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TOTAL AND DIFFERENTIAL CROSS-SECTIONS OF ^{16}O(γ,n)^{3}Heα^8Be$_0$ REACTION

Making use of a diffusion chamber embedded into a magnetic field and a beam of bremsstrahlung γ-quanta with the endpoint energy $E_\gamma^{\max} = 150$ MeV, the $^{16}O(\gamma,n)^3He3\alpha$ reaction has been studied. A resonance identified as the ground state of ^{8}Be nucleus is revealed in the excitation curve of the system of 2α-particles. The partial $^{16}O(\gamma,n)^3He\alpha^8Be_0$ reaction channel is resolved, and the corresponding kinematic parameters of the γ-quantum and the neutron are calculated. The dependence of the total cross-section of the reaction on the γ-quantum energy in the interval from the threshold energy to 120 MeV is measured. The reaction is shown to have a successive two-particle character: a neutron is knocked out and an excited ^{15}O nucleus is formed at the first stage. The differential cross-sections of the $^{16}O(\gamma,n)^3He\alpha^8Be_0$ reaction are measured, and the dependences of the asymmetry coefficient for the angular distributions on the γ-quantum energy and the excitation energy of the intermediate nucleus at the first decay stage are obtained.

Keywords: photonuclear reactions, ground state of ^{8}Be nucleus, total and differential cross-sections.

1. Introduction

The (γ, N) process of nucleon knockout from light nuclei in the energy interval between the giant resonance and the meson production threshold has been intensively studied for many years both experimentally and theoretically. However, till now, there is no definite answer to the question about the mechanism of nucleon emission from the nucleus. Calculations performed in the nonrelativistic approximation [1–4] led to a conclusion that the mechanism of direct knockout cannot explain both the magnitude of the cross-section for the (γ, N) reaction and the same shape of angular distributions in the (γ, p) and (γ, n) reactions. The process of γ-quantum interaction with the nucleon pair at the moment, when the nucleons exchange a meson, was recognized to provide the main contribution.

However, those conclusions do not coincide with the result of calculations in the relativistic approximation [5, 6]. By the example of a few nuclei, it was shown that a contribution from the direct mechanism to the (γ, N) reaction is much larger than that in the nonrelativistic approximation and agrees with the experiment. Calculations in the nonrelativistic approximation [3, 4] gave rise to a conclusion that the role of exchange currents is small, if the final nucleus is in the ground state, but it grows with the increase of the nucleus excitation energy.

In order to test those predictions, experimental data are required concerning reactions that leave the nucleus in a highly excited state. Earlier, review [7] on photonuclear reactions with ^{12}C, ^{14}N, and ^{16}O nuclei giving rise to the emission of nucleons from the p-shell and work [8] on the photonuclear reactions with the emission of nucleons from the s-shell of ^{12}C nucleus were published. The analyzed $^{16}O(\gamma, n)^3He3\alpha$ reaction can run with the formation of highly excited

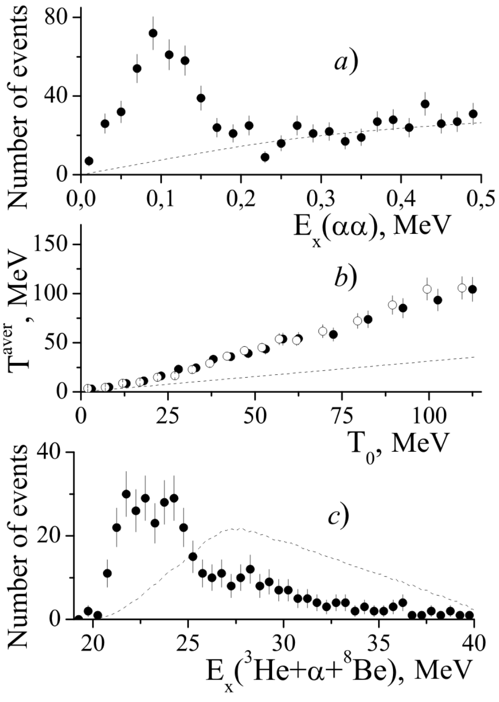

Fig. 1. Excitation energy distribution for the 2α-system (a). Dependence of the average kinetic energy of a neutron on the total kinetic energy (b): symbols ● correspond to $^{16}\mathrm{O}(\gamma,n)^3\mathrm{He}\alpha^8\mathrm{Be}_0$, and symbols ○ to $^{12}\mathrm{C}(\gamma,n)^3\mathrm{He}2\alpha$. Excitation energy distribution for the $^3\mathrm{He}+\alpha+^8\mathrm{Be}_0$ system. See explanations in the text (c)

intermediate states, and a neutron can be emitted in this reaction from the s-shell of the oxygen nucleus.

