PHOTONUCLEAR REACTIONS ON *p*-SHELL NUCLEI AT INTERMEDIATE ENERGIES

A.F. Khodyachikh

National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine
e-mail: mailto: akhod@kipt.kharkov.ua

Absolute total and differential cross sections for (γ,p)-, (γ,n)- and (γ,pn)- reactions on the ^{12}C, ^{14}N and ^{16}O nuclei have been measured using a diffusion chamber placed in a magnetic field and irradiated by a beam of bremsstrahlung photons with an end-point energy of 150 MeV. The applicability of photoabsorption model on a correlated proton-neutron pair was proved. It is concluded that models with essential contribution of meson exchange currents provide a qualitative description of energy dependence of total and differential cross sections at energies above 50 MeV.

PACS: 25.20-x

1. INTRODUCTION

For many years the reaction mechanisms leading to the knock out of one or two nucleons from nuclei by a real photon of intermediate energies have been the subject of a discussion. The basic aim of photonuclear interaction investigations was establishment of a reaction mechanism and specification of nuclear models. A model construction of photonuclear reactions with knock out of one nucleon fell to its way from the model of the direct mechanism in base of which lie one-particle currents and impulse approximation [1]. The two-particle effects were taken into account by the phenomenological quasideuteron model [2]. The modified quasideuteron interpretation was introduced in order to explain how the momentum mismatch in the (γ,p) and (γ,n) reactions may be overcome. Later this model was developed by introducing nucleon-nucleon correlations [3], which was realized through meson-exchange currents [4]. Reactions with two nucleons in final state always were a source of information about nucleon correlations on small and middle distances. The microscopic models which have been presented recently [5,6] introduced a formal description of the previous concepts. An attempt was made to incorporate shell model contributions, nucleonic correlations and meson-exchange currents.

And now the role of meson-exchange currents in photonuclear reactions is under intensive investigation. The one-particle model explained the photoproduction of residual nuclei in ground and low excited states. Here the role of meson-exchange currents is not large [7]. Theory predicts that with the growth of residual nucleus excitation energy the contribution from meson-exchange currents becomes dominant [6]. Therefore, the experimental data on photoproduction of high-excited states of nuclei were important. As a rule, these nuclei break up to hadrons forming multiparticle photonuclear reactions. Analyzing decay modes it is possible to select a certain excited states of residual nuclei almost without a background. The problem of exclusive event selection could be solved by means of a track 4π-detector registering all charged particles in a final state. The decay products have small energies. The diffusion chamber combining a gas target with a detector, became the effective instrument for research of multiparticle photonuclear reactions in KIPT.

2. EXPERIMENTAL METHOD

For research of interaction mechanisms of electromagnetic radiation with light and lightest nuclei in KIPT the experimental complex was created on the basis of the diffusion chamber [8] that was positioned in a magnetic field of strength 1.5 T and irradiated by a beam of bremsstrahlung photons with an end-point energy of 150 MeV. To decrease a target density the chamber was filled by 13 % mixture of a methane, oxygen or nitrogen with helium in the experiments of the *p*-shell nucleus photodesintegration. Owing to the gas filling, the tracks of slow residual nuclei had measurable lengths, and their images on a photographic film were sufficiently clear at pressures close to an atmospheric one. A large angular coverage and low density of the detector medium made it possible to measure the angular distributions of all charged products of multiparticle photonuclear reactions in a broad energy range. To suppress the soft component of the bremsstrahlung spectrum, which produced a high electron flux in the chamber a beryllium filter having thickness of 2.5 radiation lengths was used. The Schiff distribution of the photon spectrum was corrected for a nonuniform suppression by the filter. The method of an event reconstruction [9] on the basis of point coordinates that were measured by means of semiautomata PUOS-1 along tracks and complex of programs for its implementation on computers were created.

