https://doi.org/10.46813/2024-151-023

INVESTIGATION OF THE PARTIAL CHANNEL OF ^{8}Be NUCLEUS GROUND STATE FORMATION IN THE ^{14}N(γ,2α^{6}Li) REACTION

S.N. Afanasiev[1,]*, I.O. Afanasieva[2]

[1]NSC "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine;

[2]V.N. Karazin Kharkiv National University, Kharkiv, Ukraine

****E-mail: afanserg@kipt.kharkov.ua***

Using the track 4π-detector method (a diffusion chamber arranged in a magnetic field on the way of a beam of bremsstrahlung photons with the final energy E_γ^{max} = 150 MeV), the reaction ^{14}N(γ,2α^{6}Li) has been studied. The distributions of events over the excitation energy of 2α-particles were analyzed and a channel of the formation of the ^{8}Be nucleus in the ground state was revealed and has been separated. Events in which the α-particle pairs correspond to the formation of the ^{8}Be nucleus in the ground state can be reliably identified. The energy and angular distributions of α particles at each stage of decay are analyzed.

PACS: 25.20.-x

INTRODUCTION

The study of multiparticle photoreactions is of particular interest for studying the properties of virtual cluster structures in nuclei [1], their influence on the mechanism of nuclear reactions and on the dynamics of nucleosynthesis in the Universe [2]. The ^{14}N nucleus can be considered as an intermediate one between the ^{12}C and ^{16}O nuclei, which are considered as 3α- and 4α-cluster structures in the cluster model. Recently, the theory of cluster photofission of light nuclei within the nucleon association model has made significant progress [3].

In treating excited states of the nucleus within the triangle-diagram technique [4], we can single out the following stages of the reaction: a virtual decay of the nucleus to the cluster and the core; photon absorption by the cluster or the core; and cluster scattering on the core, whereby the core goes over to the ground state. In the simple cluster model, an atomic nucleus is assumed to consist of two structure-less fragments whose properties coincide or are close to those of the corresponding nuclei in the free state. The two-cluster model assumes the presence of only two separate fragments – clusters, between which all the nucleons of the nucleus are redistributed. The photon does not enter into strong nuclear interactions with the target nucleus, but only electromagnetic interactions with the cluster structure, whose operators are known exactly. Therefore, we can take into account only the nuclear interactions of related clusters, which greatly simplifies the consideration compared to the three-dimensional problem, when, along with inter-cluster forces, we must take into account the nuclear interaction of the incoming particle.

In this article, we present results obtained by studying the photodisintegration of nitrogen nuclei via the reaction ^{14}N(γ,2α^{6}Li), which will provide new information on the evolution of a complex cluster structure beyond α-clustering.

This report is a continuation of work [5], which published the results of the study of this reaction. Earlier it was reported [6] about the creation of a digital bank of stereo photographs obtained by photographing the working area of a 4π detector (diffusion camera in a magnetic field). The diffusion chamber [17] was placed in a magnetic field and was exposed to bremsstrahlung photons at an endpoint energy 150 MeV.

With the aim of reducing the target density, the chamber was filled with a mixture of helium and working gas (methane, nitrogen, oxygen). This made it possible to obtain, for slow final nuclei, track lengths acceptable for measurements and sufficiently high sharpness of their image at pressures close to atmospheric pressure. Owing to combining a 4π-detector and a low-density target in one device, we were able to study the reaction ^{14}N(γ,2α^{6}Li) nearly from its threshold.

The measurement error of the particle impulse depends on its size and track length, and ranges from 3 to 10%. The energy of stopped particles was determined by the range–energy relationship. We evaluated the range in the mixture with allowance for the ion charge exchange in the medium, employing tabulated data from for several target components.

In [5], a technique for digital track reconstruction was presented using the example of the ^{14}N(γ,2α^{6}Li) reaction.

For a further treatment, we selected three-prong stars whose tracks were coplanar and were associated with multicharged particles. The chamber used operated in a mode that made it possible to separate of differently charged particles visually and to compare the ionization density and the width of a track after measuring its radius of curvature. To obtain the physical parameters of events, a graphical application with the ability to automatically measure the coordinates of points along tracks on digital photographs was created in the Python programming language. The main procedure is to analyze the intensity of pixels in the track area along a circular trajectory of a certain radius.

