УДК 539.172

α + t THREE-BODY REACTIONS AND EXCITED LEVELS OF THE LIGHTEST NUCLEI

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The three-body reactions from interaction alpha-particle with energy 67.2 MeV and tritium were investigated in kinemanically-complete experiment. The excitation energies and energy widths of some unbound levels of nuclei ^{4}H, ^{5}He and ^{6}Li were determined using of sequential decay model.

1. Introduction

Nuclei have a discrete number of bound states, which appear at excitation energies below the break-up threshold, and there are numerous numbers of unbound continuum states above it. In standard nuclear structure models square-integrable bases are used, disregarding thresholds and the decay of some states. But the state instability is often essential. Neglecting it may also lead to false conclusions about other properties as well. The problem is especially acute for the light nuclei, which often have just one bound state or none. Without consideration of unbound states or disregarding their instability, the description is incomplete and unreliable.

Exact determination of excitation energy, life-time and modes of decay of such unbound levels is very important for more adequate understanding of nature of nuclear forces which causes their formation and decay.

However, present experimental information about the excitation spectra of lightest nuclei is rather contradictory [1, 2]. Such ambiguity is the most essential for energy splitting of ground and first excited states of ^{5}He, level structure of this nuclear around 20 MeV excitation energy. The same is possible to say about the structure of levels of ^{6}He and ^{6}Li above and below the break-up thresholds on t + t and ^{3}He + t respectively.

Our attempt to specify some of these white spots is based on the use of α + t interaction at energies higher than decay thresholds of ^{4}He. Then the three-body break-up sequential and multi-body reactions caused by interaction of alpha-particles beam with tritium nuclei are a powerful spectroscopy information source about the unbound states of ^{4}H, ^{5}H, ^{4}He, ^{5}He, ^{6}He and ^{6}Li:

Nucleus	Mode of decay	Reaction
^{4}H	t + n	^{3}H(α, τt)n
	d + 2n	^{3}H(α, τd)nn
^{5}H	t + 2n	^{3}H(α, ^{2}He t)n
^{4}He	t + p	^{3}H(α, tt)p
	τ + n	^{3}H(α, τt)n
	d + d	^{3}H(α, td)d)
^{5}He	α + n	^{3}H(α, dα)n
	d + t	^{3}H(α, dd)t
^{6}He	α + 2n	^{3}H(α, pα)nn
	T + p	^{3}H(α, pt)t, ^{3}H(α, tt)p
^{6}Li	α + d	^{3}H(α, dα)n
	τ + t	^{3}H(α, τt)n

2. Experiment

Triturated titan targets and alpha-particle beam were used in the experiment (Fig. 1). It was established that alpha-particle beam's energy in this experiment was equal 67.2 ± 0.4 MeV by using time of flight technique, developed for measurement of time and energy characteristics of cyclotron's beam. Four ΔE-E telescopes were used for identification and determination energy of outgoing charge particles on coincidences. Two of these, consisting of 400 μm Si ΔE-detector and ∅20 mm × h 20 mm NaJ(Tl) E-detector allocated for the registration long-range reaction products (protons, deuterons and tritons) positioned on one side to the beam's direction (left arm) and other two consisting of