3. EXPERIMENTAL RESULTS

3.1 A(γ,p)(A-1*)* REACTIONS ON ^{12}C AND ^{16}O NUCLEI

Our experiments on two-particle photodesintegration of ^{12}C [10] and ^{16}O [11] nuclei started at the time when there was competition of the compound nucleus and direct mechanism models in explanation of experimental data at energies of the giant resonance region and above it. The cross section measurements were fulfilled at energies from a reaction threshold up to a meson production region overlapping the applicability areas of the models such as a compound nucleus, a direct mechanism and absorption by nucleon pairs. The total cross section of the $^{12}C(\gamma,p)^{11}B$ reaction is shown in Fig. 1 [10]. Curve 1 shows the theoretical prediction of the direct mechanism model [1]. The energy dependence of the total cross section, predicted by this model, was confirmed by these experiments in the energy range of the giant resonance, and rejected above it. At intermediate energies the experimental results have found explanation in photoabsorption models by nuclear clusters: quasideuteron [2,3] (curves 2 and 3) and quasialfaparticle [12] (curve 4). The experimental results have shown applicability of the quasideuteron model at energies above 50 MeV, whereas earlier theory predicted its applicability above the meson production threshold.

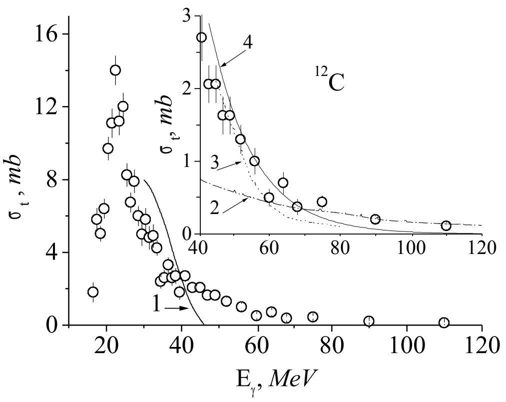

Fig. 1. *The $^{12}C(\gamma,p)^{11}B$ total cross section vs the photon energy*

In pure dipole approximation separated from the *p*-shell protons have their angular distribution (s.c.) $d\sigma/d\Omega \sim (a+b\sin^2\theta)$ with $a/b=2/3$. The energy dependence of the ratio *a/b* is shown in Fig. 2 [10,11]. At energies of the giant resonance the experimental data are consistent with the ratio a/b=2/3 (curve 1) and confirm the applicability of the direct mechanism model. Above the resonance the value *a/b* decreases drastically.

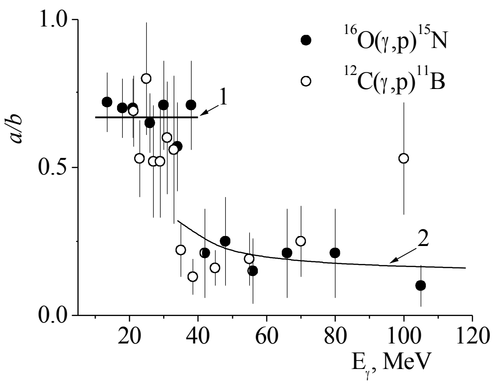

Fig. 2. *The a/b ratio vs the photon energy*

The quasideuteron model (curve 2) explained its energy dependence at the intermediate energies. In these two reactions such a leap change of the parameters was observed for the first time.

3.2. A(γ,pn)(A-2) REACTIONS ON ^{12}C, ^{14}N AND ^{16}O NUCLEI

Photonuclear reactions at energies above the giant resonance provide an efficient tool for studying intranuclear nucleon correlations, because the energy introduced in the irradiated nucleus by a real photon must be divided between the correlated nucleons to satisfy momentum conservation. Therefore, investigations of reactions featuring two final-state nucleons and having a branching fraction that grows with increasing energy can furnish important information about the nucleon correlations. In the microscopic approach to a description of (γ, pn) reactions the model of photo-absorption by nucleon pairs predicts different behaviour of partial cross sections appropriate to knock-out of nucleons from different shells. A nucleon separation from the *s*-shell results in a high excited state formation of residual nuclei which as a rule break up into particles, which can be registered by this experimental method. At the energies close to a giant resonance a reaction mechanism manifestation may be masked by a final state interaction (FSI). Therefore, an experimental investigation of the (γ, pn*)* reactions at the energies from a giant resonance to the meson production threshold was an actual problem.

