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Random-test multipole analysis of two-body (γ, p) and (γ, n) reactions of ^{4}He nuclear disintegration

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Abstract

The angular dependence of azimuthal asymmetry of cross sections for the $^4\text{He}(\vec{\gamma}, p)\text{T}$ and $^4\text{He}(\vec{\gamma}, n)^3\text{He}$ reactions was measured at linearly polarized photon energies of 40, 60 and 80 MeV. With the data obtained as the basis and using the previously measured differential cross sections, a multipole analysis of the reactions was performed in the E1, E2 and M1 approximation. The cross sections for the multipole transition and their errors were estimated by multiply solving the set of equations that relate the Legendre coefficients to the multipole amplitude moduli. Cross sections for spin $S = 1$ transitions of the final-state particles were determined.

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1. Introduction

Measurements of cross sections for the multipole transition present interest from the viewpoint of determining both the contribution of meson exchange currents (MEC) to the reaction cross sections and the wave function components of the ^{4}He nucleus with nonzero orbital momentum of nucleons. By the present time, only the cross sections for spin $S = 0$ electric dipole and quadru-

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pole transitions of final-state particles have been determined to sufficient accuracy [1–3]. The difficulties in determining the $S = 1$ transition cross sections are mainly due to their small values, and also to the absence of reliable theoretical predictions as to which particular spin $S = 1$ transition is the basic one. The available experimental data are also contradictory. For example, when investigating the inverse $^3\mathrm{H}(\vec{p}, \gamma)^4\mathrm{He}$ reaction in the polarized proton beam of energy $E_p = 2$ MeV the authors of Ref. [4] have concluded that E1 $^3P_1$ is the basic transition ($^{2S+1}L_j$ in spectroscopic notation, where S is the final-state spin, L is the orbital momentum of the nucleon, j is the total momentum of the photon). However, in studies of the same reaction in the polarized proton beam of energy E_p between 0.8 and 9 MeV, the authors of Ref. [5] have suggested that it is the M1 $^3S_1$ transition that is basic. At higher photon energies the measurements are complicated by the necessity of considering the M1 $^3D_1$ amplitude, which is suppressed at low proton energies $E_p < 10$ MeV ($E_\gamma < 27$ MeV) by the angular momentum barrier.

The present paper first presents the multipole analysis of the $^4\mathrm{He}(\gamma, p)\mathrm{T}$ and $^4\mathrm{He}(\gamma, n)^3\mathrm{He}$ reactions in the energy range up to $E_\gamma \sim 60$ MeV. The analysis is based on the experimental data obtained at KIPT on differential cross sections and azimuthal asymmetry of cross sections. The amplitude magnitudes were calculated by the random-test method. At the present time it is common practice to use the least squares method (LSM) for the multipole analysis of meson photoproduction [6], nuclear photodisintegration, as well as for the phase analysis of elastic scattering of particles. It should be noted that the sought-for values of multipole amplitudes bilinearly enter into theoretical expressions that describe the experimental data, and this may lead to two positive solutions of the problem. In this case, the LSM method must be used with certain care. In particular, in the case of closely adjacent solutions the LSM method may give overestimated errors in the calculation of amplitudes. In the present work we have calculated the coefficients that linearly enter into the equations for the multipole expansion. With the use of relationships between the coefficients and the multipole amplitudes, combined equations were set up, which were solved numerically. The amplitude moduli and their errors were calculated as a result of multiple Monte Carlo samplings of coefficients and their uncertainties, and also by averaging the corresponding solutions of the mentioned equations.

