TOTAL AND PARTIAL CROSS SECTIONS OF THE $^{12}C(\gamma,3\alpha)$ REACTION

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The total cross-section of the $^{12}C(\gamma,3\alpha)$ reaction in the energy range from the threshold to 40 MeV has been measured by the method using a diffusion chamber. It has been established that the two-stage mechanism is dominant: first, α-particles and a ^{8}Be nucleus are formed, then the latter disintegrates into two α-particles. Partial cross-sections of channels of forming excited states of ^{8}Be were measured.

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1. INTRODUCTION

The results of photodisintegration of a carbon nucleus into three alpha particles are interesting for the studies of the mechanism of interaction of the electromagnetic radiation with nucleus and for checking of nucleus models. Ascertained data on the $^{12}C(\gamma,3\alpha)$ reaction at low energies are useful to astrophysics for construction of evolutionism of stars.

At energies up to 40 MeV the process of ^{12}C nucleus photodisintegration into three α particles can proceed via two mechanisms: immediate disintegration into three interactive α particles and two-stage disintegration with formation of intermediate ^{8}Be nucleus and subsequent its disintegration into two α-particles.

Up to the present the certain choice between them is not done: in work [1] a satisfactory agreement with the experiment in the model of immediate disintegration was obtained, while in [2] it was necessary to involve the second mechanism.

Previously, the experimental study of the $^{12}C(\gamma,3\alpha)$ reaction was carried out more than once on monochromatic beams from inverse reactions and radioactive sources, as well as, on the bremsstrahlung beams from the electron accelerators, but only by the method of nuclear photoemulsions [3-10]. There is a considerable disagreement in data on the reaction total cross-section.

Therefore it is useful to investigate the reactions by the other method. The experiment with a diffusion chamber offers some advantages: practically clean target, low threshold of α-particle registration due to the low density of the target, magnetic field and ionization losses will allow to identify more reliable the reaction products.

Recently one accumulated and systematized the extensive information on low-lying excited states of ^{8}Be nucleus [11] disintegrating into two α-particles. Because of an insufficient energy resolution and low statistic substantiation, in this experiment we do not state a problem to define more exactly the parameters of ^{8}Be excited states, but and now this problem is under investigation [12]. The resonances observed in the αα-frame are identified with the known states of ^{8}Be nucleus, and, for the first time, the cross-sections of channels of formation of these states are measured.

Preliminary results on the total cross-section and photoproduction of a ground state of ^{8}Be nucleus were reported earlier [13-14].

2. EXPERIMENTAL METHOD

The experiment was performed using the diffusion chamber placed in the magnetic field having the strength of 1.5 T. The chamber was irradiated with bremsstrahlung γ-quanta from the electron accelerator LUE-300 with a maximum energy of 150 MeV. To decrease the target density the chamber was filled with a mixture of methane and helium in the proportion 1:7 up to the pressure of 1.5 ata.

Thus it was possible to have lengths of tracks of slow residual nuclei acceptable for measurements and sufficient sharpness of their images on the photographic film at pressures near to the atmospheric one. Owing to the combination of a 4π-detector with a target of a low density the experimental method made it possible to investigate the $^{12}C(\gamma,3\alpha)$ reaction practically from its threshold. A soft component of the bremsstrahlung spectrum has been removed by means of the beryllium filter of a thickness 2.5 rad. units. The spectral distribution of photons was taken as the Schiff distribution one corrected for a uniform spectrum attenuation by the filter.

For the treatment three-ray events were selected whose tracks are near to the coplanarity and belong to two-charge particles. As a result of measurements, one can expect for them the obtaining of a transverse momentum balance.

The main background is expected from the $^{12}C(\gamma,n)^{3}He2\alpha$ reaction, since the experimental method does not separate ^{3}He and ^{4}He. The yield of this reaction is higher by a factor of 2.5 than in the reaction under study. In the lab system the tracks of particles of the $^{12}C(\gamma,n)^{3}He2\alpha$ reaction, as a rule, are far from the coplanarity. Therefore, these events, in main, are separated in the process of visual selection.

