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POSSIBLE MEASUREMENT OF THE PROBABILITY OF P-STATES IN THE GROUND STATE OF ^{4}He NUCLEUS

Using the experimental data on the total cross-sections of $^4He(\gamma,p)^3H$ and $^4He(\gamma,n)^3He$ reactions with $S = 1$ transitions as the base, we discuss the possibility of measuring the probability of $^3P_0$-states in the ground state of ^4He nucleus. The analysis of the experimental data has suggested the conclusion that, within the statistical error, the ratio of the cross section of the reaction in the collinear geometry to the cross section of the electrical dipole transition with the spin $S = 0$ at the angle of the emission of nucleons $\theta_N = 90^\circ \nu_p$ and ν_n in the range of photon energies $22 \le E\gamma \le 100$ MeV does not depend from the photon energy. This is in agreement with the assumption that the $S = 1$ transitions can originate from $^3P_0$ states of ^4He nucleus. The average values of ν_p and ν_n in the mentioned photon energy range are calculated as $\nu_p = 0.01 \pm 0.002$ and $\nu_n = 0.015 \pm 0.003$ (the errors are statistical only).

K e y w o r d s: nuclear forces, few-body systems.

1. Introduction

The model-independent calculation of the ground state of the nucleus, as well as its scattering states, can be carried out on the basis of realistic internucleonic forces and exact methods of solving the many-nucleon problem. ^{4}He nucleus can serve as a good test for setting this approach to work. In [1], the ground states of the lightest nuclei using the realistic NN Argonne AV18 [2] and CD Bonn [3] potentials and the $3N$ forces UrbanaIX [4] and Tucson-Melbourne [5, 6] were calculated. The calculations were carried out, by using the Faddeev–Yakubovsky (FY) technique [7, 8], which was generalized by Gloeckle and Kamada (GK) [9] to the case of two- and three-nucleon forces. The authors estimated the error of the nuclear binding energy calculations for ^{4}He to be ∼50 keV. The calculated binding energy appeared to be by ∼200 keV higher than the experimentally measured value. In view of this, the authors drew conclusion that there is a possible contribution of the $4N$ forces that could have a repulsive character. Another possible explanation of this result might be the inconsistency of the data on NN and $3N$ forces.

The tensor part of the NN interaction and the $3NF$ forces generate the ^{4}He nuclear states with nonzero orbital momenta of nucleons. Table 1 gives the probabilities of $^1S_0$, $^3P_0$, and $^5D_0$ states of ^{4}He nucleus calculated in [1] (notation: $^{2S+1}L_J$). The calculations gave the probability of $^5D_0$ states having the total spin $S = 2$ and the total orbital momentum of nucleons $L = 2$ of ^{4}He nucleus to be ∼16%, and the probability of $^3P_0$ states having $S = 1$ and $L = 1$ to be 0.75%. It is obvious from Table 1 that the consideration of the $3NF$ contribution increases the probability of $^3P_0$ states by a factor of ∼2.

In [10], Kievsky *et al.* have calculated the ground states of the lightest nuclei by the method of hyperspherical harmonics, by using the NN and $3N$ potentials calculated from the effective field theory. Various versions of the mentioned potentials predict the contribution from $^3P_0$ states of ^{4}He nucleus to be between 0.1% and 0.7%. Thus, the measurement of the probability of states with nonzero orbital momenta of nucleons can provide a new information about internucleonic forces.

