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KINEMATIC CALCULATION OF THE $^{16}O(\gamma,4\alpha)$ REACTION†

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The event distribution over the excitation energy of a system of two α-particles (E_x) is measured for the reaction $^{16}O(\gamma,4\alpha)$. It is found that an intermediate excited ^{8}Be nucleus is formed, and the channels of the ^{8}Be nucleus ground state (GS) formation are extracted. After the separation of the GS ^{8}Be nucleus, a broad maximum with a center at ~ 3 MeV appears in the distribution of E_x, which may correspond to the first excited state of the ^{8}Be nucleus. There are two possible channels for the formation of this state in the reaction - $\gamma + {}^{16}O \to \alpha_1 + {}^{12}C^* \to \alpha_1 + \alpha_2 + {}^8Be^* \to \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4$ and $\gamma + {}^{16}O \to {}^8Be^* + {}^8Be^* \to (\alpha_1 + \alpha_2) + (\alpha_3 + \alpha_4)$. Each decay mode is reduced to several two-particle systems. For a comprehensive study of the channel for the formation of the first excited state of the ^{8}Be nucleus in the $^{16}O(\gamma,4\alpha)$ reaction, a kinematic model for calculating the parameters of α-particles has been developed. The model is based on the assumption of a sequential two-particle decay with the formation of intermediate excited states of ^{8}Be and ^{12}C nuclei. For the kinematic model of the $^{16}O(\gamma,4\alpha)$ reaction, a graphical application was created in the Python programming language. The matplotlib library is used for data visualization. To generate random values, a set of functions from the standard random library of the Python programming language is used. Monte Carlo simulations of several distributions for one parameter with a given numerical function were performed. Several excited states of the ^{12}C and ^{8}Be nuclei can contribute to the reaction. The created scheme allows us to choose the relative contribution for each channel of decay, as well as the contribution of a separate level in each channel. To correctly comparison of the experimental data and the results of the kinematic calculation, the α-particles were sorted by energy in such a way that $T^1_{sort} > T^2_{sort} > T^3_{sort} > T^4_{sort}$. As a result of comparing the experimental and calculated data, it was determined that predominantly occurs the process $\gamma + {}^{16}O \to \alpha_1 + {}^{12}C^* \to \alpha_1 + \alpha_2 + {}^8Be^* \to 4\alpha$ with the formation of the ^{12}C nucleus in states with $E_0 = 13.3$ MeV, $E_0 = 15.44$ MeV, and the 1^{st} excited state of the ^{8}Be nucleus with $E_0 = 3.04$ MeV. The conditions for the identification of α-particles in the experiment for each decay of the stage are determined.

Keywords: *photonuclear reactions; diffusion chamber; the excited states of ^{8}Be and ^{12}C nuclei*

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1. INTRODUCTION

The study of photonuclear reactions of total α-decay is of particular interest for studying the properties of virtual α-cluster structures in nuclei [1, 2], their influence on the mechanism of nuclear reactions and on the dynamics of α-synthesis in the Universe [3]. In particular, the study of ^{8}Be, ^{12}C, and ^{16}O nuclei as 2-, 3-, and 4-α-cluster structures, respectively, is important for estimating the abundance of elements in the Universe through the process of stellar nucleosynthesis. The α-shaped cluster is the most probable because it has the highest binding energy and is compact enough to fit into the inter-nucleon distance in the nucleus [4]. In addition, the α-particle is a crucial ingredient in the concept of the Ikeda diagram [5], where highly clustered states are predicted by excitation energies around energy thresholds for decay into specific cluster channels.

In recent years, the interest in understanding the structure of α-cluster nuclei (^{12}C and ^{16}O) has been significantly renewed and numerous theoretical calculations have been performed using various non-relativistic macroscopic and microscopic methods - the antisymmetrized molecular dynamics (AMD) [6], the fermionic molecular dynamics (FMD) [7], the Bose-Einstein condensate cluster model [8], the no-core shell model [9], the algebraic cluster model (ACM) [10] and others. Despite the general agreement on the structure of the ground state of nuclei, there is no consensus on the structure of the excited states of the nucleus. The models do not necessarily contradict each other; it is just that each model is too narrow in scope.

