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IMPROVED PARAMETRIZATION OF INCLUSIVE PROTON SPECTRA FROM ^{3}H(α, p)^{6}He REACTION USING DATA OBTAINED IN A CORRELATION EXPERIMENT

The new analysis of inclusive proton spectra from ^{3}H(α, p)^{6}He reaction was performed. The existence of two new excited levels of ^{6}He with energy parameters $E_{2ex.s.}$*= 2.4 MeV, Γ = 0.4 MeV; $E_{3ex.s.}$*= 3.0 MeV, Γ = 0.6 MeV was confirmed as a result of new parameterization performed using energy parameters obtained from the correlation kinematic-incomplete experimental study of ^{3}H(α, pα)nn reactions at $E_α$ = 27.2 MeV and $E_α$ = 67.2 MeV in contrast to the initial analysis, in which the resonance observed above the known first excited ^{6}He level $E_{1ex.s.}$ = 1.8 MeV was treated as the second broad excited level $E_{2ex.s.}$ = 2.98 (0.17) MeV, $Γ_{2ex.s.}$ = 2.39 (0.27) MeV.

Keywords: excited states of ^{6}He, ^{3}H(α, p)^{6}He and ^{3}H(α, pα)nn reactions, titanium-tritium target, methods of Monte Carlo modeling.

1. Introduction

The neutron-rich nucleus ^{6}He is one of the weakly bound nuclei near the stability line, all excited states of which are unbound as they decay by radiating the constituent particles.

Despite numerous studies, experimental results, and theoretical calculations of the excitation spectrum of ^{6}He in the energy gap between the decay threshold (0.973 MeV < E* < 12.203 MeV) into three (α + n + n) and two (t + t) particles are very contradictory. There is no doubt only about the first excited state 2^+ (E* = 1.797 MeV). In the interval between these two threshold energies, only 4 excited states are shown in compilation [1], only one narrow state 1.8 MeV is shown in compilations [2, 3], while compilation [4] shows the presence of an excited state with energy 5.6 MeV.

Our previous studies of the ^{6}He nucleus obtained from the interaction of α-particles with tritium were also ambiguous [5 - 7]. Therefore, the idea arose to repeat the analysis of the inclusive proton spectra obtained from the ^{3}H(α, p)^{6}He reaction ($E_α$ = 27.2 MeV) [5] using the energy parameters obtained in the correlation studies of the ^{3}H(α, pα)nn reaction at $E_α$ = 27.2 MeV [6] and $E_α$ = 67.2 MeV [7].

2. Analysis of inclusive spectra of quasi-binary reactions

The study of the low-energy part of the excitation spectrum of the ^{6}He nucleus was performed by measuring the inclusive spectra of protons with ^{3}H(α, p)^{6}He reaction on the U-120 cyclotron at an α-beam energy of 27.2 MeV [5]. Titanium and titanium-tritium foils with a thickness of 2.7 mg/cm^2 were used as targets, the ratio between tritium atoms and titanium atoms in the target was approximately equal to one.

Fig. 1, *a* shows the proton spectra obtained by irradiating titanium-tritium target and titanium target by the beam of alpha-particles, and Fig. 1, *b* shows the inclusive spectrum of protons with ^{3}H(α, p)αnn reaction obtained after the procedure of taking into account the background.

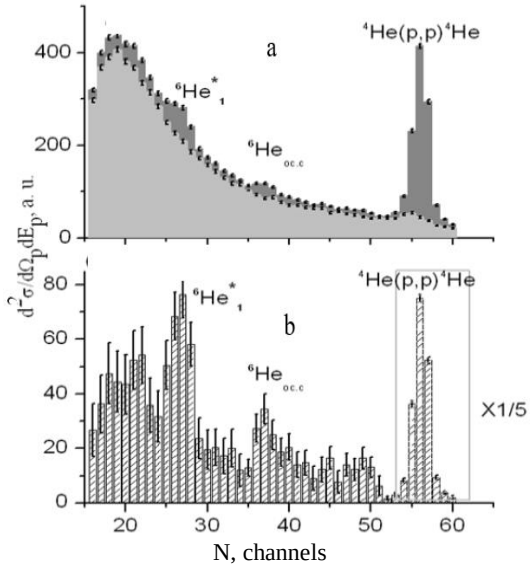


Fig. 1. Differential spectrum (*b*) of protons from ^{3}H(α, p)αnn reaction, as a consequence of subtraction from the proton spectrum (*a* – dark grey color) caused by α + Ti(T) interaction, background proton spectrum with α + Ti interactions (*a* – light grey color).

