The values of flux reduction factor obtained as $F = e^{-\lambda 75}$ for neutrons passing through the 75 mm thick BC-404 scintillator are given in Table 1 in last raw. Thus, the probability that neutrons with energy 20–30 MeV could produce any of the specified above reaction is estimated as $1 - F \approx 0.43$. Detection probability $\varepsilon_n \approx 0.28$ was estimated comparing these reaction probabilities with those which were typical for the neutron modular detector DEMON [6].

2. DETECTOR ARRAY TRIGGERING THE DATA STORAGE

The suggested choice for the detector array, giving trigger signals produced by the ^{3}He recoil nuclei emitted in the ^{2}H(^{8}He,^{3}He)^{7}H reaction, is to place at position *2a* (see Fig. 2) a detector telescope made of a pair of annular Si detectors. Each detector is segmented in 64 rings and 64 sectors and has the 28 mm central hole and sensitive area with the 32 mm inner diameter and 125 mm outer diameter. The 0.140 mm thick front detector is the source of trigger signals generated from the recoil ^{3}He nuclei. The second detector will be 1.0 mm thick.

Energy range 9–22 MeV is inherent to the ^{3}He recoils emitted in the ^{2}H(^{8}He,^{3}He)^{7}H reaction populating the ^{7}H nucleus excitation spectrum in a range of 0–9 MeV above the ^{3}H+4n decay threshold. Such recoils with energy >14 MeV pass through the 0.140 mm front Si detector and are stopped in the second, 1 mm thick Si detector. These nuclei will be identified by the ΔE–E method against the background made by the other recoil nuclei (^{2}H, ^{3}H, ^{4}He, ^{6}He, etc.) which are emitted from the target. The 9–14 MeV ^{3}He recoils, stopped in the front Si detector, will be safely discriminated from the ^{3}H recoils, emitted from the target with similar energy, because for these ^{3}H recoil nuclei the ΔE–E identification signals are provided by the detector telescope placed in position *2a*.

As for the ^{3}He and ^{4}He recoil nuclei emitted from the target with energy $E_{3\text{He}} < 14$ MeV and $E_{4\text{He}} < 16$ MeV, respectively, their identification will be performed on the basis of the E-ToF method consisting in the comparison of the measured energy deposit made by the recoil nucleus in the front, 0.140 mm detector, and its flight time (ToF) expended on the 155 mm distance from the target to this detector. The "start" (zero-mark) time is given by the radioactive-beam (RIB) diagnostic array situated upstream the target, and the signal coming from the front, 0.140 mm ΔE detector will provide the stop mark for the ToF evaluation. The zero-time start signal is provided by the ACCULINNA-2 RIB diagnostic with a root-mean-square error 0.2 ns, and the time measurement made with the ΔE Si detector gives the 0.5 ns stop-signal time spread. This will result in the safe separation of individual nuclides between the whole group of the ^{3}He, ^{4}He, ^{6}He, ^{8}He, ^{6}Li, and ^{7}Li recoil nuclei hitting the 0.140 mm Si detector. Results obtained by means of Monte Carlo (MC) simulations testify in behalf of this estimation. All simulations assumed that the 8He beam, having emittance 75π mm·mrad in both transverse phase-space planes and energy spread $\Delta E/E = 5\%$ (FWHM), was focused on a target within a circle with diameter 15 mm.

Table 1. Depletion constant and flux-decrease factors in the material of plastic BC-404 obtained for the neutrons at five energy values. F is the factor of flux reduction obtained at plastic depth 75 mm

E_n, MeV	10	20	25	30	35
λ, mm^{-1}	0.00760	0.00770	0.00738	0.00724	0.00630
F	0.56	0.56	0.57	0.58	0.68

One simulation result is presented in Fig. 3. Shown are the Energy–ToF distributions simulated for the ^{3}He recoil nuclei and ^{4}He background nuclei emitted from the target and detected by the 0.140 mm thick annular Si detector *2a* shown in Fig. 2. The source of the ^{3}He recoil nuclei is the ^{2}H(^{8}He,^{3}He)^{7}H reaction populating the ^{7}H 2.2 MeV ground state in the center-of-mass angular range 0–20 deg. These nuclei are assumed to be formed in the thick, 2.5 mg/cm^2 cryogenic deuterium target. It is evident that the distributions, simulated for the two recoils, only weakly overlap in this two-dimension plot. More than 95% of these ^{3}He recoil nuclei can be separated without a noticeable ^{4}He impurity. Being taken in 1.0 MeV ^{3}He energy bands, these distributions have roughly 0.5 ns width (FWHM).

