Analysis of $^4\text{He}(\gamma,p)\text{T}$ and $^4\text{He}(\gamma,n)^3\text{He}$ Reactions with Linearly Polarized Photons in the Energy Range up to 100 MeV

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In a number of investigations, one can find the data on the $^4\text{He}(\gamma,p)\text{T}$ and $^4\text{He}(\gamma,n)^3\text{He}$ reaction cross sections in the collinear geometry, which are due to spin $S=1$ transitions of the final-state particles. The ratio of the differential cross section in the collinear geometry to the differential reaction cross section at the nucleon emission angle $\theta_N=90^\circ$, and specified by the $S=0$ electric dipole transition at photon energies in the range $20 \leq E_\gamma \leq 100$ MeV, is independent of the photon energy, within the experimental error. In the meantime, experiments were made to measure the asymmetry of the cross section $\Sigma(\theta_N)$, for the mentioned reactions with linearly polarized photons. It has been found that in the energy range between 20 and 90 MeV, the $\Sigma(\theta_N)$ value is also independent of the photon energy, within the experimental error. These data are in agreement with the assumption that transitions with spin $S=1$ can be due to the contribution of $^3P_0$ states of the $^4\text{He}$ nucleus, and are inconsistent with the assumption that the spin-flip of the particle system occurred during the reaction as a result of the meson exchange current contribution. The available measured data on the collinear geometry reaction cross sections and the ones on the cross-section asymmetry of the reaction with linearly polarized photons do not agree between themselves. The above mentioned reactions seem to be more convenient for measuring the degree of photon beams linear polarization than the deuteron photodisintegration reactions.

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I. INTRODUCTION

The total momentum and parity of the $^4\text{He}$ nucleus $J^P=0^+$, the two-body of the reactions, and also the absence of excited states in the final nuclei make it possible to perform a detailed multipole analysis in $E1$, $E2$ and $M1$ approximation. In the course of the $^4\text{He}(\gamma,p)\text{T}$ and $^4\text{He}(\gamma,n)^3\text{He}$ reactions the final-state spin of the particle system can take two values: $S=0$ and $S=1$. The main part total cross section of the reaction is contributed by $S=0$ transitions. The contribution of these transitions is explained by the direct nucleon knockout mechanism, the recoil mechanism, and a number of exchange diagrams [1]. In Ref. [2] the origination of $S=1$ transitions is explained by the assumption that in the course of the reaction the spin-flip of the hadronic particle system takes place, which results from the contribution of meson exchange currents (MEC’s). Based on the realistic $NN$ potential and $3N$ forces, Nogga et al. [3] have demonstrated that in the initial state the $^4\text{He}$ nucleus can also have the spin $S=1$ and $S=2$, and possibly, the $S=1$ transitions may be due to the $^4\text{He}$ nuclear structure. Thus, the occurrence of multipole transitions may be of different origin. The analysis of the available experimental data along with obtaining new data is of considerable importance for gaining new information on the nuclear structure and mechanisms of nuclear reactions.

II. MULTIPOLe ANALYSIS OF $^4\text{He}(\gamma,p)\text{T}$ AND $^4\text{He}(\gamma,n)^3\text{He}$ REACTIONS

Complete expressions of expanding the differential cross sections and cross-sectional asymmetry $\Sigma(\theta_N)$ in $E1$, $E2$ and $M1$ multipoles for the $^4\text{He}(\gamma,p)\text{T}$ and $^4\text{He}(\gamma,n)^3\text{He}$ reactions with linearly polarized photons in the center-of-mass system can be written as:

\[
d\sigma = \frac{\chi^2}{32}\left[|\sin^2(\theta)|^2 [18 |E1P_1|^2 - 9 |E1P_1|^2 + 9 |M1D_1|^2 - 25 |E2D_2|^2 - 18 \sqrt{2} Re(M1^3S_1^2 M1^3D_1) + 30 \sqrt{3} Re(M1^3D_1^2 M1^3D_2) + 30 \sqrt{3} Re(M1^3S_1^2 E2^2D_2) + \cos\theta(60 \sqrt{3} Re(E1^3P_1^2 E2^2D_2) - 60 Re(E1^3P_1^2 E2^2D_2)) + \cos^2\theta(150 |E2^2D_2|^2 - 100 |E2^2D_2|^2)]\right]
\]

where $\lambda$ is the reduced wavelength of the photon. (Notation: $^{2S+1}L_J$, $J$ is the total momentum of the system).

