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$\alpha + t$ AND $\alpha + {}^3$He INTERACTIONS AND THE EXCITED-STATE SPECTRUM OF ^{6}Li NUCLEUS

A kinematically complete analysis of the $^3He(\alpha, p\alpha)d$ reaction on ^3He nuclei of radiogenic origin accumulated in titanium-tritium targets, as well as the $^3H(\alpha, d\alpha)n$ and $^3H(\alpha, \tau t)n$ reactions on tritium nuclei accumulated on the same targets, has been carried out to study the excitation spectrum of ^6Li nucleus at excitation energies $E^* < 26$ MeV with the energies of accelerated alpha particles $E_\alpha = 27.2$ and 67.2 MeV. Three unbound excited levels are observed in the excitation energy interval of ^6Li nucleus from 7 to 16 MeV, as well as two excited levels of ^6Li with excitation energies of 21.30 and 21.90 MeV, which are consistent with theoretical calculations, but were not reliably confirmed experimentally. The application of the particle decay spectroscopy method made it possible to eliminate some ambiguities in the energy parameters of the excited states of the ^6Li nucleus.

Keywords: ^{6}Li, three-particle reactions, two-dimensional coincidence spectrum, $\alpha + t$ interaction, $\alpha + {}^3$He interaction.

1. Introduction

Despite numerous studies, the excitation spectrum of the ^{6}Li nucleus is quite controversial [1, 2], especially at excitation energies above 6 MeV. At the same time, the exact determination of the excitation energy, lifetime, and decay modes of unbound states is very important for an adequate understanding of the nature of the nuclear forces that are responsible for the formation and decay of those states. The excitation schemes of the lightest nuclei contain excitation sections 3–7 MeV in width and separate levels, which requires a more detailed experimental study concerning the presence of new, theoretically predicted excited levels and because of substantial differences between experimentally and theoretically obtained energy parameters of already known levels. For example, the theoretical calculations based on modern ideas about the nature of the nucleon-nucleon interaction [3–7] predict the existence of excited levels in the ^{6}He, ^{6}Li, and ^{6}Be nuclei belonging to the isospin triplet with $A = 6$, which are located below the decay threshold of those nuclei into $3 + 3$ nucleons but above the excitation energies of low-excited 2^+ states of the ^{6}He ($E^* = 1.8$ MeV) and ^{6}Be ($E^* = 1.67$ MeV) nuclei and above the excitation energies for the ^{6}Li nucleus (>6 MeV).

The energy parameters (the energy position and the width) of excited levels with very short lifetimes are determined by studying the interaction of the constituent particles into which those states decay and analyzing the presence of resonances in the required energy interval of the relative energies of those constituent particles. Such experimental conditions can be created by considering a wide range of three- and four-particle reactions, namely, by studying the in-

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clusive spectra of three-particle $p(T,1)(2+3)^*$ reactions, where the examined nuclei are formed as final (unbound) ones, and by studying the coincidence spectra of p(T,12)3 reactions in those phase space regions, where the interaction in the selected pair of initial particles – e.g., in the pair 2–3 – occurs in the given interval of relative energies E_{2-3} provided the absence of resonances in the pairs 1–2 and 1-3, with the exclusion of simple mechanisms such as quasi-free scattering and interaction in the final state.

This work summarizes the cycle of studies of the ^{6}Li nucleus [8–10], where the particle decay spectroscopy method [11, 12] was applied to consider numerous three-particle channels of reactions induced by the interaction of α-particle beams with hydrogen and helium isotopes.

The subject of our study was excited unbound levels of ^{6}Li nuclei, which were formed in the first stage of the interaction of α-particle beams with tritium and helium nuclei. In the second stage, the ^{6}Li nuclei decayed via $d+\alpha$ or $t+\tau$ emission. In this paper, the excitation spectrum of the ^{6}Li nucleus up to an excitation energy of 26 MeV was studied by analyzing two-dimensional $E_p \times E_\alpha$, $E_d \times E_\alpha$, and $E_\tau \times E_t$ matrices obtained as a result of the complete experimental kinematic study of the three-particle nuclear reactions: ^{3}He(α, $p\alpha$)n ($E_\alpha = 27.2$ MeV) [8], ^{3}H(α, $d\alpha$)n ($E_\alpha = 67.2$ MeV) [9], and ^{3}H(α, $t\tau$)n ($E_\alpha = 67.2$ MeV) [10].

2. Determination of the Energy Parameters of Unbound States of the ^{6}Li Nucleus Below the Excitation Energy of 6 MeV Using the Three-Particle ^{3}He(α, $p\alpha$)d Reaction

Consider the level scheme for the ^{6}Li nucleus in the excitation energy interval up to 6 MeV, which is the most studied one for this nucleus. According to the literature data [1], more than 40 different types of nuclear transformations were used to study the first five excited levels of the ^{6}Li nucleus, and no substantial discrepancies were found among the energy level positions obtained from different experiments. However, the values of the energy level widths differ considerably, except for the first narrow state.

Promising for the study of the excited states of the ^{6}Li nucleus can be the analysis of the ^{3}He+α interaction because owing to the low Coulomb barrier, various output channels of this interaction are characterized by substantial cross section values, which is confirmed by the study of the binary ^{3}Ne(α, p)^{6}Li* reaction [13]. In addition, at such interaction, the influence of the continuum is minimal, and control over it is possible. In the case of solid targets, the localization of nuclear reaction is confined by the size of the beam of accelerated particles at the target. However, ^{3}Ne and ^{4}Ne are gases, and the interaction of incident particles with the nuclei of the gaseous target occurs within the beam-cord space, which complicates the maintenance of necessary kinematic conditions.

When studying the interaction of α-particles with tritium, it is possible to avoid the difficulties of working with a gaseous target in the correlation experiment via using solid titanium-tritium targets. In this case, it turned out that, during long-term storage of such targets, an accumulation of radiogenic – i.e., generated by β-decay – tritium nuclei, ^{3}H, took place. From the analysis of the experimental data obtained during the study of the interaction between a beam of α-particles with an energy of 27.2 MeV and tritium, it was found that, in addition to the events corresponding to the formation and decay of ^{6}He nucleus in the four-particle reaction ^{3}H(α,$p\alpha$)nn [14] and lying on the corresponding calculated kinematic curve (marked by number *1* in Fig. 1), if certain targets were used, a locus was observed, which corresponded to the three-particle reaction ^{3}He(α, $p\alpha$)d with $Q_3 = -5.49$ MeB. The results of kinematic calculations for this reaction are also depicted in Fig. 1 and marked with number *2*. Titanium-tritium targets with a thickness of 2.7 mg/cm^2 and a ratio between the tritium atoms sorbed by the titanium foil and the titanium atoms close to unity were used in the experiment. Events corresponding to the three-particle reaction ^{3}He(α, $p\alpha$)d were observed when the targets whose storage time exceeded two years were applied. The reliability of this phenomenon is evidenced by the fact that the loci of this three-particle reaction were observed for various pairs of registration angles of the p-α coincidence matrices. An additional argument for the appearance of events induced by $\tau+\alpha$ interaction in the two-dimensional spectra of p-α coincidences is the spectrum of the energy balance $Q_{3\,\mathrm{exp}}$ shown in Fig. 1, *b* and obtained as a result of the recalculation of the two-dimensional spectrum of p-α coincidences (Fig. 1, *a*). Two peaks are observed in this spectrum. One of them is slightly wider, its maximum is at an energy of about -8.5 MeV, and it corresponds to the four-particle reaction ^{3}H(α, $p\alpha$)$2n$ through the population and decay of the first excited ^{6}He state. The other peak is slightly narrower, has a maximum at about -5.487 Mev, and corresponds to the three-particle reaction ^{3}He(α, $p\alpha$)d. The results of kinematic calculations for the latter are marked in Fig. 2 with number *2*.

