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A SEARCH FOR EXCITED STATES OF ^3He BY THE REACTION $^7Li(d,^6He)^3He$

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At deuteron energy of 37 MeV the ^6He inclusive spectra are measured in the exit channel of reaction $^7Li(d,^6He)^3He$. The resonance-like structure of spectra in the range of ^6He energies corresponding to the excitation of ^3He recoil nuclei in the range of $E^* = 6…16$ MeV was observed. The experimental data can be described in assumption of existence of ^3He resonances with excitation energies of $E^* = 9$, 13 and 16 MeV. An analysis of the experimental spectra shows that observed structure of ^6He spectra can be as well explained by the more probable processes of excitation and decay of ^7Li and ^7He unbound states in accompanied reaction channels.

Introduction

In accordance with the reviews [1 - 3] of experimental and theoretical studies devoted to search the excited states of ^3H and ^3He nuclei. There are no unambiguous evidences for resonance existence for these three-nucleon systems. Recently the resonance-like structure of α-particle spectrum was observed in reaction $^1H(^6He,\alpha)^3H$ studied by the secondary ^6He beam with energy of 23,9 MeV [4]. It corresponds to experimental data previously received for the same reaction at energy of 19,3 MeV [5], where the excited state of ^3H with the width $\Gamma = 0{,}6$ MeV and excitation energy $E^* = 7$ MeV was observed. It was shown in [6] that interpretation of reaction cross section maximum as the excited state of ^3H [5] does not contradict the theoretical conception concerning the poles of *S*-matrix in doublet channel of *nd*-interaction, while the absence of resonance in elastic *nd*-scattering can be reasoned in the destructive interference of phases of potential and resonance scattering. The existence of similar virtual pole is theoretically predicted [3] for *pd*-system as well.

To some extent the results obtained for ^3H [4 - 6] have initiated the present study of ^3He excitation spectrum in the exit channel of reaction

$$d + {}^7Li \rightarrow {}^6He + {}^3He, \qquad (1)$$

which has been studied at a deuteron laboratory energy of 37 MeV [7]. Besides the peaks connected with population of the ground state of ^3He all measured ^6He spectra reveal some structure at energies corresponding to the excitation of ^3He recoil nuclei in the range of $E^* = 6…16$ MeV. The aim of present work is to analyze the possible ways of resonance-like continuum formation in this energy range of ^6He spectra.

Experiment

The differential cross sections of reaction (1) at deuteron beam energy of 37 MeV have been measured at the cyclotron U-240 of the Institute for Nuclear Research. The target with the thickness of 1,5 mg/cm^2 has been produced by rolling of lithium film with natural content of ^7Li. The reaction products have been detected by ΔE-E-method using two ΔE-E telescopes of silicon semi-conductor detectors with the thickness of ~ 50 μm for ΔE- and 550 μm for E-detectors. The thicknesses of ΔE-detectors have been specified in a way to have a low energy threshold of registration preserving appropriate mass resolution. Solid angles of detector telescopes were $\Omega_1 = 0{,}65\cdot10^{-3}$ sr and $\Omega_2 = 0{,}92 \times 10^{-3}$ sr. Total energy resolution at reaction products registration was mainly determined by the dispersion of the beam energy and by the energy losses of particles in the target and approximately consists of 1,5 % of the beam energy. The signals from the detectors were processed in the same manner as described in details in [8].

Fig. 1, *a* shows typical *(E-ΔE)*-spectrum measured for the reactions $^7Li(d,^{3,4,6}He)$. Isotopes ^3He, ^4He and ^6He have been distinctly separated by mass in the whole energy range of measurements. The distribution of energy losses in ΔE-detector illustrates the mass separation of helium isotopes at their fixed energy of 23,7 MeV (see Fig. 1b). The yield of β-radioactive ^6He isotope for all angles within the registration range ($\Theta = 15°…45°$ in laboratory system) is much lesser than of stable helium isotopes. For example, for the angle $\Theta = 22{,}5°$ the ratio of total yields of ^3He, ^4He and ^6He is equal 22 : 86 : 1.

