Examining measuring the degree of linear photon-beam polarization in the energy range up to 100 MeV with the use of ^{4}He($\vec{\gamma}$, p)^{3}H and ^{4}He($\vec{\gamma}$, n)^{3}He reactions

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The paper gives physical justification of a new method for measuring the degree of linear photon-beam polarization, which relies on the experimental data for the total cross section of spin $S = 1$ transitions in the ^{4}He(γ, p)^{3}H and ^{4}He(γ, n)^{3}He reactions. The experimental information on the cross section was obtained from both the mentioned reactions and the reactions of radiative capture of protons by tritium nuclei. The total cross section for transitions with spin $S = 1$ is $\approx$1% of the total cross section for the reaction. The ratio of the differential cross section in the collinear geometry, specified by the $S = 1$ transitions, to the differential reaction cross section at the nucleon emission angle $\theta_N = 90^\circ$ in the energy range $20 \leqslant E_\gamma \leqslant 100$ MeV is independent of the photon energy within the experimental error. The total cross section for the $S = 1$ transitions can be also determined from the experimental data on the cross-section asymmetry of the reaction with linearly polarized photons $\Sigma(\theta_N)$. However, the total cross section for transitions with spin $S = 1$, calculated from the asymmetry of the cross section $\Sigma(\theta_N)$, is several times greater than that calculated from the differential cross section. This inconsistency of the experimental data may be due, in particular, to the overestimate of the degree of linear photon-beam polarization. The above-mentioned reactions seem to be more convenient for measuring the degree of linear photon-beam polarization than the deuteron photodisintegration reactions.

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I. INTRODUCTION

The total momentum and parity of the ^{4}He nucleus $J^\pi = 0^+$, the two-body nature of the reactions, and the absence of excited states in the final nuclei make it possible to perform a detailed multipole analysis in the $E1$, $E2$, and $M1$ approximation. In the course of the ^{4}He(γ, p)^{3}H and ^{4}He(γ, n)^{3}He reactions, the final-state spin of the particle system can take two values: $S = 0$ and $S = 1$. The main part of the 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 (MECs). Based on the realistic NN potential and $3N$ forces, Nogga *et al.* [3] have demonstrated that in the initial state the ^{4}He nucleus can also have the spins $S = 1$ and $S = 2$, and possibly, the $S = 1$ transitions may be due to the ^{4}He nuclear structure [4]. Thus, the occurrence of multipole transitions may be of different origin. Measurements of the small effects of nuclear structure and the mechanisms of nuclear reactions require measurements of polarization observable with increased accuracy.

New information about the nucleus can be obtained using linearly polarized photons. To measure the degree of photon beam polarization, various methods are used. For instance, Boldyshev and Peresun'ko[5] have calculated the asymmetry of the cross section for electron-positron pair photoproduction on the electron versus the photon energy and the minimum recoil electron momentum. The asymmetry of the cross section for this reaction has been found to be $\lambda \approx 0.15$, and the error in calculating this value was $\Delta\lambda \approx 1\%$. This method is applicable in a wide range of photon energies. Based on the given calculation, Iwata *et al.* [6] have created a polarimeter and measured the degree of polarization of the 1.2-GeV coherent electron bremsstrahlung beam in a silicon crystal at photon energies ranging from 240 to 620 MeV. The reaction products were registered with the use of scintillation counters. By way of example, it was found that at an energy of 360 MeV, the measured asymmetry of the reaction cross section amounted to $\Sigma(e^-) = 4.4 \pm 1.3\%$. Then, using the calculated value of the asymmetry of the cross section λ, it is possible to calculate the photon beam polarization from the measured asymmetry $\Sigma(e^-)$ value. As to the shortcomings of the method, one may mention a low asymmetry λ value of the process of e^+e^- pair photoproduction on the electron and a rapid decrease in the total reaction cross section with an increase in the minimum recoil electron momentum.

The position of the reaction plane during photoproduction of e^+e^- pairs in the Coulomb field of the nucleus is also correlated with the position of the photon polarization vector [7]. However, the azimuthal distribution of the emission plane of these pairs is difficult to measure to the required accuracy because of a small angle of e^+e^- pair spreading $\theta_e \approx m_e/E_\gamma$, where m_e is the electron mass.

In Ref. [8], to measure the degree of polarization of the channeled radiation of 1.2-GeV electrons in a diamond crystal, the asymmetry of the reaction cross section for deuteron disintegration by linearly polarized photons was used as a reference. That asymmetry was measured, in particular, with monoenergetic photon beams having nearly a 100% linear polarization. The beams were obtained as a result of Compton backscattering of light from a laser [9] or from an undulator [10] by high-energy electrons. The theoretically calculated value of the photon beam polarization was equal to $P_\gamma = 0.997$ [11]. However, as a result of the contribution of unconsidered small effects, some spread in the direction of the photon polarization vectors can occur from pulse to pulse of the beam, and that can lead to a decrease in its degree of polarization. The authors of Ref. [11] have measured the polarization of the photon beam using the resonant scattering of polarized photons of energy corresponding to the excitation energy (15.1 MeV) of the 1^+ level of the ^{12}C nucleus. In this case, the measured photon beam polarization value was $P_\gamma = 0.99 \pm 0.02$. It should be noted that this method of measuring the degree of polarization of photons is applicable only for the fixed photon energy.