2. The Analysis of the Experimental Data on the Cross-Sections of ^{4}He$(\gamma,p)^3$H and ^{4}He$(\gamma,n)^3$He Reactions in the Collinear Geometry

Here, we discuss the possibility of measuring the probability of $P(^3P_0)$ states of the ground state of ^{4}He nucleus through the studies of two-body (γ,p) and (γ,n) reactions of ^{4}He. In these reactions, the transition matrix elements of two types, with spins $S = 0$ and $S = 1$ of the final state of the particle system, may take place. It is known [11] that, under the electromagnetic interaction, the spin-flip of a hadronic particle system is significantly suppressed. The $S = 1$ transitions can originate from $^3P_0$ nuclear states with no spin-flip. Maybe, such transitions can occur also from $^1S_0$ or $^5D_0$ states of ^{4}He nucleus as a result of the different channels of the reaction coupled, for example, with the existence of states with nonzero orbital momentums of nucleons of the residual nucleus and from the secondary effects. It can be supposed that the cross section of the (γ, N) reaction is independent of the total spin of the ground state of ^{4}He nucleus. Then the ratio

$$\alpha = \frac{\sigma(^3M_{1,2})}{\sigma_{\text{tot}}(\gamma, N)} \quad (1)$$

of the total cross sections of the transitions with the spin $S = 1$ to the total cross section $\sigma_{\text{tot}}(\gamma, N)$ of the reaction, after the subtraction of the contribution of other possible mechanisms of formation of the transitions with spin $S = 1$, can be sensible to the contribution of the P-wave component to the wave function of ^{4}He nucleus. The indices (1,2) correspond to the total momenta 1^-, 1^+, and 2^+ of the final state of the particle system at the transitions with $S = 1$.

In the *E1*, *E2*, and *M1* approximation, the laws of conservation of the total momentum and the parity

Table 1. **Probabilities of the $^1S_0$, $^3P_0$, and $^5D_0$ states for the ground state ^{4}He nucleus (in percentage terms)**

Interaction	$^1S_0, \%$	$^3P_0, \%$	$^5D_0, \%$
AV18	85.87	0.35	13.78
CD-Bonn	89.06	0.22	10.72
AV18+UIX	83.23	0.75	16.03
CD-Bonn+TM	89.65	0.45	9.9

Table 2. **Angular distributions for $E1$, $E2$, and $M1$ multipoles**

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

for the two-body (γ, p) and (γ, n) reactions of ^{4}He nuclear disintegration permit the occurrence of two multipole transitions $E1\,^1P_1$ and $E2\,^1D_2$ with the spin $S = 0$ and four transitions $E1\,^3P_1$, $M1\,^3D_1$, $M1\,^3S_1$, and $E2\,^3D_2$ with the spin $S = 1$ of final-state particles. According to the present experimental data, the sum of the total cross sections of transitions with the spin $S = 1$ is $\sim 10^{-2}$ of the total cross section of the reaction. The nucleon emission distributions in the polar angle for each of the mentioned transitions are presented in Table 2.

It can be seen from Table 2 that the reaction cross-section in the collinear geometry can be due only to the $S = 1$ transitions, at that $\mathrm{d}\sigma(0°) = \mathrm{d}\sigma(180°)$. In order to determine the reaction cross-section in the collinear geometry, the analysis of the information available in the literature about the differential cross sections of the $^4\mathrm{He}(\gamma, p)^3\mathrm{H}$ and $^4\mathrm{He}(\gamma, n)^3\mathrm{He}$ reactions in the energy range of photons up to the meson-producing threshold was made.

In [12, 13], the reaction products were registered at nucleon-exit polar angles $0° \le \theta_N \le 180°$, by using chambers placed in a magnetic field. However, the number of events registered in those experiments was insufficient for measuring the reaction cross-section in the collinear geometry (the cross-section estimation is shown by full circles in Fig. 1).

Jones *et al.* [14] have measured the differential cross section for the $^4\mathrm{He}(\gamma, p)^3\mathrm{H}$ reaction at tagged photon energies between 63 and 71 MeV (triangles in Figs. 1 and 2). The reaction products were registered by means of a wide-acceptance detector LASA. The measurements were performed in the interval of polar proton-exit angles $22.5° \le \theta_p \le 145.5°$. The lack of data for large and small angles of proton escape has led to significant errors in the measurement of the reaction cross-section in the collinear geometry.

