THREE-BODY PHOTODISINTEGRATION OF ^4He NUCLEUS BY LINEARLY POLARIZED PHOTONS

A. A. Peretiatko, R. T. Murtazin*, A. F. Khodyachikh

Institute of High-Energy Physics and Nuclear Physics, NSC KIPT, 61108, Kharkiv, Ukraine

(Received February 27, 2018)

Experimental data are reported from studies of the reaction $^4He(\gamma,\, pn)d$ through the use of the streamer chamber placed in the magnetic field and exposed to a linearly polarized photon beam from the electron linac LUE-2000. A structure has been revealed in the momentum distribution of deuterons. Studies were made into the effects of nucleon-deuteron correlation. The azimuthal distribution of reaction products and the asymmetry of proton production cross-section were measured. The obtained data were analyzed in the framework of the quasideuteron model.

PACS: 25.20.-x

1. INTRODUCTION

The photonuclear reactions with two-nucleon yield are used as a tool for investigating nucleon correlations. At energies up to the meson production threshold, the photon contributes a low momentum to the nucleus. High nucleon momenta can be attained due to momentum distribution of nucleons and their correlations in the nucleus.

In this context, the $^4He(\gamma,\, pn)^2H$ reaction has been chosen for the studies. The reaction products have no excited states, and this facilitates the kinematic analysis of the experimental results. As the number of nucleons is small, it can be expected that the distortions caused by the final state interaction (FSI) would be insignificant. Therefore, the $^4He(\gamma,\, pn)^2H$ reaction yield, measured with respect to the kinematic parameters of reaction products and their angular and energy correlations, will be of use for identification of the reaction mechanism. Being the few-nucleon system, the ^{4}He nucleus has been the subject of intensive theoretical investigations. The experimental information on the angular and energy correlations is of importance for verifying the theoretical predictions. At subthreshold meson production energies, the $^4He(\gamma,\, pn)^2H$ reaction was investigated many times, using the Wilson chamber [1] and diffusion chambers [2-5] on bremsstrahlung beams of unpolarized photons. The main result of those studies was the statement that it was the quasideuteron mechanism that was predominant at those energies. According to the quasideuteron model, the deuteron is considered to be a spectator. Therefore, it is hoped that the investigation of its yield may provide information of the FSI.

In the bremsstrahlung beam experiment using the diffusion chamber, the reaction cross-section measured as a function of the deuteron momentum has exhibited the peak at about 87 MeV/c [6]. The maximum position of the peak and its width are independent of the photon energy. As the momentum increases, the cross-section smoothly decreases. The result has been explained within the frame of the quasideuteron model, where the FSI is absent. At high momenta, the FSI manifests itself. The result is an agreement with the mechanism represented by a triangular diagram. The models provide explanation of the angular and energy correlations of nucleons both in the region of the peak and at high deuteron momenta.

In the $\gamma +^4 He \rightarrow p + n + d$ reaction induced by linearly polarized photons, the investigation of polarization effects enables one to obtain additional information of the reaction mechanism.

2. EXPERIMENTAL TECHNIQUE

The experiment was carried out with the use of a streamer chamber placed in a magnetic field of 10 kGs intensity. The chamber was filled with helium to a pressure of 1 atm, and was exposed to linearly polarized photons produced during coherent deceleration of 600, 800 and 1200 MeV electrons by a diamond crystal. The peaks of photon spectra showed up at energies of 40, 60 and 80 MeV. The energy dependence of the average degree of photon polarization P_γ resulting from summation of three spectra, was estimated in the range from 25 to 100 MeV with the use of the results from paper [7] dedicated to a detailed study of energy and polarization properties of those spectra. The polarization varies only slightly with energy, and its average value in the range under study is found to be $P_\gamma = 54\%$. The magnetic field direction and the directions of main optical axes of three camera lenses are in line with the OZ axis.

*Corresponding author E-mail address: rumurtazin@gmail.com

The OX axis is directed along the beam. The photon polarization vector makes the angle $\alpha = -45°$ with the OZ axis. With reduction in the angle between the charged particle momentum and the OZ axis, the accuracy of momentum measurement and identification gets worse because of reduction in the projected track length on the plane perpendicular to the magnetic field vector.