Also, in theoretical calculations, there are differences in the interpretation of the reaction mechanism, taking into account the possible realization of partial channels: 4α, $\alpha+{}^{12}C^*$, ${}^8Be^*+{}^8Be^*$.

The experimental study of the $^{16}O(\gamma,4\alpha)$ reaction has been repeatedly carried out under irradiation of nuclear photographic plates with both monochromatic γ-quanta from reverse reactions and radioactive sources, and exposed to a beam of bremsstrahlung photons [11-15]. The previously obtained data have low statistics and a significant scatter over the full cross section. In the study of the reaction, the relative contribution of the channels for the formation of intermediate excited states of ^{8}Be nuclei was mainly estimated.

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In the present work, we continue [16, 17] the study of the ^{16}O(γ,4α) reaction. The results given here were obtained by using a diffusion chamber [17] placed in a magnetic field and exposed to a beam of bremsstrahlung photons, their endpoint energy being 150 MeV. Earlier, a narrow near-threshold maximum was found in the excitation energy distribution of the 2α-particle system for all events, which corresponds to the formation of the ground state (GS) of the ^{8}Be nucleus. In [16], a partial channel for the formation of the ground state was identified and it was determined (distribution by the excitation energy of the 3α-particle system) that an intermediate excited state of the ^{12}C nucleus could be formed in two levels (E_0 = 7.65 MeV and 10.3 MeV).

The excitation energy of a system of several α-particles (n) was defined as

$$E_x(n \cdot \alpha) = M^{eff} - (n \cdot m_\alpha - Q_{n \cdot \alpha}) \tag{1}$$

where M^{eff} is their effective mass, m_α is the mass of the α-particle, and $Q_{n \cdot \alpha}$ is the decay threshold. The histograms in Fig.1 shows the distribution of the dependence of events on the excitation energy for: a) two α-particles $E_x(2\alpha)$ and b) three α-particles $E_x(3\alpha)$. In Fig.1 shows the distributions of events without combinations that correspond to the formation of GS [16].

For the four final α-particles, there are 6 combinations of 2α-particle system (one resonant and 5 background) and 4 combinations of 3α-particle system (one resonant and 3 background). From these combinations, for each event, it is impossible to choose in advance a combination that can correspond to the production of excited ^{8}Be and ^{12}C nuclei. Therefore, the distributions in Fig.1 shows all values of the combinations for each event.

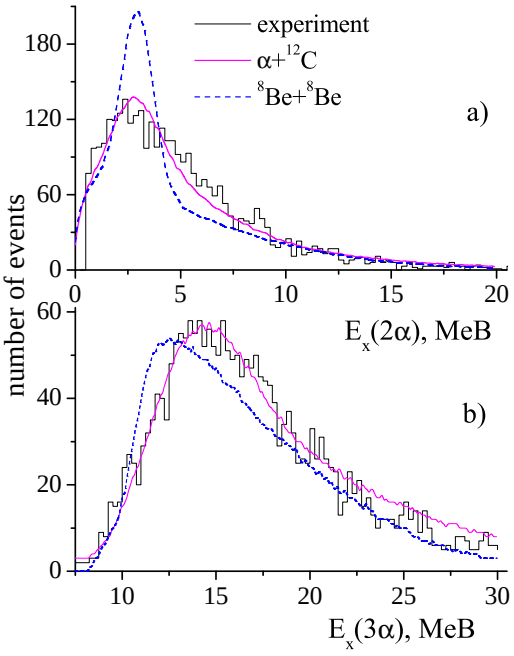

Figure 1. Distribution of events by excitation energy: a) 2α-particles, b) 3α-particles.

It should be noted that in Figs.1a and 1b, no obvious resonance structure is observed and all possible combinations lie in a wide range both in terms of $E_x(2\alpha)$ and $E_x(3\alpha)$.