The asymmetry of the cross section for the $^2\mathrm{H}(\vec{\gamma}, p)n$ reaction at the nucleon emission angle $\theta_N = 90^\circ$ decreases from ≈ 0.9 at a photon energy of 20 MeV to zero at a photon energy of ≈ 100 MeV. In this regard, at photon energies $E_\gamma \gtrsim 40$ MeV, the measurement of the degree of photon beam polarization by using the deuteron disintegration reaction becomes ineffective, since the low value of the cross-section asymmetry must be compensated for by additional statistics. The high value of the asymmetry of the cross sections for $^4\mathrm{He}(\vec{\gamma}, p)\,^3\mathrm{H}$ and $^4\mathrm{He}(\vec{\gamma}, n)\,^3\mathrm{He}$ reactions, as well as its independence from the photon energy, provides high accuracy and efficiency in measuring the degree of linear polarization of photon beams.

II. MULTIPOLE ANALYSIS OF $^4\mathrm{He}(\gamma, p)\,^3\mathrm{H}$ AND $^4\mathrm{He}(\gamma, n)\,^3\mathrm{He}$ REACTIONS

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

$$\begin{aligned}
\frac{d\sigma}{d\Omega} = \frac{\lambda\!\!\!^{-2}}{32}&\{\sin^2\theta[18|E1^1P_1|^2 - 9|E1^3P_1|^2 \\
&+ 9|M1^3D_1|^2 - 25|E2^3D_2|^2 \\
&- 18\sqrt{2}\mathrm{Re}(M1^3S_1^* M1^3D_1) \\
&+ 30\sqrt{3}\mathrm{Re}(M1^3D_1^* E2^3D_2) \\
&+ 30\sqrt{6}\mathrm{Re}(M1^3S_1^* E2^3D_2) \\
&+ \cos\theta(60\sqrt{3}\mathrm{Re}(E1^1P_1^* E2^1D_2) \\
&- 60\mathrm{Re}[E1^3P_1^* E2^3D_2)] \\
&+ \cos^2\theta(150|E2^1D_2|^2 - 100|E2^3D_2|^2)] \\
&+ \cos\theta[-12\sqrt{6}\mathrm{Re}(E1^3P_1^* M1^3S_1) \\
&- 12\sqrt{3}\mathrm{Re}(E1^3P_1^* M1^3D_1) + 60\mathrm{Re}(E1^3P_1^* E2^3D_2] \\
&+ 18|E1^3P_1|^2 + 12|M1^3S_1|^2 + 6|M1^3D_1|^2 \\
&+ 50|E2^3D_2|^2 + 12\sqrt{2}\mathrm{Re}(M1^3S_1^* M1^3D_1) \\
&- 20\sqrt{6}\mathrm{Re}(M1^3S_1^* E2^3D_2) \\
&- 20\sqrt{3}\mathrm{Re}(M1^3D_1^* E2^3D_2)\},
\end{aligned} \tag{1}$$

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

The asymmetry $\Sigma(\theta_N)$ reaction cross section is given by the expression:

$$\begin{aligned}
\Sigma(\theta) = \sin^2\theta\{&18\mid E1^1P_1|^2 - 9|E1^3P_1|^2 \\
&- 9|M1^3D_1|^2 + 25|E2^3D_2|^2 \\
&+ 18\sqrt{2}\mathrm{Re}(M1^3S_1^* M1^3D_1) \\
&+ 10\sqrt{3}\mathrm{Re}(M1^3D_1^* E2^3D_2) \\
&+ 10\sqrt{6}\mathrm{Re}(M1^3S_1^* E2^3D_2) \\
&+ \cos\theta[60\sqrt{3}\mathrm{Re}(E1^1P_1^* E2^1D_2) \\
&- 60\mathrm{Re}(E1^3P_1^* E2^3D_2)] \\
&+ \cos^2\theta[150|E2^1D_2|^2 - 100|E2^3D_2|^2]\}/\frac{32}{\lambda\!\!\!^{-2}}\frac{d\sigma}{d\Omega}.
\end{aligned} \tag{2}$$

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

$$\frac{d\sigma}{d\Omega} = A[\sin^2\theta(1 + \beta\cos\theta + \gamma\cos^2\theta) + \varepsilon\cos\theta + \nu]. \tag{3}$$

$$\Sigma(\theta) = \frac{\sin^2\theta(1 + \alpha + \beta\cos\theta + \gamma\cos^2\theta)}{\sin^2\theta(1 + \beta\cos\theta + \gamma\cos^2\theta) + \varepsilon\cos\theta + \nu}. \tag{4}$$

