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STUDY OF $^{14}N(\gamma,np)3\alpha$ REACTION FOR E_γ UP TO 150 MeV[†]

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The reaction $^{14}N(\gamma,np)3\alpha$ induced by bremsstrahlung photons of endpoint energy E_γ^{max} = 150 MeV has been investigated using diffusion chamber, which is placed into the magnetic field. The distribution functions of the reaction yield, the energy and momentum of the final particles from E_γ were measured and it was determined that at E_γ > 45 MeV, change in the behavior of these functions occurs. The average energy T^{aver} was calculated for the particles with the energy falling within a 1 MeV interval of the total kinetic energy $T_0 = E_\gamma - Q$, where Q is the energy threshold of the reaction (Q = 19.77 MeV). At T_0 ~ 20 MeV, the dependence of the contributions from T^{aver} to T_0 changes sharply. At T_0 > 20 MeV, most of the energy is carried away by nucleons, their relative contribution is equal, and this agrees with the assumption of the quasideuteron interaction mechanism. The momentum distribution distributions for the neutron and proton have a similar form, with a strong shift of the maximum towards higher energies with an increase in the energy of the γ quantum. For a system of 3α-particles, in each distribution, peak is observed centered at 100 MeV/*c*, the relative contribution of which smoothly decreases with increasing momentum, and a wide high-energy "tail" appears. The energy and angular correlations of the np-pair depends on both of the energy E_γ and the momentum of the system of 3α-particles.

Keywords: diffusion chamber, photoreaction, ^{14}N nucleus, np-pair, energy and angular distributions.

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The mechanism of (γ,np) -reactions has been a subject of research interest for many years. At energy above the giant resonance, the photonuclear reactions represent an effective instrument for studying nucleon correlations, which are an important component of information on nuclear forces, cluster configurations, and meson-exchange currents in nuclei. Studying of the photon absorption mechanism by the correlated np-pair offers a possibility to look into the problem of nucleonic interactions at small and medium distances. The phenomenological quasideuteron model has successfully explained (γ,np)-reactions at intermediate energies [1-3]. This model can express two-nucleon knockout cross-section by two factors: the function, proportional to the probability of finding a nucleon pair in the nucleus and a Fourier transform of the correlation function. At energies below the meson production threshold *γ*-quanta are absorbing by correlated nucleon or by nucleon pair at the time of the meson exchange. Single-nucleon emission arises when either the proton or the neutron escapes and the other participating nucleon being reabsorbed into the nucleus through final-state interactions. Recently, the model has a further development in new microscopic approaches. An agreement with experimental results was achieved taking into account meson exchange currents [4] and collective nucleus characteristics in the framework of shell model [5]. Experimental results about of a highly excited final nuclear state formation in (γ,np)-reactions are needed to verify the prediction of the model.

In this article, we present results obtained by studying the photodisintegration of nitrogen nuclei via the reaction $^{14}N(\gamma,np)3\alpha$ at the energies below the meson production threshold. The results given here were obtained by using a diffusion chamber [6-7] placed in a magnetic field and exposed to a beam of bremsstrahlung photons, their endpoint energy being 150 MeV. Low pressure in the chamber and matching of the target and the detector made possible to measure the kinematic parameters of all charged particles from reaction threshold in a wide range of energies and angles and to obtain information on excited intermediate states of nuclei.

The chamber used operated in a mode that made it possible to separate singly and doubly charged particles visually and to compare the ionization density and the width of a track after measuring its radius of curvature. Four-prong events featuring three doubly charged and one singly charged particles were measured simultaneously. The reaction being studied was separated on the basis of the imbalance of the transverse momentum P⊥, which is equal to the sum of the transverse momenta of the four particles involved. If this imbalance was equal or greater than 30 MeV/*c*, the respective event was attributed to the reaction being studied. The background-reaction ($\gamma+^{14}N\rightarrow d3\alpha$) contribution was estimated at 3%. From the laws of conservation of energy and momentum, the energy of a γ-quantum equals

$$E_\gamma = \frac{m^2 + P^2 - (M - E)^2}{2\cdot(M - E + P_x)}, \tag{1}$$

where m and M are the neutron and the ^{14}N nucleus masses; E and P are, respectively, the total energy and the total momentum of the proton and three ^4He nuclei appearing in the final state; and P_x is the projection of this total momentum onto the direction of the photon momentum. In the experiment, the axis OX was directed along the beam of γ-quanta. The

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kinematic parameters of a neutron were obtained with the help of conservation laws after having calculated the γ-quantum energy.