2. METHOD OF KINEMATIC CALCULATION OF THE ^{16}O(γ,4α) REACTION

To determine the decay channel and reliably identification of α-particles in the experiment, a program for calculating the kinematic parameters of α-particles was created. Under the assumption of sequential decay with the formation of intermediate excited states, multiple reactions can be represented as a sequence of two-particle acts. In this case, the calculation of the reaction kinematics can be reduced to several tasks of generating particle parameters. In the system of the center of mass of a two-particle reaction, the kinematics is determined by the fact that, regardless of the specific type of interaction, the reaction products scatter at an angle of 180° and have an equal modulus momentum, and their energies depend only on the masses of the particles and the total energy of the system. For the reaction of ^{16}O(γ,4α), sequential two-particle decay is possible via two channels:

$\gamma + {}^{16}O \rightarrow \alpha_1 + {}^{12}C^* \rightarrow \alpha_1 + \alpha_2 + {}^{8}Be^* \rightarrow \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4$ (I)
$\gamma + {}^{16}O \rightarrow {}^{8}Be^* + {}^{8}Be^* \rightarrow (\alpha_1 + \alpha_2) + (\alpha_3 + \alpha_4)$ (II)
Each decay mode is reduced to several two-particle systems:
- $(\gamma + {}^{16}O)$ – the initial,
- $(\alpha_1 + {}^{12}C^*)$ or $({}^{8}Be^* + {}^{8}Be^*)$ – the first intermediate,
- $(\alpha_2 + {}^{8}Be^*)$ – the second intermediate,
- $(\alpha + \alpha)$ – the final.

The mathematical calculation is based on the literature data on the parameters of the levels of ^{12}C and ^{8}Be nuclei and the corresponding assumptions about the angular distributions in the center of mass (c.m.) of the reaction and the particles in a system at rest (s.r.) of the intermediate nucleus.

For the kinematic model of the $^{16}O(\gamma,4\alpha)$ reaction, a graphical application was created in the Python programming language on the platform of the Tkinter graphics library.

The matplotlib library is used for data visualization.

To generate random values, a set of functions from the standard random library of the Python programming language is used. Monte Carlo simulations of several distributions for one parameter with a given numerical function were performed.

For the initial system, the distribution of the number of events from the energy of γ-quanta $N(E_\gamma)$ was taken from this experiment, and random values of E_γ were generated by the random.choice() function.

Several excited states of the ^{12}C and ^{8}Be nuclei can contribute to the reaction. The created scheme allows us to choose the relative contribution for each channel (I) or (II), as well as the contribution of a separate level in each channel. For this purpose, the random.randint(0,100) function was used, which creates arbitrary, uncorrelated numbers evenly distributed in the range from 0 to 100.

The excitation curves $f(E_x)$ of the states of the nuclei ^{12}C and ^{8}Be were taken as Gaussian functions with the maximum position E_0 and the half-width at half-height Γ from the compilation of spectroscopic data. Random values were generated by the random.gauss(E_0,Γ) function.

In Fig.1a shows that the events are concentrated at $E_0(2\alpha) \sim 3$ MeV, which coincides with the 1^{st} excited state of the ^{8}Be nucleus ($E_0 = 3.04$ MeV, $\Gamma = 1.5$ MeV [18]). To describe $E_0(3\alpha)$ in Fig.1b, two broad levels of the ^{12}C nucleus with $E_0 = 13.3$ MeV, $\Gamma = 1.7$ MeV and $E_0 = 15.44$ MeV, $\Gamma = 1.77$ MeV were chosen [19]. These levels have spin-parity 4^+ and 2^+ with isotopic spin $T = 0$, which is important for α-particle decay.

The parameters of the particles at the first intermediate stage were determined. In the non-relativistic approximation, in the case of a two-particle channel, the law of conservation of energy is $E_\gamma = T_{P1} + T_{P2} + E_x + Q$, where T is the kinetic energy of particles P_1 and P_2 ($P_1 = \alpha_1$, $P_2 = {}^{12}C$ or $P_1 = {}^{8}Be$, $P_2 = {}^{8}Be$), E_x is the excitation energy of the intermediate particle ($E_x({}^{12}C)$ in the case of channel (I) or $E_x = E_x({}^{8}Be_1) + E_x({}^{8}Be_2)$ for channel (II)), and Q is the energy threshold of the corresponding channel.

Using a two-particle channel and an unambiguous connection between the particles, we obtain:

$$T_{P1} = \frac{M_{P1}}{M_{P1} + M_{P2}}(E_\gamma - Q - E_x) \tag{2}$$

The polar (θ) and azimuthal (ϕ) angles were generated and the kinematic parameters P_1 and P_2 in the c.m. were fully determined.