Nowadays, a significant progress is observed in experimental researches of (γ,N) reactions, in which tagged photons and semiconductor detectors are used. However, the capabilities of this method are restricted to the study of the processes of creation of narrow excited states of the final nucleus, which decay with the emission of γ-quantum. In addition, experimental installations for the tagged photon method have restricted capabilities with respect to the measurements of the nucleon emission angle (from 60° to 120°). Therefore, when comparing predictions of the models with the direct mechanism and the pair-absorption one, it is difficult to give preference to any of them, because the basic difference between their predictions takes place at angles less than 60°. Therefore, measurements of differential cross-sections in the angular interval from 0° to 180° are required. A track 4π-detector satisfies those requirements.

Experimental results for the $^{16}\mathrm{O}(\gamma,\mathrm{n})^3\mathrm{He}3\alpha$ reaction were obtained making use of a diffusion chamber embedded into a magnetic field [9]. The chamber simultaneously served a gas target and a detector. It was irradiated with a beam of bremsstrahlung γ-quanta with the end-point energy $E_\gamma^{\max} = 150$ MeV. The main background reaction was the reaction $^{16}\mathrm{O}(\gamma,4\alpha)$. Four-beam events with doubly charged particles were measured simultaneously. The researched $^{16}\mathrm{O}(\gamma,n)^3\mathrm{He}3\alpha$ reaction was resolved by analyzing an imbalance for the transverse momentum $P_\perp$, which was taken to be equal to the sum of transverse components of the momenta of four particles. In the case of the imbalance $P_\perp > 50$ MeV/s [10], the event was regarded to be a studied reaction. The contribution of the background reaction was estimated to equal 3.5%.

2. Partial Channel of the ^{8}Be Nucleus Formation in the Ground State

The chamber was operated in a mode that allowed single-charged particles to be visually distinguished from doubly charged ones by comparing the ionization density and the track width after the curvature radius of the track had been measured. But this method failed to identify ^{3}He and ^{4}He nuclei. Therefore, at the first stage of the analysis, all particles were assumed to be α-particles.

The excitation energy was determined by the formula [11]

$$E_x = M^{\mathrm{eff}} - M, \tag{1}$$

where M^{eff} is the effective mass, which is equal to the total energy of researched particles in the system, where they are at rest, and M is the mass of the possible intermediate nucleus in the ground state. The results of calculations of the excitation energy for a pair of α-particles in the interval from 0 to 0.5 MeV with a step of 0.02 MeV are exhibited in Fig. 1, a by solid circles. The symbols are drawn at the centers of 0.02-Mev intervals. The statistical errors are also indicated. Six possible values of the excitation energy for the 2α-particle system were calculated for each event, and all relevant values for each event were taken into account when plotting the distribution.

The experimental distribution was compared with the phase one [12],

$$f(E_x) = E_x^{\frac{3}{2}k-\frac{5}{2}}(E_x^{\max} - E_x)^{\frac{3}{2}(n-k)-1}, \tag{2}$$

where n is the number of final particles, k the number of particles formed in the excited state ($k < n$), and $E_x^{\max}$ the end-point excitation energy of the system of k particles. In the case concerned, $n = 5$ and $k = 2$. The phase distribution was calculated for a bremsstrahlung beam by summing up the distributions for narrow intervals, in which the energy of a γ-quantum was assumed to be constant. The area under the phase curve was normalized by the number of events within each interval. The phase distribution is shown in Fig. 1, *a* by a dashed curve.

A significant difference between the experimental and phase distributions in the excitation energy interval below 0.2 MeV allows a conclusion to be drawn that the ground state (GS) of ^{8}Be nucleus could be formed in the reaction concerned. From spectrometric measurements [13], the GS of ^{8}Be nucleus is known to be unstable and to possess a maximum at $E_0 = 0.092$ MeV with the width $\Gamma = 5.57$ eV.

The maximum at $E_x(\alpha\alpha) < 0.2$ MeV was fitted by the Gaussian distribution with the parameters $E_0 = 0.104 \pm 0.013$ MeV and $\sigma = 0.033 \pm 0.004$ MeV. Within the error limits, the maximum position agrees with the results of work [13]. The width observed in the experiment is an apparatus parameter.