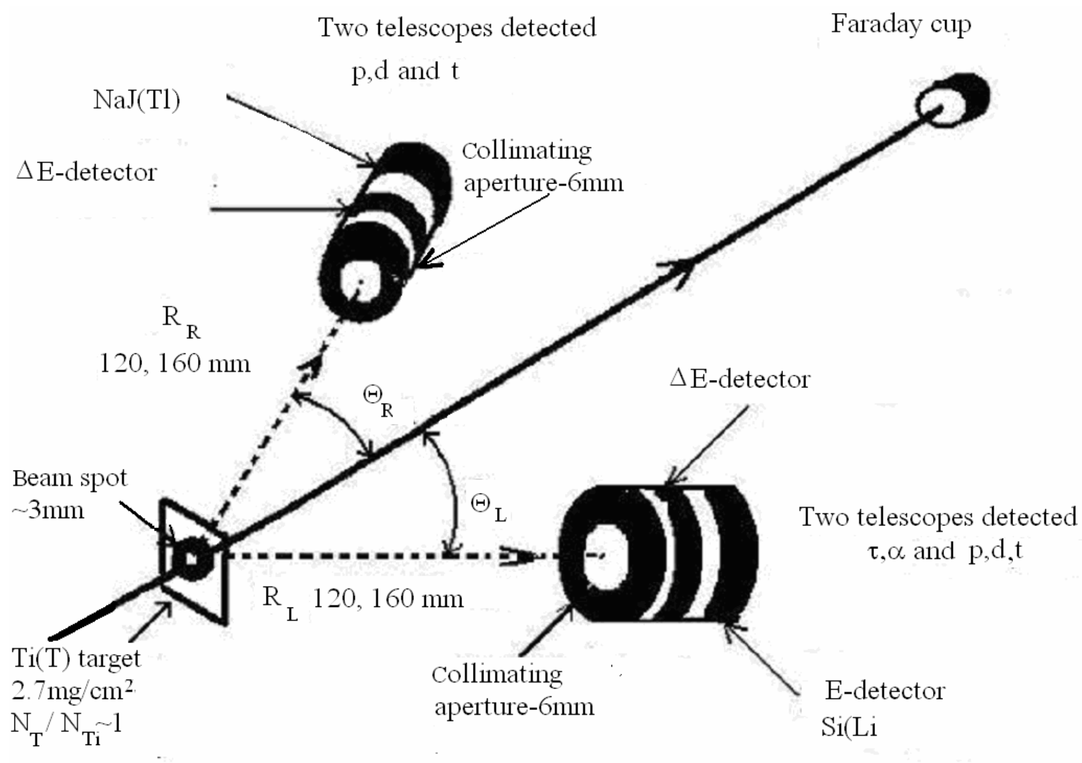

Fig. 1. Schematic diagram of experimental setup for study sequential three-body reactions caused α + t interaction.

90 μm Si ΔE-detector and 3 mm Si(Li) E-detector assigned for registration τ-particle, α-particles and low-energy protons, deuterons and tritons were situated on the other side of the beam's direction(right arm). Coincidence between the pair of ΔE detectors of telescopes as well as prescaled single output from each telescope generated the event trigger for the acquisition system. The analog-to-digital information from each detector together with time-to-digital convertors (TAC's) and bit-pattern register to label each by event were storied for later analysis.

The selected pairs of charged particles (for a example t + τ or t + t) from ^3H + ^4He interaction were identified in *ΔE-E* spectra (Fig. 2, *1*, *2*) and were sorted with an account energy calibration of all four detector into ($E_\tau + \Delta E_\tau$) - ($E_t + \Delta E_t$) matrices (see Fig. 2, *3*, *4*) by choosing windows on the corresponding bit-pattern and the relevant time-to-amplitude converter spectra. Two-dimensional spectra for added control of sorting procedure were recalculated in Q_3-value spectra by using laws of saving of momentum and energy [3]

$$\vec{P}_{p(n)} + \vec{P}_t + \vec{P}_{t(\tau)} = \vec{P}_{\alpha 0}, \qquad (1)$$

$$E_{p(n)} + E_t + E_{t(\tau)} + Q_3 = E_{\alpha 0}, \qquad (2)$$

where $P_{p,n,t,\tau,\alpha 0}$, $E_{p,n,t,\tau,\alpha 0}$ - momenta and energies of outgoing particles, $P_{\alpha 0}$ - momentum of the incident particle. As one can see (Fig. 2, *5*, *6*) maxima of experimental Q_3 spectra and Q_3-values of correspond three-body reaction practically coincide. Since $Q_3 = E_{\alpha 0} - E_t - E_{t(\tau)} - E_{p(n)}$ – all usual contributions influence experimental energy resolution. Then ΔQ_3

$$(\Delta Q_3)^2 = (\Delta E_t)^2 + (\Delta E_{t(\tau)})^2 + (\Delta E_{p(\tau)})^2 + (\Delta E_{\alpha 0})^2 \qquad (3)$$

includes detector resolution, beam resolution, energy straggling in the target, effects of differential target thickness and kinematic shifts from beam spots size and beam divergence and represents total energy resolution of kinematically complete three-body experiment. In this investigation it was typically about 1.2 MeV.

3. About the first excited state of ^{5}He [4]

Alpha-particles and deuterons detected in coincidence can appear as a result of sequential decay of the unbound states of ^{5}He: $^3H + \alpha \rightarrow d + {}^5He \rightarrow d + \alpha + n$. The matrixes of αd coincidences were obtained for several pair of angles; one of them