At the second stage, the kinematic parameters of the decaying particles were determined in a similar way, but in the s.r. of the intermediate excited nucleus ($^{12}C^* \rightarrow \alpha_2 + {}^{8}Be^*$ for channel (I) or $^{8}Be_1 \rightarrow \alpha_1 + \alpha_2$ and $^{8}Be_2 \rightarrow \alpha_3 + \alpha_4$ for channel (II)). Using the value of the intermediate excited nucleus in c.m. determined at the first stage of decay, the parameters of decaying particles were also converted to c.m.

If necessary, at the third stage, the kinematic parameters of the final decaying particles were determined in the s.r. of the next intermediate excited nucleus (for channel (I), the final two-particle system $^{8}Be \rightarrow \alpha_3 + \alpha_4$, which were converted to c.m. using the parameters of the excited nucleus determined at the second decay stage according to the above scheme.

Further, for both channels, the kinematic parameters of α-particles were converted from the c.m. reaction to the laboratory reference frame and the laws of conservation of energy and momentum were checked. An event was considered to be formed if it complied with these conservation laws.

In Figs.1a and b, the solid curve represents the distributions of all combinations of 2α- and 3α-systems for channel (I), and the dashed curve for channel (II). We generated 10^6 events for each of the channels. The results of the kinematic modeling are normalized by the area per experiment. It is clear from the figures that qualitatively the simulation results for channel (I) better describe the experimental data.

3. SORTING α-PARTICLES BY ENERGY. ANGULAR AND ENERGY CORRELATIONS OF $\alpha\alpha$-PARTICLE PAIRS

To correctly comparison of the experimental data and the results of the kinematic calculation, the α-particles were sorted by energy in such a way that $T^1_{sort} > T^2_{sort} > T^3_{sort} > T^4_{sort}$.

Consider the relative contribution of the sorted α-particles to the total reaction energy, which was defined as $T_0 = E_\gamma$ - Q, where Q is the energy threshold of the reaction under study. The experimental value of the energy T^{aver} was determined for particles falling into the MeV interval T_0, the points are placed in the middle of the interval. In Fig.2 shows the distribution of T^{aver}: squares for T^1_{sort}, circles for T^2_{sort}, triangles for T^3_{sort}, and stars for T^4_{sort}.

The linear function fit was performed and the coefficients of the relative contribution of particles to the total energy were determined to be 0.409, 0.303, 0.190, and 0.098 for T^1_{sort}, T^2_{sort}, T^3_{sort}, T^4_{sort}, respectively. It should be noted both the linear dependence of the distributions and some consistency (change to ~ 0.1) in these coefficients.

The results of the kinematic calculation with the above sorting procedure are shown in Fig.2 - solid lines for channel (I) and dashed lines for channel (II). The figure shows that qualitatively, for all 4 α-particles, the best agreement is observed in the case of channel (I).

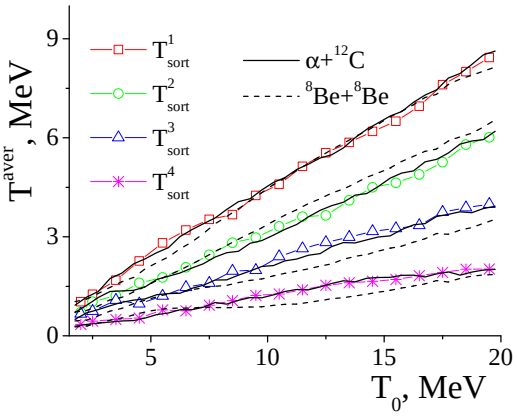

Figure 2. Distribution of events by the average energy of the α-particles. Dots - experimental value, solid lines - channel (I), dashed lines - channel (II).

For a more detailed comparison of the modeling results, a comparison was chosen by the angle of departure and relative energy of the α-particles pair. Two maximum and two minimum pairs were chosen as reference pairs: (α^1_{sort}, α^2_{sort}) and (α^3_{sort}, α^4_{sort}), which may show different types of dependencies.

The angle of departure of two α-particles (i and j) was defined as

$$\theta_{ij} = \frac{\vec{\mathbf{P}}_i \cdot \vec{\mathbf{P}}_j}{|P_i| \cdot |P_j|} \tag{3}$$

where $\mathbf{P}$ is the momentum vector of α-particles, and P is their momentum modulus.