2. Experimental data

The multipole analysis of the $^4\mathrm{He}(\gamma, p)\mathrm{T}$ and $^4\mathrm{He}(\gamma, n)^3\mathrm{He}$ reactions was carried out with the use of data on differential cross sections $d\sigma/d\Omega$ and azimuthal asymmetry of cross section $\Sigma(\theta)$. Differential cross sections were measured using the bremsstrahlung beam of photons at the KIPT linac LEA-300 at the maximum energy $E_\gamma^{\max} = 150$ MeV. The reaction products were detected in a diffusion chamber placed in the magnetic field. The total number of registered events of ^{4}H disintegration made up $\sim 3 \times 10^4$ per reaction channel. The differential cross sections were measured with a 1 MeV step up to a photon energy of 45 MeV, and with a greater step at higher energies. The step in the measurements of the polar angle of nucleon emission was 10^0 in the c.m.s. Some results of the analysis have been published in a number of papers [1,7]. The data on the differential cross sections were partially published in Refs. [8,9]. Unfortunately, not all measured points have been presented in the theoretical paper [9]; this led to a small χ^2 value ($\chi^2 \sim 0.1$) per point [10].

The data on the angular dependence of the azimuthal asymmetry of cross section of two-body $(\vec{\gamma}, p)$ and $(\vec{\gamma}, n)$ reactions were obtained with a linearly-polarized photon beam of energies of 40, 60 and 80 MeV at the KIPT accelerator LEA-2000. The beam of linearly polarized photons was produced as a result of coherent bremsstrahlung of 500, 600 and 800 MeV electrons, respectively, in a thin diamond single crystal. The reaction products were registered by the use of a streamer chamber located in the magnetic field [11]. The streamer chamber was flushed by pure ^{4}He. The total number of treated events makes $\sim 3 \times 10^3$ per reaction channel. The two-body $(\vec{\gamma}, p)$ reaction identified by the coplanarity of photon, proton and tritium momentum, by the equality of the transverse components of proton and tritium momentum, and also visually, by the track density. As a result, the contribution of background reactions to the (γ, p) reaction under study was negligibly small. The two-body $(\vec{\gamma}, n)$ reaction was registered through the recoil nuclei ^{3}He. In the streamer chamber, the ^{3}He nuclei could not be distinguished from the ^{4}He nuclei, which could be produced, for example, in the reaction $^4\mathrm{He}(\gamma, \pi^0)^4\mathrm{He}$ induced by photons of energy higher than the pion threshold. A nearly 5-fold increase of the coherent radiation of photons in comparison with the bremsstrahlung spectrum reduced the contribution of background reactions to the (γ, n) channel. The calculations have demonstrated that at $E_\gamma^{\mathrm{peak}} = 40$ MeV the contribution of background reactions to the (γ, n) channel was less than 5%, and at $E_\gamma^{\mathrm{peak}} = 60$ and 80 MeV the corresponding corrections were introduced. When calculating the corrections we have used the experimental data of Ref. [12] on the total cross sections of π^0-photoproduction. The details of the experiment and the first results from measurements of the asymmetry have been published earlier [13].

Events occurring in the measured gamma-quantum energy ranges $34 \leqslant E_\gamma < 46$ MeV, $46 \leqslant E_\gamma < 65$ MeV and $65 \leqslant E_\gamma < 90$ MeV were used to determine the asymmetry at each of the mentioned average energies of linearly polarized photons, respectively. The measured data for the azimuthal asymmetry are given in Table 1. The errors are statistical only. The total error may also be contributed by the systematic error, which is due, in particular, to inaccuracy in determining the effective degree of photon beam polarization, and also, to an insufficiently cor-

Table 1
Angular dependence of the azimuthal asymmetry of the $^4\mathrm{He}(\vec{\gamma}, p)\mathrm{T}$ and $^4\mathrm{He}(\vec{\gamma}, n)^3\mathrm{He}$ reactions cross-section

