EXPERIMENTAL METHODS AND PROCESSING OF DATA

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TOTAL AND PARTIAL CROSS SECTIONS IN THE (γ,np)-REACTIONS ON ^{12}C, ^{14}N, AND ^{16}O NUCLEI

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For the reactions ^{12}C(γ,np)^{10}B, ^{14}N(γ,np)^{12}C and ^{16}O(γ,np)^{14}N, the total cross-section has been determined as a function of the γ-quantum energy. The distributions are similar in appearance: as the photon energy increases, the reaction yields rise from the threshold, reaching a maximum in the region of 30...50 MeV; thereafter, the reaction yields decrease smoothly. Taking the reaction threshold ($T_0 = E_\gamma - Q$) into account has allowed us to determine that the positions and widths of the maxima coincide qualitatively. Assuming that the momentum distribution of a multicharged particle (^{10}B, ^{12}C and ^{14}N) reflects various mechanisms of the quasi-deuteron model of photon absorption by the nucleus, the events of all reactions were divided into two parts according to the momentum of the multicharged particles. The corresponding partial cross-sections were determined, and it was found that at $T_0 < 10$ MeV, there occurs the predomination of the model in which nucleons do not interact with the spectator (multi-charged particle) after the quasi-deuteron splits, while for $T_0 > 10$ MeV, the contribution from the other model, where interaction between a nucleon and the spectator is possible in the final state, rises rapidly, and the contributions from the different interaction models become equal.

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INTRODUCTION

Photoparticle reactions resulting in the production of two nucleons are used as a tool for studying nucleon correlations. At energies below the meson production threshold, a photon imparts a relatively small momentum to the nucleus. High nucleon momenta can be achieved through the distribution of nucleon momenta and their correlations within the nucleus. Information on nucleon correlations is an important component of our understanding of nuclear structure.

For the 'magic' nuclei ^{12}C and ^{16}O, the (γ,np)-reaction competes with simple single-nucleon emission channels – (γ,n) or (γ,p). In the giant resonance region (~20...25 MeV), the relative contribution of the (γ,np)-reaction cross-section to the total cross-section is relatively small, but as the photon energy increases, the relative contribution rises sharply, becoming the primary decay channel for the nucleus at energies above 50 MeV. The ^{14}N(γ,np)^{12}C-reaction is of particular interest for study, as the ground state of the ^{14}N nucleus has a spin and parity of 1^+ – just like the deuteron. This is due to the fact that, in the photon energy range from 30 to 150 MeV, the quasi-deuteron mechanism plays a dominant role, whereby the photon is absorbed not by the entire nucleus, but by an np-pair in a state similar to that of a deuteron.

This paper is a continuation of a series of studies [1–3] on the reactions ^{12}C(γ,np)^{10}B (I), ^{14}N(γ,np)^{12}C (II) and ^{16}O(γ,np)^{14}N (III), which are being carried out at the NSC KIPT. To study photonuclear reactions, an experimental setup was created comprising a digital database of stereo frames obtained from a 4π-detector track system and a suite of graphical applications that enable the reconstruction of events and the physical analysis of the data obtained. The software has been developed using the Python programming language [4] and it enables all necessary procedures to be carried out on a computer.

TOTAL CROSS-SECTION OF (γ,np)-REACTIONS

A complete cycle of measurements of two-track events on ^{12}C, ^{14}N and ^{16}O nuclei was carried out using a digital technique. For the analysis, there were selected two-track events which appear identical in the photograms: a long track with noticeable curvature for a proton and a short track for a multicharged particle.

From the laws of conservation of energy and momentum, the energy of the γ-quantum equals [5]:

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

where m and M are the neutron and the nucleus-target (^{12}C, ^{14}N or ^{16}O) masses; E and P are, respectively, the total energy and the total momentum of the proton and multi-charged particle (^{10}B, ^{12}C or ^{14}N, respectively); 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 kinematic parameters of the neutrons were obtained with the conservation laws after calculating the γ-quantum energy.

Fig. 1 shows the total cross-section in the photon energy range from the reaction threshold up to 150 MeV for the photodissociation reactions of carbon, nitrogen and oxygen nuclei resulting in the formation of a neutron-proton pair – (a) reaction [I], (b) reaction [II] and (c) reaction [III]. The histogramming step for all reactions was the same – 1 MeV. The reaction thresholds are - $Q_{^{12}C} = 27.413$ MeV, $Q_{^{14}N} = 12.497$ MeV and $Q_{^{16}O} = 22.961$ MeV, respectively.

All histograms have a similar appearance: as the energy of the γ-quantum increases, the reaction yields rise from the threshold, reaching a maximum in the region of 30...50 MeV; thereafter, the reaction yields decrease gradually as E_γ increases. It is visually apparent

that the rate of decrease in reaction yield at $E_\gamma > 60$ MeV is almost identical.

