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THE HOYLE STATE OF ^{12}C NUCLEUS IN THE ^{14}N(γ, np)3α REACTION

The distributions over the excitation energies of the systems of two and three α-particles in the $^{14}N(\gamma, np)3\alpha$ reaction have been analyzed. In the 2α-particle distribution, a channel of the ^8Be nucleus formation in the ground state is revealed and resolved. For the events corresponding to this channel, a distribution of events over the excitation energy of three α-particles is plotted. A maximum is found in the near-threshold 3α-particle region, which can correspond to the Hoyle state of ^{12}C nucleus. Events corresponding to the partial channel of the $^{14}N(\gamma, np)^{12}C^*(0^+)$ reaction with the subsequent two-particle decay $^{12}C^* \to \alpha + {}^8Be(0^+)$ are separated, and the energy and angular distributions of α-particles at each decay stage are analyzed. The channel of ^{12}C nucleus formation in the Hoyle state in photonuclear reactions has not been identified earlier.

Keywords: photonuclear reactions, 4π-detector, ground state of ^{8}Be nucleus, Hoyle state of ^{12}C nucleus.

1. Introduction

The Hoyle state of ^{12}C nucleus (HS) with $E_0 = 7.65$ MeV and $J^\pi = 0^+$ plays a special role in nucleosynthesis; in particular, it governs the elemental composition of the Universe [1, 2]. Calculations performed in the framework of the shell model do not reproduce the internal structure of the HS [3], and the proximity to the α-particle threshold allows the HS to be taken as an ideal candidate for studies in the framework of the α-cluster nuclear model. The HS is believed to exist as a system of three α-particles, but a wide set of other geometric configurations were considered in numerous theoretical studies [4–9].

Immediately after its experimental discovery, it was assumed [4] that the HS could be a linear chain of three α-particles. According to this hypothesis, the HS could be the first element of the rotational odd-positive band. However, this hypothesis was discarded experimentally in work [5]. According to the predictions of the algebraic cluster model, the α-particles in the HS are located at the vertices of an equilateral triangle [6, 7]. In this case, each of them is expected to possess almost the same energy. In the framework of fermionic molecular dynamics, the HS is simulated as the triangular configuration α + ^{8}Be [8, 9]. It was also suggested that the HS can be a nuclear analog of the atomic Bose–Einstein condensation [10], in which the 3α-system is sufficiently diffusive for the bosonic origin of the α-particle to dominate. The simulation of a no-core lattice using the chiral effective field theory [11] predicts that three α-particles have to be located at the vertices of an obtuse triangle. Despite huge differences in their formulations and predicted HS structures, each of those models can successfully explain various experimental observations.

The body of experimental studies of HS is rather large [12–16]: various reactions with various detection systems were analyzed. A specific feature of the events responsible for the HS formation is the circumstance that all three α-particles are confined in a narrow geometric cone. Therefore, detectors capable of simultaneously detecting several particles, but under restricted geometric conditions, were mainly selected for the experiments. The reactions of elastic scattering of deuterons and α-particles [12–15] were mainly used to analyze the energy correlations between α-particles. Certain energy distributions of α-particles were assumed to testify to corresponding structural features of the HS. In particular, the decay of three α-particles with the same energies is related to the α-condensate structure, whereas the decay with two energy-equal particles is related to the long-discussed linear-chain structure. At the same time, the supposed direct relation between the energy distribution and the structure was disputed in work [15], where it was suggested that only the accurate measurement of the energy distribution on the Dalitz plot can provide a sensitive test of structural models. Furthermore, in work [16], angular distributions were also added as the analyzed variables of the almost medium-free reaction (the β-decay of ^{12}N).

It should be noted that experimental works mainly concern reactions of the type A(a,b)^{12}C* with charged incident particles. There are practically no studies aimed at researching the HS in photonuclear reactions invoked by the electromagnetic interaction, although the properties of the latter have been studied well in detail. In photonuclear reactions rather than in reactions under the influence of neutrons and charged particles, it is easier to distinguish the effects of nuclear structure from the mechanisms of its excitation. A gamma quantum introduces a low momentum into the nuclear system, which allows the interaction between nucleons and cluster substructures to be studied at short internucleon distances. However, for example, earlier, the experimental resolution of the HS in the reaction ^{12}C(γ,3α), which is inverse to the (γ,3α)^{12}C* one, was complicated because of a specific kinematic configuration.