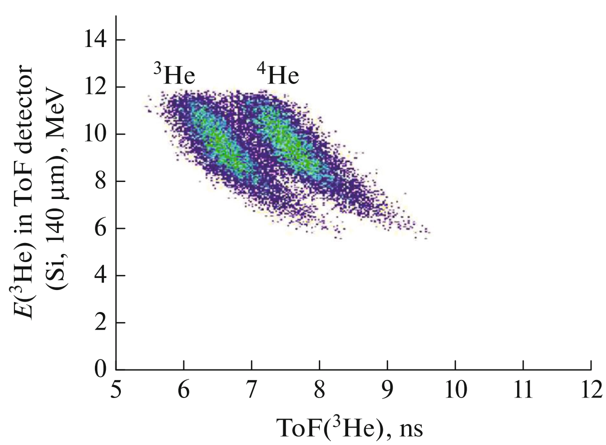

Fig. 3. The Energy–ToF spectra simulated for the ^{3}He and ^{4}He nuclei emitted from the target and stopped in the 0.140 mm annular Si detector. Further explanations are given in text.

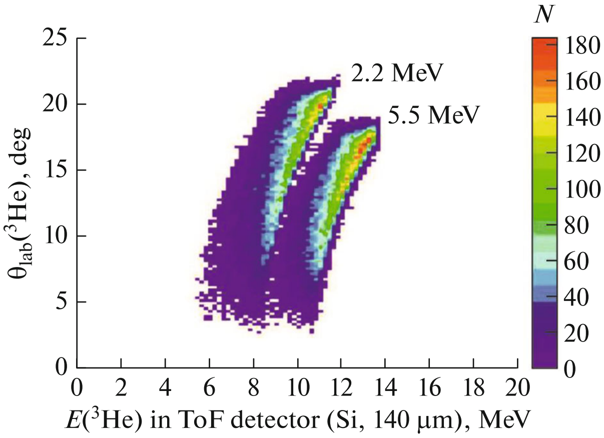

Fig. 4. The θ_{lab} vs. E_{lab} distributions obtained by the complete MC simulations made for ^{3}He recoil nuclei appearing in the ^{2}H(^{8}He,^{3}He)^{7}H reaction resulting in the population of the ^{7}H resonance states with energy 2.2 and 5.5 MeV. Simulations were made for the cryogenic D_2 target with a thickness of 2.5 mg cm^{-2}, in the center-of-mass angular range 0–20 deg.

3. INFORMATION DEDUCED ON THE ^{7}H SPECTRUM USING THE COMBINED MASS METHOD

We will discuss now the application of the combined-mass method, originally developed in [7], to the study of ^{7}H spectrum obtained in the ^{2}H(^{8}He,^{3}He)^{7}H reaction. Discussed here is the experiment which will be carried out with the 25 AMeV radioactive ^{8}He beam bombarding a 2.5 mg cm^{-2} (7.5 × 10^{20} cm^{-2}) deuterium gas target. So thick target leads to the ^{7}H missing mass determination practically useless with very bad energy resolution. However, the poorly measured energy and emission angle of the ^{3}He recoil nucleus cause the good determination of the center-of-mass momentum value and the trajectory angle made for the complete pattern of five decay products (^{3}H + 4*n*) emitted by the ^{7}H nucleus in the ^{2}H(^{8}He,^{3}He)^{7}H reaction. Precision achieved by this procedure depends on the errors inherent to the measured ^{3}He energy (E_{lab}) and angle (θ_{lab}).

Realistic estimates come out for these errors from the complete MC simulation made for the ^{2}H(^{8}He,^{3}He)^{7}H reaction populating the known ^{7}H resonance states [2] with energies 2.2 and 5.5 MeV above the ^{3}H + 4*n* decay threshold. The θ_{lab} vs. E_{lab} distributions obtained for ^{3}He recoils showing the population of these ^{7}H states are presented in Fig. 4. The pattern displayed in Fig. 4 shows that less than 1.5% of 5.5 MeV states populated in the ^{2}H(^{8}He,^{3}He)^{7}H reaction mix with the 2.2 MeV states. Having θ_{lab} measured with a 20 mrad precision, one knows, with precision better than 4 mrad, the center-of-mass emission angle of the produced ^{7}H nucleus. At that time, the ^{7}H momentum value in laboratory system is defined with accuracy 0.05%. For that reason, the accurate knowledge of the ^{7}H momentum vector together with information about only four of the five ^{7}H → ^{3}H + 4*n* decay products enables one to reconstruct the ^{7}H excitation energy with high resolution.