In [15] (cross in Fig. 1), a monoenergetic photon beam in the energy range from 21.8 to 29.8 MeV and nearly a 4π time projection chamber were used to measure the total and differential cross-sections for the photodisintegration reactions of ^{4}He nucleus. The authors found that the M1 strength was about $2 \pm 1\%$ of the $E1$ strength.

The differential cross sections of the two-body (γ, p) and (γ, n) reactions have been measured in [16, 17] in the bremsstrahlung photon energy range from the reaction threshold up to $E_\gamma = 150$ MeV. The reaction products were registered with the help of a diffusion chamber placed in a magnetic field in the interval of polar nucleon-exit angles $0^\circ \leq \theta_N \leq 180^\circ$. Later on, Nagorny *et al.* [18] reprocessed this experiment, by using a new program for the geometric remodeling of events, a more powerful (for that time) computer, and an upgraded particle track measuring system. The number of the processed events was increased by a factor of 3 and amounted to $\sim 3 \times 10^4$ for each of the (γ, p) and (γ, n) reaction channels. The differential cross-sections were measured with a 1-MeV step up to $E_\gamma = 45$ MeV and with a greater step at higher energies, as well as with a 10° c.m.s. step in the polar nucleon-exit angle. The authors published their data on the differential cross-sections at photon energies of 22.5, 27.5, 33.5, 40.5, 45, and 49 MeV. The comprehensive data on the differential cross-sections for the $^4\mathrm{He}(\gamma, p)^3\mathrm{H}$ and $^4\mathrm{He}(\gamma, n)^3\mathrm{He}$ reactions can be found in [19].

The differential cross-section for these reactions in the c.m.s. can be presented as

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

where $\nu = [d\sigma(0^\circ) + d\sigma(180^\circ)]/2d\sigma_1(90^\circ)$, and $\varepsilon = [d\sigma(0^\circ) - d\sigma(180^\circ)]/2d\sigma_1(90^\circ)$, where $d\sigma_1(90^\circ)$ is the cross section of the $E1\,^1P_1$ transition at the nucleon emission angle $\theta_N = 90^0$.

It can be supposed that the transition $M1\,^3S_1$ is the main one only at the reaction threshold [20]. In the majority of works, it was supposed that the $E2\,^3D_2$ amplitude is the smallest one. This suggestion is confirmed by experimental hints [21]. Assuming that basic transitions, which give contribution to the ratio ν, are electric dipole transitions with the spins $S = 1$ and $S = 0$ and executing the integration of the proper angular distributions over the solid angle, we obtain

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

If it is supposed that the main transition with the spin $S = 1$ is the $M1\,^3D_1$ transition, then

$$\alpha = \frac{\sigma(M1\,^3D_1)}{\sigma(E1\,^1P_1)} = \frac{3d\sigma(0^\circ)}{d\sigma_1(90^\circ)} = 3\nu. \tag{4}$$

The ratio ν was calculated as a result of the least-squares fitting (LSM) of expression (2) to the experimental data on the differential cross-sections [19]

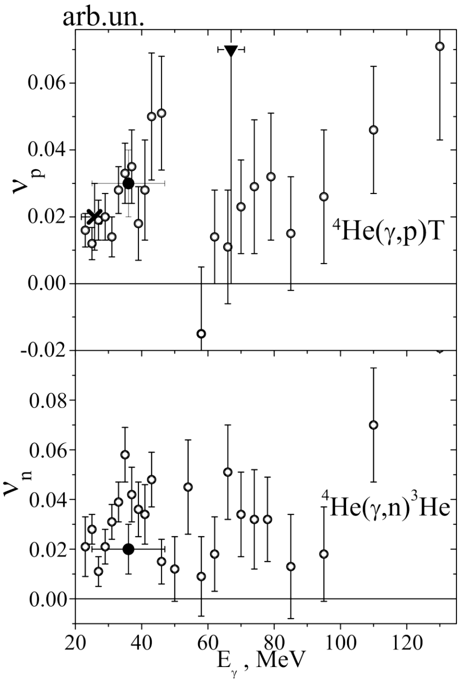

Fig. 1. Coefficients ν_p and ν_n. The cross shows the data from [15]; triangle – data from [14]; full circles – data from [13]; open circles – data from [19]. The errors are statistical only