The asymmetry of the linearly polarized-photon reaction cross section $\Sigma(\theta_N)$ is given by the expression:
The multipole amplitudes as:

\[ \Sigma(\theta) = \sin^2 \theta (1 + \beta \cos \theta + \gamma \cos^2 \theta) + \nu \cos \theta + \nu \]

Expressions (1) and (2) can be represented in the following forms:

\[ \frac{d\sigma}{d\Omega} = A \sin^2 \theta (1 + \beta \cos \theta + \gamma \cos^2 \theta + \epsilon \cos \theta + \nu) \]

\[ \Sigma(\theta) = \frac{\sin^2 \theta (1 + \alpha + \beta \cos \theta + \gamma \cos^2 \theta)}{\sin^2 \theta (1 + \beta \cos \theta + \gamma \cos^2 \theta + \epsilon \cos \theta + \nu)} \]

The coefficients \( A, \alpha, \beta, \gamma, \epsilon, \) and \( \nu \) are expressed in terms of the multipole amplitudes as:

\[ A = \frac{\lambda^2}{32} \sqrt{[18|E_1^3P_1|^2 - 9|E_1^3P_1|^2 + 9|M_1^3D_1|^2 - 25|E_2^3D_2|^2 - 18\sqrt{2}|M_1^3S_1| |M_1^3D_1| |\cos(\delta^3S_1) - \delta^3D_1]| + 30\sqrt{6}|M_1^3S_1| |E_2^3D_2| |\cos(\delta^3S_1) - \delta^3D_2]| + 30\sqrt{3}|M_1^3D_1| |E_2^3D_2| |\cos(\delta^3D_1) - \delta^3D_2]| \sqrt{32} } \]

\[ \alpha = \{ -18|M_1^3D_1|^2 + 50|E_2^3D_2|^2 + 36\sqrt{2}|M_1^3S_1| |M_1^3D_1| |\cos(\delta^3S_1) - \delta^3D_1]| - 20\sqrt{6}|M_1^3S_1| |E_2^3D_2| |\cos(\delta^3S_1) - \delta^3D_2]| - 20\sqrt{3}|M_1^3D_1| |E_2^3D_2| |\cos(\delta^3D_1) - \delta^3D_2]| \sqrt{32} } A \]

\[ \beta = \{ 60\sqrt{3}|E_1^3P_1| |E_2^3D_2| \cos(\delta^3P_1) - \delta^3D_2]| \sqrt{32} } A \]

\[ \gamma = \{ 150|E_2^3D_2|^2 - 100|E_2^3D_2|^2 \sqrt{32} } A \]

\[ \epsilon = \{ -12\sqrt{3}|E_3^3P_1| |M_1^3D_1| |\cos(\delta^3P_1) - \delta^3D_1]| - 12\sqrt{6}|E_1^3P_1| |M_1^3S_1| |\cos(\delta^3P_1) - \delta^3S_1]| + 60|E_1^3P_1| |E_2^3D_2| |\cos(\delta^3P_1) - \delta^3D_2]| \sqrt{32} } A \]