For this reason, the restriction was imposed on the directional cosine of the particle momentum $|n| < 0.71$. The azimuthal angle φ is more conveniently reckoned from the OZ axis. It is expected that the azimuthal distribution of the events in the ranges $45° < \varphi < 135°$ and $225° < \varphi^{'} < 315°$ will be the same. Therefore, the events falling within the second range were entered in the first range, assuming that $\varphi = \varphi^{'} - 180°$.

3. DEUTERON MOMENTUM DISTRIBUTION

Fig.1 shows the reaction yield distribution in the deuteron momentum modulus of P_d for photon energies ranging from threshold up to $150\,MeV$.

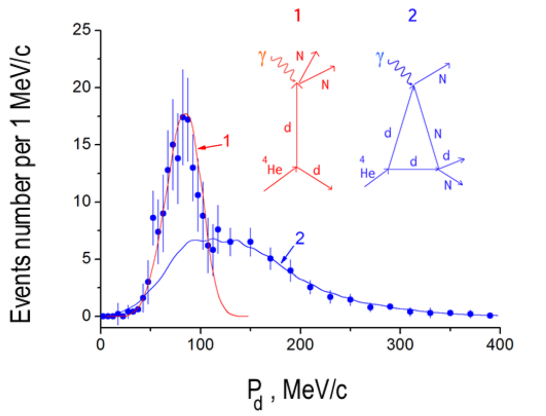

Fig.1. *Events distribution versus deuteron pulse*

The dots are marked in the middle of the histogram step. The distribution exhibits the structure, viz., the peak with the maximum at $P_d = 84 \pm 2\,MeV$, and a smooth yield reduction with the momentum increase over $100\,MeV/c$. For the analysis of the experimental data, the simplest models of the quasideuteron mechanism were used; they are depicted in the inset in Fig.1. One is the pole diagram, where the nucleons leave the nucleus without interaction with the deuteron. The other is the triangular diagram representing the process with due regard for the nucleon-deuteron interaction. The models were used to generate the reaction events by the Monte-Carlo technique. For the peak the experimental deuteron photodisintegration data were used. The final-state nucleon-deuteron interaction was treated as the elastic scattering of the nucleon by the deuteron. We have used a similar simulation procedure for this reaction on the unpolarized beam [6]. The pole diagram calculation is represented in Fig.1 by curve 1. In simulation, the error of the deuteron momentum measurement, equal to 7%, was taken into account. The calculation was normalized to the experimental peak value. The calculated curve shape is found to be in agreement with the experiment. Curve 2 represents the triangular diagram calculation, which was normalized to the area under the experimental curve at the momenta exceeding $100\,MeV/c$. The calculation is found to be in agreement with the experiment. On the assumption of the validity of this representation, the ratio of the area under curve 2 to the area under the experimental curve can be considered as the estimate of the FSI contribution, found to be $\eta = 0.74 \pm 0.06$. The deuteron momentum values P_d up to $100\,MeV/c$ and above will serve as the parametric variables in the further analysis of the results.

4. DEUTERON-NUCLEON CORRELATIONS

The analysis of the deuteron momentum distribution has led to the conclusion about the presence of FSI in the reaction under study. However, the manifestation of FSI is also possible in the particle correlation. Figure 2a shows the event distribution in the kinetic energy of relative motion of the nucleon and the deuteron in their rest frame: $E_{Nd} = ((E_N + E_d)^2 - (P_N + P_d)^2)^{\frac{1}{2}} - m_N - m_d$, where E_N, P_N, E_d, P_d, m_N and m_d are, respectively, the total energies, momenta and masses of the particles.