Earlier in our experiment, we mainly carried out [8 - 10] studies of (γ,np)-reactions on ^{4}He, ^{12}C, ^{14}N, and ^{16}O nuclei with the formation of a residual nucleus in the ground state. There is also information about the reaction (γ,np)α^{6}Li on the ^{12}C nucleus [9]. At energies above the giant dipole resonance, the experimental data agrees with the calculations within the framework of the mechanism of photon absorption by an np-pair.

EXPERIMENTAL RESULTS

We have measured dependence of the number of events for the reaction ^{14}N(γ,np)3α in the photon energy range from the reaction threshold up to 150 MeV with a step of 2 MeV. The results are shown in Fig. 1a as a histogram.

The measured energy dependence of the number of events exhibits a broad resonance centered at 40 MeV. The rate of decrease in the energy dependence undergoes a change in the region around 45 MeV. Solid curve in Fig. 1a demonstrate the fitting experimental data by using of a linear combination of two Gaussian functions with parameters $E_\gamma^1 = 34.8 \pm 0.41$ MeV and $\Gamma^1 = 10.39 \pm 1.19$ MeV (curve 1), $E_\gamma^2 = 62.99 \pm 2.74$ MeV and $\Gamma^2 = 54.79 \pm 6.65$ MeV (curve 2). The fit qualitatively describes the presented distribution. The area of the function in the region of the first maximum is half that in the region of the second maximum. For $E_\gamma > 45$ MeV, the main contribution is made by the function describing the "high-energy" tail.

A similar irregularity in the region of this energy value was previously observed in the reactions ^{14}N(γ,np)^{12}C [8]. The results are normalized in the region around 40 MeV and are represented by open circles in Fig. 1b. The experimental curves have the same slope and this, apparently, is associated with the same mechanism of interaction of the γ-quantum with the nucleus.

Previously (article [8]), a comparison of the cross sections (γ,np) of reactions on ^{12}C, ^{14}N, and ^{16}O nuclei with calculations in different theoretical approaches was made. The change in the rate of decrease in the cross section at around 40 MeV may possibly be due to a transition from the mechanism of direct nucleon knockout to the pair-absorption mechanism.

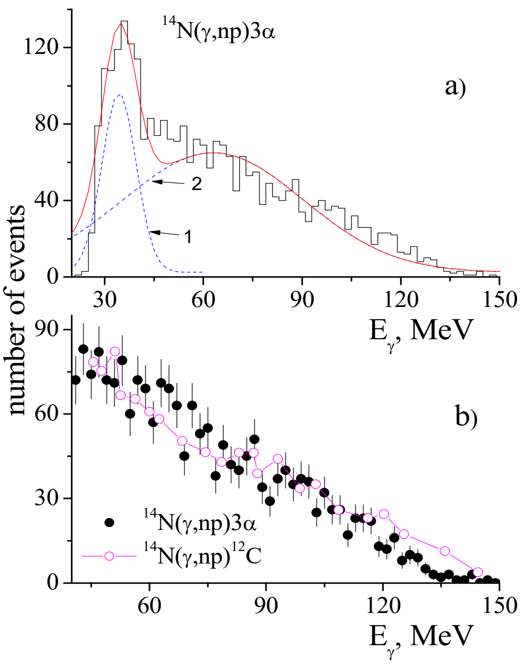

Figure 1. The reaction yield depending on the energy of the γ-quantum: a) – histogram, b) - closed points. Curves - fitting by a linear combination of two Gaussian functions. Open points - reaction ^{14}N(γ,np)^{12}C.

