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MONTE CARLO SIMULATION IN THE STUDY OF THE EXCITED LEVELS OF THE ^{5}He NUCLEUS

O. Jachmenjov, O. Povoroznyk, O. Gorpinich, Y. Roznuk

Institute for Nuclear Research of the National Academy of Sciences of Ukraine, Kyiv, Ukraine

The structure of the ^{5}He nucleus in the excitation energy range of 17…21 MeV in the kinematically complete three-particle reactions ^{3}H(α,αd)n, ^{3}H(α,dd)t, ^{3}H(α,td)d was studied using the Monte Carlo method in order to take into account all real experimental conditions. The energies and widths of the excited levels of the ^{5}He nucleus in the given energy range were obtained.

Studies of the ^{5}He nucleus in the excitation energy range of 17…21 MeV, where decay via the α+n and t+d channels is possible, provide contradictory information [1, 2]. Data on the energy parameters of the excited levels were usually obtained from the analysis of inclusive spectra, fixing one of the decay products of the ^{5}He nucleus, such as t from the reaction ^{7}Li(p,t)^{5}He [3], d from the reaction ^{6}Li(p,d)^{5}He [4], α from the reaction ^{7}Li(d,α)^{5}He [5], ^{7}Be from the reaction ^{6}Li(^{6}Li,^{7}Be)^{5}He [6], where, in addition to the level with excitation at 16.7 MeV, a wide level in the region of 18 and 20.5 MeV was observed. Such experiments are not kinematically complete and require additional information on the formation and decay of the ^{5}He nucleus, which is unstable and decays with γ, n, p, d, t, α radiation, which should be taken into account when processing experimental data.

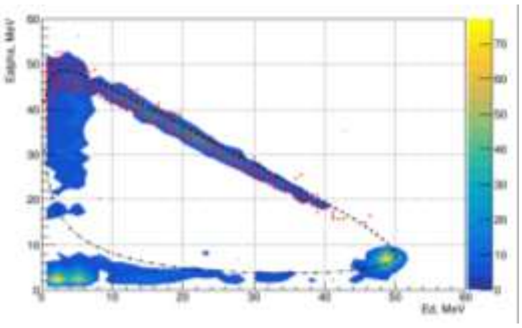
In the correlation experiments from the reactions ^{2}H(α,pd)t and ^{2}H(α,dt)p [7], narrow levels of the ^{5}He nucleus with excitation energies of 18.6, 18.8, and 19.2 MeV were obtained.

In this work, we studied the interaction of α-particles with an energy of 67.2 MeV with a titanium-tritium target with a thickness of 2.7 mg/cm^2. The nuclear reaction products were recorded by detector telescopes, which were conditionally divided into left (100 μm n/a ΔE and 3 mm n/a E detectors) at angles of 15^0, 20^0, and right (400 μm n/a ΔE and NaJ(Tl) Ø20 mm h 20 mm E detectors) at angles of 15^0, 21^0. More detailed information on the experimental conditions is presented in [11].

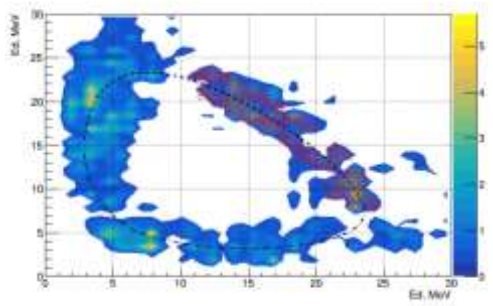
In Fig. 1 shows the α-d (Fig. 1,a), d-d (Fig. 1,b), and t- d (Fig. 1,c) coincidence matrices for the three-particle reactions ^{3}H(α,αd)n, ^{3}H(α,dd)t, ^{3}H(α,td)d, respectively, and the kinematically calculated locus of the three-particle reaction is shown as a solid line. The kinematic conditions of the experiment were chosen to simultaneously study the formation and decay of the ^{5}He nucleus in the 17…21 MeV excitation region via the α+n and t+d channels (see red circles in Fig. 1).