The discussed approach will allow one to see the real profiles of the ground state (2.2 MeV) and the first excited state (5.5 MeV) ^{7}H resonances with the FWHM resolution making 0.45 and 0.75 MeV, respectively. These values are almost 2 times better than the resolutions achieved in [1, 2].

4. ^{3}H NUCLEI AND NEUTRONS EMITTED AT THE ^{7}H DECAY

The detection of ^{7}H decay neutrons, their time-of flight and trajectory measurement, is the principal function of the Neutron Wall presented above. Operating together with the RIB diagnostic system of the ACCULINNA-2 separator the Neutron Wall placed at a distance 230 cm downstream the target will provide one-percent precision in the velocity measurement done for the neutrons. Their trajectory angles will be measured with accuracy ±20 mrad.

The 1.5 mm thick annular Si multi-strip detector *2b* (see Fig. 2), having the same sensitive area as the recoil detectors *2a*, will give Δ*E* signal for the main part of the ^{3}H nuclei emitted from the target offering the measurement of their specific energy loss (Δ*E*) and emission angle (θ_{lab}) made with accuracy 150 keV and 7.5 mrad, respectively. Some of these ^{3}H nuclei, emitted at the ^{7}H decay at larger lab angles, will miss *2b*. But information on their specific energy loss and emission angles will come from the Δ*E*–*E* array *2a*.

The plastic detector array *4* is placed in front of NW (see this in Fig. 2). It is intended for measuring the rest energy E and the flight time (ToF) of ^{3}H nuclei at the distance from the target making 225 cm. It is made of ten 1 m long and 88 mm wide BC-404 scintillator plates having thickness equal 20 mm. Being disposed as two groups in five plates these plastics will be placed on the two sides of axis *Y*, marked in Fig. 1. Each scintillator plate is viewed from two sides by the PMTs resulting in the definition of ^{3}H stop time made with 0.2 ns accuracy. The ^{3}H nuclei emitted from the target with energy ≤100 MeV are stopped in the 20 mm thick plastic.

The pair of 45 cm long, 20 mm thick plastics, each coupled with PMT on one side, will be placed in front of NW to cover its middle area left uncovered by the 1 m plastics. This plastic pair will leave open free way for ^{8}He nuclei to pass to the beam stopper. Thus, the ToF–Δ*E*–*E* identification will be provided for the ^{3}H nuclei coming from the target. The ToF values mea-

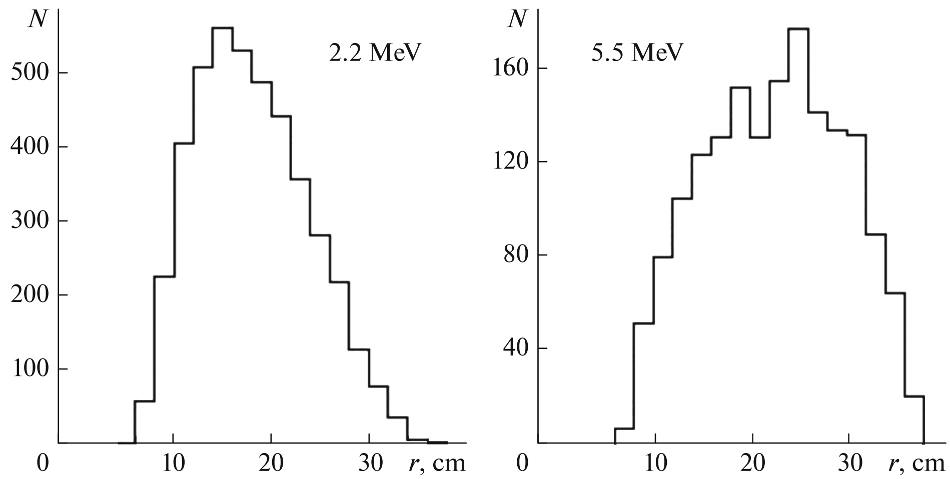

Fig. 5. MC simulated radial distributions obtained at the distance 225 cm from the target for the ^{7}H decay tritons. On the left and right sides shown are the distributions obtained for the decay of the ground (2.2 MeV) and first (5.5 MeV) ^{7}H states, respectively, populated in the ^{2}H(^{8}He,^{3}He)^{7}H reaction in the center-of-mass angular range 0–20 deg.