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 $\Delta_x = \Sigma P_x^i - E_\gamma$, $\Delta_y = \Sigma P_y^i$, and $\Delta_z = \Sigma P_z^i$, 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 the 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.

1. EXTRACTION OF THE ^{8}Be NUCLEUS GROUND-STATE FORMATION CHANNEL

The excitation energy of a pair of particles was determined as

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

where $M^{ef}(^8Be)$ is the effective mass equal to the total energy of a pair of α-particles in their resting state, and m_α is the mass of the particle. In Fig. 1,a, the histogram is shown the distribution according to $E_x(\alpha\alpha)$, the histogramming step was 0.25 MeV.

The experimental distributions were compared with the phase ones [7]:

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

where n is the number of final particles, k the number of particles formed in the excited state ($k < n$), and E^{max}_x the end-point excitation energy of the system of k particles. In the case concerned, $n = 3$ 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.

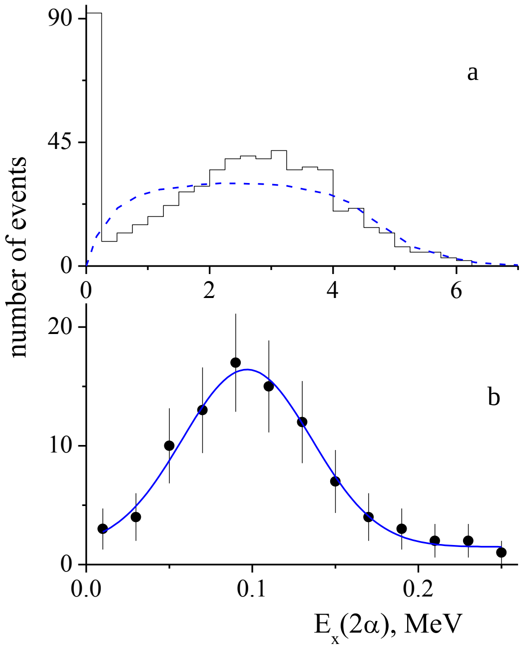

Fig. 1. Distribution of events with respect to the excitation energy of a pair of particles (a), the GS of the ^{8}Be nucleus (b)

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 the ^{14}N(γ,2α^{6}Li) reaction.

The resonance is obtained at the excitation energy of a pair of particles varying from 0 to 0.25 MeV (see Fig. 1,a) is shown in Fig. 1,b by solid circles placed at the midpoint of a step with a step of 20 keV. The displayed errors are purely statistical.

The obtained peak was fitted to the Gaussian distribution with the maximum position at E_0 = (0.096 ± 0.005) MeV and the halfheight width Γ = (0.064 ± 0.01) MeV. It is known from the data of spectrometric measurements [8] that the ground state (GS) of the ^{8}Be nucleus has the following parameters: E_0 = 0.092 MeV, Γ = 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. Due to the insufficient energy resolution and low statistical power, this experiment did not attempt to refine the GS parameters. The width observed in this experiment is hardware widths. The events (N^{GS}) in which a pair of α-particles correspond to the formation GS of the ^{8}Be nucleus are reliably identified. The relative yield of this partial channel is η=14.98% (η = N^{GS}/N, where N is the total number of reaction events).

Earlier, in [9], we also identified partial channels for the formation GS of the ^{8}Be nucleus in the reactions of ^{12}C(γ,3α) and ^{16}O(γ,4α).

The Table in column 2 shows the position of the maximum corresponding to the GS of the ^{8}Be nucleus for comparison. Within the error limits, the value for all three reactions (column 1) coincides, but it should be noted that the value shifts upward with the increasing atomic number of the target nucleus. A more obvious picture is seen in the quantitative dependence – column 3 shows the relative yields (η) of the GS of the ^{8}Be nucleus formation channel for these reactions.

The channel of formation of the GS of the ^{8}Be nucleus

Channel	$E_0(^8Be)$, MeV	η, %	T_0, MeV
^{12}C(γ,3α)	0.089 ± 0.004	12.20	3.55±0.22
^{14}N(γ,2α^{6}Li)	0.092 ± 0.004	14.98	3.59±0.25
^{16}O(γ,4α)	0.095 ± 0.005	25.44	3.96±0.21

In Fig. 2,a, the histogram shows the dependence of the number of events on the γ-quantum energy in the ^{14}N(γ,^{6}Li)^{8}Be$_0$ reaction with a step of 0.5 MeV in E_γ.