Fig. 1, *a* clearly shows the isolated event group in ^6He spectrum which is responsible for the formation of the ground state of ^3He recoil nucleus

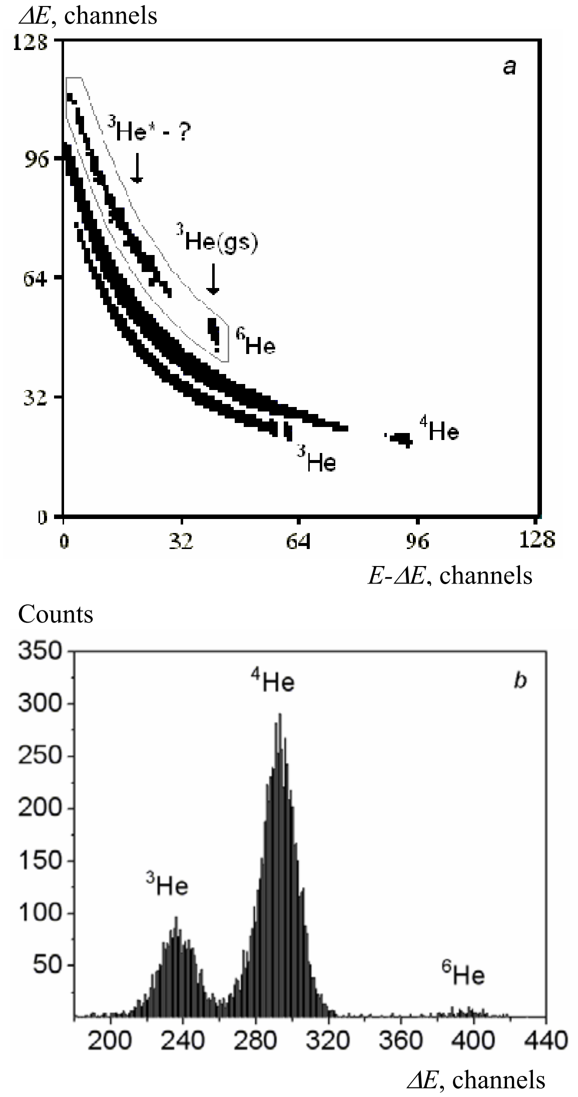

Fig. 1. (E-ΔE)-spectrum of reaction ^{7}Li(d,^{3,4,6}He) products measured at the angle Θ = 22,5° in the laboratory system (*a*) and mass spectrum of ^{3,4,6}He isotopes at their energy of 23,7 MeV (*b*). The number of ^{3,4,6}He events is multiplied by factor 10 for better display of this part of spectrum.

in reaction (1). Events that might correspond to the process of excitation of ^{3}He broad states are also observed at lower ^{6}He energies. The energy spectra of helium isotopes have been obtained by selection of the registered events with corresponding restrictive masks in *(E-ΔE)*-spectra (see Fig. 1, *a*) and summing up the signals' amplitudes from E and ΔE-detectors. The spectra obtained by this procedure are shown in Fig. 2.

The peaks in the ^{3}He and ^{4}He spectra indicated by arrows in the Fig. 2, *a, b* correspond to the population of the ground and known excited states [9, 10] of recoil nuclei of ^{6}He and ^{5}He in reactions ^{7}Li(d,^{3}He)^{6}He and ^{7}Li(d,^{4}He)^{5}He, respectively. Besides these peaks the continuum distributions of events are observed in these spectra up to energies

