OBSERVATION OF GROUND STATE OF ^{4}H IN ^{3}H(α,τt)n REACTION

O.K. Gorpinich, O.M. Povoroznyk, O.O. Jachmenjov

Institute for Nuclear Research of Ukrainian Academy of Science, Kyiv, Ukraine
e-mail: orestpov@kinr.kiev.ua

In kinematical complete investigation of ^{3}H(α,τt)n reaction by using beam with $E_\alpha = 67.2$ MeV and titan trituated target the ground state of ^{4}H was observed with $E_{g.s.} = E_{nt} = 3.22 \pm 0.25$ MeV and $\Gamma = 2.9 \pm 1,1$ MeV.

PACS 24. 25.10.+s 25.55.-e 27.10.+h

1. INTRODUCTION

The lightest nuclei which have excited levels are few-nucleons systems with A = 4. Most of these states are unbound and the only known particle stable state is ground state of ^{4}He [1]. There is enough experimental evidence showing that ^{4}H and ^{4}Li have only short living particle unstable states. But obtained data on the energy positions and widths of these states have often been contradictory.

All numerous investigations of excited levels of ^{4}H [2-16] were indicated on it's *n+t* structure. The most contradictory are results of experiments on neutron tritium interaction. For example energy dependence of total cross section interaction neutrons with nuclei of tritium shows strong resonance behavior at $E_n \sim$ 3.5 MeV [2]. In this time phase shift analysis [2] of ^{3}H(n,n)^{3}H data indicated that lowest T=1 levels of ^{4}H are broad resonances having assignments 2^- and 1^-, resonance energies of 3.4 and 5.1 MeV, and equal reduced widths of 5.4 MeV. However, this analysis was questioned by publication [4]. Microscopic calculations predict broad overlapping resonances at low excitation energies of *n+t* system [5-6]. On the other hand in different reaction measurements such as 7Li(π$^-$,tt)n [7-10] ^{6}Li(π,dt)n [6-9], ^{4}He(π,γ)tn, [11], ^{6}Li(^{6}Li,^{8}B)tn [12], ^{7}Li(τ,ττ,)tn [13], ^{7}Li(n,αt)n [14], ^{3}H(d,pt)n [15-16] and ^{2}H(t,pt)n [17] was observed the only ground resonance state of ^{4}H. The values of ^{4}H ground state energy as obtained in this reactions range from 0.3 to 8 MeV in the excitation energy in *n+t* system. The differences of obtained values such as energy positions and energy width could be explained by the complexity of studied processes and experimental difficulties that accompanied these investigations.

Additional source of information about energy scheme and structure of excited levels of ^{4}H may be study of their occupation and different modes of decay (on *t+n* and *d+2n*) by using *α+t* interaction at energy that exceed threshold of decay of alpha-particle on two deuterons. Then, investigating in kinematically complete experiment ^{3}H(α,τt)n and ^{3}H(α,τd)2n reactions may specify energy parameters of level decayed on *t+n* by using the first, and by using the second reaction to turn out if is it 4-particle resonance formation with *d+2n* structure.

2. EXPERIMENT

Three-particle ^{3}H(α,τt)n reaction in kinematical complete experiment with using triturated titan foils with thickness 2.7 mg/cm^2 and alpha-particle beam was investigated on Kyiv isochronous cyclotron U-240. By using time of flight technique, developed for measurement of time and energy characteristics of cyclotron's beam was established that alpha-particle beam's energy in this experiment was equal 67.2 ± 0.4 MeV [18]. For identification and determination energy of outgoing charge particles on coincidence four ΔE-E telescopes were used. Two of these, consisting of 400 μm Si ΔE-detector and ∅ 20 mm×h 20mm NaJ(Tl) E-detector allocated for the registration singly charged reaction products positioned on one side to the beam's direction(left arm) and other two consisting of 90 μm Si ΔE-detector and 3 mm Si(Li) E-detector assigned for registration of double charged reaction products were situated on the other side of the beam's direction(right arm). Collimation of telescopes was carried out by circular copper slits. Diameter of slit is 6mm, distance from target to telescopes situated on angle nearer to the beam's direction is 120 mm and 100 mm for telescopes situated farther. Angular separation between two pairs of telescopes situated as on the left arm and on the right arm was 15 °. Coincidence between the pair of ΔE detectors of telescopes which were purposed for registration of single and double – charged reaction products generated the event trigger for the acquisition. The parameters of every event (amplitudes of analog signals from each detectors, time lag between moments of the registration of the particles in different pairs of detectors, and the code of an event) were stored in the form of the sequence of vectors for later analysis.