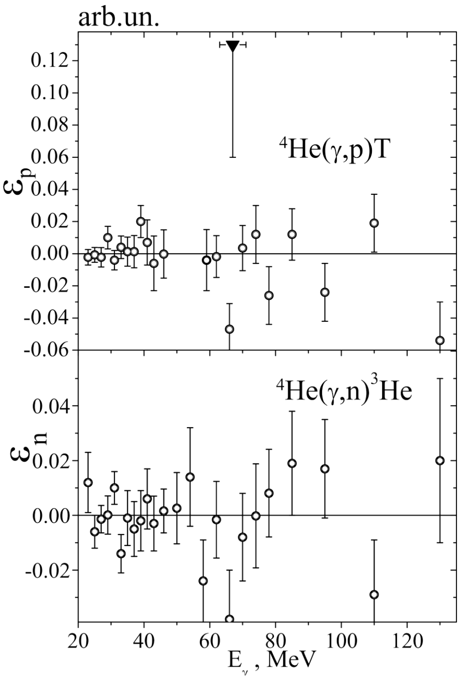

Fig. 2. Coefficients ε_p and ε_n. Triangle are data from [14]; open circles – data from [19]. The errors are statistical only

(with a double step in the photon energy). The results of calculations are presented in Figs. 1 and 2 as open circles. It can be seen from the figures that, within the statistical errors, the ratio of the cross-section in collinear geometry with the $S = 1$ transitions to the cross-sections at polar nucleon-exit angle $\theta_N = 90^\circ$ reaction in the photon energy region $22 \leq E_\gamma \leq 100$ MeV is independent of the photon energy. This is in agreement with the assumption that these transitions might originate from P-states of ^{4}He nucleus. The average values of ratio ν in the mentioned photon energy range are calculated to be $\nu_p = 0.019 \pm 0.002$ and $\nu_n = 0.028 \pm 0.003$. The average values of coefficients are $\varepsilon_p = 0 \pm 0.002$ and $\varepsilon_n = -0.001 \pm 0.003$.

The calculated ν_p and ν_n values may be displaced as a result of the histogramming of experimental data with regard for the polar nucleon-exit angle measurement errors, which were $\delta\theta_N = 0.5^\circ \div 1^\circ$, as reported in ref. [22]. In this connection, we have determined, by the simulation, the corrections for the histogramming step as 10° for $\delta\theta_N = 1^\circ$ [23]. Taking these corrections into account, we have $\nu_p = 0.01 \pm 0.002$ and $\nu_n = 0.015 \pm 0.003$.

The systematic error of the data might be caused by the inaccuracy in the measurement of the resolution on the polar angle of the nucleon emission. In particular, the difference in the coefficients ν_p and ν_n might be conditioned by the fact that the resolution of the neutron $\delta\theta_n$ emission angle was worse than that the angle of the proton $\delta\theta_p$ emission. In addition, a small number of events in some histogramming steps, especially at high photon energies, can lead to a systematic error specified by the use of the LSM method. The conclusion in [24] about large errors in the cross-section measurements in the collinear geometry was based on the early works of Arkatov *et al.* [16,17].

The cross-sections with the spin $S = 1$ transitions can be measured by means of polarization observables. For example, the transitions $E1\,^1P_1$ and $E2\,^1D_2$ with the spin $S = 0$ exhibit the asymmetry of the cross-section with linearly polarized photons $\Sigma(\theta) = 1$ at all polar nucleon-exit angles, except $\theta_N = 0^\circ$ and 180°. The difference of the asymmetry Σ from unity can be due to the spin $S = 1$ transitions. With an aim of separating the contributions from the $E1\,^3P_1$, $M1\,^3D_1$, and $M1\,^3S_1$ transitions, Lyakhno *et al.* [21] performed a combined analysis of both the experimental data on the cross-section asymmetry $\Sigma(\theta)$ and the data on the differential cross-sections for the reactions under discussion [19] at the photon energies $E_\gamma^{\text{peak}} = 40$, 56, and 78 MeV. Because of the small cross-sections with the spin $S = 1$ transitions, the errors of asymmetry $\Sigma(\theta)$ measurements have led to considerable errors in the measurements of the cross-sections with these transitions.

