FORMATION OF THE GROUND STATE OF ^{8}Be NUCLEUS IN ^{12}C(γ ,n)^{3}He2α AND ^{12}C(γ,p)^{3}H2α REACTIONS

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By exposing a diffusion chamber in a magnetic field to bremsstrahlung γ-quanta with a maximum energy of 150 MeV, the partial channel of formation of a ^{8}Be nucleus excited up to an energy of 1.5 MeV in the ^{12}C(γ,n)^{3}He2α and ^{12}C(γ,p)^{3}H2α reactions has been studied. On the excitation curve for a system of two α-particles, a resonance structure with a maximum located at $E_0 \approx 0.72$ MeV, possessing the width $\Gamma = 0.75$ MeV, and identified as a ghost anomaly (GA) was revealed between the ground state and the first excited state of the ^{8}Be nucleus. The reactions were demonstrated to be of the sequential type of decay. After removal of a nucleon from the *s*-shell of a ^{12}C nucleus, the excited states of ^{11}C and ^{11}B nuclei are formed; the decay of those nuclei gives rise to the formation of a ^{8}Be nucleus, which decays afterwards into two α-particles. Possible mechanisms of γ-quantum absorption by the carbon nucleus have been discussed.

1. Introduction

This report is a continuation of work [1] concerning the study of four-particle reactions of carbon nucleus photofission, ^{12}C(γ,n)^{3}He2α and ^{12}C(γ,p)^{3}H2α (in what follows, they will shortly be designated as (γ,n)- and (γ,p)-reactions, respectively). The study was carried out making use of a diffusive chamber located in a magnetic field and irradiated by bremsstrahlung γ-quanta with a maximal energy of 150 MeV. It was revealed that the ^{8}Be nucleus in the ground and the first excited state is formed at the end of both reactions, as well as the nuclei ^{7}Be and ^{7}Li in the second excited state in the reactions (γ,n) and (γ,p), respectively. The results obtained were analyzed irrespectively of their distribution among partial reaction channels.

This paper contains the results of our researches concerning the reaction channel of the ^{8}Be nucleus formation in the ground state. The experimental conditions are favorable for its separation, because the excitation energy of ^{7}Be, ^{7}Li, and ^{8}Be nuclei, which decay with the emission of an α-particle, is high and their decay does not create a background if the energy in the system of two α-particles is lower than 1.5 MeV. In the near-threshold range, besides the ground state of the ^{8}Be nucleus, we also found another resonance, which was intuitively identified as a GA [1].

The GA has been repeatedly observed in the near-threshold spectra of the ^{8}Be-nucleus excitation in the multiparticle reactions caused by hadrons [2–5]. Various mechanisms of GA emergence were proposed. An explanation given in the framework of the R-matrix theory of nuclear reactions [6] and in the single-level approximation [7] was most successful. The width of the resonance and the position of its maximum depend on the potential barrier permeability for an α-particle. The modulation of the excitation curve by the permeability probability not only makes it asymmetric, but, in some cases, also gives rise to the appearance of an accompanying resonance [4, 5]. For the substantiation of this model, it is necessary to demonstrate similarity between resonances. They must have both identical quantum-mechanical numbers and identical angular distributions of the ^{8}Be nucleus in the center-of-mass system (CMS) of the reaction, as well as the identical dependences of the emergence probability on the excitation energy [5]. Such information can be obtained in the given experiment carried out with the help of a 4π-detector.

Photonuclear reactions comprise a useful tool for the verification of models which describe the interaction between a γ-quantum and a nucleus. Earlier, the model of direct mechanism [8] satisfactorily described the angular distributions of protons in the (γ,p)-reaction [9] within the energy range from the reaction threshold up to 100 MeV, while the α-particle model [10] did it for the dependence of the total cross-section of the reaction on energy. Nevertheless, a comparison of those results with ours [1], which were obtained without making a division among partial reaction channels, demonstrated the inadequacy of those experimental models. The separation of the partial channel removes the uncertainty that appears at the stage of ^{3}He and ^{3}H nuclei formation, because, in this case, they appear only if the excited ^{11}C and ^{11}B nuclei decay. The results provided by the partial reaction channel enable the models to be checked more carefully.

2. Experimental Technique

The experiment was carried out with the help of a diffusion chamber [11] located in a magnetic field with a strength of 1.5 T. The chamber was irradiated with bremsstrahlung γ-quanta, which had the maximal energy of 150 MeV and were produced by an LPE-300 accelerator at the KhPTI. In order to reduce the background in the chamber given by electrons that were generated by low-energy photons, a berillium filter 2.5 rad. units in thickness was used. The spectral distribution of γ-quanta was considered as a Schiff one, with corrections made for the relative weakening in its soft range made by the filter. The chamber was filled with a mixture of methane and helium of various concentrations (13, 20, and 23%) up to a pressure of 2 atm, which allowed us to obtain long enough and sufficiently clear particle tracks in photographic films [12]. Single- and double-charged particles were distinguished visually by their ionization. Selection of events and mapping them onto special forms ("masks") were carried out manually. The track coordinates were measured with the help of semiautomatic devices of the PUOS-1 type.