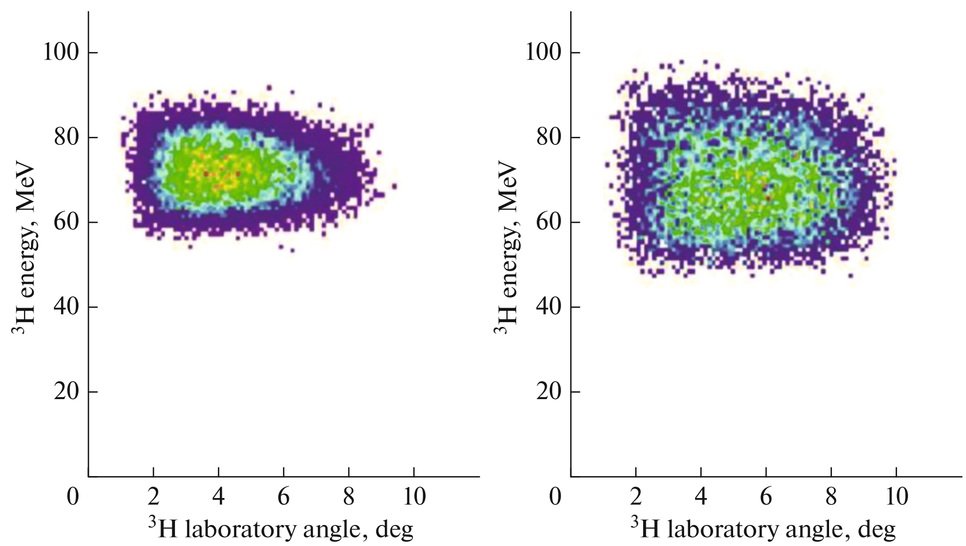

Fig. 6. Energy vs. angle distributions obtained by MC simulation for the ^{3}H nuclei emitted at the 5-body decay of ^{7}H nuclei produced in the ^{2}H(^{8}He,^{3}He)^{7}H reaction in their 2.2 MeV ground state (left side) and in the 5.5 MeV first resonance state (right side).

sured with resolution 0.4 ns will give energy determination made for the ^{3}H nuclei emitted at the five-body decay of ^{7}H nucleus.

MC simulations were made for the ^{7}H five-body decay in the framework of phase-space volume approximation. In particular, shown in Fig. 5 are the MC simulated radial distributions obtained at the distance 225 cm from the target for the ^{7}H decay tritons being detected by the annular Si multi-strip detector *2b*. Patterns in Fig. 6 allow one to see the energy values of these tritons shown against their emission angles. Presented in this figure are the simulation results where the detection of the ^{3}He recoils, emitted at the reaction center-of mass angles 0–20 deg, is supplemented with the arrival of all ^{7}H decay products, ^{3}H and 4 neutrons, to the plastic array *4* and NW *5*, respectively (see Fig. 2).

Distributions simulated for the neutron arrival positions at the Neutron Wall are shown in Fig. 7.

Looking at the neutron energy spectra shown in Fig. 8 one can see a quite large spread in the energy and ToF values.