Hence, the concentration of events near 0.1 MeV can be explained by the formation of ^{8}Be nucleus in the GS. We selected events, in which one of the α-particle pairs corresponded to the formation of ^{8}Be nucleus in the GS. Below, only this partial channel, $^{16}\mathrm{O}(\gamma,n)^3\mathrm{He}\alpha^8\mathrm{Be}_0$, is analyzed. Its relative yield amounted to 31.2% of the total reaction yield. The contribution of the phase distribution to the maximum at $E_x(\alpha\alpha) < 0.2$ MeV was estimated by the area criterion and was found to equal 4.7%.

The uncertainty at the identification of ^{3}He and ^{4}He nuclei inserts an error into the determination of the γ-quantum energy E_γ and the neutron momentum P_n. From the conservation laws of energy and momentum, the energy of a γ-quantum equals

$$E_\gamma = \frac{m_\mathrm{n}^2 + P^2 - (M_\mathrm{O} - E)^2}{2(M_\mathrm{O} - E - P_x)}, \tag{3}$$

where m_n and M_O are the masses of a neutron and ^{16}O nucleus, respectively; E and P are the total energy and the total momentum, respectively, for the system consisting of one ^{3}He nucleus and three ^{4}He nuclei; and P_x is the projection of the total momentum of this system on the direction of γ-quantum motion. The kinematic parameters of a neutron were obtained with the help of conservation laws after having calculated the γ-quantum energy.

The identification of a pair of particles that do not form ^{8}Be nucleus in the GS with ^{3}He nucleus gave two values for each of the E_γ and P_n quantities. The average value over those two sets was considered to be a measurement result, and the difference made it possible to evaluate the calculation errors for E_γ and P_n: $\delta E_\gamma = 0.6$ MeV and $\delta P_\mathrm{n} = 3.9$ MeV/s.

In Fig. 1, *b*, the dependence of the average kinetic energy T^{aver} of a neutron (solid circles) on the total kinetic energy T_0 is depicted. The latter equals $T_0 = E_\gamma - Q$, where Q is the reaction threshold. 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 5 MeV in the energy interval $T_0 < 60$ MeV and 10 MeV in the energy interval $T_0 > 60$ MeV.

The dashed curve in Fig. 1, *b* corresponds to the statistical distribution [11]

$$T^{\mathrm{aver}} = \frac{A - b}{(n-1)A}\, T_0, \tag{4}$$

where A and b 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 the whole energy interval, the distribution of T^{aver} for a neutron does not correspond to the statistical distribution, which testifies to the indirect decay of the excited oxygen nucleus. For the sake of comparison, hollow circles in Fig. 1, *b* demonstrate the T^{aver} distribution for neutrons in the $^{12}\mathrm{C}(\gamma,n)^3\mathrm{He}2\alpha$ reaction [2]. The agreement between the shapes of distributions for the (γ,n) reactions is evident. 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 neutron as one of its components.

The distribution over excitation energies was measured for the system of three particles ($^3\mathrm{He} + \alpha + {}^8\mathrm{Be}_0$) with the use of formula (1), in which M^{eff} is the effective mass of the system, and M the mass of ^{15}O nucleus in the GS. The value of E_x was determined as the average value after the identification of a pair of particles with ^{3}He nucleus. The error was deter-

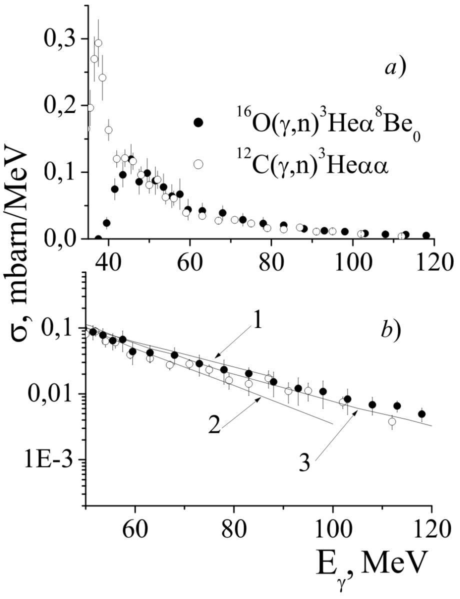

Fig. 2. Dependences of the total reaction cross-section on the γ-quantum energy: (●) this experiment, (○) $^{12}\mathrm{C}(\gamma, n)^3\mathrm{He}2\alpha$. See explanations in the text

mined as the difference δE_x $[\delta E_x(^3\mathrm{He} + \alpha + {}^8\mathrm{Be}_0) = 0.3$ MeV].