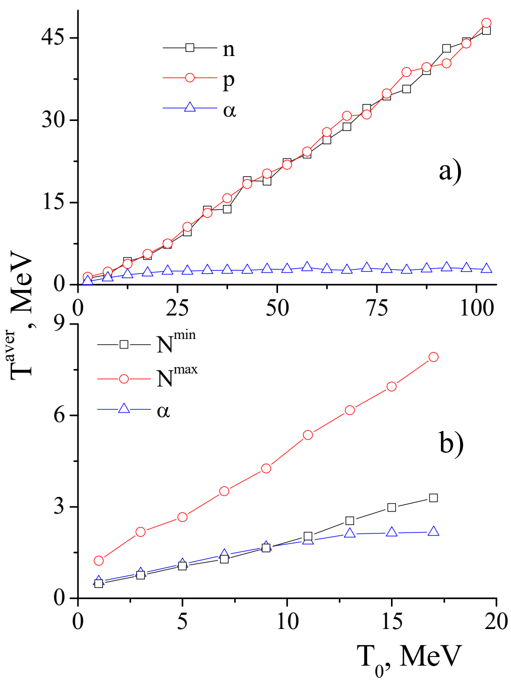

Figure 2. Dependence of the average kinetic energy of the final particles on the total kinetic energy.

Let us consider the relative contribution of the final particles to the total energy dependence of the reaction T_0, which was defined as $T_0 = E_\gamma - Q$, where Q is the energy threshold of the reaction (Q = 19.77 MeV). The average energy T^{aver} was calculated for the particles with the energy falling within a 1 MeV interval of the total kinetic energy. The circles are in the centers of intervals and in Fig. 2a the dependence T^{aver} of the final particles are plotted. The histogram step equals 5 MeV. The squares show the distribution of T^{aver} for the neutron, circles – for the proton, and the triangles – for α-particles (due to the inseparability of α-particles, the figure shows the average value for three α-particles).

At T_0 ~ 20 MeV, the dependence of the contributions from T^{aver} to T_0 changes sharply. The value 20 MeV corresponds to the position of the maximum of the reaction's yield at E_γ ~ 40 MeV (fig. 1) and will be used further as the boundaries of the intervals in the analyze of events. The dependences of the average kinetic energy was approximated by the linear functions and the results of these fits are given in the second and third columns of the Table 1 for all final particles.

At $T_0 > 20$ MeV, most of the energy is carried away by nucleons, their relative contribution is equal, and this agrees with the assumption of the quasi-deuteron interaction mechanism.

At $T_0 < 20$ MeV another mechanism is possible. In the direct mechanism, knocked out nucleon carries most of energy of the final state. The energy of other products of the reaction amounts a smaller portion and weakly increases with the energy of the γ-quantum. Therefore, in each event are compared proton and neutron energy in c.m.s. Nucleon, which has higher energy, was considered the leading nucleon (N^{max}), and nucleon, which has lower energy, was considered the accompanying nucleon (N^{min}). In the γ-quanta energy interval of 1 MeV the kinetic energies of the leading and accompanying nucleon, which fall into this interval, are separately summed. Total energies are divided on number of events, which fall into interval (Table 1, rows 5-6). Received average values are shown in Fig. 2b with circles for the leading nucleon, the squares are for the accompanying nucleon data and the triangles are for α-particles. An average energy divided by the intervals increases with γ-quanta energy increasing. This fact applies not only to the leading nucleon but also to the rest of nuclear decay products, which is a spectator in the direct mechanism model. The nucleon average energies are proportional to the total energy of the reaction product.

The leading nucleon average energy to the accompanying nucleon average energy ratio was determined and within the limits of errors, it has a value of 2. According to γ-quantum, absorption by the nucleon pair model it should be expected this ratio near 1.

T^{aver} for a α-particle increases at small T_0, but already at $T_0 > 20$ MeV the relative contribution $T^{aver}(\alpha)$ is constant and insignificant.

Assuming a statistical distribution of energy between particles, we can calculate the average energy carried away by each particle as a function of T_0 [11]:

$$T = \frac{(A-M)}{(n-1)\cdot A}\cdot T_0, \qquad (2)$$

where A and M are the atomic numbers of the target nucleus and the researched particle, respectively; and n is the number of particles in the final state.

In this reaction, the values of calculation by eq. (2) correspond: for the nucleon – 0.23 and for α-particles – 0.18 (should be remembered that there are three α-particles in the final state).