For carrying out the calibration were used binary and three-particle reactions due to interaction of incident alpha particles with ^{1}H, ^{2}H, ^{3}H, ^{12}C nuclei. As in the experiment were used NaJ(Ti) detectors which response function depends on the type of charged particles the methods of modeling of energetic dependence of light output of scintillator from specific ionization losses of the registered particle [19] and the empiric dependence of specific energetic losses of the charged particles in the matter $dE/dx \approx En/a$ [20] were worked out and used.

Different charged particles from $^3H + ^4He$ interaction were identified in ΔE-E spectra, and selected τt coincidences for each pair of telescopes were sorted into $(E_\tau + \Delta E_\tau) - (E_t + \Delta E_t)$ matrices by choosing windows on the corresponding bit-pattern and the relevant time-to-amplitude converter spectra

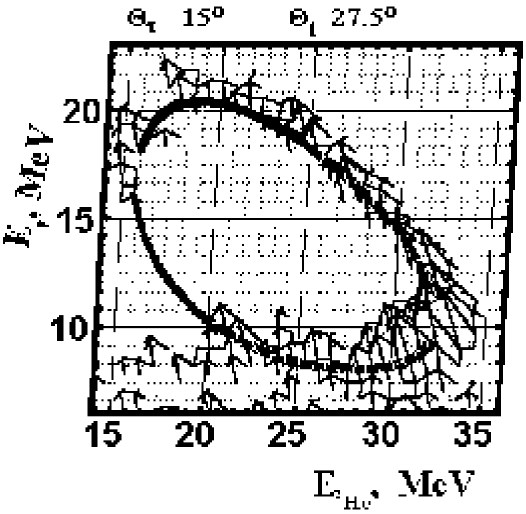

Fig. 1. *Two-dimensional spectrum from $^3H(\alpha,\tau t)n$ reaction*

Fig. 1 shows one of the τt coincidence matrix, where solid line represent kinematic curve estimated for correspondent geometric conditions of investigation of the three-particle $^3H(\alpha,\tau t)n$ reaction. Their arrangement according to the experimental locus of coincidences testifies the correctness of provided energy calibration**.**

3. DATA ANALYSIS

The obtained for different geometric conditions τt-coincidence matrices were selected to look for resonances in the n-t relative energy spectra corresponding to the ^4H state in the absent of resonances of ^4He and ^6Li in corresponded relative τ-n and τ-t energies. Some of the calculated dependencies of relative energies of nτ, τt and tn outgoing pairs from the energy detected τ-particles were represented on Fig. 2. Dotted, dash and solid lines correspond to relative τ-t, τ-n and t-n energies accordingly. The arrows directed to the right axe to the right and to the left indicate the energy position of resonance levels of ^4He and ^6Li, correspondingly. The arrow directed to the left axe indicate on magnitude energy of relative motion of particles t and n equal 3 MeV, corresponded energy position of ground state of ^4H obtained in most of experiment [12-16]. The levels of ^4He were displayed due to τ+n interaction, levels of ^6Li due to $\tau+t$. The excitation energy $E_{ex}^{4He}(E_{ex}^{6Li})$ of nucleus $^4He(^6Li)$ is related with kinetic energy $E_{\tau n}(E_{\tau t})$ of relative motion of particles τ and n (τ and t) and energy $Q^{dec4He}(Q^{dec6Li})$ available in the decay of ground state of $^4He(^6Li)$ into $\tau + n$ ($\tau+t$) channel by

$$E_{ex}^{^4He}\left(E_{ex}^{^6Li}\right) = E_{\tau n}\left(E_{\tau t}\right) - Q_{\tau+n}^{dec\,^4He}\left(Q_{\tau+t}^{dec\,^6Li}\right). \quad (1)$$

The values of excitation energy of resonance of ^4He and ^6Li labeled above of arrows were determined from relation (1).