The total and differential cross-sections of the (γ,pn) reactions were measured on ^{12}C [13-17], ^{14}N [18], and ^{16}O [19,20] nuclei. A typical energy dependence of the total cross-section of the (γ,pn) reaction on ^{12}C [13] is shown in Fig. 3.

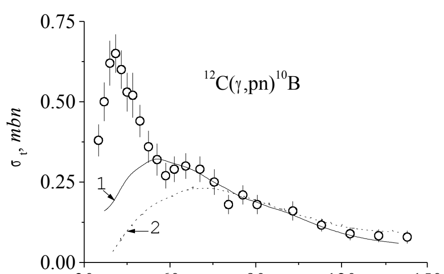

Fig. 3. *Total cross section vs the photon energy*

Curve 1 shows the normalized result of Hebach et al. [3]. It represents the cross section of photon absorption by a correlated nucleon pair from *p*-shell in the dipole approximation. In their model, nucleons forming the pair exchange by the meson at the instant of photon absorption, and final state interactions were disregarded. The predicted energy dependence does not contradict the experimental data. The doted curve corresponds to the normalized calculation [3] assuming the nucleons were from different shells. It is clear that the contributions of transition with nucleons from the different shells are small.

In the traditional quasideuteron model of Levinger [2] the cross section of the (γ,pn) process on nuclei is proportional to the cross section of the deuteron photodesintegration. The ratios of total cross sections are shown in Fig. 4. The proportionality occurs at the energies above 50 MeV. Boato and Giannini [21] refined the quasideuteron model taking into account the meson exchange currents. According to this model, a photon interacts with a *pn* pair whose nucleons are located at the same point and exchanged the momentum *q*.

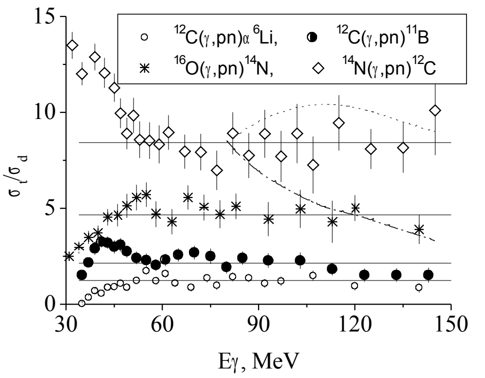

Fig. 4. *Energy dependence of the total cross section ratios to the deuteron photodesintegration cross section. The solid lines represent averaged values over the 50-150 MeV interval*

The rate of variation of the cross section with increasing energy depends on *q*: the greater *q*, the lower the rate at which the cross section decreases. The doted and dash–doted curves in Fig. 4 represent the normalized at 80 MeV ratio of the calculated cross sections to the deuteron cross section for the values *q*=0.4 and 1.2 fm^{-1}. The agreement with the experimental data becomes for *q*≈1 fm^{-1}. The data confirmed the quasideuteron model at energies above 50 MeV. One of manifestations that photon interact with a correlated pn-pair is more often appearance of the nucleon pairs with the higher energy, than it is expected on the basis of the statistical model. In Fig. 5 the distribution of events (points) is shown as a function of t that is equal to the ratio of s.c. pn-pair energy to total energy in s.c. of the $^{12}C(\gamma, pn)\ ^{10}B$ reaction. The nucleon pairs take a grater part of the total energy than the statistical model (curve 1) predicts. There are no theoretical calculations of the relative energy *pn*-pair distribution for photoreactions. The comparison is performed with the normalized calculation $d\sigma/dt$ for the $^{12}C(\pi^-,pn)^{10}B$ reaction [22], that is possible only if a meson is absorbed by a correlated nucleon pair. The solid line (curve 3) shows the cross section of the both nucleons separation from the *p*-shell, and the doted line (curve 2) shows the same but when both nucleons are from *s*-shell. The experimental results are in a good agreement with the theoretical prediction when both nucleons were separated from the *p*-shell.