The experimental distribution (Fig. 1, *c*, solid circles) was compared with the phase one [Eq. (2)], which is exhibited in the panel by the dashed curve. The phase distribution was plotted for the partial channel $^{16}\mathrm{O}(\gamma, n)^3\mathrm{He}\alpha^8\mathrm{Be}_0$. The difference in the near-threshold region testifies that one or several unresolved excited states of ^{15}O nucleus were formed. There are no reliable data on the levels of ^{15}O nucleus in the examined energy interval. It is known [14] that, at those nucleus energies, there are wide levels, which decay with the emission of ^{3}He and ^{4}He particles. However, we did not manage to identify the observed deviation from the phase distribution with any specific level.

3. Total Cross-Section of $^{16}\mathrm{O}(\gamma, n)^3\mathrm{He}\alpha^8\mathrm{Be}_0$ Reaction

In Fig. 2, *a*, the dependence of the number of events on the γ-quantum energy is shown in the energy interval from the reaction threshold to 120 MeV with a step of 2 MeV at $E_\gamma = 35 \div 60$ MeV and 5 MeV at $E_\gamma > 60$ MeV. The data are depicted by solid circles drawn at the centers of step intervals. The statistical errors are also indicated. In the measured reaction yield, a wide resonance with a maximum at 47 MeV is observed.

At present, there are no calculations for the oxygen photonuclear reactions giving rise to the neutron emission and the formation of a final nucleus in a highly excited state. Therefore, we will compare our results with the data on the $^{12}\mathrm{C}(\gamma, n)^3\mathrm{He}2\alpha$ reaction (hollow circles in Fig. 2), in which a consecutive process takes place, which results in the formation of highly excited states of ^{11}C nucleus. The cross-section values are almost identical above 60 MeV. For the sake of comparison with the results of calculations in various models, a fragment of Fig. 2, *a* to the right from the resonance and with the log-scaled Y-axis is shown in Fig. 2, *b*.

The calculations carried out within the model with direct nucleon knockout mechanism [15] and the model of γ-quantum absorption by an α-cluster [16] predict a shift of the maximum toward higher energies. The corresponding results were reported in work [8].

In the model of γ-quantum absorption by a nucleon pair with the account for the contribution of exchange meson currents [4, 5], the differential cross-sections were obtained for the $^{12}\mathrm{C}(\gamma, N)$ reaction at several γ-quantum energies and the excitation energy of the final nucleus $E_x = 7$ MeV. The result obtained after the integration of the cross-sections over angles and their normalization at about 55 MeV is exhibited by curve *1* in Fig. 2, *b*. This curve satisfactorily describes the energy dependence of the total cross-section in the interval 55–90 MeV.

The total cross-section of the (γ, n_0) reaction was obtained within the self-consistent random-phase approximation [17]. The nucleon-nucleon interaction was given by Skyrme forces (Sk3). Curve *2* in Fig. 2, *b* demonstrates the results of the corresponding cross-section calculations after their normalization at about 55 MeV. The obtained dependence decreases faster than the experimental one.

Curve *3* in Fig. 2, *b* exhibits the results of calculations performed within the quasideuteron model [18]. The excitation energy of the intermediate nucleus is rather high to allow a possibility for a nucleon to be emitted from the *s*-shell. Therefore, the calculations were carried out under the assumption that the nucleons can be emitted from the *p*-shell or the *s*-shell, or the both. The results of calculations were normalized to the experimental value and practically coincide for all three variants. Curve *3* satisfactorily describes the energy dependence of the number of events for both ^{12}C$(\gamma,n)^3$He2α and ^{16}O$(\gamma,n)^3$Heα^8Be$_0$ reactions.

4. Differential Cross-Sections

We also measured the differential cross-sections in three energy intervals: (i) from the reaction threshold to 47 MeV, (ii) in the interval from 47 to 60 MeV, and (iii) above 60 MeV. The polar angle step for the nucleon emission was equal to 10° in the center-of-mass system. The results are shown in Fig. 3. The symbols are plotted at the centers of intervals. The statistical errors are shown.

The results of our experiment in the near-threshold region (Fig. 3, *a*) have a considerable isotropic component. This phenomenon can arise due to the suppression of the yield of low-energy nucleons with a nonzero orbital momentum by a centrifugal potential. As the γ-quantum energy grows, the angular distributions (Fig. 3, *b* and *c*) demonstrate a reduction of the energy dependence of the relative contribution given by the free parameter, as well as an asymmetry growth with respect to 90°.