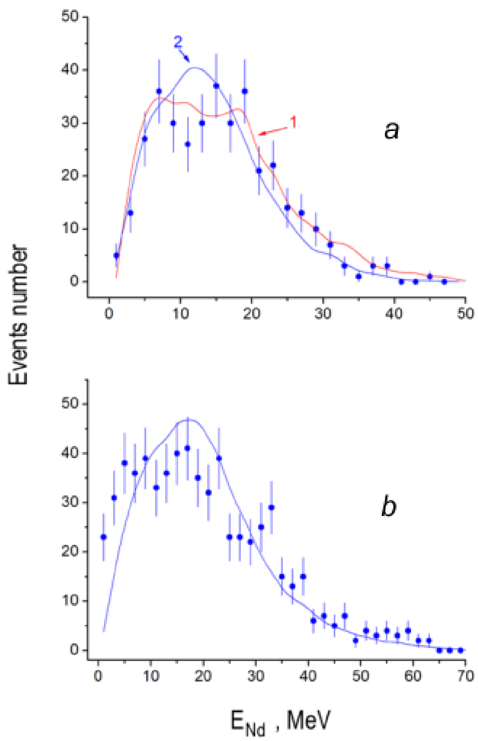

Fig.2. *Energy of relative motion of nucleon and deuteron*

The events were taken with the deuteron momentum P_d to be below $100\,MeV/c$. Curve 1 corresponds to the pole diagram. Curve 2 is the calculation by the triangular diagram model. The two curves are normalized to the experiment areas. At the deuteron momenta below 100 MeV/c the both models show agreement with the experiment.

Fig.2,b shows the event distribution with the deuteron momentum P_d higher than 100 MeV/c. The curve shows the triangular diagram calculation normalized to the experiment. There is agreement between theory and the experimental data. The pole diagram gives no contribution.

The events distribution with P_d below 100 MeV/c in the divergence angles of nucleon and deuteron is shown in Fig.3,a. Curves 1 and 2 represent the calculations by the pole diagram and the triangular diagram, respectively. In simulation, as in the experiment, restrictions were imposed on the angle of vertical position of the particle pulses. The calculation data are normalized to the area under the experimental curve. The both models are in agreement with experiment.

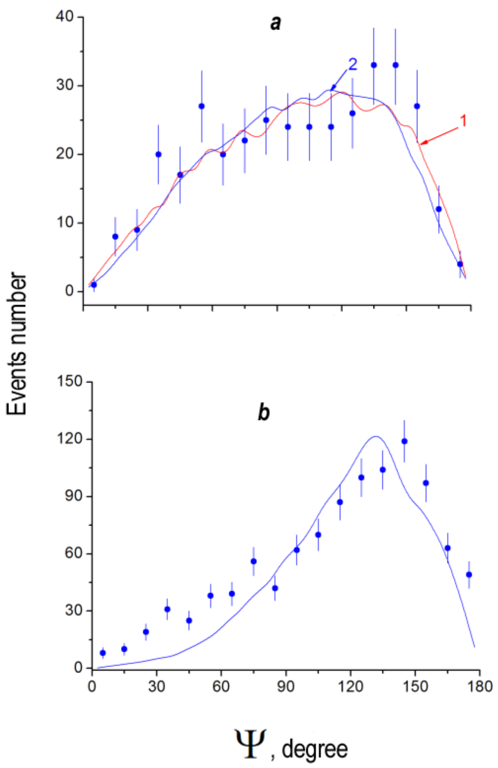

Fig.3. *Recession angle of nucleon and deuteron*

Fig.3,b shows the event distribution with the momentum P_d higher than 100 MeV/c. The curve represents the calculation in the context of the triangular diagram. The simulation was carried out on the same assumptions as those for the curves of Fig.3,a. The calculation data were normalized to the experimental peak. The figure shows a satisfactory fit of the curve shapes. The pole diagram gives no contribution.

5. THE POLARIZATION EFFECTS

Polarized photons provide additional observables for verification of the models. Reasoning from the measurement accuracy requirements for kinematic parameters, restrictions were introduced on the angle of proton and deuteron verticality so that the projections of their directional cosines onto the OZ axis were $|n_p| < 0.71$ and $|n_d| < 0.71$.