E_γ^{peak}, MeV	$\Delta\theta_N$, deg	$\Sigma(\theta_p)$	$\Sigma(\theta_n)$
40	20–40	1.1 ± 0.3	0.79 ± 0.34
	40–60	0.86 ± 0.18	1.15 ± 0.22
	60–80	0.81 ± 0.18	0.77 ± 0.19
	80–100	1.02 ± 0.19	0.93 ± 0.16
	100–120	0.72 ± 0.25	0.79 ± 0.17
	120–140	0.94 ± 0.28	1.03 ± 0.16
	140–160	0.73 ± 0.74	0.7 ± 0.35
60	20–40	0.73 ± 0.28	0.35 ± 0.3
	40–60	0.90 ± 0.2	0.7 ± 0.21
	60–80	1.1 ± 0.2	0.9 ± 0.2
	80–100	0.37 ± 0.26	0.9 ± 0.21
	100–120	0.95 ± 0.3	0.49 ± 0.22
	120–140	1.17 ± 0.33	0.81 ± 0.2
	140–160	0.64 ± 1.08	0.85 ± 0.4
80	20–40	0.71 ± 0.48	1.1 ± 0.38
	40–60	0.90 ± 0.27	1.2 ± 0.25
	60–80	0.86 ± 0.26	1.06 ± 0.28
	80–100	0.77 ± 0.41	0.84 ± 0.32
	100–120	1.56 ± 0.26	0.69 ± 0.29
	120–140	-1.34 ± 0.53	0.64 ± 0.29
	140–160	–	1.28 ± 0.37

rect consideration of the background π^0-meson photoproduction process in the (γ, n) channel at $E_\gamma \geqslant 60$ MeV [13].

3. Multipole analysis of the ^{4}He(γ, p)T and ^{4}He(γ, n)^{3}He reactions

The laws of conservation of the total momentum and parity for two-body (γ, p) and (γ, n) reactions in the E1, E2 and M1 approximation permit two multipole transitions E1 $^1P_1$ and E2 $^1D_2$ with the spin $S = 0$ and four transitions E1 $^3P_1$, E2 $^3D_2$, M1 $^3S_1$ and M1 $^3D_1$ with the spin $S = 1$ of final-state particles. The differential cross section in the c.m.s. can be expressed in terms of multipole amplitudes as follows [14,15]:

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

where $\lambda\!\!\!^{-}$ is the reduced wavelength of the photon.

It can be shown that the azimuthal asymmetry of cross sections is described by the following expression:

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

Expressions (1) and (2) comprise 11 independent parameters. The currently available experimental data on the (γ, p) and (γ, n) reactions are insufficient for determining all the parameters. Here we assumed the E2 $^3D_2$ amplitude to be the smallest of the amplitudes entering into expressions (1) and (2), this being in agreement with both the theoretical estimate [16] and the experimental evidence [5]. After elimination of the E2 $^3D_2$ amplitude-containing components, there remained 9 unknown parameters.

According to the isotopic-spin selection rules [17], the isoscalar parts of the E1 and M1 amplitudes in the ^{4}He nucleus are substantially suppressed. Therefore, in the present analysis we have

Table 2
Average δ_{sl}^{j} phases values for two photon energy ranges

Phase, deg	$E_\gamma = (34–46)$ MeV	$E_\gamma = (46–65)$ MeV
δ_{10}^{1}	$-115°$	$-136°$
δ_{11}^{1}	$40°$	$18°$
δ_{12}^{1}	$-14°$	$6°$

used the isovector phase differences between the E1 $^3P_1$, M1 $^3S_1$ and M1 $^3D_1$ amplitudes [15] calculated from the phase analysis of elastic $(p, {}^3\mathrm{He})$ scattering [18,19]. The data were available for the proton energy range $18 \leqslant E_p \leqslant 50$ MeV or, correspondingly, for the photon energy range $33 \leqslant E_\gamma \leqslant 58$ MeV. The phase differences between the E1 $^3P_1$, M1 $^3S_1$ and M1 $^3D_1$ amplitudes that enter into expressions (1) and (2) were considered as fixed parameters, and the remaining six parameters as free. The phase analysis data were used to calculate the average values of phases δ_{sl}^{j} (j is the total momentum, l is the relative orbital momentum, s is the spin of the particle system) in the photon energy ranges, for which the asymmetry of (γ, p) and (γ, n) reaction cross sections was measured. The average phase values used in the calculation are presented in Table 2. The experimental data on the differential cross sections were also averaged in the same photon energy ranges.