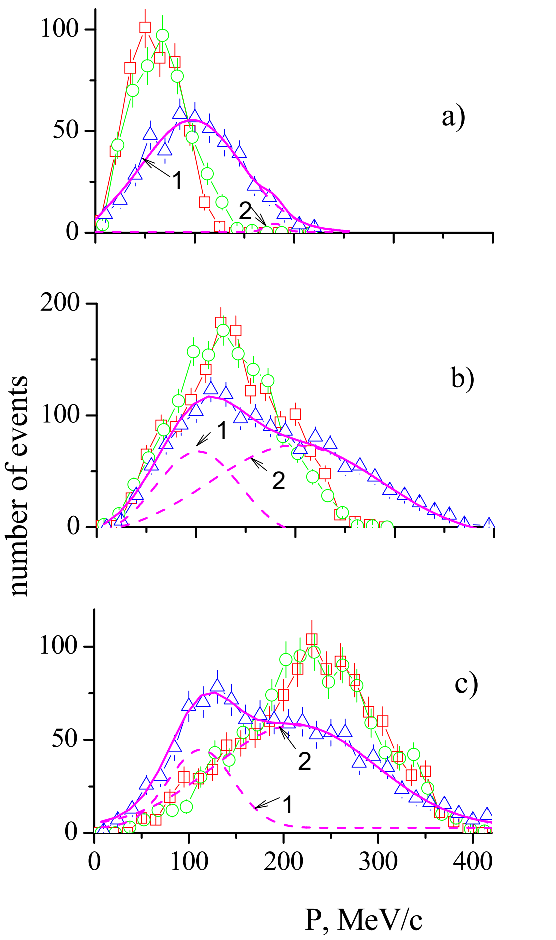

Figure 3. Reaction yield as a function of the particles momentum: a) $E_\gamma < 45$ MeV, b) $E_\gamma = 45 - 70$ MeV, c) $E_\gamma > 70$ MeV. The notation for the curves is explained in the text.

The experimental values for all final particles at $T_0 < 20$ MeV (Table 1, column 2, lines 2 - 4) agree with the calculation. Note the sharp change in the dependence at $T_0 > 20$ MeV, main part of the energy is carried away by the nucleons. The low rate of change in the dependence of distributions for α-particles may indicate that they are decay products of intermediate excited states.

The momentum distribution of final particles f(P) was measured in a laboratory system in three energy intervals: a) $E_\gamma < 45$ MeV, b) $E_\gamma = 45 - 70$ MeV, c) $E_\gamma > 70$ MeV. The intervals are chosen so that the statistical coverage in each is approximately the same.

The results are given in Fig. 3. The points are placed at the middle of the histogram step, which is equal to 15 MeV/*c*. The number of events per 1 MeV/*c* are plotted along the ordinate, and the measurement errors are statistical. The squares show the distribution of for the neutron (P_n), circles – for the proton (P_p), and the triangles – for the system 3α-particles ($P_{3\alpha}$). The distributions for the neutron and proton have a similar form, with a strong shift of the maximum towards higher energies with an increase in the energy of the γ-quantum.

For a system of 3α-particles, in each distribution, a peak is observed centered at 100 MeV/*c*, the relative contribution of which smoothly decreases with increasing momentum, and a wide high-energy "tail" appears.

In the region of the peak, the distribution for the neutron and proton was approximated by a Gaussian function. The position of the maxima (columns 2-3) are given in Table 2 for various values of the photon energy (column 1) and they coincide for both particles within the error limits.

Solid curve in Fig. 3a demonstrates the fitting of the momentum distribution for the system 3α-particles, by using of a linear combination of two Gaussian functions (curves 1 and 2). The fitting parameters are the momentum positions of the peaks and the results of fitting are quoted in Table 2 (column 4). The positions of the 1st peak for all three energy intervals coincide within the error limits, but the relative contribution decreases with increasing energy E_γ – a) 89.25 %, b) 31.55 %, c) - 23.55 %.

Table 1. Dependence of the relative contributions of the average kinetic energy of particles on T_0.

	$T_0 < 20$ MeV	$T_0 > 20$ MeV
n	0.28± 0.1	0.48± 0.1
p	0.27± 0.1	0.49± 0.1
α	0.15± 0.1	0.01± 0.1
N^{min}	0.16± 0.1	0.32± 0.1
N^{max}	0.39± 0.1	0.66± 0.1

Table 2. Momentum distributions of reaction products.