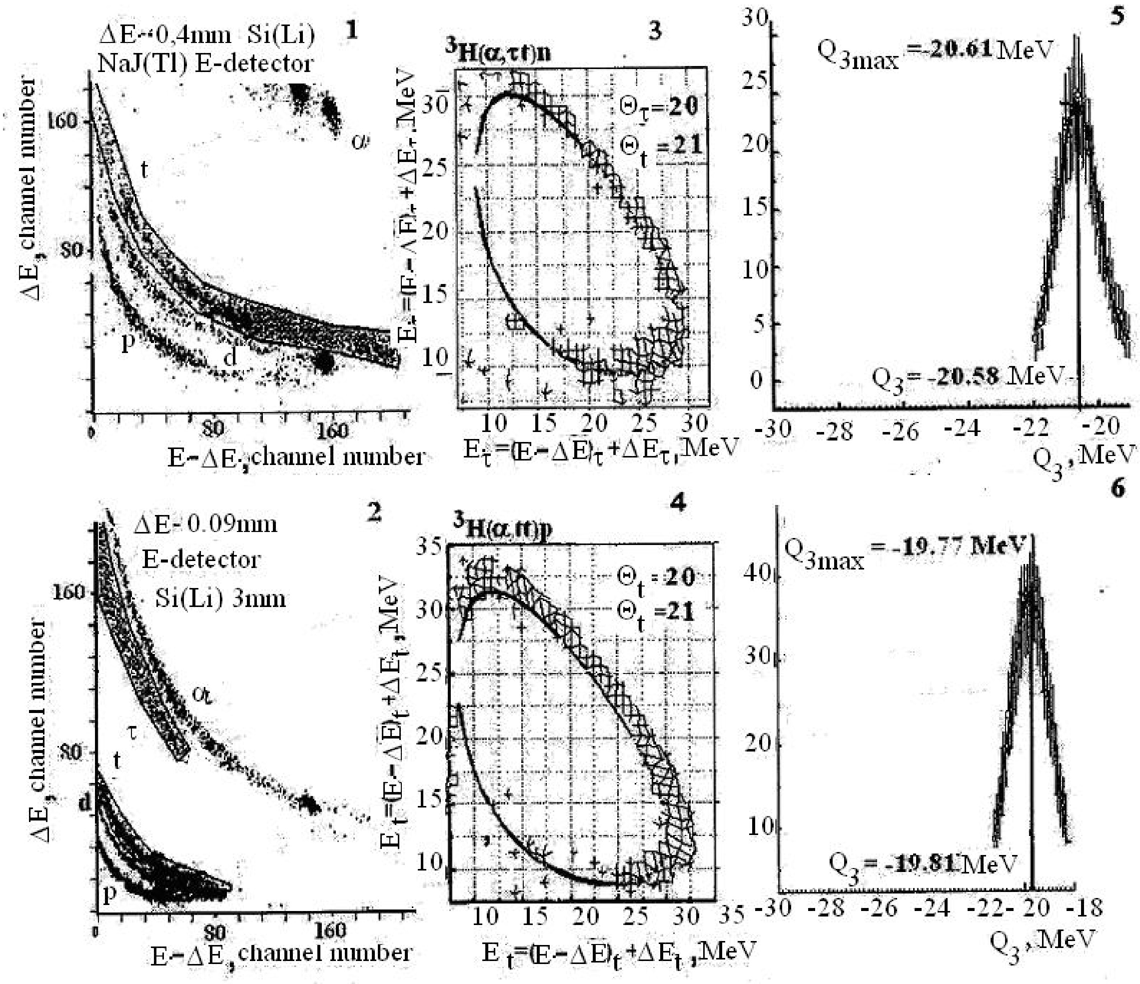

Fig. 2. *1*, *2* – two-dimensional Δ*E*-*E* spectra. *3*, *4* - two-dimensional τt and tt coincidence matrices, kinematical curves for proper three-body reactions presented by solid lines. *5*, *6* – spectra of three-body Q_3 values, calculated from two-dimensional matrices *3*, *4*.

is presented in Fig. 3. Analysis with using calculated values of the third particle (E_n) and relative energies in α - n ($E_{\alpha n}$) and α - d ($E_{\alpha d}$) pairs allowed to select part of upper branch of αp coincidence locus where the mechanism of sequential decay of unbound states of ^{5}He is dominant.

The projection of selected part of upper branch on the axis of α-particle energy is presented in Fig. 4. The low energy part of this spectrum $E_\alpha \leq 12$ MeV was obtained without α-particle identification as width of Si ΔE-detector was 90 μm. As one can see the most intensive contributions for these kinematical conditions are caused by sequential processes through the ground and first exited states of ^{5}He, which are not bad resolved. The pair of resonance states is displayed in this spectrum twice: at α-particle energy ranges of 6 - 13 MeV and 13 - 25 MeV, correspondingly. The energy dependence of relative energy in α-n pair on the α-particle energy is shown in Fig. 4 by dashed line. Using non-interfering Breit - Wigner terms fitting procedure was carried out for each energy range separately. The low energy range was fitted firstly. Obtained parameters (energy positions and widths) were used for spectrum interpretation in the next energy range, where only values of Breit - Wigner amplitudes were fitted. Dotted lines marked by *1*, *2* represent fitting contributions of the ground and the first exited states in low energy range, respectively, and *3*, *4* ibidem in other range. Solid lines represent the sums of contributions. Some discrepancy in fitting high-energy range is caused by the contribution of quasi-free αd-scattering, since at $E_\alpha = 21.6$ MeV the energy of the third non-detected particle (neutron) is equal to 50 keV. From this analysis, $E_{n\alpha} = (1.79 \pm 0.65)$ MeV and $\Gamma = (3.92 \pm \pm 3.23)$ MeV for the first exited state of ^{5}He were obtained. Obtained values of parameters of ^{5}He ground state are in agreement within the experimental errors with well known parameters of this state [1, 2] and equal $E_{n\alpha} = (0.63 \pm 0.18)$ MeV, $\Gamma = (0.61 \pm 0.22)$ MeV.

