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INVESTIGATION OF THE $^{16}O(\gamma, p)^3H3\alpha$ REACTION AT THE ENERGIES BELOW THE MESON PRODUCTION THRESHOLD

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The reaction $^{16}O(\gamma, p)^3H3\alpha$ induced by bremsstrahlung photons of endpoint energy $E^{max}{}_{\gamma}$ = 150 MeV has been studied by the method of a diffusion chamber in a magnetic field. The energy dependence of the total cross section has been measured in the energy range from the threshold and has been founded a broad resonance centered at 55 MeV. The rate of decrease in the cross section undergoes a change in the region around 55 MeV. A comparison was made with the cross section for reactions $^4He(\gamma, p)^3H$ and $^{12}C(\gamma, p)^3H2\alpha$. The agreement between the shapes of distributions for the $(\gamma, p)^3H$ reactions is evident and was concluded that the mechanism of interaction of the γ-quantum with the nucleus is similar. The dependence of average kinetic energy of particles on the total kinetic energy was determined. In the whole energy interval, the distribution for a proton is more than the statistical distribution. Distribution of relative energy of the proton and ^3H nucleus in their c.m.s. does not agree with the predictions of the mechanism of photon absorption by an α-particle cluster, but at energies above the maximum, it agrees with calculations within the framework of the quasi-deuteron model of photoabsorption.

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INTRODUCTION

The interest to the investigation of (γ, N)-photonuclear reactions is determined by the possibility of proving the notions about nuclear forces, cluster configurations and meson exchange currents in nuclei. All these questions are associated with determination of a reaction mechanism. With an increase in the γ-quantum energy, a main contribution to the total effective cross section for absorption of photons given by manyparticle photoreactions and their analysis is of interest for studying the mechanism of the interactions between photons with virtual dynamic cluster systems and of the evolution of the nuclei cascade processes. The reaction in question may proceed via the direct decay of the nucleus to particles or via a sequential process involving the formation of excited states nucleus, which subsequently decays to two particles. Therefore, the possibility of extracting a channel with the formation of a definite excited state of the intermediate nucleus can facilitate the determination of the mechanism of interaction between the γ-quantum and the target nucleus.

In this article, we present results obtained by studying the photodisintegration of oxygen nuclei via the reaction $^{16}O(\gamma, p)^3H3\alpha$ in the energy range from the reaction threshold up to 150 MeV. A detailed experimental study of this reaction has not been found. However, we have previously performed a series of works on four-body photodisintegration of the carbon nucleus – the reactions $^{12}C(\gamma, p)^3H2\alpha$ and $^{12}C(\gamma, n)^3He2\alpha$ [1] and five-particle photodisintegration of the oxygen nucleus – the reaction $^{16}O(\gamma, n)^3He3\alpha$ [2, 3].

It was revealed [1] that within identical energy intervals, the angular distributions for the «mirror» $^{12}C(\gamma, p)^3H2\alpha$ and $^{12}C(\gamma, n)^3He2\alpha$ reactions have similar shapes. In [3], an analysis of (γ, n)-reactions on ^{12}C and ^{16}O nuclei was carried out, and a similarity was observed in the energy and angular distributions.

The theoretical and experimental investigations of the p-^3H- and n-^3He-correlations are also necessary for identification of the α-cluster mechanism. Such problem was discussed in [1, 4 - 6] for the $^{12}C(\gamma, p)^3H2\alpha$ reaction. Note that the analysis of the channels becomes complicated because of the possible manifestation of the quasideuteron [1, 6] and α-cluster mechanisms [4 - 6] with the corresponding singularities of the triangular diagrams. Such cluster mechanism with rescattering in the final state was analyzed in only for the energy distributions of the final particles in the reaction $^{12}C(\gamma, p)^3H2\alpha$ 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 «mirror» reactions $(\gamma, p)^3H$ and $(\gamma, n)^3He$ on the ^{12}C and ^{16}O nuclei. At the present time, experimental data on $(\gamma, p)^3H$ and $(\gamma, n)^3He$ reactions are scanty.