A structure is observed in the distribution. The solid line shows the fitting of the intersection by a combination of 2 Gaussian functions (dashed lines), which resulted in the determination of the energies of the position of the maxima and their widths – E_γ^1 = (19.66 ± 0.25), Γ^1 = (1.25 ± 0.29) MeV and E_γ^2 = (22.75 ± 0.42), Γ^1 = (2.79 ± 0.51) MeV.

Earlier, in [9], the partial cross sections of the channels the formation GS of the ^{8}Be nucleus in the ^{12}C(γ,3α) and ^{16}O(γ,4α) reactions were also presented. If we move from the energy of γ-quanta to the total energy of the system $T_0 = E_\gamma - Q$, where Q is the reaction threshold, we can compare the positions of the maxima of each reaction (for the $^{12}C(\gamma,3\alpha)$ reaction – Q = 7.28 MeV, for the $^{14}N(\gamma,2\alpha^6Li)$ reaction – Q = 16.07 MeV and for the $^{6}O(\gamma,4\alpha)$ reaction – Q = 14.44 MeV). The results for the first maximum (see Fig. 2,a) are given in the table in column 4. It can be seen that the values of T_0 coincide with the error.

Fig. 2,b shows the dependence of the relative yield of the GS of ^{8}Be nucleus η for three intervals at T_0. The boundaries of the intervals were chosen so that the number of events in the intervals was approximately the same. In the figure, the dependence for the $^{12}C(\gamma,\alpha)^8Be_0$, reaction is represented by squares, for the $^{14}N(\gamma,^6Li)^8Be_0$ reaction by circles, and for the $^{16}O(\gamma,2\alpha)^8Be_0$ reaction by triangles. For all three reactions, a decrease in the contribution of the GS of ^{8}Be nucleus is observed with increasing T_0. In addition, a sharp (almost 2-fold for all reactions) decrease in the contribution after the first maximum can be noted (see Table, column 4).

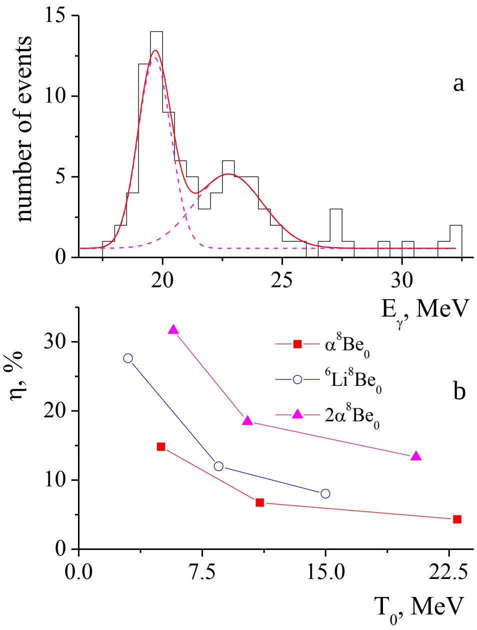

Fig. 2. the dependence of the number of events on the γ-quantum energy for the GS of ^{8}Be nucleus in the $^{14}N(\gamma,2\alpha^6Li)$ reaction (a), the dependence of the relative yield (η) of the GS of ^{8}Be nucleus to the total energy of the system T_0 (b)

Earlier, in the $^{12}C(\gamma,3\alpha)$ and $^{16}O(\gamma,4\alpha)$ reactions, the resonance structure of the partial cross section was qualitatively 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 $^8Be^*$. The position of the first maximum (see column 4 in the Table) is close to the value of the first excited state of the nucleus ^{8}Be – E_0 = 3.04 MeB [8]. At the second stage, one α-particle first escapes from $^8Be^*$ nucleus, whereas the remaining α-particles forms an intermediate excited nucleus, which decays later. In the case of the $^{12}C(\gamma,3\alpha)$ and $^{16}O(\gamma,4\alpha)$ reactions, this is the GS of ^{8}Be nucleus, which we observed experimentally.

