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TWO-PARTICLE PHOTODISINTEGRATION OF ^{4}He: ^{4}He$(\gamma, d)d$, ^{4}He$(\gamma, p)T$, ^{4}He$(\gamma, n)^3$He

Using a covariant diagram technique and the concept of a nucleus as an elementary particle, we calculated the differential cross-sections for two-particle photodisintegration reactions of ^{4}He. The only functional parameter is the vertex structure function, which describes the "collapse" of ^{4}He nucleus and the nucleon remnants. The interaction of a real photon is determined by the value of particles charge, since the electromagnetic (EM) form factors are calculated at the photon point. The inseparability property of the electric charge from the particle mass allowed us to match the energy-momentum and charge conservation laws in the interaction. Therefore, the requirement of gauge symmetry is immediately satisfied. The covariant amplitude of the process equals to the sum of pole diagrams and the regular part, which is added to fulfil the EM current conservation requirement.

Keywords: gauge invariance, vertex function, photodisintegration of ^{4}He, regular amplitude.

1. Introduction

Quantum theory of gauge fields (QTGF) is a widely recognized basis of the elementary particle physics. QTGF is based on the thesis that all the known interactions in the Nature are transferred by means of gauge fields. The principle of gauge symmetry is one of the most important heuristic principles. The considerable success in understanding the properties of electromagnetic and weak interactions was achieved by using the gauge invariance principle. The implementation of this principle led to the modern electroweak interaction theory.

Quantum electrodynamics (QED) as an important part of QTGF was formed in order to describe electromagnetic (EM) interactions and those of charged matter fields. The considerable breakthrough in the description of EM interactions was achieved on the basis of the following assumption[1]: the interaction of a gauge field with fundamental matter fields is of a local nature.

However, the matter fields that form the nature variety are of a nonlocal formation and are closely related to the strong interaction. Thus, there is the additional uninvestigated interaction in EM processes, which forms a bounded state and, at the same time, originates all difficulties in using the Lagrangian approach. A nonlocal nature of the strong interaction, which appears in vertices that describe the disintegration of a compound strongly coupled nuclear system into constituents, does not allow us to "add" properly[2] the EM field to the Lagrangian. As a result of this bewildering fact, a vast number of nonrelativistic approaches, which describe photonuclear reactions, appeared. These traditional, quantum-mechanical approaches, which are aimed to consider a nucleus structure and many-particle effects, result in a gauge invariance violation. The problem of creation of the gauge-invariance theory that could describe the EM disintegration of atomic nuclei has not been solved so far.

The approach that considers a possibility to construct an analogous Lagrangian that can describe a nonlocal and EM field interactions was proposed in papers [1, 2]. It satisfies the universality principle. The method is based on the theory of fiber spaces, in which an electromagnetic field vector-potential provides a connection. Due to the fact that the electric charge cannot be separated from the mass and,

[1] The assumption was assured by the universality property.
[2] According to the standard QED approach.

consequently, it is not an independent quantity, it is necessary to consider additionally the movements in the associated charge space, while describing the particles movement in the base space. As a result of these operations, it was succeeded to harmonize the 4-momentum and charge conservation laws in the amplitude of processes. In papers [2, 3] with the use of generalized Feynman rules, the mentioned approach was applied to the description of the photodisintegration of a deuteron.

While applying this approach to the electromagnetic and nonlocal interactions of the matter field, it is essential to follow the requirement of a general covariance and to consider dynamically the requirement of the gauge invariance. The only unknown parameter is the vertex, which describes the collapse of strongly interacting particles. The dependence of the vertex on the space-like four-momenta of fragments allows us to keep the invariance of the approach irrespective of its explicit form.

Several points that are infusion into the theory by the new approach or, to be more precise, by the regular (pole) part of the amplitude should be noted.

Momentum distributions of the components in various nonlocal fields of matter are individual and contain information about the steady-state interactions in a coupled system. They also reflect the space-time evolution of a coupled system during the whole energy and structural ranges. The information about the each nonlocal field is determined by the following things: the decrement of the momentum distribution function, its rate of change, and the nature of the curve curvature (its convexity or concavity).

Another established property of the generalized, gauge-invariant pole amplitude, which occurs independently of the explicit form of a vertex function, is related to the degree of its increase or decrease. The relative sign between the pole and regular parts in the amplitude is fixed by the total electromagnetic current conservation requirement. If the vertex function of the strong interaction is constant, then the regular part of the amplitude turns to a zero. At the same time, the pole part is determined by Yukawa asymptotic behavior [3]. For a decreasing function, its derivative is negative. This fact changes the sign in the amplitude for the regular part, making the sign equal to the sign of the pole part. In this case, the contribution from the regular part to the total cross section is constructive (a positive interference). In the case where the vertex function increases with the argument, its derivative is positive, and the contribution to the cross section is changed to the destructive one.