The coefficients A, α, β, γ, ε, and ν are expressed in terms of the multipole amplitudes as

$$\begin{aligned}
A = \lambda\!\!\!^{-2}/32\{&18|E1^1P_1|^2 - 9|E1^3P_1|^2 + 9|M1^3D_1|^2 \\
&- 25|E2^3D_2|^2 \\
&- 18\sqrt{2}|M1^3S_1||M1^3D_1|\cos[\delta(^3S_1) - \delta(^3D_1)] \\
&+ 30\sqrt{6}|M1^3S_1||E2^3D_2|\cos[\delta(^3S_1) - \delta(^3D_2)] \\
&+ 30\sqrt{3}|M1^3D_1||E2^3D_2|\cos[\delta(^3D_1) - \delta(^3D_2)]\};
\end{aligned} \tag{5}$$

where δ is the phase of the corresponding amplitude,

$$\begin{aligned}
\alpha = \{&-18|M1^3D_1|^2 + 50|E2^3D_2|^2 \\
&+ 36\sqrt{2}|M1^3S_1||M1^3D_1|\cos[\delta(^3S_1) - \delta(^3D_1)] \\
&- 20\sqrt{6}|M1^3S_1||E2^3D_2|\cos[\delta(^3S_1) - \delta(^3D_2)] \\
&- 20\sqrt{3}|M1^3D_1||E2^3D_2|\cos[\delta(^3D_1) - \delta(^3D_2)]\}\,/\,\frac{32}{\lambda\!\!\!^{-2}}A\,;
\end{aligned} \tag{6}$$

$$\begin{aligned}
\beta = \{&60\sqrt{3}|E1^1P_1||E2^1D_2|\cos[\delta(^1P_1) - \delta(^1D_2)] \\
&- 60|E1^3P_1||E2^3D_2|\cos[\delta(^3P_1) - \delta(^3D_2)]\,/\,\}\frac{32}{\lambda\!\!\!^{-2}}A\,;
\end{aligned} \tag{7}$$

TABLE I. Polar-angle nucleon emission distribution for $E1$, $E2$, and $M1$ multipole transitions.

Spin of the final states	Multipole transition	Angular distribution
$S=0$	$\|E1^1P_1\|^2$	$\sin^2\theta$
	$\|E2^1D_2\|^2$	$\sin^2\theta\cos^2\theta$
	$\|E1^3P_1\|^2$	$1+\cos^2\theta$
$S=1$	$\|M1^3S_1\|^2$	const
	$\|M1^3D_1\|^2$	$5-3\cos^2\theta$
	$\|E2^3D_2\|^2$	$1-3\cos^2\theta+4\cos^4\theta$

$$\gamma=\{150|E2^1D_2|^2-100|E2^3D_2|^2\;/\;\frac{32}{\lambda\!\!\!^{-2}}A\,; \tag{8}$$

$$\begin{aligned}\varepsilon=\{&-12\sqrt{3}|E1^3P_1||M1^3D_1|\cos[\delta(^3P_1)-\delta(^3D_1)]\\&-12\sqrt{6}|E1^3P_1||M1^3S_1|\cos[\delta(^3P_1)-\delta(^3S_1)]\\&+60|E1^3P_1||E2^3D_2|\cos[\delta(^3P_1)-\delta(^3D_2)]\}\;/\;\frac{32}{\lambda\!\!\!^{-2}}A\,;\end{aligned} \tag{9}$$

$$\begin{aligned}\nu=\{&18|E1^3P_1|^2+12|M1^3S_1|^2+6|M1^3D_1|^2+50|E2^3D_2|^2\\&+12\sqrt{2}|M1^3S_1||M1^3D_1|\cos[\delta(^3S_1)-\delta(^3D_1)]\\&-20\sqrt{6}|M1^3S_1||E2^3D_2|\cos[\delta(^3S_1)-\delta(^3D_2)]\\&-20\sqrt{3}|M1^3D_1||E2^3D_2|\cos[\delta(^3D_1)-\delta(^3D_2)]\}\;/\;\frac{32}{\lambda\!\!\!^{-2}}A.\end{aligned} \tag{10}$$

Thus, having determined the coefficients A, α, β, γ, ε, and ν 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 $\theta_N=90^\circ$. The coefficient γ is proportional to the contribution of the spin $S=0$ electric quadrupole $E2$ transition. The coefficient β describes the interference between the electric dipole $E1$ and electric quadrupole $E2$ amplitudes having spin $S=0$. The coefficients α, ε, and ν designate the contributions from $S=1$ transitions of final-state particles. Expression (3) leads to the following relations: $\varepsilon=[d\sigma(0^0)-d\sigma(180^\circ)]/2A$, $\nu=[d\sigma(0^\circ)+d\sigma(180^\circ)]/2A$. Neglecting the contribution of transitions with spin $S=1$, one obtains that $\varepsilon=[d\sigma(0^\circ)-d\sigma(180^\circ)]/2d\sigma_1(90^\circ)$, $\nu=[d\sigma(0^\circ)+d\sigma(180^\circ)]/2d\sigma_1(90^\circ)$, where $d\sigma_1(90^\circ)$ is the differential cross section for the $S=0$ electric $E1$ transition at the angle of nucleon emission $\theta_N=90^\circ$. Table I shows distribution over the polar angle of nucleon emission in c.m.s. for $E1$, $E2$, and $M1$ multipole transitions. It can be seen from Table I that for all the mentioned transitions one has $d\sigma(0^\circ)=d\sigma(180^\circ)$, and hence should be about $\varepsilon\approx0$. If $\varepsilon\neq0$, then this may be indicative of the experimental errors, or of the insufficiency of $E1$, $E2$, and $M1$ approximation.