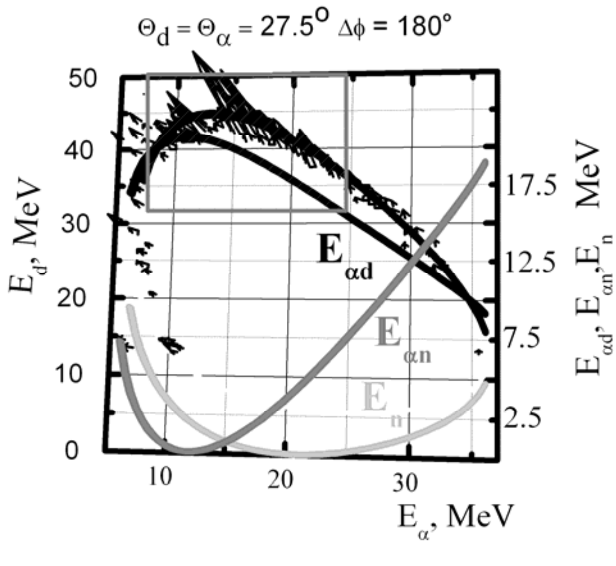

Fig. 3. The matrix of αd coincidences and kinematical relations.

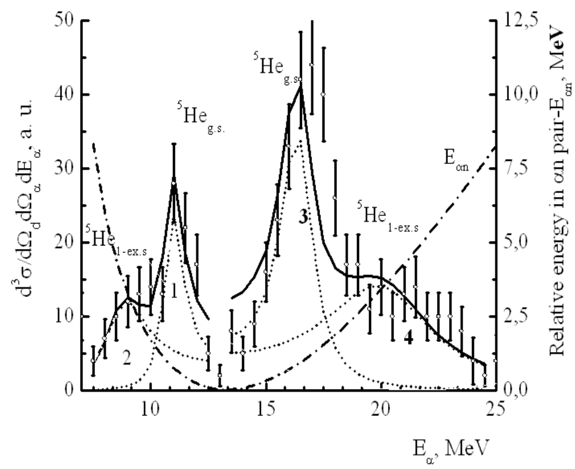

Fig. 4. Projection of upper branch of matrix αd coincidences on the axis of the energy of alpha-particles.

4. The structure of high exited state of ^{5}He [5]

We explored the three-body sequential break-up ^{3}H(α, dα)n and ^{3}H(α, dt)d reactions in order to find the presence of fine structure in the excitation spectrum of ^{5}He nucleus (E*~20MeV) and determinations of its nature. In Fig. 5 the experimental events of dt-coincidences (black), the results of Monte Carlo simulation of three-body kinematics (grey) and kinematical curve calculated for punctual geometry (white dot) are presented.

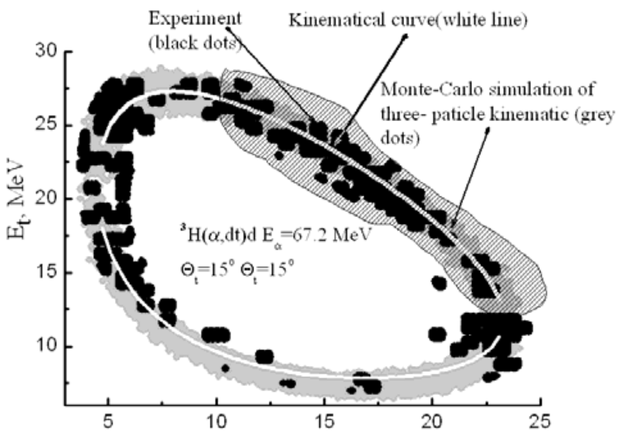

Fig. 5. The matrix of dt coincidences and kinematical relations.

Each coincidence event from upper or lower branches of dd and dα coincidence matrix has been additionally multiplied by inverse of its phase space factor to eliminate not interesting kinematical dependence. Spectra of ^{5}He excitation energy for different decay channels are represented in Fig. 6 and 7. One can see that these spectra have similar resonance structure. The result of spectra approxi-

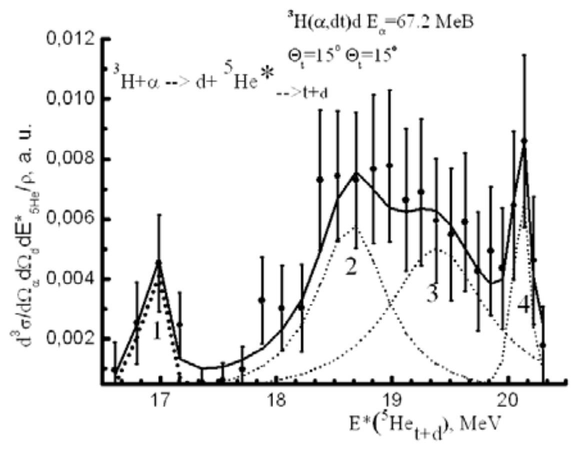

Fig. 6. The excitation spectrum of ^{5}He, got from analysis of matrix of dt-coincidences.