Proton spectra were measured in the range of angles 9° - 41° in the laboratory coordinate system. The spectra of excited levels in the ^{6}He, starting from the level of 1.797 MeV and above, from α + t interactions, are presented as dependent on the excitation energy of the ^{6}He nucleus. One of these is shown in Fig. 2. The spectra were analyzed using the standard procedure of Gaussian decomposition and fitting by the method of χ^2. Fig. 2 shows the results of this fit, which is the sum of the contributions of the three states marked with numbers *1*, *2*, and *3*.

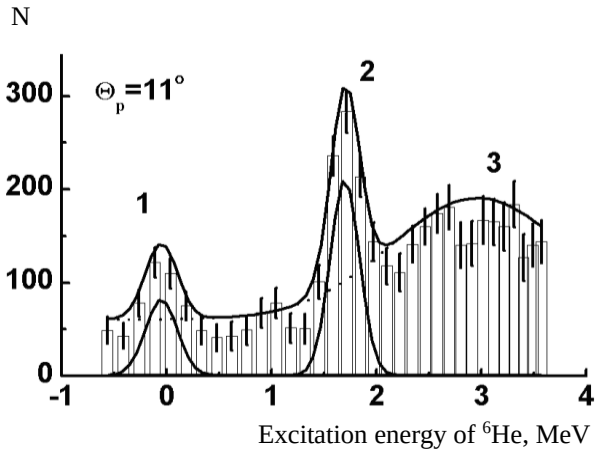


Fig. 2. Excitation spectrum of ^{6}He nucleus from ^{3}H(α, p)αnn reaction and parameterization results.

Dotted lines indicate the contributions of the main and first excited states, and the dashed line, which almost coincides with the solid line for almost the entire energy range, was attributed to the settlement of the second excited state of the ^{6}He nucleus, the average parameters of which were obtained in this work: energy position $E_{2ex.s.}$ = 2.98 (0.17) MeV, energy width $\Gamma_{2ex.s.}$ = 2.39 (0.27) MeV.

3. Study of the low-energy excitation spectrum of the ^{6}He nucleus in a correlation experiment

More reliable information on the unbound states of the ^{6}He nucleus can be obtained in correlation experiments when, in addition to the registration of particles that indicate the formation of an excited ^{6}He nucleus, one of the decay products of the unbound excited state is also recorded. In [6, 7] the spectra of p-α coincidences with the ^{3}H(α, pα)nn reaction at an α-particle beam energy of 27.2 and 67.2 MeV were obtained. As a result of the Monte Carlo simulation of the measured experimental two-dimensional spectra of p-α coincidences from ^{3}H(α, pα)nn reaction at an α-beam energy of 27.2 MeV [6], two new three-particle levels with excitation energies in the region of 2 - 3.5 MeV were obtained in addition to the known first excited state. In the projection spectra obtained at an α-particle beam energy of 67.2 MeV, in addition to the two above-mentioned excited states, 8 more excited ^{6}He states were observed [7].

Figs. 3 and 4 show the projections of the spectra of pα-coincidence on the axis of proton energy at α-particle energies 27.2 and 67.2 MeV. The obtained energy parameters, namely: excitation energies (E*) and width (Γ) of unbound excited levels of ^{6}He as a result of using the Monte Carlo modeling method for analysis of two-dimensional spectra from correlation kinematically incomplete experimental study are shown in Table.