But in the studied reaction ($^{14}N(\gamma,2\alpha^6Li)$), it is not possible to form a virtual αα-pair, because we see the formation of the GS of ^{8}Be nucleus at the final stage. If we proceed from the cluster model of the nucleus as a system – the cluster and the core, then the scheme $\alpha+^{10}B$ and the interaction of the γ quantum with the ^{10}B nucleus is possible. The excited level of the ^{10}B nucleus is calculated as $E_0^{exp} = E_\gamma - Q_{\alpha+10B}$ and is equal to 8.054 MeV. From the spectrometric measurements [8], it is known that there is a ^{10}B nucleus level with E_0 = 7.96 MeV, G = 0.285 eV, which decays into $\alpha+^6Li$, which coincides with E_0^{exp}.

2. ENERGY AND ANGULAR DISTRIBUTIONS OF PARTICLES IN THE CHANNEL $^{14}N(\gamma,^6Li)^8Be_0$

Sequential two-particle decay allows us to determine the energy and angular distributions at each stage of decay.

In Fig. 3,a, solid circles are used to exhibit the dependence of the number of events on the escape angle of the GS of ^{8}Be nucleus, Θ(^{8}Be), in the center of the mass coordinate frame for the reaction in whole. After, the circles are drawn in the middle of the histogram steps, and vertical bars mark statistical errors. The quantization axis in the reaction system was directed along the *O* axis. The figure demonstrates that the GS of ^{8}Be nucleus yield is symmetric about 90^0 and looks similar to $\sin^2\Theta\cos^2\Theta$.

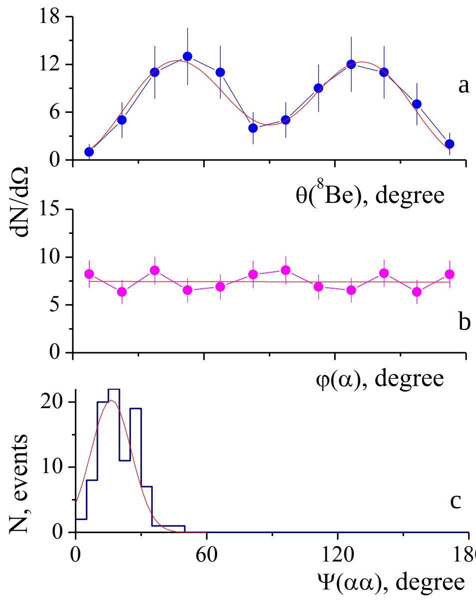

Fig. 3. Event distribution over the escape angle of the GS of the ^{8}Be nucleus (a), angular distributions of α-particles in the system of the center of mas of the ^{8}Be nucleus (b), dependence of the angle of separation of two α-particles (c)

We performed the Legendre polynomial fit:

$$f(\Theta) = a*f_1 + b*f_2 + c*f_3 + d*f_3, \quad (3)$$

where a, b, c, d are coefficients containing information about the reaction mechanism and wave functions of the nuclei, and $f_1 = \sin^2\Theta$, $f_2 = \sin^2\Theta\cos\Theta$, $f_3 = \sin^2\Theta\cos^2\Theta$, f_4 =1. In the figure, the solid curve represents the function f(Θ) з a = 3.84 ± 0.87, b = 0.23 ± 1.98, c = 39.29 ± 4.35, d = 0.46 ± 0.55. For the parameters b and d, the values and errors of their measurements are close and their contribution to the fit is insignificant. The main contribution is given by the parameter c. The data obtained allows us to estimate the multipole amplitudes of the photoprocess in the future, since for this two-particle process we know the spin-parity of the particles – 1^+ for ^{6}Li and 0^+ for ^{8}Be.

In Fig. 3,b, the solid circles represent the angular distributions of α-particles in the system of the center of mass of the ^{8}Be nucleus. The polar angle φ(α) is reckoned from the direction of the ^{8}Be nucleus motion. The angular distributions are isotropic (solid line in Fig. 3,b is a fit with a linear function with a slope of –0.004 ± 0.012). This means that the orbital momentum l=0. It follows that the quantum numbers $J^\pi=0^+$, is in the GS of ^{8}Be nucleus.

In Fig. 3,c, the histogram shows the distribution of the number of events as a function of the angle of departure (Ψ) of the α-particle pair. Fitting with the Gaussian function gave the values of the maximum and width at the half-height – Ψ_0 = (16.28 ± 0.71)° and Γ(Ψ) = (18.71 ± 1.52)°.

