ANALYSIS OF THE $^{12}C(\gamma, pt)2\alpha$ REACTION MECHANISM

V.N. Guryev*

National Science Center "Kharkov Institute of Physics and Technology", 61108, Kharkov , Ukraine

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Calculation of the (p, t) and (α, α) energy correlations in reaction $^{12}C(\gamma, p\,t)2\alpha$ at photon energies $E_\gamma = 27 - 140\,MeV$ is carried out using the pole α-cluster diagram with two-spectator α particles. These energy correlations agree with experimental data at photon energies $E_\gamma = 32 - 50\,MeV$.

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1. INTRODUCTION

The investigation of the many-particles photonuclear reactions on the light nuclei opens larger possibilities for the analysis of the mechanism of the interactions of photons with virtual dynamic clusters $(p, d, t, h, \alpha;\ A > 4)$ systems and of the evolution of the nuclei cascade processes. In principle for the reaction $^{12}C(\gamma, p\,t)2\alpha$ several mechanisms are possible at $E_\gamma = 27 - 140\,MeV$: (a) one-particle interaction

$$\gamma + {}^{12}C \rightarrow p + {}^{11}B^*, \quad {}^{11}B^* \rightarrow t + {}^8Be^*, \quad {}^8Be^* \rightarrow 2\alpha\,; \tag{1}$$

$$^{11}B^* \rightarrow \alpha + {}^7Li^*, \quad {}^7Li^* \rightarrow t + \alpha\,; \tag{2}$$

$$\gamma + {}^{12}C \rightarrow t + {}^9B^*, \quad {}^9B^* \rightarrow p + {}^8Be^*, \quad {}^8Be^* \rightarrow 2\alpha\,; \tag{3}$$

$$\gamma + {}^{12}C \rightarrow \alpha + {}^8Be^*, {}^8Be^* \rightarrow p + t + \alpha\,; \tag{4}$$

(b) two-particles direct production

$$\gamma + {}^{12}C \rightarrow p + t + 2\alpha \left({}^8Be^*\right), \quad {}^8Be^* \rightarrow 2\alpha; \tag{5}$$

$$\gamma + {}^{12}C \rightarrow p + \alpha + {}^7Li^*, \quad {}^7Li^* \rightarrow t + \alpha; \tag{6}$$

$$\gamma + {}^{12}C \rightarrow t + \alpha + {}^5Li^*, \quad {}^5Li^* \rightarrow p + \alpha; \tag{7}$$

(c) $^{12}C^*$ decay-schemes

$$\gamma + {}^{12}C \rightarrow {}^{12}C^*, \quad {}^{12}C^* \rightarrow p + t + {}^8Be^*, \quad {}^8Be^* \rightarrow 2\alpha; \tag{8}$$

$$^{12}C^* \rightarrow t + {}^9B^*, \quad {}^9B^* \rightarrow p + {}^8Be^*, \quad {}^8Be^* \rightarrow 2\alpha; \tag{9}$$

$$^{12}C^* \rightarrow \alpha + {}^8Be^*, \quad {}^8Be^* \rightarrow p + t + \alpha; \tag{10}$$

$$^{12}C^* \rightarrow {}^5Li^* + {}^7Li^*, \quad {}^5Li^* \rightarrow p + \alpha, \quad {}^7Li^* \rightarrow t + \alpha. \tag{11}$$

The $^{12}C(\gamma, pt)2\alpha$ reaction has been experimentally studied with several methods. The photoemulsive method [1] was used to obtain the preliminary data about energy dependence of the total cross section for photons energies $E_\gamma = 27,5 - 80\,MeV$, proton and triton energy distributions and proton angular distributions at $E_\gamma < 70\,MeV$. The kinematical analysis of 132 events has been carried out. Only the channel (1) has been analyzed. As a result for the most of the events for $^{12}C(\gamma, pt)2\alpha$ reaction the manifestation of ground and $3\,MeV$ excited states of ^8Be was observed.