USING THE MONTE CARLO METHOD IN CORRELATION EXPERIMENTS

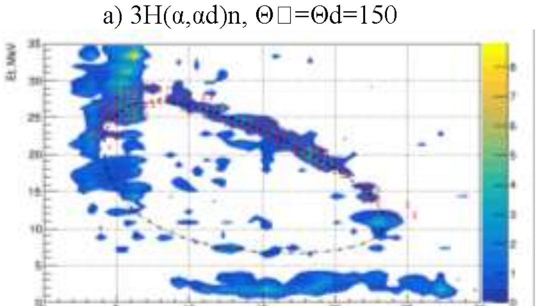
In a kinematically complete correlation experiment (p+T->1+2+3), two out of three particles in the initial reaction channel coincidentally register, which makes it possible, using the laws of conservation of momentum and energy, to determine the energy of the third unrecorded particle, as well as the relative energy in pairs of 1-2, 1-3, 2-3 particles corresponding to the formation of an intermediate system. Fig. 2 shows the calculations of the three-particle reaction α(t,dd)t with Eα = 67,2 MeV ($\Theta_{d1} = \Theta_{d2} = 15^0$) in the point geometry with a solid line.



a) 3H(α,αd)n, Θ□=Θd=150



b) 3H(α,dd)t, Θd1=Θd2=150



c) ^{3}H(α,td)d, Θ_t=Θ_d=15^0

Fig. 1. Two-dimensional coincidence spectra, solid line is the kinematic locus, red indicates the studied area of space

The three-particle nuclear reaction [8] is considered within the framework of the sequential decay mechanism, in which the first stage involves the formation of a nucleus in an excited state with its subsequent decay. When analyzing experimental data, it is necessary to take into account other mechanisms of the three-particle reaction [9], such as quasi-free scattering (QFS – virtual decay of a nucleus or an incoming particle into clusters with subsequent scattering on one of the clusters); final-state interaction (FSI – when the relative energy in the output channel in any pair of particles is close to zero); passage of the reaction through simultaneous decay into three particles, which is described by the phase space factor (PSF) [10].

The Monte Carlo method was used to take into account the experimental conditions. The following parameters were taken into account: energy blurring and beam size, target thickness, angular capture of detector apertures, and energy resolution of the detectors. For each event of the reaction p+T->1+(2+3) (from 2000000 to 5000000 events were used), the energy of the bombarding particle p, the point of reaction in the target, the energy loss of the primary beam in the target, the calculation of the relative excitation energy of the decaying intermediate system (2+3), and the energy and angle of the particle were determined. Fig. 2 shows the calculation of the energies of particle 2 and the relative energies in pairs of particles depending on the energy of particle 1 for the three-particle reaction ^{3}H(α,dd)t with E_α = 67.2 MeV (Θ_{d1}=Θ_{d2}= 15^0) by the Monte Carlo method.

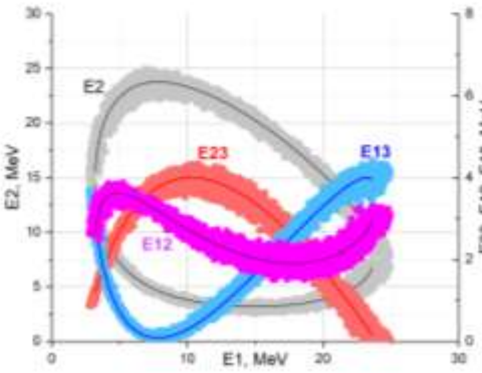


Fig. 2. Calculations of the energy of particle 2 and relative energies in pairs of particles as a function of the energy of particle 1 for the reaction ^{3}H(α,dd)t, E_α=67,2 MeV, deuteron registration angles 15^0. Solid lines - calculations in point geometry, circles - Monte Carlo calculations

The simulation takes into account the energy losses in the target of both the initial particle beam and the reaction products, which significantly affect the resulting energy spectrum of the excited level. If during the simulation the relative energy in the 2+3 pair corresponds to the excitation energy of the system under study and the angles of departure of the particles to be recorded correspond to the angles of the detectors, the event of coincidence of registration of particles 2 and 3 in the detector is recorded (Fig. 3).

This methodology allows us to construct simulated graphs of the dependence of the energies of the particles recorded at the coincidence (E_2 from E_1) and their projections on the energy axis, which makes it possible to compare them with experimental spectra. The calculation methodology takes into account the passage of the reaction without the formation of any excited level, i.e., it takes into account the contribution of statistical decay (PSF).