The relative energies of α-particles were determined as the ratio

$$\varepsilon_i = T_{id}/T_0, \quad (4)$$

where T_0 is the sum of the kinetic energies (T) of the final particles, and id is the particle identifier.

To test the possible mechanisms of interaction of the γ quantum with the nucleus, the particles forming in the GS of ^{8}Be nucleus were sorted by energy for each event as $T_\alpha^{max} > T_\alpha^{min}$.

Fig. 4,a demonstrates the distribution of the number of events over the relative energy ε for the α-particles (squares (ε_α^{min}) and circles (ε_α^{max})) and ^{6}Li (asterisks). The distributions were fitted with the Gaussian function and the values of the corresponding maxima were obtained – ε_α^{min} = 0.17 ± 0.03, ε_α^{max} = 0.25 ± 0.03, ε_{6Li} = 0.55 ± 0.02. The slight deviation between α^{min} and α^{max}, taking into account the small value of the angle of separation between α-particles (see Fig. 3,c), explains the formation of a narrow near-threshold state (see Fig. 1,b). The value of ε_{6Li} can be explained within the framework of the two-particle process (^{14}N(γ,^{6}Li)^{8}Be$_0$), where ε_{6Li} takes 8/14 T_0 ~ 0.57 T_0.

Details of the mechanisms of the channel of formation of the GS of the ^{8}Be nucleus can be studied with the help of the symmetric Dalitz plot. This technique is particularly suitable for the geometric visualization of the decay into three particles with identical masses and makes it possible to illustrate the population of the available phase space at three-body decays. If the decay is a true direct 3-particle decay, the distribution of events in the Dalitz diagram must be uniform. However, as a rule, 3-particle decays occur via resonances, i.e., the excited particle decays into a resonance and a particle, and then the resonance, in turn, decays into two other particles. In this case, the distribution of events in the Dalitz diagram reveals an essentially non-uniform structure, with an increased concentration of events in the region of invariant masses coinciding with the resonance masses. The Dalitz diagram is a convenient tool for studying the dynamics of 3-particle decays.

The Cartesian coordinates for plotting a Dalitz diagram can be obtained as follows [10]:

$$x=\sqrt{3}(\varepsilon_j-\varepsilon_k),\, y=2\varepsilon_i-\varepsilon_j-\varepsilon_k\,. \quad (5)$$

By definition, the sum of the relative energies of three particles equals 1. In our experiment, the contribution of each component can be evaluated from the general plot.

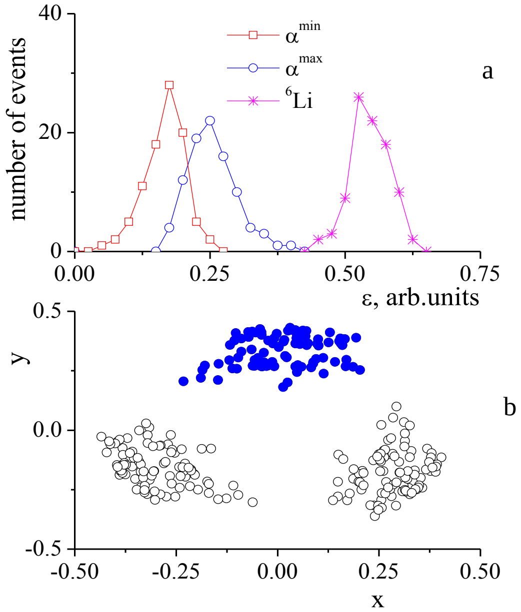

Fig. 4. Dependence of the number of events on the relative energy of particles ε (a), Dalitz diagram for the channel of formation of the GS of the ^{8}Be nucleus (b)

In Fig. 4,b, solid circles represent the dependence when the X coordinate was calculated using the α-particles. As one can see, the values are concentrated at $(X,Y) > 0$, which provides an additional criterion for distinguishing a pair of α-particles forming ^{8}Be nucleus in the GS. For other combinations (hollow circles), either of X or Y is negative. The Dalitz distribution confirms the presence of a transient excited particle (^{8}Be) and correlates with the distribution in Fig. 3,a.

CONCLUSIONS

The reaction of ^{14}N(γ,2α^{6}Li) was studied using the diffusion chamber method in a magnetic field on a beam of bremsstrahlung photons at E_γ^{max} = 150 MeV. The reaction events were reconstructed using the digital track measurement technique.