To the (γ,p)-reaction, we referred four-beam events, the tracks of which belonged to two single-charged and two double-charged particles, for which the disbalance of transverse momentum was less than 20 MeV/c. More detailed information concerning the selection of events belonging to this reaction is given in work [13].

The reaction (γ,n) gives rise to the formation of three-beam stars, the tracks of which are produced by double-charged particles. Similar three-beam stars are also formed as a result of the background reaction ^{12}C(γ,3α), where the balance of transverse momentum must be satisfied. Events were classified as the (γ,n)-reaction, if the transverse momentum disbalance exceeded 15 MeV/c in the assumption that all the tracks belonged to α-particles. The ground state of the ^{8}Be nucleus is unstable with respect to its decay into two α-particles and has the excitation energy $E_0 = 0.092$ MeV and the half-height width $\Gamma = 5.57$ eV [14]. Selection of events with the low energy of relative motion of two particles, which have left double-charged tracks, enables the third particle to be identified as a ^{3}He nucleus with a high probability. This allows one to find the kinematic parameters of a neutron, using the conservation laws for energy and momentum. The energy of the γ-quantum is equal to the sum of the kinetic energies of all particles in the final state and the reaction threshold energy.

The average measurement error for the momentum of an α-particle (3.7 MeV/c) was estimated in both reactions as an instrumental width of the ^{8}Be ground state. The average measurement error of the ^{3}He momentum was put equal to that of the ^{4}He one. Taking into account the width of the experimental curve of excitation of the second level of the ^{7}Li nucleus, the measurement error of the tritium momentum in the (γ,p)-reaction was equal to 10.7 MeV/c. The measurement error of the nucleon momenta was estimated on the basis of the transverse momentum balance for a neutron (6.4 MeV/c) and a proton (11.9 MeV/c). The measurement errors of the γ-quantum energy in (γ,n)- and (γ,p)-reactions were 0.62 and 0.93 MeV, respectively.

The error of momentum measurement increases as the angle between the particle momentum vector and the vector of the magnetic field strength increases. Therefore, those events, where this angle was less than 50° for at least one track, were not taken into consideration, and a corresponding geometrical correction was introduced for them.

3. Separation of the Partial Channel of Reaction

The distribution of events over the energy of relative motion of two α-particles

$$E_x = M_{\text{eff}} - 2m, \tag{1}$$

where M_{eff} is the effective mass equal to the total energy of the system in the rest reference system and m is the mass of α-particle, is shown by points in Fig. 1,*a*. In this and other figures, dark points correspond to the (γ,n)-reaction and light points to the (γ,p)-one. For the

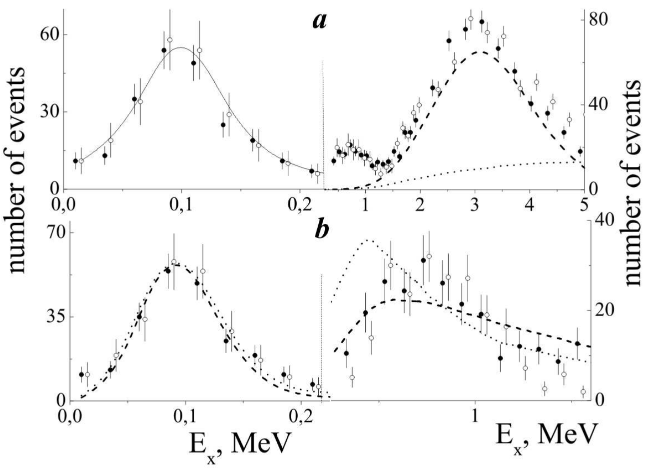

Fig. 1. Excitation energy distribution for the system of two α-particles. See explanations in the text

energy of 0.25 MeV, the scale along the abscissa axis was changed. The left axis corresponds to excitation energies lower than 0.25 MeV, the right one to energies above this value. Since the efficiency of registration was not absolute, the number of (γ,p)-reaction events was approximately by 25% lower than that of the (γ,n)-reaction. In order to make a comparison of this and other figures convenient, the number of (γ,p)-reaction events was normalized to the number of (γ,n)-reaction events. The points correspond to the event number of reactions in the point-to-point interval of energies. The distributions are similar.