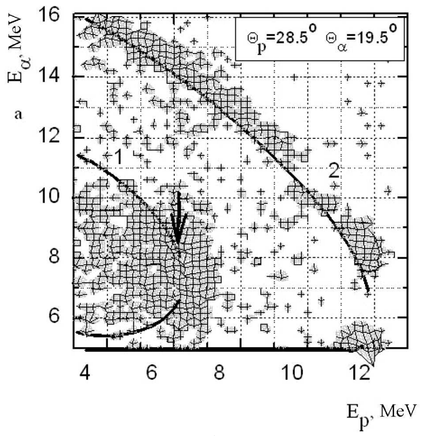
The coincidence matrices for protons and α-particles were obtained using four semiconductor silicon $\Delta E - E$ telescopes, in which the thickness of "thin" ΔE detectors was equal to 60–100 μm, and the thickness of "thick" E-detectors to 1–1.5 mm. The detector telescopes were located in pairs on the left and right with respect to the beam of α-particles accelerated by a U-120 cyclotron at the Institute for Nuclear Research. Two-dimensional spectra of p-α coincidences were obtained for the following pairs of registration angles of protons and α-particles: $\Theta_p/\Theta_\alpha = 28.5°/10°$, 13°, 16.5° and $\Theta_p/\Theta_\alpha = 36°/10°$, 13°, 16.5° [5]. All two-dimensional spectra demonstrated loci corresponding to the three-particle ^{3}He(α,$p\alpha$)d reaction. α-particles and protons registered at coincidences can be formed as a result of the mechanism of successive decays of the unbound states of the ^{5}Li and ^{6}Li nuclei, as well as a result of the quasi-free scattering where the deuteron plays the role of particle-observer, namely,

$$\nearrow \quad d + {}^5\,\mathrm{Li}^*_{\to p+\alpha} \tag{1}$$

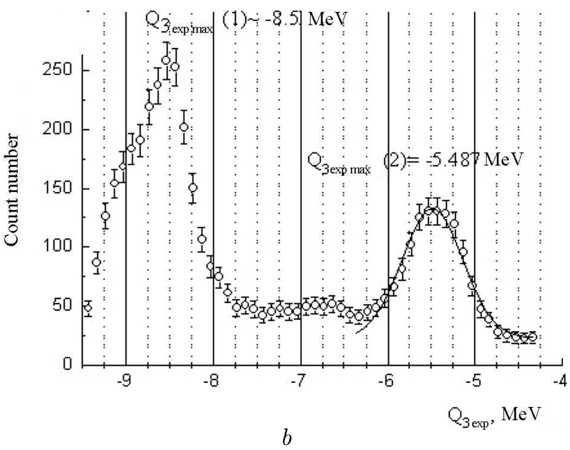
$$ {}^3\mathrm{He} + \alpha \longrightarrow \quad p + {}^6\,\mathrm{Li}^*_{\to \alpha+d}, \tag{2}$$

$$\searrow \quad d + \alpha - p. \tag{3}$$

An analysis performed on the basis of calculations of the energies of three particles, the values of the relative energies in the α-p and α-d pairs, and accounting for the kinematic features in the formation of the excited states of the ^{5}Li and ^{6}Li nuclei in the first stage, made it possible to select two-dimensional spectra of α-p coincidences for several pairs of registration angles, namely, $\Theta_p/\Theta_\alpha = 28.5°/10°$, 13°, and 36°/19°, for which the mechanism of population and decay of unbound levels of the ^{6}Li nucleus is most manifested. It turned out that, for some selected registration angles of protons (for example, $\Theta_p = 28.5°$), the corresponding registration angles of α-particles either coincided ($\Theta_\alpha = 1°$, 13°) or were close to the escape angle of ^{6}Li* in the binary reaction ^{3}He(α, p)^{6}Li*. Such a choice of angles is responsible for the appearance of the second excited



a



b

Fig. 1. Two-dimensional p-α coincidence spectrum (*a*); the corresponding energy-balance, $Q_{3\,\mathrm{exp}}$, spectrum (*b*)

state in the two-dimensional spectrum of p-α coincidences. The angles of the detectors for the registration of α-particles and protons and their angular overlap had such values that for some pairs of angles both products of the binary ^{3}He(α, p)^6 reaction were registered completely or partially at the coincidence: the proton and ^{6}Li$_{3,56}$ whose lifetime was sufficient to reach the detector and not decay with the emission of γ-quantum. Since the time selection signals for the electronic scheme of fast-slow coincidences were taken from ΔE detectors, and the two-dimensional p-α coincidence spectra contained some of the events that were registered only by ΔE detectors, therefore, in the loci corresponding to the three-particle ^{3}He(α, $p\alpha$)d reaction, we obtained a peak corresponding to the ^{6}Li* state with an excitation energy of 3.56 MeV, which is stable with respect to decay into clusters and

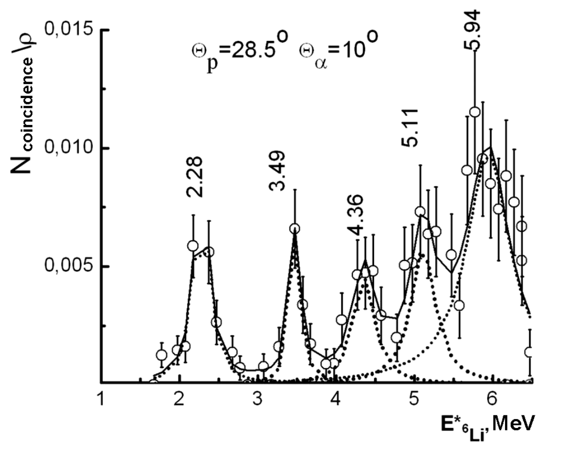


Fig. 2. Projection of the upper branch of the p-α coincidence matrix. The numbers indicate the fitted excitation energies of the first five excited states of the ^{6}Li nucleus. The corresponding individual contributions of excited levels and their sum are shown by the dotted and solid curves

nucleons. Just this circumstance was used when determining and taking into account the experimental resolution of this research.

