EXPERIMENTAL METHODS AND PROCESSING OF DATA

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DIFFERENTIAL CROSS SECTION ASYMMETRY IN MULTIPARTICLE (γ,N)-REACTIONS

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For the deep photodisintegration reactions of ^{12}C and ^{16}O nuclei $^{12}C(\gamma,p)^3H2\alpha$, $^{12}C(\gamma,n)^3He2\alpha$, $^{16}O(\gamma,p)^3H3\alpha$, and $^{16}O(\gamma,n)^3He3\alpha$, it was established that a two-body process occurs, leading to the formation of intermediate excited ^{11}B, ^{11}C, ^{15}N, and ^{15}O nuclei, respectively. In the excitation-energy distributions of systems of particles other than nucleons, a broad near-threshold maximum is observed in all reactions. Accounting for the decay thresholds of these systems, the position of the peak remains identical for all reactions. The average nucleon energy distribution is identical for reactions on the same target nucleus and agrees with calculations based on the two-body decay assumption. For photon energies of 70…100 MeV, the differential cross sections for all reactions were determined, and the asymmetry coefficient of the angular distributions was calculated. A decrease in the asymmetry coefficient is observed as the excitation energy of the residual nucleus increases, confirming calculations within the quasi-deuteron model of nuclear photon absorption under the assumption of nucleon–spectator interaction.

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INTRODUCTION

The (γ,N) nucleon knockout process from light nuclei in the energy range between the giant dipole resonance and the meson production threshold has been intensively investigated for many years, both experimentally and theoretically. However, to date, there is no definitive answer to the question regarding the mechanism of nucleon removal from the nucleus. Calculations in the non-relativistic approximation [1–4] led to the conclusion that the direct knockout mechanism cannot account for either the magnitude of the (γ,N)-reaction cross section or the similar shape of the angular distributions in (γ,p)- and (γ,n)-reactions. It has been recognized that the main contribution comes from the interaction of the γ-quantum with a nucleon pair during meson exchange between the nucleons. However, these conclusions do not agree with calculations in the relativistic approximation [5, 6]. Using several nuclei as examples, it was shown that the contribution to the (γ,N)-reaction from the direct mechanism is significantly larger than in the non-relativistic approximation and is in agreement with experimental data. At the same time, non-relativistic calculations [3, 4] suggest that the role of exchange currents is small if the residual nucleus is left in the ground state, but increases as its excitation energy rises. To test these predictions, experimental data are required for reactions leaving the nucleus in a highly excited state.

In this study, deep photodisintegration (γ,N)-reactions on ^{12}C and ^{16}O nuclei yielding multiple α-particles in the final state were investigated: $^{12}C(\gamma,p)^3H2\alpha$ [I], $^{12}C(\gamma,n)^3He2\alpha$ [II], $^{16}O(\gamma,p)^3H3\alpha$ [III], and $^{16}O(\gamma,n)^3He3\alpha$ [IV], which can proceed via the formation of highly excited intermediate states. Currently, theoretical calculations for deep photodisintegration reactions of ^{12}C and ^{16}O nuclei with nucleon emission are unavailable. Furthermore, a comparison of (γ,N)-reactions on different nuclei in reaction channels producing multiple particles in the final state has not yet been performed. Previously, a review [1] was presented on the photodisintegration of ^{12}C, ^{14}N, and ^{16}O nuclei accompanied by nucleon knockout from the p-shell. In the reactions studied here, nucleon knockout from the s-shell of carbon and oxygen nuclei is possible. While experimental data for reaction [I] are limited [7, 8], no such data exist for the remaining reaction channels.

The experimental data were obtained using a 4π-track detector - a diffusion chamber placed in a magnetic field. Details of event selection and preliminary analysis have been reported previously [9–11]. Those studies s focused primarily on examining reaction yields and the possibility of forming intermediate excited states in 2α- or 3α-systems.

Determining the total cross section for reactions [II] and [IV] presented certain difficulties, as our experimental technique does not allow visual discrimination between ^{3}He and ^{4}He nuclei in the $^{12}C(\gamma,n)^3He2\alpha$ and $^{16}O(\gamma,n)^3He3\alpha$ reactions. The γ-ray energy (E_γ) in the $^{12}C(\gamma,n)^3He2\alpha$ reaction was determined by sequentially assigning each particle as a ^{3}He nucleus and averaging over all combinations (3 combinations). In the $^{16}O(\gamma,n)^3He3\alpha$ reaction, this approach increases the number of combinations to 6, resulting in significant uncertainty in E_γ and the neutron kinematic parameters. However, as demonstrated in [9, 10], partial channels involving the formation of the ^{8}Be nucleus in its ground state can be identified and isolated in these reactions, thereby reducing the number of combinations for (γ,n)-reactions. This approach reduces the uncertainty in particle identification, resulting in more reliable data.