Earlier, it was shown that, in the "mirror" reactions ^{12}C(γ,p)α^7Li–^{12}C$(\gamma,n)\alpha^7$Be [19] and ^{12}C$(\gamma,p)^3$H2α–^{12}C$(\gamma,n)^3$He2α [8], the equality of cross-sections and the same shape of angular distributions for the (γ,p) and (γ,n) reactions are observed. Therefore, we will make comparison with the results of calculations carried out for the ^{16}O$(\gamma,p)^{15}N^*$ reaction.

The angular distributions of protons emitted in the ^{16}O$(\gamma,p)^{15}N$ reaction under the irradiation of photoemulsions with bremsstrahlung γ-quanta with a maximum energy of 70 MeV was measured in [20]. The distributions were found to be proportional to $\sin^2(\theta)$ in the whole energy interval, which was explained in the framework of the direct mechanism model and in the electric dipole approximation. However, the data on the ^{16}O$(\gamma,p)^{15}N^*$ reaction with the formation of an intermediate nucleus at the excitation energy 13 MeV [21, 22], which were obtained at a γ-quantum energy of 88 MeV, had asymmetric angular distributions.

In Fig. 3, the solid curves correspond to the results of calculations in the framework of the direct mechanism model [5], whereas the dashed ones to the calculation data obtained in the framework of the model of pair absorption with the dominating contribution from exchange meson currents [3]. The calculated curves were normalized by the area under the experimental curve. A conclusion can be drawn that the results of calculations in the model of pair absorption agree better with the experimental data than the results obtained in the direct mechanism model.

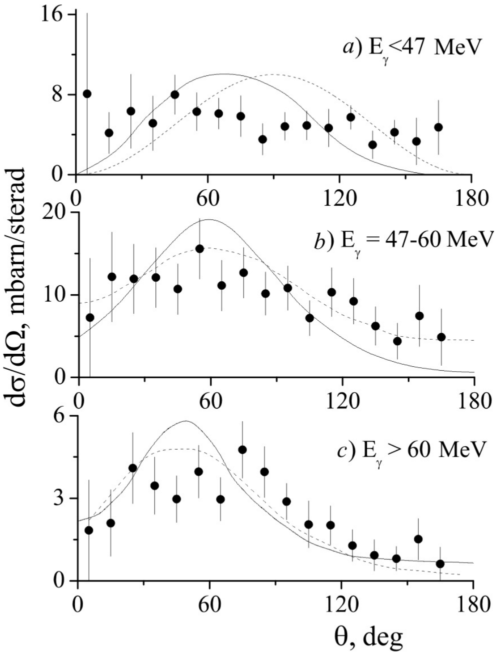

Fig. 3. Differential cross-sections in the center-of-mass system of the reaction ^{16}O$(\gamma,n)^3$Heα^8Be$_0$: $E_\gamma < 47$ MeV (*a*), $E_\gamma =$ $= 47\div60$ MeV (*b*), and $E_\gamma > 60$ MeV (*c*). See explanations in the text

The large solid registration angle of a detector allowed the coefficient of angular distribution asymmetry, β, to be determined as the ratio of the difference between and the sum of the areas under the experimental curve from 0° to 90° and from 90° to 180°,

$$\beta = \frac{\int_0^{\pi/2} \frac{d\sigma}{d\Omega} d\theta - \int_{\pi/2}^{\pi} \frac{d\sigma}{d\Omega} d\theta}{\int_0^{\pi} \frac{d\sigma}{d\Omega} d\theta}. \qquad (5)$$

The dependence of the asymmetry coefficient on the γ-quantum energy is shown in Fig. 4, *a* by asterisks. In the framework of the direct mechanism model, owing to the lack of a negative effective quadrupole charge for neutrons [17], one should expect that the angular distributions are symmetric with respect to 90° in the whole energy interval. Earlier, such a behavior was revealed only in the ^{12}C$(\gamma,p)^{11}$B [23] and ^{16}O$(\gamma,p)^{15}$N [20] reactions with the formation of the

