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ENERGY CORRELATIONS OF α-PARTICLES IN THE ^{8}Be-NUCLEUS GROUND-STATE FORMATION CHANNEL OF THE ^{12}C(γ,3α) AND ^{16}O(γ,4α) REACTIONS

The method of diffusion chamber in the magnetic field making use of a bremsstrahlung beam with a maximum photon energy of 150 MeV is applied to study the ^{12}C(γ,3α) and ^{16}O(γ,4α) reactions. A resonance identified as the ground state of ^{8}Be nucleus is found in the distribution of events over the energy of the relative motion of two α-particles. The partial cross-sections of the ^{8}Be nucleus formation channels are measured. It is shown that the mechanism of interaction between a γ-quantum and a virtual α-particle pair takes place in this case.

Keywords: photonuclear reactions, ground state of ^{8}Be nucleus.

1. Introduction

This work is devoted to the study of the complete α-particle photodisintegration of ^{12}C and ^{16}O nuclei: ^{12}C(γ,3α) (reaction I) and ^{16}O(γ,4α) (reaction II), respectively. Those reactions can be used to verify the $N\alpha$-particle nuclear model [1] and to obtain the additional information about the nature of α-α interaction. The results are of interest both for the many-body problem as a whole and for the astrophysics and the physics of thermonuclear fusion [2]. In the framework of the successive two-particle decay, reactions I and II may result in the formation of excited ^{8}Be* and ^{12}C* nuclei. The existence of an unstable ground state of ^{8}Be nucleus and the exotic Hoyle state in ^{12}C nucleus (0^{+}, $E^{*} = 7.65$ MeV) promoted a substantial progress in the development of the star evolution theory [3]. Furthermore, 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.

An attempt to interpret the experimental data on the nuclear photodisintegration with a release of α-particles in the framework of the compound nucleus model led to fundamental difficulties: the impossibility of predicting the total cross-section structure [4] and contradictions associated with the selection rules for the isotopic spin [5]. Recently, the theory of the cluster photodisintegration of light nuclei in the framework of the nucleon association model has been considerably advanced [6]. When interpreting the excited states of a nucleus with the help of the diagram technique [7], the following stages can be distinguished in the photodisintegration reaction: the virtual decay of the nucleus into a cluster and a core, photon absorption by the cluster or the core, and subsequent particle rescattering.

This work is a continuation of publications [8, 9] devoted to the study of the reactions ^{12}C(γ,3α) and ^{16}O(γ,4α). In the cited works, those reactions were observed to run following a scheme of the successive two-particle type. In the presented material, the channels of the ^{8}Be nucleus ground state formation are extracted for each reaction, and their mutual analysis is done.

2. Experimental Technique

The experiment was performed using a diffusion chamber in a magnetic field [10]. The chamber was placed in the path of a beam of bremsstrahlung photons with a maximum energy of 150 MeV emitted from a linear electron accelerator. In order to reduce the target density, the chamber was filled with a mixture of methane and helium in the first measurement cycle and with a mixture of oxygen and helium in the second one. The target–detector combination made it possible to register the products of a low-energy reaction and analyze it practically from its threshold [11]. The measurement error of the momentum of α-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. The particle range in the mixture was obtained considering the ion charge exchange with the medium. Tabular data [12] for several target components were used at that.

Three- (the ^{12}C(γ,3α) reaction) and four-pronged (the ^{16}O(γ,4α) reaction) stars, whose rays belonged to doubly charged particles, were selected for the analysis. Events were identified after the measurement on the basis of momentum balance. In the experiment, the axis OX was directed along the beam of γ-quanta. Boundary conditions were imposed on the quantities $\Delta_x = \sum P_x^i - E_\gamma$, $\Delta_y = \sum P_y^i$, and $\Delta_z = \sum P_z^i$, 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 α-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.