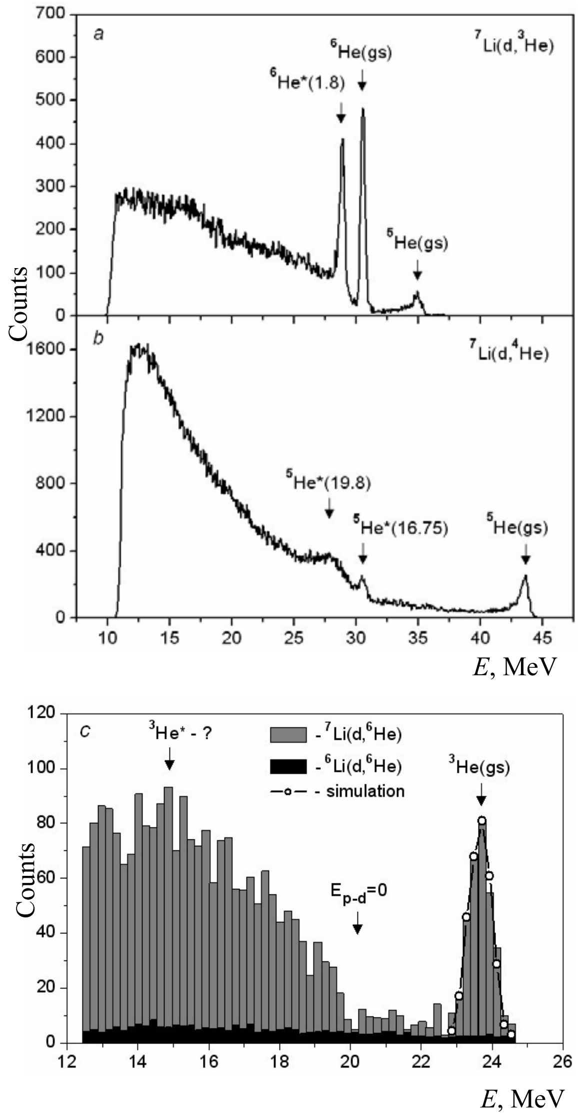

Fig. 2. The energy spectra measured at the angle Θ = 22,5° for reactions: *a* – ^{7}Li(d,^{3}He); *b* – ^{7}Li(d,^{4}He); *c* – ^{7,6}Li(d,^{6}He). The contribution of the ground state of ^{3}He in reaction ^{7}Li(d,^{6}He) simulated by Monte Carlo method and normalized to the peak maximum is shown with circles. Arrow at E = = 20,3 MeV ($E_{p\text{-}d}$ = 0) indicates the upper threshold of possible ^{6}He energies in the exit channel of reaction (2).

E(^{3}He) = 30 MeV and E(^{4}He) = 44 MeV, where the detected particles can be originated from different three- and four-particle reactions.

In ^{6}He spectrum (see Fig. 2, *c*) the peak at energy of 23,7 MeV corresponds to the population of the ground state of ^{3}He in the exit channel of reaction (1). The position and shape of this peak is well reproduced by Monte Carlo calculation which takes into account the incident beam parameters, the target thickness, geometry of the measurements and energy resolution of the detectors. The value of binding energy of proton and deuteron in ^{3}He nucleus equals

5,493 MeV [1, 2]. In reaction (1) such excitation energy of ^{3}He corresponds to the energy of 20,3 MeV of ^{6}He nuclei detected at the angle Θ = 22,5° (see Fig. 2, *c*). Hence at $E << 20{,}3$ MeV we have three-particle reaction

$$d + {}^7Li \rightarrow {}^6He + p + d, \qquad (2)$$

where the unbound states of ^{3}He as result of interaction of protons and deuterons in the final state can be hypothetically observed.

As can be seen from spectra in Fig. 2, *a, b* there are no visible background contributions of reactions induced by the interactions of deuterons with target contaminated nuclei besides the ^{6}Li (see the contribution of reaction ^{6}Li(d,^{3}He)^{5}He in Fig. 2, *a* at energy of 35 MeV). To separate the background events associated with ^{6}Li containing in the target the measurements of ^{3,4,6}He spectra for reaction d + ^{6}Li were carried out using the isotopic enriched (up to 95 %) target of ^{6}Li. The energy spectrum from reaction ^{6}Li(d,^{6}He) normalized by factor that takes into account the content of ^{6}Li in natural lithium is shown in Fig. 2, *c*. The contributions of reactions with the target contaminated nuclei ^{12}C, ^{16}O in measured ^{6}He spectra can be observed at energies lower than the registration threshold.

