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INVESTIGATION OF (γ,n) REACTIONS IN THE CHANNEL OF MULTIPARTICLE PHOTODISINTEGRATION OF ^{12}C AND ^{16}O NUCLEI

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The reactions $^{12}C(\gamma,n)^3He2\alpha$ and $^{16}O(\gamma,n)^3He3\alpha$ is investigated by a method that employs a diffusion chamber placed in a magnetic field and irradiated by a beam of bremsstrahlung photons with an end-point energy of 150 MeV. In the excitation curve for the 2α system, a resonance is found, and this resonance identified as the ground state of the ^{8}Be nucleus. The parameters of the γ-quantum and neutron are calculated, and the partial channels $^{12}C(\gamma,n)^3He^8Be_0$ and $^{16}O(\gamma,n)^3He\alpha^8Be_0$ reactions are singled out. It is shown that these reactions proceed according a sequential-type scheme with the formation of one or several unresolved excited states of ^{11}C and ^{15}O nuclei at the first step. The total cross section of the reactions was determined and a similarity in their behavior was found for $E_\gamma > 55$ MeV. A jumplike change in the dependence of the kinetic energy of the neutron on E_γ in different energy intervals of the γ-quantum was observed.
KEY WORDS: diffusion chamber, photodisintegration, the excitation energy, ground state of the ^{8}Be nucleus

ДОСЛІДЖЕННЯ (γ,n)-РЕАКЦІЙ У КАНАЛІ БАГАТОЧАСТИНКОВОГО ФОТОРОЗЩЕПЛЕННЯ ЯДЕР ^{12}С ТА ^{16}О

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Виконано аналіз реакцій $^{12}C(\gamma,n)^3He2\alpha$ та $^{16}O(\gamma,n)^3He3\alpha$, отриманих методом дифузійної камери в магнітному полі на пучку гальмівних фотонів з $E_\gamma^{макс}$=150 МеВ. У кривій збудження системи 2 α-частинок виявлено резонанс, ідентифікований як основний стан ядра ^{8}Ве. Обчислено кінематичні параметри γ-кванта і нейтрона, та виділено парціальні канали $^{12}C(\gamma,n)^3He^8Be_0$ та $^{16}O(\gamma,n)^3He\alpha^8Be_0$. Було показано, що реакції мають послідовний двочастинковий тип розпаду з утворенням одного або декількох нероздільних збуджених станів ядер ^{11}С і ^{15}О на першому етапі розвалу. Визначено повний перетин реакцій і виявлена подоба в їхньому поводженні при $E_\gamma > 55$ МеВ. Виявлено різку зміну залежності кінетичної енергії нейтрона від E_γ у різних інтервалах енергії γ-кванта.
КЛЮЧОВІ СЛОВА: дифузійна камера, фоторозщеплення, енергія збудження, основний стан ядра ^{8}Ве

ИССЛЕДОВАНИЕ (γ,n)-РЕАКЦИЙ В КАНАЛЕ МНОГОЧАСТИЧНОГО ФОТОРАСЩЕПЛЕНИЯ ЯДЕР ^{12}С И ^{16}О

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Выполнен анализ реакций $^{12}C(\gamma,n)^3He2\alpha$ и $^{16}O(\gamma,n)^3He3\alpha$, полученных методом диффузионной камеры в магнитном поле на пучке тормозных фотонов с $E_\gamma^{макс}$=150 МэВ. В кривой возбуждения системы 2α-частиц обнаружен резонанс, идентифицированный как основное состояние ядра ^{8}Ве. Вычислены кинематические параметры γ-кванта и нейтрона, и выделены парциальные каналы $^{12}C(\gamma,n)^3He^8Be_0$ и $^{16}O(\gamma,n)^3He\alpha^8Be_0$. Было показано, что в реакциях происходит последовательный двохчастичный тип распада с образованием одного или нескольких неразделенных возбужденных состояний ядер ^{11}С и ^{15}О на первом этапе распада. Определено полное сечение реакций и обнаружено подобие в их поведении при $E_\gamma > 55$ МэВ. Обнаружено резкое изменение зависимости кинетической энергии нейтрона от E_γ в разных интервалах энергии γ-кванта.
КЛЮЧЕВЫЕ СЛОВА: диффузионная камера, фоторасщепление, энергия возбуждения, основное состояние ядра ^{8}Ве

The development of models for the photodisintegration of light nuclei with knockout of one nucleon fell to its way from the model of the direct mechanism in base of which lie one-particle currents and impulse approximation to the absorption models of the γ-quantum by nuclear substructures: quasideutron and quasiα-particle. However, the reaction mechanism for nucleon knockout from a nucleus has yet to be clarified conclusively.