For further analysis, the two-dimensional spectra were projected onto one of the energy axes. The projection procedure consists in the summation of point events in the corresponding locus within a cell of a given size, which allows one to obtain projections of the branches of two-dimensional energy loci with an arbitrary channel price increment. The projection spectra are characterized by a resonance structure, which can be explained by assuming it to be a result of the simple two-stage mechanism of three-particle reactions, in which the excited levels of the ^{6}Li nucleus are populated in the first stage, and, in the second stage, they decay via the deuteron and α-particle escape. For further analysis, we used the Monte Carlo simulation method, which was also used to evaluate the registration efficiency of coincidence events by our proposed experimental technique, and, at the same time, to simulate directly obtained projection spectra in the framework of our assumption that the main source of events is the simple model of sequential decay.

Suppose that, as a result of the interaction between the incoming particle p and the nucleus of the target T, three particles (1, 2, and 3) are formed in the output channel. Particles 1 and 2 are registered by coincidence, and a two-stage process takes place. In the first stage, particle 1 and a nucleus R are formed in some excited state J; in the second stage, the nucleus R decays via the emission of particles 2 and 3. In this case, in the framework of the sequential decay model, the projection of the two-dimensional coincidence matrix transformed into the excitation spectrum of the nucleus R can be approximated by the following expression:

$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE_{\text{ex}}} \sim \rho\left(\Omega_1, \Omega_2, E_{\text{ex}}\right) \times \\ \times \sum_j^n \frac{\Gamma_j/2}{(E_j - E_{2-3})^2 + (\Gamma_j/2)^2}, \tag{4}$$

where C_j is the amplitudes of formation of the j-th excited state. Expression (4) can be divided by the value of the phase space multiplier calculated for the given kinematic conditions. By representing the result as a function of the excitation energy of the ^{6}Li nucleus, it can be transformed as follows:

$$\frac{d^3\sigma}{d\Omega_p d\Omega_\alpha dE_{\text{ex}}} / \rho(\Omega_p, \Omega_\alpha, E_{\text{ex}}) = \\ = \sum_j^n C_j \frac{\Gamma_j/2}{(E_{^6Li_j^*} - E_{\text{ex}})^2 + (\Gamma_j/2)^2} = \\ = \sum_j^n C_j BW^j(E_{\text{ex}}), \tag{5}$$

Here, the value of the excitation energy of the ^{6}Li nucleus is determined as the sum of the calculated relative energy in the α-d pair and the threshold energy needed for this nucleus to decay into an α-particle and a deuteron ($E_{\text{por}} = 1.475$ MeV), i.e., $E_{\text{ex}} = E_{23} + E_{\text{por}} = E_{\alpha d} + E_{\text{th}h}$. The energy positions of the ^{6}Li nucleus levels are defined as $-E_{^6\text{Li}_j} = E_j + E_{\text{por}}$.

In Fig. 2, the projections of the upper branch of the p-α coincidence matrix obtained for a proton registration angle of 28.5° and an α-particle registration angle of 10°are shown. The solid curve corresponds to the approximation of experimental data in the point geometry using expression (5) and the least-squares method. The contributions of separate states excited at the interaction are plotted by dashed curves. A similar procedure was carried out for experimental data obtained for other pairs of registration angles of protons and α-particles. This approximation does not

Table 1. **Excitation energies and energy widths of excited ^{6}Li states calculated in the framework of the kinem $E_\alpha = 27.2$ MeV**

No.	$^*\Theta_p/\Theta_\alpha$ 36°/19°		$^*\Theta_p/\Theta_\alpha$ 28,5°/13°		$^*\Theta_p/\Theta_\alpha$ 28,5°/10°		$^{**}\Theta_p/\Theta_\alpha$ 36°/10° $\sigma = 0{,}20$	
	$E^* \pm \Delta E$, MeV	$\Gamma \pm \Delta\Gamma$, MeV	$E^* \pm \Delta E$, MeV	$\Gamma \pm \Delta\Gamma$, MeV	$E^* \pm \Delta E$, MeV	$\Gamma \pm \Delta\Gamma$, MeV	$E^* \pm \Delta E$, MeV	$\Gamma \pm \Delta\Gamma$, MeV
1	2.1 ± 0.2	0.23 ± 0.20	2.15 ± 0.2	0.23 ± 0.1	2.28 ± 0.015	0.24 ± 0.08	2.23 ± 0.09	0.06 ± 0.07
2	3.53 ± 0.20	–	–	–	3.49 ± 0.26	0.17 ± 0.22	3.47 ± 0.03	–
3	4.56 ± 0.26	0.43 ± 0.30	4.47 ± 0.25	0.46 ± 0.25	4.36 ± 0.22	0.33 ± 0.14	4.38 ± 0.05	0.25 ± 0.06
4	5.29 ± 0.25	0.5 ± 0.5	5.05 ± 0.22	0.48 ± 0.38	5.11 ± 0.23	0.38 ± 0.19	5.11 ± 0.05	0.30 ± 0.06
5	–	–	5.75 ± 0.28	0.98 ± 0.36	5.94 ± 0.26	0.68 ± 0.15	5.94 ± 0.04	0.63 ± 0.04

N o t e: * approximation by expression (6) without taking the energy resolution into account, ** approximation taking the energy resolution into account via expression (7)

take into account the energy resolution with which the projections of the branches of the coincidence matrices were obtained. If we take, in Eq. (5), the convolution of the expression $BW^j(E_{\rm ex})$, which is responsible for the resonance contribution of the excited state, and the function $q(\epsilon,\sigma)$ describing the energy resolution, then we get the quantity $BW^{j_m}(E_{\rm ex})$ that already depends on the energy resolution,

$$BW^{j_m}(E_{\rm ex}) = \int\limits_{-5\sigma}^{-5\sigma} BW^j(E_{\rm ex}+\epsilon)q(\epsilon,\sigma)d\epsilon, \qquad (6)$$

As a result, from Eq. (5), we obtain

$$\frac{d^3\sigma}{d\Omega_p d\Omega_\alpha dE_{\rm ex}}/\rho(\Omega_p,\Omega_{p\alpha},E_{\rm ex}) = \sum_j^5 C_j BW^{j_m}(E_{\rm ex}), \qquad (7)$$

The function $q(\epsilon,\sigma)$ in Eq. (6) was chosen in the Gaussian form,

$$q(\epsilon,\sigma) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{\epsilon^2}{2\sigma^2}\right), \qquad (8)$$

where the parameter σ was determined by fitting the very narrow peak that corresponds to the second excited state of the ^{6}Li nucleus from the binary $^3{\rm He}(\alpha,p)^6{\rm Li}^*_{3.56}$ reaction and manifests itself due to the simultaneous coincidence registration of protons and ^{6}Li nuclei excited to an energy of 3.56 MeV. As a result, we obtained the value $\sigma = (2° \pm 5°)$ keV, which was used in further calculations. In the framework of this procedure, first, the line shape of each j-th excited state was fitted separately. Then, by varying only the amplitudes C_j in expression (7) and using the least-squares method, the total curve was calculated. on the figure scale, this curve practically coincides with the solid curve in Fig. 2, which was obtained by performing the calculations in the point geometry. The contributions of each level also differ insignificantly, and, therefore, they are not shown in the figure.