The events of the reaction under study also are imitated by the $^{4}He(\gamma,n)^{3}He$ process with subsequent scattering of ^{3}He on ^{4}He. In this process three rays are always coplanar, but vertex of an event is not always in the beam zone.

The final identification of events was performed after measurements on the base of the momentum balance. We counted only the event whose unbalance did not exceed 12 MeV/c. The estimated background from the $^{12}C(\gamma,n)^3He2\alpha$ reaction was equal to 2.6 %. The $^4He(\gamma,n)^3He$ reaction did not make the contribution.

The experimental procedure does not permit to determine with a certain accuracy the kinematic parameters of particles not stopped in the working volume of the chamber, which went out at an angle less than 50° in the direction of the magnetic field strength. For the events, nontreated because of this, a geometrical correction was done. It is calculated under the assumption of azimuthal symmetry, as the γ-quanta beam is not polarized.

For identification of ^8Be state a kinematic model of the reaction is developed. It is based on the literature data on the maximum position and resonance width [11] and corresponding suppositions about angular distributions of both the α-particle, the first leaving the ^{12}C nucleus in the system of reaction center, and the α-particles in the ^8Be rest system. In the model the error of momentum measurement and restrictions by the angle between the particle momentum and the magnetic field vector are taken into account.

At energies near the threshold all particles stop in the working volume of the chamber, but in the range of 30…40 MeV, as a rule, they do not stop. Therefore, the measurement accuracy decreases from 5.3 MeV to 10 MeV.

3. EXPERIMENTAL RESULTS

3.1. The total cross-section

The total cross-section of the $^{12}C(\gamma,3\alpha)$ reaction in the energy interval from the reaction threshold up to 40 MeV is presented in Fig. 1(a). The errors are statistic. The integral cross-section equals to 5.58± 0.16 MeV mbn.

In the curve of carbon excitation two maxima are observed. The first one is at E_γ=17.17±0.12 MeV with a half-width 2.65±0.14 MeV, and the second one – at E_γ =27.12±0.34 MeV with a half-width 4.56±0.14 MeV.

For comparison the results of earlier works [4,5,9] are presented in Fig. 1(a) and Fig. 1(b). It should be noted that the structure of curves is similar: two maxima are observing, the position of one of them differs insignificantly. At the same time, the difference in the cross-section value is noticeable. In the near-threshold area the transverse cross-section, obtained in the given experiment, exceed the results of all the previously performed measurements.

Because of the high target density in the emulsion method the losses of low-energy α-particles are possible. In the event distribution by the kinetic energy of α-particles about 30 % of events have, at least, one α-particle with a kinetic energy less than 1 MeV. In the cited papers [3-10] the threshold of α-particle registration by the kinetic energy is not given and the possible losses, caused by it, are not discussed. At the same time, there is information that the threshold value takes place within the range from 0.3 to 1.0 MeV. In Fig. 1(b) the points present the total cross-section for the case when excluded are the events which have, at least, one α-particle of an energy less than 1.0 MeV. It is seen that an accord with the results of [4,5] at E_γ<20 MeV is better.