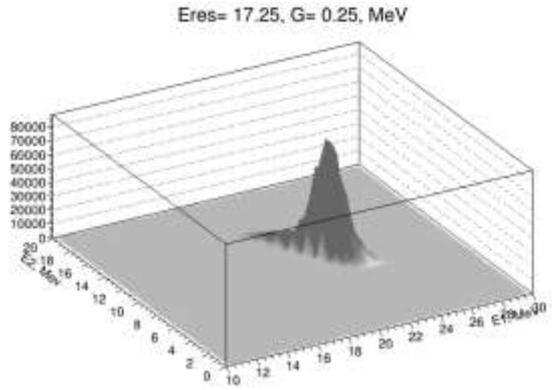


Fig. 3. Monte Carlo simulation (2 million events) of the excited state of the ^{5}He nucleus (E_{ex}=17.25 Γ= 0.25 MeV) decaying on d+t from the reaction ^{3}H(α,dd)t, E_α = 67.2 MeV, Θ_{d1} = Θ_{d2} = 15^0

The width of the excited state in the experimental spectra is the sum of the width of the physical level, which is determined by the level lifetime, and the components that depend on the kinematic conditions and experimental errors. In modeling the excited state of the studied nucleus, the physical level width was used as the energy parameter, which increased after the modeling procedure, depending on the point in the phase space where the excitation was observed and the energy errors. The study of the nucleus states using correlation experiments allows us to fix the decay channel of the excited level, which makes it possible to obtain the partial widths of the excited level.

Thus, this technique allows us to obtain more reliable energy parameters of excited levels when analyzing experimental data.

To perform this work, a low-level program was written using the ROOT 6.30 software package.

In Fig. 4 shows the projections of the upper branch of the locus of the coincidence matrix and the least-squares fit of the excited levels of the ^{5}He nucleus, in the α+n decay channel, from the ^{3}H(α,αd)n reaction, at registration angles Θ_α= Θ_d=15^0 (Fig. 4a), in Fig. 4b the t+d decay channel from the reaction ^{3}H(α,dd)t (Θ_{d1}=Θ_{d2}=15^0), and in Fig. 4c, the t+d decay from the ^{3}H(α,td)d reaction (Θ_t=Θ_d=15^0). In Fig. 4a shows the excited states of ^{6}Li in the α+d pair, the contribution of which was modeled by the Monte Carlo method. The solid line indicates the total contribution of all excited states.

Fig. 5 shows the projections of the upper branch of the matrix of coincidences and the least-squares fitting of the excited levels of the ^{5}He nucleus, in the α+n decay channel, from the ^{3}H(α,αd)n reaction, at registration angles Θ_α=20^0, Θ_d=21^0 (see Fig. 5,a), in Fig. 5,b the t+d decay channel from the reaction ^{3}H(α,dd)t (Θ_{d1}=20^0, Θ_{d2}=21^0), and in Fig. 5,c the t+d decay from the reaction $^3H(\alpha,td)d$ ($\Theta_t=20^0$, $\Theta_d=21^0$). Fig. 5,a shows the excited states of ^6Li in the α+d pair, the contribution of which was also modeled by the Monte Carlo method. Fig. 5,b shows the contribution of the excited state of the ^5He nucleus from another pair of particles (1+3), which was obtained using the Monte Carlo method. In the figures, the numbers denote the contribution of the excited states of the ^5He nucleus, the symbols 6Li* and 6Li** denote the contribution of the excited states of the ^6Li nucleus, and the solid line is the total contribution of all excited states.