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 $\theta_N=0^\circ$ and 180°. The difference of the asymmetry $\Sigma(\theta_N)$ from 1 may be due only to spin $S=1$ transitions. The smaller the contribution from $S=1$ transitions, the more rectangular the reaction cross-section asymmetry becomes.

It is apparent from expression (6) that if the $E1^3P_1$ or $M1^3S_1$ transition is the basic one then the coefficient α equals 0 (since $M1^3D_1\sim E2^3D_2\sim0$). The angular dependences of the cross-section asymmetry $\Sigma(\theta_N)$ for these two transitions, calculated by relation (4), are identical in form. Thus, the data on the reaction cross section in the collinear geometry ν are not sufficient to separate the contributions of these two transitions. However, if the total cross section $\sigma(S=1)$ of the transition with spin $S=1$ is known, then these transitions under discussion can be separated by the value of the asymmetry $\Sigma(\theta_N)$. By integrating the angular distributions of the transitions (see Table 1) over the solid angle, one obtains

$$\eta_1=\frac{\sigma(E1^3P_1)}{\sigma(E1^1P_1)}=\frac{d\sigma(0^0)}{d\sigma_1(90^0)}=\nu. \tag{11}$$

If the $M1^3S_1$ transition is dominant, then

$$\eta_2=\frac{\sigma(M1^3S_1)}{\sigma(E1^1P_1)}=\frac{1.5d\sigma(0^0)}{d\sigma_1(90^0)}=1.5\nu. \tag{12}$$

It is evident from expressions (11) and (12) that at a given total cross section for the $S=1$ transition, the cross section in collinear geometry for the $M1^3S_1$ transition will be 1.5 times larger than for the $E1^3P_1$ transition. Accordingly, the asymmetry of the cross section $\Sigma(\theta_N)$ for the $E1^3P_1$ transition will be higher than for the $M1^3S_1$ transition.

One can see from expressions (6) and (10) that if the $M1^3D_1$ amplitude is dominant, then

$$\alpha=-3\nu\,, \tag{13}$$

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

$$\alpha=\nu\,. \tag{14}$$

At $E1^3P_1$, $M1^3D_1$, and $E2^3D_2$ transitions, the angular dependences of the cross-section asymmetry $\Sigma(\theta_N)$ have different forms.

At the nucleon emission angle $\theta_N=90^\circ$ expression (4) leads to simple relations. If $E1^3P_1$ or $M1^3S_1$ is the basic transition, then one has

$$\Sigma(90^\circ)=\frac{1}{1+\nu}. \tag{15}$$

With the basic $M1^3D_1$transition, the asymmetry is equal to

$$\Sigma(90^\circ)=\frac{1-3\nu}{1+\nu}, \tag{16}$$

and with the basic $E2^3D_2$ transition one has $\Sigma(90^\circ)=1$.

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

III. REVIEW OF EXPERIMENTAL INFORMATION ON THE CROSS SECTION FOR ^{4}He$(\gamma, p)^3$H and ^{4}He$(\gamma, n)^3$He REACTIONS IN COLLINEAR GEOMETRY

The measurement of reaction cross section in the collinear geometry presents a certain methodical problem. The first differential cross-section measurements of the reactions [12] 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 [1,13–16] and the reactions of radiative capture of polarized protons by tritium nuclei [17,18].

The differential cross sections for (γ, p) and (γ, n) reactions in the 4π geometry were measured [1,13] 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 least squares (LS) method was used in Ref. [4] to calculate the coefficients A, α, β, γ, ε, and ν (circles in Figs. 1 and 2). The closed points in Fig. 1 show the mean values of the coefficients $\overline{\nu}_p = 0.019 \pm 0.002$ and $\overline{\nu}_n = 0.028 \pm 0.003$, which were calculated from the data of Refs. [1,13] in the photon energy range from the reaction threshold up to 100 MeV. The root-mean-square deviations of the coefficients from their mean values amount to $\chi_p^2 \approx 1$ and $\chi_n^2 \approx 1.5$ per point. The errors on the data points are statistical only. It is apparent from Fig. 1 that in the photon energy range $20 \leqslant E_\gamma \leqslant 100$ MeV the coefficients ν are independent of the photon energy.

The mean values of the coefficients ε made up $\overline{\varepsilon}_p = 0. \pm 0.002$ and $\overline{\varepsilon}_n = -0.001 \pm 0.003$. In the considered range of photon energies, the contribution of $E1$, $E2$, and $M1$ of multipoles with spin $S = 1$ is very small, and the contribution of higher multipoles should be even smaller. This is confirmed by the experimental data on the coefficients $\varepsilon_p \sim \varepsilon_n \sim 0$ (Fig. 2).

