SPIN-TRIPLET TRANSITIONS IN (γ,p) AND (γ,n) REACTIONS OF TWO-BODY ^{4}He DISINTEGRATION BY PHOTONS OF ENERGIES BELOW 80 MeV

Yu.P. Lyakhno, E.S. Gorbenko, I.V. Dogyust
National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine

The simultaneous least-square fit of expressions for differential cross-sections and asymmetry to the experimental data on $d\sigma/d\Omega$ and $\Sigma(\theta)$, obtained at NSC KIPT, was realized. A set of three bilinear equations with three unknown amplitude modules $|{}^3P_1|E1$, $|{}^3S_1|M1$ and $|{}^3D_1|M1$ was derived; preliminary data about the magnitudes of these amplitude modules were obtained. It is shown that the $^3D_1\,M1$ amplitude is the highest in magnitude.

PACS: 25.20.Dc; 29.27.Hj; 29.40. Cx

INTRODUCTION

The interest in the studies of two-body (γ,p) and (γ ,n) reactions of ^{4}He disintegration by low energy photons is determined by their relatively simple spin structure and a small number of particles participating in the reaction. On the one hand, this makes possible a more detailed theoretical calculation with a minimum of model assumptions introduced. On the other hand, the laws of conservation of the total momentum and parity significantly restrict the number of multipole transitions participating in the reaction. Neglecting the contributions of higher multipoles which correspond to high total- momentum values of the photon, one can determine to sufficient accuracy the amplitudes of the basic multipole transitions. This makes possible the comparison between the theoretical calculations and the experimentally measured multipole amplitudes. This comparison is of great importance because each of the multipole transitions can be governed by different reaction mechanisms. It should be also noted that for the low particle energy range there exist the phase-analysis data on elastic (N,T) scattering. These data can be used for theoretical calculations of photodisintegration reactions on ^{4}He.

The laws of conservation of the total momentum and parity at two-body (γ,p) and (γ,n) disintegration of ^{4}He in E1, E2 and M1 approximations permit six multipole amplitudes: $^1P_1\,E1$, $^1D_2\,E2$, $^3P_1\,E1$, $^3D_2\,E2$, $^3S_1\,M1$ and $^3D_1\,M1$ (in spectroscopic notation). At present, only the values of the first two amplitudes with ΔS=0 are determined. The analysis of experimental data has revealed that in the low photon energy region it is the electric dipole E1 transition that is dominant, and the next in prominence is the E2 transition with ΔS=0. These transitions occur without any change in the final-state spin ΔS=0, the remaining four transitions take place with changing the spin ΔS=1. Unfortunately, no evidence for the amplitudes of the processes with ΔS=1, obtained from the direct reactions, can be found in the literature, and the data gained from the inverse reactions are available only for low photon energies ($E_\gamma < 30$ MeV). Moreover, most of the data are contradictory. Wagenaar etal. [1] have investigated the radiative capture of polarized protons of energies T_p between 0.8 and 9 MeV by tritium nuclei. Those authors have come to the conclusion that the cross-section for the reaction with ΔS=1 is mainly contributed by the magnetic dipole M1 transition. The investigation [2] of the same reaction with a polarized proton beam at T_p=2 MeV has led the investigators to the conclusion that the dominant amplitude in the ΔS=1 transitions is $^3P_1\,E1$. It has been reported in ref. [3] that the cross-section for the M1 transition in ^{3}He(n,γ)^{4}He is extremely low at thermal neutron energies, and also on extrapolation of the data to the nucleon energy range of a few MeV [2]. In view of this, an additional experimental information on the nature of ΔS=1 is needed. The NSC KIPT team has obtained the most comprehensive experimental data on both the differential cross-sections [4] and the azimuthal cross-sectional asymmetry $\Sigma(\theta)$ of (γ,p) and (γ,n) reactions [5,6], that enables one to derive new information on the transitions with ΔS=1. In this paper we report our preliminary results from the multipole analysis of these data.