EXPERIMENTAL PROCEDURE

The results given here were obtained by using a diffusion chamber [7] placed in a magnetic field and exposed to a beam of bremsstrahlung photons, their endpoint energy being 150 MeV.

For a further treatment, we selected five-prong stars whose tracks were associated with two single charged particles and three doubly charged particles. Oxygen nucleus photodisintegration events was easily separated visually. Low pressure in the chamber and target and detector matching made possible to investigate reaction from reaction threshold. The measurement error of the momentum of particles depended on the momentum value itself and the particle track length, and varied from 3 to 10%. The energy of stopped α-particles was determined from the range/energy ratio.

Events were identified after the measurement based on momentum balance. In the experiment, the axis OX was directed along the beam of γ-quanta. Boundary conditions were imposed on the quantities ΣP_X^i, ΣP_y^i, and ΣP_z^i, where $P_{X(Y,Z)}^i$ are the components of the three-dimensional momentum of the i-th final particle. The γ-quantum energy E_γ was determined as the sum of the kinetic energies of final i-particles and the reaction threshold. A distinctly pronounced peak in region 0 corresponded to events of the examined reaction. The energy and momentum conservation laws allowed the measurement results obtained for one of the tracks, which turned out to be the worst in comparison with the results obtained for all other tracks, to be made more exact.

Because of an insufficient length of the projection of a track onto the median plane, we were unable to measure, with the required precision, the kinematical parameters of particles that did not stop in the chamber fiducial volume and which escaped from it at an angle smaller than 50° with respect to the vector of the magnetic-field strength. For events not processed for this reason, we introduced a geometric correction calculated under the assumption of an isotropic distribution with respect to the azimuthal angle since the photon beam was unpolarized.

EXPERIMENTAL RESULTS

We have measured dependence of the number of events for the reaction $^{16}O(\gamma, p)^3H3\alpha$ in the photon energy range from the reaction threshold up to 150 MeV with a step of 2 MeV. The results are shown in Fig. 1,a by solid circles placed at the midpoint of a step. The displayed errors are purely statistical.

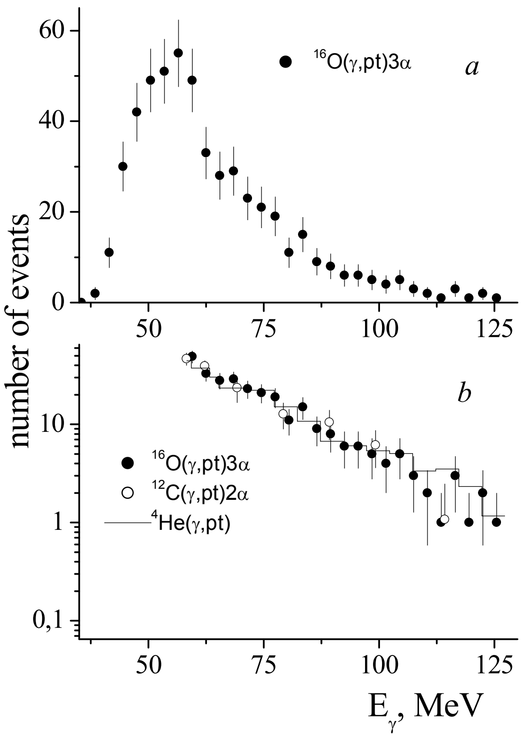

Fig. 1. Dependence of the number of events for the reaction $^{16}O(\gamma, p)^3H3\alpha$ (solid circles) as a function of the photon energy. The histogram and open circles represent, respectively, the experimental results reported in [8] on the reaction $^4He(\gamma, p)^3H$ and in [9] on the reaction $^{12}C(\gamma, p)^3H2\alpha$

The measured energy dependence of the number of events exhibits a broad resonance centered at 55 MeV. The rate of decrease in the energy dependence undergoes a change in the region around 55 MeV. A similar irregularity in the region of this energy value was previously observed in the reactions $^4He(\gamma, p)^3H$ [8] and $^{12}C(\gamma, p)^3H2\alpha$ [9].