It was indicated in Ref. [4] that the errors in the measurements of the nucleon emission polar angles $\delta(\theta_N)$ result in the overestimate of the coefficient ν. In the limit, when calculating the coefficient ν from the differential cross section with $d\sigma(0^\circ) = d\sigma(180^\circ) = 0$, i.e., $\nu = 0$, one obtains 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. [4] on the assumption that the angular resolution was $\delta(\theta_N) = 1^\circ$ and the step of histogramming the experimental data on the differential reaction cross section was 10° [13]. After taking into account those corrections, the average values of the coefficients in the mentioned photon energy range were determined to be $\overline{\nu}_p = 0.01 \pm 0.002$ and $\overline{\nu}_n = 0.015 \pm 0.003$. The difference between the coefficients $\overline{\nu}_p$ and $\overline{\nu}_n$ 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 squares in Fig. 1 show the data of Ref. [14]. The differential cross sections of the reaction were measured in the 4π 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. [14] estimated the ν coefficients to be $\nu_p = 0.03 \pm 0.01$ and $\nu_n = 0.02$

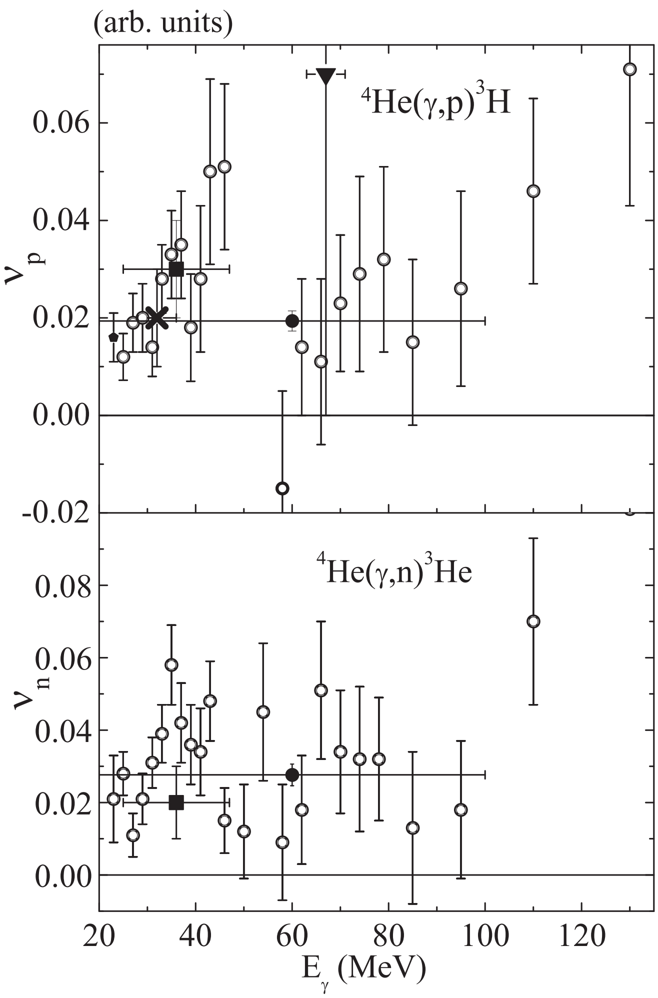

FIG. 1. The ratio of the total $S = 1$ transition cross section in the collinear geometry to the $S = 0$ electric dipole transition cross section at the nucleon emission angle $\theta_N = 90^\circ$. Open circles show the data of Refs. [1,13]: Closed points show mean values of these data in the photon energy range $20 \leqslant E_\gamma \leqslant 100$ MeV, squares show data of Ref. [14], triangles show data of Ref. [15], and crosses show data from Ref. [16]. The errors on the data points are statistical only.

$\pm$ 0.01 in the photon energy region of the giant dipole resonance. The triangle in Fig. 1 shows the data of Ref. [15]. The measurements were made using the tagged bremsstrahlung technique with photon of energy 67±4 MeV. The (γ, 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 of proton emission polar angles $35^\circ \leqslant \theta_p \leqslant 140^\circ$. Considering that the detector did not register the reaction events at large and small angles, the coefficients ν_p and ε_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}He nuclear photodisintegration reactions through the use of the 4π time projection chamber in the photon energy range $22.3 \leqslant E_\gamma \leqslant 32$ MeV [16]. Based on the measured differential ^{4}He$(\gamma, p)^3$H reaction cross section, those authors have