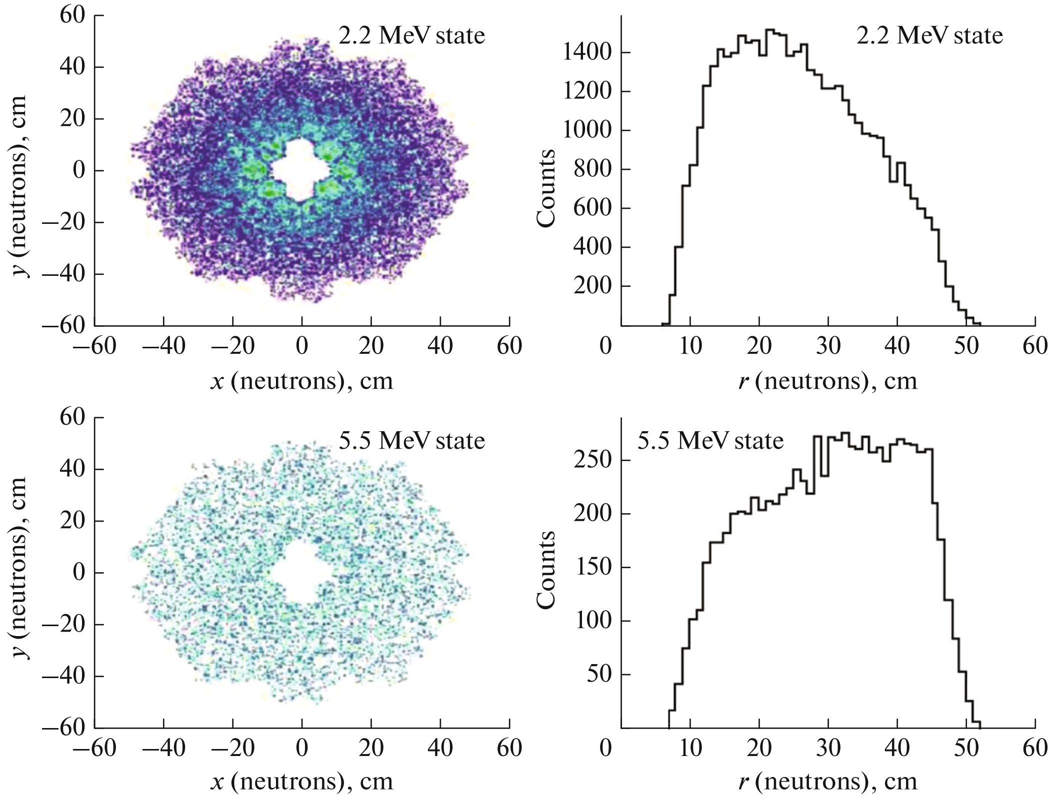

Fig. 7. MC simulated transverse profiles (left column) and radial distributions (right column) obtained at the Neutron Wall for the ^7H decay neutrons emitted from the ground (2.2 MeV) and the first excited (5.5 MeV) ^7H states.

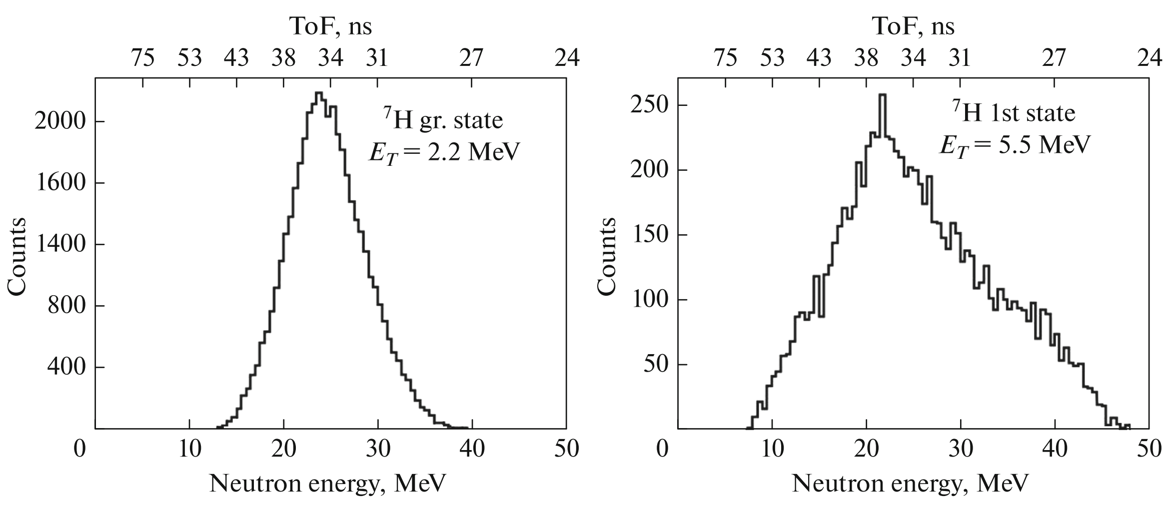

Fig. 8. The energy spectra of neutrons emitted from the deuterium target when ^7H is produced in its ground (2.2 MeV) and the first excited (5.5 MeV) states in the $^2H(^8He,^3He)^7H$ reaction. Given on top are the neutron ToF values calculated for the 230 cm distance to the Neutron Wall.