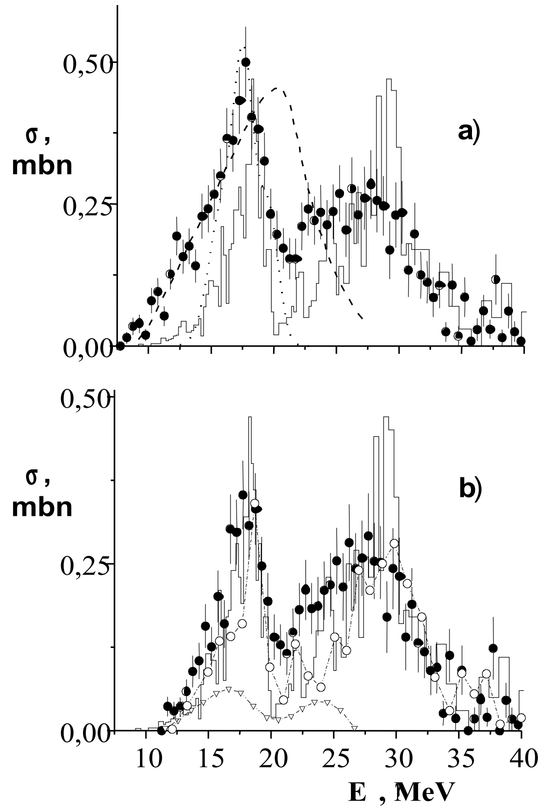

Fig. 1. The total cross-section for the $^{12}C(\gamma,3\alpha)$ reaction, histogram - [4], • – present data: a) dash dot line - [1], dot line - explanation in the text; b) o - [5], ∇ - [9].

Below, it will be clear that the minimum at energies in the range of 20…22 MeV coincides with the boundary of finishing the formation of the first and starting the formation of the second excited states of ^8Be nuclei. The second state has the excitation energy of 11.4 MeV and the resonance half-width of 3.5 MeV. Therefore, its formation can be accompanied by the low-energy third α-particle. The loss of these events qualitatively explains the relative deepening of the dip in Fig. 1(b) in this energy region.

At energies from 12 to 20 MeV the ^{12}C nuclei has three wide levels [15]. The position of the first resonance maximum in the curve of ^{12}C nucleus excitation coincides, within limits of errors, with the level of E_0=17.23 MeV and Γ=1.15 MeV. But they cannot be identified, as the resonance half-width exceeds, by a factor of 2.3, the half-width of the level. The resonance can obtain the contribution from the two wide level of E_0=15.44 MeV, Γ=1.5 MeV and E_0=19.2 MeV, Γ=1.1 MeV. The superposition of three levels in the proportion 1:2:1 is shown the doted line in Fig. 1(a). Insufficient statistic accuracy does not permit to separate the levels.

The dashed line in Fig. 1(a) shows the calculation [1] of the total reaction cross-section in the model when the nucleus composed of three α-particles disintegrate immediately into three particles if the γ-quantum interacts with one of them. The predicted cross-section is close by the value to the experimental one, but the position of the resonance maximum does not coincide.

3.2. Analysis of the in-pair relative energy distribution

The in-pair relative energy of two α-particles was determined as:

$$W_{ik} = (p_i - p_k)^2 / 4m \quad (1)$$

where *i*,*k*,*m* are the numbers and the mass of α-particles, respectively. It is not possible to select from three pairs of α-particles of every event a pair that was produced as a result of ^{8}Be disintegration. Therefore, for the distribution of the in-pair relative energy of two α-particles, three values of W_{ik} for every event are plotted in Fig. 2.

In the curve of αα-system excitation, shown in Fig. 2(a) with a step of 20 keV in the range $0 \le W_{ik} \le 0.25$ MeV the resonance is revealed. The solid line presents the phase distribution calculated by formula of [16]:

$$f(W_{ik}) = W_{ik}^{1/2} \cdot (W_{max} - W_{ik})^{1/2}, \quad (2)$$

where W_{max} is the maximally possible value of the ^{8}Be excitation energy, equal to the maximum energy of the γ-quanta in the given interval minus the reaction threshold. The phase distribution is calculated for the bremsstrahlung beam with a maximum energy of 32 MeV. The fitting of experimental data of the Brait-Weigner curve gave, as a result, E_0=0.089±0.004 MeV, Γ=0.056±0.003 MeV. It is known [17] that in the case of the ^{8}Be ground state disintegration into two α-particle there takes place a resonance with a maximum at E_0=0.092 MeV and the half-width Γ=6.8±1.7 eV. The positions of maxima are in good agreement. Therefore, it can be assumed that the resonance is the result ^{8}Be nuclei ground state production. The half-width observed in the experiment is the apparatus value, and it is the measurement error for the in-pair relative energy of two α-particles W_{ik}.