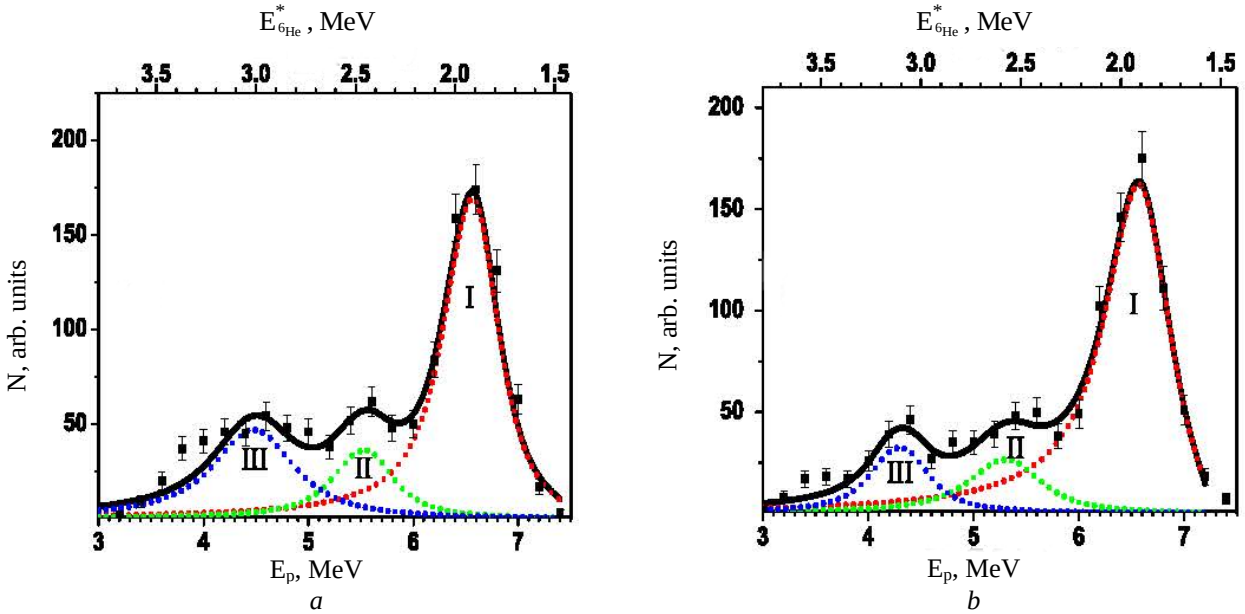
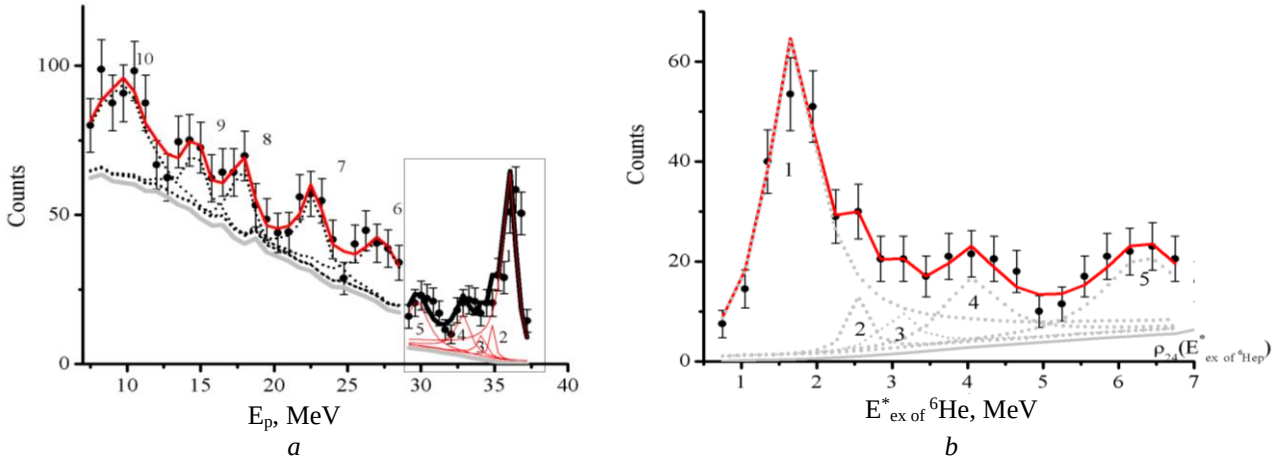


Fig. 3. Projections of spectra of pα coincidences on the energy axis of protons, registered at the angle θ_p = 28.5° for a four-particle reaction ^{3}H(^{4}He, pα)nn, E_α = 27.2 MeV [6]. Dotted lines show contributions from resonant states I, II, and III; a solid line is the sum of resonant contributions. Spectrum (*a*) at θ_α = 13°; (*b*) – at θ_α = 16.5°. (See color Figure on the journal website.)



a *b*

Fig. 4. *a* – Projections of pα-coincidence spectra on the proton energy axis for the four-particle reaction ^{3}H(^{4}He, pα)nn, $E_α$ = 67.2 MeV [7]. *b* – Selected low-energy part of the spectrum from frame (*a*) is listed in the excitation spectrum of the ^{6}He nucleus. The approximation results obtained using the Breit - Wigner formula are shown in red and black solid lines. The contributions of individual excited levels marked as 6 - 10 and 1 - 5 are presented by dotted lines. Contributions 1 - 5 in a frame (*a*) are shown by red solid lines. *a* – spectrum at $θ_p$ = 27.5°; *b* – spectrum at $θ_α$ = 15°. (See color Figure on the journal website.)