The relative energy of a pair of α-particles was determined as

$$\varepsilon_{ij} = \frac{T_i + T_j}{T_0} \tag{4}$$

In Fig.3a, the dots represent the distribution of the dependence of the number of events on the angle of departure of the 2α-particle system $\theta_{\alpha\alpha}$, and Fig.3b - the distribution of events by the relative energy of the 2α-particle system $\varepsilon_{\alpha\alpha}$. Open points are α^1_{sort}+α^2_{sort}, closed points are α^3_{sort}+α^4_{sort}. The solid lines represent the results of the calculation within the channel (I), and the dashed lines represent the results of the calculation within the channel (II). The modeling results are normalized to the experiment by area.

The general conclusion can be drawn as follows: the distributions within channel (I) are in good agreement with the experimental data, while the distributions within channel (II) for both $\theta_{\alpha\alpha}$ and $\varepsilon_{\alpha\alpha}$ differ in terms of the position of the maxima.

4. IDENTIFICATION OF α-PARTICLES IN THE DECAY CHANNEL OF THE $^{16}O(\gamma,\alpha)^{12}C^*$ REACTION

After choosing the most probable decay channel, the main task is to identify α-particles in the experiment, taking into account the fact that a sequential two-particle decay is taking place. It should be noted that this decay leads to a direct relationship of the kinematic parameters in the c.m. reaction. At the first intermediate

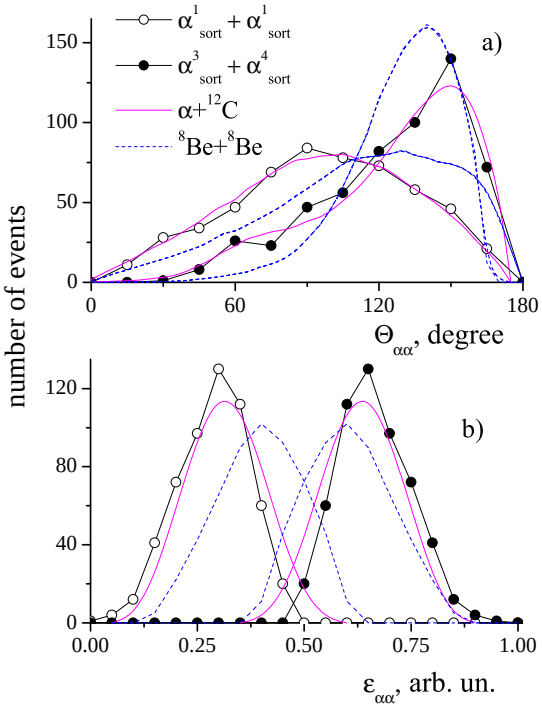

Figure 3. a) distribution of events by the angle of departure of the 2α-particle system, b) distribution of events by the relative energy of the 2α-particle system. Solid lines - channel (I), dashed lines - channel (II).

stage for $T_{\alpha 1}$ from Eq.(2):

$$T_{\alpha 1} = \frac{M_{12C}}{M_\alpha + M_{12C}}(E_\gamma - Q_{\alpha 12C} - E_x(^{12}C)) \tag{5}$$

There is also a relationship at the second intermediate stage:

$$T_{\alpha 2} + T_{8Be} - \frac{M_\alpha}{M_{12C}} T_{\alpha 1} = E_x(^{12}C)) - E_x(^{8}Be)) - Q_{\alpha 8Be} \tag{6}$$

where M_{12C} – the mass of carbon, and $Q_{\alpha 12C} = 7.16$ MeV and $Q_{\alpha 8Be} = 7.37$ MeV – the decay thresholds of the $^{16}O \rightarrow \alpha + {}^{12}C$ and $^{12}C \rightarrow \alpha + {}^{8}Be$ reactions, respectively. The discrete levels of ^{8}Be ($E_0 = 3.04$ MeV) and ^{12}C ($E_0 = 13.3$ MeV and $E_0 = 15.44$ MeV) [18, 19] lead to the appearance of some special values of α-particle energy. Thus, at low E_γ, one should expect a small $T_{\alpha 1}$ (Eq. 5); and with the growth of E_γ, there is a significant increase in the value of $T_{\alpha 1}$ and, accordingly, a change in the growth rate of $T_{\alpha 2}$ (Eq. 6).