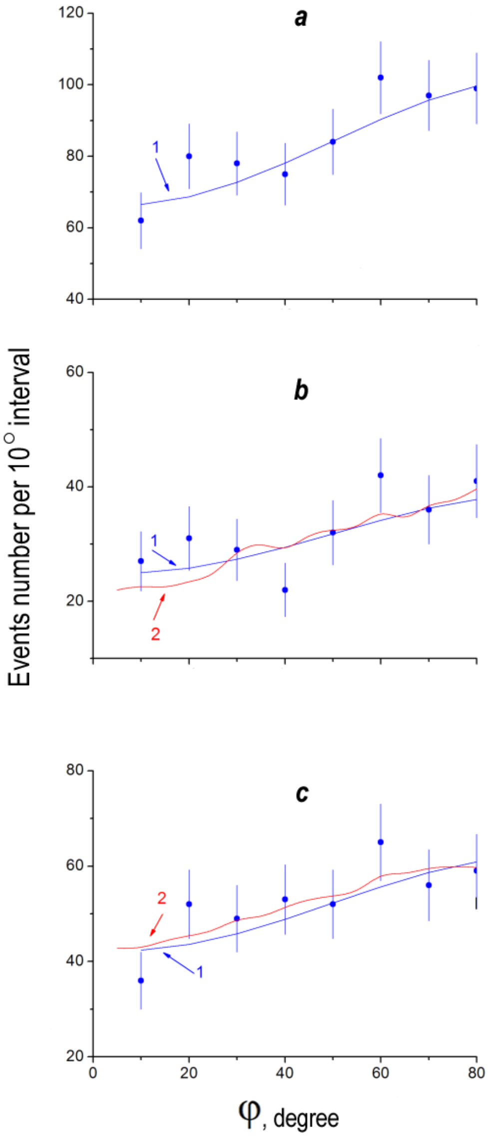

Fig.4. *Azimuthal distribution of protons*

Within the limits of the pole model, considering the unpolarized beam, we have checked the isotropy of azimuthal proton and deuteron distributions in the experimentally allowed region. Since the nucleons are correlated, the azimuthal distribution of the neutron is non-isotropic because of the restrictions on the proton verticality angle. Therefore, it is not analyzed in the given experiment.

Fig.4,a illustrates the event distribution in the azimuthal angle of the proton, reckoned from the polarization vector direction. The photon energy ranges from 30 to 100 MeV. The deuteron momentum is not limited. Visually, the yield increase can be noticed with an increasing azimuthal angle. As a result of the distribution approximation by the function $f(\varphi) = a(1 + p \cdot \cos(2\varphi))$, we have obtained the asymmetry coefficient $p = -0.21 \pm 0.06$. The function $f(\varphi)$ is represented by the curve 1.

Fig.4,b shows the azimuthal distribution of protons from the events, where $P_d < 100\,MeV/c$. The increase in the yield becomes obvious as the azimuthal angle increases. The approximation of the distribution by the function $f(\varphi)$ has given the asymmetry coefficient $p = -0.23 \pm 0.09$. The function $f(\varphi)$ is shown by curve 1. The pole diagram calculation is represented by curve 2. The simulation was made in the assumption that $p = P_\gamma \Sigma$, where P_γ is the degree of beam polarization, Σ is the cross-section asymmetry.

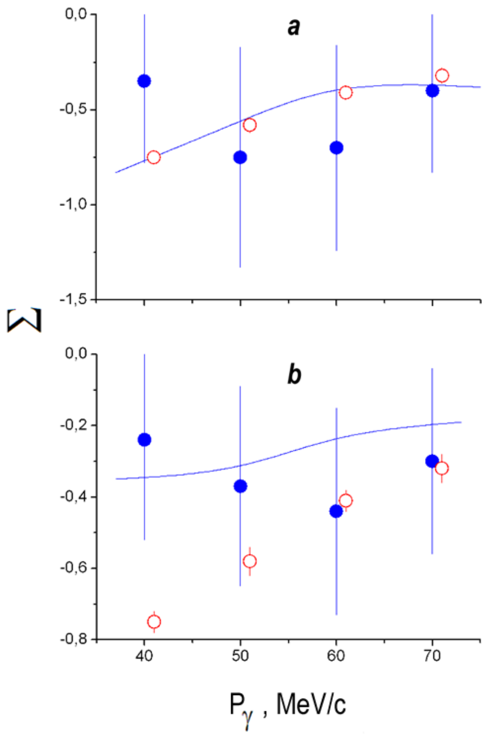

Fig.5. *Cross-section asymmetry*

Depending on the energy, the Σ value was taken from ref. [8]. The calculated and experimental data were normalized to the area. The model is consistent with the experiment.

Fig.4,c gives the events distribution with the deuteron momentum being higher than $100\,MeV/c$. The yield growth is noticeable with an increase in the azimuthal angle. The approximation by the function $f(\varphi)$ has given $p = -0.16 \pm 0.07$. The data calculated with the function f(φ) are shown by curve 1.The simulation was carried out using the triangular diagram model. The result is represented by curve 2. The calculation was normalized to the experiment. The triangular diagram predicts the slope of the curve in accordance with experiment.