Analysis of ^{6}He inclusive spectra

According to the theory of many-particle nuclear reactions [11] the differential cross sections of reaction

$$p + T \rightarrow 1 + 2 + 3 \qquad (3)$$

depend on the three-body scattering amplitudes T_{123}, which are defined by the two-particle amplitudes corresponding to the interaction in all pairs of particles in the final state:

$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE_1} = C\rho_2(E_1)\left|T_{123}\right|^2, \qquad (4)$$

$$T_{123} = T_{12} + T_{13} + T_{23}, \qquad (5)$$

where T_{12}, T_{13}, T_{23} are the two-particle amplitudes; $\rho_2(E)$ – phase space factor [12] for the case of two particles coincidence measurements; C – energy independent coefficient. If only particle *1* is observed the Eq. (4) must be integrated over all possible angles of unobserved particle *2*:

$$\frac{d^2\sigma}{d\Omega_1 dE_1} = C\rho_1(E_1)\int d\Omega_2 \left|T_{123}\right|^2. \qquad (6)$$

On the first step of ^6He spectra analysis with the aim of testing the possibility of observation of ^{3}He excited states in reaction (2) the interaction in ^6He-p and ^6He-d subsystem has not been considered (T_{12} = = 0, T_{13} = 0). To simplify the calculations the influence of nuclear and Coulomb field of accompanying ^{6}He nucleus on the resonance interaction [11] in *p-d* pair has not been taken into account as well. Within this approach the ^{6}He inclusive spectra in the region of hypothetical resonances of ^{3}He can be described by simple well known formula

$$\frac{d^2\sigma}{d\Omega_1 dE_1} = C\rho_1\left|T_{23}\right|^2 = \rho_1\frac{C}{(E_{2-3}-E_R)^2 + (\frac{\Gamma}{2})^2}, \qquad (7)$$

where Ω_1, E_1 are the solid angle of registration and energy of ^6He, respectively; $E_{2\text{-}3}$ – relative energy of proton and deuteron; E_R – energy of ^3He resonance.

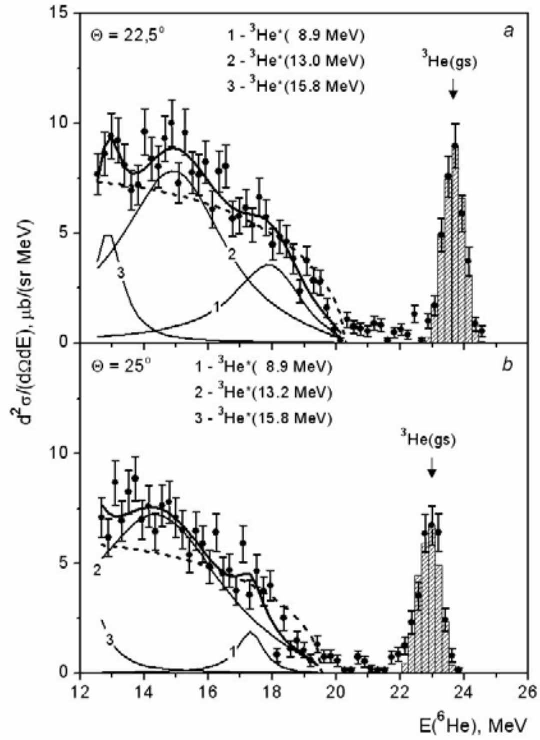

Fig. 3. Energy spectra of ^{6}He nuclei from reaction ^{7}Li(d,^{6}He) measured at the angles: *a* – Θ = 22,5°; *b* – Θ = 25°. The background caused by ^{6}Li containing in the target was subtracted from the measured spectra. The peaks which correspond to the population of the ^{3}He ground state are indicated by arrows. Thin lines 1 - 3 correspond to the possible contributions of excited states of ^{3}He recoil nucleus and thick line shows their sum. The dashed curves represent the calculations of ^{6}He-p-d phase space for reaction (2).