The near-threshold resonances were approximated by the Breit–Wigner distribution with the parameters $E_0 = (0.101 \pm 005)$ MeV, $\Gamma = (0.051 \pm 006)$ MeV for the (γ,n)-reaction and $E_0 = (0.099 \pm 004)$ MeV, $\Gamma = (0.059 \pm 008)$ MeV for the (γ,p)-one. The results of fitting are depicted by a solid curve in Fig. 1,*a*. A conclusion can be drawn that the resonances are a manifestation of the ^{8}Be nucleus ground state decay, with both the parameters of the nucleus $E_0 = 0.092$ MeV, $\Gamma = 5.57$ eV and its quantum numbers $J^\pi = 0^+$ being known [14]. As compared with the results of work [14], the shift of the maximum position, the magnitude of which goes beyond the error limits, towards higher energies can be explained by the abnormal near-threshold behavior of the density function, which is discussed below. The observed resonance width is instrumental in this case and corresponds to the average measurement error of 3.7 MeV/c for the momentum of α-particle.

Earlier, we have demonstrated [1] that two particles are formed in the (γ,n)- and (γ,p)-reactions either simultaneously in the course of the ^{8}Be nucleus decay

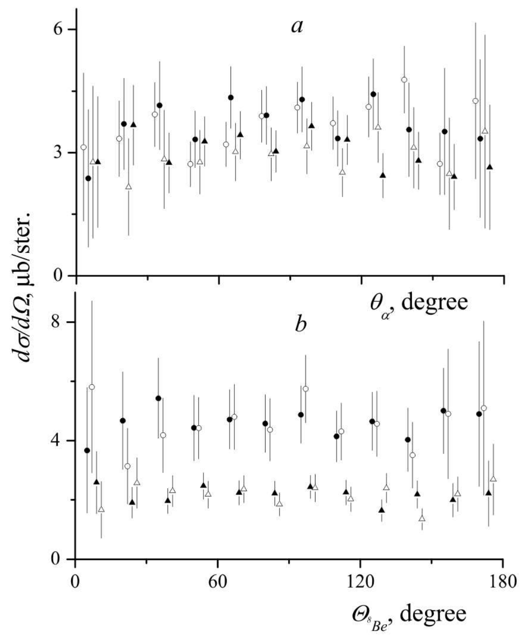

Fig. 2. (*a*) Angular distributions of α-particles in the CMS of the ^{8}Be nucleus in the ground state (● for (γ,n)-reaction and ○ for (γ,p)-one) and the GA (▲ for (γ,n)-reaction and △ for (γ,p)-one); (*b*) angular distributions of the ^{8}Be nucleus in the CMS of the ^{11}C and ^{11}B nuclei at $E_\gamma < 40$ MeV (● for (γ,n)-reaction and ○ for (γ,p)-one) and $E_\gamma > 40$ MeV (▲ for (γ,n)-reaction and △ for (γ,p)-one)

or at different stages of the sequential two-stage decay ^{11}C(^{11}B) $\rightarrow \alpha + {}^7$Be(^{7}Li) $\rightarrow 2\alpha + {}^3$He(^{3}H), respectively. The decays of a ^{8}Be nucleus in its ground and first excited states and ^{7}Be and ^{7}Li nuclei in their second states were found to give the main contribution to the distribution. In Fig. 1,*a*, the dashed curve exhibits the contribution of the ^{8}Be nucleus in the first excited state, and the dashed one that of the sequential process [1].

The distribution obtained after the subtraction of contributions made by the decay of the ^{8}Be nucleus in the ground state and the two-stage process is depicted in Fig. 1,*b* by points. The resonance, which corresponds to the ^{8}Be nucleus in the ground state, remained unchanged. To the right side, there remained a wide resonance with a maximum at about 0.72 MeV. Does it satisfy the criteria, which could classify it as a GA [4,5]?

The GA must be characterized by the same quantum-mechanical properties as the ground state is [4,5]. In the experiment concerned, the differential cross-sections of particles in the CMS of the ^{8}Be nucleus can be measured. In Fig. 2,*a*, the angular distributions for the ground state and the GA are exhibited. The polar

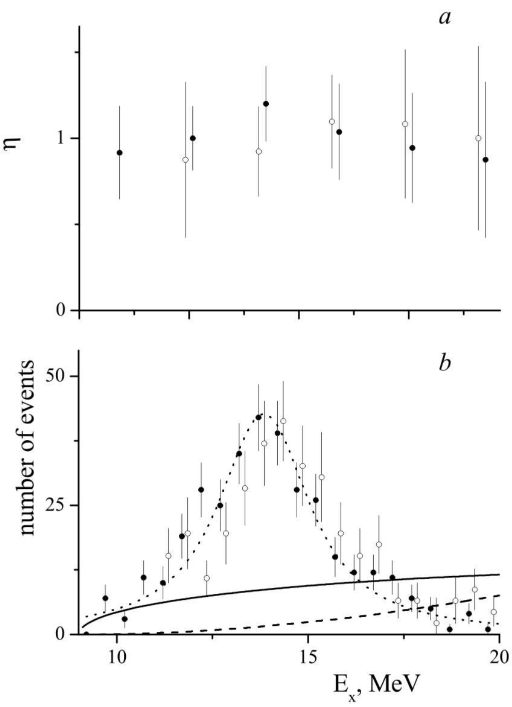

Fig. 3. (a) The ratio η between the yields of the GA and the ground state; (b) distribution over the excitation energy of the ^{11}C and ^{11}B nuclei