In Table 1, the energy positions and widths obtained for three pairs of registration angles by fitting experimental spectra are shown: in the point geometry ($\Theta_{\rm p}/\Theta_\alpha = 36^{°}/19°$, $28.5°/13°$, $28.5°/10°$) and taking the experimental resolution into account ($\Theta_{\rm p}/\Theta_\alpha = 28.5^{°}/10°$). As one can see, the energy parameter values obtained for the first five excited levels of the ^{6}Li nucleus both assuming the point geometry [Eq. (5)] and taking the experimental energy resolution within the experimental error limits into account [Eq. (7)] coincide and agree with the values obtained by various methods and quoted in Table 1. In this case, the account for the experimental resolution did not allow us to go beyond the error limits, although we obtained somewhat smaller values for all state widths; this fact thereby confirms the reliability of the values obtained for the energy parameters of the unbound ^{6}Li levels.

Due to the fact that four of five indicated excited levels (except for the second level, which nevertheless manifests itself owing to the coincidence of experimental circumstances) decay with the emission of primarily α-particles, we managed, by studying the three-particle ^{3}He(α, $p\alpha$)d reaction, to get the energy parameter values for all these levels in almost one exposure.

The experimental energy resolution ($\sigma = 200$ keV) did not allow us to measure the energy width of the first excited state of the ^{6}Li nucleus. The estimation of this quantity using expression (7) gave the value $\Gamma_1 = (0.057 \pm 0.078)$ keV.

It is known that the excited state with $E^* = 5.36$ MeV and isospin $T = 1$ can decay only through three-particle decay with the simultaneous emission of a proton, a neutron, and an α-particle. The manifestation of the fourth excited state of ^{6}Li in the p-α coincidence matrix indicates that after its population due to the $\tau + \alpha$ interaction, its decay occurs via the emission, besides an α-particles, of a proton and a neutron with the relative energy close to zero. If the fraction of decays with the emission of protons and neutrons with non-zero relative energies were larger, then a vertical band similar to that registered at the ^{6}He nucleus decay ($E^* = 1.8$ MeV) with $t + \alpha$ interaction (it is marked by an arrow in Fig. 2, *a*) would be observed in the p-α coincidence matrix at a proton energy value corresponding to the formation of this level. To specify the features of the three-particle nature of this excitation, it is necessary to carry out a more detailed study of the phase space region corresponding to the formation and decay of the ^{6}Li nucleus state with $E^* = 5.36$ MeV.

If we compare the obtained energy parameters of the levels (Table 1) with the corresponding literature data [1, 2], then it should be noted first of all that the excitation energy values obtained taking the experimental errors into account practically coincide. But the values of the state energy widths determined from the correlation experiment with the interaction of the lightest nuclei belong to the lower limit of the array of all parameter values obtained experimentally. It must be said that this result is in good agreement with the results of theoretical calculations [15] performed in the framework of the three-particle model based on the Faddeev equations and two-particle nonlocal separable potentials of interaction between particles.

The obtained results confirm the high information content of the kinematically complete study of the interaction between the lightest nuclei when determining their energy parameters.

3. Study of the Excitation Spectrum of the ^{6}Li Nucleus ($6 < E_{\rm ex} < 16$ MeV) Using the Three-Particle ^{3}H(α, $d\alpha$)n Reactions

Numerous theoretical studies based on various approaches [3–7] predict the existence of several excited levels below the threshold of the ^{6}Li decay into $^3\mathrm{H} + {}^3\mathrm{He}$. However, there are few experimental confirmations of this prediction. For example, by analyzing the inclusive spectrum of α-particles obtained for the ^{9}Be$(p, \alpha)^6$Li reaction at a proton beam energy of 30 MeV, an anomaly was revealed at ^{6}Li nucleus excitation energies of 8–12 MeV, which can be explained as a manifestation of one or more excited ^{6}Li levels [16]. Among other arguments for the availability of excited states in this energy interval can be the results of R-matrix analysis [17], where broad levels of ^{6}Li nucleus with excitation energies of 14 and 15.8 MeV were found. Excitation levels at $E^* = 14.5$ and 16 MeV and with widths of about 1 MeV were observed in paper [18], where some experimental data concerning the study of the ^{3}H(α, $d\alpha$)n reaction induced by $\alpha + t$ interaction were analyzed.

The three-particle ^{3}H(α, $d\alpha$)n reaction was studied in the framework of the kinematically complete correlation experiment on a U-240 isochronous cyclotron using an α-particle beam and tritium-saturated titanium self-supporting hard targets 2.7 mg /cm^2 in thickness. The titanium-to-tritium atomic ratio in the target was close to unity. In order to experimentally study the nuclear reactions, a scattering chamber was used, which was equipped with an angularly movable detector desk and a unit for changing the targets and formation systems, as well as the diagnostics of the charged particle beam. With the help of a specially developed technique for measuring the energy and time characteristics of particles accelerated by the isochronous cyclotron, it was found that the energy of α-particles in the experiment was equal to (67.2 ± 0.4) MeV [19].

To identify and measure the energy of the charged products of nuclear reactions, four $\Delta E - E$ telescopes were used. They were arranged two on the left and two on the right with respect to the cyclotron beam direction. Two of them, which were intended to register single-charged products of nuclear reactions, consisted of semiconductor surface-barrier silicon detectors 400 μm in thickness and total-absorption detectors composed on the basis of NaJ(Tl) scintillators 20 mm in diameter and 20 mm in height. The other two, intended to register doubly charged particles, consisted of semiconductor ΔE and E detectors 100 μm and 3 mm in thickness, respectively. A detailed description of the experiment was given in work [9].

In order to perform a correct energy calibration of the combined $\Delta E \times E$ spectrometers, in which scintillation NaJ(Tl) detectors were used (their response function depends on the type of charged particles), methods for modeling the energy dependence of the light yield on the basis of the Birks formula [20, 21] and the known empirical dependence $dE/dx \sim E^n/a$ for specific energy losses of charged particles in the matter [20, 22] were developed and used. As a result of the processing of accumulated "off-line" information (it consisted in sorting experimental files taking the spectrometer calibration into account and distinguishing the events that corresponded to the registration of deuterons in either telescope, and α-particles in the other, using a software package adapted to a personal computer [23]), we obtained two-dimensional spectra of d-α coincidences for the following pairs of registration angles of deuterons and α-particles, respectively: 15–15°, 15–27.5°, 27.5–15°, 27.5–27.5°, 21–15°, 21–20°, 21–27.5°, and 21–32.5°.