Measured ^6He inclusive spectra have been analyzed by fitting procedure using Eq. (7) and assuming the existence of three ^{3}He resonances in the region of E^* = 5,5…16 MeV. The results of spectra parameterization are shown in Fig. 3 and

Table. The obtained values of excitation energies and widths of ^{3}He resonances partly correspond to the data of some experimental studies (see references in [3]).

^{3}He resonance parameters obtained from the analysis of ^{6}He inclusive spectra measured at Θ = 22,5 and 25°

*E**, MeV		*Г*, MeV	
Θ = 22,5°	Θ = 25°	Θ = 22,5°	Θ = 25°
8,9 ± 0.4	8,9 ± 0.4	3,9 ± 1.3	1,5 ± 0,9
13,2 ± 0,3	13,0 ± 0,2	5,4 ± 2,0	7,2 ± 1,2
15,8 ± 0,2	15,8	1,3 ± 0,7	1,3

The second possibility to observe the continuum in ^{6}He spectra is the production of non-interacting particles in the reaction (2). In this approximation (T_{123} = *const*) the cross section (6) is determined only by phase space factor $\rho_1(E_1)$. One can see in Fig. 3 that phase space approximation can describe generally the observed continuum. But according to numerous studies of three-particle reactions with light nuclei no evidences for essential contribution of this purely statistical process have been obtained (see, for example, [13] and reviews [9, 10]).

The interaction of deuterons with ^{7}Li at E_d = = 37 MeV is characterized by the numerous open reaction channels where stable as well as unstable states of nuclei are being produced. It is known that decay of unbound states in accompanied many-particle reaction channels can substantially contribute to the inclusive spectra of reaction products [14]. At *d-^{7}Li* interaction besides the reactions (1) and (2) ^{6}He nuclei can be produced at the decay of unbound states of ^{7}Li*, ^{8}Li*, ^{7}He and ^{8}Be* in the following reaction channels (see Fig. 4):

$$d + {}^7Li \left| \begin{array}{ll} \rightarrow d + {}^7Li^* \rightarrow d + {}^6He + p, & (8) \\ \rightarrow p + {}^8Li^* \rightarrow p + {}^6He + d, & (9) \\ \rightarrow 2d + {}^7He \rightarrow 2p + {}^6He + n, & (10) \\ \rightarrow n + {}^8Be^* \rightarrow n + {}^6He + 2p. & (11) \end{array} \right.$$

In the reactions (8), (9) and (2) the same particles in the final state are produced. According to Eq. (4), (5) full description of these reactions needs to consider the interaction in all three pairs: *p-d, ^{6}He-p* and *^{6}He-d*. In addition the interaction of *^{6}He-n* and *^{6}He-2p* in reactions (10), (11) have to be considered as well. The observation of ^{6}He at the angle Θ as a decay product in reactions (8) - (11) is possible for different angles of emission and decay of ^{7,8}Li*, ^{7}He and ^{8}Be* resonances. Consequently the corresponding amplitudes T_{12} or T_{13} should be integrated over all angles allowed by reaction kinematics. The procedure of such integration for calculation of cross sections corresponding to energy spectra of particles from decay of nuclear unbound states is described in [14].

Fig. 4 shows the energy spectra of ^{6}He from reactions (8) - (11) calculated according [14] and in assumption that the values of excitation cross sections of nuclei ^{7,8}Li*, ^{7}He and ^{8}Be* equal $d\sigma/d\Omega$ = = 1 mb·sr^{-1}. The values of excitation energies and widths of unbound states of ^{7,8}Li, ^{7}He and ^{8}Be are taken from [9, 10]. The approach of isotropic excitation and decay of mentioned nuclear states were used in calculations due to of absence of the cross sections data for reactions (8) - (11) at E_d ~ 30…40 MeV. Fig. 4 shows that the contribution of reactions (8) - (11) to the ^{6}He inclusive spectrum in the range of energy up to 20 MeV can be substantial (up to 1…2 mb · sr^{-1} · MeV^{-1} at the cross section of resonance excitation $d\sigma/d\Omega$ = 1 mb · sr^{-1}).