The authors of [20, 25, 26] investigated the reactions of radiative capture of polarized protons by tritium nuclei. In [25], Wagenaar *et al.* investigated the capture reaction at the proton energies $0.8 \leq E_p \leq$ ≤ 9 MeV. They came to the conclusion that the main transition with the spin $S = 1$ is $M1\,^3S_1$. In [20], this reaction was investigated at the proton energy $E_p = 2$ MeV. It was concluded that the main transition with $S = 1$ is $E1\,^3P_1$. These contradictory statements were caused by considerable statistical and systematic errors of the experimental data. Within experimental errors, the data obtained in studies of the (γ, N) and $(\mathbf{p}, \gamma)$ reactions are in satisfactory agreement between themselves [21].

3. Conclusions

In [20], it was found that the transitions with the spin $S = 1$ can be conditioned by the contribution of meson exchange currents (MEC). It should be noted that the MEC contribution depends on the photon energy [27]. Despite the considerable MEC contribution into the total cross section of the reaction, the contribution of the spin-flip of the hadronic particle system can be insignificant. The weak dependence of the ratio of the cross-sections with the $S = 1$ transition to that with $S = 0$ on the photon energy in the energy region from the reaction threshold up to $E_\gamma \sim 100$ MeV (this corresponds to the nucleon momentum $P_N \sim 350$ MeV/c) may point to an insignificant contribution of the final-state particle interactions and of other photon energy-dependent reaction mechanisms to the total cross-section with the spin $S = 1$ transition. The present experimental data coincide with the supposition that the contribution of the $^3P_0$ components of the ground state of ^{4}He nucleus to the formation of the transitions with the spin $S = 1$ in the two-body (γ, N) reaction can be considerable, and these data can be used in measurements of the contribution of the P-wave component of the wave function of ^{4}He nucleus.

A number of investigations of the reaction $^2\mathrm{H}(\mathbf{d}, \gamma)^4\mathrm{He}$ (e.g., [28–32]) were made with an aim of measuring the probability of $^5D_0$ states of ^{4}He nucleus. This reaction permits the occurrence of three types of transitions with $S = 0$, 1, and 2. In this connection, the analysis of the experimental data on this reaction may be more complicated than that of the two-body (γ, N) reaction. It might be reasonable to perform a combined detailed theoretical analysis of these reactions.

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МОЖЛИВІСТЬ ВИМІРУ ВАГИ
P-СТАНІВ ОСНОВНОГО СТАНУ ЯДРА ^{4}He

Р е з ю м е

На основі експериментальних даних про повні поперечні перерізи переходів із спіном $S = 1$ в реакціях $^4\text{He}(\gamma, p)^3\text{H}$ і $^4\text{He}(\gamma, n)^3\text{He}$ обговорюється можливість виміру ваги P-станів основного стану ядра ^{4}He. В результаті аналізу експериментальних даних було знайдено, що в межах статистичних похибок відношення перерізу реакції в колінеарній геометрії до перерізу електричного дипольного переходу із спіном $S = 0$ при полярному куту емісії нуклона $\theta_N = 90^\circ$ ν_p і ν_n в області енергій фотонів $22 \leq E_\gamma \leq 100$ МеВ не залежить від енергії фотонів. Це узгоджується з допущенням про те, що переходи із спіном $S = 1$ можуть походити із P-станів ядра ^{4}He. Було обчислено середні значення величин ν_p і ν_n в цій області енергій фотонів, які становлять $\nu_p = 0{,}01 \pm 0{,}002$ і $\nu_n = 0{,}015 \pm 0{,}003$ (похибки статистичні).