MULTIPOLE ANALYSIS

The differential cross-section can be expressed in terms of multipole transition amplitudes as follows:

$$\frac{d\sigma}{d\Omega} = \square^2/_{32}\, A\cdot[\sin^2\theta\,(1+\beta\cos\theta+\gamma\cos^2\theta)+\varepsilon\cos\theta+\nu], \qquad (1)$$

where

$$A = 18\left|{}^1P_1\right|^2 E1 - 9\left|{}^3P_1\right|^2 E1 + 9\left|{}^3D_1\right|^2 M1 - 25\left|{}^3D_2\right|^2 E2 - 18\sqrt{2}\,\mathrm{Re}({}^3D_1 M1\,{}^3S_1^* M1) + 30\sqrt{6}\,\mathrm{Re}({}^3D_2 E2\,{}^3S_1^* M1) + 30\sqrt{3}\,\mathrm{Re}({}^3D_2 E2\,{}^3D_1^* M1) \quad (2)$$

$$\beta = [60\sqrt{3}\,\mathrm{Re}({}^1D_2 E2\,{}^1P_1^* E1) - 60\,\mathrm{Re}({}^3D_2 E2\,{}^3P_1^* E1)]/A \quad (3)$$

$$\gamma = [150\left|{}^1D_2\right|^2 E2 - 100\left|{}^3D_2\right|^2 E2]/A \quad (4)$$

$$\varepsilon = [-12\sqrt{6}\,\mathrm{Re}({}^3S_1 M1\,{}^3P_1^* E1) - 12\sqrt{3}\,\mathrm{Re}({}^3D_1 M1\,{}^3P_1^* E1) + 60\,\mathrm{Re}({}^3D_2 E2\,{}^3P_1^* E1)]/A \quad (5)$$

$$\nu = [18\left|{}^3P_1\right|^2 E1 + 12\left|{}^3S_1\right|^2 M1 + 6\left|{}^3D_1\right|^2 M1 + 50\left|{}^3D_2\right|^2 E2 + 12\sqrt{2}\,\mathrm{Re}({}^3D_1 M1\,{}^3S_1^* M1) - 20\sqrt{6}\,\mathrm{Re}({}^3D_2 E2\,{}^3S_1^* M1) - 20\sqrt{3}\,\mathrm{Re}({}^3D_2 E2\,{}^3D_1^* M1)]/A \quad (6)$$

In the approximation used here, Eqs. (2) to (6) allow the determination of only five relationships between the multipole transition amplitudes from the differential cross-section.

It can be demonstrated that the azimuthal cross-sectional asymmetry ***Σ(θ)*** is given by the expression

$$\Sigma(\theta) = \frac{\sin^2\theta\,(1+\alpha+\beta\cos\theta+\gamma\cos^2\theta)}{\sin^2\theta\,(1+\beta\cos\theta+\gamma\cos^2\theta)+\varepsilon\cos\theta+\nu}\ , \quad (7)$$

where:

$$\alpha = [-18\left|{}^3D_1\right|^2 M1 + 50\left|{}^3D_2\right|^2 E2 + 36\sqrt{2}\,\mathrm{Re}({}^3D_1 M1\,{}^3S_1^* M1) - 20\sqrt{6}\,\mathrm{Re}({}^3D_2 E2\,{}^3S_1^* M1) - 20\sqrt{3}\,\mathrm{Re}({}^3D_2 E2\,{}^3D_1^* M1)]/A \quad (8)$$

Thus, the data on ***Σ(θ)*** permit the determination of an additional relationship between the amplitudes of multipole transitions; it is specified by expression (8).

The coefficients A, α, β, γ, ε and ν were calculated by the least-squares method (LSM) from the fit of expressions (1) and (7) to the experimental data histogrammed with a bin value of 10°. It should be noted that for determination of cross-sections for low multipole amplitudes some experimental errors must be taken into account. In particular, the calculated cross-section in the collinear geometry, entering into the coefficient ν, can depend on the bin value of the differential cross-section, and also on the resolution of measuring device in the polar angle of nucleon emission. Besides, the calculated multipole amplitude values can appear to be biased as a result of using the LSM. Strictly speaking, this method is applicable only with a great body of statistics in each bin, this being not fulfilled in the case of reactions under study in the vicinity of the angles θ_n~0°, 180°. The corresponding corrections were calculated through the Monte-Carlo simulation of the differential cross-section. The values of the parameters calculated by expression (1) were used as initial. More exact values of the parameters were calculated by averaging over 1000 simulations using the relation

$$L_i = 2L_{i0} - L_{im}\ , \quad (9)$$

where *i* is the parameter number, L_{i0} is the parameter value computed by the LSM, L_{im} is the average parameter value computed by the LSM.

The computed values are listed in Table 1 and Table 2 for the ^{4}He(γ,p)T and ^{4}He(γ,n)^{3}He reactions, respectively.