Thus, having determined the coefficients \( A, \alpha, \beta, \gamma, \epsilon, \) and \( \nu \) from the measured data on the differential cross section and the asymmetry of linearly polarized photon reaction cross sections, one can gain information about the contributions of individual multipole amplitudes to the reaction cross section. The coefficient \( A \) represents the differential cross section for the electric dipole transition with spin \( S=0 \), and the contribution of spin \( S=1 \) transitions at the angle of nucleon emission \( \theta_N = 90^0 \). The coefficient \( \gamma \) is proportional to the contribution of the spin \( S=0 \) electric quadrupole \( E2 \) transition. The coefficient \( \beta \) describes the interference between the electric dipole \( E1 \) and electric quadrupole \( E2 \) amplitudes having spin \( S=0 \). The coefficients \( \alpha, \epsilon, \) and \( \nu \) designate the contributions from \( S=1 \) transitions of final-state particles. Expression (3) leads to the following relations:

\[ \epsilon = [\sigma(0^0) - \sigma(180^0)]/2A, \nu = [\sigma(0^0) + \sigma(180^0)]/2A \]

Table 1 shows the distribution over the polar angle of nucleon emission in c.i.s. for \( E1, E2 \) and \( M1 \) multipole transitions. It can be seen from Table 1 that for all the mentioned transitions we have \( \sigma(0^0) = \sigma(180^0) \), and hence should be about \( \epsilon \approx 0 \). If \( \epsilon \neq 0 \), then this may be indicative of the experimental errors, or of the insufficiency of \( E1, E2 \) and \( M1 \) approximation.

| Spin of the Multipole final-states transition | Angular distribution |
|-----------------------------------------------|----------------------|
| S=0 \{ |E_1^3P_1|^2 |E_2^3D_2|^2 \sin^2 \theta \} | 1 + \cos^2 \theta sin^2 \theta cos^2 \theta |
| S=1 \{ |E_1^3P_1|^2 |M_1^3S_1|^2 |M_1^3D_1|^2 |E_2^3D_2|^2 5-3\cos^2 \theta 1-3\cos^2 \theta + 4 \cos^2 \theta | |

According to expression (4), the contributions of each of the spin \( S=0 \) amplitudes lead to the asymmetry \( \Sigma(\theta_N) = 1 \) at all polar angles of nucleon emission, except the angles \( \theta_N = 0^0 \) and \( 180^0 \). The difference of the asymmetry \( \Sigma(\theta_N) \) from 1 may be due only to spin \( S=1 \) transitions. The smaller is the contribution from \( S=1 \) transitions, the more rectangular the reaction cross-section.
asymmetry becomes. It is evident from expression (6) that if it is the $E1^3P_1$ or $M1^3S_1$ amplitude is predominant, then we have the coefficient $\alpha = 0$, and according to the $\Sigma(\theta_N)$ data for the reaction with linearly polarized photons, the contributions of the mentioned two amplitudes are not separated. One can see from expressions (6) and (10) that if the $M1^3D_1$ amplitude is predominant, then

$$\alpha = -3\nu;$$ \hspace{1cm} (11)

and if the $E2^3D_2$ amplitude is dominant, then we have

$$\alpha = \nu;$$ \hspace{1cm} (12)

Thus, if the reaction cross section in collinear geometry is known and knowing what particular $S=1$ transition is the basic one, we can unambiguously calculate the asymmetry of the cross-section $\Sigma(\theta_N)$ for the reaction with linearly polarized photons.

### III. EXPERIMENTAL INFORMATION REVIEW

The measurement of reaction cross-section in the collinear geometry presents a certain methodological problem. The first differential cross-section measurements of the reactions $[4]$ led to the conclusion about the absence of the isotropic component, i.e., about the absence of transitions with parallel spins of final-state particles. By now, the experimental evidence of the cross sections has been obtained in both the $^4$He photodisintegration reactions $[8]$ and the reactions of radiative capture of polarized protons by tritium nuclei $[10, 11]$.