In the model of photon absorption by a nucleon pair, the residual nucleus is a spectator. Therefore, it is natural to expect that its angular distribution will be isotropic in the laboratory frame. In Fig. 6 the asymmetry of the angular distributions β_r for the residual nuclei *l.s.* is shown *vs* the photon energy [23]. Within errors, this asymmetry takes the same value for the corresponding particles from the two reactions. In region of intermediate energies, there are distortions in the A(γ,pn)(A-2) reaction induced by the final state interaction. In the quasideuteron model, the asymmetry of the angular distribution of a residual nucleus can be due to FSI: nucleons travelling predominantly in the forward direction transfer a part of their momentum to a residual nucleus. A calculation within the quasideuteron model that takes into account FSI in the simplest form (the curve in Fig. 6) satisfactorily describes the experimental data.

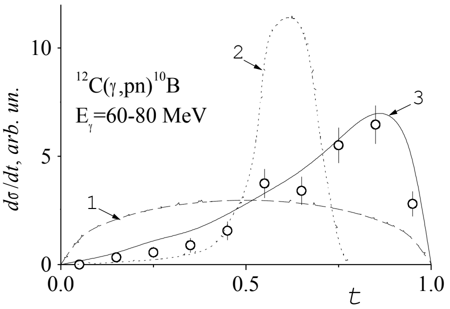

Fig. 5. *The relative energy distribution*

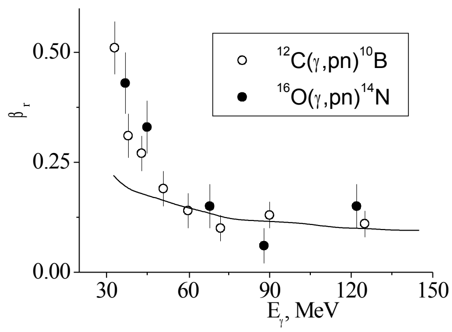

Fig. 6. *Asymmetry β_r vs the photon energy*

3.3 REACTIONS WITH HADRON DECAYS OF HIGH EXCITED FINAL NUCLEI

In A(γ,p)(A-1)$^*_{\to a+b}$ reactions a high excited final nucleus brakes up into fragments and usually one nucleon takes away the main part of the energy. A type of such reactions predominates up to the meson production threshold. Till now even in the most sequential theoretical analyses the consent about the mechanism of photonuclear reactions with the separation of one nucleon is not reached. Nonrelativistic analyses suggest that the direct knockout contribution is small compared to the data and evinced itself only for low excited ground state transitions. It was concluded that contributions from meson exchange currents must be the main mechanism responsible for the observed cross sections of high-excited final nucleus formation at the intermediate energies. The results are quite different from those of a recent relativistic analysis [24] where it was found that the direct knockout of a single proton by a real photon is the main mechanism responsible for the observed cross sections for missing moment below 500 MeV/c. The contribution of meson exchange currents is important at the energies above the meson production threshold.

The model of the direct mechanism suggested that the characteristics (γ,p) and (γ,n) reactions were essentially different in the intermediate energy interval. Because a neutron has no charge the cross section of (γ ,n) reactions and asymmetry of angular distributions relative to 90° in *s.c.* should be small in comparison with the similar values for (γ,p) reactions. While the model of absorption by nucleon pairs predicted their equality. To verify these hypotheses the mirror $^{12}C(\gamma,p)\alpha^7Li$ and- $^{12}C(\gamma,n)\alpha^7Be$ reactions were