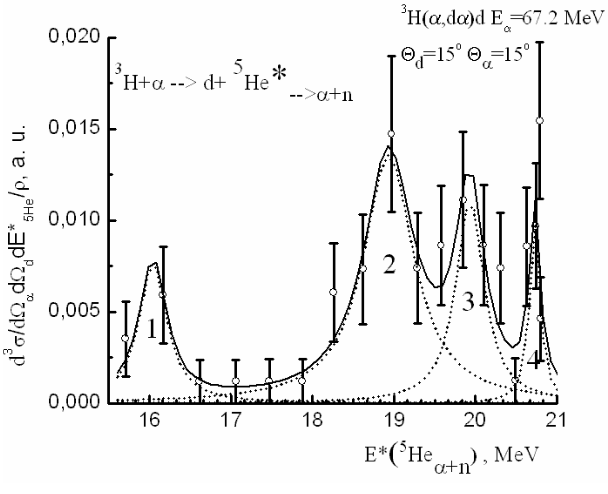

Fig. 7. The excitation spectrum of ^{5}He, got from analysis of matrix of dα-coincidences.

mation with using four non-interfering Breit - Wigner's terms was represented by dotted and solid lines. Dotted lines labelled by *1*, *2*, *3*, *4* show contributions of each of observed exited states then solid lines represents their sums. Energy positions and widths of observed levels of ^{5}He decayed into d + t and α + n channels are presented in Table 1.

Obtained results are agreed with the last compilation publication [1], in contrary with the level's parameters data presented in paper [2].

Table 1

Ref. [1]	Ref. [2]	^{2}H(α, pd)t ^{2}H(α, dt)p $E_α$ = 70 MeV [6]	^{6}Li(n,d) ^{5}He E_n = 56.3 MeV [7]	Our data			
				Channel ^{3}H(α, αd)n		Channel ^{3}H(α, dt)d	
E, MeV	E, MeV	E, MeV	E, MeV	$E^* = E_{thr} + E_{nα}$, MeV	Γ, MeV	$E^* = E_{thr} + E_{td}$ MeV	Γ, MeV
	21.30						
	21.20		20.5	20.73(0.34)	0.15(0.08)	20.11(0.14)	0.14(0.20)
19.8		19.2		19.95(0.10)	0.42(0.37)	19.59(0.31)	1.03(0.58)
	19.08	18.8		18.94(0.11)	0.75(0.29)	18.65(0.22)	0.73(0.55)
	18.31	18.6	18.5				
	18.28						
	18.14						
16.75	16.84	16.7	16.7	16.09(0.34)	0.41(0.37)	16.89(0.10)	1.2(0.70)

5. Investigation of excited levels of ^{6}Li nucleus by ^{3}H(α, dα)n three-body reaction [8]

In upper branches of matrices of dα coincidences (Fig. 8) obtained at the angle pairs of registration of deuterons and α-particles 15 - 15°; 27.5 - 15°; 21 - 15° three exited levels of ^{6}Li nucleus with excitation energy from 7 to 14 MeV were observed.

The analysis of calculated relative energies E_{an} (dashed line) and $E_{αd}$ (solid line) confirm that the main mechanism is sequential formation and decay of unbound states of ^{6}Li into d + α.

Experimental spectrum obtained as a result of projecting upper branch of αd coincidences locus was approximated with the help of non-interfering Breit - Wigner terms using the least squares method (Fig. 9). The results of approximation are given by solid line. Dotted lines, marked by *1*, *2* and *3*, show the contributions of separate excited levels of ^{6}Li which excitation energies and widths: E_1 = 9.61(0.08) MeV, $Γ_1$ = 2.11(0.26) MeV; E_2 = 12.01(0.21 MeV, $Γ_2$ = 1.00(0.82) MeV; E_3 = 14.09(0.54) MeV, $Γ_3$ = 1.98(1.43) MeV.

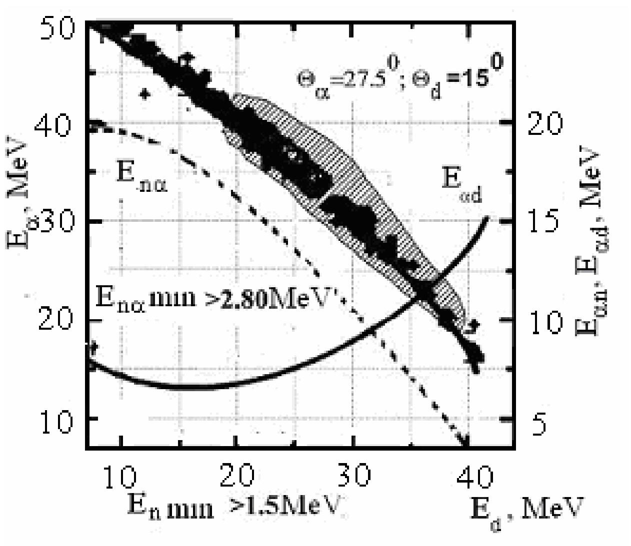

Fig. 8. The matrix of dα coincidences and kinematical relations.