The differential cross sections for $(\gamma, p)$ and $(\gamma, n)$ reactions in the $4\pi$ geometry were measured $[1, 3]$ with a diffusion chamber placed in the magnetic field, at bremsstrahlung photon energies ranging from the reaction threshold up to 150 MeV. Relying on those data, the LS-method was used in Ref. $[6]$ to calculate the coefficients $A$, $\alpha$, $\beta$, $\gamma$, $\varepsilon$, and $\nu$ (circles in Figs. 1, 2). It is apparent from Fig. 1 that in the photon energy range $20 \leq E_\gamma \leq 100$ MeV the coefficient $\nu$ is independent of the photon energy. The mean values of coefficients were found to be $\bar{\nu}_p = 0.019\pm0.002$, and $\bar{\nu}_n = 0.028\pm0.003$, and also $\bar{\tau}_p = 0.02\pm0.002$ and $\bar{\tau}_n = 0.01\pm0.003$ (Fig. 2). The errors on the data points are statistical only. The obtained coefficients $\varepsilon_p \sim \varepsilon_n \sim 0$ are in agreement with the assumption that the $E1$, $E2$ and $M1$ approximation is sufficient for describing the available experimental data, and the contribution from the higher multipoles can be neglected.

It was indicated in Ref. $[6]$ that the errors in the measurements of the nucleon emission polar angles $\delta(\theta_N)$ result in the over-estimate of the coefficient $\nu$. In the limit, when calculating the coefficient $\nu$ from the differential cross section with $d\sigma(0^0)=d\sigma(180^0)=0$, i.e. $\nu = 0$, we obtain a coefficient $\nu > 0$, which depends on the angular resolution in the measurements of the nucleon emission polar angle. By the use of simulation, the corresponding corrections were calculated in Ref. $[6]$ on the assumption that the angular resolution was $\delta(\theta_N)=1^0$ and the step of histograming the experimental data on the differential reaction cross section was $10^0$. After taking into account those corrections, the average values of the coefficients in the mentioned photon energy range were determined to be $\bar{\tau}_p = 0.01\pm0.002$ and $\bar{\tau}_n = 0.015\pm0.003$. The difference between the coefficients $\tau_p$ and $\tau_n$ may be due to the fact that the errors in the measurement of the neutron emission polar angle $\delta(\theta_n)$ were greater than the ones in measuring the proton emission polar angle $\delta(\theta_p)$.

The closed points in Fig. 1 show the data of Ref. $[7]$. The differential cross-sections of the reaction were measured in the $4\pi$ geometry on the bremsstrahlung beam at the maximum photon energy $E_\gamma^{max}=80$ MeV, using the diffusion chamber placed in the magnetic field. The authors of Ref. $[7]$ estimated the $\nu$ coefficients to be $\nu_p = 0.03\pm0.01$ and $\nu_n = 0.02\pm0.01$ in the photon energy region of the giant dipole resonance. The triangle in Fig. 1 shows the data of paper $[8]$. The measurements were made using tagged-bremsstrahlung technique with photon of energy $67\pm4$ MeV. The $(\gamma, p)$ reaction was registered with the use of the large solid-angle cylindrical detector based on a set of proportional wire chambers and the scintillation-counter telescope in the range

![Image](image-url)
of proton emission polar angles $35^\circ < \theta_p < 140^\circ$. Considering that the detector did not register the reaction events at large and small angles, the coefficients $\nu_p$ and $\varepsilon_p$ were determined with large errors, $\nu_p = 0.07 \pm 0.07$ and $\varepsilon_p = 0.13 \pm 0.07$. The cross in Fig. 1 shows the data obtained in studies of $^4\text{He}$ nuclear photodisintegration reactions through the use of the $4\pi$ time projection chamber in the photon energy range $22.3 \leq E_\gamma \leq 32\text{ MeV}$ [9]. Based on the measured differential $^4\text{He}(\gamma, p)\text{T}$ reaction cross section, those authors have determined by the LS method that at $E_\gamma = 32\text{ MeV}$ the value makes $\nu_p = 0.02 \pm 0.01$.