The dash-dot line in Fig. 2(a) shows the distribution obtained by the mathematic simulation under supposition of isotropic angular distributions in the ^{8}Be rest system. The angular distributions in the system of the α-particle and ^{8}Be center are taken from the preliminary experiment [14]. The agreement with the experiment evidences on the model correctness. The events with production of the ground state of the ^{8}Be nucleus were not used for construction of the following distributions on W_{ik}.

In the distribution of all other events on W_{ik}, distinct resonances are not observed. The ^{8}Be excited states were observed in the limited γ-quanta energy intervals.

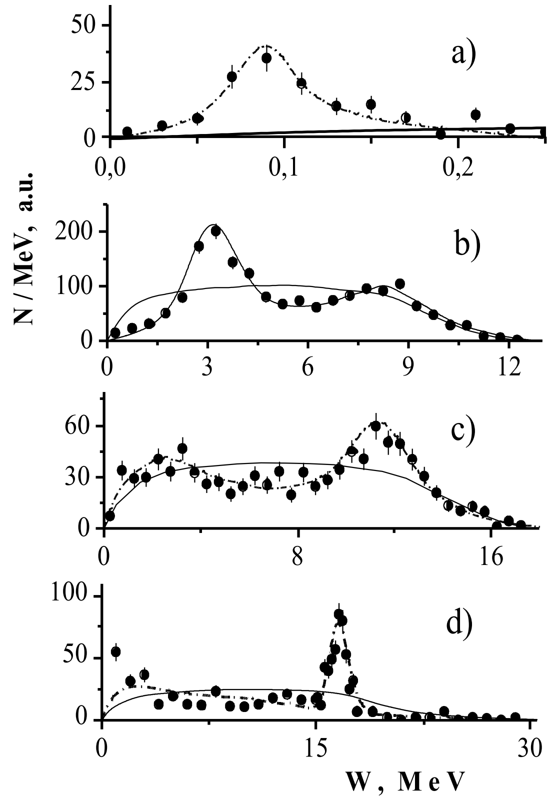

Fig. 2. *The in-pair relaive energy of two α-particles distribution. Point - the present experiment, full line – the phase distribution, dash-dot line – the model. a) the ground state of ^{8}Be, b) the first excitation state of ^{8}Be, c) the second excitation state of ^{8}Be, d) the superposition of third and fourth excited states of ^{8}Be*

Fig. 2(b) presents the distribution on W_{ik} in the γ-quantum energy range from 16 to 20 MeV, as it was found that the first excitation of the ^{8}Be state is producesd only in the region of the first maximum in the curve of Fig. 1. The solid line is the curve of the phase distribution. In the experiment two maximum are observed. The first one has the parameters E_0=3.12±0.04 MeV, Γ=1.89±0.07 MeV, and the second one E_0=8.13±0.12 MeV, Γ=4.17±0.24 MeV. The dashed curve shows the results of mathematical simulation with the parameters of the first excited state of ^{8}Be [11]. The simulation result is not sensitive to the form of angular distributions of ^{8}Be in the reaction center system. The better agreement with the experiment is obtained for the case when the angular distributions of α-particles in the ^{8}Be rest system are taken in the form $d\sigma/d\Omega \sim (1+\sin^2\theta \cos^2\theta)$. The curves are normalized for the area under the experimental curve. The agreement of the mathematical model with the experiment makes it possible to identify the first resonance with the first excited state of ^{8}Be. The second resonance is the background one. It becomes apparent in the system of the α-particle, the first leaving the ^{12}C nucleus, and the ^{8}Be fission product. The events, referred to the first excited state of ^{8}Be, were excluded from the further analysis.