In Fig. 4a shows the distribution of the average energy (T^{aver}) of α-particles depending on the total energy T_0 in channel (I) - $\gamma + {}^{16}O \rightarrow \alpha_1 + {}^{12}C^* \rightarrow \alpha_1 + \alpha_2 + {}^{8}Be^* \rightarrow \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4$. In this figure, unlike to Fig.2, the numbering of α-particles corresponds to their sequence of formation. The distribution is shown for: $T_{\alpha 1}$ - squares, $T_{\alpha 2}$ - circles, $T_{\alpha 3}$ - triangles, $T_{\alpha 4}$ - stars.

The average energy distributions of α-particles can be divided into three intervals: $T_0 < 7$ MeV, $T_0 = 7$–11 MeV, and $T_0 > 11$ MeV. And while there is a certain regularity in the behavior of the distributions in the first and third intervals, the second interval is characterized by a sharp increase in the relative contribution coefficient of $T_{\alpha 1}$. The behavior of α_2-, α_3-, α_4-particles is due to the fact that they are formed in the process of decay of discrete levels of ^{12}C and ^{8}Be nuclei. Therefore, their dependence has a low growth rate.

At the first stage of the identification, the conditions for the identification of two α-particles (α_3, α_4) forming the ^{8}Be nucleus in the 1^{st} excited state with $E_0 = 3.04$ MeV were chosen.

All α-particles are reliably identified at $T_0 < 7$ MeV: - the α_1-particle has the minimum energy, while the α_3, α_4-particles have the maximum energy (their distributions are close in value).

Furthermore, the figure shows that at $T_0 > 11$ MeV, all α-particles are also reliably identified: the α_1-particle already has the maximum energy, while α_3-, α_4-particles have the minimum energy.

In the range of 7-11 MeV, the α_2-particle has the maximum energy. In the narrow interval (9-11 MeV), when E_γ - $Q_{\alpha 12C} > E_x(^{12}C)$ (Eq. (5)), the relative contribution of the α_1-particle increases rapidly and all

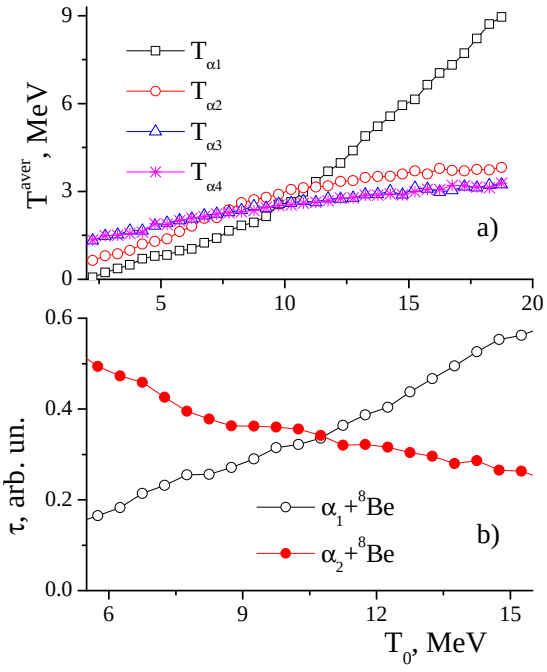

Figure 4. a) distribution of events by the average energy of α-particles in the channel $\alpha + {}^{12}C^*$, b) distribution of the relative magnitude of τ from the total energy T_0.

α-particles account for the same contribution of total energy. It was assumed that a pair of α-particles (α_3, α_4) is the pair with an excitation energy closer to $E_0({}^8Be) = 3.04$ MeV. Statistically, less than 7% of all events are in this range.

Thus, at the first stage of identification, two α-particles corresponding to the formation of the ^{8}Be nucleus were identified with high confidence.