It should also be noted that for the 'magic' nuclei ^{12}C and ^{16}O, the cross-section of the (γ,np)-reactions is almost identical at the maximum, whereas for the (γ,np)-reaction on the ^{14}N nucleus, the value at the maximum is significantly higher (~ 5 times greater).

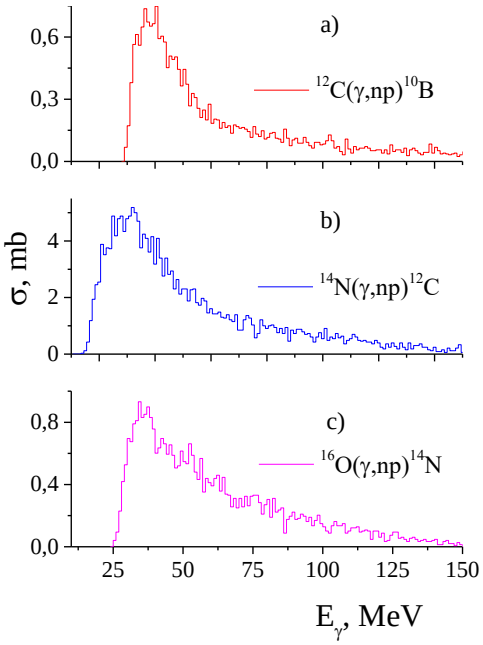


Fig. 1. The dependence of the total cross-section on the energy of the γ-quantum: a – the reaction $^{12}C(\gamma,np)^{10}B$, b – the reaction $^{14}N(\gamma,np)^{12}C$ and c) the reaction $^{16}O(\gamma,np)^{14}N$

It should be noted that the different response thresholds mean that it is difficult to make a qualitative comparison of the positions of the maxima in Fig. 1. Furthermore, the different peak heights do not allow for a quantitative comparison of the data.

One way to address the first problem might be to present the results not as a function of E_γ, but as a function of the total reaction energy T_0, which was defined as:

$$T_0 = E_\gamma - Q, \quad (2)$$

where Q – the energy threshold of the reaction.

To address the second issue, a procedure was developed to normalise events based on their integral sum. The number of events requiring a response was selected as the reference value [II].

Position and width of the maxima of the reaction output functions

Reaction	x_c	σ
$^{12}C(\gamma,np)^{10}B$	13.35±0.62	5.44±0.79
$^{14}N(\gamma,np)^{12}C$	13.55±0.71	6.76±0.72
$^{16}O(\gamma,np)^{14}N$	13.44±0.61	7.11±1.04

Fig. 2,a shows the total cross-section of the reactions, taking into account the normalisation factors and as a function of T_0. The results are presented in the region of the reaction maxima (E_γ = 30...50 MeV in Fig. 1). The figure shows that the positions of the maxima for all three reactions are close. Each peak was fitted to a Gaussian function, yielding the peak position (x_c) and the half-width at half-height values (σ) for these distributions. The results are given in columns 2 and 3 of the table for all the reactions under investigation (column 1).

The positions of the maxima of the total cross-section distributions as a function of T_0 coincide within the margin of error. It is therefore possible that this method of joint analysis may yield a more accurate result when determining the mechanism of interaction between the γ-quantum and the nucleus.

Fig. 2,b shows the total cross-section of reactions at $T_0 > 50$ MeV. The distributions are also similar, but it should be noted that the normalisation effect and corrections for reaction thresholds are not as pronounced there due to insufficient statistical coverage.

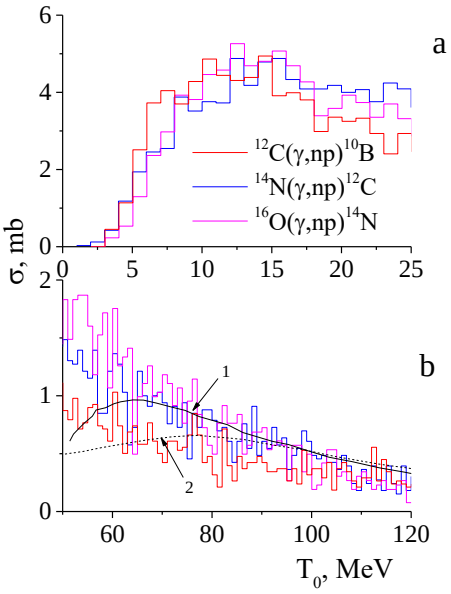


Fig. 2. Dependence of the total cross-section on the total energy of the system T_0