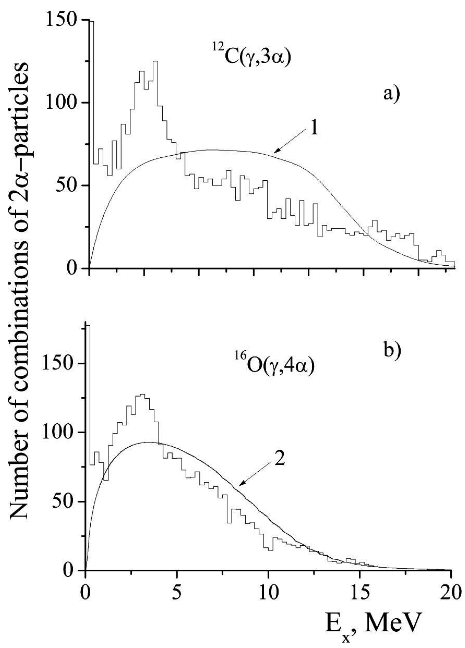

Fig. 1. Distribution of the energy of the relative motion in the $\alpha\alpha$-system for the reactions (a) ^{12}C(γ,3α) and (b) ^{16}O(γ,4α). Solid curves *1* and *2* demonstrate the corresponding phase distributions

3. Extraction of the ^{8}Be-Nucleus Ground-State Formation Channel

The energy of the relative motion of two α-particles in the considered reactions equals

$$E_x = \frac{(\mathbf{p_i} - \mathbf{p_k})^2}{4m},$$

where i and k are the particle numbers, and m is the mass of α-particle. Owing to the indistinguishability of α-particles, an advance choice of their pair that is formed as a result of the ^{8}Be nucleus decay is impossible. Therefore, for one event, three E_x-values for reaction I and six E_x-valuesfor reaction II were measured. The histograms in Fig. 1 show all combinations of E_x-values for both examined reactions. The histogram step equals 0.25 MeV.

The experimental distributions were compared with the phase ones [13]:

$$f_1(E_x) = E_x^{1/2}(E_x^{\max} - E_x)^{1/2}$$

for reaction I (curve *1* in panel a) and

$$f_2(E_x) = E_x^{1/2}(E_x^{\max} - E_x)^2$$

for reaction II (curve *2* in panel b). Here, $E_x^{\max}$ is the maximum energy in the system of two α-particles, which is equal to the total energy in the system of the reaction center of mass (SCM) The phase distribution was calculated for the beam of bremsstrahlung γ-quanta by summing up the distributions in narrow intervals, in which the energy of γ-quanta was considered to be constant. The area calculated in every

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of those intervals was normalized by the number of events that occurred within this interval. The phase distributions are shown in Fig. 1 by solid curves. The difference between the experimental distributions and the phase ones, especially in the interval where $E_x < 0.25$ MeV, allows a conclusion to be made that excited states of ^{8}Be nucleus are formed in reactions I and II. The attention should be attracted to the similarity of the excitation functions for reactions I and II. In particular, their two maxima are located at the same E_x-values (at about 0.1 and 3.0 MeV), which testifies to the formation of the same levels in ^{8}Be nucleus.

The resonances obtained in reactions I and II at the energy of the relative motion of two α-particles varying from 0 to 0.25 MeV (see Fig. 1) are shown in Fig. 2, *a* with a step of 20 keV. Hereafter, the solid and hollow circles correspond to the results obtained for reactions I and II, respectively, whereas the vertical segments denote the corresponding statistical errors. The data for reaction I were taken from work [8]. The obtained peaks were fitted to the Gaussian distributions: with the maximum position at $E_0^{\mathrm{I}} = (0.089 \pm 0.004)$ MeV and the half-height width $\Gamma^{\mathrm{I}} = (0.056 \pm 0.003)$ MeV for reaction I (curve *1*), and with the maximum position at $E_0^{\mathrm{II}} = (0.095 \pm 0.005)$ MeV and the half-height width $\Gamma^{\mathrm{II}} = (0.088 \pm 0.009)$ MeV for reaction II (curve *2*).