	P_n, MeV/*c*	P_p, MeV/*c*	$P_{3\alpha}$, MeV/*c*
a)	54.5± 1.4	56.3± 1.3	1. 97.3±2.6 2. 184.4±3.5
b)	129.5± 2.8	121.2± 1.3	1. 95.6±3.1 2. 192.7±3.3
c)	228.2± 2.8	222.4± 2.2	1. 101.2±2.3 2. 204.9±5.1

Earlier, in the ^{4}He(γ,np)d reaction, a peak in the momentum distribution of deuterons was revealed [10] in the interval between 50 and 100 MeV/*c*. As the momentum grows above 100 MeV/*c*, the reaction yield decreases smoothly. The peak in the momentum distribution of deuterons is explained by the contribution of the quasideuteron model without final-state interaction. The position of the maximum is independent on the photon energy. This can be explained based on the law of conservation of energy - deuteron is a spectator and the peak width is associated with the momentum distribution of quasideuterons in the target nucleus.

It is concluded that the momentum distribution of the residual nucleus in (γ,np)-reactions can be very sensitive to changes in the reaction mechanism and can help to find the area of the manifestation of models of interaction of a γ-quantum with a nucleus.

In the studied reaction (^{14}N(γ,np)3α) the peak at $P_{3\alpha}$ ~ 100 MeV/c can also appear due to the contribution of the quasideutron model without taking into account the interaction in the final state.

The dependences of the relative energy (η_{np}) and relative angle (τ_{np}) distributions on the energy of the γ-quantum and the momentum of the system of 3α-particles are obtained.

The kinetic energy of the relative motion of the proton and neutron in their center-of-mass system is $T_{np} = [(E_n + E_p)^2 - (\mathbf{P}_n + \mathbf{P}_p)^2]^{1/2} - (m_n + m_p)$ where E_n, E_p; $\mathbf{P}_n$, $\mathbf{P}_p$; m_n, m_p - total energies, momentums and masses of the nucleons respectively. It forms a part of the relative energies $\eta_{np} = T_{np} / (E_\gamma - Q)$, where E_γ - γ-quantum energy, Q - reaction threshold.

The relative angle of the nucleon pair is $\tau_{np}=\Theta_{np}/180$, where Θ_{np} is the nucleon scattering angle in center-of-mass system.

The distribution of events by η_{np} is shown in Fig. 4a in two intervals of the γ-quantum energy: $E_\gamma < 45$ MeV (opened circles) и $E_\gamma > 70$ MeV (closed circles). The distribution of events by τ_{np} is shown in Fig. 4b in two intervals of the momentum distribution the system 3α-particles: $P_{3\alpha} < 110$ MeV (opened circles) and $P_{3\alpha} > 170$ MeV (closed circles). Such intervals on E_γ and $P_{3\alpha}$ are chosen to estimate the influence of the boundary conditions on distributions on η_{np} and τ_{np}. In the first region, the distribution is practically symmetric with respect to 0.3, and in the second the distribution maximum shifts to η ~ 0.85. The phase distribution for the three-body final state is nearly symmetrical in relation to 0.5.

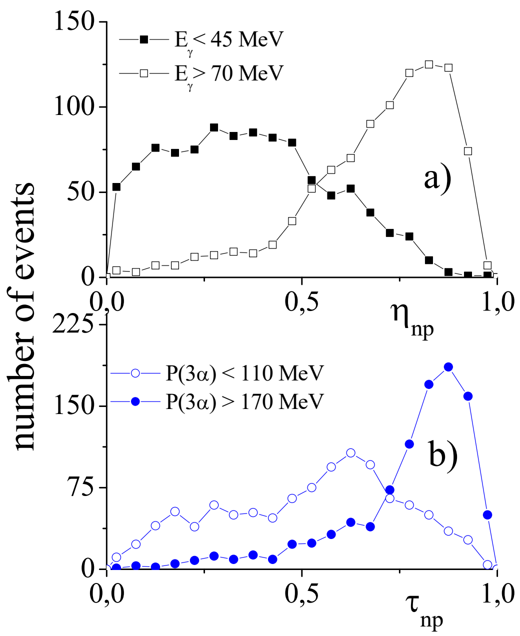

Figure 4. The dependences of the relative energy (a) and relative angle (b) distributions on the energy of the γ-quantum and the momentum of the system of 3α-particles.