Distribution of other events by the in-pair relative energy of two α-particles reveals the maximum in the region of 17 MeV. Distribution of events, one W_{ik} value of which lies in the range from 15.0 to 18.0 MeV, is presented in Fig. 2(d). The solid line shows the phase distribution for gamma-quantum energy from 25 to 40 MeV. It is known [11] that the ^{8}Be nuclei has two narrow nearly-lying excited states with parameters E_0=16.6 MeV, Γ=0.1 MeV and E_0=16.9 MeV, Γ=0.07 MeV. Simulation is performed for equiprobable production of these states. The better agreement with the experiment is obtained for the case when the angular distributions of α-particles in the ^{8}Be rest system were taken in the form $d\sigma/d\Omega \sim (4-3\sin^2\theta)$. The simulation results practically do not depend on the form of ^{8}Be angular distributions in the reaction center system. The measurement error of the momentum δP=5.3 MeV/c was found from the analysis of event distribution by the momentum unbalance in the given energy range. The events referred to the third and fourth excited states of ^{8}Be were excluded from the further analysis.

Fig. 2(c) presents the event distribution in the energy range from 20 to 25 MeV. The difference with the phase distribution is visible. In the experiment observable are two maximum with parameters E_0=1.23±0.36 MeV, Γ=1.51±0.37 MeV and E_0=10.86±0.21 MeV, Γ=2.91±0.23 MeV. Simulation is performed for the resonance with parameters E_0=11.4 MeV and Γ=3.5 MeV [11]. The better agreement with the experiment is obtained for the case when the angular distributions of α-particles in the ^{8}Be rest system were taken in the form $d\sigma/d\Omega \sim (1-2\sin^2\theta+2\sin^2\theta\cos^2\theta)$. The simulation results practically do not depend on the form of ^{8}Be angular distributions in the reaction center system. The agreement of the mathematical model with the experiment permits to identify the second resonance with the second excited state of ^{8}Be. The maximum at E_0=1.23±0.36 MeV is the background resonance in the system of two α-particles leaving the nucleus at different time.

3.3. Partial cross-sections

To determine the probability of formation of ^{8}Be states the event distributions by the energy of relative motion of two α-particles in the narrow energy intervals of γ-quanta were plotted. It has been found that the ground state is produced at energies from 8 to 32 MeV. The total cross-section of the ground state of ^{8}Be is shown in Fig. 3(a) in comparison with the result of [7]. The integral cross-section equals to 0.501±0.044 MeV mbn.

At energies up to 20 MeV the main contribution is obtained from the channel of formation of the ^{8}Be first excited state. In Fig. 2(b) is seen that the model describes rather well the experimental points at 9≤W_{ik}≤12 MeV and there is no appreciable contribution from the second excited state. The total cross-section of the channel of formation of the ^{8}Be first excited state is obtained as a difference of the total cross-section of the reaction (Fig. 1(a)) and the total cross-section of ground state formation (Fig.3 (a)) and that is shown in Fig.3 (b) in comparison with the results of [6,7]. A possible cause of the significant disagreement was discussed above. The integral cross-section of this reaction channel σ_{int}=2.240±0.094 MeV mbn.

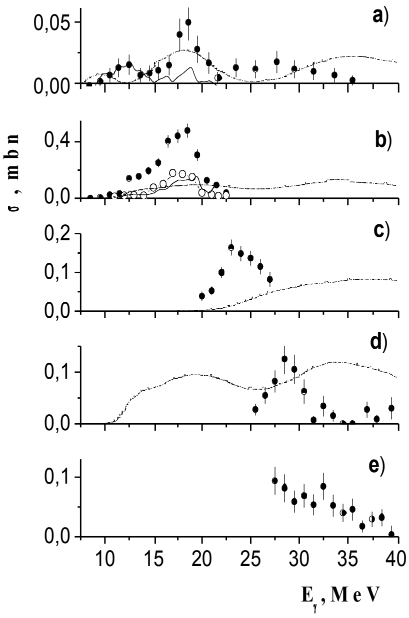

Fig. 3. *The partial cross-section for the $^{12}C(\gamma,3\alpha)$ reaction by mode of breakup: a) via the ground state of ^{8}Be, b) via the first excitation state of ^{8}Be, c) via the second excitation state of ^{8}Be, d) via the superposition of third and fourth excited states of ^{8}Be, e) uncertain events. • –present data, full line - [7], o - [6], dash line - [2].*

In the energy range from 20 to 27 MeV after deduction of events relating to the nonseparated third and fourth excited states, the W_{ik} distributions do not reveal other resonances except the second excited state. The total cross-section of second excited state formation is shown in Fig. 3(c). The integral cross-section σ_{int}=1.273±0.081 MeV mbn. The earlier cross-section of this reaction channel was not measured.