It is known from the data of spectrometric measurements [14] that the ground state (GS) of ^{8}Be nucleus has the following parameters: $E_0 = 0.092$ MeV, $\Gamma = 5.57$ eV, and the quantum number $J^\pi = 0^+$. The maximum positions (experimental and tabular) coincide within the error limits. Therefore, the accumulation of events in the vicinity of 0.1 MeV can be explained by the formation of the GS of ^{8}Be nucleus. Earlier, it was noted [8] that the resonance width, which was observed in this experiment, can be driven by a hardware factor. It should also be noted that, with an increase in the number of final particles, the position of the GS maximum becomes shifted toward higher energies, and the level width grows. Perhaps the resonance width magnitude is broadened by the effect of a particle interaction in the final state.

Figure 2, *b* demonstrates the angular distributions of α-particles in the SCM of ^{8}Be nucleus for events at $E_x < 0.25$ MeV. The polar angle β_α is reckoned

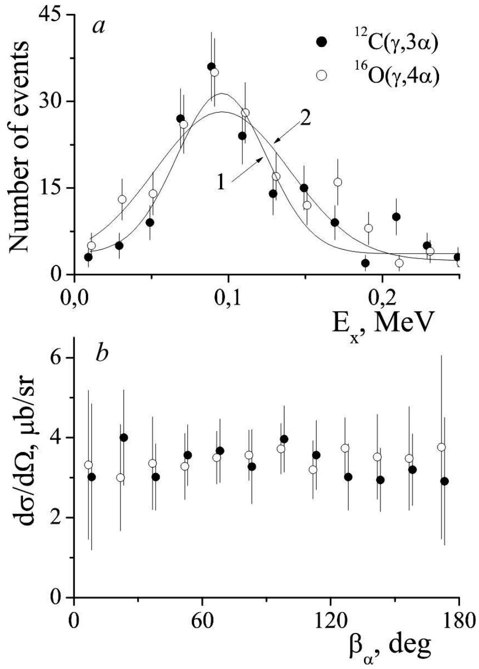

Fig. 2. Energy of the relative motion in the $\alpha\alpha$-system at $E_x < 0.25$ (*a*) and the angular distributions of α-particles in the center-of-mass system of ^{8}Be nucleus in the ground state (*b*)

from the direction of the ^{8}Be nucleus motion. The angular distributions are close to isotropic. This fact means that the orbital moment $l = 0$ and the quantum number $J^\pi = 0^+$, as it has to be in the GS of ^{8}Be nucleus.

It was found that a dominant contribution to this resonance is given by only one of the possible $\alpha\alpha$-combinations. More than one event combination can contribute to this energy region in 1.17% of reaction I or 1.85% of reaction II events. The presence of several combinations manifests itself at low photon energies, and one of the particles in all those combinations is a low-energy α-particle.

Events, in which one of the α-particle pairs corresponds to the formation of the GS of ^{8}Be nucleus, can be reliably distinguished. The further analysis will be carried out only for events of those partial channels. The relative yield of the channel equals 12.2% for reaction I and 25.44% for reaction II, despite that the numbers of events are approximately identical for them (the value at $E_x = 0.1$ MeV in Fig. 1). In the events, for which several combinations are possible in this energy interval, a pair, for which E_x

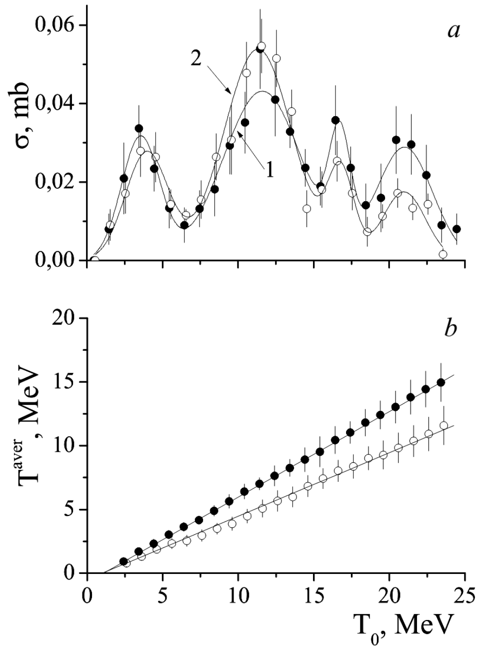

Fig. 3. Dependences of the cross-sections of the ^{8}Be-nucleus ground-state formation channels (*a*) and the average energy of α-particle on the total energy of the final system (*b*)