angle is reckoned from the direction of the ^{8}Be nucleus motion. The angular distributions are isotropic. This means that the orbital moment $l = 0$, whence it follows that the GA quantum numbers are $J^\pi = 0^+$, as it is in the ground state.

The fact that the second resonance state is an anomaly of the ground one is also confirmed by the independence of the relative yield of resonances of the energy in the ^{8}Be + ^{3}He(^{3}H) system [5], since the GA is an internal effect of the ^{8}Be nucleus. In Fig. 3,a, the dependences of the ratio between the GA and the ground state yields on the excitation energy of the intermediate nucleus ^{11}C (^{11}B) are depicted. Within the whole energy interval, this ratio is constant and close to unity.

The ground and the first excited state do not overlap. Therefore, the single-level approximation with one decay channel can be used in the analysis. For the ground state, provided that the position of the resonance maximum R_r does not depend on the kinetic energy of the ^{8}Be nucleus, the spectral density looks like [5, 15]

$$\rho(E_x) = \frac{\frac{1}{2}\Gamma_0}{\left(E_0 - \Delta_0 - E_x\right)^2 + \left(\frac{1}{2}\Gamma_0\right)^2}, \qquad (2)$$

where the quantities $\Gamma_0 = 2P_0\gamma_0^2$ and Δ_0 are associated with the regular, F_0, and irregular, G_0, Coulomb functions, respectively; ${\gamma_0}^2$ is the reduced width of α-particle decay; $P_0 = a_0/A_0^2$ is the potential barrier permeability; a_0 is the channel radius; and $A_0^2 = F_0^2 + G_0^2$. The Coulomb functions F_0 and G_0 for the orbital moment $l = 0$ were calculated making use of the method and results of work [16].

If the resonance parameters do not depend on energy, it is possible to put $E_0 - \Delta_0 = E_r$ [15]. The spectral density was found for two sets of parameters of the ^{8}Be nucleus decay channel, namely, $a_0 = 4.44$ fm, $\gamma_0^2 = 0.624$ MeV and $a_0 = 3.5$ fm, $\gamma_0^2 = 4.28$ MeV; they were obtained using the phase analysis of experimental data on scattering [7]. In the course of calculations, the availability of two resonances, which correspond to the ground state and the GA, was supposed. The variation of the ground-state excitation curve shape and the emergence of the second peak can formally be explained by different rates of variation of the numerator and the denominator in ratio (2), because the growth of E_x results in a change of the permeability.

Thus, the second resonance appeared owing to the modulation of the ground state resonance by the permeability of the potential barrier. The position of the maximum and the width of the ground state practically do not depend on the channel parameters. At the same time, by varying the latter, an agreement between the theoretical shape of the GA curve and experimental results can be attained. The variation of the channel parameters weakly affects the relative probability of resonances, whereas the small variations of E_r change it substantially. Nevertheless, by varying parameters, we did not succeed in achieving the equality of probabilities, which is observed in experiment.

To make a comparison with experiment, we simulated events by the Monte-Carlo method, using the spectral distribution calculated according to relationship (2). The measurement error of momenta and the value for the ratio between the probabilities of resonance formation were taken from experiment. In Fig. 1,b, the dashed curve displays the results of calculations for the first set of channel parameters, and the dotted curve depicts those obtained for the second one. The width of the first peak does not depend on the choice of parameters and is determined only by the measurement error of particle momentum. The agreement with experiment was attained for $\delta p = 3.7$ MeV/c. Taking the measurement error into account does not lead to the shift of the GA maximum.

In Fig. 4, the spectral distribution of the GA density after subtracting events attributed to the ground state is shown. For the sake of comparison, the ratio (in per cent) between the number of events that fall within the given energy interval and the total number of ground state events, divided by the 0.2-MeV interval width, is put along the ordinate axis. This ratio has a resonance appearance. The fitting of the Breit–Wigner curve gave the following values of parameters: $E_0 = (0.72 \pm 0.03)$ MeV, $\Gamma_0 = (0.75 \pm 0.09)$ MeV for the (γ,n)-reaction and $E_0 = (0.72 \pm 0.04)$ MeV, $\Gamma_0 = (0.69 \pm 0.12)$ MeV for the (γ,p)-one. The peak excitation energy of the ^{8}Be nucleus amounts to 0.63 MeV. The GA yield from the ground state is equal to 1.08 ± 0.09 in the (γ,n)-reaction and 1.11 ± 0.12 in the (γ,p)-one.