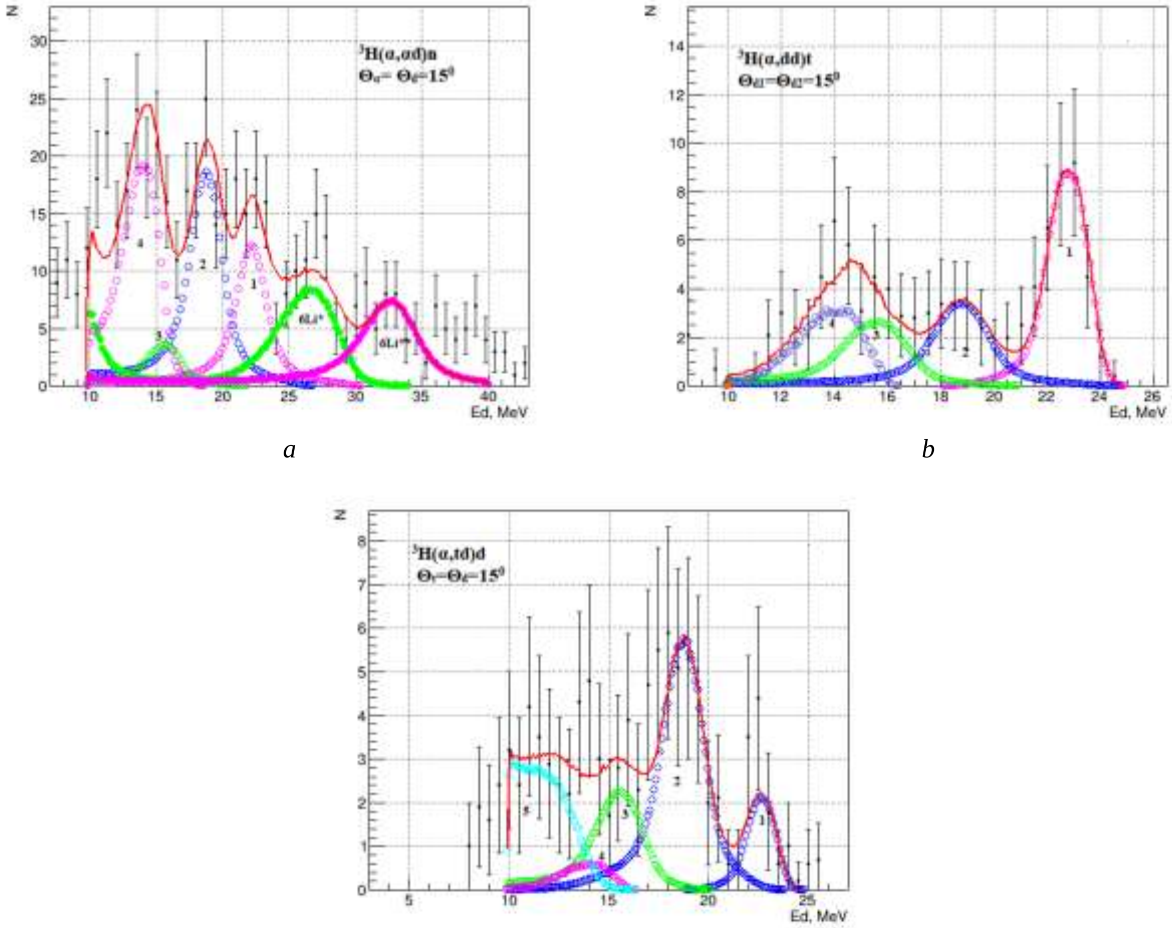


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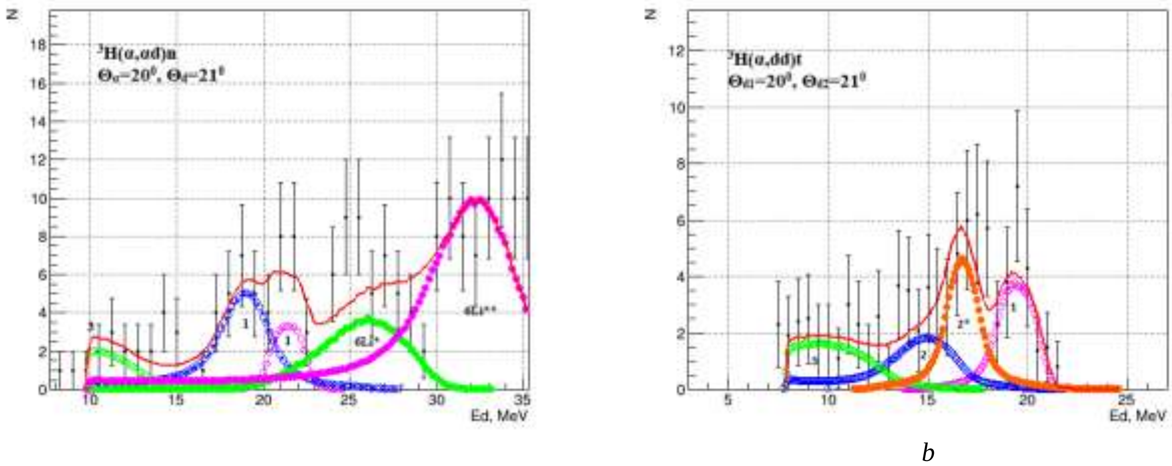
Fig. 4. Projections of the upper branch of the two-dimensional spectrum onto the deuteron energy axis and Monte Carlo approximation. Numbers indicate the contribution of excited levels of the ^5He nucleus, 6Li, 6Li** – the contribution of the ^6Li nucleus (Table). Solid curve - total contribution of excited levels*