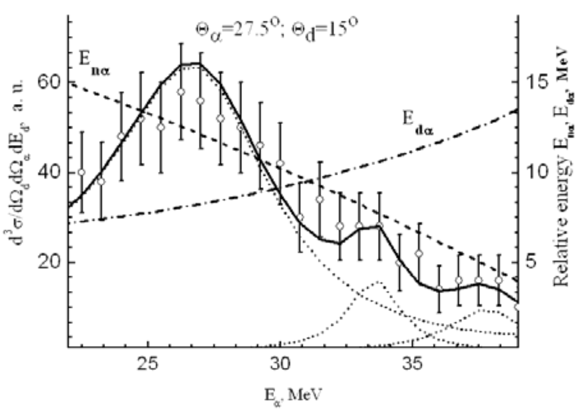

Fig. 9. Projection of the upper branch of the locus of ^{3}H(α, dα)n reaction.

The scheme of energy levels of ^{6}Li with estimation data obtained in the basis of the shell model modified for light nuclei [9] and experimental values [2] are presented in Fig. 10. Averaged values of energy positions of the excited levels of ^{6}Li, obtained in this work with taking into consideration experimentally determined widths, are showed on Fig. 10. By the mark “*” are noted the levels, which were observed earlier [13]. Obtained new experimental data about excited states of ^{6}Li is agreed with theoretical calculations [9, 10] and also with experimental investigations of other authors [11, 12].

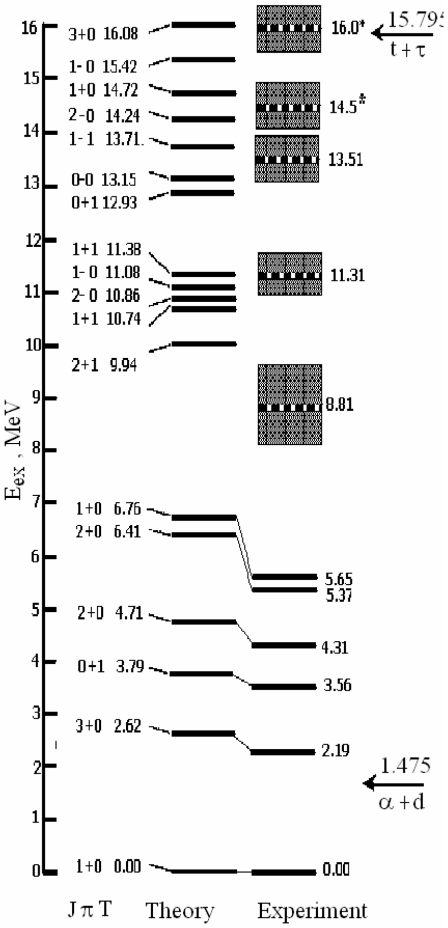

Fig. 10. Scheme of ^{6}Li energy levels.

6. The observation of the ground state of ^{4}H in ^{3}H(α, τt)n reaction [14]

Additional source of information about energy scheme and structure of excited levels of ^{4}H may be studied of their formation and subsequent decay into t + n and d + 2n channels by using α + t interaction at energy that exceed the threshold of decay of alpha-particle into d+d. Then, investigating in kinematically complete experiment ^{3}H(α, τt)n and ^{3}H(α, τd)2n reactions may specify energy parameters of levels that decayed as into t +n channel and into d + 2n channel.

Obtained for different geometric conditions τt-coincidence matrices were selected to look for resonances in the n - t relative energy spectra corresponding to ^{4}H state in the absence of resonances of ^{4}He and ^{6}Li in corresponded relative τ - n and τ - t energies. Some of calculated dependencies of relative energies of nτ, τt and tn outgoing pairs on the energy of detected τ-particles were represented in Fig. 11. Dotted, dash and solid lines correspond to relative τ - t, τ - n and t - n energies respectively. The arrows directed to the right axis to the right and to the left indicate the energy position of resonance levels of ^{4}He and ^{6}Li, respectively. The arrow directed to the left axis indicates the magnitude of relative energy of particles t and n equal 3 MeV, which corresponds to energy position of ground state of ^{4}H obtained in most of experiments [16 - 20].

The most optimal conditions for the investigation of formation and decay of resonance states of ^{4}H in excitation range from 2 to 5 MeV carried out from τt coincidences matrix at registration angles of τ-particles – 27.5° and tritons – 15°(see Fig. 11). Then values of energy of relative motion in n + τ and τ + t outgoing pairs don’t correspond to formations of resonance levels in ^{4}He and ^{6}Li.

The events of upper branch of locus in two-dimensional spectrum were projected on ^{3}He energy axis and had been additionally multiplied by inverse of its phase space factor and is shown in Fig. 12.

The result of fitting procedure using Breit - Wigner formula was represented in Fig. 12 by solid line. Wide resonance structure observed in the experiment corresponds to the ground unbound state of ^{4}H with the following energy parameters: $E_{nt} = 3.22 \pm 0.25$ MeV; $\Gamma = 2.93 \pm 1.09$ MeV.