In Fig. 1,b, the energy dependence for the reaction in question is contrasted against the energy dependence of the cross section measured for the reactions $^4He(\gamma, p)^3H$ (histogram) and $^{12}C(\gamma, p)^3H2\alpha$ (open circles) at an energy more 55 MeV. The results normalize in the region around 55 MeV. The experimental curves have the same slope. The change in the rate of decrease in the cross section at around 55 MeV may possibly be due to a transition from the mechanism of direct nucleon knockout to the pair-absorption mechanism [1].

In Fig. 2 the dependence of the average kinetic energy T^{aver} of the final particles on the total kinetic energy T_0 is depicted. The latter equals $T_0 = E_\gamma - Q$, where Q is the reaction threshold (Q = 34.302 MeV). The value $T_0 \sim 20$ MeV corresponds to the position of the maximum of the reaction yield at $E_\gamma \sim 55$ MeV and will be used further as the boundaries of the intervals in the analyze of events.

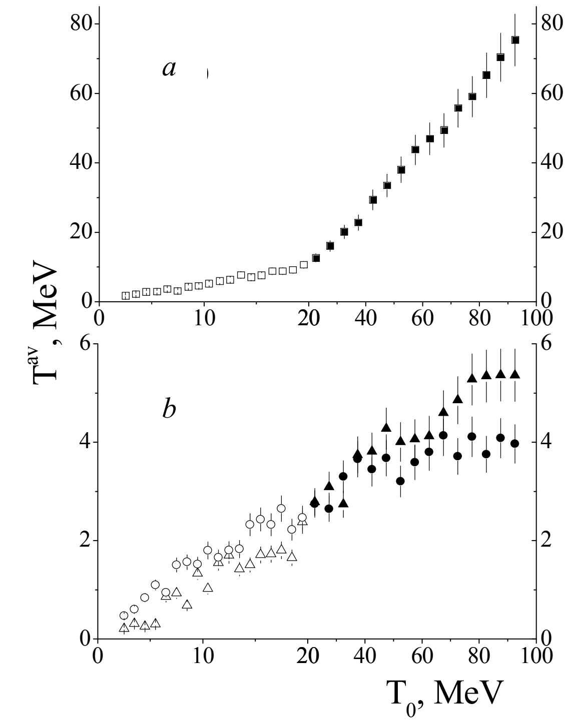

Fig. 2. Dependence of the average kinetic energy of the final particles on the total kinetic energy: the squares correspond to proton, triangles – for the ^3H nuclei and circles – for α-particles

The average energy T^{aver} was calculated for the particles with the energy falling within a 1 MeV interval of the total kinetic energy. The circles are plotted at the centers of intervals. The histogram step equals 1 MeV in the energy interval $T_0 < 20$ MeV (open circles) and 5 MeV in the energy interval $T_0 > 20$ MeV (solid circles). The squares show the distribution of T^{aver} for the proton (see Fig. 2,a), triangles – for the ^3H nuclei (see Fig. 2,b), and circles – for α-particles (see Fig. 2,b).

Due to the inseparability of α-particles, the figure shows the average value for three α-particles.

The dependences of the average kinetic energy was approximated by the linear functions and the results of these fits are given in the second and third columns of the table for all final particles.

Dependence of the relative contributions of the average kinetic energy of particles on T_0

Energy	$T_0 < 20$ MeV	$T_0 > 20$ MeV
T^{aver}_{p}	0.50 ± 0.02	0.90 ± 0.01
T^{aver}_{3H}	0.11 ± 0.01	0.04 ± 0.01
T^{aver}_{α}	0.13 ± 0.01	0.02 ± 0.01

Assuming a statistical distribution of energy between particles, we can calculate the average energy carried away by each particle as a function of T_0 [10]

$$T^{av} = \frac{A\text{-}M}{(n\text{-}1)\cdot A}\cdot T_0, \qquad (1)$$

where A and M are the atomic numbers of the target nucleus and the researched particle, respectively; and n is the number of particles in the final state.

In this reaction, the values of calculation by eq. (1) correspond: for the proton – 0.23, for the ^{3}H nuclei – 0.2, and for α-particles – 0.19 (should be remembered that there are three α-particles in the final state).