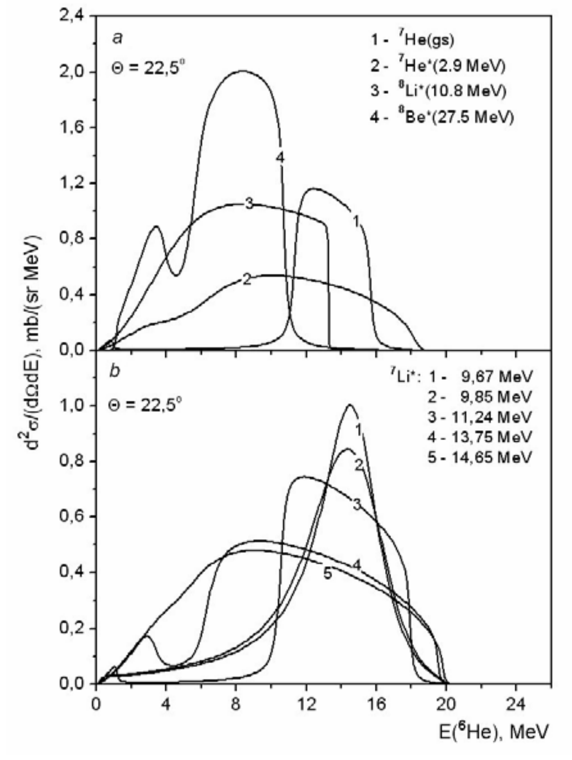

Fig. 4. The calculations of ^{6}He energy spectra for reactions (9) - (11) (*a*). The same for reaction (8) (*b*).

To estimate these contributions the measured spectra have been fitted by the following expression (Fig. 5):

$$\frac{d^2\sigma}{d\Omega_1 dE_1} = \sum_{i=1}^{n} C_i F_i(E_1), \qquad (12)$$

where i is the number of resonance which can be excited in reactions (8) - (11); $F_i(E_1)$ – ^{6}He energy spectra from resonance decay (see calculations in Fig. 4); C_i – fitting coefficients. The reaction (11) has not been involved in the analysis because the energies of ^{6}He from decay of ^{8}Be*→^{6}He + 2p are