The total cross-section of formation of nonseparated third and fourth excited states is shown in Fig. 3(d). The integral cross-section σ_{int}=0.629±0.068 MeV mbn.

At E_γ>27 MeV remained still 140 events which cannot be referred to any of above-mentioned excited states. These events are either the products of immediate ^{12}C disintegration into 3α or the products of the subsequent reaction with formation of higher excited states. The cross-section of formation of these events is shown in Fig. 3(e). The integral cross section σ_{int}=0.937±0.082 MeV mbn.

The normalized (for experiment) calculation [2] of the cross-section of the partial channel of ^{8}Be 0^+ state formation in the model of immediate α-particle release is shown in Fig. 3(a). The position of the maximum near 18 MeV is predicted satisfactory, while the other two are shifted in comparison with the experiment.

The normalized calculation [2] of the cross-section of the partial channel of the ^{8}Be 2^+ state formation is shown in Fig. 3(b) and Fig. 3(d). From Fig. 3(b) one can see that the first maximum of the curve coincides with the experiment. However, the value is less by a factor of ~ 5 and in the experiment the second maximum is not observed. The calculation [2] in Fig. 3(d) is not in accordance with the experiment.

The normalized calculation of the cross-section of the partial channel of the 4^+ state formation is shown in Fig. 2(c). It is not in accordance with the experiment.

4. CONCLUSIONS

The total cross-section of the $^{12}C(\gamma,3\alpha)$ reaction is measured in the energy interval from the reaction threshold to 40 MeV. Appreciable difference between the results obtained by the emulsion method, particularly in the range of lower energies, was observed. The differences can be explained by the loss of low-energy α-particles in emulsions.

In the in-pair relative energy of two α-particles a contribution from the ground state, of the first, second, and non-separated third and fourth excited states of ^8Be was observed. The partial cross-sections of channels of production of these states were measured. The ground sate is produced at energies ranging from the reaction threshold to 32 MeV. The first excited state makes a contribution in the interval of γ-quantum energy from 12 to 22 MeV, the second in the interval from 20 to 27 MeV. At higher energies the superposition of non-separated third and fourth excited states of ^8Be is prevailing. The two-stage mechanism is dominant: first, α-particles and ^8Be nucleus are formed, then the latter disintegrates into two α particles. Calculations in the model of both the gradual-type disintegration and the immediate disintegration, when the wave function of the nucleus is constructed in the shell model or in the α-cluster model, are not in agreement with the experimental results.

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ПОЛНОЕ И ПАРЦИАЛЬНЫЕ СЕЧЕНИЯ РЕАКЦИИ $^{12}C(\gamma,3\alpha)$

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Методом диффузионной камеры в магнитном поле измерено полное сечение реакции $^{12}C(\gamma,3\alpha)$ в энергетическом интервале от порога до 40 МэВ. Установлено, что основным является двухступенчатый механизм: сначала образуются α-частица и ядро ^8Be, которое потом распадается на две α-частицы. Измерены парциальные сечения каналов образования возбужденных состояний ядра ^8Be.

ПОВНИЙ І ПАРЦІАЛЬНІ ПЕРЕТИНИ РЕАКЦІЇ $^{12}C(\gamma,3\alpha)$

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Методом дифузійної камери в магнітному полі обмірен повний перетин реакції $^{12}C(\gamma,3\alpha)$ в єнергетичному інтервалі від порога до 40 МеВ. Встановлено, що основним є двохступеневий механізм: спочатку утворяться α-частка і ядро ^{8}Be, яке потім розпадається на дві α-частки. Обмірено парціальні перетини каналів утворення збуджених станів ядра ^{8}Be.