The mechanisms of nuclear reactions with the generation of three particles in the output channel can mainly be considered as sequential processes of double two-particle interactions of various types: quasi-elastic scattering or quasi-two-particle reaction (QTPR), interaction in the final state (IFS), and the sequential decay. The three-particle ^{3}H(α, dα)n reaction, when generating a deuteron, an α-particle, and a neutron in the output channel, proceeds via the following simple mechanisms:

$$\nearrow \quad d + {}^5\mathrm{He}^*_{\to\alpha+n}, \qquad (9)$$

$${}^3\mathrm{He} + \alpha \longrightarrow \quad n + {}^6\mathrm{Li}^*_{\to\alpha+d}, \qquad (10)$$

$$\searrow \quad \text{quasi-free } \alpha - d \text{ scattering}, \qquad (11)$$

where reactions (9) and (10) are the formation of the ^{5}He nucleus in the ground state and the ^{5}He and ^{6}Li nuclei in the excited states, with the subsequent decay of the resonances into $\alpha + n$ and $\alpha + d$, respectively.

In order to obtain reliable information about the parameters of certain excited states of the ^{6}Li nucleus, it is necessary to create such experimental conditions that would prevent the population of the known levels

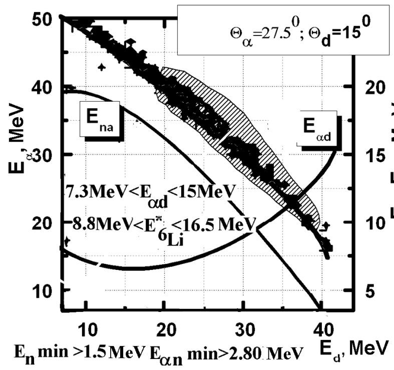


Fig. 3. Two-dimensional αd-coincidence spectrum of the ^{3}H(α, $d\alpha$)n reaction ($E_\alpha = 67.2$ MeB). The shaded area marks the experimental events of resonance formation. Curves $E_{n\alpha}$ and $E_{\alpha d}$ demonstrate the calculated relative energies in the $n + \alpha$ and $d + \alpha$ pairs, respectively

of ^{5}He nucleus and hamper the manifestations of the mechanism of quasi-free $\alpha - d$ scattering (11).

In the case of the three-particle ^{3}H(α, $d\alpha$)n reaction at $E_\alpha = 67.2$ MeV, it is most optimal to study the mechanism of formation and decay of the ^{6}Li nucleus levels with excitation energies of 6–15 MeV at the following angle pairs of deuteron and α-particle registration: 15–15°, 27.5–15°, and 21–15°. An analysis of the values for the relative energies in the $d - \alpha$ and $\alpha - n$ pairs for the $d - \alpha$ coincidence matrices, which were calculated for the three indicated pairs of angles, testifies that in an energy interval of ^{6}Li nucleus excitation (6–14 MeV), the relative energy in the $\alpha - n$ pair changes from approximately 5 to 15 MeV, which corresponds to the ^{5}He nucleus excitation in an energy interval of 4–14 MeV. According to the latest compilation publication dealing with the study of the level schemes in light nuclei with $A = 5$, 6, and 7 [1], there is no excitation level of the nucleus in this energy interval. At the same time, this is just in this part of projection spectra (7 MeV < $E_{\alpha d}$ < 14 MeV) where a certain resonance structure appears.

For further analysis of experimental data, the $d - \alpha$ coincidence matrices for registration angle pairs of 15°–15°, 21°–15°, and 27.5°–15° were projected onto the deuteron energy axis. In Fig. 3, a two-dimensional $d - \alpha$ coincidence spectrum for a deuteron registration angle of 27.5° and an α-particle registration angle of 15°. Figure 4 illustrates the projection of the shaded part in the upper branch of the ^{3}H(α, $d\alpha$)n reaction locus onto the deuteron energy axis.

Table 2. **Energy parameters of the excited levels of the ^{6}Li nucleus, obtained using approximation (13) and the least squares method**

Θ_α	Θ_α	Level No. (in the figures)	$E_{\rm ex}(\Delta E_{\rm ex})$ MeV	$E_{\alpha d}(\Delta E\alpha d)$ MeV	$\Gamma(\Delta\Gamma)$ keV
15	15	3	9.28(0.28)	7.80(0.28)	2.09 (1.17)
		4	11.59(0.33)	10.11(0.33)	0.62(0.70)
		5	13.99(1.12)	12.51(1.12)	0.60(1.71)
15	21	3	8.47(0.14)	6.99(0.14)	1.33(0.72)
		4	10.32(0.51)	8.84(0.51)	2.22(2.75)
		5	12.46(0.43)	10.98(0.43)	1.78(2.42)
15	27,5	3	9.61(0.08)	8.13(0.08)	2.11(0.26)
		4	12.01(0.21)	10.53(0.21)	1.00(0.82)
		5	14.09(0.54)	12.61(0.54)	1.98(1.43)
Averaged parameter values for the excited levels of the ^{6}Li nucleus wit hin an energy interval of 6–15 MeV		3	8.81(0.13)	7.33(0.13)	1.84(0.71)
		4	11.31(0.38)	9.83(0.38)	1.28(1.09)
		5	13.51(0.38)	12.03(0.38)	1.45(1.52)

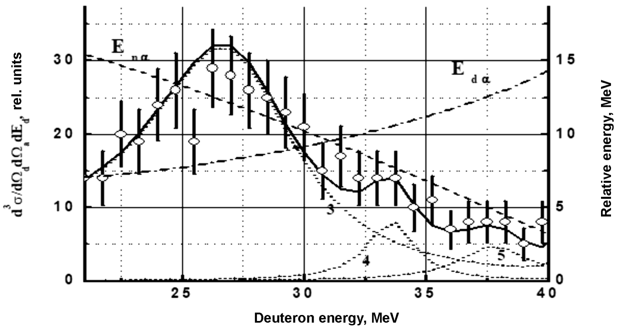


Fig. 4. Projection of the upper branch of the locus of the three-particle ^{3}H(α,$d\alpha$)n reaction at $E_\alpha = 67.2$ MeV onto the deuteron-energy axis. The registration angles are 27.5° for deuterons, and 15° for α-particles. The dashed and dash-dotted curves demonstrate the calculation results for the relative energy in the $d-\alpha$ and $\alpha-n$ pairs, respectively. The solid curve is the approximation of the spectrum by the sequential decay mechanism (the Breit–Wigner formula) assuming the formation and decay of the ^{6}Li nucleus levels. The dotted curves marked with numbers 3, 4, and 5 are the contributions from separate excited levels

The formula describing the cross-section of a three-particle $T(p,12)3$ reaction can be expressed as follows:

$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE_1} = \frac{(2\pi)^4}{\hbar\nu_{\rm in}} \left|T_{if}\right|^2 \rho(E_1), \tag{12}$$

where $T_{\rm if}$ is the matrix element of the transition operator, the function ρ describes the density of final states and is the phase-space factor of the three-particle reaction, and $\nu_{\rm in}$ is the relative velocity in the input channel.