The free parameters were calculated in two ways: Firstly, by the standard LSM method in fitting the right-hand sides of expressions (1) and (2) to the experimental data on $d\sigma/d\Omega$ and $\Sigma(\theta)$. Secondly, the random-test method was used. This approach consisted in determination of the coefficients A_i at the Legendre polynomials from the differential cross section data, with their subsequent use for calculation of multipole amplitude moduli.

$$d\sigma/d\Omega = \sum_{i=0}^{4} A_i P_i(\cos\theta). \tag{3}$$

The coefficients A, β, γ, ε and ν are of frequent use in the literature. With their use, the differential cross section can be presented as

$$d\sigma/d\Omega = A\big[\sin^2\theta\big(1 + \beta\cos\theta + \gamma\cos^2\theta\big) + \varepsilon\cos\theta + \nu\big]. \tag{4}$$

These coefficients are more obvious and are unambiguously related to the Legendre polynomial coefficients:

$$A = 1/8(12A_2 + 5A_4), \qquad \beta = 20A_3/(12A_2 + 5A_4), \qquad \gamma = 35A_4/(12A_2 + 5A_4),$$
$$\varepsilon = -8(A_1 + A_3)/(12A_2 + 5A_4), \qquad \nu = -8(A_0 + A_2 + A_4)/(12A_2 + 5A_4). \tag{5}$$

In the same terms, the azimuthal asymmetry of cross section can be represented as follows:

$$\Sigma(\theta) = \frac{\sin^2\theta(1 + \alpha + \beta\cos\theta + \gamma\cos^2\theta)}{\sin^2\theta(1 + \beta\cos\theta + \gamma\cos^2\theta) + \varepsilon\cos\theta + \nu}. \tag{6}$$

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

$$A = \lambda\!\!\!^{-2}/32\Big\{18\big|\mathrm{E1}\,{}^1P_1\big|^2 - 9\big|\mathrm{E1}\,{}^3P_1\big|^2 + 9\big|\mathrm{M1}\,{}^3D_1\big|^2 - 18\sqrt{2}\big|\mathrm{M1}\,{}^3S_1\big|\big|\mathrm{M1}\,{}^3D_1\big|\cos\big[\delta\big({}^3S_1\big) - \delta\big({}^3D_1\big)\big]\Big\}, \tag{7}$$

$$\beta = \left\{60\sqrt{3}\left|\mathrm{E1}\,{}^1P_1\right|\left|\mathrm{E2}\,{}^1D_2\right|\cos\left[\delta\left({}^1P_1\right)-\delta\left({}^1D_2\right)\right]\right\}\Big/\frac{32}{\lambda\!\!\!^{-2}}A, \tag{8}$$

$$\gamma = \left\{150\left|\mathrm{E2}\,{}^2D_1\right|^2\right\}\Big/\frac{32}{\lambda\!\!\!^{-2}}A, \tag{9}$$

$$\varepsilon = -\Big\{12\sqrt{6}\left|\mathrm{E1}\,{}^3P_1\right|\left|\mathrm{M1}\,{}^3S_1\right|\cos\left[\delta\left({}^3P_1\right)-\delta\left({}^3S_1\right)\right] + 12\sqrt{3}\left|\mathrm{E1}\,{}^3P_1\right|\left|\mathrm{M1}\,{}^3D_1\right|\cos\left[\delta\left({}^3P_1\right)-\delta\left({}^3D_1\right)\right]\Big\}\Big/\frac{32}{\lambda\!\!\!^{-2}}A, \tag{10}$$

$$\nu = \Big\{18\left|\mathrm{E1}\,{}^3P_1\right|^2 + 12\left|\mathrm{M1}\,{}^3S_1\right|^2 + 6\left|\mathrm{M1}\,{}^3D_1\right|^2 + 12\sqrt{2}\left|\mathrm{M1}\,{}^3S_1\right|\left|\mathrm{M1}\,{}^3D_1\right|\cos\left[\delta\left({}^3S_1\right)-\delta\left({}^3D_1\right)\right]\Big\}\Big/\frac{32}{\lambda\!\!\!^{-2}}A, \tag{11}$$

$$\alpha = \Big\{-18\left|\mathrm{M1}\,{}^3D_1\right|^2 + 36\sqrt{2}\left|\mathrm{M1}\,{}^3S_1\right|\left|\mathrm{M1}\,{}^3D_1\right|\cos\left[\delta\left({}^3S_1\right)-\delta\left({}^3D_1\right)\right]\Big\}\Big/\frac{32}{\lambda\!\!\!^{-2}}A. \tag{12}$$