Parameters of ^{6}He low excited states

Experiment		
27.2 MeV ^{3}H(α, pα)nn [6]		
J	E*, MeV	Γ, MeV
1	1.8 ± 0.2	0.3 ± 0.15
2	2.4 ± 0.2	0.4 ± 0.2
3	3.0 ± 0.2	0.6 ± 0.2
67.2 MeV ^{3}H(α, pα)nn [7]		
1	1.7 ± 0.2	0.65 ± 0.15
2	2.5 ± 0.2	0.4 ± 0.2
3	3.1 ± 0.3	0.4 ± 0.2
Theory-Potential MP [7]		
	E*, MeV/spin and parity	Γ, MeV
2	2.32/1$^-$	1.63
3	3.10/2$^+$	1.04

In addition to the experimental results of studies of the excitation spectrum of the nucleus, the lower part of the Table contains theoretical predictions of the parameters of the studied levels of the ^{6}He nucleus.

4. Improved parametrization of inclusive proton spectra from the two-particle reaction ^{3}H(α, p)^{6}He

The presence of two excited levels in the range of 1.8 - 3.2 MeV, as can be seen from the table, prompted a new and improved analysis of the inclusive spectra of protons of the ^{3}H(α, p)^{6}He reaction. For this analysis of inclusive proton spectra, the differential spectra of protons obtained by channel subtraction from the proton spectrum obtained by irradiating the titanium-tritium target (effect + background) of the proton spectrum with α + Ti interactions (background) were used (see Fig. 1). Repeated parameterization was based on the assumption that 4 excited states of nucleus ^{6}He and the phase space factor (PSF) for reaction ^{3}H(α, p)αnn contribute to the spectra.

The contribution of each excited level in the spectrum of protons was taken into account using the methods of Monte Carlo modeling. During the parametrization procedure, the values of the excitation energy and the lifetime of the second and third excited levels of the ^{6}He nucleus obtained in the previous experiment [6] were used (see Table). For the first excited state were used the values $E_{1ex.s.}$ = 1.7 MeV, Γ = 0.1 MeV. All experimental features of the study of this nuclear reaction were taken into account: energy scatters of the α-particle beam, energy resolution of the detector system, the size of the spot from the beam, the size of the diaphragms in front of the proton detector, the location of the nuclear reaction in the target body, the energy loss of the beam to the interaction site and the energy loss of the registered protons in the target. The parameterization was performed using the least-squares method. Parameterization was performed for 11 inclusive spectra using the Monte Carlo simulation method. An example of the application of such a procedure for the proton spectrum at $θ_p$ = 11° and the α-particle energy of 27.2 MeV is shown in Fig. 5.

If we compare the results of parameterization of this spectrum in Figs. 2 and 5 in the same energy scale (Fig. 6), we see that the assumption of the existence of two excited states instead of one broad describes more adequately the inclusive experimental spectrum (for excitation energy of ^{6}He more 1.3 MeV) and confirms the correctness of the parameters in a correlation experiment. Thus, the presence of two excited states in the ^{6}He nucleus ($E_{2ex.s.}$*= 2.4 MeV, Γ = 0.4 MeV; $E_{3ex.s.}$*= 3.0 MeV, Γ = 0.6 MeV) was confirmed.

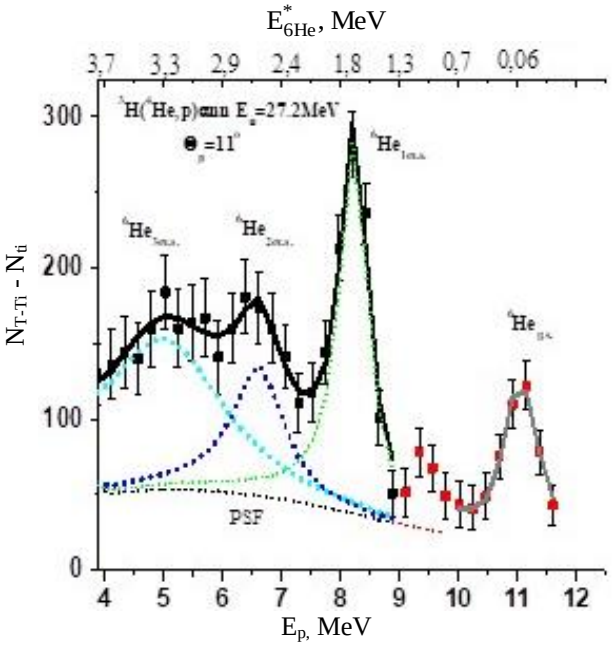


Fig. 5. Spectra of protons from α + t interaction (q_p = 11°). Dotted lines indicate the contribution: green – of the first excited state; blue – of the second excited state; azure – of the third excited state; black – of the phase space multiplier. Solid lines: grey – indicates the contribution from the ground state; black – indicates the sum of all contributions. (See color Figure on the journal website.)