At the second stage, the angle of departure in the $\alpha_1 + \alpha_2 + {}^8Be$ system (θ_{ij}) was used to correctly identify α_1- and α_2-particles. At low energies ($T_0 < 11$ MeV), the $\alpha_2 + {}^8Be$ the angle of departure should be larger (since the two-particle decay $^{12}C^* \rightarrow \alpha_2 + {}^8Be$ occurs) and, obviously, larger than the $\alpha_1 + {}^8Be$ scattering angle, which is close to the phase distribution. At high energies ($T_0 > 11$ MeV), due to the high energy of $T_{\alpha1}$ and to fulfill the laws of conservation of energy and momentum, the angle of departure of $\alpha_1 + {}^8Be$ is already larger than the angle of departure of $\alpha_2 + {}^8Be$.

In Fig. 4b shows the distribution by the relative value of $\tau = \varepsilon_{ij} \cdot \theta_{ij}/180^\circ$, where ε_{ij} and θ_{ij} were determined by (Eq. 3) and (Eq. 4), respectively. For the correctness of comparison, the angle of departure was normalized to 180°. Open circles are for the pair α_1+^{8}Be, closed circles are for the pair α_2+^{8}Be. As expected, the distributions have different angles of change and, therefore, the α_1- and α_2-particles can be separated in different T_0 intervals: at $T_0 < 10.5$ MeV - $\tau(\alpha_1{+}{}^8Be) > \tau(\alpha_1{+}{}^8Be)$, and conversely at $T_0 > 10.5$ MeV.

Thus, conditions were obtained under which experimental α-particles can be identified with high confidence in the decay channel $\alpha_1 + {}^{12}C^* \rightarrow \alpha_1 + \alpha_2 + {}^8Be^* \rightarrow \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4$.

In Fig. 5 shows the experimental [16, 17] distribution of events by excitation energy: a) 2α-particles, b) 3α-particles. The distributions were obtained using the set of conditions defined above for the identification of α-particles. Compared to Fig.1, only resonant combinations are shown.

The fitting with Gaussian functions was performed and the positions of the maxima and their widths were determined: $E_0(2\alpha) = 3.06 \pm 0.22$ MeV, $\Gamma = 1.95 \pm 0.14$ MeV (Fig. 5a); $E_0{}^1(3\alpha) = 13.13 \pm 0.26$ MeV, $\Gamma^1 = 1.64 \pm 0.31$ MeV and $E_0{}^2(3\alpha) = 15.56 \pm 0.27$ MeV, $\Gamma^2 = 1.86 \pm 0.33$ MeV (Fig. 5b), which are consistent with the data of spectroscopic studies [18, 19] within the error.

5. CONCLUSION

In the $^{16}O(\gamma,4\alpha)$ reaction, a detailed study of the formation of final particles has been performed. For the events, after the channel for the formation of the ground state of the ^{8}Be nucleus has been isolated, distributions

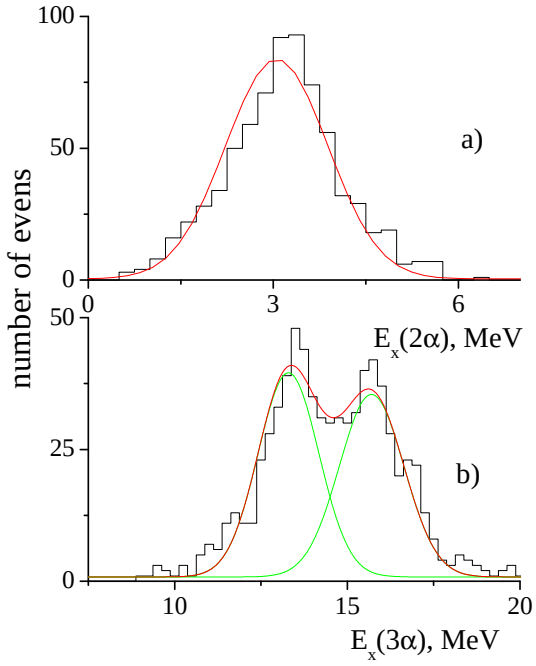

Figure 5. Distribution of events by excitation energy: a) 2α-particles, b) 3α-particles. The decay channel $\gamma + {}^{16}\mathrm{O} \to \alpha_1 + {}^{12}\mathrm{C}^* \to \alpha_1 + \alpha_2 + {}^{8}\mathrm{Be}^* \to \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4$.

of 2 and 3 combinations of α-particles have been constructed. Due to the inseparability of α-particles, it is difficult to separate the resonant combination from the background ones.

