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O.M. POVOROZNYK, O.K. GORPINICH, O.A. PONKRATENKO

Institute for Nuclear Research, Nat. Acad. of Sci. of Ukraine
(47, Prosp. Nauky, Kyiv 03680, Ukraine; e-mail: orestpov@kinr.kiev.ua)

ON THE PECULIARITIES OF STUDYING UNBOUND EXCITED STATES OF ^{4}He NUCLEUS BY $\alpha + {}^3$H INTERACTION

Due to the alpha-particle beam interaction with tritium, the two-dimensional spectra of tt, t^{3}He, and dd coincidences are obtained using the particle-decay spectroscopy from three-particle $^3H(\alpha,tt)p$, $^3H(\alpha,t^3He)n$, and $^3H(\alpha,td)d$ reactions (E_α = 67.2 MeV). Excitation energies and energy widths for seven excited ^{4}He states, as well as the ratio of their different decay modes, namely $t+p$, $n+{}^3He$, and $d+d$, are obtained by using the Monte Carlo method.

K e y w o r d s: excited states, decay modes.

1. Introduction

The specificity of the study of the excited states of the lightest nuclei is that most of them are unbound (i.e. they are resonances), and the decay of such excitations occur mainly due to the flight of two or more particles. The ^{4}He nucleus is a doubly magic strongly bound system in which, apart from the main bound state, all excited levels are unbound, that is, decaying mainly through the emission of a pair of particles.

Over the last half-century, several experimental and theoretical studies of the excitation spectrum of ^{4}He nucleus have been done. Experiments on elastic $p+t$, $n+{}^3$He, and $d+d$ scattering, as well as binary scattering, were carried out over a wide energy range. The ^{3}He$(n,p)^3$H, ^{3}H$(p,n)^3$He, ^{3}H(p,d)2H, ^{2}H$(d,p)^3$H, and ^{2}H$(d,n)^3$He nuclear processes, as well as the accompanying theoretical analysis of the data collected in these experiments using the R-matrix approach [1]. Excitation energies and lifetime excited states are derived indirectly in such experiments, which might lead to considerable inaccuracies.

A more accurate method is the method of particle-decay spectroscopy, which consists in registering at the coincidences of the particles into which the excited state of the investigated state decays. For the ^{4}He study, such an experiment may involve the interaction of alpha particles with any of the isotopes of hydrogen (^{1,2,3}H) or the ^{3}He nucleus, in which unrelated levels can be observed by recording the coincidence of recoil nuclei (^{1,2,3}H, ^{3}He) simultaneously with all possible decay products of excited states of ^{4}He nucleus. The use, in the input channel, of a beam of accelerated alpha particles ($m_p \approx 4$ a.o.) and a target any of the isotopes of hydrogen or ^{3}He has a number of advantages, namely: because the mass of the flying particle, m_p, is greater than the mass of the target nucleus m_T, then this kind of experiments has the inverse kinematics [2], in which the departure of the reaction products is directed mainly at the front angles. If we ensure the accurate determination of the energies and angles for the departure of the reaction products recorded at the coincidence, there is a kinematic increase in the yield of products, which improves the statistics of experimental results compared to the direct kinematics. In addition, the relatively small number of nucleons involved in the input channel (from 5 to 7) allows a kinematically complete study of three-particle reactions of the type (^{1,2,3}H, ^{3}He)[α,(^{1,2,3}H, ^{3}He)]^{4}He* $\rightarrow t+p$ or $\tau+n$ or $d+d$ with a relatively small background of other open three-particle channels caused by the same input channels.

In this work, in one experiment, the interaction of alpha particles with tritium nuclei at the energy of accelerated alpha particles $E_\alpha = 67.2$ MeV, sufficient to observe all possible two-particle decay channels of ^{4}He nucleus, was studied with a simultaneous analysis of a kinematically complete experiment with three-particle ^{3}H$(\alpha,tt)\,p$, ^{3}H$(\alpha,t^3$He$)\,n$, and ^{3}H$(\alpha,td)\,d$ re-

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actions to an excitation energy of 28 MeV. Based on the minimality of the accompanying three-particle channels, it would be more optimal, if the beam of alpha particles interacted with ^{1}H hydrogen nuclei, but then to achieve the excitation energy of ^{4}He nucleus equal to 28 MeV requires a beam of alpha particles with an energy of at least 140 MeV, which is not available to us.