5. LUMINOSITY ESTIMATION

Basic for the estimations made on the setup efficiency is the chance that minimum four of the five ^7H decay products (four or three neutrons with the triton detected in *2a* and/or *2b*, and 4 neutrons without the triton) arrive at the array *4* and at NW *5* (see Fig. 2) when the ^3He recoil emitted in the $^2H(^8He,^3He)^7H$ reaction is detected in *2a*. The results of such MC esti-

Table 2. Probabilities to have the ^{7}H decay products arriving at the position in front of the Neutron Wall

^{7}H states	Ground state, 2.2 MeV		1st state, 5.5 MeV		2nd state, 7.5 MeV	
θ_{cm}	0°–20°	20°–30°	0°–20°	20°–30°	0°–20°	20°–30°
^{3}He + t4n	0.25	0.27	0.049	0.032	0.019	0.012
^{3}He + t3n	0.32	0.36	0.29	0.22	0.18	0.14
^{3}He + 4n	0.065	0.027	0.013	0.019	0.008	0.009

Table 3. Luminosity estimations

^{7}H states	Ground state, 2.2 MeV		1st state, 5.5 MeV		2nd state, 7.5 MeV	
θ_{cm}	0°–20°	20°–30°	0°–20°	20°–30°	0°–20°	20°–30°
ε_d	0.0370	0.0362	0.0122	0.0096	0.0065	0.0052
$\Delta\Omega$, sr	0.35	0.08	0.33	0.27	0.31	0.46
L, cm^{-2} s^{-1}	8.5×10^{23}	2.2×10^{23}	3.0×10^{23}	2.0×10^{23}	1.5×10^{23}	1.8×10^{23}

mations, made for ^{7}H obtained in the three different states and in the two reaction angular ranges, are given in the three last rows in Table 2.

Taking these results and assuming the detection probability $\varepsilon_n = 0.28$ for single neutrons in NW, the detection probability is estimated numerically for any combination of minimum four of the five ^{7}H decay products (^{3}H with 3n, ^{3}H with 4n, 4n without ^{3}H) being recorded in the ^{2}H(^{8}He,^{3}He)^{7}H reaction in coincidence with the ^{3}He recoil. The sum of these numbers gives the probability ε_d that the five-body decay of ^{7}H is detected in our setup.

The corresponding ε_d values are presented in Table 3, third raw. The expected luminosity values L appearing in the experiment made for the study of the ^{7}H system formed in the three energy states, 2.2, 5.5, and 7.5 MeV, are presented in Table 3, last raw.

Luminosity is calculated as the product

$$L = \varepsilon_d t I \Delta\Omega,$$

with the detection probability ε_d given in Table 3, with the assumed target thickness $t = 7.5 \times 10^{20}$ cm^{-2}, the ^{8}He beam intensity $I = 2 \times 10^5$ s^{-1}, and with the estimated values of the solid angle covered by the triggering array *2a* shown in Fig. 2.

Data reported in [2] provide rough estimations made on the cross sections of the ^{2}H(^{8}He,^{3}He)^{7}H reaction resulting in the population of the ^{7}H ground state and its first excited state having energy ≈2.2 MeV and ≈5.5 MeV, respectively, above the ^{3}H + 4n decay threshold. Average differential cross section estimated in [2] for the ^{2}H(^{8}He,^{3}He)^{7}H reaction populating the ^{7}H ground state in angular range θ_{cm} = 0°–20° is 1×10^{-29} cm^2/sr. Such estimate made for the first excited state population is 3×10^{-29} cm^2/sr. Consequently, total statistics gained during the one-month time of experiment will contain ~50 five-body decay events recorded for each of these two ^{7}H states. The reaction center-of mass angle will be known in each case with accuracy 4 mrad. The recorded data will carry information allowing to determine the flight direction and energy for the triton and for each of the four neutrons emitted at the ^{7}H decay. For the 75 MeV decay tritons, the emission angle and energy in lab system will be measured with error bars making 7.5 mrad and 1 MeV, respectively (FWHM). Similar errors obtained for the 25 MeV neutrons will be 40 mrad and 0.9 MeV, respectively.