The parameter p can be used to determine the cross-section asymmetry by using the relation $p = P_\gamma \Sigma$ [8]. For determining Σ, azimuthal distributions of protons were plotted for $10\,MeV$ photon energy intervals, and the parameter p in each interval was determined. The full circles in Fig.5,a show the proton Σ value, averaged in the polar angle versus the photon energy. The events with P_d lower than $100\,MeV/c$ were taken. A weak decrease in the asymmetry with increasing photon energy can be seen in the figure. The curve shows the Σ model in the framework of the pole diagram. A slight change in the asymmetry is predicted as its absolute value decreases. Within the experimental error, the calculation is in agreement with the experiment. In Fig.5,b, the full circles show the polar angle-averaged Σ as a function of the photon energy for the events with the deuteron momentum higher than $100\,MeV/c$. The asymmetry is practically independent of the photon energy. The Σ model shown by the line in the framework of the triangular diagram is in agreement with the experiment. The empty circles show Σ from the deuteron photodisintegration reaction at a polar proton-yield angle of 90° [8]. Fig.5,a shows the agreement between the data in both the magnitude and their trend to change with increasing energy. The model agrees with the deuteron photodisintegration data. The momentum distribution of quasideuterons at photon absorption does not distort the asymmetry of the cross-section. In Fig.5,b the mode of asymmetry behavior is different. At lower energies the divergence is noticeable. This may be attributed to the final-state interaction, the influence of which increases with energy decrease.

6. DISCUSSION OF RESULTS AND CONCLUSIONS

The analysis of the $^4He(\gamma, pn)^2H$ reaction yield in the deuteron momentum has led to the conclusion that at subthreshold meson production energies two models of the quasideuteron mechanism (pole and triangular diagrams) prevail. That has induced us to estimate their relative contributions, which were found to be $\rho = 0.26 \pm 0.05$ and $\eta = 0.74 \pm 0.06$ for the pole diagram and triangular diagram, respectively. If we denote the probability of nucleon final-state interaction by α, then the probability for the two nucleons not to enter into interaction is $(1-\alpha)^2 = \rho$. Hence, we have $\alpha = 0.49 \pm 0.04$. This value is in agreement with the average value $\alpha = 0.50 \pm 0.03$, obtained with the nonpolarized beam [6] at energies up to $150\,MeV$.

At photon energies between 150 and $250\,MeV$ [9], $\alpha = 0.15$. The disagreement may be due to the difference in energies.

The maximum in the momentum distribution of α-particles in the $^6Li(\gamma, np)\alpha$ reaction is observed at $\sim 60\,MeV/c$ [10]. $^3He(\gamma, np)p$ reaction caused by $\sim 245\,MeV$ photons, the spectrum of lower energy protons exhibits the maximum in the region of $110\,MeV/c$ [11]. The reaction $^4He(\gamma, npp)n$ [12] has been investigated at energies of about $300\,MeV$. The mechanism of photon absorption by three nucleons has been established. In the momentum distribution of the spectator, the maximum has been revealed at $\sim 120\,MeV/c$. In the helium isotope reactions caused by photons of different energies, the momentum distributions of nucleons-spectators have appeared to be coincident in shape. For the lightest nuclei, the peak positions for the spectator, P_i, and the deuteron, P_d, can be related by $P_i \approx P_d(m_d/m_i)^{\frac{1}{2}}$, where m_d and m_i denote the mass of the deuteron and the spectator, respectively. It is of interest to verify this relation for other p-shell nuclei. Search must be made to find the explanation for both the energy independence of maximum positions in the spectral distribution of deuterons, and the high threshold of the deuteron yield equal to 50 MeV/c.