Calculations in the nonrelativistic approximation [1] revealed that the direct-knockout mechanism cannot explain the equality of the cross sections for (γ,p) and (γ,n) reactions or an identifiable shape of the angular distributions in these reactions. It was concluded [2] that, at intermediate energies, a dominant contribution comes from the process of photon interaction with a nucleon pair. In addition, it was concluded that the role of exchange currents is small if the residual nucleus is in the ground state and increases with growth of energy of its excitation. However, this conclusion is at odds with the results of the calculations performed in the relativistic approximation [3], where it was shown that the direct-mechanism contribution to (γ,N) reactions is greater than that in the nonrelativistic approximation, ensuring agreement with experimental data.

Therefore, the experimental data on photoproduction of high-excited states of nuclei were important. As a rule, these nuclei break up to hadrons forming multiparticle photonuclear reactions. Analyzing decay modes it is possible to select a certain excited states of residual nuclei almost without a background. The problem of exclusive event selection could be solved by means of a track 4π-detector registering all charged particles in a final state. The decay products have small energies. The diffusion chamber combining a gas target with a detector became the effective instrument for research of multiparticle photonuclear reactions. The reactions $^{12}C(\gamma,n)^3He2\alpha$ and $^{16}O(\gamma,n)^3He3\alpha$ (in what follows, they will shortly be designated as $^{12}C(\gamma,n)$ and $^{16}O(\gamma,n)$ reactions, respectively), which are studied here, proceed with the formation of highly excited states of the residual nucleus.

At present, there are no calculations have been performed so far for the ^{12}C and ^{16}O nucleus photodisintegration accompanied by neutron escape and the formation of a final nucleus in a highly excited state. However, in a line of experimental studies on the "mirror" reactions of $^4He(\gamma,p)^3H$ and $^4He(\gamma,n)^3He$ [4, 5], $^{12}C(\gamma,p\alpha)^7Li$ and $^{12}C(\gamma,n\alpha)^7Be$ [6], $^{12}C(\gamma,p)^3H2\alpha$ and $^{12}C(\gamma,n)^3He2\alpha$ [7], the cross sections of the (γ,p) and (γ,n) reactions were found to be equal. The experimental data of the "mirror" reactions were compared with the calculations for (γ,p) reactions. Further, in work [8] a comparison is made between the asymmetry coefficients of the differential cross sections in the $^{12}C(\gamma,p)^{11}C$ and $^{16}O(\gamma,p)^{15}N$ reactions and also their similarity was found as a function of the energy of the γ-quantum. But comparisons of (γ,n) reactions on different nuclei in channels with the formation of several particles in the final state have not been carried out at the present time.

Thus, the $^{12}C(\gamma,n)$ and $^{16}O(\gamma,n)$ reactions proposed for the study corresponds to several criteria for testing the models of interaction of the γ-quantum with the nucleus:

- similar channels of multiparticle decays on different nuclei,
- the formation of photoneutrons in a channel with highly excited states of residual nuclei,
- formation of a system ($n+^3He$) corresponding to a quasiαparticle.

Here we present the results from studies into the reaction $^{12}C(\gamma,n)$ and $^{16}O(\gamma,n)$. The experiments were made using a diffusion chamber in the magnetic field, exposed to bremsstrahlung γ-quanta that had a maximum energy of 150 MeV [9]. The chamber combined a target and a detector with a large-acceptance solid angle. The reactions $\gamma+^{12}C\rightarrow 3\alpha$ and $\gamma+^{16}O\rightarrow 4\alpha$, respectively, was the main source of background. Events featuring doubly charged particles were measured simultaneously. The reactions being studied was separated on the basis of the transverse momentum $P_\perp$, which is equal to the sum of the transverse momenta of the final particles involved. The procedure used to separate the $\gamma+^{12}C\rightarrow 3\alpha$ and $\gamma+^{16}O\rightarrow 4\alpha$ reactions in question was described previously in [10, 11].