In this work, the ^{14}N(γ,np)3α reaction has been studied at energies up to the meson threshold. The experiment was carried out using a track 4π-detector (a diffusion chamber in a magnetic field 1.5 T in strength). The chamber was exposed to a beam of bremsstrahlung photons with a final energy of 150 MeV. A low density of the medium in the chamber and the application of the magnetic field allowed the kinematic parameters of all charged particles to be measured in wide energy and angle intervals. The chamber operated in a mode that made it possible to visually distinguish single- and double-charged particles by comparing the ionization density and the track width after measuring its curvature radius. The working area of the diffusion chamber was photographed with the help of a two-lens stereo camera.

The selection technique and some results obtained for this reaction were reported earlier [17]. The multiparticle reaction character made it possible to eliminate the uncertainty associated with the kinematic conditions of HS registration. In this work, we present the energy and angular distributions of α-particles in the partial channel of the ^{12}C nucleus formation in the Hoyle state.

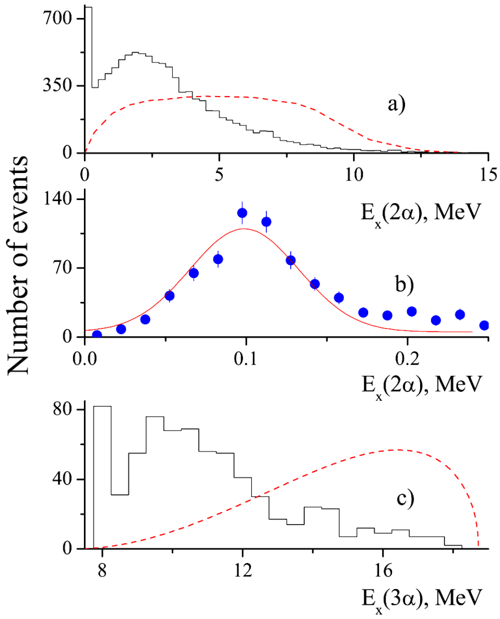

Fig. 1. Distribution of events over the excitation energy of two α-particles (a). The ground state of the ^{8}Be nucleus (b). Distribution of events over the excitation energy of the system of three α-particles (c)

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

The excitation energy for a pair of α-particles was determined according to the formula

$$E_x(\alpha\alpha) = M^{\rm eff}(^8{\rm Be}) - 2m_\alpha, \tag{1}$$

where $M^{\rm eff}(^8$Be) is an effective mass equal to the total energy of a pair of α-particles in their rest coordinate frame, and m_α is the mass of α-particle.

The distribution of events over $E_x(\alpha\alpha)$ is shown in Fig. 1, a (here, the histogram step was taken to equal 0.25 MeV). Since α-particles are indistinguishable, a preliminary selection of α-particles forming a pair as a result of the ^{8}Be nucleus decay is impossible. Therefore, all possible combinations of $E_x(\alpha\alpha)$ were calculated for every reaction event, and all obtained values are presented in the figure.

The experimental distribution was compared with the phase distribution

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

where $E_x^{\max}$ is the maximum energy in the system of two α-particles, which is equal to the total energy of the system in the center-of-mass coordinate frame minus the reaction threshold. In our case, $n = 5$ and $k = 2$. The phase distribution was calculated for the bremsstrahlung beam by summing up the distributions obtained for narrow intervals, where the energy of γ-quantum was assumed to be constant. The area under the phase curve was normalized by the number of events per each interval. The resulting phase distribution is shown in Fig. 1, *a* by a dashed curve. The difference between the experimental and phase distributions, especially at $E_x < 0.25$ MeV, allowed us to conclude that excited states of ^{8}Be nucleus were formed in the considered reaction.