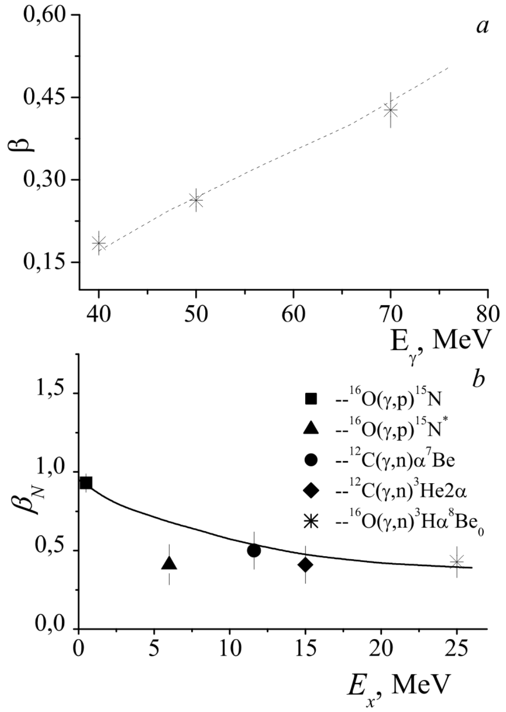

Fig. 4. Asymmetry of the angular distributions in the dependences on the γ-quantum energy (a) and on the excitation energy of the intermediate nucleus (b) in the $A(\gamma, N)(A{-}1)^*$ reactions. See explanations in the text

final nucleus in the ground state and for the γ-quantum energies not exceeding 36 MeV.

In reactions of the $A(\gamma$,N)(A $-$ 1)* type with the formation of excited (A $-$ 1)* states [8, 19], a growth of the asymmetry coefficient was observed. The energy dependence of β at γ-quantum energies above 40 MeV was qualitatively explained under the assumption of the pair absorption. Owing to the momentum distribution, the nucleon pair and the other part of nucleus move to the opposite sides in the laboratory frame. After the pair has absorbed the γ-quantum, one nucleon and the other part of nucleus form an intermediate nucleus in the excited state. If to change to the reaction center-of-mass system, the parameter β can be evaluated by the formula [7]

$$\beta_N = \frac{4}{3\pi}\left(\frac{3v_c}{v_0} + \frac{v_1}{v_N}\right), \qquad (6)$$

where $v_s \cong \frac{E_\gamma}{A\,m_N}$ is the velocity of the reaction center-of-mass system in the laboratory frame, A the atomic number of the target nucleus, m_N the nucleon mass,

$$v_0 \cong \frac{p_{\text{av}}}{(A-2)m_N}$$

is the average velocity of the system of $(A-2)$ nucleons in the laboratory frame, p_{av} the average absolute value of the momentum of the np pair in the laboratory frame,

$$v_1 \cong \frac{E_\gamma(A-2)}{2A\,m_N}$$

is the average velocity of the $\gamma + np$ system in the center-of-mass frame, and v_N the velocity of a nucleon in the $\gamma + np$ system. The results of calculations by formula (6), which are shown by a dashed curve in Fig. 4, a, agree satisfactorily with the experiment. Hence, the irregularity in the energy dependence of the angular distribution parameters can be explained in the framework of the pair absorption mechanism.

In Fig. 4, a comparison is made between the asymmetry coefficients for the (γ,N) reactions with the carbon and oxygen nuclei stimulated by γ-quanta with an energy of 70–100 MeV and with the formation of an intermediate nucleus in various excited states. The coefficients were determined with the help of formula (5). For the reaction $^{16}\text{O}(\gamma, p)^{15}N$, the value of β_N (the square) was determined making use of the data of work [24]. The triangle corresponds to the data for the $^{16}\text{O}(\gamma, p)^{15}N^*$ reaction [25] without the fission of the excited states of the intermediate nucleus. The circle and the diamond exhibit the data on the reactions $^{12}\text{C}(\gamma, n)\alpha^7\text{Be}$ [19] and $^{12}\text{C}(\gamma, n)^3\text{He}2\alpha$ [8], respectively. The asterisk corresponds to our experimental data. As the excitation energy of the final nucleus increases, a reduction of the asymmetry coefficient is observed. The solid curve illustrates the results of calculations [19] in the framework of the quasideuteron model. The theoretical results agree with the experimental ones.

5. Conclusion

With the help of a detector with a large solid angle of registration, the multiparticle photonuclear reaction with the oxygen nucleus, $^{16}\text{O}(\gamma, n)^3\text{He}3\alpha$, has been studied. A resonance was revealed in the excitation dependence of the 2α- particle system, which was identified as the ground state of ^{8}Be nucleus. The partial channel $^{16}\text{O}(\gamma, n)^3\text{He}\alpha^8\text{Be}_0$ was resolved, and the corresponding kinematic parameters of a γ-quantum and a neutron were calculated.