SEQUENTIAL TWO-BODY DECAY OF THE TYPE A(γ,N)(A-1)*

The excitation energy distribution of the multi-particle system excluding the nucleon нуклону – $2\alpha + {}^3H({}^3He)$ in carbon reactions and $3\alpha + {}^3H({}^3He)$ in oxygen reactions – was measured and defined as

$$E_x = M^{eff} - M, \quad (1)$$

where M^{eff} is the effective mass of the three-particle system, and M is the ground-state mass of the ^{11}B or ^{11}C nuclei for reactions [I] or [II], respectively, and ^{15}N or ^{15}O for reactions [III] or [IV], respectively.

The distributions are presented in Fig. 1,a as open circles (for ^{11}B) and solid circles (for ^{11}C), and in Fig. 1,b as open triangles (for ^{15}N) and solid triangles (for ^{15}O). Since the reactions have different decay thresholds, for qualitative comparison, the spectra are plotted as a function of $E_x - Q$ with specific Q-values for each reaction: Q_{11B} = 11.13 MeV, Q_{11C} = 9.10 MeV, Q_{15N} = 22.12 MeV, Q_{15O} = 19.32 MeV.

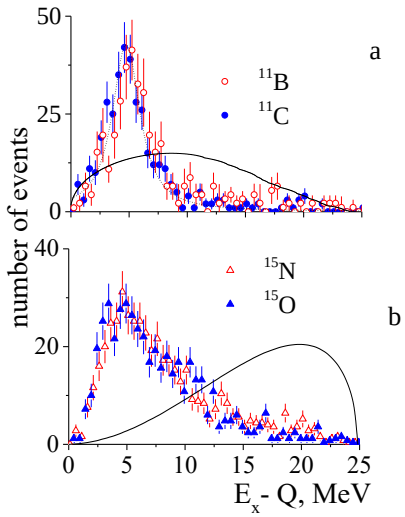


Fig. 1. Excitation energy distribution of the system of particles excluding the nucleon: a – open circles: $2\alpha + {}^3H$, solid circles: $2\alpha + {}^3He$; b – open triangles: $3\alpha + {}^3H$, solid triangles: $3\alpha + {}^3He$. The curves represent the phase-space distributions for the corresponding systems

The phase-space distribution was defined [12] as:

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

where n is the number of final particles, k the number of particles formed in the excited state (k < n), and E_x^{max} the end-point excitation energy of the system of k particles. The phase-space distribution was calculated for a bremsstrahlung beam by summing up the distributions for narrow intervals, in which the energy of a γ-quantum was assumed to be constant. The area under the phase-space curve was normalized to the number of events within each interval.

A comparison of the experimental distributions with the phase-space distributions (the curves in Fig. 1,a correspond to k = 3, n = 4, and in Fig. 1,b to k = 4, n = 5) indicates the formation of one or several unresolved excited states of the ^{11}C, ^{11}B nuclei in Fig. 1,a, and ^{15}N, ^{15}O nuclei in Fig. 1,b.

Separately, one can note the similar structure of the experimental distributions across all reactions, characterized by a peak position at E_x–Q ~ 5 MeV and a high-energy non-resonant "tail". Furthermore, a sharp change in the slope of the curve near the peak is observed for ^{11}C and ^{11}B nuclei, whereas for ^{15}N and ^{15}O nuclei, the slope curve appears smoother.

To confirm the occurrence of a sequential two-body process at the first stage (schematically denoted as γ + A → N + (A - N)*, where A represents ^{12}C or ^{16}O nuclei, and N denotes a proton or neutron), the dependence of the nucleon energy on the total system energy, $T_0=E_\gamma - Q_{react}$ (Q_{react} being the reaction threshold), can be examined. Fig. 2 shows the dependence of the average nucleon energy across the total energy range T_0 = 20…80 MeV. The average energy T^{aver} was calculated for particles falling within a 5-MeV interval of T_0. The data points are plotted at the center of each interval.

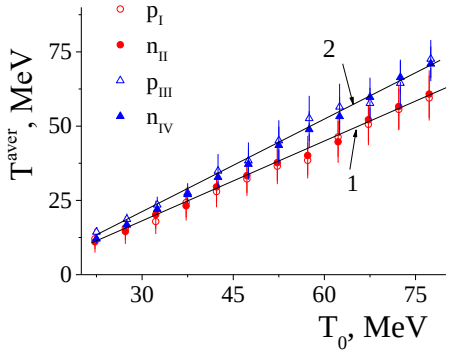


Fig. 2. Dependence of the average nucleon energy on the total energy of the final system for reactions [I]–[IV]. Curves 1 and 2 represent calculations for ^{12}C and ^{16}O nuclei, respectively

The straight lines were calculated according to [12]:

$$T = \frac{T_0 \cdot (A-M)}{A \cdot (n-1)}, \qquad (3)$$

where A and M are the mass number and the mass of the target nucleus (in atomic mass units), respectively, and n is the number of particles in the final state.