In order to describe the spectra obtained while studying the three-particle reaction, various forms are chosen for $T_{\rm if}$. In particular, in our case (the study of the ^{3}H(α, $d\alpha$)n reaction as a sequential process), the expression for the factorization of spectrum (12) takes the form

$$\frac{d^3\sigma}{d\Omega_d d\Omega_\alpha dE_1} \approx \rho(E_d) \sum_j^n C_j \times$$
$$\times \frac{\Gamma_j/2}{(E_{R_j} - E_{d\alpha})^2 + (\Gamma_j/2)^2}, \tag{13}$$

where $\rho(E_d)$ is the phase space factor; E_{R_j} and Γ_j are the position and the width, respectively, of the j-th excited state of the ^{6}Li nucleus; C_j is the relative contribution of the j-th resonance; $E_d\alpha$ is the relative energy in the $d\alpha$ pair; and n is the number of excited states that are taken into account.

The spectra obtained by projecting the upper branches of the αd coincidence loci were approximated on the basis of formula (13), considering three excited levels and using the least-squares method. In Fig. 4, the approximation results are presented by a solid curve. Dotted curves marked with numbers 3, 4, and 5 illustrate the contributions of separate excited levels of the ^{6}Li nucleus. The fitted energy

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position and width values are as follows: $E_3 = (9.61 \pm 0.08)$ MeV, $\Gamma_3 = (2.11 \pm 0.26)$ MeV, $E_4 = (12.01 \pm 0.21)$ MeV, $\Gamma_4 = (1.00 \pm 0.82)$ MeV, $E_5 = (14.09 \pm 0.54)$ MeV, and $\Gamma_5 = (1.98 \pm 1.43)$ MeV.

For the studied excitation levels of the ^{6}Li nucleus within an energy interval from 7 to 14 MeV (they are denoted by the numbers 3, 4, and 5) and for all exposures, the values of their averaged energy positions and widths are quoted in Table 2.

In Fig. 5, a schematical diagram of the energy levels of the ^{6}Li nucleus is depicted. It illustrates the data calculated on the basis of the shell model modified for light nuclei [3] and the corresponding experimental values [1]. In the column with the experimental data for the excited levels of the ^{6}Li nucleus, three excited states obtained in this work (averaged over the results) and two levels observed earlier [18] (marked with an asterisk) are plotted. Those five levels are exhibited taking their widths into account.

4. Highly Excited States of the ^{6}Li Nucleus with Excitation Energies Near 21 MeV

If comparing the compilation data on the energy levels presented in [1] and [2], discrepancies can be observed, especially at high energies. For example, two ^{6}Li levels at 21 and 21.5 MeV are absent in work [2]. Moreover, when studying the ^{7}Li(^{3}He,α)^{6}Li reaction at $E_\tau = 150$ MeV [24], ^{6}Li states with energies $E_{\rm ex} = (18 \pm 0.5)$ MeV and (22 ± 1) MeV, and widths $\Gamma = (5.0 \pm 0.5)$ MeV and (8 ± 1) MeV, respectively, were observed.

Theoretical studies point to the existence of trinucleon (t and τ) clusters at high excitation energies of ^{6}Li. The authors of work [25] theoretically researched the existence of the trinucleon (τ and t) clusters in ^{6}Li accounting for the LS pairing and using the resonance group method (RGM). They predicted the availability of the P doublet (^{1}P$_1$ and ^{3}P$_{\circ,1,2}$) and the F doublet (^{1}F$_3$ and ^{3}F$_{2,3,4}$) with $E_{\rm ex} \approx 22$ and 29 MeV, respectively. In turn, in paper [26], according to the results of the analysis of elastic $\tau + t$ scattering, a report was made about the presence of four levels ^{3}P$_2$, ^{3}P$_\circ$, ^{3}F $_4$, and ^{3}F$_3$ with excitation energies of 21.0, 21.5, 25.7, and 26.7 MeV, respectively.

On the other hand, in contrast to the low-energy excited ^{6}Li states, which are formed by boson particles, the high-energy excited states are $t + \tau$ particle systems composed of fermions. From the analysis of

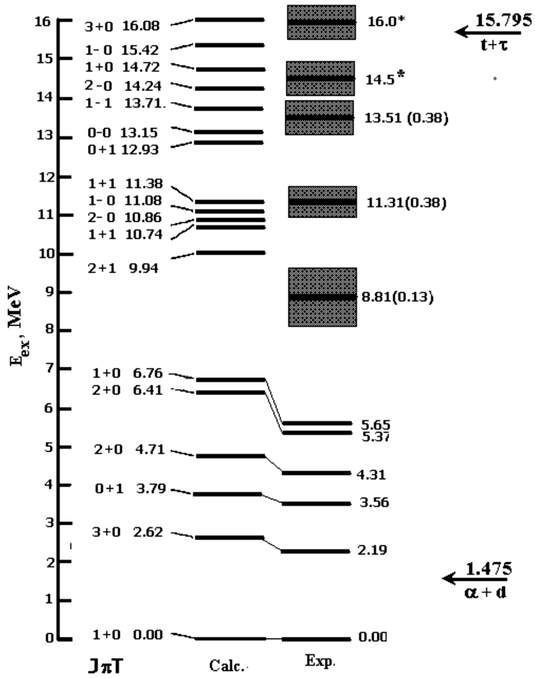


Fig. 5. Schematic diagram of the ^{6}Li nucleus levels

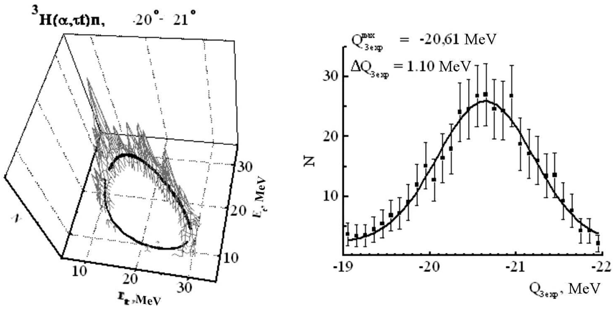
^{3}He$\,+\,t$ elastic scattering [26], ^{6}Li nucleus levels were predicted at excitation energies of 21.0, 21.5, 25.7, and 26.7 MeV.

A kinematically complete ^{3}H(α, τt)n experiment was performed at an incoming α-particle energy of 67.2 MeV, which is sufficient for the excitation of ^{6}Li levels above the threshold of cluster decay into $3 + 3$, and the excitation energy interval can be observed to about 27 MeV.

Two-dimensional $E_\tau \times E_t$ spectra were obtained together with other two-dimensional spectra for the interaction of α-particles with tritium nuclei. The reactions ^{3}H(α, τt)n and ^{3}H(α, $d\alpha$)n were studied simultaneously in the same experiment. Its more detailed description can be found in work [10].

In Fig. 6, *a*, one of two-dimensional τt coincidence spectra is shown. The solid curve represents a kinematic curve estimated under appropriate geometric conditions for the study of three-particle ^{3}H(α, τt)n reaction. Since scintillation E-detectors were used in the experiment, a special procedure based on the well-known Birks approach [21] was applied to calibrate them in some telescopes.