Parameters of resonances in the cross-sections of the ^{8}Be-nucleus ground-state formation channels

Experiment				Literature data [14]	
Reaction I		Reaction II		^{8}Be-nucleus levels	
T_0, MeV	Γ, MeV	T_0, MeV	Γ, MeV	E_0, MeV	Γ, MeV
3.55 ± 0.22	2.49 ± 0.38	3.96 ± 0.21	2.81 ± 0.34	3.04	1.5
11.61 ± 0.26	$5,14 \pm 0.67$	11.32 ± 0.19	4.51 ± 0.42	11.4	3.5
16.72 ± 0.21	1.33 ± 0.46	16.79 ± 0.22	1.67 ± 0.47	$\sim$16.78	$\sim$0.5
21.01 ± 0.35	3.67 ± 0.68	20.97 ± 0.43	2.82 ± 0.63	>20	$\sim$2.0

was the closest to the value $E_0 = 0.092$ MeV, was taken as the resonance one. It can also be marked that the ratio between the yield values for the channel of the ^{8}Be-nucleus GS formation in reactions I and II (12.2 : 25.44) is proportional to the ratio between the corresponding numbers of the possible α-particle combinations (3 : 6).

4. Partial Cross-Sections of the ^{8}Be-Nucleus Ground-State Formation Channel

In Fig. 3, *a*, the dependences of the partial cross-sections for the channel of the ^{8}Be-nucleus GS formation in reactions I and II on the total kinetic energy of the final system, which was determined as $T_0 = E_\gamma - Q_{\rm I,II}$, where $Q_{\rm I,II}$ are the thresholds of reactions I and II, are plotted by circles with a step of 1 MeV. The symbols are drawn in the middle of the corresponding intervals. In the earlier work [8], the data concerning the partial cross-section for the sum of channels of the ^{8}Be-nucleus GS and the anomaly-ghost (AG) resonance formation were reported. It was found that the AG is a satellite of the GS. It emerges owing to the distortion of the GS excitation function, which rapidly changes near the threshold of the ^{8}Be nucleus decay as a result of the α-particle penetration through the potential barrier. In this work, for the comparison of the partial channels for reaction I to be correct, only the data concerning the GS of ^{8}Be nucleus are presented. The integral cross-sections of the partial channel of the ^{8}Be-nucleus ground-state formation were determined to equal $\sigma_0^{\rm I} = (0.56 \pm 0.04)$ MeV mb for reaction I and $\sigma_0^{\rm II} = (0.51 \pm 0.04)$ MeV mb for reaction II.

There are several maxima in the curve describing the excitation of partial cross-sections. Curves *1* and *2* in Fig. 3, *a* demonstrate the fitting of cross-section data for reactions I and II, respectively, with the help of a linear combination of four Gaussian functions. The fitting parameters were the energy positions of the peaks T_0' and the peak widths Γ's. The results of fitting are quoted in Table: columns 1 and 2 for reaction I, and columns 3 and 4 for reaction II. The positions of the peaks and their widths for both reactions coincide within the error limits.

At the qualitative level, the resonant structure of the partial cross-section can be explained in the framework of the model describing the absorption of a γ-quantum by an α-particle pair. At the first stage, the photon interacts with the virtual quasiberyllium and converts it into the excited state, ^{8}Be*. With the growth of the γ-quantum energy, the channels associated with higher levels of the virtual ^{8}Be* nucleus become open. The parameters of those states manifest themselves in the cross-section of partial channels, $E_\gamma - Q_{\rm I,II} = E_0^*$, where E_0^* is the level maximum value for ^{8}Be nucleus. Columns 5 and 6 in Table contain the parameters for a number of levels of the ^{8}Be nucleus taken from work [14]. The positions of experimental maxima (columns 1 and 3) qualitatively coincide with the literature data (column 5). The experimental peak widths (columns 2 and 4) exceed the widths calculated for the excited states of the virtual ^{8}Be quasinucleus (column 6).