Calculating the coefficient of T_0 for the ^{12}C nucleus under the assumption of a two-body decay (n = 2) yields a value of 0.917 (curve 1), while for the ^{16}O nucleus, it yields 0.938 (curve 2). As can be seen from the figure, the proton and neutron average energies for reactions [I] and [II] correspond to curve 1, whereas the proton and neutron average energies for reactions [III] and [IV] correspond to curve 2.

Thus, the results indicate that in all studied reactions, a two-body decay, A(γ,N)(A-1)*, occurs at the first stage.

DIFFERENTIAL CROSS SECTION ASYMMETRY IN THE A(γ,N)(A-1)* CHANNEL

The sequential two-body nature of the reactions allows for the analysis of nucleon angular distributions in the center of mass within the framework of two-body kinematics.

Fig. 3 shows the differential cross sections for the $^{12}C(\gamma,p)^{11}B^*$, $^{12}C(\gamma,n)^{11}C^*$ reactions (a) and $^{16}O(\gamma,p)^{15}N^*$, $^{16}O(\gamma,n)^{15}O^*$ reactions (b) in the energy range of 70…100 MeV. This energy range was selected based on the conclusions of experimental [1, 2, 4] and theoretical studies [3, 5, 6], which indicate that at energies up to ~ 50 MeV, the direct nucleon knockout mechanism predominates**;** on the other hand, at higher energies, the pair absorption mechanism (with possible nucleon rescattering) becomes dominant. The step size

for the nucleon polar angle in the center-of-mass system is 15°. The data points are plotted at the center of each interval, and the error bars represent statistical uncertainties.

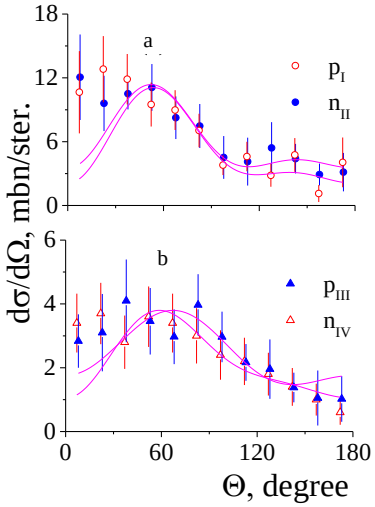


Fig. 3. Differential cross sections in the c.m. of the reactions: a – $^{12}C(\gamma,p)^{11}B^*$ and $^{12}C(\gamma,n)^{11}C^*$; b – $^{16}O(\gamma,p)^{15}N^*$ and $^{16}O(\gamma,n)^{15}O^*$

The data were fitted using the function:

$$f(\Theta)=a\cdot\sin^2\Theta+b\cdot\sin^2\Theta\cos\Theta+c\cdot\sin^2\Theta\cos^2\Theta+d, \quad (4)$$

where a, b, c, d are coefficients containing information about the wave functions of the nucleus. The results are presented in the Table (rows 2–5) for the corresponding reactions (columns 2–5).

Fitting coefficients of the differential cross sections using the function (4)

	I	II	III	IV
a	2.04±1.60	3.24±1.95	1.67±0.68	1.49±0.54
b	9.65±2.18	10.55±3.04	2.71±1.10	2.52±0.82
c	9.30±6.31	9.65±2.18	2.57±2.73	0.42±2.18
d	3.52±2.29	2.09±1.86	1.05±0.42	1.76±0.43

An asymmetry with respect to 90° is observed in the differential cross sections for all reactions. For reactions [I] and [II], a high contribution of parameters b and c is noted, whereas for reactions [III] and [IV], coefficient c is zero within the experimental uncertainty, having no effect on the fit. It can also be noted that "mirror" reactions, i.e., (γ,p) and (γ,n), exhibit a similar shape of the differential cross sections.

The large acceptance of the detector enabled the determination of the differential cross section asymmetry coefficient β, calculated as the difference between the areas under the experimental curve in the 0…90° and 90…180° ranges, divided by their sum:

$$\beta = \frac{\int_0^{\pi/2}(d\sigma/d\Omega)d\theta - \int_{\pi/2}^{\pi}(d\sigma/d\Omega)d\theta}{\int_0^{\pi}(d\sigma/d\Omega)d\theta}. \quad (5)$$

Fig. 4 compares the asymmetry coefficients β_N for (γ,N)-reactions on carbon and oxygen nuclei induced by γ-quanta in the energy range of 70…100 MeV, leading to the formation of an intermediate nucleus in various excited states E_x. The coefficients were determined using Eq. (5).