It can be seen from expression (3) that in the E1, E2 and M1 approximation only 5 independent coefficients can be determined from the measured differential cross sections. So, an increase in the accuracy of measuring only the differential cross section in order to determine the coefficients at the Legendre polynomials of the degree higher than $\cos^4(\theta)$ fails to provide information on subsequent multipole amplitudes. In this case, the number of unknown parameters in the right side of Eq. (1) will increase much quicker than the number of measured coefficients in the left side. Therefore, to get more detailed information on the multipole amplitudes, further polarization experiments or other information sources are needed. It is evident from expression (6) that experimental data on the azimuthal asymmetry can provide the sixth independent coefficient.

4. The calculational procedure

The multipole amplitude moduli were calculated as follows. From the fit of expressions (4) and (6) to the experimental differential cross section and azimuthal asymmetry data described in Section 2 the coefficients A, α, β, γ, ε, and ν were calculated by the LS method. Since these coefficients enter linearly into expansions (4) and (6), the solution was the one. In Table 3 the coefficient A values are given in μb/sr, the rest coefficient values are dimensionless. The experimental data obtained in Ref. [10] on the coefficients ε, and ν at the photon energy $E_\gamma = 67 \pm 4$ MeV have the errors higher than the ones calculated with the data from Refs. [1,8], and exerted no essential effect on the results of the multipole analysis.

The calculated coefficients were used to construct a set of six equations (7)–(12) containing six unknown parameters. The parameters and their errors were determined through 5000 Monte Carlo samplings of the coefficients A, α, β, γ, ε, and ν and their experimental errors. The errors of the coefficients were assumed to be distributed by the normal law. After each sampling the set of equations was solved numerically. As the set of equations comprised 6 equations, the number of all the solutions made up 2^6, the positive solutions being two in the majority of cases. The solution, where the $|\mathrm{E1}\,{}^3P_1|$ amplitude value was smaller than in the other solution was considered to be the first. At a small number of samplings there was one positive solution. The positive solutions were stored and used for calculating the average values of multipole amplitude moduli and phase differences $\delta({}^1P_1)$–$\delta({}^1D_2)$, and also their dispersions.

Table 3
Expansion coefficients of the differential cross section and azimuthal asymmetry $\Sigma(\Theta)$

Coeff.	$E_\gamma = (34–46)$, MeV	$E_\gamma = (46–65)$, MeV	$E_\gamma = (65–90)$, MeV
^{4}He(γ, p)T			
A_p	87.98 ± 1.55	27.65 ± 0.9	13.4 ± 0.4
β_p	0.76 ± 0.03	1.19 ± 0.07	1.07 ± 0.06
γ_p	0.43 ± 0.06	0.92 ± 0.13	0.88 ± 0.12
ε_p	0.014 ± 0.005	-0.003 ± 0.008	-0.004 ± 0.008
ν_p	0.029 ± 0.005	0.014 ± 0.008	0.019 ± 0.012
α_p	-0.08 ± 0.09	-0.1 ± 0.09	-0.08 ± 0.13
χ^2	20.7	29.4	43.0
^{4}He$(\gamma, n)^3$He			
A_n	85.6 ± 1.31	33.66 ± 0.84	14.9 ± 0.46
β_n	-0.08 ± 0.03	0.15 ± 0.044	0.35 ± 0.06
γ_n	0.62 ± 0.06	0.75 ± 0.1	0.83 ± 0.13
ε_n	0.002 ± 0.004	-0.013 ± 0.006	0.007 ± 0.008
ν_n	0.027 ± 0.004	0.018 ± 0.007	0.027 ± 0.012
α_n	-0.07 ± 0.08	-0.27 ± 0.1	-0.04 ± 0.13
χ^2	20.3	23.0	22.3