To determine the most probable decay channel and identify the particles at each stage of decay, a kinematic model of the ^{16}O(γ,4α) reaction was created assuming a sequential two-particle process with the formation of intermediate excited states of ^{8}Be and ^{12}C nuclei. To compare the experimental data and modeling results, α-particles were sorted by energy $\mathrm{T}^1_{sort} > \mathrm{T}^2_{sort} > \mathrm{T}^3_{sort} > \mathrm{T}^4_{sort}$ in both data sets (experimental and calculated).

It was determined that the experimental data can be mainly described within the process $\gamma + {}^{16}\mathrm{O} \to \alpha_1 + {}^{12}\mathrm{C}^* \to \alpha_1 + \alpha_2 + {}^{8}\mathrm{Be}^* \to \alpha_1 + \alpha_2 + \alpha_3 + \alpha_4$ with the formation of the ^{12}C nucleus in states with $\mathrm{E}_0 = 13.3$ MeV, $\mathrm{E}_0 = 15.44$ MeV, and the 1^{st} excited state of the ^{8}Be nucleus with $\mathrm{E}_0 = 3.04$ MeV.

The identification of α-particles corresponding to each stage of the chosen decay process was performed.

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КІНЕМАТИЧНИЙ РОЗРАХУНОК РЕАКЦІЇ ^{16}O(γ,4α)

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В реакції ^{16}O(γ,4α) виміряно розподіл подій за енергією збудження (E$_x$) системи двох α-частинок. Визначено, що утворюється проміжне збуджене ядро ^{8}Be, виділено канал утворення основного стану (ОС) ядра ^{8}Be. Після виділення ОС ядра ^{8}Be у розподілі за E$_x$ проявляється широкий максимум з центром при $\sim$ 3 МеВ, що може відповідати першому збудженому стану ядра ^{8}Be. В реакції можливо два каналу утворення цього стану - γ + ^{16}O $\rightarrow$ α_1 + ^{12}C* $\rightarrow$ α_1 + α_2 + ^{8}Be* $\rightarrow$ α_1 + α_2 + α_3 + α_4 і γ + ^{16}O $\rightarrow$ ^{8}Be* + ^{8}Be* $\rightarrow$ (α_1 + α_2) + (α_3 + α_4). Кожна мода розпаду зводиться до кількох двочастинкових систем. Для комплексного дослідження каналу утворення першого збудженого стану ядра ^{8}Be в реакції ^{16}O(γ,4α) розроблено кінематичну модель розрахунку параметрів α-частинок. Модель створено в припущенні послідовного двочастинкового розпаду ядра ^{16}O з утворенням проміжних збуджених станів ядер ^{8}Be і ^{12}C. Для кінематичної моделі реакції ^{16}O(γ,4α) створено графічне застосування мовою програмування Python. Для візуалізації даних використовується бібліотека matplotlib. Для генерації випадкових значень використовується набір функцій стандартної бібліотеки random мови програмування Python. Проводилося моделювання методом Монте-Карло кількох розподілів за одним параметром із заданою чисельною функцією. У реакції можливий вклад декількох збуджених станів ядер ^{12}C і ^{8}Be. Створена схема, що дозволяє вибирати відносний вклад як для кожного каналу розпада, так і вклад окремого рівня в кожному каналі. Для коректного порівняння експериментальних даних і результатів кінематичного розрахунку було виконано сортування α-частинок за енергією таким чином, що $T^1_{sort} > T^2_{sort} > T^3_{sort} > T^4_{sort}$. У результаті порівняння експериментальних і розрахункових даних визначено, що переважно йде процес γ + ^{16}O $\rightarrow$ α_1 + ^{12}C* $\rightarrow$ α_1 + α_2 + ^{8}Be* $\rightarrow$ 4α з утворенням ядра ^{12}C у станах з E$_0$ = 13.3 МеВ, E$_0$ = 15.44 МеВ та першого збудженого стану ядра ^{8}Be з E$_0$ = 3.04 МеВ. Визначено умови для ідентифікації α-частинок в експерименті на відповідність кожному етапу розпаду.

Ключові слова: *фотоядерні реакції; дифузійна камера; збуджені стани ядер ^{8}Be і ^{12}C*