To describe the processes of photoabsorption at energies below the meson production threshold, a number of authors have developed microscopic models of (γ,np)-reactions. These works have shown that two-particle currents, caused by nucleon-nucleon interactions, play a significant role in the processes of nuclear photodissociation with the production of nucleon pairs. Most authors have modified the wave function of the shell model by using a model with a correlated wave function. For example, in [6], the authors calculated the total cross-sections for the photoproduction of nucleon pairs as a function of the gamma-ray energy. This theoretical calculation of the cross-section for the $^{16}O(\gamma,np)^{14}N$ reaction is represented by the solid curve 1 in Fig. 2,b. Curve 1, normalised at 100 MeV to the yield of the $^{16}O(\gamma,np)^{14}N$ reaction, satisfactorily describes the energy dependence of the total cross-sections. Furthermore, in the study of the dynamic aspects of photonic nuclear reactions [7], the cross-sections for the interaction of the γ-quantum with correlated pairs of nucleons located in different nuclear shells were calculated. The correlations between the nucleons were established via the π-meson exchange current. Curve 2 shows these theoretical calculations of the

photodissociation of correlated nucleon pairs from the p-shell of the oxygen nucleus. For comparison, curve 2 is also normalised to the yield of the $^{16}O(\gamma,np)^{14}N$ reaction at 100 MeV. The shape of curve 2 also satisfactorily describes the reaction yields, but the values exceed the experimental values.

From 80 MeV onwards, the reaction products exhibit identical energy behaviour. This supports the model of gamma-ray absorption by a correlated nucleon pair. In this case, the interaction between the neutron and the proton must significantly influence the reaction mechanism. The figure shows that at $T_0 > 90$ MeV, the shapes of curves 1 and 2 are identical, and it is difficult to give preference to either calculation. Therefore, it is advisable to compare the predictions of different models at low energies, where differences in the predictions become apparent.

PARTIAL CROSS-SECTIONS OF THE INTERACTION CHANNELS BETWEEN THE γ-QUANTUM AND THE NUCLEUS

It was previously established [3] that the momentum distribution of the multicharged particles ^{10}B, ^{12}C, and ^{14}N for reactions (I), (II) and (III) exhibits a structure with two maxima. It was found that the position of the first peak does not depend on the photon energy. With a certain probability, for each reaction, events corresponding to different peaks can be separated. The position of the cut-off momentum for each multi-charged particle required for separation is different: $P^{lim}(^{10}B) \sim 140$ MeV/c for ^{10}B, $P^{lim}(^{12}C) \sim 155$ MeV/c for ^{12}C, $P^{lim}(^{14}N) \sim 175$ MeV/c for ^{14}N. It has been suggested [8] that events falling within different P^{lim} intervals correspond to different mechanisms of the quasi-deuteron model of photon absorption by the nucleus (inner inset in Fig. 3,a) – the 'polar' (nucleons do not interact with the spectator after the quasi-deuteron splits (model 1)) and 'triangular' (in the final state, interaction of a nucleon with the spectator is possible (model 2)).

Fig. 3 shows partial cross-sections for various intervals according to P^{lim}. The solid histograms show the distributions of the number of events for $P < P^{lim}$, whilst the dotted histograms show those for $P > P^{lim}$. The histogram step size is 1 MeV. It should be noted that the sum of both histograms coincides with the data in Fig. 1.

A similar pattern is observed for all reactions: in the subthreshold region, a significant number of events correspond to the case where $P < P^{lim}$. As the the γ-quantum energy increases, the number of events at various intervals above P^{lim} levels out.

It is also worth noting the following: the reaction cross-sections vary (for example, the $^{14}N(\gamma,np)^{12}C$ reaction has the smallest one), but the yield functions for the reactions at different P^{lim} intervals converge at approximately the same value of $E_\gamma \sim 40...45$ MeV. This limit is shown as a vertical dotted line across all figures.

It is worth noting the similarity between the distribution for $P > P^{lim}$ and curve 1 in Fig. 2,b within the model, while taking into account two-particle currents caused by nucleon-nucleon interactions.

Fig. 4 shows the ratio of the number of events (η) for $P < P^{lim}$ and for $P > P^{lim}$ as a function of the total reaction energy T_0.

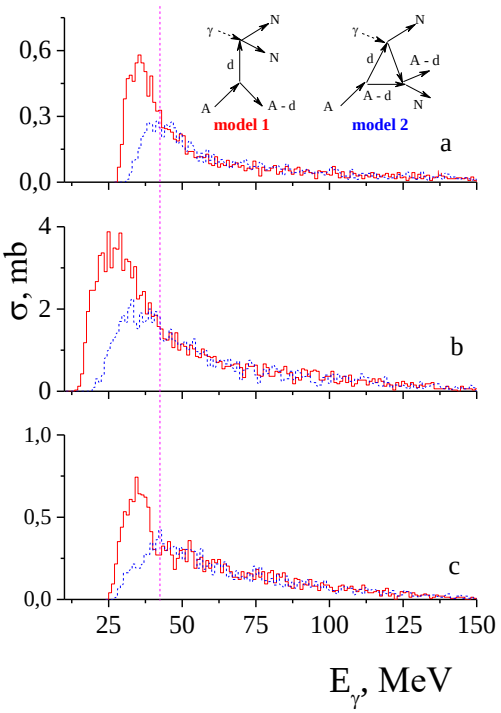


Fig. 3. Partial cross-sections for various mechanisms of interaction between γ-quantum and nucleus