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

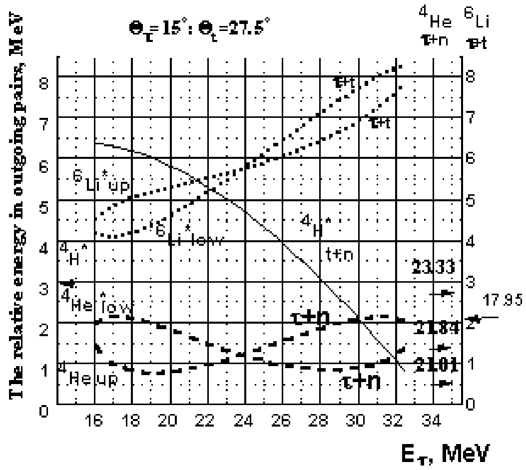

Fig. 2. *The dependencies of relative motion of nτ, tτ and tn outgoing pairs energy of detected τ-particle*

The events of the upper branch of locus in two-dimensional spectrum were projected on ^3He energy axe and had been additionally multiplied by inverse of its phase space factor. The spectrum of relative *n-t* energy was built in this way and is shown in Fig. 3.

The cross-section of three-body reaction $^3H(\alpha,\tau t)n$ can be expressed by:

$$\frac{d^3\sigma}{d\Omega_\tau d\Omega_t dE_{ex}} = \frac{(2\pi)^4}{\hbar v_{in}}\left|T_{if}\right|^2 \rho\left(\Omega_\tau, \Omega_t, E_{nt}\right), \quad (2)$$

where T_{if} is transition matrix element and ρ a density of final states is three-body phase space factor, E_{nt} ($\equiv E_{nt}(E_{ex})$) stands for the relative energy of particle n and t corresponding to the excitation energy of the nucleus $(n+t)$ –^4H and v_{in} is the relative velocity in entrance channel.

It will be assumed that process is sequential and reaction proceeds in two steps. In the first step the nucleus ^4H is formed in state unstable to particle emission $^3H+\alpha\rightarrow\tau+^4H$, which subsequently decays $^4H\rightarrow t+n$. The first step of the reaction can be treated as two-body reaction and the matrix element of three-body transition T_{if} can be expressed as multiplication of two terms

$$T_{if}^{j}(k, E_{nt}) = F^{j}(k) X^{j}(E_{nt}), \quad (3)$$

where first $F^J(k)$ describes amplitude of formation of ^{4}H nucleus in state j and second term $X^J(E_{nt})$ indicate it's decay in Breit-Wigner representation:

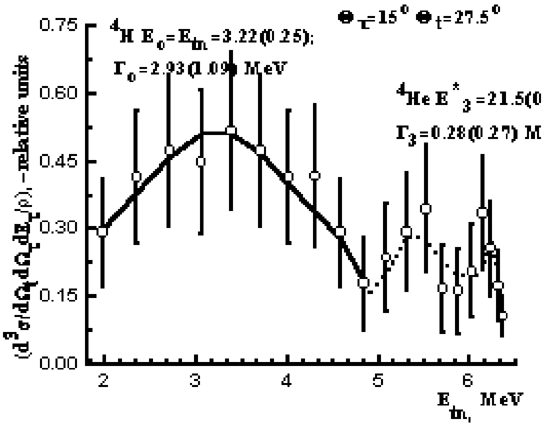

Fig. 3. *The result of fitting procedure for upper branch of τt- coincidence measurement. The solid line: contribution of ^{4}H ground state, dotted: of third excited level of ^{4}He*

$$X^{j}(E_{nt}) = \frac{\Gamma_j / 2}{E_j - E_{nt} + i\Gamma_j / 2}, \quad (4)$$

where E_{nt}-energy of relative motion of neutron and triton, E_j-energy position of resonance level, Γ_j-energy width of resonance level.

For single wide resonance expression (2) turns into

$$\frac{d^3\sigma}{d\Omega_\tau d\Omega_t dE_{ex}} \rho(\Omega_\tau, \Omega_t, E_{nt}) = \frac{C_j \Gamma_j / 2}{(E_j - E_{nt})^2 + (\Gamma_j / 2)^2}, \quad (5)$$

where C_j is the resonance constant.

The result of fitting procedure in frame of method of least square with using expression (5) was represented on Fig. 3 by solid line. Wide resonance abundance that is observed in experiment is ground resonance state of ^{4}H and obtained their energy parameters are the following $E_{nt} = 3.22 \pm 0.25$ MeV; $\Gamma = 2.93 \pm 1.09$ MeV.