The maximum at $E_x < 0.25$ MeV in Fig. 1, *a* is shown in a narrower interval in Fig. 1, *b* by circles calculated with a smaller step – 15 keV. Statistical errors are also indicated by vertical bars. Fitting those data using the Gaussian distribution (the solid curve in Fig. 1, *b*) gave the peak position at $E_0 = 0.096 \pm 0.005$ MeV and the half-height peak width $\Gamma = 0.064 \pm 0.011$ MeV. From spectrometric measurements [18], it is known that the ground state (GS) parameters of ^{8}Be nucleus are $E_0 = 0.092$ MeV, $\Gamma = 5.57$ eV, and the quantum numbers $J^\pi = 0^+$. The maximum positions (the experimental value and the value obtained in work [18]) coincide within the error limits. Therefore, the concentration of events around an energy of 0.1 MeV can be explained by the formation of ^{8}Be nucleus in the GS. Because of an insufficient energy resolution and a low statistical reliability, the accurate determination of the GS parameters was not a task of this experiment. The experimentally observed width of state had an instrumental origin.

Only one of three possible $\alpha\alpha$-combinations gives the main contribution to the observed maximum, and events in which one of the α-particle pairs corresponds to the formation of ^{8}Be nucleus in the GS can be reliably identified. For events with several possible combinations in this energy interval, the pair for which the E_x-value was closest to $E_0 = 0.092$ MeV was selected as the resonance one. The relative contribution of the partial channel $^{14}\mathrm{N}(\gamma, \mathrm{np})\alpha\,^8\mathrm{Be}_0$ was 20.85%. The α-particles corresponding to the formation of ^{8}Be in the GS were denoted as α_2 and α_3, whereas the α particle accompanying ^{8}Be nucleus was denoted as α_1.

3. Excitation Energy of the System α + ^{8}Be$_0$

For the channel of the ^{8}Be nucleus formation in the GS, the excitation energy of the 3α-particle system ($\alpha_1 + {}^8\mathrm{Be}_0 \to 3\alpha$) was determined using the formula

$$E_x(3\alpha) = M^{\mathrm{eff}}(3\alpha) - 3m_\alpha, \qquad (3)$$

where $M^{\mathrm{eff}}(3\alpha)$ is an effective mass that is equal to the total energy of three α-particles in their rest coordinate frame. The distribution over $E_x(3\alpha)$ is presented in Fig. 1, *c* in the form of a histogram with a step of 0.5 MeV. The distribution demonstrates a structure with a few maxima.

The experimental distribution was compared with the phase one calculated via formula (2) with $n = 5$ and $k = 3$ (the dashed curve in Fig. 1, *c*). The difference between the experimental and phase distributions may testify to the formation of the excited ^{12}C nucleus. The position of the first maximum, at $E_x(3\alpha) < 8.0$ MeV, agrees with the data of work [19] concerning the narrow 0^+ state of ^{12}C nucleus with $E_0 = 7.654$ MeV, which is called the Hoyle state (HS) in the literature and plays a special role in astrophysics. The resonance width observed in this experiment has an instrumental origin.

The events corresponding to the partial channel of HS formation are separable so that the reaction is reduced to the three-particle one, $^{14}\mathrm{N}(\gamma, \mathrm{np})^{12}\mathrm{C}^*$, with the identification of α-particles in two-particle processes

$$^{12}\mathrm{C}^* \to \alpha_1 + {}^8\mathrm{Be}_0 \to \alpha_1 + \alpha_2 + \alpha_3.$$

The application of the 4π-detector in the experiment and the identification of the sequential two-particle decay channel made it possible to analyze the angular and energy distributions of α-particles at each decay stage. The relative HS yield in the reaction $^{14}\mathrm{N}(\gamma, \mathrm{np})3\alpha$ equals 11.77% of the number of events in the partial channel of the ^{8}Be nucleus formation in the GS.

4. Energy and Angular Distributions for the Channel of the ^{12}C Nucleus Formation in the Hoyle State

In Fig. 2, *a*, solid circles are used to exhibit the dependence of the number of events on the escape angle of ^{12}C nucleus, $\Theta(^{12}\mathrm{C})$, in the center of mass coordinate frame for the reaction in whole. Hereafter, 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 OX axis. The figure demonstrates that the HS yield is strongly asymmetric, with a maximum at $61.74 \pm 3.75°$ and with a half-height width of $42.74 \pm 7.53°$ (in Fig. 2, *a*, the solid curve is the fitting Gaussian function). Such information can be useful for planning further experiments and selecting optimal geometric conditions.

