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

Using the experimental data on the total cross-sections of 4He(γ, p)3H and 4He(γ, n)3He reactions with S = 1 transitions as the base, we discuss the possibility of measuring the probability of 3P0-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 θN = 90°νp and νn in the range of photon energies 22 ≤ Eγ ≤ 100 MeV does not depend from the photon energy. This is in agreement with the assumption that the S = 1 transitions can originate from 3P0 states of 4He nucleus. The average values of νp and νn in the mentioned photon energy range are calculated as νp = 0.01 ± 0.002 and νn = 0.015 ± 0.003 (the errors are statistical only).

Key words: 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. 3He 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 4He 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 4He nuclear states with nonzero orbital momenta of nucleons. Table 1 gives the probabilities of 1S0, 3P0, and 3D0 states of 4He nucleus calculated in [1] (notation: 25LJ). The calculations gave the probability of 3D0 states having the total spin S = 2 and the total orbital momentum of nucleons L = 2 of 4He nucleus to be ∼16%, and the probability of 3P0 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 3P0 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 3P0 states of 4He 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 4He(γ, p)3H and 4He(γ, n)3He Reactions in the Collinear Geometry

Here, we discuss the possibility of measuring the probability of P(3P0) states of the ground state of 4He nucleus through the studies of two-body (γ, p) and (γ, n) reactions of 4He. 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 $(\gamma, N)$ reaction is independent of the total spin of the ground state of $^4$He nucleus. Then the ratio

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

(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 for the two-body $(\gamma, p)$ and $(\gamma, n)$ 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 $d\sigma(0^\circ) = d\sigma(180^\circ)$. 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 $^4$He$(\gamma, p)^3$H and $^4$He$(\gamma, n)^3$He reactions in the energy range of photons up to the meson-producing threshold was made.

<table>
<thead>
<tr>
<th>Table 1. Probabilities of the $^1S_0$, $^3P_0$, and $^5D_0$ states for the ground state $^4$He nucleus (in percentage terms)</th>
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<td>Interaction</td>
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<td>AV18</td>
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<td>CD-Bonn</td>
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<td>AV18+UIX</td>
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<td>CD-Bonn+TM</td>
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<th>Table 2. Angular distributions for $E1$, $E2$, and $M1$ multipoles</th>
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<td>Spin of final-states</td>
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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 $(\gamma, p)$ and $(\gamma, n)$ 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 $10^\circ$ 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 $^4\text{He}(\gamma, p)^3\text{H}$ and $^4\text{He}(\gamma, n)^3\text{He}$ reactions can be found in [19].

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

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

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 $\theta_N = 90^\circ$.

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 $\nu$, 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

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

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

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

The ratio $\nu$ was calculated as a result of the least-squares fitting (LSM) of expression (2) to the experimental data on the differential cross-sections [19].
performed a combined analysis of both the experiments at all polar nucleon-exit angles, except 180°. The difference of the 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 \((\gamma, N)\) and \((p, \gamma)\) 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 spin \( S = 1 \) 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 \((\gamma, N)\) 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 \(^2\)H(d, \(\gamma\))\(^4\)He (e.g., [28–32]) were made with an aim...
of measuring the probability of $^5D_0$ states of $^4\text{He}$ 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 ($\gamma, N$) reaction. It might be reasonable to perform a combined detailed theoretical analysis of these reactions.

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