With respect to the maximum position and the curve shape, our results agree with the data of work [15] for the reaction ^{9}Be(p,d)^{8}Be (curve *1*), whereas, in the reaction ^{9}Be(d,t)^{8}Be (curve *2*), the maximum is shifted towards higher energies and the distribution is broad. In our experiment, the relative yield of GA was much higher. Earlier, the variation of the distribution peak value in the range from a few to 70 per cent was observed in various reactions [3]. Difficulties of separating the GA are connected with background conditions; this fact becomes obvious if one compares Fig. 1,*b* of this work with Figs. 2 and 3 of work [15].

The spectral distribution has been repeatedly calculated in the framework of the *R*-matrix formalism and the single-level approximation. Curve *3* demonstrates the results of calculations for the reaction ^{9}Be(p,d)^{8}Be made in work [7]. The probability of GA formation is considerably smaller, and the resonance width is larger. The possible reason for such a discrepancy may be a very large value of the channel radius, $a_0 = 7$ fm. Curve *4* depicts the results of calculations made in work [5] for the reaction ^{10}B(p,^{3}He)^{8}Be and the channel radius $a_0 = 3$ fm, normalized, with respect to the area, by our experimental data. The distribution is close to our data both by the curve shape and the maximum position.

Thus, the second resonance appeared owing to the modulation of the spectral distribution curve for the ground state density by the permeability of the potential barrier, and is its part. While analyzing the experimental data further, we will build a distribution for the total statistics – the ground state + the GA.

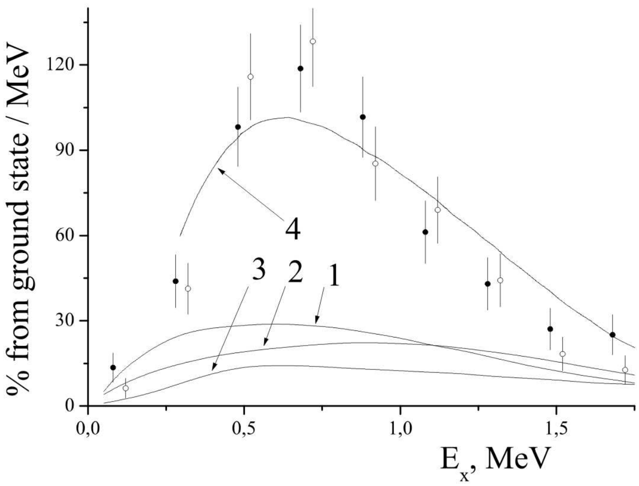

Fig. 4. Excitation function for the ghost anomaly. See explanations in the text

4. Mechanisms of Reactions

4.1. Reactions of sequential type

In Fig. 3,*b*, points represent the distribution over the excitation energy $E_x = M_{\rm eff} - M$ of the system of nuclei ^{3}He(^{3}H) + 2α, where $M_{\rm eff}$ is the effective mass of three particles and M is the mass of nuclei ^{11}C or ^{11}B in the ground state. The distributions are similar to each other. The dashed curve exhibits the phase distribution [17] for three particles of the final four-particle system, and the solid one does that for two particles of the three-particle system, when the ground state of the ^{8}Be nucleus is formed. Since the spectrum of photons is continuous, the phase distribution is a sum of distributions in narrow intervals, where the γ-quantum energy was considered constant. The area under the phase curve was normalized to the number of events that fell within every interval. A comparision of energy distributions with phase ones gives the basis to assert that the reactions run through the channel of formation of a single or several unsplit excited states of ^{11}C and ^{11}B nuclei. Fitting by the Breit–Wigner curve (the dotted curve) resulted in the following values of parameters: the maximum position $E_0 = (13.6 \pm 0.3)$ MeV and the width $\Gamma = (3.2 \pm 0.7)$ MeV for the ^{11}C nucleus, and $E_0 = (13.9 \pm 0.5)$ MeV and $\Gamma = (3.5 \pm 0.2)$ MeV for the ^{11}B one. The positions of maxima and the widths of resonances coincide within the error limits. We did not succeed in identifying these resonances with any levels provided by the known compilations of spectroscopic data [18]. Thus, at the first stage of the reaction, the nucleon is knocked out, and the intermediate nucleus