The aim of this work is the comparisons of (γ,n) reactions on different nuclei (^{12}C and ^{16}O) in channels with the formation of several particles in the final state. This information is an important component of information for understanding the γ-quanta absorption processes at energies below giant resonance.

EXPERIMENTAL RESULTS

Ground state of the ^8Be nucleus

We will touch upon special features of the detection of the relevant the $^{12}C(\gamma,n)^3He2\alpha$ and $^{16}O(\gamma,n)^3He3\alpha$ reactions. The chamber used operated in a mode that made it possible to separate singly and doubly charged particles visually and to compare the ionization density and the width of a track after measuring its radius of curvature. However, we were unable to identify ^3He and ^4He nuclei by this method. The error in measuring the photon energy and the angle of neutron escape is determined by the error in measuring the momenta of visible particles and the error because of the indistinguishability of ^3He and ^4He particles. Therefore, a method was proposed for identifying α- particles from the formation of the ground state (GS) of the ^8Be nucleus. The resonance corresponding to the formation of a GS in experimental data is manifested in the form of a narrow near-threshold resonance and in many-particle nuclear reactions with several α-particles in the final state [12, 13] its formation is most probable in the intermediate stage.

The excitation energy of a system of two α-particles was determined as [14]:

$$E_x(\alpha\alpha) = M^{eff}(^8Be) - 2m_\alpha, \quad (1)$$

where $M^{eff}(^8Be)$ is the effective mass equal to the total energy of the system in the rest reference system, m_α is the rest mass of α-particles.

In this and the following figures, the experimental results are presented: for the $^{12}C(\gamma,n)$ reaction by light circles (○), for the $^{16}O(\gamma,n)$ reaction by dark circles (●).

It is not possible to select from of several combination of α-particles pairs of every event a pair that was produced as a result of ^8Be disintegration. Therefore, for the distribution of the in-pair relative energy of two α-particles, all values of $E_x(\alpha\alpha)$ for every event are plotted in Fig. 1a at energy $E_x(\alpha\alpha) < 0.5$ MeV. The histogramming step was 0.025 MeV, and the points were placed in the middle of intervals; the displayed errors are pure statistical. Data on the reaction $^{12}C(\gamma,n)$ are normalized to the $^{16}O(\gamma,n)$ reaction in area.

The concentration of events in the 0.1 MeV regions can be explained by the formation of the ground state of ^8Be. The width observed experimentally is of instrumental origin. It is well known from [15] that the mass of the ^8Be nucleus exceeds the mass of two alpha particles by 0.092 MeV and that the resonance FWHM is Γ = 6.8 eV. Because of insufficient energy resolution and low statistical validity, this experiment does not attempt to refine the parameters of the excited states of the ^{8}Be nucleus. The resonance observed in the αα-system is identified with the known data. Two α-particles corresponding to the formation of the GS are reliably identified. Subsequently, only the partial channels for the formation of the GS of the ^{8}Be nucleus (^{12}C(γ,n)^{3}He^{8}Be$_0$ and ^{16}O(γ,n)^{3}Heα^{8}Be$_0$) will be analyzed.

For the ^{12}C(γ,n) reaction, all particles are identified. In the case of the ^{16}O(γ,n) reaction, there are two particles that do not form the ^{8}Be nucleus. The particle momentum determined from the track curvature is independent of the particle mass. Therefore, arbitrary assignments of a particle type to a track lead to the same total momentum P. By consecutively identifying the particle with the final nucleus ^{3}He, we arrive at two values for the of E_γ and P_n: E_γ^1, E_γ^2 and P_n^1, P_n^2. The average value of these two is taken to be the result of a measurement.