The resonance structure which takes place in spectrum (see Fig. 3)in range relative energies from 5 to 6.5 MeV is due to formation and decay on τ+n channel of excited levels of ^{4}He (see Fig. 2). The fitting procedure carried out with using expression (5) for excited levels of ^{4}He is represented on Fig. 3 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 to compare obtained energy parameters of excited level ^{4}He with represented in compilation paper [1] scheme of ^{4}He energy levels the value of energy excitation with accounting experimental error is close to energy position of the third excited ^{4}He level ($E^* = 21.84$ MeV) but observed energy width is less ($\Gamma_n = 0.75$ MeV).

4. CONCLUSIONS

In our correlation experiment were created conditions for investigation of the behavior of *n+t* interaction in energy range of the relative energy of particle *n* and *t* from 2 to 5 MeV. In this range of phase space we observed resonance structure which corresponded ground state of ^{4}H. The results of analysis were presented as on Fig. 3 and in table where for comparison ^{4}H ground state parameters obtained from others different correlation experiments were represented too.

^{4}H ground state parameters obtained by correlation experiments

Reaction	E_P, MeV	E_{tn}, MeV	Γ, MeV
^{2}H(t,pt)n[16]	35.3	3.1±0.3	2.1
^{7}Li(n,αt)n[13]	14.6	2.6±0.4	2.1±0.3
^{3}H(d,pt)n[14]	27.2	3.4±0.3	3.0±0.3
^{3}H(d,pt)n[15]	47.3	2.2±0.4	3.4±1.2
^{3}H(α,τt)n[*]	67.2	3.22±0.25	2.93±1.09
^{7}Li(τ,ττ)tn[12]	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 in to account experimental errors. But the question about the accordance between the results of investigation of excitation of ^{4}H only in *n+t* interaction as for a example from 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. Represented in [1] results of analysis of direct n+t interaction were indicated on complex scheme of excited levels of ^{4}H, on manifestation of some resonance structure not only near E_{nt}~3 MeV but at E_{nt}~5 and 6.5 MeV. In the same time presented in table results of correlation experiments were limited by one resonance ground state of ^{4}H. Unfortunately as in our correlation experiment and in others presented in table one can't investigate *n+t* interaction at E_{nt}>5 MeV, But for the solution of discrepancy problem it is necessary to increase maximum value of investigated energy of relative motion of *n+t* in correlation experiment to 8 MeV.

REFERENCES

1. D.R. Tilley, H.R. Weller and. G.M. Energy Levels of Light Nuclei A=4 // *Nucl. Phys. A*. 1992, v. 541, p. 1-157.
2. T.W. Philips,B.L Berman and J.D. Seagrave Neutron total cross section for tritium // *Phys. Rev. C* 1980, v. 22, p. 384–396.
3. T.A. Tomberello. Phase-Shift Analysis of T(n,n)T // *Phys. Rev.* 1966, v. 143, p. 772-774.
4. W. Morrow, W. Haerli. Proton polarization in p-^{3}He elastic scattering between 4 and 11 MeV // *Nucl. Phys. A*. 1969, v. 126, p. 225-232.