In the whole energy interval, the experimental distribution of T^{aver} does not correspond to the statistical distribution, which testifies to the indirect decay of the excited oxygen nucleus. Note the sharp change in the dependence at $T_0 > 20$ MeV, main part of the energy is carried away by the proton. The low rate of change in the dependence of distributions for other particles may indicate that they are decay products of intermediate excited states.

Qualitatively, such a behavior can be explained by a similarity of the mechanism of interaction between a γ-quantum and the target nucleus: the interaction takes place with a virtual quasiparticle that includes a proton as one of its components.

It seems interesting to study the correlation in the p+^{3}H system, which can be interpreted as a virtual α-particle. If a photon is absorbed by a α-particle, then one can expect that the energy of the relative motion of the p+^{3}H pair will account for most of the total kinetic energy in the final state T_0.

The kinetic energy of the relative motion of the proton and the ^{3}H nuclei in their c.m.s. is

$$E_x(p^3H) = M^{eff}_{p3H} - (m_p + m_{3H}), \qquad (2)$$

where M^{eff}_{p3H} is the effective mass of two particles and m_p, m_{3H} are the masses of the p and ^{3}H respectively.

It forms a part of the relative energies

$$_3 = \frac{E_x(p^3H)}{T_0}. \qquad (3)$$

The distribution of events for $T_0 < 20$ MeV interval is shown in Fig. 3,a by open circles and for $T_0 >$ 20 MeV – by solid circles (Fig. 3,b).

The distribution structure changes significantly. On the first region, the distribution is practically symmetric with respect to 0.4, and on the second, the distribution maximum shifts to η~0.75. A similar change was observed for the p^{3}H system and in the reaction ^{12}C(γ, p)^{3}H2α [11] previously. Therefore, for a qualitative comparison, the following are theoretical calculations performed for the four-particle photodisintegration of the carbon nucleus. The calculated curve was normalized to the area under the experimental curve.

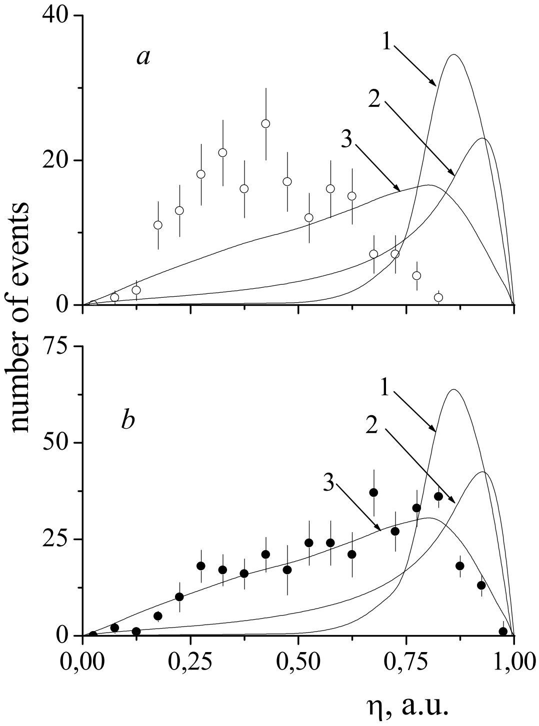

Fig. 3. Function of distribution in relative energy of a proton and the ^{3}H nuclei. The notation for the curves is explained in the main body of the text

The results of the calculation performed on the basis of the α-particle model of the nucleus [5, 6] predicted that the maximum of this distribution curve lies at a value η close to unity, which indicates that a proton and the ^{3}H nuclei fly out mainly in opposite directions.

Curve 1 shows the calculation [5] in the model of direct absorption of a γ-quantum by α-particle with a further emission of p and ^{3}H. In [6] we can single out the following stages of the reaction: a virtual decay of the ^{12}C nucleus to an α-particle cluster and core in the ground state; photon absorption by the cluster; and cluster scattering on the core, where by the core goes over to the ground state. Curve 2 represents the results in this model. The curve 3 corresponds to the calculation [1] within the quasi-deuteron model. The excitation energy of the intermediate nucleus is sufficiently high for nucleon knockout from the s-shell to be possible.