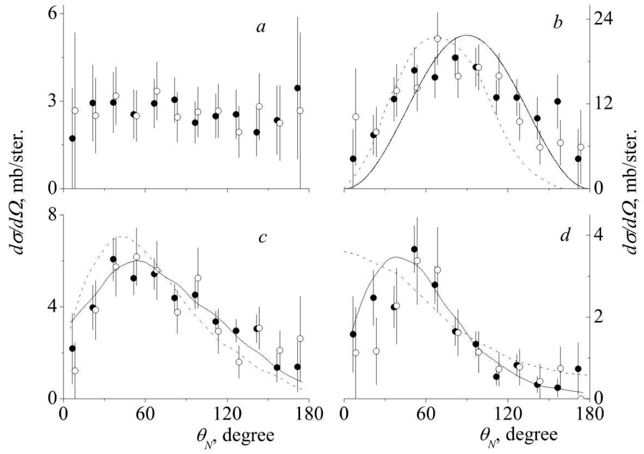

Fig. 5. Angular distributions of nucleons for several energy intervals: < 36 (*a*), 36–40 (*b*), 40–60 (*c*), and 60–120 MeV (*d*). See explanations in the text

remains in the excited state which decays into the ^{8}Be and ^{3}He(^{3}H) nuclei. The high excitation energy of the intermediate nucleus (14 MeV) allows us to assert that the nucleon is emitted from the *s*-shell.

4.2. Angular distributions of nucleons

The sequential character of reactions allows the angular distributions of nucleons to be analyzed in the CMS of a reaction in the framework of two-particle kinematics. In Fig. 5, the differential cross-sections are depicted for the following energy intervals: up to 36, 36–40, 40–60, and 60–120 MeV. The analysis included events associated with both the ground state and the GA. In the relevant energy intervals, the angular distributions of (γ,p)- and (γ,n)-reactions have similar forms.

Up to 36 MeV, the distributions are close to isotropic (Fig. 5,*a*). Such a behavior can be explained by the suppression of the yield of nucleons with the orbital moment distinct from zero, which is exerted by the centrifugal potential. Visually (see Fig. 5,*b*), a conclusion can be drawn that the differential cross-sections are proportional to $\sin^2\theta$ (the solid curve) in the energy interval 36–40 MeV. In the model of the direct knocking out of the nucleon and in the electric dipole approximation, such a form of angular distributions can be expected [19] if the final nucleus is in the $1/2^+$ state. Thus, the shape of angular distributions also testifies that nucleons are emitted from the *s*-shell.

In Fig. 5,*b*, the dashed curve corresponds to the results of calculations obtained in the model of the direct knocking out of the proton from the *s*-shell of a carbon nucleus in the (γ,p)-reaction and normalized to the experimental data of work [8]. It agrees satisfactorily with experiment. The calculations were carried out for the energy interval from the reaction threshold up to 90 MeV, in the approximation of electric dipole and quadrupole transitions. The corresponding results predicted a larger, as compared with experiment, asymmetry, maybe owing to the inclusion of a wide energy interval into consideration. In this approximation, an increase of the asymmetry with the energy was observed [20]. A conclusion can be made that, at energies up to 40 MeV, the mechanism of the direct knocking out of the nucleon from the *s*-shell of a carbon nucleus prevails. The further increase in energy is accompanied by the appearance of the isotropic component in the angular distributions and a substantial asymmetry with respect to 90°.

In Fig. 5,*c*, the dashed curve corresponds to the results of calculations in the framework of the phenomenologic quasi-deuteron model, where the differential cross-sections in the system γ + np were taken from the experiment on photodisintegration of a free deuteron [21], and the solid curves in Figs. 5,*c* and *d* correspond to the angular distributions of the $\sin^2\theta$-form, which are connected with the electric dipole transition of the nucleon pair from a singlet into a triplet state [20]. The results of calculations are normalized to experimental data. They satisfactorily predict the shape of the angular distribution curve. Hence, the asymmetry in the system γ + np does not govern the asymmetry of angular distributions of nucleons at such energies.

The asymmetry of angular distributions is usually explained by the interference of electric quadrupole and octupole amplitudes with dipole ones [20, 22]. At the qualitative level, the agreement between the results of calculations in the pure dipole approximation and the experimental data can be explained kinematically: the interaction system γ+np moves with respect to the CMS of the reaction. The angular distributions, which are symmetric with respect to 90° in the interaction system, become asymmetric in the CMS, with a prevailing yield of nucleons at angles less than 90°. On the one hand, the asymmetry arises owing to the transfer velocity. On the other hand, the nucleon emitted backwards in the interaction system has a lower energy in the laboratory system and, consequently, can be absorbed with a higher probability by the nucleus.