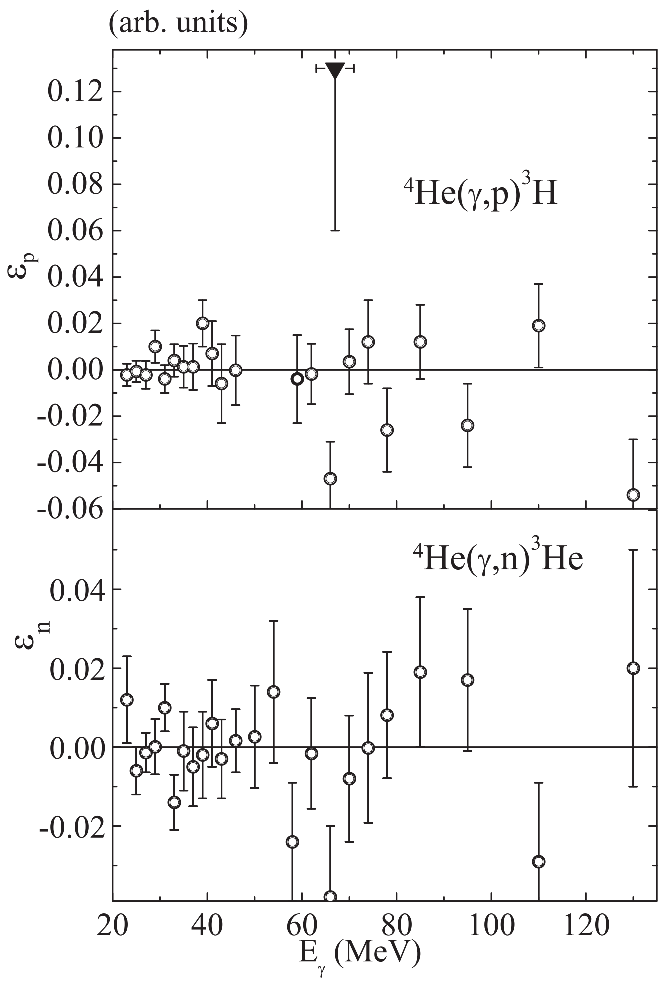

FIG. 2. Coefficients ε_p and ε_n. Points are the same as in Fig. 1. Error bars are statistical only.

determined by the LS method that at $E_\gamma = 32$ MeV the value is $\nu_p = 0.02\pm0.01$.

Important information about the $S = 1$ transition cross section was derived from the reactions of radiative capture of polarized protons by tritium nuclei. In Ref. [17], 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_y were measured in the angular range $20^\circ \leqslant \theta_\gamma \leqslant 155^\circ$. It was inferred that the $^3S_1\, M1$ transition was the basic $S = 1$ transition. The average ratio of this transition cross section to the $^1P_1\, E1$ 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 ($E_\gamma = 21.25$ MeV), the differential cross section and the analyzing power A_y were measured in the angular range $0^\circ \leqslant \theta \leqslant 155^\circ$ [18]. The multipole analysis has given the cross sections for the $^1D_2\, E2$, $^3P_1\, E1$ and $^3D_2\, E2$ transitions in relation to the $^1P_1\, E1$ transition cross section. It is noted in the paper that the $^3S_1\, M\,1$ transition can be the basic one at the reaction threshold only. 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 $^3P_1\, E1$ transition among spin $S = 1$ transitions. The $^3P_1\, E1$ transition cross section has made up 0.72(+0.29–0.18)% of the total cross section of the reaction.

The coefficient ν value, measured from the reaction of the radiation proton capture by tritium nuclei, is lower than the measured from the ^{4}He photodisintegration reactions. It should be noted that in the studies of ^{4}He nucleus photodisintegration reactions [14–16], there were no corrections made for the angular resolution in the measurement of nucleon emission polar angle, which could substantially reduce the coefficient's ν value. After taking these corrections into account, the data on the coefficient's ν value obtained from the mentioned reactions 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 ν may lie within the limit $\nu = 0.010\pm0.005$. The experimental data show that in the photon energy range $20 \leqslant E_\gamma \leqslant 100$ 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.

IV. REVIEW OF EXPERIMENTAL DATA ON THE ASYMMETRY OF THE CROSS SECTION FOR ^{4}He($\vec{\gamma}, p$)^{3}H AND ^{4}He($\vec{\gamma}, n$)^{3}He REACTIONS WITH LINEARLY POLARIZED PHOTONS

Figures 3 and 4 show the data on the angular and energy dependencies of the asymmetry of cross sections for the ^{4}He($\vec{\gamma}, p$)^{3}H and ^{4}He($\vec{\gamma}, n$)^{3}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_γ 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 Figs. 3 and 4 show the results of work [19]. The linearly polarized photon beam was produced as a result of coherent bremsstrahlung of electrons of energies E_e = 500, 600, and 800 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 [20]. The effective degrees of photon polarization in the energy ranges $34 < E_\gamma \leqslant 46$ MeV, $46 < E_\gamma \leqslant 65$ MeV, and $65 < E_\gamma \leqslant 90$ MeV were determined to be P_γ^{eff}= 0.62, 0.71, and 0.75, respectively. The statistical error is $\Delta P_\gamma^{\mathrm{eff}} = \pm0.03$. The events of ^{4}He nuclear disintegration were registered using the magnetic spectrometer with a helium streamer chamber.