The existing experimental data are not sufficient to determine the cross-sections of all the mentioned transitions, and also the interference terms. In the first variant of the analysis it was supposed that the lowest of the ΔS=1 amplitudes under discussion is $^3D_2$ E2, and the terms involving this amplitude were neglected. It is known [7] that E1 and M1 transitions are isovectoral. This enables us to determine the phase differences between $^3P_1$ E1, $^3S_1$ M1 and $^3D_1$ M1 amplitudes from the phase analysis data for the elastic scattering of protons by ^{3}He nuclei, available [8] in the energy range from 35 to 59 MeV.

Table 1. *Fitting coefficients for (γ,p) reactions on ^{4}He for three intervals of photons energy*

Coef-fic.	Eγ=34-46 MeV	Eγ=46-65 MeV	Eγ=65-90 MeV
A	87.98±1.55	29.91±0.75	13.4±0.4
β	0.76± 0.03	1.15±0.05	1.06±0.06
γ	0.43±0.06	0.85±0.10	0.88±0.12
ε	0.014±0.005	0.008±0.006	0.003±0.008
ν	0.030±0.005	0.018±0.006	0.019±0.008
α	-0.16±0.09	-0.15±0.1	-0.10±0.14
χ^2 d.o.f.	1.2	1.4	1.16

Table 2. *Fitting coefficients for (γ,n) reactions on ^{4}He for three intervals of photons energy*

Coef-fic.	Eγ=34-46 MeV	Eγ=46-65 MeV	Eγ=65-90 MeV
A	85.6±1.31	33.63±0.84	14.9±0.46
β	-0.08±0.03	0.152±0.044	0.35±0.06
γ	0.62±0.06	0.76±0.10	0.83±0.13
ε	0.002±0.004	0.013±0.006	0.008±0.008
ν	0.027±0.004	0.018±0.007	0.027±0.009
α	-0.10±0.11	-0.28±0.11	-0.08±0.14
χ^2 d.o.f	1.18	1.26	1.06

Thus, the coefficients A, β and γ are also used to calculate the amplitude modules $|{}^1P_1|$E1 and $|{}^1D_2|$E2, and also the phase differences δ($^1P_1$)-δ($^1D_2$). The remaining relationships for α, ε и ν represent a set of three bilinear equations with three unknown amplitude modules $|{}^3P_1|$E1, $|{}^3S_1|$M1 and $|{}^3D_1|$M1:

$$\alpha = [-18\left|{}^3D_1\right|^2 M1 + 36\sqrt{2}\left|{}^3D_1\right|M1\left|{}^3S_1\right|M1\cos(\delta({}^3S_1) - \delta({}^3D_1))]/A$$

$$\varepsilon = [-12\sqrt{6}\left|{}^3S_1\right|M1\left|{}^3P_1\right|E1\cos(\delta({}^3S_1) - \delta({}^3P_1)) - 12\sqrt{3}\left|{}^3D_1\right|M1\left|{}^3P_1\right|E1\cos(\delta({}^3P_1) - \delta({}^3D_1))]/A$$

$$\nu = [18|^3P_1|^2 E1 + 12|^3S_1|^2 M1 + 12\sqrt{2}|^3D_1|M1|^3S_1|M1$$
$$\cos(\delta(^3S_1) - \delta(^3D_1))]/A \qquad (10)$$

The experimental data on the coefficients α_0, ε_0 and ν_0 have appeared such that the set (8) had no solutions. Therefore, the set was solved for the following values of the coefficients:

$$\alpha = \alpha_0 + k\Delta\alpha$$
$$\varepsilon = \varepsilon_0 + k\Delta\varepsilon \qquad (11)$$
$$\nu = \nu_0 + k\Delta\nu$$

where $\Delta\alpha$, $\Delta\varepsilon$ and $\Delta\nu$ are the statistical errors of the corresponding coefficients, and κ takes on the lowest possible value. In this case, the set has two positive solutions. However, at $\kappa_{min}\neq 0$ these solutions coincide. The solution of the set was determined in the range of one standard deviation *($|k|\leq 1$)*. The computational results are presented in Table 3 and Table 4 for $^4He(\gamma,n)^3He$ and $^4He(\gamma,p)T$ reactions, respectively.

It is evident from the tables that it is the $^3D_1$ M1 amplitude that has the highest value.

In the subsequent analysis it was assumed that $|^3D_2|E2 >> |^3D_1|M1$. From expression (8) it is obvious that in this case there should be $\alpha\geq 0$, and this does not agree with the experimental data.