The photon energy was determined by the formula:

$$E_\gamma = \frac{m^2+P^2-(M-E)^2}{2\cdot(M-E+P_x)}, \qquad (2)$$

where m and M are the neutron and target-nucleus masses (^{12}C or ^{16}O), E and P are, respectively, the total energy and the total momentum of the visible particles in final state; and P_x is the projection of this total momentum onto the direction of the photon momentum.

Excitation-energy distribution in the system of charged particles

For both reactions, we have measured the excitation-energy distribution in the system of visible particles (^{3}He+^{8}Be$_0$ for the ^{12}C(γ,n) reaction and ^{3}He+α+^{8}Be$_0$ for the ^{16}O(γ,n) reaction), defining as:

$$E_x = M^{eff} - M, \qquad (3)$$

where M^{eff} is the effective mass of charged particles and M is the ground-state mass of the ^{11}C or ^{15}O, respectively. For comparison of distributions in Fig. 1b are represented the value of $E_{sum} = E_x - Q$, where Q is the threshold of the decay of ^{11}C or ^{15}O. The excitation functions of the excitations have a similar form.

The curves (1 is ^{12}C(γ,n) reaction, 2 is ^{16}O(γ,n) reaction) in Fig. 1b represent phase-space distribution [14]:

$$f(E_{sum}) \propto E_{sum}^{\frac{3}{2}k-\frac{5}{2}} \cdot (E_{sum}^{max} - E_{sum})^{\frac{3}{2}(n-k)-1}, \qquad (4)$$

where n is the number of final particles, k is the number of particles forming a resonance (k < n), E_{sum}^{max} is the maximum possible excitation energy of a system of k particles equal to the maximum energy of a γ-quantum in a given interval minus the reaction threshold. For a continuous photon spectrum, phase-space distributions were calculated step by step. First, this was done for photon-energy intervals 1 MeV wide. The area under the curve was normalized to the number of events per interval. After that, summation of probabilities was performed for identical intervals of energies E_{sum}.

A comparison of the distributions in question with the phase-space distributions is indicate of the formation of one or several unresolved excited states of the ^{11}C or ^{15}O nuclei. It is well known from [16, 17] that, at such energies ^{11}C and ^{15}O nuclei have broad levels decaying to final state involving ^{3}He and ^{4}He nuclei. However, the observed resonances do not coincide with some specific level. Therefore, the reactions being studies are of a sequential type: the initial step involves nucleon knockout and the formation of excited states of the ^{11}C or ^{15}O nuclei.

The total cross section for the reactions ^{12}C(γ,n)^{3}He^{8}Be$_0$ and ^{16}O(γ,n)^{3}Heα^{8}Be$_0$

We have measured the total cross section for the reactions ^{12}C(γ,n) and ^{16}O(γ,n) in the photon-energy range between the energy threshold of the reaction and 120 MeV with a variable step – specifically, with a step of 2 MeV at E_γ < 60 MeV and a step of 5 MeV at higher energy. The results are shown in Fig. 2a at the midpoint of a step. The displayed errors are purely statistical.

The measured cross sections exhibit a broad maximum at the near-threshold area. The rate of decrease in cross section undergoes a change in the region around 55 MeV. The histogram represents the total cross section for the ^{4}He(γ,n)^{3}He [5] reaction, and the measurement results are normalized around 40 MeV. The experimental cross section at different nuclei ((^{4}He, ^{12}C and ^{16}O) have the same slope at E_γ > 55 MeV (Fig. 2b). The change in the rate of decrease in the cross section may possibly be due to a change the mechanism interaction of γ-quantum with nuclei.

No cross-section calculations have been performed so far for carbon and oxygen nuclei photodisintegration accompanied by neutron escape and the formation of a final nucleus in a highly excited state; therefore, a comparison with data on the “mirror” reaction ^{12}C(γ,p)^{3}H2α [7]. The total cross section was obtained within the mechanism of direct proton knockout from the s-shell [18]. After normalization at the maximum cross section for the reaction ^{12}C(γ,n), it is represented by curve 1 in Fig. 2b. The calculation within the model assuming photon absorption by an alpha-particle cluster [19] is shown by curve 2. The total cross section for the relevant $^{12}C(\gamma,n)^{11}C$ reaction was calculated in [2] within the self consistent random-phase approximation. The nucleon–nucleon interaction was simulated by Skyrme forces (Sk3). The cross section obtained after normalization in the region around 40 MeV is represented by curve 3. All calculations at E_γ > 55 MeV decreases faster than its experimental counterpart.