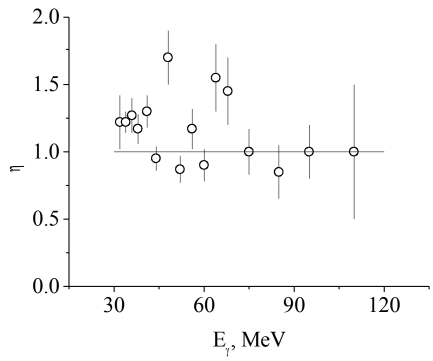

Fig. 7. *The ratio of total cross-sections η vs the photon energy*

investigated [25]. It was concluded that the reactions pass through the two-particle stages resulting in formation of the intermediate nucleus excited states ^{11}B and ^{11}C with excitation energies 11.0±0.3 and 10.6± 0.2 MeV respectively. The ratio of total cross-sections η is shown in Fig. 7 as a function of the energy. The experimental results do not contradict the value $\eta = 1$, that is shown in the figure as a solid line. In Fig. 8 for both reactions the asymmetry coefficient of the angular distributions is represented in the energy dependence. Within the framework of the direct mechanism the behavior of the asymmetry coefficient was explained at the energies below 50 MeV. This model predicted that the coefficient of the $^{12}C(\gamma,n)\alpha^7Be$ reaction is to be small in comparison with the $^{12}C(\gamma,p)\alpha^7Li$ reaction because of the neutron quadruple charge smallness. At higher energies the experimental data rejected the model of the direct mechanism. They were explained within the frameworks of the model of photoabsorption by correlated nucleon *pn* pair when exchange meson currents were taken into account [3]. In this model a photon interacts with π-meson by which nucleons of a pair exchange. According to this model both total cross sections and the angular distributions in two reactions are expected to be identical. At the energies higher 50 MeV experimental results confirm the model of photoabsorption by a nucleon pair.

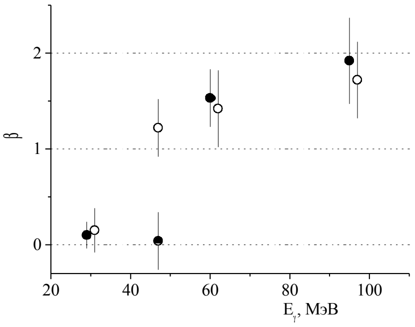

Fig 8. *The asymmetry coefficient vs the photon energy: open circles $^{12}C(\gamma,p)\alpha^7Li$, solid circles - $^{12}C(\gamma,n)\alpha^7Be$*

Within the frameworks of a quasideuteron kinematics one can expect the asymmetry coefficient to decrease with excitation energy of an intermediate nucleus growth [26]. Fig. 9 displays the asymmetry coefficient of the nucleon angular distributions as an excitation energy function of an intermediate nucleus at photon energies 80-100 MeV. The asymmetry coefficient for the final nucleus formation in the ground or low excited states is extracted from angular distributions of carbon and oxygen photodesintegration (solid squares and open circle) [27,28].

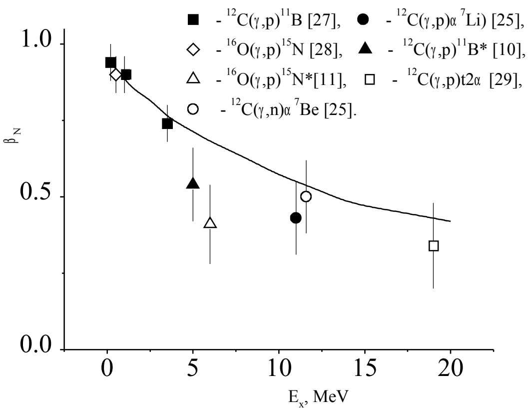

Fig. 9. *The asymmetry coefficient vs the intermediate nucleus excitation energy*

The aggregate of the experimental data exhibits dependence of the asymmetry coefficient on excitation energy of an intermediate nucleus. The curve was calculated in the model of a photon absorption by a correlated nucleon pair [26]. It is consistent with the experimental data.

4. CONCLUSIONS

Absolute total and differential cross sections were measured for (γ,p), (γ,n) and (γ,pn) reactions on the ^{12}C, ^{14}N and ^{16}O nuclei. It was shown that the photon absorption model by a correlated nucleon pair is valid at the energies above the giant resonance in the reactions with one and two nucleons in final states. It was observed a leap change of angular distributions parameters in consequence of a reaction mechanism change.