In some part of samplings, the set of equations appeared to be inconsistent and had no positive solutions. The consistency coefficient k, being the ratio of the number of samplings with a consistent system to the total number of samplings, is given in Table 4. A small consistency coefficient may be due to a poor compatibility of the experimental data on photodisintegration, errors phase differences of the E1 $^3P_1$, M1 $^3S_1$ and M1 $^3D_1$ amplitudes or to inadequacy of the E1, E2 and M1 approximation. For the cases of the consistent set of equations, one of the solutions appeared to be close to the solution found by the LS method at fitting expressions (1) and (2) (with $|\mathrm{E2}\,^3D_2| = 0$) to the experimental data on $d\sigma/d\Omega$ and $\Sigma(\theta)$. An insignificant divergence between the LSM solutions and the solutions by the random-test method, and correspondingly, between their χ^2 values (see Table 3), was due to the fact that, for example, all samplings with $\alpha > 0$ were inconsistent with the statement of the problem. Considering that $\cos[\delta(^3S_1)–\delta(^3D_1)] < 0$, then according to relation (12), the value must be only $\alpha < 0$. The χ^2 values of the two solutions calculated by the random-test method were very close. Their values are listed in Table 4. A systematic increase in the measured asymmetry values led to an insignificant increase in the consistency coefficient k. By varying the differential cross section or asymmetry values it was possible to choose such conditions, at which the two solutions appeared close. In this case, the errors calculated by the LSM tended to infinity, whereas the errors calculated by the random-test method were practically independent of the difference between the solutions of the set of equations. Correctness of miscalculations computation for both methods may require an additional research. To find the two solutions by the LS method, χ^2 calculations of the sought-for parameters on the six-dimensional lattice are necessary.

The calculated cross sections of multipole transitions are presented in Table 4. Column 1a gives the cross sections calculated through samples, where there was one solution. Since the M1 transition cross section, measured in the ^{3}He$(n, \gamma)^4$He reaction in the vicinity of the threshold at thermal neutron energies, makes up $\sigma(\mathrm{M1}\,^3S_1) = 57 \pm 3$ μb [20], and with an increase in the photon energy it decreases as $1/v$ [4], where v is the final-state nucleon velocity, it can be assumed that it is solution 2 that is correct. The calculational results are presented in Fig. 2,

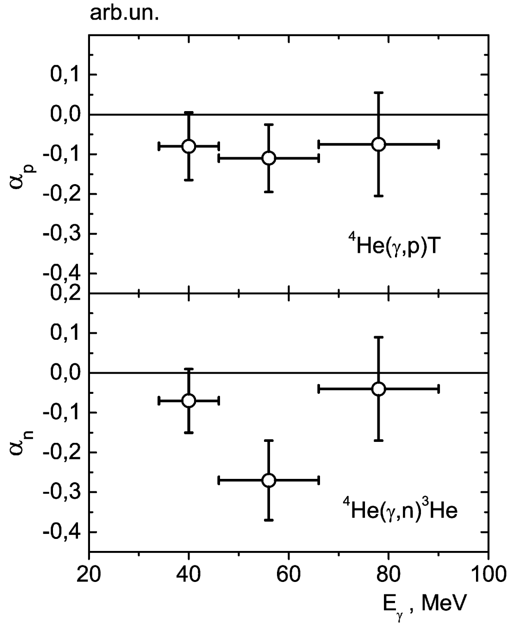

Fig. 1. The coefficients α_p and α_n for two-body $(\vec{\gamma}, p)$ and $(\vec{\gamma}, n)$ reactions. In the assumption of the dominant contribution of the E1 $^3P_1$ transition amongst spin $S = 1$ transitions of the coefficients α_p and α_n would be equal to zero.

where the diamond the data from Ref. [4]. To calculate the cross section for the E1 $^3P_1$ transition in absolute units, we have used the data of Ref. [1]: $\sigma_{\gamma p}(E_\gamma = 21.25\ \text{MeV}) = 0.42$ mb. The triangles show the data obtained from the study of the inverse reaction [5], the points stand for our present data. The errors are statistical only.