With the Wilson chamber method [2] there were obtained analyzing 77 events of the reaction $^{12}C(\gamma, pt)2\alpha$ the energy and angular correlations of the proton-triton for $E_\gamma = 40 - 60\,MeV$ and $60 - 140\,MeV$, also the excitation spectra of the intermediate nuclei ^{11}B and ^9B up to $80\,MeV$ with the aim of studying the channels (1)-(3) and (9). According to experimental data [1], [2] together with the one-proton mechanism (1),(2) the interactions of the photons with the triton and α-clusters in the channels (3) and (4), (5) respectively are possible. The diffusion chamber placed in the magnetic field has been used in [3] to measure the total cross sections of the $^{12}C(\gamma, pt)2\alpha$ reaction, the energy correlations and mean energies distribution of the final particles at $E_\gamma = 27 - 140\,MeV$. The kinematical analysis of 786 events of this reaction has been carried out. The excitation spectra of the intermediate nuclei ^4He, ^5Li, ^7Li, ^8Be, ^9B, ^{11}B were obtained. The results of the experiment show that at energies of the photons $E_\gamma > 50\,MeV$ the dominant mechanism of the reaction is direct interaction with $S_{1/2}$ -protons of the carbon nucleus in the channels (1),(2). The experimental energy distributions of particles in the reaction $^{12}C(\gamma, pt)2\alpha$ were obtained in [4] for $E_\gamma = 27,5 - 150\,MeV$ by further processing the data of [3]. Calculations for the channel (5) carried out in the pole α-cluster approximation [4] with and without taking into account final state interaction in the three-particle version of the $^{12}C(\gamma, pt)^8Be$ reaction have not allowed to describe in a satisfactory way energy distributions of protons at $E_\gamma > 40\,MeV$ and

*Corresponding author. E-mail address: guryev@kipt.kharkov.ua

tritons at $E_\gamma > 32\,MeV$. In [5] the theoretical computations of the total cross sections of the reaction $^{12}C(\gamma, pt)2\alpha$ in the range $15-21\,MeV$ of $^{11}B^*$ excitation energies have been carried out in the approximation of the one-particle mechanism (1) with the ejection of $S_{1/2}$ protons. These computations, as well as ones carried out in the α cluster model [6] for the three-particle version of the reaction $^{12}C(\gamma, pt)^8Be$, are in a satisfactory agreement with the experimental data of [3] at $E_\gamma < 80\,MeV$. However, calculation results of (p,t) energy correlations in [6] turned out to be essentially larger than experimental data [3].As one can deduce from theoretical results of [5] and [6] total cross sections are practically the same for both mechanisms. Therefore, to distinguish among them one should deal with energy and angular distributions and correlations of the final particles. In this connection we have carried out calculation of energy (p,t) and (α,α) correlations in approximation of the pole (α-cluster mechanism for the channel (5) with two-spectator α particles. In contrast to the calculation [6] with the one-particle spectator ^8Be we obtained an essential improvement of the agreement with the experimental data [3] of the theoretical estimations of the energy (p,t)-correlations in the energy range of the photons $E_\gamma = 32-50\,MeV$.

2. METHOD

We consider the four-particle photonuclear reaction $\gamma + A \to a + b + c + d$ whose amplitude is described by the pole diagram (Fig.1) of the direct production of (a) and (b) particles, where (A) is the nuclear-target, (c) and (d) are the two-particle spectators, and (i) is the dynamic virtual cluster.

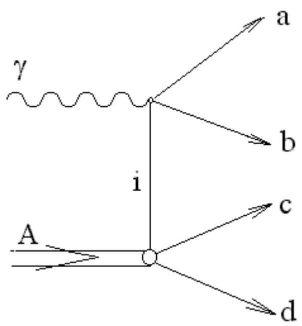

Fig.1. *Pole diagram for the two-particles direct production in the photonuclear reaction* $\gamma + A \to a + b + c + d$