ACKNOWLEDGMENT

The survey was written making use of the experimental results received in collaboration with Yu.M. Arkatov, V.I. Voloshchuk, V.V. Kirichenko, I.V. Dogyust, V.A. Zolenko, V.P. Yarkov, and V.N. Gur'ev. It is a pleasure to thank V.M. Yarovyenko, A.V. Bazayeva, V.I. Zavertanaya, G.V. Zalimskaya, T.L. Bratashevskaya, L.F. Tsymbalyuk and M.M. Yarovyenko for assistance in running the experiments, and assembly and data taking.

REFERENCES

1. M.G. Mustafa, F.B. Malik. Analysis of the high-energy photonucleon emission from ^{16}O and ^{12}C in a direct model // *Phys. Rev. C.* 1970, v. 1, p. 753-762.
2. J.S. Levinger. The high energy nuclear photo-effect // *Phys. Rev*. 1951, v. 84, p. 43-51.
3. H. Hebach, A. Wortberg, M. Gari. Photonuclear reactions at intermediate eneries // *Nucl. Phys. A.* 1976, v. 267, p. 425-460.
4. R.C. Carrasco, M.J.V. Vacas, E. Oset. Inclusive (γ,N), (γ,NN) and (γ,Nπ) reactions in nuclei at intermediate energies // *Nucl. Phys. A*. 1994, v. 570, p. 701-721.
5. K. Gottfried. On the determination of the nuclear pair correlation function from high energy photo-effect // *Nucl. Phys*. 1958, v. 5, p. 557-587.
6. J. Ryckebusch, M. Vanderhaeghen, L. Machenil, M. Warognier. Effects of the final-state interaction in (γ,pn) and (γ,pp) processes // *Nucl. Phys. A*. 1994, v. 568, p. 828-854.
7. J. Ryckebusch, K. Heyde, L. Machenil et al. Meson exchange currents and high resolution (γ,p) reactions // *Phys. Rev. C.* 1992, v. 46, p. 829-832.
8. Yu.M. Arkatov, P.I. Vatset, V.I. Voloshchuk, E.A Vinokurov, V.L. Marchenko, A.F. Khodyachikh. The setup for investigation of photonuclear reactions // *PTE*. 1969, №4, p. 205 (in Russian).
9. Yu.M. Arkatov, A.V. Bazayeva, P.I. Vatset, V.I. Voloshchuk, A.F. Khodyachikh. *The method of diffusion chamber photographic film processing:* Preprint. Kharkov: KFTI 70-37. 1970, 24p. (in Russian).
10. V.V. Kirichenko, Yu.M. Arkatov, P.I. Vatset, I.V. Dogyust, A.F. Khodyachikh. The $^{12}C(\gamma,p)^{11}B$ reaction at $E_{\gamma max}$=120 MeV // *Yad. Fiz.* 1978 v. 27, p. 588-597 (in Russian).
11. A.F. Khodyachikh, P.I. Vatset, I.V. Dogyust, V.V. Kirichenko. The reaction $^{16}O(\gamma,p)^{15}N$ at $E_\gamma \leq 120$ MeV // *Ukr. Phys. Journ*. 1980, v. 25, p. 229-234 (in Russian).
12. V.M. Mamasahlisov, R.I. Dzibuti. High energy photodesintegration of ^{9}Be and ^{12}C nuclei // *JETF.*1961, v. 41, p. 1493-1497 (in Russian).
13. A.F Khodyachikh, P.I. Vatset, I.V. Dogyust, V.A. Zolyenko, V.V. Kirichenko. Correlated np pairs from *p*-shell of the carbon nucleus // *Yad. Fiz.* 1980, v. 32, p. 881-884 (in Russion).
14. A.F. Khodyachikh, P.I. Vatset, V.N. Guryev, I.V. Dogyust, V.V. Kirichenko. Momentum distribution of quasideutrons in the *p* shell of carbon nucleus // *Yad. Fiz.* 1981, v. 34, p. 1425-1430 (in Russion).