Important information about the $S=1$ transition cross-section was derived from the reactions of radiative capture of polarized protons by tritium nuclei. In [10], the reaction was investigated at polarized proton energies $E_p$ between 0.86 and 9 MeV. The differential cross section and the analyzing power $A_p$ were measured in the angular range $20^\circ \leq \theta_p \leq 155^\circ$. It was inferred that the $^3S_1M1$ transition was the basic $S=1$ transition. The average ratio of this transition cross-section to the $^1P_1E1$ transition cross-section was found to be $\nu = 0.006 \pm 0.004$.

In investigation of the same reaction at the 2 MeV proton energy ($E_p = 21.25\text{ MeV}$), the differential cross section and the analyzing power $A_p$ were measured in the angular range $0^\circ \leq \theta \leq 155^\circ$. The multipole analysis has given the cross sections for the $^1D_2E2$, $^3P_1E1$ and $^3D_2E2$ transitions in relation to the $^1P_1E1$ transition cross-section. It is noted in the paper that the $^3S_1M1$ transition can be the basic one at the reaction threshold. However, this transition is determined by the $S$-state of the particle system, the contribution of which should decrease with energy increase as $1/V$, where $V$ is the nucleon velocity. The conclusion was made about the dominant contribution of the $^3P_1E1$ transition among spin $S=1$ transitions. The $^3P_1E1$ transition cross-section has made up $0.72(\pm 0.29-0.18)\%$ of the total cross section of the reaction.

It should be noted that in the studies of $^4\text{He}$ nuclear photodisintegration reactions [7–9], there were no corrections made for the angular resolution in the measurements of nucleon emission polar angles, which could substantially reduce the coefficient $\nu$ value. After taking these corrections into account, the data on the coefficient $\nu$ obtained from the reactions of photodisintegration of the $^4\text{He}$ nucleus and from the reaction of radiation capture of protons by tritium nuclei can be agreed among themselves.

Summarizing the results of the above-considered works, the following conclusions can be made. The true value of the coefficient $\nu$ may lie within the limit $\nu = 0.01 \pm 0.005$. The experimental data show that in the photon energy range $20 \leq E_\gamma \leq 100\text{ MeV}$ the ratio of the $S=1$ transitions cross section in the collinear geometry to the cross section of the $S=0$ electric dipole transition at the nucleon emission angle $\theta_N = 90^\circ$ is independent of the photon energy, within the statistical error.

Figures 3 and 4 show the data on the angular/energy dependencies of the asymmetry of cross-sections for the $^4\text{He}(\gamma, p)\text{T}$ and $^4\text{He}(\gamma, n)^3\text{He}$ reactions with linearly polarized photons. The polarization of the currently available photon beams is estimated to be less than unity. Therefore, in experiments, the product of the photon beam polarization $P_\gamma$ by the reaction cross-section asymmetry $\Sigma(\theta_N)$ is measured, and consequently, the asymmetry measurement errors include the uncertainty in the measurement of photon beam polarization. The circles in the Figures 3 and 4 show the results of work [12]. The linearly polarized photon beam was produced as a result of coherent bremsstrahlung of electrons of energies $E_e = 500, 600$ and $800\text{ MeV}$ in a diamond single crystal. The coherent bremsstrahlung peaks were situated near the energies 40, 60 and 80 MeV, respectively. The degree of photon beam polarization was calculated under the assumption of the unambiguous relationship between the coherent effect value and the photon polarization [13]. The effective degrees of photon polarization in the energy ranges $34 < E_e \leq 46\text{ MeV}$, $46 < E_e \leq 65\text{ MeV}$ and $65 < E_e \leq 90\text{ MeV}$ were determined to be $P_\gamma = 0.62, 0.71,$ and 0.75, respectively. The statistical error being $\Delta P_\gamma = \pm 0.03$. The events of $^4\text{He}$ nuclear disintegration were registered using the magnetic spectrometer with a helium streamer chamber.