2. Features of the Experiment

Particle-decay spectroscopy is a kinematically complete experiment in which excited unbound levels of ^{4}H nucleus are investigated using three-particle $^3\mathrm{H}(\alpha, tt)\,p$, $^3\mathrm{H}(\alpha, t\tau)\,n$, and $^3\mathrm{H}(\alpha, td)\,d$ reactions by applying a solid titanium target saturated with tritium and a beam of alpha particles with an energy of 67.2 MeV, which was conducted on a U-240 cyclotron. Schematically in this case, the formation of three particles $t + t + p$, $t + \tau + n$, and $t + d + d$ in the corresponding source channels of three-particle reactions is interpreted as a two-stage process of settlement and decay of excited states of ^{4}He nucleus caused by the $\alpha + t$ interaction:

$$\begin{array}{lll} & \nearrow & t + p, \qquad (1) \\ ^3\mathrm{H} + \alpha \to t + {}^4\mathrm{He}^* & \to & \tau + n, \qquad (2) \\ & \searrow & d + d. \qquad (3) \end{array}$$

If we obtain two-dimensional spectra caused by coincidences of tritons corresponding to the first stage of the reaction – the formation of excited states of ^{4}H nucleus with tritons or protons, α-particles or neutrons and one of the deuterons formed by the decay through channels 1, 2, and 3, then such experimental data contain information about the energy characteristics of excited ^{4}He levels. Two-dimensional spectra of tt, τt, and td coincidences were obtained for six pairs of the placement angles of the first detector (θ_1), which registered the recoil triton and the second (θ_2), which simultaneously recorded different decay modes of unbound excited states of ^{4}He nucleus by detecting the decay products of these states (tritons α-particles and deuterons): $\theta_1/\theta_2 = 15^\circ/15^\circ$; $15^\circ/27.5^\circ$; $21^\circ/15^\circ$; $21^\circ/15^\circ$; $21^\circ/20^\circ$; $27.5^\circ/15^\circ$.

In this case, it is important to choose the geometry of the input $\alpha + t$ channel, i.e., the angular location of the detector systems. Due to the inverse kinematics, helium nuclei formed in excited states will fly in a limited cone of the frontcorners in the laboratory

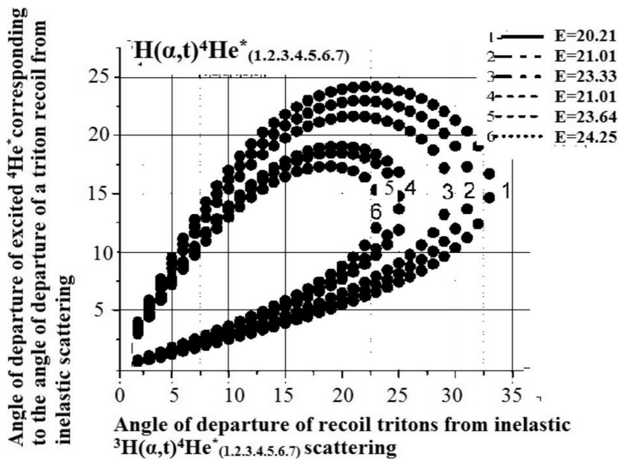

Fig. 1. Relationships between the angles of departure of recoil ^{3}H nuclei and ^{4}He* nuclei in excited states for the $^3\mathrm{H}(\alpha, t)^4\mathrm{He}^*$ reaction

coordinate system. Thus, for recoil nuclei at an excitation energy of 21 MeV, such a cone will have an angle of 33°, and, at an energy of 25 MeV – 22°. Accordingly, the cone of excited helium nuclei is in the interval from 18° to 25°. Figure 1 shows the relationship between the angles of departure of tritium recoil nuclei and those formed during the interaction of ^{4}He nuclei in excited states. The part of the excitation spectrum of ^{4}He ($E_{\mathrm{ex}} < 23.5$ MeV) was studied previously. The energy positions and widths of the first 4 excited states of ^{4}He and the ratio of decay modes 2, 3, and 4 in the channels $t + p$ and $\tau + n$ were determined [3].

Accordingly Fig. 2 depicts the angular dependence of the energy of tritium recoil nuclei corresponding to the population of these levels in the $^3\mathrm{H}(\alpha, t)^4\mathrm{He}^*$ reaction. The arrows indicate the angles of the tritons in the experiment. This implies that it is more expedient to analyze the two-dimensional coincidence spectra measured when the triton detector is placed at an angle of 15°, since, in this case, it is possible to study the excited levels of ^{4}He nuclei up to an excitation energy of 26–27 MeV.