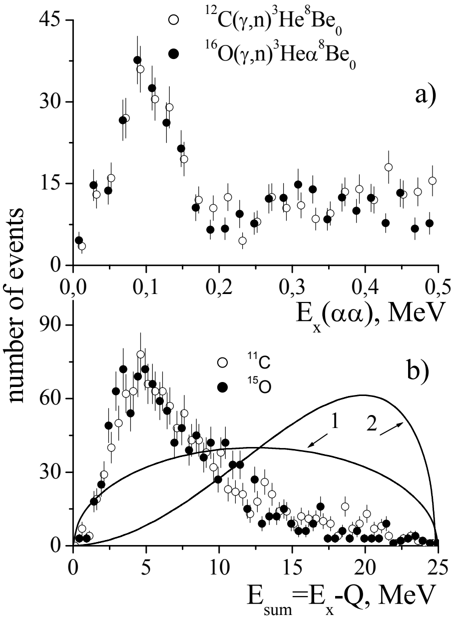

Fig. 1. Distribution of events with respect to the excitation energy: a) system of two α-particles at $E_x(\alpha\alpha)$ < 0.5 MeV, b) system of visible particles. The notation is explained in the main body of the text.

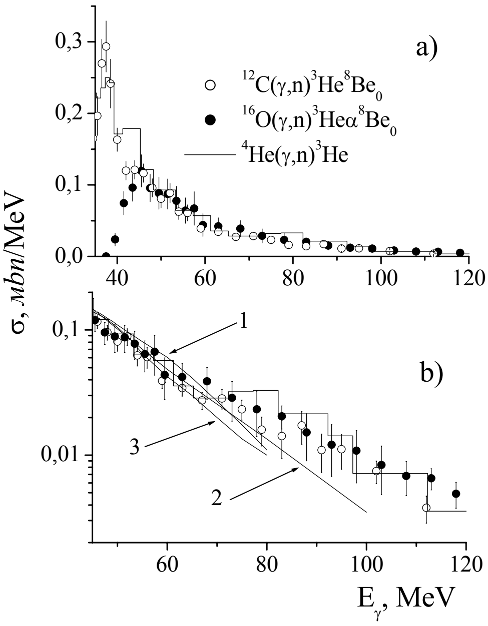

Fig. 2. Total cross section for the reactions $^{12}C(\gamma,n)$ and $^{16}O(\gamma,n)$ as a function of the photon energy: a) all spectr, b) at E_γ > 45 MeV. The histogram is the reaction $^4He(\gamma,n)^3He$ [5]. The displayed curves in the main body of the text.

The dependence of the average energy of the neutron on the total energy

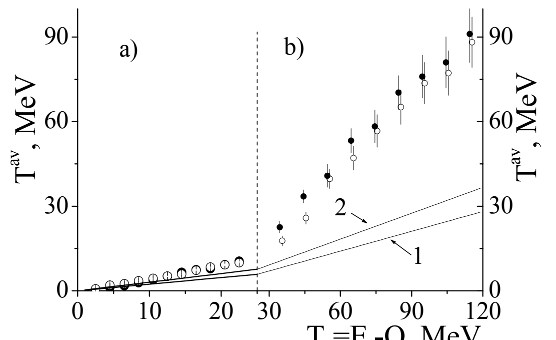

Fig. 3. The dependence of the average energy of the neutron (T^{av}) on the total energy T_0 = (E_γ - Q). The displayed curves were calculated in (5).

In Fig. 3 we show the dependence of the average kinetic energy (T^{av}) of the neutron on the total kinetic energy equal to $T_0 = E_\gamma$ - Q (Q is the energy threshold of the reaction). The average energy T^{av} was determined for particles corresponding to an interval T_0 of 1 MeV. The results are shown in Fig. 3 by points placed at the midpoint of a step. The displayed errors are purely statistical. We have measured T^{av} in the T_0 range with a variable step – specifically, with a step of 2 MeV at T_0 < 24 MeV (zone a) and a step of 10 MeV at T_0 > 24 MeV (zone b).