Figure 2, *b* shows the differential cross-section $dN/d\Theta$ in the rest coordinate frame of the system $\alpha_1 + {}^8\text{Be}$. The results are depicted as hollow triangles. At this decay stage, the α-particle and ^{8}Be nucleus have the quantum characteristics $J^\pi = 0^+$. The obtained results were fitted with a linear function (the solid line), and it was found that its slope almost equals zero within the error limits. This fact made it possible to conclude that the quantum characteristics $J^\pi = 0^+$ is also valid for ^{12}C nucleus, which agrees with the data of spectroscopic studies for the Hoyle state.

Figure 2, *c* illustrates the dependence of the parameter Θ_{12} on the parameter Θ_{13}, which are defined as the separation angles between the α_1-particle and the α_2- and α_3-particles, respectively. In the rest coordinate frame of ^{12}C nucleus, the sum of all separation angles has to equal 360°. In the framework of the cluster model with the α-particles located at the vertices of an equilateral triangle, the events must be concentrated near the point with the coordinates (120°, 120°). As can be seen from the figure, the experimental results do not confirm this assumption. Most likely, the data demonstrate the obvious dominance of the $\alpha_1 + {}^8\text{Be}$ configuration, where the α_2- and α_3-particles with a small separation angle correspond to the formation of ^{8}Be nucleus. It is also worth noting that the distribution has a certain cone-like shape (the solid lines in Fig. 2, *c* mark the corresponding cone boundaries) that expands toward large angles.

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

$$\varepsilon_{\text{id}} = \frac{T_{\text{id}}}{T_0}, \qquad (4)$$

where T_0 is the sum of the kinetic energies (T) of α-particles, and id = 1, 2, 3 is the α-particle identifier. In the literature, owing to the identification uncertainty, it was adopted to enumerate the α-particles according to their energy sequence $T_1 > T_2 > T_3$. In our experiment, where the α_1-particle could be reliably identified, this assumption about the energies of α-particles was verified, and it was found that, really, the α_1-particle mainly possessed the maximum energy (it was not the case only in 1.2% of events and observed at low HS excitation energies). Two α-particles composing ^{8}Be nucleus in the GS were also sorted with respect to their energies.

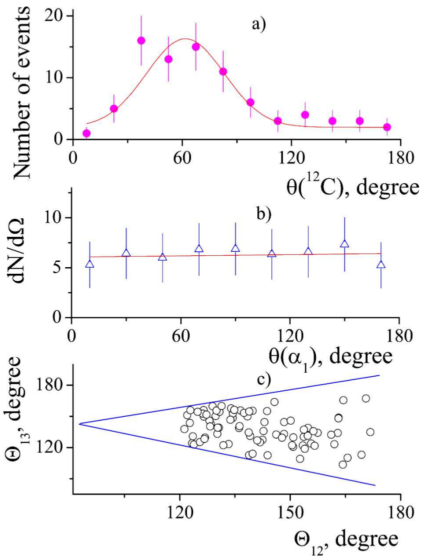

Fig. 2. Event distribution over the escape angle of the ^{12}C nucleus in the Hoyle state (*a*), dependence of the differential cross section on the escape angle of the α_1-particle for the $\alpha_1 + {}^8\text{Be}_0$ system (*b*), and correlation between the divergence angles between the α_1- and α_2-particles (Θ_{12}) and the α_1- and α_3-particles (Θ_{13}) (*c*)

Figure 3, *a* demonstrates the distributions of the number of events over the energy differences $\varepsilon_i - \varepsilon_k$, where i and k are indices enumerating the α-particles. It should be noted that the distributions over the energy differences between the neighbor pairs – these are $\varepsilon_1 - \varepsilon_2$ (hollow triangles) and $\varepsilon_2 - \varepsilon_3$ (hollow squares) – are concentrated near the threshold value, with the maximum positions at 0.2. At the same time, the distribution over the difference $\varepsilon_1 - \varepsilon_3$ (solid circles) extends from 0.15 to 0.55, with the maximum at about 0.5. Thus, for example, in the direct mechanism case (without the formation of a transient excited ^{8}Be nucleus), these values are expected to be at a level of about 0.33 (if the particles equally share the decay energy) or there arises a max-