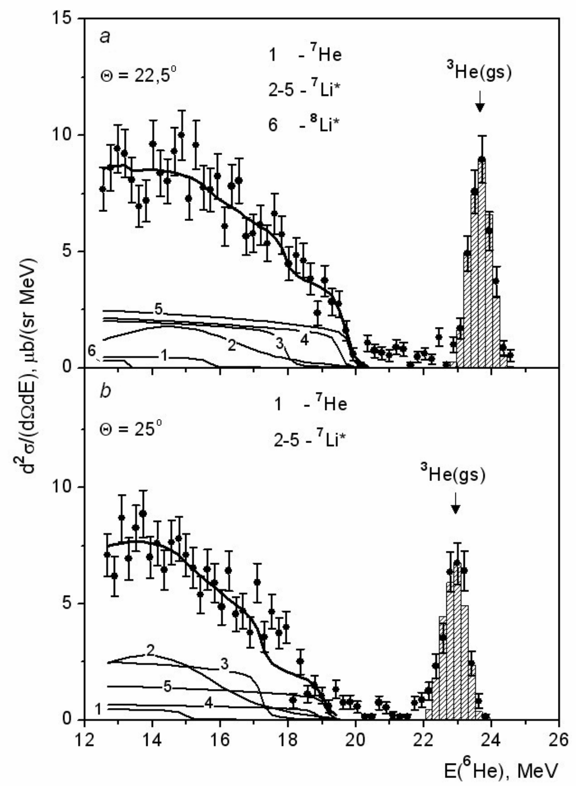

Fig. 5. Description of experimental ^{6}He spectra (*a* – Θ = 22,5°; *b* – Θ = 25°) by the processes (8) - (10). Thin lines correspond to the decay of the following unbound states: *1* – the ground state of ^{7}He (Γ = = 0,16 MeV) [10]; *2 - 5* – the excited states of ^{7}Li with E* = 9,85, 11,24, 13,75, 14,65 MeV and Γ = 1,2, 0,26, 0,5, 0,7 MeV respectively [10]; *6* – ^{8}Li*(E* = = 10,8 MeV, Γ = 0,012 MeV) [9]. Thick lines show the sum of all contributions.

lower than registration threshold (see Fig. 4). The contribution of reaction (9) can be observed only at energies near to this threshold at $\Theta \leq 22,5°$ (see Fig. 5, *a*).

One can see in Fig. 5 that the calculations of energy distributions of ^{6}He nuclei as decay products in reactions (8) - (11) provide quite appropriate description of experimental data in the energy range $E < 20$ MeV, where the contribution of ^{3}He resonances can be also observed.

Conclusions

The resonance-like distributions of events in ^{6}He inclusive spectra in the range that corresponds to the excitation energies E^* = 6…16 MeV of ^{3}He nuclei was observed in the exit channel of reaction ^{7}Li(d,^{6}He) induced by deuterons with energy of 37 MeV. The experimental data may be satisfactorily described in assumption of existence of ^{3}He resonances with excitation energies of E^* = 9, 13 and 16 MeV.

The observed structure of ^{6}He spectra can be as well explained considering more probable processes, that is excitation and decay of ^{7}Li* and ^{7}He nuclei in accompanied reaction channels. The largest contribution may be conditioned with the decay of ^{7}Li* nuclei which become excited at the inelastic scattering of deuterons. The experimental data about the excitation and decay of ^{7}Li* into ^{6}He+p channel are currently absent, however, we can presume that the cross sections of inelastic scattering are large enough for the formation of observed continuum in ^{6}He inclusive spectra. Kinematically complete experiments are required to clarify the mechanism of continuum formation in ^{7}Li(d,^{6}He) reaction.

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ПОШУК ЗБУДЖЕНИХ СТАНІВ ^{3}He В РЕАКЦІЇ ^{7}Li(d,^{6}He)^{3}He

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При енергії дейтронів 37 МеВ проведено вимірювання інклюзивних спектрів ядер ^{6}He з реакції ^{7}Li(d,^{6}He)^{3}He. В області енергій, що відповідають збудженню ядра віддачі ^{3}He в діапазоні $E^* = 6…16$ МеВ, спостерігалась резонансноподібна структура спектрів. Експериментальні дані можна описати в припущенні існування резонансів ^{3}He з енергією збудження $E^* = 9$, 13 та 16 МеВ. Аналіз експериментальних спектрів показав, що спостережувану структуру спектрів ^{6}He може бути зумовлено більш імовірними процесами збудження й розпаду незв'язаних станів ядер ^{7}Li та ^{7}He в супутніх каналах реакцій.

ПОИСК ВОЗБУЖДЕННЫХ СОСТОЯНИЙ ^{3}He В РЕАКЦИИ ^{7}Li(d,^{6}He)^{3}He

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При энергии дейтронов 37 МэВ измерены инклюзивные спектры ядер ^{6}He из реакции ^{7}Li(d,^{6}He)^{3}He. В области энергий, соответствующих возбуждению ядра отдачи ^{3}He в диапазоне $E^* = 6…16$ МэВ, наблюдалась резонансноподобная структура спектров. Экспериментальные данные можно описать в предположении существования резонансов ^{3}He с энергией возбуждения $E^* = 9$, 13 и 16 МэВ. Анализ экспериментальных спектров показал, что наблюдаемая структура спектров ^{6}He может быть обусловлена более вероятными процессами возбуждения и распада несвязанных состояний ядер ^{7}Li и ^{7}He в сопутствующих каналах реакций.

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