The so measured flight directions and energies of the ^{7}H decay products will yield the decay energy of ^{7}H 2.2 MeV ground-state obtained with FWHM resolution making about 0.4 MeV, i.e., by 2.5 times better than reported in [2]. Results reported in [3] about the four-body decay of the ^{6}H nucleus obtained in the ^{2}H(^{8}He,^{4}He)^{6}H reaction show that such data accuracy will allow the revelation of dineutron-type correlation in the five-body decay of ^{7}H.

6. CROSS-TALK AND PILE-UP CAUSED LOSSES

The Neutron Wall composition made with the 75 mm thick plastics results that less than 5% of the total number of detected 3-fold and 4-fold neutron events are spoiled by the occurrence of such events when a single neutron is detected, due to re-scattering, in two adjacent scintillators (the so-called cross-talk). Time difference < 1 ns between the two neutron signals distinguishes these cross-talks from the overwhelming part of events obtained with two ^{7}H decay neutrons detected in adjacent scintillators. Throwing out all events looking as cross-talks will not result in any noticeable loss in the luminosity of the experiment. The loss occurring from this ejection in the real collected data will be less than 2%.

Probability to have two neutrons hitting a single plastic makes about 8% when four neutrons emitted at the ^{7}H decay arrive at the Neutron Wall. More than one-half of such pile-up events will be stored with the complete data set, characterizing the ^{3}He recoil, and with four (3 neutrons and ^{3}H) of the five ^{7}H decay products. About 4% of pile-up events are possible when three neutrons, emitted at the ^{7}H decay, arrive at the Neutron Wall. Therefore, conclusion is made that the neutron pile-up results in a 4% reduction of detection efficiency as compared with the data given in the last row of Table 3.

In summary, taking into account the cross-talk rejection and the losses caused due to pile-ups one should take luminosity estimates reduced by 6% as compared with the numbers presented in Table 4.

In addition, we expect only a small contribution from the gamma-ray background. The main sources of gamma-ray background could be materials *1*, *2a*, *2b* and *3* (Fig. 2). In this case, the time of flight to the Neutron Wall will be less than ~9 ns, which is far from the typical time of flights corresponding to neutrons (see Fig. 8).

6. EXPERIMENTAL TEST AND CONCLUSIONS

The given above estimations of cross-talk and detection efficiency, made for the Neutron Wall looking as a very compact assembly of BC-404 plastics, should be checked experimentally in a wide energy range of neutron energy 15–45 MeV. For this task the measurements of the ^{1}H(^{3}H,^{3}He)n reaction, induced by the ^{3}H beam obtained at ACCULINNA-2 with energy 25–60 MeV and intensity 10^6 s^{-1}, are foreseen. The recoil ^{3}He nuclei are emitted from the target showing the neutron energy and flight direction. At the ^{1}H(^{3}H,^{3}He)n reaction cross section making ~1 mb/sr and the thickness of hydrogen target ~10^{21} cm^{-2} about 1 neutron per minute will be detected by a single BC-404 detector module included into an array of 7 plastics shown in Fig. 1. In these measurements the triggering process (detection of low energy, ~10–20 MeV, ^{3}He recoil nuclei) using Si annular telescope will be optimized as well.

The proposed detector systems[1], together with the existing array of stilbene modules [8], will increase significantly the luminosity of the ACCULINNA-2 setup which plays a key role in the experiments with radioactive beams [9]. These simulations, carried out for the ^{2}H(^{8}He,^{3}He)^{7}H reaction, are the first approximation to the detailed studies made on the multi-neutron decay of exotic nuclei like ^{7}H, ^{7}He* and ^{6}H, produced with the ^{8}He beam bombarding deuterium target, and on the 4n excitation spectrum obtained in the ^{2}H(^{8}He,^{6}Li)4n reaction.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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[1] Present status of the new detector array is as follows: (1) there are all components of NW, i.e. 100 BC-404 plastics and ETE-9822B photomultipliers; (2) the annular Si detectors with 32/125 mm inner/outer diameter segmented in 64 rings and 64 sectors will be ready in fall 2023; (3) the array of ten 1 m long plastic scintillators, 88 mm wide and 20 mm thick, is under design.