The resonance structure which takes place in spectrum (see Fig. 12.) in the range of relative energies from 5 to 6.5 MeV is due to the formation and decay of excited levels of ^{4}He into τ + n channel (see Fig. 11). The result of fitting procedure carried out for excited levels of ^{4}He is represented in Fig. 12 by dotted line. This part of spectrum was described in assumption that energy position of excited level of ^{4}He is equal 21.5 ± 0.4 MeV and energy width – $\Gamma = 0.28 \pm 0.27$ MeV. If we compare obtained energy parameters of ^{4}He excited level with represented in compilation paper [15] scheme of ^{4}He energy levels the value of energy excitation with taking into account experimental error is close to the energy position of the third excited ^{4}He level ($E^* = 21.84$ MeV) but observed energy width is less (Γ_n = 0.75 MeV).

Obtained results for ^{4}H ground state were represented in Table 2 for comparison with parameters obtained in other correlation experiments.

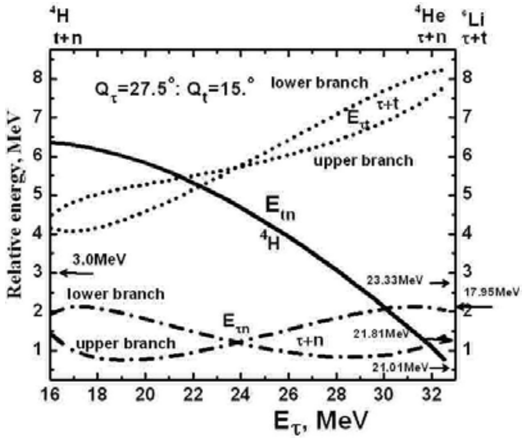

Fig. 11. The dependencies of relative motion of nτ, τt and tn outgoing pairs on energy of detected τ-particle.

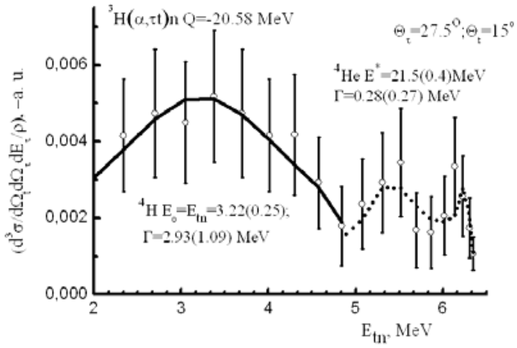

Fig. 12. The projection of upper branch of τt-coincidence.

Table 2

Reaction	E_P, MeV	E_{tn}, MeV	Γ, MeV
^{2}H(t, pt)n[20]	35.3	3.1 ± 0.3	2.1
^{7}Li(n, αt)n[17]	14.6	2.6 ± 0.4	2.1 ± 0.3
^{3}H(d, pt)n[18]	27.2	3.4 ± 0.3	3.0 ± 0.3
^{3}H(d, pt)n[19]	47.3	2.2 ± 0.4	3.4 ± 1.2
^{3}H(α, τt)n[*]	67.2	3.2 ± 0.25	2.9 ± 1.1
^{7}Li(τ, ττ)tn[16]	120	2.6 ± 0.4	—
E_p - energy of incident beam. [*] parameters obtained in this experiment.			

As one can see all these data agree quite well if one takes into account experimental errors. But the question about the accordance between the results of investigation of ^{4}H excitation only in n + t interaction as for example by measurements energy dependence of total cross-section of n + t interaction or energy dependencies phase shifts of elastic n + t scattering and the results of correlation investigation is remained. Results of analysis of direct n + t interaction represented in [11] were indicated on complex scheme of excited levels of ^{4}H, on presence, of some resonance structure not only near E_{nt} ~ 3 MeV but at E_{nt} ~ 5 MeV and 6.5 MeV. In the same time results of correlation experiments presented in Table 2 were limited by only ground state of ^{4}H, because for investigating others levels it is necessary to increase the maximum value of energy of n + t relative motion up to 8 MeV.

7. Conclusions

Despite rather simple experimental equipment (only four telescopes) represented experimental investigation of α + t three-body and multi-particle reactions allowed to get valuable experimental information that is far not always accessible with the use of more improved methods based on beams of radioactive nuclei and whole walls filled by complex detecting devices.