The asymmetry of the $^4\text{He}(\gamma, p)\text{T}$ reaction cross-section was measured [14] on the polarized photon beam, which resulted from planar channeling of $1200\text{ MeV}$ electrons in the diamond single crystal (triangles in Fig. 4). The calculations of the degree of polarization were checked against the data, which were obtained when measuring the asymmetry of deuteron photodisintegration cross-section [15]. The polarization decreased from
0.88 in the range of the reaction threshold to 0.58 at Eγ=50 MeV. The reaction was registered with the use of the helium streamer chamber. It has been concluded in [14] that in the angular range 20° ≤ θp ≤ 160° the asymmetry of the reaction cross section is independent of the polar angle emission of the proton.

The squares in Fig. 4 show the preliminary measurement data on the asymmetry of the 4He(γ, n)3He reaction cross section as observed in Ref. [16]. The experiment was done there at energies 40 < Eγ < 56 MeV on the beam of polarized tagged photons, which resulted from the coherent bremsstrahlung of 192.6 MeV electrons in the diamond single crystal. The neutrons were registered with a scintillation counter system using the time-of-flight method. The measurements were carried out at the neutron emission angles θn=45°, 90° and 130°.

![Figure 4](image4.png)

**FIG. 4.** Energy dependences of the asymmetry of cross-sections for the 4He(γ,p)T and 4He(γ,n)3He reactions with linearly polarized photons. Circles - data of Ref. [12], triangles - data of Ref. [14], squares - data of Ref. [16].

It is evident from Fig. 4 that within the limits of experimental error, the asymmetry Σ(Eγ) of the cross sections for linearly polarized photon reactions is also independent of the photon energy.

In computing the curves shown in Figs. 3 and 5, the coefficients β and γ were calculated by the LS method from the differential cross sections for these reactions [1, 3], and the coefficients ε=0 and ν=0.01 were used. Figure 5 shows the calculation of the cross-section asymmetry Σ(θn) of the 4He(γ, n)3He reaction at photon energy of 40 MeV. The solid curve represents the calculation under the assumption that E13P1 or M13S1 is the basic transition; the dashed curve - with the basic M13D1 transition; the dash-dot curve - with the basic E23D2 transition; the dash-and-dot curve - with E13P1 or M13S1 as the basic transition for the 4He(γ,p)T reaction.

![Figure 5](image5.png)

**FIG. 5.** Angular dependencies for the 4He(γ,n)3He reaction cross-section asymmetry, calculated at photon energy of 40 MeV and the coefficients ε=0 and ν=0.01. The solid curve was calculated with E13P1 or M13S1 assumed as the basic transition; the dash curve - with the basic M13D1 transition; the dash-and-dot curve - with the basic E23D2 transition; the dash-and-two dots curve - with E13P1 or M13S1 as the basic transition for the 4He(γ,p)T reaction.
used. At the nucleon emission angle $\theta_N=90^\circ$ expression (4) leads to simple relations. If $M1^3D_1$ is the basic transition, then we have

$$\Sigma(90^\circ) = \frac{1 - 3\nu}{1 + \nu}. \quad (13)$$

With the basic $E1^3P_1$ or $M1^3S_1$ transition, the asymmetry is equal to:

$$\Sigma(90^\circ) = \frac{1}{1 + \nu}. \quad (14)$$

and with the basic $E2^3D_2$ transition we have $\Sigma(90^\circ)=1$

It is obvious from Fig. 3 that there is some disagreement between the experimental data and the calculated curves for the cross-section asymmetry $\Sigma(\theta_N)$. To determine the discrepancy, the experimental data on the asymmetry $\Sigma(\theta_N)$ were averaged in the interval of nucleon emission polar angles $20^\circ \leq \theta_N \leq 160^\circ$ for the both $(\vec{\gamma},p)$ and $(\vec{\gamma},n)$ reaction channels. The asymmetry values calculated in the same interval of nucleon emission polar angle were averaged for each of the possible $S=\pm 1$ transitions. Then the difference between the averaged asymmetry values $\overline{\Sigma} = \overline{\Sigma}_{th} - \overline{\Sigma}_{exp}$ was determined. The calculated results are given in Table 2.