The dependence of the average kinetic energy of a neutron on the total kinetic energy of the system considerably exceeds the statistical one, and the excitation energy distribution for the $^3\mathrm{He}+\alpha+{}^8\mathrm{Be}_0$ system differs from the phase distribution. Therefore, the reaction concerned has a consecutive character: at the first stage, a neutron is emitted, and highly excited states of the ^{15}O nucleus are formed.

The dependence of the number of events on the γ-quantum energy for the $^{16}\mathrm{O}(\gamma,n)^3\mathrm{He}\alpha^8\mathrm{Be}_0$ reaction was measured in the interval from 35 to 120 MeV. The dependence reveals a wide resonance with a maximum at 47 MeV. At about 60 MeV, the rate of dependence recession changes. The results obtained in the high-energy interval are explained in the framework of the pair absorption mechanism of a γ-quantum.

The differential cross-sections of the $^{16}\mathrm{O}(\gamma,n)^3\mathrm{He}\alpha^8\mathrm{Be}_0$ reaction are measured, and the dependence of the coefficient of distribution asymmetry on the γ-quantum energy and the excitation energy of ab intermediate nucleus at the first decay stage is obtained. The experimental results agree with the theoretical ones obtained in the framework of the quasideuteron model.

1. H. Hebach, A. Wortberg, M. Gari. Photonuclear reactions at intermediate energies. *Nucl. Phys. A* **267**, 425 (1976).
2. K. Mori, P.D. Harty, Y. Fujii, O. Konno, K. Maeda, I. Nomura, G.J. O'Keefe, J. Ryckebusch, T. Suda, T. Terasawa, M.N. Thompson, Y. Torizuka. $^{12}\mathrm{C}(\gamma,p_{0+1})^{11}\mathrm{B}$ cross section from 44 to 98 MeV. *Phys. Rev. C* **51**, 2611 (1995).
3. J. Ryckebush, P.D. Harty, L. Machenil, D. Ryckbosch, M. Vanderhaeghen, M.Waroquier. Meson exchange currents and high-resolution (γ,p) reactions. *Phys. Rev. C* **46**, R829 (1992).
4. P.D. Harty, J.C. McGeorge, I.J.D. MacGregor, R.O. Owens, J.R.M. Annand, I. Anthony, G.I. Crawford, S.N. Dancer, S.J. Hall, J.D. Kellie, G.J.Miller, B. Schoch, R. Beck, H. Schmieden, J.M. Vogt, J. Ryckebusch. $^{12}\mathrm{C}(\gamma,p_{0+1})^{11}\mathrm{B}$ cross section from 80 to 157 MeV. *Phys. Rev. C* **51**, 1982 (1995).
5. G.M. Lotz, H.S. Sherif. Relativistic calculations for photonuclear reactions: (I). The direct knockout mechanism. *Nucl. Phys. A* **537**, 285 (1992).
6. J.I. Johansson, H.S. Sherif. Importance of the direct knockout mechanism in relativistic calculations for (γ,p) reactions. *Phys. Rev. C* **56**, 328 (1997).
7. A.F. Khodyachikh. Asymmetry of of the angular distributions of products of the $A(\gamma,n)(A-2)$ reaction on ^{12}C and ^{16}O nuclei at energies of at most 150 MeV. *Yad. Fiz.* **62**, 1355 (1999) (in Russian).
8. S.N. Afanasyev, E.S. Gorbenko, A.F. Khodyachikh. Research of the mechanism of four-particle photonuclear reaction for carbon nucleus. *Yad. Fiz.* **70**, 873 (2007) (in Russian).
9. Yu.M. Arkatov, P.I. Vatset, V.I. Voloshchuk *et al.* On the complete mechanism of three-particle photofission of ^{4}H. *Yad. Fiz.* **32**, 5 (1980) (in Russian).
10. S.N. Afanasyev. Formation of the ground state of ^{8}Be nucleus in the $^{16}\mathrm{O}(\gamma,4\alpha)$ reaction. *Visn. Kharkiv. Univ.* **4** (56), 4 (2012) (in Russian).
11. A.M. Baldin, V.I. Goldanskii, V.M. Maksimenko, I.L. Rosenthal. *Kinematics of Nuclear Reactions* (Atomizdat, 1968) (in Russian).
12. G.I. Kopylov. *Fundamentals of Resonance Kinematics* (Nauka, 1970) (in Russian).
13. D.R. Tilley, J.H. Kelley, J.L. Godwin, D.J. Millener, J.E. Purcell, C.G. Sheu, H.R. Weller. Energy levels of light nuclei $A=8,9,10$. *Nucl. Phys. A* **745**, 155 (2004).
14. F. Ajzenberg-Selove. Energy levels of light nuclei $A=13-15$. *Nucl. Phys. A* **523**, 1 (1991).
15. V.V. Balashov, V.N. Fetisov. Role of nucleon clusters in deep photo-disintegration of light nuclei. *Nucl. Phys.* **27**, 337 (1961).
16. R.I. Jibuti, T.I. Kopaleishvili, V.I. Mamasakhlisov. Nucleon clusters in light nuclei. *Nucl. Phys.* **52**, 345 (1964).
17. M. Cavinato, M. Marangoni, A.M. Saruis. Photoreactions of ^{12}C, ^{16}O and ^{40}Ca in self-consistent RPA theory: (II). Unpolarized (γ,p) and($\gamma,n)$ angular distributions below pion threshold. *Nucl. Phys. A* **422**, 237 (1984).
18. A.F. Khodyachikh. Asymmetry of angular distributions in $A(\gamma,N)(A-1)$-type reactions on p-shell nuclei. *Vopr. At. Nauki Tekhn.* No. 1, 14 (1999).
19. V.V. Kirichenko, A.F. Khodyachikh, P.I. Vatset *et al.* Study of the reactions $^{12}\mathrm{C}(\gamma,p\alpha)^7\mathrm{Li}$ and $^{12}\mathrm{C}(\gamma,n\alpha)^7\mathrm{Be}$ at $E_{\gamma\,\max}\leq 120$ MeV. *Yad. Fiz.* **29**, 572 (1979) (in Russian).
20. V.N. Maikov. Some photoreactions on light nuclei. *Sov. Phys. JETP* **34**, 973 (1958).
21. V.I. Voloshchuk, I.V. Dogyust, V.V. Kirichenko, A.F. Khodyachikh. $^{12}\mathrm{C}(\gamma,p)t2\alpha$ reaction at $E_{\gamma\,\max}\leq 150$ MeV. *Yad. Fiz.* **49**, 916 (1989) (in Russian).
22. I.V. Dogyust, V.A. Zolenko, V.V. Kirichenko. Energy distributions in the $^{12}\mathrm{C}(\gamma,p)t2\alpha$ reaction. *Yad. Fiz.* **51**, 913 (1990) (in Russian).
23. V.V. Kirichenko, Yu.M. Arkatov, P.I. Vatset *et al.* $^{12}\mathrm{C}(\gamma,p)^{11}\mathrm{B}$ reaction at $E_{\gamma\,\max}\leq 120$ MeV. *Yad. Fiz.* **27**, 588 (1978) (in Russian).
24. J.L. Matthews, D.J.S. Findlay, S.N. Gardiner, R.O. Owens. High energy photoprotons from light nuclei. *Nucl. Phys. A* **267**, 51 (1976).