Then, the differential probability of this reaction in the non-relativistic approximation [7] can be written in the laboratory system, as

$$d\Lambda \approx \frac{|F_i(\vec{p}_c,\vec{p}_d)|^2\,\overline{|M_i|^2}\,\delta(\vec{p}_a+\vec{p}_b+\vec{p}_c+\vec{p}_d-\vec{p}_\gamma)\delta(T_a+T_b+T_c+T_d-T_0)}{|k(\varepsilon_0+T_{cd})+\vec{p}^{\,2}_{cd}|^2}d\vec{p}_a d\vec{p}_b d\vec{p}_c d\vec{p}_d, \qquad (12)$$

where F_i is the form-factor of the virtual decay $A \to i + c + d$; $\overline{|M_i|^2}$ is the average over the spin states matrix element squared of the reaction $\gamma + i \to a + b$; T_n, p_n, m_n is the kinetic energy, the momentum and the mass of the particle (n),..., respectively, T_{cd} and p_{cd} is the relative energy and total momentum of the particles (c) and (d),

$$\begin{aligned}
T_0 &= E_\gamma - \varepsilon_c, &(13)\\
\varepsilon_c &= m_a + m_b + m_c + m_d - m_A, &(14)\\
\varepsilon_0 &= m_i + m_c + m_d - m_A, &(15)\\
k &= \frac{2m_i(m_c+m_d)}{m_i+m_c+m_d}, &(16)\\
T_{cd} &= \frac{\vec{q}^{\,2}_{cd}}{2m_{cd}}, &(17)\\
\vec{q}_{cd} &= \frac{m_d\vec{p}_c - m_c\vec{p}_d}{m_c+m_d}, &(18)\\
m_{cd} &= \frac{m_c m_d}{m_c+m_d}, &(19)\\
\vec{p}_{cd} &= \vec{p}_c + \vec{p}_d. &(20)
\end{aligned}$$

Since we are interested only in the manifestation of the pole mechanism of the reaction we put $|F_i|$ and $|M_i|$ to be constants [7].

Transforming Eq.(12) from variables $\vec{p}_n$ $(n = a,\, b,\, c,\, d)$ to $\vec{p}_{ab}$, $\vec{q}_{ab}$, $\vec{p}_{cd}$, $\vec{q}_{cd}$ and integrating over $\vec{p}_{ab}$, $\vec{p}_{cd}$, $\vec{q}_{cd}$ for the distributions in variables $t_{ab} = T_{ab}/T_0$ and $t_{cd} = T_{cd}/T_0$ at $T_0 = const$ one can get

$$\frac{d\Lambda}{dt_{ab}} = C_1\frac{(1-t_{ab})^2\sqrt{t_{ab}}}{[\varepsilon_0/T_0 + b(1-t_{ab})]^2}F(2,3/2;3;z), \qquad (21)$$

$$\frac{d\Lambda}{dt_{cd}} = C_2\frac{(1-t_{cd})^2\sqrt{t_{cd}}}{[\varepsilon_0/T_0 + b + (1-b)t_{cd}]^2}F(2,3/2;3;z'), \qquad (22)$$

where C_1 and C_2 are the constants, $F(\alpha,\beta;\gamma;z)$ is the Gauss hypergeometric series (for example Eq.(15.3.1) [8]),

$$z = \frac{(b-1)(1-t_{ab})}{\varepsilon_0/T_0 + b(1-t_{ab})}, \qquad (23)$$

$$z' = \frac{b(1-t_{cd})}{\varepsilon_0/T_0 + b + (1-b)t_{cd}}, \qquad (24)$$

$$b = \frac{(m_a+m_b)(m_i+m_c+m_d)}{m_i(m_a+m_b+m_c+m_d)}. \qquad (25)$$

Eq-s (21) and (22) have been obtained in the factorized form where the distribution over variables t_{kn}

for the four-particle phase volumes were separated explicitly

$$\frac{dV}{dt_{kn}} = C_3(1-t_{kn})^2\sqrt{t_{kn}}, \qquad (26)$$

which essentially differs from the three-particle phase volumes

$$\frac{dV}{dt_{kn}} = C_4\sqrt{t_{kn}(1-t_{kn})}. \qquad (27)$$

So for the reaction $\gamma + A = a + b + B$ with the one-particle spectator B from Eq.(27) [9] at $T_0 = const$ one can get