In the literature, the role of exchange meson currents in photonuclear reactions is actively discussed [23]. The increase of their contribution in the intermediate energy range with the growth of the residual nucleus excitation energy was predicted. Nevertheless, the body of experimental data concerning the angular distributions of protons in the interval 58–128° [24] is not enough for the verification of the model. The results of calculations carried out in the framework of the model of pair absorption with the dominant contribution of exchange meson currents [23] and at $E_\gamma = 88$ MeV are shown in Fig. 5,*d* by a dashed curve. The calculation was made for a final ^{11}B nucleus in the excited state with $E_0 = 13$ MeV. The result obtained was normalized to the area under the experimental curve. The experiment confirmed the relative increase in the isotropic part of angular distributions with the energy, which was predicted by the theory, but negated the growth of differential cross-sections with reduction of the polar angle at $\theta < 60°$.

4.3. Energy distinction of (n,^{3}He) and (p,^{3}H) systems at $E_\gamma > 40$ MeV

Of the energy of all particles in the CMS of the reaction, the energy, which is contained in the n + ^{3}He or p + ^{3}H system, is equal to [17]

$$t_{12} = [T_1 + T_2 - \frac{(\vec{p}_1 + \vec{p}_1)^2}{2\,(m_1 + m_2)}](E_\gamma - \varepsilon), \qquad (3)$$

where T_i, $\vec{p}_i$, and m_i are the kinetic energy, the momentum, and the mass, respectively, of the i-th particle ($i = 1, 2$); E_γ is the photon energy, and ε is the reaction threshold energy. In Fig. 6, the distribution of events over t_{12} is exhibited by points. It is compared with the phase distribution [17]

$$f(t_{12}) = \sqrt{t_{12}}\sqrt{1 - t_{12}}, \qquad (4)$$

normalized to the area under the experimental curve (dashed curve). The phase distribution does not describe experimental results.

4.3.1. Quasi-alpha-particle mechanism

One can expect that the fragments of the cluster, which absorbed the γ-quantum, would carry out a large part of energy released in the reaction. The dashed curve in Fig. 6 represents the results of calculations made in the framework of the α-cluster model [10] (for the relevant Feynman diagram, see inset *a*). According to experimental data, the absorption of a γ-quantum by a quasi-α-particle and the simultaneous output of both fragments are impossible. The heavy fragment ^{3}He(^{3}H) even can not quit the nucleus; then, it forms, together with ^{8}Be, an intermediate excited state of a system with

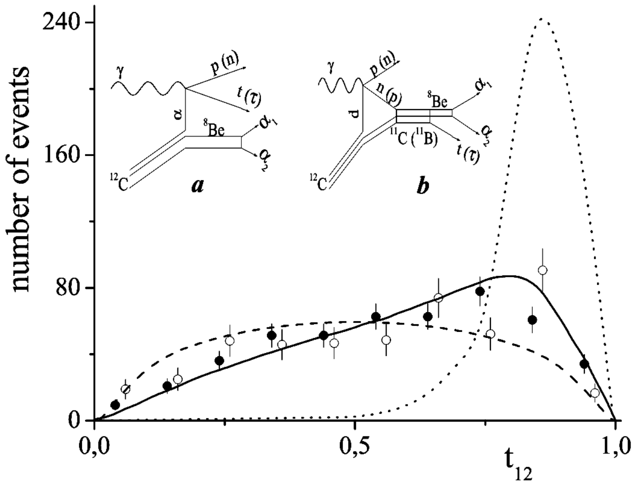

Fig. 6. Distributions of (n,^{3}He) and (p,^{3}H) over the relative energy of particle pairs. See explanations in the text

11 nucleons, the decay of which results again in the formation of ^{3}He(^{3}H). Such a variant of the scenario agrees with the sequential character of reactions, which is confirmed by the experiment concerned. However, the calculations for the α-particle mechanism represented by the triangular diagram have not been carried out.

4.3.2. Quasi-deuteron mechanism

The calculations of the distribution for the energy part that is carried out by the pair of particles, n + ^{3}He or p + ^{3}H, were made in the framework of the quasi-deuteron model (see the Feynman diagram *b* in Fig. 6). As the A(γ,N)(A − 1) reaction, there were considered those events, in which no nucleon quits the nucleus. The decay events were simulated by the Monte-Carlo method. The method used for calculating the characteristics of the first reaction stage and the corresponding approximations made at that were described earlier [25]. There were the simulated events with the excitation energy of the final nucleus in the interval from 13 to 15 MeV. The state excitation curves were taken in the Gaussian form. The GA parameters were as follows: $E_0 = 0.72$ MeV and $\Gamma = 0.75$ MeV. Literature data $E_0 = 0.092$ MeV and $\Gamma = 5.57$ MeV were used as the parameters of a ^{8}Be nucleus in the ground state. The angular distributions for ^{3}He and ^{3}H in the coordinate system, where ^{11}C or ^{11}B is at rest and the polar axis of which is directed along their momenta, as well as the particle momentum errors, were taken from the actual experiment. The results of calculations are presented in the figure by the solid curve. The scenario, when a γ-quantum is absorbed by a nucleon pair, in which only one nucleon quits the nucleus and ^{3}He or ^{3}H is the product of the decay of the intermediate excited nucleus, ^{11}C or ^{11}B, respectively, this scenario agrees with experiment.