For the $^{12}C(\gamma,p)^{11}B$, $^{12}C(\gamma,p)^{11}B^*$, $^{16}O(\gamma,p)^{15}N$, and $^{16}O(\gamma,p)^{15}N^*$ reactions, β_N was determined using the data from [1–6, 14] and is denoted by open and solid circles and squares, respectively. For the $^{12}C(\gamma,p)^{11}B^*$ and $^{16}O(\gamma,p)^{15}N^*$ reactions, the residual nucleus excited states were not resolved. Open and solid triangles represent the data for the $^{12}C(\gamma,n)\alpha^7Be$ and $^{12}C(\gamma,p)\alpha^7Li$ reactions, respectively [15]. A diamond and a star mark the data from our experiment. A decrease in the asymmetry coefficient with increasing excitation energy of the residual nucleus is observed.

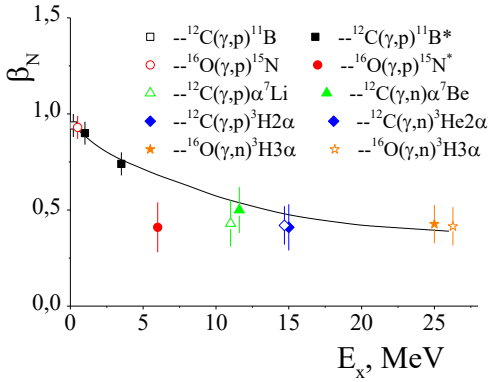


Fig. 4. Differential cross section asymmetry as a function of the excitation energy of the residual nucleus (E_x) for A(γ,N)(A-1) reactions. The solid curve represents the calculation within the framework of the quasideuteron model*

In the direct mechanism model, due to the absence of a negative effective quadrupole charge for neutrons [13], angular distributions symmetric with respect to 90° are expected over the entire energy range.

The solid line shows the calculations [16] within the framework of the quasideuteron model, assuming that the nucleon is separated from the s-shell. The results are in good agreement with experimental data.

Notably, the data points at high excitation energy E_x, which extended the energy range above 12 MeV, are the results of our experiments – reactions [I]–[IV].

CONCLUSIONS

A study of deep photodisintegration (γ,N)-reactions on ^{12}C and ^{16}O nuclei – $^{12}C(\gamma,p)^3H2\alpha$, $^{12}C(\gamma,n)^3He2\alpha$, $^{16}O(\gamma,p)^3H3\alpha$, and $^{16}O(\gamma,n)^3He3\alpha$ – has been performed. The excitation function of the particle system other than the nucleon was determined, revealing that a sequential two-body decay occurs with the formation of excited states of ^{11}B, ^{11}C, ^{15}N, and ^{15}O nuclei, respectively. A comparison of the excitation functions showed that, taking into account the decay threshold, the peak positions coincide for all reactions.

Differential cross sections were obtained in the energy range of 70…100 MeV under the assumption of a two-body decay, A(γ,N)(A-1)*. An asymmetry with respect to 90° is observed in these distributions. The asymmetry coefficient was determined, and a comparison of various (γ,N)-reactions on carbon and oxygen nuclei was carried out. The asymmetry coefficient decreases with increasing excitation energy of the residual nucleus, which is explained within the framework of the quasideuteron model taking into

account the interaction of the nucleon with the spectator nucleus.

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АСИМЕТРІЯ ДИФЕРЕНЦІАЛЬНИХ ПЕРЕРІЗІВ У БАГАТОЧАСТИНКОВИХ (γ,N)-РЕАКЦІЯХ

С.М. Афанасьєв

Для реакцій глибокого розщеплення ядер ^{12}C та ^{16}O – $^{12}C(\gamma,p)^{3}H2\alpha$, $^{12}C(\gamma,n)^{3}He2\alpha$, $^{16}O(\gamma,p)^{3}H3\alpha$ та $^{16}O(\gamma,n)^{3}He3\alpha$ визначено, що відбувається двохчастинковий процес з утворенням проміжних збуджених ядер ^{11}B, ^{11}C, ^{15}N та ^{15}O відповідно. У розподілі за енергією збудження системи частинок, відмінних від нуклону, для всіх реакцій проявляється широкий біляпороговий максимум. Його положення, з урахуванням порогу розпаду цієї системи, співпадає для всіх реакцій. Розподіл середньої енергії нуклонів однаковий для реакцій на одному і тому ж ядрі та відповідає розрахункам у припущенні двочастинковості розпаду. Для енергетичного інтервалу 70…100 МеВ за енергією γ-кванта визначено диференційні перерізи всіх реакцій та розраховано коефіцієнт асиметрії кутових розподілів. Спостерігається зменшення коефіцієнта асиметрії з ростом енергії збудження кінцевого ядра, що підтверджує розрахунки в рамках квазідейтронної моделі поглинання фотона ядром у припущенні взаємодії нуклона зі спектатором.