25. A.F. Khodyachikh, P.I. Vatset, I.V. Dogyust *et al.* $^{16}O(\gamma,p)^{15}N^*$ reaction at $E_\gamma \leq 120$ MeV. Ukr. Fiz. Zh. **25**, 229 (1980) (in Russian).

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ПОВНИЙ ТА ДИФЕРЕНЦІАЛЬНІ ПЕРЕРІЗИ РЕАКЦІЇ $^{16}O(\gamma,n)^{3}He\alpha^{8}Be_0$

Резюме

Методом дифузійної камери в магнітному полі на пучку гальмівних фотонів з $E_\gamma^{\max} = 150$ МеВ виконано дослідження реакції $^{16}O(\gamma,n)^{3}He3\alpha$. У кривій збудження системи 2α-частинок виявлено резонанс, ідентифікований як основний стан ядра ^{8}Be. Виділено парціальний канал $^{16}O(\gamma,n)^{3}He\alpha^{8}Be_0$ і розраховано кінематичні параметри γ-кванта та нейтрона. Виміряно залежність повного перерізу реакції від енергії γ-кванта в інтервалі від порога до 120 МеВ. Показано, що реакція має послідовний двочастинковий характер: на першому етапі вилітає нейтрон і утворюється збуджене ядро ^{15}O. Виміряні диференціальні перерізи й отримана залежність коефіцієнта асиметрії кутових розподілів від енергії γ-кванта та енергії збудження проміжного ядра на першому етапі розпаду.