At the second stage, one α-particle first escapes from ^{8}Be* nucleus, whereas the remaining α-particles form an intermediate excited nucleus, which decays later. In the case of reaction I, this is the GS of ^{8}Be nucleus, which we observe experimentally.

From the proposed interaction model, it follows that the energy T of the first escaping α-particle correlates with the total kinetic energy of the system, T_0. In Fig. 3, b, the dependences of the average kinetic energy of the α-particle, $T^{\rm aver}$, on T_0 are plotted. The average energy $T^{\rm aver}$ was calculated for particles in the 1-MeV interval of T_0. In the case of reaction I, the first α-particle was reliably identified, and, in the case of reaction II, the α-particle with a higher energy was selected from two α-particles that did not form the GS of ^{8}Be nucleus.

The dependences $T^{\rm aver}(T_0)$ were fitted by the linear function

$$T^{\rm aver} = a + bT_0,$$

and the corresponding slopes were determined: $b_{\rm I}^{\rm exp} = 0.671 \pm 0.023$ for reaction I (curve *1*) and $b_{\rm II}^{\rm exp} = 0.498 \pm 0.022$ for reaction II (curve *2*). It is worth noting that, in the whole energy interval, the obtained $b_{\rm I}^{\rm exp}$ and $b_{\rm II}^{\rm exp}$ values are larger than the corresponding statistical values, $b_{\rm I}^{\rm stat} = T_0/3$ for reaction I and $b_{\rm II}^{\rm stat} = T_0/4$ for reaction II. However, the ratio $b^{\rm exp}/b^{\rm stat} \approx 2$ is satisfied for both reactions. At the qualitative level, the experimental dependence can be described by the formula $T^{\rm aver} = \frac{M}{A}T_0$, where M and A are the atomic numbers of ^{8}Be and target (^{12}C or ^{16}O) nuclei, respectively.

5. Conclusions

The event distribution over the energy of the relative motion of two α-particles is measured for the reactions ^{12}C(γ,3α) and ^{16}O(γ,4α). It is found that an intermediate excited ^{8}Be nucleus is formed, and the channels of the ^{8}Be-nucleus ground-state formation are extracted. For both reactions, the dependences of the partial cross-sections of the ^{8}Be-nucleus ground-state formation channels on the total kinetic energy of the system are measured. The dependences demonstrate the presence of four maxima, whose positions coincide for both reactions. A correlation between the energy corresponding to the cross-section maximum and the excitation energy E_0 of ^{8}Be nucleus is revealed: $E_\gamma - Q_{\rm I,II} = E_0$, where $Q_{\rm I,II}$ are the threshold values for reactions I and II. The results obtained are qualitatively explained in the framework of the model describing the absorption of a γ-quantum by a virtual α-particle pair.

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ЕНЕРГЕТИЧНІ КОРЕЛЯЦІЇ α-ЧАСТИНОК В КАНАЛІ УТВОРЕННЯ ОСНОВНОГО СТАНУ ЯДРА ^{8}Be РЕАКЦІЙ ^{12}C(γ,3α) І ^{16}O(γ,4α)

Р е з ю м е

Методом дифузійної камери в магнітному полі на пучці гальмівних фотонів з $E_\gamma^{\max} = 150$ МеВ, досліджено реакції ^{12}C(γ,3α) і ^{16}O(γ,4α). У розподілі подій за енергією відносного руху двох α-частинок для обох реакцій виявлено резонанс, ідентифікований як основний стан ядра ^{8}Be. Виміряно парціальні перетини каналів його утворення й показано, що реалізується механізм взаємодії γ-кванта з віртуальною α-частинковою парою.