15. I.V. Dogyust, P.I. Vatset, V.V. Kirichenko, A.F. Khodyachikh. Differential cross sections for the reaction $\gamma+^{12}C\rightarrow p+n+^{10}B$ // *Yad. Fiz.* 1982, v. 35, p. 810-813 (in Russion).
16. I.V. Dogyust, V.I. Voloshchuk, V.V. Kirichenko, A.F. Khodyachikh. Correlated effects in the reaction $\gamma+^{12}C\rightarrow p+n+\alpha+^{6}Li$ at intermediate energies // *Ukr. Phys. Journ*. 1982, v. 27, p. 1465-1469 (in Russian).
17. I.V. Dogyust, V.I. Voloshchuk, V.V. Kirichenko, A.F. Khodyachikh. Differitial cross-sections of the reaction products from $\gamma+^{12}C \rightarrow p+n+\alpha+^{6}Li$ at intermediate energies // *Ukr. Phys. Journ*. 1983, v. 28, p. 966-969 (in Russian).
18. I.V. Dogyust, A.F. Khodyachikh, V.P. Yarkov. $^{14}N(\gamma,pn)^{12}C$ reaction up to meson production threshold // *Yad. Fiz.* 1995, v. 58, p. 773-778 (in Russion).
19. V.I. Voloshchuk, I.V. Dogyust, V.V. Kirichenko, A.F. Khodyachikh. The reaction $^{16}O(\gamma,pn)^{14}N$ at energies up to 150 MeV // *Ukr. Phys. Journ*. 1989, v. 34, p. 511-515 (in Russian).
20. A.F. Khodyachikh, I.V. Dogyust. Reactions A(γ,pn)(A-2) on *p*-shell nuclei // *Ukr. Fiz. Zh.* 1995, v. 40, p. 648-654 (in Russion).
21. L. Boato, M.M. Giannini. The high energy photo-effect on light nuclei // *J. Phys. G*. 1989, v. 15, p. 1605-1617.
22. R.I. Jibuti, T.I. Kopaleishvili. Absorption of π^- mesons and the correlation of nucleons in light nuclei // *Nucl. Phys. A*. 1964, v. 55, p. 337-352.
23. A.F Khodyachikh. Asymmetry of the angular distributions of the products of the A(γ,pn)(A-2) reactions on ^{12}C and ^{16}O nuclei at energies up to 150 MeV // *Yad. Fiz.* 1999, v. 62, p. 1355-1357 (in Russian).
24. J.I. Johansson, H.S. Sherif. Importance of the direct knotout mechanism in relativistic calculations for *(γ,p)* reactions // *Phys. Rev. C.* 1997, v. 56, p. 328-337.
25. V.V. Kirichenko, A.F. Khodyachikh, P.I. Vatset, I.V. Dogyust, V.A. Zolyenko. Study of reactions $^{12}C(\gamma,p)\alpha^{7}Li$ and $^{12}C(\gamma,n)\alpha^{7}Be$ at $E_{\gamma max}$=120 MeV // *Yad. Fiz.* 1979, v. 29, p. 572-581 (in Russian).
26. A.F. Khodyachikh. Multiparticle photonuclear reactions on *p*- shell nuclei in the intermediate energy interval // *VANT. Series: Nucl.Phys. Invest*. 2001, №1, p. 13-14.
27. J.L. Matthews, D.J.S. Findlay, S.N. Gardiner, R.O. Owens. High energy photoprotons from light nuclei // *Nucl. Phys. A.* 1976, v. 267, p. 51-76.
28. D.J.S. Findlay, R.O. Owens. The $^{12}C(\gamma,p_0)$ reaction at intermediate photon energies // *Nucl. Phys. A.* 1977, v. 279, p. 385-393.

29. V.I. Voloshchuk, I.V. Dogyust, V.V. Kirichenko, A.F. Khodyachikh. $^{12}C(\gamma,pt)2\alpha$ reaction at $E_{\gamma\,max}$= 150 MeV // *Yad. Fiz.* 1989, v 49, p. 916-921 (in Russian).