$$\frac{d\Lambda}{dt_{ab}} = C_5\frac{\sqrt{t_{ab}(1-t_{ab})}}{|\varepsilon/T_0 + b'(1-t_{ab})|^2}, \qquad (28)$$

where

$$b' = \frac{(m_a+m_b)(m_i+m_B)}{m_i(m_a+m_b+m_B)}, \qquad (29)$$

$$\varepsilon = m_i + m_B - m_A. \qquad (30)$$

In Eq-s (26...28) C3, C4 and C5 are the constants.

3. RESULTS

On Figs. 2 and 3 the solid curves represent the energy correlations of the particles in the reaction $^{12}C(\gamma,pt)2\alpha$ which were calculated using (21) and (22) respectively.

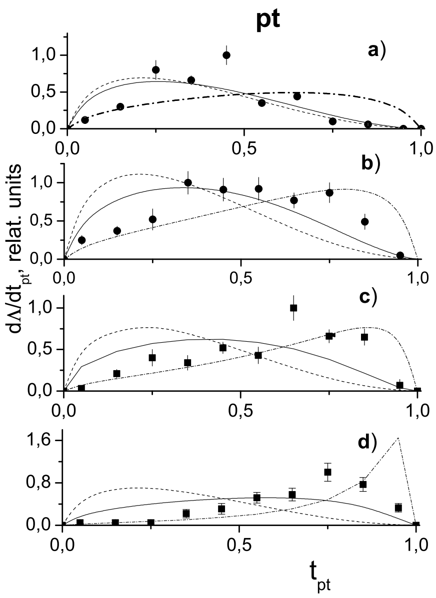

Fig.2. *The energy (p,t) correlations for the reaction $^{12}C(\gamma,pt)2\alpha$ were calculated by (21) (solid curves) and by (26) (dashed curves); for the reaction $^{12}C(\gamma,pt)^8Be$ by (28)(dot-dashed curves); $(a-d)$ for $E_\gamma = 27-32,\ 32-40,\ 40-50, 50-140\,MeV$, respectively. Experimental data are taken from [3]*

Here $(a,\ b)$ denote $(p,\ t)$ and $(c,\ d)$ denote $(\alpha,\ \alpha)$. The dot-dashed curves show the energy $(p,\ t)$ correlations for the reaction $^{12}C(\gamma,pt)^8Be$ which were calculated using (28). The calculated curves are normalized accordingly to the experimental data [3]. They are demonstrated with the experimental data [3] in the energy intervals $E_\gamma = 27-32$, $32-40$, $40-50$, $50-140\,MeV$. Comparison with experimental data [3] suggests that the α-cluster mechanism dominates in the reaction $^{12}C(\gamma,pt)2\alpha$ in channel (5) for the photon energy range $32-50\,MeV$(look at solid curves in Figs.2,3). At the same time, for $E_\gamma = 50-140\,MeV$ (Fig.2) the α-cluster mechanism with the one-body spectator ^8Be (dot-dash curve) appears to be more preferable. However, the results of analyzing of the experimental data [3] shows that mechanism of reactions (1) and (2) is dominant at these energies E_γ.

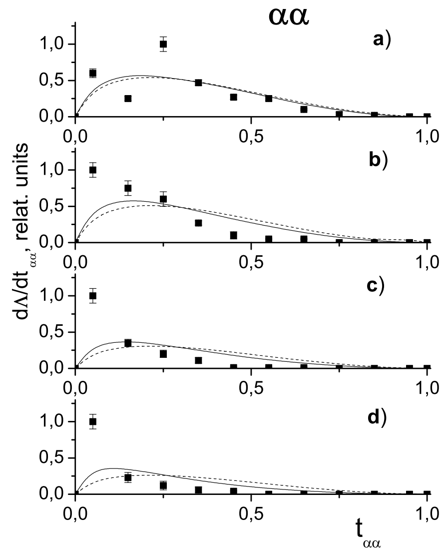

Fig.3. *The energy (α,α) correlations for the reaction $^{12}C(\gamma,pt)2\alpha$ were calculated by (22) (solid curves), by (26) (dashed curves); (a...d) for $E_\gamma = 27-32,\ 32-40,\ 40-50,\ 50-140\,MeV$ respectively. Experimental data are taken from [3]*