The simplest models of the mechanism of photon absorption by ^{4}He nucleus were used in analyzing experimental data for the reaction ^{4}He(γ,np)d [10]. The pole diagram represents the quasideuteron model (model 1) - nucleons arising after quasideuteron disintegration do not interact with the remaining quasideuteron. In the final state, a nucleon may interact, however, with the second quasideuteron - the triangle diagram (model 2) represents this process. The last diagram corresponds to photon absorption by a three-nucleon system without final-state interaction (model 3). The analysis reaction yield in the deuteron momentum has led to the conclusion that at subthreshold meson production energies two models of the quasideuteron mechanism (model 1 and model 2) prevail. Triangular diagram dominates with a gradual increase in the contribution with increasing E_γ.

In our experiment, we also can see that the change in the interval from E_γ and from $P_{3\alpha}$ significantly changes the form of distributions by η_{np} and τ_{np}. Moreover, η_{np} is sensitive to the change of E_γ, and τ_{np} - to $P_{3\alpha}$. It is possible to select the conditions ($E_\gamma > 70$ MeV for η_{np} and $P_{3\alpha} < 110$ MeV for τ_{np}) under which events, corresponding to a pure pole diagram are distinguished.

CONCLUSIONS

Using a spectrometer based on a diffusion chamber, which is placed in the magnetic field, the $^{14}N(\gamma,np)3\alpha$ reaction was researched in the energy range from the reaction threshold up to 150 MeV. The reaction yield was measured and it was determined that the distribution has a broad resonance centered at 40 MeV. The distribution functions of the energy and momentum of the final particles from the total energy dependence of the reaction T_0 were measured and it was determined that at $T_0 > 20$ MeV occurs the change in the behavior of these functions. The distributions for the neutron and proton have a strong shift of the maximum towards higher energies with an increase in the energy of the γ quantum and for a system of 3α-particles; the peak is observed centered at 100 MeV/*c*. The energy and angular correlations of the np-pair are dependent on both the energy E_γ and the momentum of the system of 3α-particles.

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ДОСЛІДЖЕННЯ РЕАКЦІЇ $^{14}N(\gamma,np)3\alpha$ ПРИ $E_\gamma^{макс}$ = 150 МеВ

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Виконано дослідження реакції $^{14}N(\gamma,np)3\alpha$ за допомогою дифузійної камери, розміщеної в магнітному полі. і опроміненої гальмівними фотонами з кінцевою енергією E_γ^{max} = 150 МеВ. Виміряно функції розподілу виходу реакції, енергії та імпульсу кінцевих частинок в залежності від E_γ і встановлено, що при $E_\gamma > 45$ МеВ відбувається зміна поведінки цих функцій. Середню енергію T^{aver} було розраховано для частинок з енергією, що потрапляє в інтервал 1 МеВ від повної кінетичної енергії $T_0 = E_\gamma$ - Q, де Q – енергетичний поріг реакції (Q = 19.77 МеВ). При $T_0 > 20$ МеВ , залежність вкладів T^{aver} частинок до T_0 різко змінюється. При $T_0 > 20$ МеВ більшу частину енергії забирають нуклони, їх відносний внесок однаковий і це узгоджується з припущенням про механізм взаємодії γ-кванта з квазідейтроном. Розподіли імпульсів для нейтрона та протона мають подібний вигляд, із сильним зсувом максимуму в бік високих енергій із збільшенням енергії γ-кванту. Для системи 3α-частинок у кожному розподілі спостерігається пік з центром при 100 МеВ/с, відносний внесок якого плавно спадає із збільшенням імпульсу і з'являється широкий високоенергетичний «хвіст». Енергія та кутові кореляції np-пари залежать як від енергії E_γ, так і від імпульсу системи 3α-частинок.

Ключові слова: дифузійна камера, фотореакції, ядро ^{14}N, np-пара, енергетичні та кутові розподіли.