If we calculate the dependencies of the relative energies of the outgoing pairs of particles tp, τn, and dd on the energy of the recorded recoil triton for the upper branches of the three-particle $^3\mathrm{H}(\alpha, tt)\,p$, $^3\mathrm{H}(\alpha, t\tau)\,n$, and $^3\mathrm{H}(\alpha, td)\,d$ reactions ($\theta_t = 15^\circ$; $\theta_{t,\tau,d} = 27.5^\circ$) and add, to the calculated values of the relative energies, the corresponding threshold energies of the decay of ^{4}He nucleus. Then we obtain

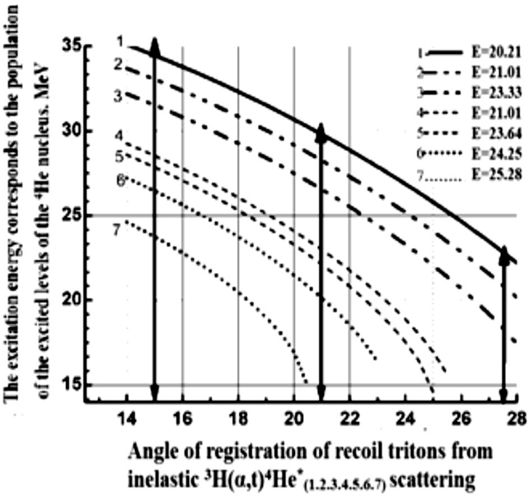

Fig. 2. Angular dependencies of the energy of tritons of recoil from ${}^{3}\mathrm{H}(\alpha, t)^{4}\mathrm{He}^{*}$(1,2,3,4,5,6,7) reaction

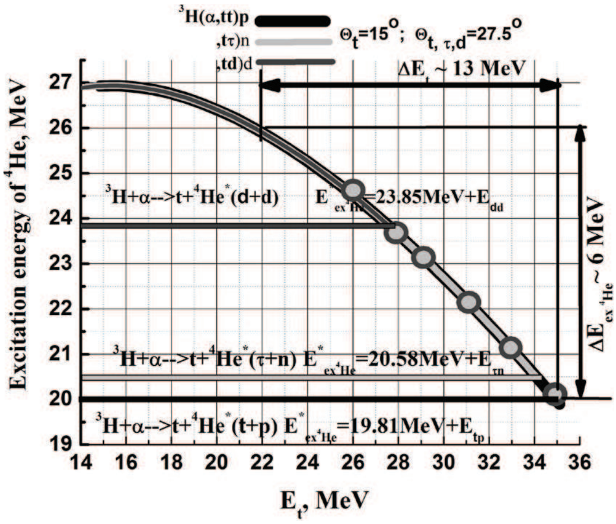

Fig. 3. Dependence of the excitation energy of ^{4}He nucleus on the energy of tritons (upper branch). The black, white, and dashed black curves represent ${}^{3}\mathrm{H}(\alpha, tt)\, p$, ${}^{3}\mathrm{H}(\alpha, t\tau)\, n$, and ${}^{3}\mathrm{H}(\alpha, td)\, d$ three-particle reactions, respectively. Numbers 1, 2, 3, 4, 5, 6, and 7 indicate the positions of the first seven excited levels of ^{4}He nucleus from work [1]

the dependence of the excitation energy of ^{4}He nucleus on the energy of the registered recoil tritons (see Fig. 3). The resulting dependences are determined for the ${}^{3}\mathrm{H}(\alpha, tt)\, p$ reaction in the entire given interval of triton energies ($14 < E_t < 35$ MeV). As can be seen, the first three-particle reaction covers the excitation energies for ^{4}He nucleus from 19.8 MeV to 27 MeV, the other two, respectively, from 20.58 MeV and 23.85 MeV to the same 27 MeV. In addition, we have the opportunity to take advantage of the phenomenon of the so-called kinematic lens, since, for example, in the case of the three-particle reaction ${}^{3}\mathrm{H}(\alpha, tt)\, p$, a decrease in the triton energy by 13 MeV leads to an increase in the excitation energy by only 6 MeV (see Fig. 3).