The asymmetry of the ^{4}He($\vec{\gamma}, p$)^{3}H reaction cross section was measured [21] on the polarized photon beam, which resulted from planar channeling of 1200 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

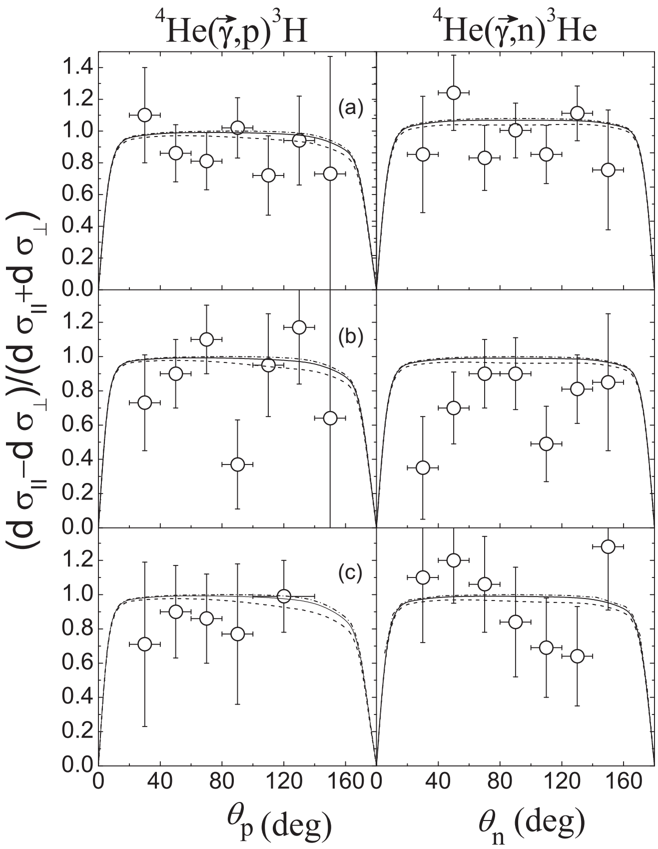

FIG. 3. Angular dependences of the asymmetry of cross sections for the ^{4}He$(\vec{\gamma}, p)^3$H and ^{4}He$(\vec{\gamma}, n)^3$He reactions with linearly polarized photons at energies of (a) 40, (b) 60, and (c) 80 MeV. Circles show the data of Ref. [19]. The curves are explained in Fig. 5.

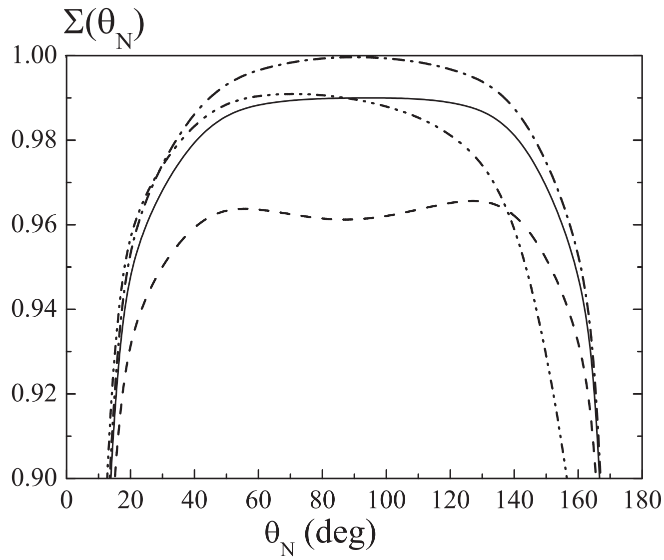

FIG. 5. Angular dependencies for the ^{4}He$(\vec{\gamma}, n)^3$He reaction cross-section asymmetry, calculated at photon energy of 40 MeV and the coefficients $\varepsilon = 0$ and $\nu = 0.01$. The solid curve was calculated with $E1\,^3P_1$ or $M1^3S_1$ assumed as the basic transition; the dashed curve was calculated with the basic $M1^3D_1$ transition; the dash-dotted curve was calculated with the basic $E2^3D_2$ transition; and the dash-and-two-dot curve was calculated with $E1\,^3P_1$ or $M1^3S_1$ as the basic transition for the ^{4}He$(\vec{\gamma}, p)^3$H reaction.

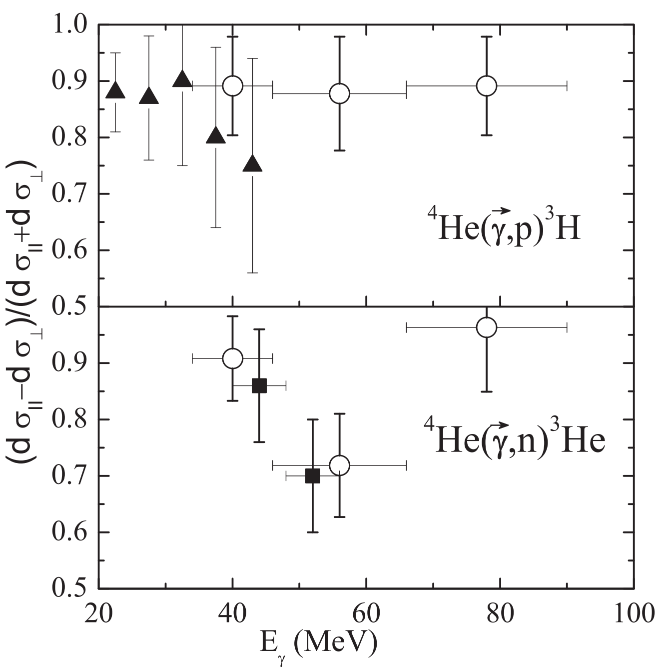

FIG. 4. Energy dependences of the asymmetry of cross sections for the ^{4}He$(\vec{\gamma}, p)^3$H and ^{4}He$(\vec{\gamma}, n)^3$He reactions with linearly polarized photons. Circles show data of Ref. [19], triangles show data of Ref. [21], and squares show data of Refs. [21,22].