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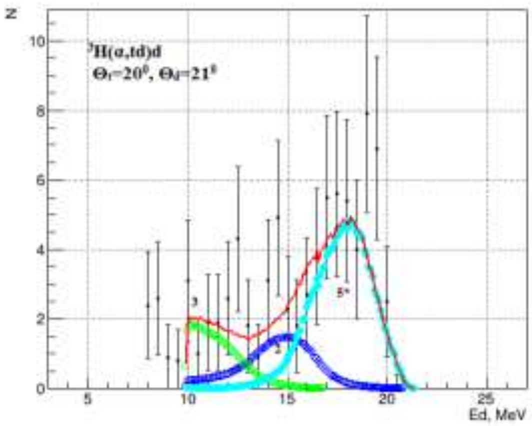

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Fig. 5. Projections of the upper branch of the two-dimensional spectrum onto the deuteron energy axis and Monte Carlo approximation. Numbers denote the contribution of excited levels of the ^{5}He nucleus, 6Li, 6Li** – the contribution of the ^{6}Li nucleus (Table). Solid curve - total contribution of excited levels*

Table shows the energy parameters of the excited states of the ^{5}He nucleus obtained through different decay channels using Monte Carlo simulations. As can be seen from the table, the values of the energy positions correlate with the compilation works [1, 2] and coincide with the experimental results [12] and with each other for different decay channels.

The study of experimental spectra using the Monte Carlo method allows modeling the nuclear three-particle reaction taking into account all experimental errors and kinematic features. Using the advantages of a kinematically complete experiment and various mechanisms of the three-particle reaction, it is possible to obtain high information content and accuracy in the analysis of experimental data.

Energy parameters of excited states of the nucleus ^{5}He

Compilations [1]	Compilations [2]	**[12] ^{3}H(α,αd)n**	**[12] ^{3}H(α,dd)t**	**This work**						
					^{3}H(α,αd)n		**^{3}H(α,dd)t**		**^{3}H(α,td)d**	
					$\Theta_\alpha=\Theta_d=15^0$		**$\Theta_{d1}=\Theta_{d2}=15^0$**		**$\Theta_t=\Theta_d=15^0$**	
E, MeV	E, MeV	E, MeV	E, MeV		E, MeV	Γ, MeV	E, MeV	Γ, MeV	E, MeV	Γ, MeV
	21.20	20.73		5					20.73	0.15
			20.00	4	20.32	0.20	20.32	0.02	20.32	0.02
19.8		19.95	1976	3	19.95	0.42	19.95	0.32	19.95	0.32
	19.08	18.94	19.05	2	18.94	0.75	18.94	0.50	18.94	0.50
	18.31									
	1828									
	1814									
16.75	16.84	16.09	16.89	1	17.55	0.91	17.25	0.35	17.25	0.35
					$\Theta_\alpha=20^0$, $\Theta_d=21^0$		**$\Theta_{d1}=20^0$, $\Theta_{d2}=21^0$**		**$\Theta_t=20^0$, $\Theta_d=21^0$**	
	21.20	20.73		5*					21.64	0.15
			20.00	4						
19.8		19.95	19.76	3	19.95	0.42	19.95	0.32	19.95	0.32
	19.08	18.94	19.05	2 2*			18.94 19.05	0.50 0.35	18.94	0.50
	18.31									
	18.28									
	1814									
16.75	16.84	16.09	16.89	1	17.55	0.91	17.25	0.35		
				1	16.49	0.21				

2* – is the excited state of the ^{5}He nucleus through the t+d decay channel, which was formed by the interaction of the first and third particles from the reaction p+T->2+(1+3)
5* – is the excited state of the ^{5}He nucleus through the t+d decay channel, which was formed by the interaction of the first and second particles from the reaction p+T->(1+2)+3.
Fig.5,a, ^{6}Li*, ^{6}Li**– excited states of the nucleus ^{6}Li, з E=6.41, Γ=0.35 and E=8.47, Γ=1.33 MeV respectively
Fig.6,a, ^{6}Li*, ^{6}Li**– excited states of the nucleus ^{6}Li, з E=9.28, Γ=0.20 and E=11.30, Γ=1.20 MeV respectively

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