**TABLE II: Difference between the averaged calculated/measured asymmetries of cross sections for $(\vec{\gamma},p)$ and $(\vec{\gamma},n)$ reaction channels.**

| $E_\gamma$, MeV | $|M1^3D_1|^2$ | $|E1^3P_1|^2$ or $|M1^3S_1|^2$ | $|E2^3D_2|^2$ | $\overline{\Sigma} = \overline{\Sigma}_{th} - \overline{\Sigma}_{exp}$ |
|----------------|---------------|-----------------------------|-----------------|----------------------------------|
| 40             | 0.055±0.067   | 0.081±0.063                 | 0.090±0.087     |                                   |
| 60             | 0.166±0.068   | 0.191±0.067                 | 0.201±0.067     |                                   |
| 80             | 0.017±0.086   | 0.046±0.086                 | 0.056±0.086     |                                   |

Supposing that the cross-section asymmetry data are correct, then the calculated difference $\overline{\Sigma}$ would lead to the value $\nu >0.04$, which is not in agreement with the cross-section data in the collinear geometry (see Fig. 1). Besides, at this $\nu$ value, the angular dependence of the cross-section asymmetry would manifest in an explicit form in the available statistics. The discordance may be attributed to the instrumental errors in the measurements of the reaction cross-section asymmetry. It should be noted that in Refs. [12], [14] and [16] the reaction products were registered by different methods, but, within the experimental error, the results are in agreement. It is also possible that there is the contribution of additional polarization caused by the off-axis collimation of the photon beam. However, in this case, the over-estimate of the degree of photon beam polarization is possible only if the vectors of the polarizations coincide, this being scarcely probable because the data were obtained in several independent experiments. It is also possible that the methods used to calculate the degree of polarization of photon beams, as well as their verification by the photodisintegration of the deuteron, can lead to an over-estimated value of their degree of polarization.

The uncertainties in the available experimental data on the asymmetry of $^4$He nuclear photodisintegration reaction cross-sections give no way of drawing a conclusion about what particular spin $S=\pm 1$ transition is dominant. Using the conclusions of Refs. [10] and [11] that the basic transition is, respectively, the $^3S_1, M1$ transition and the $^3P_1, E1$ transition, which have the same asymmetry $\Sigma(\theta_N)$, and also, the data on the reaction cross-section in the collinear geometry $\nu=0.01±0.005$, we have calculated the asymmetry of cross-sections for two-body reactions with linearly polarized photons. It is found to be $\Sigma(90^\circ)=0.9901±0.005$.

**IV. DISCUSSION OF RESULTS**

The available experimental data of two-body $^4$He nuclear disintegration reactions allows us to suggest that the ratio of the cross section of $S=\pm 1$ transitions in the collinear geometry to the cross section of $E1, S=0$ transition at the nucleon emission angle $\theta_N=90^\circ$ in the photon energy range $20 \leq E_\gamma \leq 100$ MeV is independent of the photon energy, to within the experimental errors. The cross-sectional asymmetry of the reaction with linearly polarized photons in the energy range $20 \leq E_\gamma \leq 90$ MeV is also independent of the photon energy, to within the experimental errors.

In Ref. [3], the probabilities of the $S$, $P$ and $D$ states of the $^4$He nucleus were computed. In the computations, the authors used the realistic nucleon-nucleon CD-Bonn and AV18 potentials, and also took into account the contribution of $3N$ forces in the form of the Tucson-Melbourne (TM) and Urbana IX potentials. The computational results are given Table III.