The distributions of events over the excitation energy of 2α-particles were analyzed and a channel of the formation of ^{8}Be nucleus in the ground state is revealed and has been separated. The events corresponding to the partial channel of the reaction of ^{14}N(γ,^{6}Li)^{8}Be$_0$ with the subsequent two-particle decay of ^{8}Be→α+α were identified, the partial cross section of this channel was measured, and a comparison with the reactions of ^{12}C(γ,α)^{8}Be$_0$ and ^{16}O(γ,αα)^{8}Be$_0$ was performed.

Due to the two-particle nature of the decay process, the energy and angular distributions of particles at each stage of decay were analyzed.

REFERENCES

1. M. Freer, H. Horiuchi, Y. Kanada-En'yo, et al. Microscopic clustering in light nuclei // *Rev. Mod. Phys*. 2018, v. 90, p. 035004;
https://doi.org/ 10.1103/RevModPhys.90.035004
2. V. Liccardo, M. Malheiro, M.S. Hussein, et al. Nuclear processes in astrophysics: Recent progress // *Eur. Phys. J. A.* 2018, v. 54, p. 221-249;
https:// doi.org/0.1140/epja/i2018-12648-5
3. O.F. Nemets, V.G. Neudachin, A.T. Rudchik, et al. *Nuklonnyye assotsiatsii v legkikh yadrakh i yadernyye reaktsii mnogonuklonnykh peredach*. Kyiv: "Naukova Dumka", 1988, 488 p. (in Russian).
4. G.I. Chitanava. Research of the dependence of the resonance structure of the excitation functions of ^{11}B, ^{12}C, and ^{16}O nuclei on the type of the input and output channels // *Yad. Fiz*. 1985, v. 42, p. 145 (in Russian).
5. S.N. Afanasiev, I.O. Afanasieva. Digital study of the ^{14}N(γ,2α)^{6}Li reaction // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations"*. 2023, N 3(145), p. 33-37;
https:// doi.org/10.46813/2023-145-033
6. S.N. Afanasiev, I.O. Afanasieva. Digital processing of photos from 4π track detector // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations"*. 2022, N 5(141), p. 87-91;
https://doi.org/10.46813/2022-141-087
7. A.M. Baldin, V.I. Gol'danskii, V.M. Maksimenko, I.L. Rosenthal. *Kinematics of Nuclear Reactions*. Atomizdat, 1968, 456 p. (in Russian).
8. D.R. Tilley, J.H. Kelley, J.L. Godwin, et al. Energy levels of light nuclei A = 8, 9, 10 // *Nucl. Phys. A.* 2004, v. 745, p. 155-362;
https://doi.org/10.1016/ j.nuclphysa.2004.09.059
9. S.N. Afanasyev. 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 // *Ukr. J. Phys.* 2019, v. 64, N 9, p. 787-792;
https://doi.org/ 10.15407/ujpe64.9.787
10. D. Dell'Aquila, I. Lombardo, G. Verde, et al. High-Precision Probe of the Fully Sequential Decay Width of the Hoyle State in ^{12}C // *Phys. Rev. Lett.* 2017, v. 119, p. 132501;
https://doi.org/10.1103/ PhysRevLett.119.132501

Article received 30.04.2024

ДОСЛІДЖЕННЯ ПАРЦІАЛЬНОГО КАНАЛУ УТВОРЕННЯ ОСНОВНОГО СТАНУ ЯДРА ^{8}Be У РЕАКЦІЇ ^{14}N(γ,2α^{6}Li)

С.М. Афанасьєв, І.О. Афанасьєва

Методом дифузійної камери у магнітному полі на пучці гальмівних фотонів з $E_γ^{макс}$ = 150 MeB досліджено реакцію ^{14}N(γ,2α^{6}Li). У розподілі подій за енергією відносного руху двох α-частинок виявлено резонанс, ідентифікований як основний стан ядра ^{8}Be. Виділено події, що відповідають парціальному каналу реакції ^{14}N(γ, ^{6}Li) $^{8}Be_0$ з наступним двочастинковим розпадом ^{8}Be→α+α, і виміряно парціальний перетин цього каналу. Виконано аналіз енергетичних і кутових розподілів частинок на кожному етапі розпаду.