There is agreement in the form of distributions for both (γ,n) reactions. Also, we should note a fast increase in the dependence at T_0 > 24 MeV. The lines (1 for the $^{12}C(\gamma,n)$ reaction, 2 for the $^{16}O(\gamma,n)$ reaction), shown in Fig. 3, are corresponded to the statistical distribution [20]:

$$T^{av} = \frac{A\text{-}M}{(n\text{-}1)\cdot A}\cdot T_0, \qquad (5)$$

where A, M – are the atomic number of the target and of the neutron, respectively, and n is the number of particles in the final state. In the case of direct knockout of a compound nucleus, the energy distributions of the particles must correspond to the statistical distribution calculated on the assumption of a "symmetric" distribution of the total energy between all reaction products.

The distribution of the neutron T^{av} above the statistical distribution (lines 1 and 2, respectively, for the reactions $^{12}C(\gamma,n)$ and $^{16}O(\gamma,n)$) in both energy intervals.

A fit by the linear function $T^{av} = a\cdot T_0$ to the experimental data is executed and the coefficients a_1 ($^{12}C(\gamma,n)$ reaction) and a_2 ($^{16}O(\gamma,n)$ reaction) were determined for both reactions in two energy intervals. At T_0 < 24 MeV (zone a): $a_1^a = 0.503 \pm 0.012$, and $a_2^a = 0.465 \pm 0.011$. At T_0 > 24 MeV (zone b): $a_1^b = 0.891 \pm 0.065$, $a_2^b = 0.923 \pm 0.059$. Qualitatively, the results for the first energy interval have been explained on the basis of the model of photon absorption by a quasi-deuteron pair. Upon its decay, the neutron escapes from the ^{12}C or ^{16}O nucleus with half the energy ($T_0/2$), while the remaining particles form an excited the ^{11}C or ^{15}O nucleus, which is observed experimentally. In the case of the second energy interval, the data can be explained within the framework of the direct knockout mechanism of the nucleon, where by (5) $T^{av} = T_0 (A-1) / A$. Here, it can be expected that is for the $^{12}C(\gamma,n)$ reaction is $T^{av} = 11T_0 / 12$, and for the $^{16}O(\gamma,n)$ reaction is $T^{av} = 15T_0 / 16$. Qualitatively, the experimental data consistent with this assumption.

CONCLUSION

A detector of large acceptance in solid angle has been employed to study the multi-particle photodisintegration of carbon nuclei (the reactions $^{12}C(\gamma,n)^3He2\alpha$) and oxygen ($^{16}O(\gamma,n)^3He3\alpha$).

The distribution of events with respect to the excitation energy of the subsystem of two alpha particles has been measured. A resonance that has a maximum at E_0 = 0.1 MeV has been found and was identified as a ground state of ^8Be. Events have been separated into channels of ground state formation ($^{12}C(\gamma,n)^3He^3He^8Be_0$ and $^{16}O(\gamma,n)^3He\alpha^8Be_0$ reactions). The photon energy and kinematic parameters of the neutrons was determined.

The energy dependence of the total cross section for the partial reaction $^{12}C(\gamma,n)^3He^8Be_0$ and $^{16}O(\gamma,n)^3He\alpha^8Be_0$ has been measured in the photon-energy range between the energy threshold of the reaction and 120 MeV. The measured cross sections exhibit a broad resonance at the near-threshold area. The rate of decrease in cross section undergoes a change in the region around 55 MeV.

The dependence of the average kinetic energy of the neutron (T^{av}) on the total kinetic energy of the system (T_0) is measured. The data on the $^{12}C(\gamma,n)^3He^8Be_0$ and $^{16}O(\gamma,n)^3He\alpha^8Be_0$ reactions behave identically. At T_0 <24 MeV – $T^{av} \sim 0.5T_0$, with the growth of T_0, the neutron carries away most of the total energy. This behavior can be explained by a change in the mechanism of interaction of the γ-quantum with the nucleus.

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