4. DISCUSSION

We have shown the effect of the essential influence of the four-particle phase volume on the energy correlations of the (p,t) and (α,α) particles for the channel (5) in the pole approximation. Taking into account this effect allowed us to determine the energy range of the α-cluster mechanism ($E_\gamma = 32-50\,MeV$) on the background of the other possible mechanisms for the channels $(1-4,\ 6-11)$ of the reaction $^{12}C(\gamma,pt)2\alpha$. For testing this method at $E_\gamma = 50-140\,MeV$ it is necessary to improve energy resolution of the experiment. The theoretical and experimental investigations of the angular (p,t) and (α,α)- correlations $d\Lambda/d\cos\theta_{pt}$, $d\Lambda/d\cos\theta_{\alpha\alpha}$ for $E_\gamma = 32-140\,MeV$ is also necessary for identification of the α-cluster mechanism in the $^{12}C(\gamma,pt)2\alpha$ reaction. Such problem was discussed in [9], [10] for the three-particles reactions. Note that the analysis of the channels (1-3) becomes complicated because of the possible manifestation of the quasi-deuteron and α-cluster mechanisms with the corresponding singularities of the triangular diagrams. Such α-cluster mechanism with rescattering in the final state was analyzed in [4] only for the energy distributions of the final particles in the reaction $^{12}C(\gamma,pt)^8Be$ and did not give satisfactory description of the experimental data. The analysis of these mechanisms requires comparison of the experimental data for the energy and angular distributions and correlations of the final particles in the reactions $^{12}C(\gamma,pt)2\alpha$ and $^{12}C(\gamma,nh)2\alpha$. Thus a solid support of the α-cluster mechanism in these reactions at $E_\gamma = 32-50\,MeV$ may be provided by experimentally discovered sharp increase of the asymmetry coefficients β_p and β_n in the angular distributions of photoprotons and photoneutrons at $E_\gamma = 40\,MeV$ [11]. Similar energy distributions of these parameters (especially for β_n at $E_\gamma = 40-50\,MeV$) were found in the $^4He(\gamma,p)^3H$ and $^4He(\gamma,n)^3He$ reactions (see review of the experimental data [12]). Also for the more complete analysis of the α-cluster mechanism in the reaction $^{12}C(\gamma,pt)2\alpha$ the model estimations of F_i and M_i in the formula for the differential probability (12) are required.

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АНАЛИЗ МЕХАНИЗМА РЕАКЦИИ ^{12}C(γ, pt)2α

В.Н. Гурьев

Проведен расчет (p,t) и (α,α) энергетических корреляций в реакции $^{12}C(\gamma,pt)2\alpha$ с использованием полюсной α-кластерной диаграммы с двумя спектаторными α-частицами при энергии фотонов $E_\gamma = (27-140)$ МэВ. Эти энергетические корреляции согласуются с экспериментальными данными при энергиях фотонов $E_\gamma = (32-50)$ МэВ.

АНАЛІЗ МЕХАНІЗМА РЕАКЦІЇ ^{12}C(γ, pt)2α

В.М. Гур'єв

Проведено розрахунок (p,t) та (α,α) енергетичних кореляцій в реакції $^{12}C(\gamma,pt)2\alpha$ з використанням полюсної α-кластерної діаграми з двома спектаторними α-частинками при енергші фотонів $E_\gamma = (27-140)$ МеВ. Ці енергетичні кореляції узгоджуються з експериментальними даними при енергіях фотонів $E_\gamma = (32-50)$ МеВ.