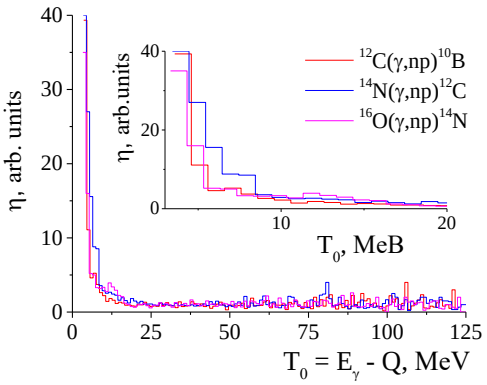


Fig. 4. The ratio of the number of events at different P^{lim} intervals as a function of the total energy of the system

The figure shows that when $T_0 > 10$ MeV, the contributions from the various decay channels become equal (1). The inset shows the range from 0 to 20 MeV as a function of T_0. It can be seen that, for all reactions, there is a rapid change in the ratio of the contributions from the various mechanisms of interaction between the γ-quanta and the nucleus.

The similarity of the distributions for reactions involving different target nuclei may indicate that the interaction mechanisms are similar and not strongly dependent on the incident nucleus – for example, variations of the quasi-deuteron model of the photon absorption by a nucleus.

CONCLUSIONS

The total cross-sections for the reactions $^{12}C(\gamma,np)^{10}B$, $^{14}N(\gamma,np)^{12}C$ and $^{16}O(\gamma,np)^{14}N$ have been determined. It was found that the cross-sections exhibit a

similar behaviour: as the photon energy increases, the reaction yields rise from the threshold, reaching a maximum in the region of 30...50 MeV; thereafter, the reaction yields decrease gradually with increasing E_γ. Changing the abscissa scale from E_γ to $T_0 = E_\gamma - Q$ (Q – the energy threshold of the reaction) allowed us to conclude that the position of the maximum and its width are qualitatively the same for all three reactions. At $T_0 > 50$ MeV, the cross-sections agree with calculations within various models – both for the interaction of gamma quanta with correlated pairs of nucleons located in different nuclear shells, and when accounting for two-particle currents caused by nucleon-nucleon interactions.

The partial cross-sections of the particles ^{10}B, ^{12}C and ^{14}N under momentum confinement have been determined for the reactions $^{12}C(\gamma,np)^{10}B$, $^{14}N(\gamma,np)^{12}C$, and $^{16}O(\gamma,np)^{14}N$, respectively. The position of the cut-off momentum for each multicharged particle for the separation was previously determined as the boundary between two maxima in the momentum distribution of multicharged particles. It has been found that near the threshold, there predominates the 'polar' mechanism of the quasi-deuteron model of photon absorption by the nucleus, where, following the decay of the quasi-deuteron, the nucleons do not interact with the spectator (a multi-charged particle); however, at $T_0 > 10$ MeV, the contributions from the various interaction models become equal.

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ПОВНІ ТА ПАРЦІАЛЬНІ ПЕРЕРІЗИ В (γ,np)-РЕАКЦІЯХ НА ЯДРАХ ^{12}C, ^{14}N ТА ^{16}O

С.М. Афанасьєв

Для реакцій $^{12}C(\gamma,np)^{10}B$, $^{14}N(\gamma,np)^{12}C$) та $^{16}O(\gamma,np)^{14}N$ визначено повний переріз залежно від енергії γ-кванта. Розподіли мають подібний вигляд – зі збільшенням енергії γ-кванта виходи реакцій зростають від порога, досягаючи максимуму в районі 30...50 МеВ; далі виходи реакцій плавно зменшуються. Врахування порогу реакції ($T_0 = E_\gamma - Q$) дозволило визначити, що положення і ширина максимумів якісно співпадають. У припущенні, що в імпульсному розподілі багатозарядної частинки (^{10}B, ^{12}C та ^{14}N) проявляються різні механізми квазідейтронної моделі поглинання фотона ядром, події всіх реакцій розділено на дві частини за імпульсом багатозарядних частинок. Визначено відповідні парціальні перерізи і отримано, що при $T_0 < 10$ МеВ переважає модель, коли нуклони після розщеплення квазідейтрона не взаємодіють зі спектатором (багатозарядна частинка), а при $T_0 > 10$ МеВ вклад іншої моделі, коли у кінцевому стані можлива взаємодія нуклона зі спектатором, стрімко зростає і вклад різних моделей взаємодії стає рівним.