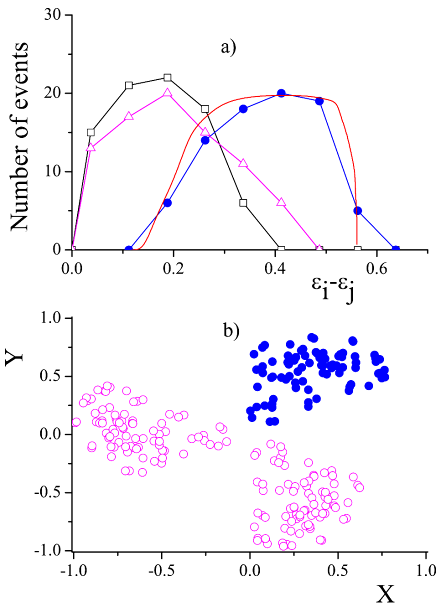

Fig. 3. Event distribution over the difference between the relative energies of α-particles (a) and Dalitz diagram for the ^{12}C nucleus in the Hoyle state (b)

imum at 0.67 (if one α-particle escapes in the opposite direction to other twos).

The experimental data in Fig. 3, a are compared with the result of Monte Carlo simulation [13] performed in the assumption of 100% sequential decay (the solid curve). One can see their qualitative coincidence, including the predicted maximum value.

Details of the mechanisms of the Hoyle state decay into three α-particles 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 [15]:

$$X = \sqrt{3}(\varepsilon_j - \varepsilon_k), \quad Y = 2\varepsilon_i - \varepsilon_j - \varepsilon_k. \tag{5}$$

By definition, the sum of the relative energies of three α-particles equals 1. In our experiment, the contribution of each component can be evaluated from the general plot. In Fig. 3, b, solid circles represent the dependence when the X coordinate was calculated using the α_2- and α_3-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).

5. Conclusions

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 $E_\gamma^{\max} = 150$ MeV), the reaction ^{14}N$(\gamma, \mathrm{np})3\alpha$ has been studied. The distributions of events over the excitation energy of 2 and 3 α-particles were analyzed. For the 2α-particle distribution, a channel of the formation of ^{8}Be nucleus in the ground state is revealed and resolved. For the events corresponding to this channel, the distribution of events over the excitation energy of three α-particles is plotted. A peak is detected in the near-threshold 3α-particle region, which can correspond to the Hoyle state of ^{12}C nucleus. Thus, a partial channel of the reaction ^{14}N$(\gamma, \mathrm{np})^{12}$C* with the subsequent two-particle decay of ^{12}C* into $\alpha_1 + {}^8$Be$_0$ is distinguished. The energy and angular distributions of α-particles at various formation stages are analyzed. The angular distributions in the center of ^{12}C nucleus mass coordinate frame are found to be isotropic, which allowed a conclusion to be drawn that the quantum characteristics of ^{12}C nucleus are $J^\pi = 0^+$. It is also shown that the energy of the α-particle accompanying the formation of ^{8}Be nucleus in the ground state is maximum. The channel of the ^{12}C nucleus formation in the Hoyle state has not been identified earlier in photonuclear reactions.

1. F.-K. Thielemann, F. Brachwitz, C. Freiburghaus *et al.* Element synthesis in stars. *Progr. Part. Nucl. Phys.* **46**, 5 (2001).