For additional control over the sorting procedure, on the basis of the momentum and energy conserva-



a *b*

Fig. 6. Two-dimensional experimental τt coincidence spectrum; the solid line represents the kinematic curve calculated in the framework of point kinematics for the corresponding experimental conditions (*a*). The corresponding experimental Q_3 spectrum (*b*)

tion laws, the two-dimensional spectrum was recalculated into the spectra of the reaction heat balance Q_3. As one can see from Fig. 6, *b*, the maximum of the experimental Q_3-distribution approximated by a Gaussian takes place at $Q_3 = -20.61$ MeV, whereas the calculated Q_3 value for the three-particle $_3\mathrm{H}(\alpha,\tau t)n$ reaction equals -20.58 MeV. The experimental error obtained from the two-dimensional τt spectra with regard for the detector resolution, the beam resolution, the energy distribution in the target, the influence of the differential target thickness, the kinematic dependence on the beam spot size, and the beam divergence was about 1.0–1.3 MeV.

The obtained two-dimensional $E_\tau \times E_t$ spectra contain information not only about unbound excited levels of ^{6}Li. The formation of three particles in a nuclear reaction can be interpreted as the sum of contributions made by successive two-particle interactions of various types together with a contribution made by a simple statistical decay. For the $^3\mathrm{H} + \alpha$ interaction, the following schemes for the formation of three $(\alpha{+}t{+}n)$ particles in the output channel are possible:

$$\longrightarrow \tau + {}^4\mathrm{H} \longrightarrow \tau + t + n + t, \quad (14)$$

$$\longrightarrow \tau + {}^4\mathrm{H} \longrightarrow \tau + t + n + t, \quad (15)$$

$$^3\mathrm{H} + \alpha \longrightarrow t + {}^4\mathrm{He}^* \longrightarrow t + \tau + n, \quad (16)$$

$$\longrightarrow n + \text{quasi-free } \tau - t \text{ scattering}, \quad (17)$$

$$\longrightarrow \tau + t + n. \quad (18)$$

Here processes (14)–(16) are mechanisms with further decays: in the first stage, nuclei are formed in the unbound ground (^{4}H) and excited (^{4}He* and ^{6}Li*) states; in the second stage, those excited states decay into the corresponding pairs of clusters. The process of quasi-free scattering of $\tau - t$-particles [17] is associated with a virtual decay of the α-particle projectile into $\tau{+}n$ and a real interaction between the α-particle and the triton (t) target. The last mechanism [18] is a statistical three-particle decay.

The manifestation of any simple quasi-two-particle mechanism depends on the kinematic conditions for the three-particle reaction. Therefore, the two-dimensional spectra obtained for various geometric conditions of τt-coincidences were considered in order to find those where the population of excited ^{6}Li states with the $\tau + t$ cluster structure occurs in the absence of the ^{4}H and ^{4}He resonances in accordance with the relative energy of $n - t$ and $\tau - n$. In addition, the choice of particle detector angles in our experiment was made taking into account the high density of highly located ^{6}Li levels. From the analysis of the upper branch in the experimental two-dimensional spectrum, the configuration with the detector angles $\Theta_\tau = 20^\circ$ and $\Theta_t = 21^\circ$ turned out the most optimal for detecting and identifying tritons (t) and τ-particles (^{3}He). The obtained spectra were interpreted using the Monte Carlo method.

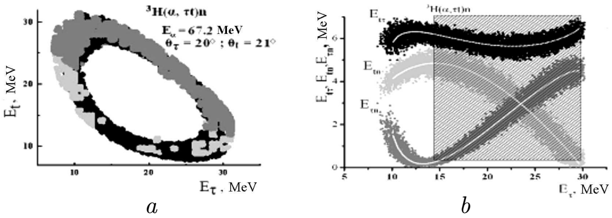
Calculations for the three-body $p(T, 12)3$ reaction are carried out using a set of random numbers suitable for obtaining 1–2 coincidences accounting for the beam energy and its dispersion, the target thickness, energy losses in the target, the beam spot size on the target, the distance of the detectors from the target, and the detectors' energy separation resolution. For this purpose, a special software was developed. Proceeding from real experimental conditions for the three-body $p(T, 12)3$ reaction, it simplified the spectral analysis procedure with the recalculation of two-dimensional cells of random events [11]. For further analysis of experimental data, the upper and lower loci of the kinematic curves obtained from the two-dimensional spectra of the reaction $^3\mathrm{H}(\alpha,\tau t)n$ are projected onto the energy axes of the τ and t particles. This procedure is carried out by recalculating the two-dimensional τt spectra of the mentioned reaction using the Monte Carlo method, as was described in work [11]. The selected two-dimensional τt-coincidence spectrum, which was obtained at an incident particle energy of 67.2 MeV and the detector angles $\Theta_\tau = 20^\circ$ and $\Theta_t = 21^\circ$, was divided into upper and lower branches using the method described above (see Fig. 7, a), and the upper branch of this locus was projected onto the energy axis of τ-particles (see Fig. 8).

From Fig. 7, b, one can see that the behavior of the function $E_{\tau t}$, as compared to that of the function E_τ, is almost constant with insignificant fluctuations. In addition, in the projection of two-dimensional spectrum, there appears a contribution from the ^{4}He decay into τ-n in the energy interval $E_\tau = 9$–15 MeV. The contribution is made by the second and third excited levels of ^{4}He with the corresponding width values. The obtained values corresponded to those reported in paper [24].

Concerning the formation of the ^{4}H nucleus, no contributions from events belonging to reaction mechanism (14) were observed in various energy intervals of the kinematic curve on the (E_τ, E_t) plane. Figure 8 illustrates the projection of the events contributing to the upper branch of the kinematic curve onto the E_τ-axis. One can see five well-resolved peaks associated with the formation and decay of the excited ^{4}He* and ^{6}Li* states. The error bars take into account both the statistical error and the finite energy resolution by the applied electronic system. The first peak in this figure appears due to the contributions of the second and third excited ^{4}He states. The other four peaks are associated with the excited ^{6}Li states.

In order to obtain the excitation energies and widths for the examined levels, we have to use a fitting procedure following the Breit–Wigner formalism. The contributions of each unbound state are shown in Fig. 8 by a dotted and a dash-dotted curve. In the experiment, the excitation energy of ^{6}Li levels was $E_{^6\mathrm{Li}} = E_{\tau t} + E_{\mathrm{por}}$, where $E_{\mathrm{por}} = 15.79$ MeV was the $\tau + t$ decay threshold. Thus, two pairs of energy parameters for the excited states of the ^{6}Li nucleus were obtained: $E_1 = (21.30 \pm 0.30)$ MeV with $\Gamma_1 = (0.25 \pm 0.30)$ MeV, and $E_2 = (21.90 \pm 0.40)$ MeV with $\Gamma_2 = (0.4 \pm 0.2)$ MeV.