**TABLE III: S, P and D state probabilities for the $^4$He wave functions.** All probabilities are in percentage terms. (The table is taken from Ref. [3])

| Interaction | $S$     | $P$   | $D$      |
|-------------|---------|-------|----------|
| CD-Bonn     | 89.06   | 90.72 | 10.72    |
| CD-Bonn+TM  | 89.65   | 90.45 | 9.90     |
| AV18        | 85.87   | 90.35 | 13.78    |
| AV18+Urb-IX | 83.23   | 90.75 | 16.03    |

It is evident from Table III that the consideration of $3N$ forces nearly doubles the probability of $P$ states. Therefore, the measurement of $P$-state probability makes it possible to obtain new information on $3N$ forces. It can be assumed that when the nucleus is split using the electromagnetic interaction, which is central, there is no spin flip of the hadron system of particles, and also that the reaction cross section does not depend on the spin state of the $^4$He nucleus. Then it is hoped that the ratio

$$\eta = \frac{4H\epsilon^3P_0}{4H\epsilon^1S_0} \to \sigma(E1^3P_1) \to \sigma(E1^1P_1) \quad (15)$$
will be independent of the photon energy. Here \( \sigma(E_1^3P_1) \) is the part of the \((\gamma, N)\) reaction cross-section caused by the spin \(S=1\) transition, \( \sigma(E_1^1P_1) \) is the part of the \((\gamma, N)\) reaction cross-section due to the electric dipole spin \(S=0\) transition. It can be assumed that

\[
\eta = \mathcal{P}(3P_0)
\]

(16)

\( \eta \) is the probability of \(3P_0\) states of the \(^4\)He nucleus.

Having integrated the angular distribution of the \(E_1^3P_1\) transition (see Table 1) with respect to the solid angle, and expressing its total cross section in terms of the differential cross section at the nucleon emission angle \(\theta_N=0^\circ\), we obtained

\[
\sigma(E_1^3P_1) = \frac{d\sigma(0^\circ)}{1 + \cos^2(0^\circ)} \frac{16\pi}{3}
\]

(17)

Similarly to the \(E1^1P_1\) transition, we have

\[
\sigma(E1^1P_1) = \frac{d\sigma(90^\circ)}{\sin^2(90^\circ)} \frac{8\pi}{3}
\]

(18)

and the total cross-section ratio is

\[
\frac{\sigma(E_1^3P_1)}{\sigma(E_1^1P_1)} = \frac{d\sigma(0^\circ)}{d\sigma(90^\circ)} = \nu
\]

(19)

If the \(M1^3S_1\) transition is predominant, then \(\eta=3\nu/2\), and if the \(M1^3D_1\) transition is predominant, then \(\eta=3\nu/2\).

The calculation of the probabilities of \(3P_0\) states of the \(^4\)He nucleus based on realistic \(NN\) potential, taking into account the contribution of \(3N\) forces and the available experimental data on the cross-section for transitions with spin \(S=1\), do not contradict each other.

In a number of theoretical [2] and experimental [10,11] works the origin of spin \(S=1\) transitions is attributed to the fact that in the course of the reaction the spin-flip of the hadronic particle system takes place, and, in turn, the spin-flip is caused by the contribution of \(\text{MEC}\). It should be noted that the \(\text{MEC}\) contribution is dependent on the photon energy [17], this being inconsistent with the given experimental data.

However, this does not preclude a \(\text{MEC}\) contribution to spin \(S=0\) transitions of the final state of the particle system.

A systematic inconsistency is observed between the experimental data on the reaction cross section in the collinear geometry and on the cross-section asymmetry of the reaction with linearly polarized photons. The inconsistency may be due, in particular, to the overestimate of the calculated degree of photon beam polarization. More information is needed to find out the source of the inconsistency.

A high cross-section asymmetry value of \((\gamma, N)\) reactions, and also, its independence of the photon energy over a wide energy range may make the \(^4\)He nucleus more convenient for measuring the degree of linear photon-beam polarization than the deuteron will do [15].

In this connection it should be noted that there is a need to substantially improve the accuracy of angular dependence measurements of the asymmetry of \(^4\)He photodisintegration reaction cross-section, using linearly polarized photons in the widest possible range of photon energies.

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