2. M. Freer, H.O.U. Fynbo. The Hoyle state in ^{12}C. *Progr. Part. Nucl. Phys.* **78**, 1 (2014).
3. A.C. Dreyfuss, K.D. Launey, T. Dytrych *et al.* Hoyle state and rotational features in Carbon-12 within a no-core shell-model framework. *Phys. Lett. B* **727**, 511 (2013).
4. H. Morinaga. Interpretation of some of the excited states of 4n self-conjugate nuclei. *Phys. Rev.* **101**, 254 (1956).
5. M. Itoh, H. Akimune, M. Fujiwara *et al.* Candidate for the 2^+ excited Hoyle state at Ex$\sim$10 MeV in ^{12}C. *Phys. Rev. C* **84**, 054308 (2011).
6. R. Bijker, F. Iachello. The algebraic cluster model: three-body clusters. *Ann. Phys.* **298**, 334 (2002).
7. D.J. Marin-Lambarri, R. Bijker, M. Freer *et al.* Evidence for triangular D3h symmetry in ^{12}C. *Phys. Rev. Lett.* **113**, 012502 (2014).
8. Y. Kanada-EnпїSyo. The structure of ground and excited states of ^{12}C. *Progr. Theor. Phys.* **117**, 655 (2007).
9. M. Chernykh, H. Feldmeier, T. Neff. The structure of the Hoyle state in ^{12}C. *Phys. Rev. Lett.* **98**, 032501 (2007).
10. Y. Funaki, H. Horiuchi, W. von Oertzen *et al.* Concepts of nuclear α-particle condensation. *Phys. Rev. C* **80**, 064326 (2009).
11. E. Epelbaum, H. Krebs, T.A. Lahde *et al.* Viability of carbon-based life as a function of the light quark mass. *Phys. Rev. Lett.* **110**, 112502 (2013).
12. Ad.R. Raduta, B. Borderie, E. Geraci *et al.* Evidence for α-particle condensation in nuclei from the Hoyle state deexcitation. *Phys. Lett. B* **705**, 65 (2011).
13. D. Dell'Aquila, I. Lombardo, G. Verde *et al.* High-precision probe of the fully sequential decay width of the Hoyle state in ^{12}C. *Phys. Rev. Lett.* **119**, 132501 (2017).
14. R. Smith, Tz. Kokalova, C. Wheldon *et al.* New measurement of the direct 3α decay from the ^{12}C Hoyle state. *Phys. Rev. Lett.* **119**, 132502 (2017).
15. T.K. Rana, S. Bhattacharya, C. Bhattacharya *et al.* New high precision study on the decay width of the Hoyle state in ^{12}C. *Phys. Lett. B* **793**, 130 (2019).
16. J. Bishop, G.V. Rogachev, S. Ahn *et al.* Almost medium-free measurement of the Hoyle state direct-decay component with a TPC. *Phys. Rev. C* **102**, 041303(R) (2020).
17. Serhii N. Afanasiev. Study of ^{14}N$(\gamma, \text{np})3\alpha$ reaction for E_γ up to 150 MeV. *East Eur. J. Phys.* **1**, 5 (2022).
18. D.R. Tilley, J.H. Kelley, J.L. Godwin *et al.* Energy levels of light nuclei $A = 8, 9, 10$. *Nucl. Phys. A* **745**, 155 (2004).
19. F. Ajzenberg-Selove. Energy levels of light nuclei $A = 11$–12. *Nucl. Phys. A* **506**, 1 (1990).

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СТАН ХОЙЛА ЯДРА ^{12}C В РЕАКЦІЇ ^{14}N$(\gamma, \text{np})3\alpha$

Для реакції ^{14}N(γ,np)3α виконано аналіз розподілів за енергією збудження 2^x і 3^x α-частинок. В 2^x α-частинковому розподілі виявлено і виділено канал утворення основного стану ядра ^{8}Be. Для подій, що відповідають цьому каналу, побудовано розподіл за енергією збудження трьох α-частинок. У біляпороговій 3α-частинковій області виявлено максимум, який може відповідати стану Хойла ядра ^{12}C. Виділено події, що відповідають парціальному каналу реакції ^{14}N(γ,np)^{12}C*(0^+) з наступним двочастинковим розпадом ^{12}C* на $\alpha + {}^8$Be(0^+), і виконано аналіз енергетичних і кутових розподілів α-частинок на кожному етапі розпаду. Раніше у фотоядерних реакціях канал утворення стану Хойла ядра ^{12}C не виділявся.

Ключові слова: фотоядерні реакції, 4π-детектор, основний стан ядра ^{8}Be, стан Хойла ядра ^{12}C.