5. J.J. Bevelacqua. Microscopic calculations for the ^{4}Hand ^{4}Li continuum // *Phys. Rev. C.* 1977, v. 16, p. 1673-1676.
6. A.M. Badalyan,T.I. Belova, N.B. Konyukhova and V.D. Efros. Resonances in the ^{4}H System // *Yad. Fiz.* 1985, v. 41, p. 1460-1467.
7. R.C. Cohen, A.D. Conaris, S. Margulies, J.L Rosen. Search for the Tetraneutron via the Reaction $\pi^- + {}^7$Li $\rightarrow {}^4$n + ^{3}He // *Phys. Lett*. 1965, v. 14, p. 292-297.
8. R.C. Minehart, L. Coulson, W.F. Grubb et al. Pion Capture in ^{6}Li and ^{7}Li, the Formation of ^{4}H, a Search for ^{5}H // *Phys. Rev*. 1969, v. 77, p. 1455-1463.
9. T.C. Meyer. A Study of Particle Unstable ^{4}H // *Nucl. Phys. A*. 1979, v. 24, p. 335-347.
10. U. Sennhausser, I. Felawka, T. Kozlowski et al. Observation of Particle Unstable ^{4}H in Pion Absorption in ^{7}Li // *Phys. Lett. B*. 1981, v. 103, p. 409-503.
11. U. Sennhausser,H.J. Pfeffer,H.K. Walter et al. Spectroscopy of single and correlated charged particles emitted following bound pion absorption in ^{6}Li and ^{7}Li // *Nucl. Phys. A.* 1982, v. 386, p. 429-446.
12. J.A. Bistirlich, K.M. Crowe, A.S.L. Parsons, P. Skarek, and P. Truoel. Radiative Pion Capture in ^{4}He // *Phys. Rev. Lett*. 1970, v. 25, p. 950-953.
13. R.B. Weisenmiller, N.A. Jelley, D. Ashery et al. Very light neutron-rich nuclei studied via the (6Li, 8B) reaction // *Nucl. Phys. A.* 1977, v. 280, p. 217-227.
14. R. Franke, H. Kockskamper, B. Steinheuer, et al. Search for highly excited states in light nuclei with three-body reactions // *Nucl. Phys. A.* 1986, v. 433, p. 351-368.
15. D. Miljanić, S. Blagus and M. Zadro. ^{4}H and (n, *alpha x*) reactions on ^{6}Li and ^{7}Li // *Phys. Rev. C.* 1986, v. 33, p. 2204-2205.
16. V.I. Grantsev, V.S. Zaritsky, V.I. Konfederatenko, B.V. Lashchenov, O.F. Nemets, V.A. Pilipchenko, O.M. Povoroznik, B.G. Struzhko. On Investigation of Resonances of ^{4}H in d + t Reaction // *Program and Theses, Proc. 38th Ann. Conf. Nucl. Spectrosc. Struct. At Nuclei,* Baku, 1988, p. 346.
17. V.I. Konfederatenko, O.M. Povoroznik, B.G. Struzhko. Three-Particle Channels of d+t Reaction at E(d) = 47.3 MeV // *Bull. Rus. Acad. Sci. Phys*. 1994, v. 58, p. 149-153.
18. S. Blagus, D. Miljanić, M. Zadro G. Calvi, M Lattuada, F Riggi, C. Spitaleri C. Blyth and O. Karban .^{4}H nucleus and the ^{2}H(*t*,*tp*)*n* reaction // *Phys. Rev. C.* 1991, v. 44, p. 325-328.
19. V.V. Zerkin,V.I. Konfederatenko, O.M. Povoroznyk et al. *The formation and diagnostics of beam in correlation and neutron experiments* Preprint: Kyiv: KINR 91-11, 1991, 11 p. (in Ukrainian).
20. O.K. Gorpinich, O.M. Povoroznyk, B.G. Struzhko, O.O. Jachmenjov. About the determination of energy parameters in correlation experiments // *Ukr. Fiz. Zhur.* 2002, v. 47, №12, p. 1180-1187 (in Ukrainian).
21. O.K. Gorpinich, O.M. Povoroznyk, O.O. Jachmenjov .Utilization of $dE/dx \sim E^n/a$ dependence for ΔE-E spectrometer calibration // Scientific papers of Institute for Nuclear Research.-Kyiv.- 2002, №2(8), p. 211-215 (in Ukrainian).

НАБЛЮДЕНИЕ ОСНОВНОГО СОСТОЯНИЯ ^{4}H В ^{3}H(α,τt)n-РЕАКЦИИ

О.К. Горпинич, О.М. Поворознык, А.А. Ячменёв

В кинематически полном исследовании ^{3}H(α,τt)n-реакции с использованием пучка альфа-частиц с энергией $E_\alpha = 67.2$ МэВ и титан-тритиевой мишени наблюдалось основное состояние ядра ^{4}H с энергетическими параметрами: $E_{o.c.} = E_{nt} = 3.22 \pm 0.25$ МэВ и $\Gamma = 2.9 \pm 1.1$ МэВ.

СПОСТЕРЕЖЕННЯ ОСНОВНОГО СТАНУ ^{4}H В ^{3}H(α,τt)n-РЕАКЦІЇ

О.К. Горпинич, О.М. Поворозник, О.О. Ячменьов

В кінематично повному дослідженні ^{3}H(α,τt)n-реакції з використанням пучка альфа-частинок з енергією $E_\alpha =$ 67.2 МеВ і титан-тритієвої мішені спостерігався основний стан ядра ^{4}H з енергетичними параметрами $Ee_{o.c.} = E_{nt} = 3.22 \pm 0.25$ МеВ та $\Gamma = 2.9 \pm 1.1$ МеВ.