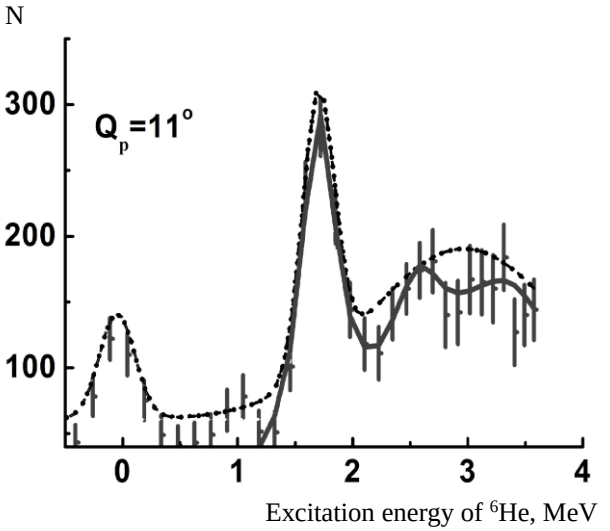


Fig. 6. Inclusive protons spectrum of ^{6}He nucleus from ^{3}H(α, p)αnn reactions and parameterization results: solid line – assumption of the existence of two excited states, dotted – one broad.

5. Conclusions

An improved description of the inclusive spectra of protons from the ^{3}H(α, p)^{6}He reaction is performed, which is based on the use of the Monte Carlo simulation method. For parameterization, the results of the correlation kinematic-incomplete experimental study of the ^{3}H(α, pα)nn reaction at $E_α$ = 27.2 MeV and $E_α$ = 67.2 MeV [6,7] were used. This made it possible, in addition to the known first excited state, to confirm the existence of two new levels with excitation energies of 2.4 and 2.9 MeV in the inclusive spectra, which is consistent with literature data. For example, resonances with energy parameters close to our results were observed in the works [8] (E_2* = 2.6 MeV, $Γ_2$ = 1.6 MeV) and [9] (E_3* = 3.5 MeV, Γ = 3.1 MeV). The use of a complex analysis of experimental data using several types of research makes our results more reliable, and the accusations [10] of an incorrect study of the excitation spectrum of the ^{6}He nucleus are groundless.

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ВДОСКОНАЛЕНА ПАРАМЕТРИЗАЦІЯ ІНКЛЮЗИВНИХ ПРОТОННИХ СПЕКТРІВ З РЕАКЦІЇ ^{3}H(α, p)^{6}He З ВИКОРИСТАННЯМ РЕЗУЛЬТАТІВ КОРЕЛЯЦІЙНОГО ДОСЛІДЖЕННЯ

Проведено повторний аналіз інклюзивних протонних спектрів реакції ^{3}H(α, p)^{6}He. Існування двох нових збуджених рівнів ^{6}He з енергетичними параметрами $E_{2зб.с.}$* = 2,4 МеВ, Г = 0,4 МеВ; $E_{3зб.с.}$* = 3,0 МеВ, Г = 0,6 МеВ підтверджено в результаті нової параметризації, виконаної з використанням енергетичних параметрів, отриманих з кореляційного кінематично неповного експериментального дослідження реакцій ^{3}H(α, pα)nn при E_{α} = 27,2 МеВ та E_{α} = 67,2 МеВ на відміну від початкового аналізу, в якому резонанс, що спостерігається вище відомого першого рівня збудженого ^{6}He $E_{1зб.с.}$ = 1,8 МеВ, розглядався як другий широкий збуджений рівень $E_{2зб.с.}$ = 2,98 (0,17) МеВ, $Г_{2зб.с.}$ = 2,39 (0,27) МеВ.

Ключові слова: збуджені стани ^{6}He, ^{3}H(α, p)^{6}He та ^{3}H(α, pα)nn реакції, титан-тритієва мішень, методи моделювання Монте-Карло.

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