REFERENCES

1. *Ajzenberg-Selove F.* Energy Levels of Light Nuclei A = 5 - 10 // Nucl. Phys. - 1988. - Vol. A490. - P. 1 - 225.
2. *Tilley D.R., Cheves C.M., Godwin J.L. et al.* Energy Levels of Light Nuclei A = 5, 6, 7 // Nucl. Phys. - 2002. - Vol. A708. - P. 3 - 163.
3. *Rae W.D.M., Cole A.J., Harvey B.G., Stokstad R.G.*. Breakup of ^{16}O and ^{20}Ne at 9 MeV Nucleon // Phys. Rev. -1984. - Vol. C30. - P. 158 - 168.
4. *Горпинич О.К., Поворознык О.М., Ячменев А.А.* О первом возбужденном состоянии ядра ^{5}He // Изв. РАН. Сер. физ. - 2005. - Т. 69, № 5. - С. 742 - 744.
5. *Горпинич О.К., Поворознык О.М., Ячменев А.А.* Структура высоковозбужденных состояний ядра ^{5}He // Там же. - С. 745 - 747.
6. *Brady F.P., King N.S.P., Bonner B.E. et al.* ^{6}Li(n, d)^{5}He and ^{7}Li(n, d)^{6}He with 56.3 MeV Neutrons // Phys. Rev. - 1977. - Vol. C16. - P. 31 - 41.
7. *Treado P.A., Lambert J.M., Kane R.J. et al.* Excited states of ^{4}He and ^{5}He from sequential α + d reactions at E = 70 MeV // Phys. Rev. - 1973. - Vol. C7. - P. 1742 - 1750.
8. *Gorpinich O.K., Povoroznik O.M., Jachmenjov O.O.* Investigation of excited levels of ^{6}Li nucleus from the three-particle ^{3}H(α, dα)n reaction // Ukr. J. Phys. - 2004. - Vol. 49, No. 1. -P. 16 - 22.
9. *Zheng D.C., Barrett B.R., Vary J.P. et al.* Large-Basis Shell Model Studies of Light Nuclei with a Multivalued G-Matrix Effective Interaction // Phys. Rev. - 1995. - Vol. C 52. - P. 2488 - 2498.
10. *Navratil P., Barrett B.R.* No-Core Shell-Model Calculations with Starting-Energy-Independent Multivalued Effective Interactions // Phys. Rev. - 1996. - Vol. C 54. - P. 2986 - 2995.
11. *Delbar T., Gregoire G., Paic G.* Structure-Dependent Corrections to the Parameters of Resonant States in

Light Nuclei //Phys. Rev. - 1983. - Vol. C 27. - P. 1887 - 1896.
12. *Jenny B., Grüebler W., König V. et al.* Phase-Shift Analysis of d-α Elastic Scattering between 3 and 43 MeV // Nucl. Phys. - 1983. - Vol. A397. - P. 61 - 101.
13. *Gorpinich O.K., Povoroznik O.M., Pshedzyal A.P., Struzhko B.G.* Highly Excited States of the ^{5}He and ^{6}Li Nuclei in α + t Interaction at E_α = 67.2 MeV // Bull. Rus. Acad. Sci. Phys. - 2000. - Vol. 64. - P. 82 - 84.
14. *Gorpinich O.K., Povoroznik O.M., Jachmenjov O.O.* The observation of ground state of ^{4}H in ^{3}H(α, τ)n reaction // ВАНТ. Сер. «Ядерно-физ. исследования». - 2004. - Т. 42, № 5. - С. 31 - 33.
15. *Tilley D.R., Weller H.R., Hale G.M.* Energy Levels of Light Nuclei A = 4 // Nucl. Phys. - 1992. - Vol. A541. - P. 1 - 157.
16. *Franke R., Kockskamper H., Steinheuer B. et al.* Search for highly excited states in light nuclei with three-body reactions // Nucl. Phys. - 1986. - Vol. A433. - P. 351 - 368.
17. *Miljanić D., Blagus S., M. Zadro.* ^{4}H and (n, *alpha x*) reactions on ^{6}Li and ^{7}Li // Phys. Rev. - 1986. - Vol. C33. - P. 2204 - 2205.
18. *Grantsev V.I., Zaritsky V.S., Konfederatenko V.I. et al.* On Investigation of Resonances of ^{4}H in d + t Reaction // Program and Thesis. Proc. 38th Ann. Conf. Nucl. Spectrosc. Struct. At Nuclei. - Baku, 1988. - P. 346.
19. *Konfederatenko V.I., Povoroznik O.M., Struzhko B.G.* Three-Particle Channels of d + t Reaction at E(d) = = 47.3 MeV // Bull. Rus. Acad. Sci. Phys. - 1994. - Vol. 58. - P. 149 - 153.
20. *Blagus S., Miljanić D., Zadro M. et al.* ^{4}H nucleus and the ^{2}H(t, tp)n reaction // Phys. Rev. - 1991. - Vol. C44. - P. 325 - 328.

α + t ТРИЧАСТИНКОВІ РЕАКЦІЇ ТА ЗБУДЖЕНІ РІВНІ НАЙЛЕГШИХ ЯДЕР

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Тричастинкові ядерні реакції, спричинені взаємодією альфа-частинок, прискорених до енергії 67.2 МеВ з ядрами тритію, досліджувались у кінематично-повному експерименті. Енергії збудження та енергетичні ширини деяких незв’язаних станів ядер ^{4}H, ^{5}He і ^{6}Li було визначено за допомогою моделі послідовного розпаду.

α + t ТРЕХЧАСТИЧНЫЕ РЕАКЦИИ И ВОЗБУЖДЕННЫЕ СОСТОЯНИЯ ЛЕГЧАЙШИХ ЯДЕР

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Трехчастичные ядерные реакции, вызванные взаимодействием альфа-частиц с энергией 67.2 МэВ с ядрами трития, исследовались в кинематически-полном эксперименте. Энергии возбуждения и энергетические ширины некоторых несвязанных состояний ядер ^{4}H, ^{5}He и ^{6}Li были определены с помощью модели последовательного распада.

Received 23.06.06,
revised - 11.04.07.