deuteron photodisintegration cross section [8]. The polarization decreased from 0.88 in the range of the reaction threshold to 0.58 at $E_\gamma = 50$ MeV. The reaction was registered with the use of the helium streamer chamber. It has been concluded in Ref. [21] that in the angular range $20^\circ \leqslant \theta_p \leqslant 160^\circ$ the asymmetry of the reaction cross section is independent of the polar angle emission of the proton and its average value is $\overline{\Sigma(\theta_p)} = 0.89 \pm 0.05$.

The squares in Fig. 4 show the preliminary measurement data on the asymmetry of the ^{4}He$(\vec{\gamma}, n)^3$He reaction cross section as observed in Refs. [21,22]. The experiment was done there at energies $40 < E_\gamma \leqslant 56$ 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 $\theta_n = 45^\circ, 90^\circ$, and 130°.

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 [1,13], and the coefficients $\varepsilon = 0$ and $\nu = 0.01$ were used. Figure 5 shows the calculation of the cross-section asymmetry $\Sigma(\theta_n)$ of the ^{4}He$(\vec{\gamma}, n)^3$He reaction at photon energy of 40 MeV. The solid curve represents the calculation under the assumption that $E1\,^3P_1$ or $M1^3S_1$ is the basic transition; the dashed curve was calculated assuming that the basic transition is $M1^3D_1$; and the dash-and-dot curve assumes $E2^3D_2$ to be the basic transition. The dash-and-two-dots curve was calculated on the assumption that $E1\,^3P_1$ or $M1^3S_1$ is the basic transition for the

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

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

^{4}He$(\vec{\gamma}, p)^3$H reaction. The reaction cross-section asymmetry $\Sigma(\theta_N)$ is weakly dependent on the coefficients β and γ. For example, in calculations of the solid curve $\beta_n = -0.05$ and $\gamma_n = 0.91$ were used, and for the dash-and-two-dots curve the coefficients $\beta_p = 0.75$ and $\gamma_p = 0.5$ were used.

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 $\Sigma(\theta_N)$ [19] were averaged in the interval of nucleon emission polar angles $20^\circ \leqslant \theta_N \leqslant 160^\circ$ 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 $S = 1$ transitions. Then the difference between the averaged asymmetry values $\overline{\Delta\Sigma} = \overline{\Sigma}_{\rm th} - \overline{\Sigma}_{\rm exp}$ was determined. The calculated results are given in Table II.

Supposing that the cross-section asymmetry data are correct, then the calculated difference $\overline{\Delta\Sigma}$ would lead to the value $\nu \gtrsim 0.04$, which is not in agreement with the cross-section data in the collinear geometry (see Fig. 1). In addition, at the polar angle of nucleon emission $\theta_N = 20^\circ$ and 160° and $\nu \gtrsim 0.04$ coefficient, the asymmetry of the cross section is $\Sigma(20^\circ, 160^\circ) \lesssim 0.8$. In this case, angular dependence of the cross section asymmetry would manifest itself 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. [19], [21], and [22] the reaction products were registered by different methods, but, within the experimental error, the results are in agreement. There may be also the contribution of additional polarization caused by the off-axis collimation of the photon beam. However, depending on the relative positions of these polarization vectors, the measured reaction cross-section asymmetry value may be both higher and lower than the calculated value. For example, the cross-section asymmetry value may appear underestimated in the case, where the vectors of the polarizations are mutually perpendicular, but this is 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 overestimated value ($\approx 5 \div 10\%$) of their degree of polarization.

V. 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 $S = 1$ 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 $20 \leqslant E_\gamma \leqslant 100$ MeV is independent of the photon energy, to within the experimental errors.

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.

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 $S = 1$ transition is dominant. Using the conclusions of Refs. [17] and [18] that the basic transitions is the $^3S_1\, M1$ transition or 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 $\nu = 0.01\pm0.005$, I have calculated the asymmetry of cross sections for two-body reactions with linearly polarized photons using relation (15). It is found to be $\Sigma(90^\circ) = 0.9901\pm0.005$. This makes it possible to measure the degree of linear polarization of photon beams with a sufficiently high accuracy. This method can serve as an additional tool for carrying out nuclear physics experiments with linearly polarized photons.

According to the theoretical prediction of Ref. [2], the $E1\,^3P_1$ transition is the basic transition at higher photon energies, too. Having measured the angular dependence of the cross-section asymmetry $\Sigma(\theta_N)$ with necessary accuracy, using the data of its form, it will be possible to confirm this conclusion experimentally.

A high cross-section asymmetry value of $(\vec{\gamma}, N)$ reactions and 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.

At the same time, it would be of importance to verify with the use of the ^{4}He polarimeter the cross-section asymmetry value for the ^{2}H$(\vec{\gamma}, p)n$ reaction in the photon energy range up to 100 MeV.

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