Curve 3 describes satisfactorily the experimental data at $T_0 > 20$ MeV.

CONCLUSIONS

The reaction ^{16}O(γ,p)^{3}H3α was studied with the aid of a diffusion chamber placed in a magnetic field and irradiated with bremsstrahlung photons of endpoint energy E_γ^{max} = 150 MeV. The energy dependence of the total cross section has been measured in the energy range from the threshold reaction. The measured cross section exhibits a broad resonance centered at 55 MeV. The rate of decrease in the cross section undergoes a

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change in the region around 55 MeV. Above the maximum, a comparison is made with the cross-section of reactions $^4He(\gamma, p)^3H$ and $^{12}C(\gamma, p)^3H2\alpha$.

Dependence of the average kinetic energy of the final particles on the total kinetic energy $T_0 = E_\gamma - Q$ have been measured. A jumplike change in the parameters of the linear approximation was found at energies $T_0 \sim 20$ MeV. The proton carries main part of the energy away.

Distribution of relative energy of the proton and ^3H nucleus in their c.m.s. does not agree with the predictions of the mechanism of photon absorption by an α-particle cluster, but at energies $T_0 > 20$ MeV it agrees with calculations within the framework of the quasi-deuteron model of photoabsorption.

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ИССЛЕДОВАНИЕ РЕАКЦИИ $^{16}O(\gamma, p)^3H3\alpha$ ПРИ ЭНЕРГИЯХ ДО ПОРОГА РОЖДЕНИЯ МЕЗОНОВ

С.Н. Афанасьев

Выполнен анализ событий реакции $^{16}O(\gamma, p)^3H3\alpha$, полученных методом диффузионной камеры в магнитном поле на пучке тормозных фотонов с $E_\gamma^{макс}$ = 150 МэВ. В энергетической зависимости реакции обнаружен широкий максимум при E_γ~55 МэВ. Выше максимума наблюдается изменение скорости убывания зависимости. Выполнено сравнение с выходами реакций $^4He(\gamma, p)^3H$ и $^{12}C(\gamma, p)^3H2\alpha$, и сделан вывод о подобии механизма взаимодействия γ-кванта с ядром. Основную часть энергии уносит протон, причем при E_γ > 55 МэВ происходит скачкообразное изменение зависимости относительного вклада частиц в полную энергию системы T_0. Поведение зависимости распределения относительной энергии пары $p+^3H$ от T_0 не согласуется с расчетами в рамках α-кластерного механизма взаимодействия γ-кванта с ядром, но при энергии выше максимума согласуется с расчетами в рамках квазидейтронной модели фотопоглощения.

ДОСЛІДЖЕННЯ РЕАКЦІЇ $^{16}O(\gamma, p)^3H3\alpha$ ПРИ ЕНЕРГІЯХ ДО ПОРОГА НАРОДЖЕННЯ МЕЗОНІВ

С.М. Афанасьєв

Виконано аналіз подій реакції $^{16}O(\gamma, p)^3H3\alpha$, отриманих методом дифузійної камери в магнітному полі на пучці гальмівних фотонів з $E_\gamma^{макс}$ = 150 МеВ. В енергетичній залежності реакції виявлено широкий максимум при E_γ ~ 55 МеВ. Вище максимуму спостерігається зміна швидкості убування залежності. Виконано порівняння з виходами реакцій $^4He(\gamma, p)^3H$ і $^{12}C(\gamma, p)^3H2\alpha$, і зроблено висновок про подібність механізму взаємодії γ-кванта з ядром. Основну частину енергії забирає протон, причому при E_γ > 55 МеВ відбувається різка зміна залежності відносного вкладу частинок у повну енергію системи T_0. Поведінка залежності розподілу відносної енергії пари $p+^3H$ від T_0 не узгоджується з розрахунками в рамках α-кластерного механізму взаємодії γ-кванта з ядром, але при енергії вище максимуму узгоджується з розрахунками в рамках квазідейтронної моделі фотопоглинання.