3. Processing of Experimental Two-Dimensional Spectra of Coincidences

The ${}^{3}\mathrm{H}(\alpha, tt)\, p$, ${}^{3}\mathrm{H}(\alpha, t\tau)\, n$, and ${}^{3}\mathrm{H}(\alpha, td)\, d$ reactions were investigated by using a target made of titanium backing saturated with tritium. The thickness of the titanium backing was 2.6 mg/cm^2. By considering the saturation of the tritium atoms in the lattice of titanium atoms, we determined that the ratio of the number of titanium atoms to that of tritium atoms was approximately equal to 1. Under these conditions, the equivalent thickness of the tritium target was about 0.15 mg/cm^2. Therefore, the total thickness of the titanium backing and tritium target was about 2.75 mg/cm^2. The target was bombarded with -particles at the isochronous cyclotron accelerator U-240 of the Institute for Nuclear Research in Kyiv. The beam energy was determined to be $E_\alpha = 67.2 \pm 0.4$ MeV by using a technique developed to measure time and energy characteristics of the cyclotron beam [4]. We used a two pairs of $E - E$ telescopes to detect t and t, τ, d in coincidence from the ${}^{3}\mathrm{H}(\alpha, tt)\, p$, ${}^{3}\mathrm{H}(\alpha, t\tau)\, n$, and ${}^{3}\mathrm{H}(\alpha, td)\, d$ reactions. The two telescopes were placed at the left side and consisted of ΔE [400 μ thick totally depleted silicon surface barrier detector (SSD)] and E [NaI(Tl) with 20 mm 20 mmt] detectors, and other two telescopes were placed at the right side and consisted of ΔE (90 μ SSD) and E [Si(Li) with 3 mmt] detectors. The detectors located on the left could detect tritons, as well as protons and deuterons, those on the right could detect τ- and α-particles together with protons, deuterons, and tritons of low energies.

A more detailed description of this correlation experiment is given in Refs. [5, 6]. Two-dimensional spectra of tt-, $t\tau$-, coincidences obtained from the study of the three-particle ${}^{3}\mathrm{H}(\alpha, tt)$, ${}^{3}\mathrm{H}(\alpha, t\tau)\, n$, and ${}^{3}\mathrm{H}(\alpha, td)\, d$ reactions were processed using Monte Carlo approaches. As a result of processing the accumulated information “off the line”, which con-

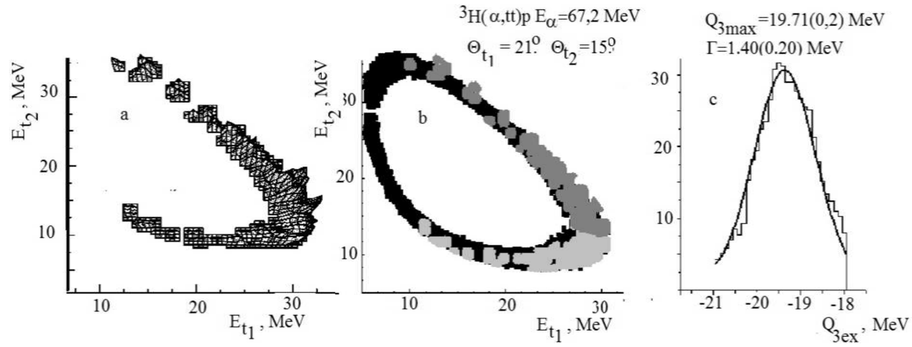

Fig. 4. Two-dimensional experimental spectra of tt – coincidences from the three-particle $^3\mathrm{H}(\alpha, tt)\,p$ reaction. b shows the same spectra after the Monte Carlo procedure [7]. c – spectrum of the energy balance of $Q_{3\mathrm{ex}}$ obtained from the recalculation of the two-dimensional spectrum b

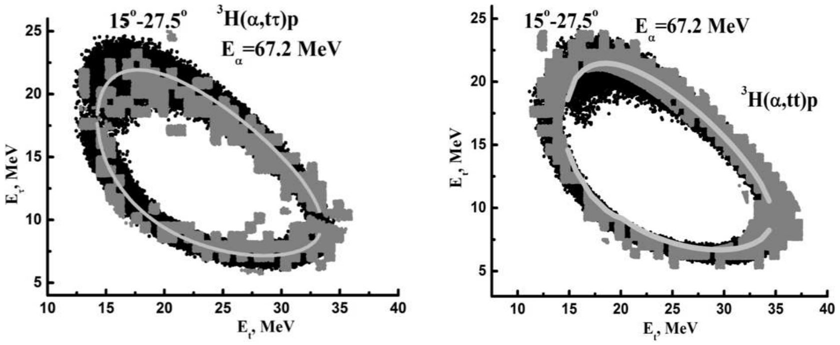

Fig. 5. Grey colors correspond to experimentally obtained loci of matrices tt and $t\tau$ coincidences. Calculations of the kinematic position of the loci of matrices tt and $t\tau$ coincidences in the assumption of point geometry was represented solid line. Black background – the results of modeling kinematic calculations in the Monte Carlo method, taking into account experimental conditions