When studying the $({}^3\mathrm{H},\alpha)$ reaction, Nakayama *et al.* [24] discovered two excited $t - \tau$ states with excitation energies of (18 ± 0.5) and (22 ± 1) MeV, and corresponding widths of (8 ± 1) and (5 ± 1) MeV, which were identified as P-states belonging to the ^{3}P and ^{1}P shells, respectively. The excitation energy interval between the two P levels, according to work [24], is about 4 MeV, whereas this difference equals 1 MeV in the three-nucleon cluster model [25, 27]. We experimentally detected with sufficient accuracy two



a *b*

Fig. 7. Upper (gray) and lower (light gray) branches of experimental τt-coincidence matrix. The kinematic calculation of the locus position is marked with black background (a). Relative energies $E_{\tau t}$, $E_{\tau n}$, and E_{tn} of the initial particle pairs in comparison with the energies of τ-particles calculated in the point geometry framework (solid curves). The results of corresponding Monte Carlo calculations are presented as point arrays. The shaded area corresponds to the energy interval $E_\tau = (15 \div 31)$ MeV where the excited ^{6}Li levels are populated and decay into τt clusters (b)

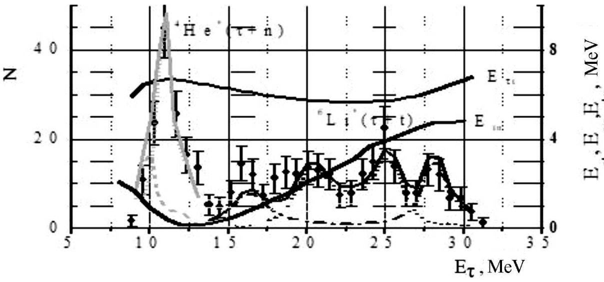


Fig. 8. Projection of the upper branch of two-dimensional $\tau - t$ spectrum obtained at $\Theta_t = 21^\circ$ and $\Theta_\tau = 20^\circ$ and an incoming energy of 67.2 MeV of α-particle beam onto the E_τ axis. Curves $E_{\tau t}$ and $E_{\tau n}$ are relative energies in the $\tau + t$ and $t + n$ pairs. The first (light gray) peak is associated with the formation and decay of the second (light gray dashed curve) and third (light gray dotted curve) excited ^{4}He levels. The consecutive dash-double-dotted curve corresponds to the relative energy E_{tn} for the analysis of the contribution made by the excited ^{4}H* state

^{6}Li levels belonging to the P shell, at $E^* = 21.30$ and 21.90 MeV. These results obtained for two very close ^{6}Li levels agree with the values presented in compilation [1].

5. Conclusions

This work is a generalization of the cycle of studies of the ^{6}Li nucleus [8–10] using the improved method of particle decay spectroscopy [3, 4] and the Monte Carlo method to study numerous three- and four-particle channels of reactions stimulated by the interaction of α-particles with tritium and ^{3}He of radiogenic origin, which are accumulated in titanium-tritium targets. It may be argued that complete and

Table 3. **Energy parameters of excited ^{6}Li levels**

No.	E^*, MeV	Γ, MeV
$E_\alpha = 27{,}2$ MeV ^{3}He$(\alpha, p\alpha)n$ ^{3}He+$\alpha \to p+^6$Li$^* \to \alpha + d$ [7]		
1	2.22(0.20)	0.20(0.15)
2	3.50(0.25)	–
3	4.44(0.30)	0.40(0.20)
4	5,15(0.25)	0.40(0.25)
5	5,85(0.30)	0.72(0.20)
$E_\alpha = 67{,}2$ MeV ^{3}H$(\alpha, d\alpha)n$ ^{3}H+$\alpha \to n+^6$Li$^* \to \alpha + d$		
6	8.80(0.15)	1.85(0.70)
7	11.30(0.40)	1.30(1.10)
8	13.50(0.40)	1.45(1.50)
$E_\alpha = 67{,}2$ MeV ^{3}H$(\alpha, t\tau)n$ ^{3}H+$\alpha \to n+^6$Li$^* \to \tau + t$ [8]		
9	21.30(0.30)	0.25(0.30)
10	21.90(0.40)	0.4(0.2)

incomplete correlation experiments with the measurement of two-dimensional spectra in the plane of particle energies for the particles into which the excited unbound state of the nucleus decays comprise a powerful tool for studying short-lived excited states of light nuclei. The advantage of this method consists in its ability to observe the energy characteristics of researched nuclei by selecting, with the help of kinematics, exactly those regions in the phase space, where the conditions for the formation of the examined state are realized. This possibility excludes the appearance of impurities from the formation and excitation of the states of other nuclei, as it happens, when measuring inclusive spectra.

The excitation energies obtained for the first five levels with excitation energies less than 6 MeV are in agreement with the corresponding data given in compilations [1, 2].

As a result of the kinematically complete study of the ^{3}H$(\alpha, d\alpha)n$ reaction [6], three new unbound excited levels of the ^{6}Li nucleus were observed for the first time within the excitation energy interval from 7 to 14 MeV. The energy parameters of those levels are consistent with the results of theoretical calculations [3–7] and the experimental data of other authors [16, 17].

By studying the ^{3}H$(\alpha,\ \tau t)n$ reaction at an α-particle energy of 67.2 MeV, two excited levels of ^{6}Li with excitation energies of 21.30 and 21.90 MeV [10] and the ^{3}He $+\, t$ cluster structure were experimentally discovered for the first time. Their existence was theoretically predicted in the late 1960s by Thomson and Tan [29], who assumed the cluster structure of the excited states of the ^{6}Li and ^{6}He nuclei.

In total, ten excited states of the ^{6}Li nucleus were observed. In Table 3, the results of our experimental research devoted to the study, using a kinematically complete analysis, of the excitation spectrum structure of three-particle reactions with the interaction of 27.2- and 67.2-MeV α-particles with tritium and ^{3}He nuclei are summarized.

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ВЗАЄМОДІЯ $\alpha + t$ І $\alpha + {}^3$He
ТА СПЕКТР ЗБУДЖЕНИХ СТАНІВ ЯДРА ^{6}Li

Проведено кінематично повне дослідження реакцій ^{3}He$(\alpha, p\alpha)d$ на ядрах ^{3}He радіогенного походження, накопичених у титан-тритієвих мішенях та ^{3}H$(\alpha, d\alpha)n$, ^{3}H$(\alpha, \tau t)n$ на ядрах тритію на цих же мішенях для вивчення спектра збудження ядра ^{6}Li до енергій збудження $E^* < 26$ МеВ при енергії пучків прискорених альфа-частинок $E_\alpha = 27{,}2$ і 67,2 МеВ. Спостерігались три незв'язані збуджені рівні в енергетичному діапазоні енергії збудження ядра ^{6}Li від 7 до 16 МеВ та два збуджені рівні ^{6}Li з енергіями збудження 21,30 та 21,90 МеВ, які узгоджуються з теоретичними розрахунками, але не були достовірно підтверджені експериментально. Використання методу спектроскопії розпаду збуджених рівнів (particle decay) дозволило усунути деякі неоднозначності в енергетичних параметрах збуджених станів ядра ^{6}Li.

Ключові слова: ^{6}Li, тричастинкові реакції, двовимірний спектр збігів, $\alpha + t$ взаємодія, $\alpha + {}^3$He взаємодія.