If it assumed that $\sigma(\text{E2}\,^3D_2) \gg \sigma(\text{M1})$, then from expression (2) we obtain:

$$\alpha = \frac{50|\text{E2}\,^3D_2|^2}{18|\text{E1}\,^1P_1|^2 - 9|\text{E1}\,^3P_1|^2 - 25|\text{E2}\,^3D_2|^2} > 0, \qquad (13)$$

i.e., this assumption is not in agreement with the experimental data obtained.

5. Discussion of results

Experimental data about azimuthal asymmetry of the cross section of two-body $(\vec{\gamma}, p)$ and $(\vec{\gamma}, n)$ reactions on the nucleus of ^{4}He were obtained with a linearly polarized photons was resulted in Table 1 and on Fig. 1 as the coefficients α_p and α_n. In case of the dominant contribution of E1 $^3P_1$ transition among all transitions with spin $S = 1$ in the final state of the particles the coefficients α_p and α_n would be equal to zero. The experimental data obtained point to the considerable contribution of the M1 transition in the photon energy range up to $E_\gamma \sim 60$ MeV. The conclusion is in agreement with the preliminary estimates of Refs. [21,22]. The results of experiment on the determination of total cross sections for the multipole transitions are given in Table 4 and in Fig. 2. The diamond present the data from Ref. [4], the triangles show the data obtained from the study of the inverse reaction of radiative capture of protons by tritium nuclei [5].

The multipole amplitude moduli were calculated by solving numerically the set of equations relating the coefficients $A, \alpha, \beta, \gamma, \varepsilon$, and ν (or their analogs at the Legendre polynomials) to the

Table 4
Total cross sections of multipole transitions of two-body reactions of ^{4}He disintegration

Photon energy range, MeV	Transition	^{4}He(γ, p)T transition cross sections, μb			^{4}He(γ, n)^{3}He transition cross sections, μb		
		Solut 1	Solut 2	Solut 1a	Solut 1	Solut 2	Solut 1a
34–46	$\sigma(\mathrm{E1}\,^1P_1)$	716 ± 13	717.9 ± 13		698 ± 11	699 ± 11	700 ± 11
	$\sigma(\mathrm{E2}\,^1D_2)$	62 ± 11	61 ± 11		88 ± 11.9	87.4 ± 12.5	88 ± 12
	$\sigma(\mathrm{E1}\,^3P_1)$	1.8 ± 1.5	13.3 ± 5.1		0.3 ± 0.4	8.9 ± 5.9	9.2 ± 5.3
	$\sigma(\mathrm{M1}\,^3S_1)$	29.4 ± 7	9 ± 5		22 ± 12.7	6 ± 3.7	3.4 ± 2.6
	$\sigma(\mathrm{M1}\,^3D_1)$	7.9 ± 8.8	10.3 ± 9.9		16.1 ± 15.2	19.7 ± 14.7	24.5 ± 15.3
	$\cos[\delta(^1P_1) - \delta(^1D_2)]$	0.59 ± 0.05	0.59 ± 0.05		-0.054 ± 0.05	-0.054 ± 0.05	-0.054 ± 0.02
	k	0.13	0.13	0.001	0.15	0.15	0.08
	χ^2	21.3	21.3		21.6	21.1	22.5
46–65	$\sigma(\mathrm{E1}\,^1P_1)$	228 ± 8	228.4 ± 8	228.4 ± 8	277 ± 7.2	277 ± 7.2	277 ± 7.8
	$\sigma(\mathrm{E2}\,^1D_2)$	44.4 ± 7.3	44.1 ± 7.3	41.5 ± 6.5	46.3 ± 7.4	46 ± 7.4	40.7 ± 6.1
	$\sigma(\mathrm{E1}\,^3P_1)$	0.2 ± 0.2	2.5 ± 1.4	4.1 ± 1.5	0.5 ± 0.5	3.3 ± 1.7	5.8 ± 1.6
	$\sigma(\mathrm{M1}\,^3P_1)$	3.8 ± 5.3	5 ± 3.2	0.9 ± 0.9	3.9 ± 3.6	9.1 ± 4.9	1.1 ± 1
	$\sigma(\mathrm{M1}\,^3D_1)$	13 ± 10.2	10.3 ± 6.3	3.5 ± 2.1	38.4 ± 12.4	28.7 ± 11	6.2 ± 2.7
	$\cos[\delta(^1P_1) - \delta(^1D_2)]$	0.64 ± 0.06	0.64 ± 0.06	0.64 ± 0.08	0.09 ± 0.03	0.092 ± 0.03	0.08 ± 0.03
	k	0.4	0.4	0.07	0.25	0.25	0.008
	χ^2	30.9	29.6	30.7	24.0	24.1	28.5