***Table 3**. The computed amplitude module ratios for* $^4He(\gamma,p)T$ *reactions for two photon energy ranges*

Ratios of amplitude modules	E_γ=34 -46 MeV	E_γ=46 – 65 MeV
$\frac{|^3D_1|^2 M1}{|^1P_1|^2 E1}$	0.054±0.03	0.046±0.03
$\frac{|^3S_1|^2 M1}{|^1P_1|^2 E1}$	0.022±0.02	0.005±0.02
$\frac{|^3P_1|^2 E1}{|^1P_1|^2 E1}$	0.010±0.02	0.008±0.02

***Table 4**. The computed amplitude module ratios for* $^4He(\gamma,n)^3He$ *reactions for two photon energy ranges*

Ratios of amplitude modules	E_γ= 34 – 46 MeV	E_γ=46 – 65 MeV
$\frac{|^3D_1|^2 M1}{|^1P_1|^2 E1}$	0.051±0.03	0.092±0.04
$\frac{|^3S_1|^2 M1}{|^1P_1|^2 E1}$	0.011±0.02	0.024±0.03
$\frac{|^3P_1|^2 E1}{|^1P_1|^2 E1}$	0.003±0.02	0.005±0.02

CONCLUSIONS

The data on the cross-section asymmetry $\Sigma(\theta)$ make it possible to derive an additional relationship between the amplitudes of multipole transitions. A simultaneous least-square fit of expressions for differential cross-sections and asymmetry to the experimental data on $d\sigma/d\Omega$ and $\Sigma(\theta)$, obtained at NSC KIPT, was realized. To extract the information about the cross-sections of $\Delta S=1$ transitions, a set of three bilinear equations with three unknown amplitude modules $|^3P_1|E1$, $|^3S_1|M1$ and $|^3D_1|M1$ has been set up, and the preliminary data on the values of these amplitude modules have been obtained. It is shown that the $^3D_1$ M1 amplitude is the highest in value, and accordingly, $\sigma(M1) >> \sigma(^3P_1 E1)$. The experimental data on the azimuthal cross-sectional asymmetry of (γ,p) and (γ,n) reactions show that the main contribution to the cross-section of transitions with spin variation comes from the M1 transition. A considerable cross-section of the M1 transition may be due to the contribution of wave function components of the ^4He nucleus with nonzero orbital moments of nucleons.

ACKNOWLEDGMENT

The authors are grateful to P.V. Sorokin, L.G. Levchuk, V.N. Gur'ev, A.F. Khodyachikh for the discussion of present results.

REFERENCES

1. D.J. Wagenaar, N.R. Robertson, H.R. Weller and D.R. Tilley. Evidence for M1 strength in the $^3He(p,\gamma)^4He$ reactions // *Phys. Rev. C.* 1989, v. 39, №2, p. 352-358.
2. W. Pitts. Spin-triplet strength in the $^3He(p,\gamma)$ ^4He reactions at E_p=2 MeV // *Phys. Rev. C.* 1992, v. 46, №1, p. 15-19.
3. R. Werwelman, K. Abrahams. Nucleon captures by ^4He and the production of solar hep -neutrons. Cross-section measurement and shell-model calculation *// Nucl. Phys. A*. 1991, v. 526, p. 265-291.
4. Yu.M. Arkatov et al. Photodisintegration of ^4He nuclei below meson production threshold // *UFZh*. 1978, v. 23, №11, p. 1818-1023 (in Russian).
5. V.B. Ganenko et al. Two-body photodisintegration of ^4He by linearly polarized γ-quanta // *Problems of Atomic Science and Technology: ser. Nuclear-physical studies (theory and experiment*). 1989, iss. 8(8), p. 64 (in Russian).
6. Yu.P. Lyakhno et al. Measurement of angular dependence of the asymmetry of cross-sections for $^4He(\gamma,p)T$ and $^4He(\gamma,n)^3He$ reactions induced by 40, 60 and 80 MeV linearly polarized photons // *Yad. Fiz.* 1996, v 49, №5, p. 18-22 (in Russian).
7. B.T. Murdoch, D.K. Hasell, A.M. Sourkes et al. $^3He(p,p)$ scattering in the energy range 19-48 MeV *// Phys. Rev. C.* 1984, v. 29, p. 2001-2008.
8. J.M. Eisenberg and W. Greiner. *Nuclear Theory*, *Mechanisms of the nucleus v.2*. Amsterdam, 1970, 345 p.