References

1. A.N. Gorbunov, V.M. Spiridonov. Photodisintegration of He III // *JETP*, 1958, v.34, p.866-873 (in Russian).
2. Yu.M. Arkatov, P.I. Vatset, V.I. Voloshchuk, V.N. Gur'ev, A.F. Khodyachikh. Photodisintegration of ^4He nucleus down to threshold of Meson production // *UJP*. 1978, v.23, p.1818-1840 (in Russian).
3. Yu.M. Arkatov, P.I. Vatset, V.I. Voloshchuk, V.N. Gur'ev, V.A. Zolenko, I.M. Prokhorets. The Pole Mechanism of Three-Particle Photodisintegration of ^4He // *Yad. Fiz.* 1980, v.32, p.5 (in Russian).
4. V.A. Zolenko. *The γ-quantum absorption mechanism at three-particle helium disintegration*/ Ph. D., Kharkov State University. 1981 (in Russian).
5. F. Balestra, E. Ballini, L. Busso, et al. Photodisintegration of ^4He in the giant - resonance region // *Nuov. Cim.* 1977, v.38a, p.145-166.
6. A.F. Khodyachikh, E.S. Gorbenko, R.T. Murtazin. Investigation of the reaction $^4He(\gamma,pn)d$ at energies below the Meson-Production threshold // *Yad. Fiz.* 2017, v.80, N1, p.1-7 (in Russian).
7. Yu.P. Lyakhno. *The investigation of mechanisms of two-particle (γ,p)- and (γ,n)- reactions of ^4He nucleus photodisintegration with bremsstrahlung and linearly polarized photons with energy below* 100 MeV/ Ph. D., NSC KIPT, Kharkov, 2007 (in Russian).
8. V.P. Barannik, V.G. Gorbenko, V.A. Gushchin, Yu.V. Zhebrovsky, L.Ya. Kolesnik, Yu.V. Kulish, A.L. Rubashkin, P.V. Sorokin. Investigation of asymmetry of cross-sections of deuterium photodisintegration induced by low energy polorized γ - quanta // *Yad. Fiz.* 1983, v.38, N5, p.1108-1110 (in Russian).
9. M.Q. Barton, J.H. Smith. Correlated Neutron-Proton pair from the High-Energy Photodisintegration of Helium and Litium // *Phys. Rev.* 1958, v.110, N5, p.1143-1155.
10. M.W. Wade, M.K. Brussel, L.J. Koester, J.H. Smith. Onset of quasideuteron photodisintegration in ^6Li between 25 and 65 MeV // *Phys. Rev. Let.* 1984, v.53, p.2540-2543.
11. T. Emura, S. Endo, G.M. Huber, H. Itoh, et al. Three-body ^3He photodisintegration in the Δ region // *Phys. Rev.* 1994, v.C49, p.R597-R600.
12. T. Emura, I. Endo, S. Endo, H. Itoh, S. Kato, et al. Measurement of the $^4He(\gamma,npp)n$ reaction in the Δ-resonance region // *Phys. Lett.* 1991, v.B267, p.460-464.

ТРЕХЧАСТИЧНОЕ ФОТОРАСЩЕПЛЕНИЕ ЯДРА ^4He ЛИНЕЙНО ПОЛЯРИЗОВАННЫМИ ФОТОНАМИ

А. А. Перетятько, Р. Т. Муртазин, А. Ф. Ходячих

Представлены экспериментальные результаты исследования реакции $^4He(\gamma,pn)d$, полученные с помощью стримерной камеры в магнитном поле, облученной пучком линейно поляризованных фотонов от ускорителя ЛУЭ-2000. В импульсном распределении дейтронов обнаружена структура. Исследованы эффекты корреляции нуклона и дейтрона. Измерено азимутальное распределение продуктов реакции и асимметрия сечения образования протона. Результаты проанализированы в рамках квазидейтронной модели.

ТРИЧАСТИНКОВЕ ФОТОРОЗЩЕПЛЕННЯ ЯДРА ^4He ЛІНІЙНО ПОЛЯРИЗОВАНИМИ ФОТОНАМИ

О. О. Перетятько, Р. Т. Муртазін, О. Ф. Ходячих

Надано експериментальні результати реакції $^4He(\gamma,pn)d$, які одержано за допомогою стримерної камери в магнітному полі, що опромінювалась пучком лінійно поляризованих фотонів від прискорювача ЛПЕ-2000. В імпульсному розподіленні дейтронів знайдено структуру. Досліджено ефекти кореляції нуклона і дейтрона. Виміряно азимутальне розподілення продуктів реакції та асіметрію перерізу створення протона. Результати проаналізовано в рамках квазідейтронної моделі.