sisted of sorting experimental files based on the calibration of spectrometers, isolating events that correspond in one of the telescopes registration tritons, and in the other – the same tritons obtained two-dimensional spectraum of tt coincidences (see Fig. 4, *a*). Figure 4, *b* shows the same spectra after the Monte Carlo procedure [7]. Point events are immediately divided into loci tt-coincidences of the upper (gray) and lower (light gray) branches, lying on a black background, which is calculated, basing on real experimental conditions, by the Monte Carlo metho for a kinematically allowed part of the phase space for these events. For each event, the played dimensional experimental spectra of tt coincidences are played out for single events. To check the reliability of the present experiment, the experimental Q-values for the three-body reaction were deduced by the momentum and energy conservations [8]:

$$\mathbf{P}_\alpha = \mathbf{P}_{tR} + \mathbf{P}_{tL} + \mathbf{P}_p, \tag{4}$$

$$E_\alpha = E_{tR} + E_{tL} + E_p + Q_{(\text{three body})}, \tag{5}$$

where $\mathbf{P}_{tR,tL,p}$ and $E_{t,tL,p}$ are the momenta and energies of outgoing particles, and $\mathbf{P}_\alpha$ and E_α are the momentum and energy of the incident α particle, respectively. Equation 4 can be used to calculate the momentum $\mathbf{P}_p$ and energy E_p of the undetected proton, and then Eq. 5 allows the determination of the $Q_{(\text{three body})}$ – value as $Q_{(\text{three body})} = E_\alpha - (E_{t1} + E_{t2} + E_p)$. Accounting for the detector resolution, beam resolution, energy straggling in the target, effect of differential target thickness, kinematic changing from the beam spot size, and beam divergence, we obtain the experimental $Q_{3\,\max}$-value peak of

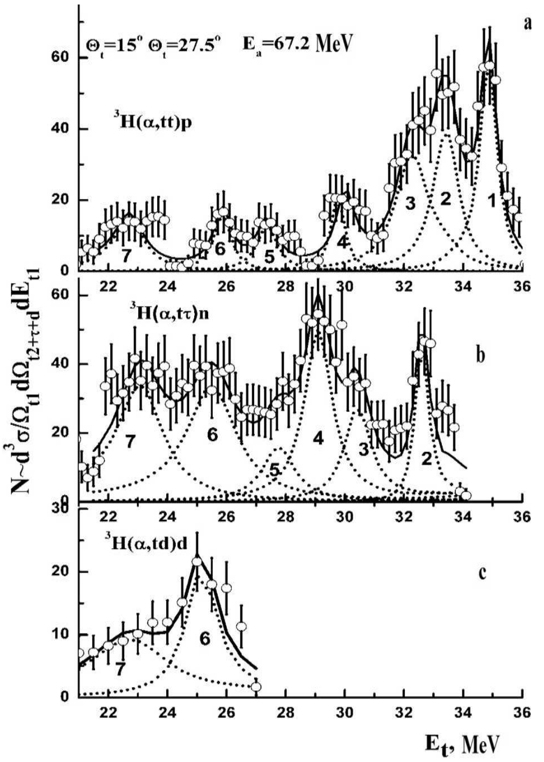

Fig. 6. Projections of the upper branches of two-dimensional spectra on the energy axis of tritons and approximation using formula (4). The numbers indicate the contributions of individual excited levels of ^{4}He nucleus

19.71 MeV for the $Q_{3\text{ex}}$ distribution (while the theoretical Q-value is 19.80 MeV), and the FWHM value of about 1.40 MeV (see Fig. 1, *c*) with a standard deviation of 0.20 MeV for the fit by a Gaussian To illustrate further analysis, the two-dimensional spectra of *tt*, τt, and *td* coincidences obtained at the recoil angle of triton –15° and the corresponding compromise angle of registration of tritons, τ-particles and deuterons generated by the decay of excited ^{4}He – 27.5° Figure 5 shows these obtained two-dimensional spectra.