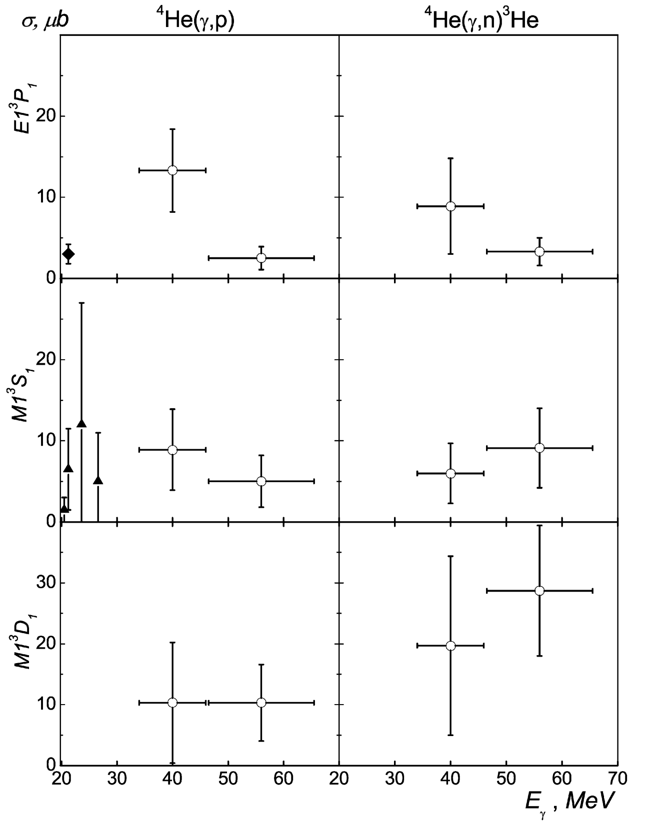

Fig. 2. Total cross sections of spin $S = 1$ transitions of ^{4}He(γ, p)T and ^{4}He(γ, n)^{3}He reactions. ♦—data from Ref. [4]; ▲—data of Ref. [5], ○-our data.

amplitude moduli with the use of the random-test method. This approach provides the calculation of all the solutions that satisfy the statement of the problem, and the calculated errors are independent of the difference between the found solutions. The approach also makes it possible to determine what particular experimental data errors give the greatest contribution to inaccuracies in the sought-for parameter values.

According to theoretical estimates, at $E_\gamma \sim 22$ MeV [4,23] the total cross section for $S = 1$ transitions of final-state particles in the one-particle approximation makes $\leqslant 0.01\%$ of the total reaction cross section. The consideration of the MEC contribution increases the E1 $^3P_1$ transition cross section to $\sim 0.5\%$ of the total cross section [4], this being consistent with our data. In the M1 $^3S_1$ transitions, the MEC present the dominant part [23]. A substantial increase in the total cross section of the M1 transition may be due to both the spin–flip reaction of the hadronic final-state particle system and a possible contribution of the ground-state wave-function components of the ^{4}He nucleus with nonzero orbital momentum of nucleons, in particular, P components. Unfortunately, few theoretical calculations of total cross sections for $S = 1$ transitions of the final-state particles can be found in the literature. More precise measuring of azimuthal asymmetry of the cross section of two-body ($\vec{\gamma}$, p) and ($\vec{\gamma}$, n) disintegration reactions of ^{4}He are needed.

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