4.4. Angular distributions of ^{8}Be in the CMSs of the ^{11}C and ^{11}B nuclei

While analyzing the angular distributions of nucleons in the reaction CMS at energies below 40 MeV, it was demonstrated that the direct mechanism of knocking out a nucleon from the *s*-shell with the formation of an intermediate nucleus with the quantum numbers $1/2^+$ is valid. Then only the case $l = 0$ is possible for the decay ^{11}C(^{11}B) $\rightarrow$ ^{3}He(^{3}H) + ^{8}Be. In Fig. 2,*b*, the angular distributions of ^{3}He(^{3}H) in the CMS of the ^{11}C(^{11}B) decaying nucleus are depicted. The distributions are isotropic. This confirms once more our conclusion made above that $J^\pi = 1/2^+$ for intermediate nuclei.

At energies above 40 MeV, the experimental data agree with the results of the quasi-deuteron model. The absorption of a γ-quantum by a nucleon pair can stimulate the reconstruction of the shells of the intermediate nucleus and change its quantum numbers. In Fig. 2,*b*, the corresponding angular distributions of ^{3}He(^{3}H) in the CMS of the decaying ^{11}C(^{11}B) nucleus are exhibited. Here, the distributions are isotropic as well. Thus, the change of the absorption mechanism for a photon does not affect the quantum numbers of intermediate nuclei.

5. Conclusions

The partial channel of the formation of a ^{8}Be nucleus with the excitation energy less than 1.5 MeV has been separated in the reactions ^{12}C(γ,n)^{3}He2α and ^{12}C(γ,p)^{3}H2α. A resonance with the parameters $E_0 \approx 0.72$ MeV and $\Gamma \approx 0.75$ MeV was found in the excitation curve of the ^{8}Be nucleus between the ground and the first excited state. The resonance and the ground state were established to have identical angular distributions in the rest systems of intermediate nuclei, identical dependences of the yield on the intermediate nucleus excitation energy, identical angular distributions of α-particles in the rest system of the ^{8}Be nucleus, and, therefore, identical spins and parities. In the single-level approximation, it has been demonstrated that the appearance of the resonance can be explained by modulation of the excitation curve of the ^{8}Be nucleus in the ground state exerted by the probability for an α-particle to penetrate through the potential barrier. Therefore, the resonance was identified as a near-threshold anomaly referred to in the literature as the ghost anomaly. In photonuclear reactions, it has been observed for the first time. The reactions were found to be of the sequential type: a nucleon is emitted and an intermediate excited nucleus ^{11}C(^{11}B) which decays into ^{3}He(^{3}H) and ^{8}Be is formed; the latter, in its turn, decays into two α-particles. The excitation curves for ^{11}C and ^{11}B nuclei have the maximum at $E_0 = 13.9$ and 14.3 MeV, respectively, and the width $\Gamma = 2.7$ and 3.3 MeV, respectively. The quantum numbers of the excited ^{11}C and ^{11}B nuclei are $J^\pi = 1/2^+$ both. The experimental results obtained at energies up to 40 MeV confirm the mechanism of the direct knocking out of a nucleon from the *s*-shell of the ^{11}C nucleus, and those obtained at higher energies confirm the mechanism of the absorption of a γ-quantum by a nucleon pair. The spin and the parity of excited states do not change. The experimental results contradict the quasi-α-particle model with a simultaneous output of n(p) and ^{3}He(^{3}H).

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УТВОРЕННЯ ОСНОВНОГО СТАНУ ЯДРА ^{8}Be В РЕАКЦІЯХ ^{12}C(γ,n)^{3}He2α І ^{12}C(γ,p)^{3}H2α

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Р е з ю м е

Методом опромінення дифузійної камери в магнітному полі гальмівними γ-квантами з максимальною енергією 150 МеВ досліджено парціальний канал утворення ядра ^{8}Be, що збуджується до енергії 1,5 МеВ, в реакціях ^{12}C(γ,n)^{3}He2α і ^{12}C(γ,p)^{3}H2α. На кривій збудження системи двох α-частинок між основним і першим збудженим станами ядра ^{8}Be виявлено резонансну структуру з максимумом $E_0\approx$0,72 МеВ і шириною $\Gamma\approx$0,75 МеВ, ідентифіковану як аномалія-"примара" (АП). Показано, що реакції мають послідовний тип розпаду. Після видалення нуклона з s-оболонки ядра ^{12}C утворюються збуджені стани ядер ^{11}C і ^{11}B, при їх розпаді формується ядро ^{8}Be, яке потім розпадається на дві α-частинки. Обговорюються можливі механізми поглинання γ-кванта ядром вуглецю.