4. Determination of Energy Parameters of Excited States of ^{4}He Nucleus

Using the Monte Carlo processing program [7] for two-dimensional spectra of *tt*, τt, and *td* coincidences, we obtain projections of the upper branches of these loci (see Fig. 6, *a, b, c*. A complex resonant structure is observed in these one-dimensional spectra. In the spectrum (Fig. 6, *a*) corresponding to the decay of the excited levels of ^{4}He nuclei, 7 excited states were identified at $t+p$, for $\tau+n$ decay mode (Fig. 6, *b*) – 6, and for $d+d$ decay mode (Fig. 6, *c*), respectively – 2. The parametrization of the spectra was performed using an expression adapted to the conditions of this study:

$$\frac{d^3\sigma}{d\Omega_t d\Omega_{t,\tau,d} dE_t} \sim \rho\left(\Omega_t,\Omega_{t,\tau,d},E_t\right)\times$$
$$\times\sum_{j=1}^{n_{t,\tau,d}} C_j^{t,\tau,d} \frac{\Gamma_j^{t,\tau,d}/2}{\left(E^j_{tp,\tau n,dd}-E_{tp,\tau n,dd}\right)^2+\left(\Gamma_j^{t,\tau,d}/2\right)^2}, \quad (6)$$

where Ω_t is the solid angle of the detector *eco newt*, $\Omega_{t,\tau,d}$ is the solid angle of the detector that detects tritons, τ-particles and deuterons from the decay of excited states of ^{4}He nucleus due to radiation of the corresponding pairs of particles – $t+p$, $\tau+n$ and $d+d$. $\rho(\Omega_t,\Omega_{t,\tau,d},E_t)$ is the multiplier of the phase space of that of the three-particle $^3\mathrm{H}\,(\alpha,tt)\,p$, $^3\mathrm{H}(\alpha,t\tau)\,n$ and $^3\mathrm{H}(\alpha,td)\,d$ reactions, corresponding to the decay of the excited states of ^{4}He nucleus due to the corresponding $t+p$, $\tau+n$, and $d+d$ decay mode. $C_j^{t,\tau,d}$, $\Gamma_j^{t,\tau,d}$ are amplitudes of formation and energy widths of the j-th excited state that decays due to the radiation of the corresponding pairs of $t+p$, $\tau+n$, and $d+d$ particles. $E^j_{tp,\tau n,dd}$ – resonance values of the relative energy of the corresponding pairs of particles – $t+p$, $\tau+n$, and $d+d$, which are related to the manifestation of the j-th excited state $E_{tp,\tau n,dd}$ – dependences of the relative energy of the outgoing pairs of particles on the energy of tritons, $n_{t,\tau,d}$ – is the number of excited levels with the corresponding $t+p$, $\tau+n$, and $d+d$ cluster structure. Calculation of energy dependences $\rho\left(\Omega_t,\Omega_{t,\tau,d},E_t\right)$, $E_{tp,\tau n,dd}(E_t)$ on the energy of tritons, in which the conditions of the experiment taken into account were calculated using the Monte Carlo method [8]. The approximations of the spectra, which were performed using the least-squares method to expression 6 in which the values $C_j^{t,\tau,d}$, $\Gamma_j^{t,\tau,d}$ and $E^j_{tp,\tau n,dd}$ are shown in Figs. 6, *a, b, c*. In the spectrum (Fig. 6, *a*), which corresponds to the decay of excited levels of ^{4}He nuclei at $t+p$, 7 excited states are identified, for $\tau+n$ decay mode (Fig. 6, *b*) – 6, and for $d+d$ decay mode (Fig. 6, *c*), respectively – 2. The resonant values of the relative energy of the corresponding pairs of particles – $t+p$, $\tau+n$, and $d+d$, obtained

Excitation energies and energy widths of excited levels of ^{4}He nucleus obtained from the study of three-body ^{3}H$(\alpha, tt)\,p$, ^{3}H$(\alpha, t\tau)\,n$ and ^{3}H$(\alpha, td)\,d$ reactions

j	$^3\mathrm{H} + \alpha \to t + ^4\mathrm{He}^* \to t + p$			$^3\mathrm{H} + \alpha \to t + ^4\mathrm{He}^* \to \tau + n$			$^3\mathrm{H} + \alpha \to t + ^4\mathrm{He}^* \to d + d$		
	E_j^*, MeV	Γ_j, MeV	Part	E_j^*, MeV	Γ_j, MeV	Part	E_j^*, MeV	Γ_j, MeV	Part
1	20.0(0.1)	0.4(0.2)	1						
2	21.0(0.1)	0.7(0.4)	0.61	21.3(0.1)	0.4(0.1)	0.39	–		
3	21.8(0.2)	0.8(0.3)	0.66	22.2(0.2)	0.7(0.3)	0.34	–		
4	23.0(0.1)	0.3(0.3)	0.65	23.1(0.1)	0.6 (0.3)	0.35	–		
5	23.9(0.1)	0.4(0.2)	0.65	23.9(0.1)	0.6(0.6)	0.35	–		
6	24.7(0.1)	0.3(0.1)	0.28	24.7(0.1)	0.8(0.4)	0.14	24.7(0.1)	0.5(0.2)	0.58
7	25.7(0.2)	0.4(0.2)	0.20	25.6(0.2)	0.6(0.2)	0.10	25.6(0.2)	1.0(0.6)	0.70

as a result of the fitting procedure, corresponding to the manifestation of the j-th excited state, were converted into the excitation energies of these levels $E^j_{\mathrm{ex}} = E^j_{tp(\tau n,dd)} + E_{\mathrm{thr.decay\ on\ } p+t(\tau+n,d+d)}$, where $E_{\mathrm{thr.decay\ on\ } p+t(\tau+n,d+d)}$ are the corresponding energies of the decay threshold of nucleus ^{4}He on $t + p$, $\tau + n$, and $d + d$, and together with the obtained energy widths of these levels and errors are given in Table.

5. Application of the Monte Carlo Method to Determine the Ratio of the Decay Modes of Excited States

Since in the experiment to simultaneously record events that correspond to the decay of the same unbound excited states of ^{4}He nucleus through different decay channels (for example, starting from the second level and ending with the seventh, decay by particle pairs – $t + p$ and $\tau + n$, and the last two of them, the sixth and seventh levels, are also characterized by the decay due to the emission of $d + d$) by registering, by coincidence, the first detector of inelastically scattered newt, which testifies to the formation of ^{4}He nucleus in one of the excited states, and the second detector registered the excited state, in addition to data on excitation energies and energy widths of levels. The additional analysis of the same experimental data allows us to obtain information about the ratio of the decay branches of excited states. If to sum up the number of events corresponding to the simultaneous registration in the correlation experiment of the decay of each of the modes of a single excited state and to determine, for this experimental method, the efficiency with which events corresponding to each decay mode are registered, the ratio of the fractions of decay modes divided by the registration efficiency will give the experimental ratio of the decay modes of a single excited state. Now, we consider the application of the Monte Carlo method to determine the ratio of the decay modes of excited states.

To evaluate the efficiency of recording the decay of excited unbound states of ^{4}He nuclei that inhabit due to the interaction of accelerated alpha particles with tritium nuclei and are investigated by recording one detector of scattered tritium nuclei at the same time as the decay products of the corresponding excited states allowed the channel of this decay, we can use the Monte Carlo simulation. Note that, for the Monte Carlo simulation procedure, it is necessary to accurately determine the experimental parameters of kinematically complete study of a three-particle nuclear reaction, namely: energy scatter of the beam energy of accelerated particles, spot size from the beam on the target, target thickness, size of body angles, and energy resolution. This three-particle reaction should be interpreted as two-step. The first stage is a quasiparticle process of formation of the tritium recoil nucleus and, accordingly, ^{4}He nucleus in the excited state. To describe this process, the energy and geometric conditions of nuclear interaction should be played out, namely: the place of the nuclear interaction in the target (position on the spot from the beam and thickness), the place of registration in the recoil detector, the primary energy of the beam before interaction – E_{pi}. It should be determined for which excited state of ^{4}He nucleus the simulation will be performed. For the played geometric conditions, in view of the energy losses by the beam in the target E^*_{pi}, calculating the value of the recoil angle of the triton θ_{1i}, we determine the energy of the first registered particle E_{1i} and the energy and angle of ^{4}He nucleus in a given excited state – E^*_{2+3i}, θ_{2+3i}. The second stage is the decay of the excited state of ^{4}He nucleus due to the available energy mode of the decay into 2 + 3 particles. For this stage, it is necessary to calculate with what energy E_{2i} the decaying particle 2 will fly, which should be registered by a detector, and to play the angle of departure of this particle in the center-of-mass system and to transform this quantity into a laboratory system θ_{2i}, must register the decay particle 2. If hit, using the laws of conservation of energy and momentum for a three-particle reaction, we determine the energy E_{3i} and the angle of departure of the third unregistered particle θ_{3i}, and calculate other kinematic parameters such as relative energies of the output pairs of particles E_{12i}, E_{23i}, E_{31i}, by repeating all the above operations. If particle 2 does not get into the second detector, then we start all over again. The ratio between the number of registered events by the second detector and the number of draw procedures will be an estimate of the efficiency of recording the decay of the selected excited state of ^{4}He nucleus decaying through channel 2 + 3 for these experimental conditions.

The Monte Carlo simulation algorithm described above is implemented as a program written in the C++ language in the Rut shell. When using it to describe the two-dimensional spectra of tt, $t\tau$, and td, there are coincidences from the reactions obtained at the recoil triton registration angle –15° and the registration of tritons, τ-particles and deuterons generated by the decay of excited levels of ^{4}He at an angle of –27.5°.

The results of calculations of the efficiency of registration of the first seven excited states, which correspond to the ratio of decay modes, are given in Table (column "Part"). In more details, the method for determining the ratio of decay modes is described in [3]. The calculations were performed under the assumption that the distribution of the interaction products is isotropic. Thus, as can be seen from Table, as the excitation energy of states increases, the number of decay modes of the nucleus increases, and the probability of the decay through a specific channel for each excited state is maximum at an excitation energy close to the nuclear decay threshold. Thus, for a state with an excitation energy of 25.69 MeV, the probability of the decay through the $d-d$ channel is 0.7 (the threshold for the collapse of ^{4}H nucleus into two deuterons is 23.85 MeV), while, in the $t-p$ channel, it is only 0.2. At the same time, the first excited state decays only through the $t-p$ channel (excitation energy equals 20.04 MeV), the probability is 1, the decay threshold is 19.81 MeV. As for the decay mode at $n + {}^3$He, it is fairly evenly distributed between the states for excitation energies from the ^{4}He decay threshold at $n + {}^3$He – 20.58 MeV to the excitation energy of 24.71 MeV. This may be due to the presence of a neutron in the decay channel, in contrast to the $t-p$ and $d-d$ channels, where both particles are charged. There is no clear correlation between the widths of the excited states and the ratio of the decay modes. It should be noted that the experimental confirmation of the decay into three particles of the excited nucleus ^{4}He gives us the reason to consider them as cluster $^3\mathrm{N}+\mathrm{N}$ states using realistic potentials in four-particle calculations [9, 10].

6. Conclusions

The method of particle decay spectroscopy with registration of t, ^{3}He, d charged particles at the coincidences is used to study the twice magical strongly bound ^{4}He nucleus. In a kinematically complete experiment, matrices of $t-t$, $t-\tau$, and $t-d$ coincidences from the three-particle $^3\mathrm{H}(\alpha,tt)p$, $^3\mathrm{H}(\alpha,t\tau)n$, and $^3\mathrm{H}(\alpha,td)d$ reactions at the alpha-particle beam energy $E_\alpha = 67.2$ MeV are obtained. The spectra of coincidences of charged particles are determined in one exposure under the same conditions according to the kinematically calculated position of the detectors, which provides the registration of seven excited ^{4}He states. From the analysis of these matrices in the framework of the Monte Carlo method, the values of excitation energies and energy widths for seven excited ^{4}He states are determined, which are consistent with the literature data [1].

The efficiency of recording the decay of excited states of ^{4}He nucleus is also evaluated by the Monte Carlo method, and the ratio of decay modes for each of the observed states is determined. It is established that the probability of decay through a specific channel for each excited state is maximum at the excitation energy, which is close to the threshold of decay of the nucleus into the corresponding particles.

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О. Поворозник, О. Горпинич, О. Понкратенко

ПРО ОСОБЛИВОСТІ ДОСЛІДЖЕННЯ НЕЗВ'ЯЗАНИХ ЗБУДЖЕНИХ СТАНІВ ЯДРА ^{4}He В $\alpha + {}^3$H ВЗАЄМОДІЇ

У процесі взаємодії пучка альфа-частинок з тритієм за допомогою спектроскопії розпаду частинок було отримано двовимірні спектри співпадіння tt, t^3He і dd з тричастинкових реакцій $^3\mathrm{H}(\alpha, tt)p$, $^3\mathrm{H}(\alpha, t^3\mathrm{He})n$ і $^3\mathrm{H}(\alpha, td)d$ ($E_\alpha =$ = 67,2 МеВ). За допомогою методу Монте-Карло отримано енергії збудження та енергетичні ширини для семи збуджених станів ^{4}He, а також відношення їх різних каналів розпаду, а саме $t + p$, $n + {}^3$He та $d + d$.

Ключові слова: збуджені стани, канали розпаду.