To sum up, the regular component of the generalized pole amplitude is a dynamic measure of the bound state nonlocality. It shows how "quickly" the structural formations of the initial level of a matter structure lose their identity upon the transition to the other scale of the space-time localization.

The regular component of the amplitude introduces an additional dependence on the vertex function in the form of its derivative. It was established in [1] that the contribution from the regular part to the full amplitude for the electric dipole splitting at low energies is determined by the derivative of a strong interaction vertex. If the electric dipole transition is absent (the case of the splitting into two identical fragments), then the regular part contribution to the total amplitude is determined by the second derivative of the strong interaction vertex.

The investigation of interaction processes between EM fields and nuclei appears to be an important technique. It helps to solve the vast number of nuclear and elementary particle physics issues. Namely: the understanding of the role of different reaction mechanisms, a revision of different nuclear models, obtaining an information about the nucleon-nucleon interaction, the structural analysis of the wave functions of nuclei, the understanding of the role of quark configurations and non-nucleon degrees of freedom in nuclei, *etc.* In the theoretical aspect, this method possesses the significant advantage: using the constant of the EM interaction, we can consider processes with the bounds of perturbation theory.

Especially valuable results can be obtained by investigating EM interactions of few-nucleon systems. The special place in nuclear physics belongs to these systems for several reasons. Some of them are: the relative simplicity of structures of such nuclei and the possibility to find the precise solution to the tree- or four-body problem. Applying the proposed theory, we will consider the two-particle photodisintegration of ^{4}He. A good agreement of the results of theoretical calculations and experimental measurements of the differential and total cross sections for these reactions was obtained by using a minimum number of parameters.

[3] A constant that is divided by the pole.

2. Process ^{4}He(γ, d)d

The ^{4}He(γ, d)d process is characterized by the fact that, because of the isospin selection and the identity of particles in a final state, the electric dipole moment is suppressed, and the process realizes mostly due to the quadrupole γ-ray absorption. Therefore, this channel is of a considerable interest to study the nature of a quadrupole transition.

Data [4–10] provide information about the total cross-section of the direct ^{4}He(γ, d)d reaction. A part of these data was obtained from experimental measurements of the differential cross-sections of the reverse reaction [4].

The information about the reverse d(d, γ)^{4}He reaction is more abundant. There are some data about differential cross-sections [11, 12]. Furthermore, the total energy dependence of cross-sections, in the assumption of the explicit form of angular distributions, was measured in [4, 7, 9, 13].

Theoretical calculations of the cross-sections of the γ^4He $\leftrightarrow$ dd reaction had appeared long time before experimental measurements [14] were done. The authors used wave functions that were not eigenfunctions of the Hamiltonian of the system and did not produce the proper values of its general characteristics [5]. Thus, their calculations did not substantially coincide with the experiment [4]. Further calculations were done to the extent of the traditional consideration of the atomic nucleus as an interacting nucleon system. This system was described by the wave function that is the solution to the nonrelativistic Schrödinger equation.

In [15], the calculations of Hulten's and Yukawa's wave functions were used to describe the ^{4}He ground state and the deuteron, respectively. However, the correct description of the cross-section form and its maxima was not achieved, despite the fact that these calculations correctly reproduced the binding energy and the charge radius of a ^{4}He nucleus.

A considerable improvement in the description of the total cross-section of the ^{4}He(γ, d)d process was achieved in [16]. In that paper, Irving's function was used as the ^{4}He nucleus wave function. The wave function that describes a relative movement of two deuterons was obtained by the total energy minimisation of a (dd)-system [17].

In [18], the total cross-section calculations were done under assumption that, at the energy of $E_\gamma = 30$ MeV, the appearance of the excited (2$^+$) ^{4}He state [6] is possible.

Erdas *et al.* [19] used the dispersion approach, in which it was assumed that the matrix element of the ^{4}He(γ, d)d process is known, if the phases of the elastic (dd)-scattering are also known. These phases were used as resonant (2$^+$), with the solid sphere phases addition. Gaussian-type functions were used to describe ^{4}He nucleus and the ground state of a deuteron. As a result, a quite good fit to the experiment was achieved.

In the more recent papers [13, 20, 21], the importance of the D-wave for the d(d, γ)^{4}He reaction cross-section formation and the influence of the D-wave on a tensorial analyzing ability were discussed. The wave function of a (dd)-system was obtained, by using the resonant group method and the Woods-Saxon potential. The importance of the D-wave was supported by the introduction of a ρ-parameter equal to the D/S ratio. As a result, a considerable influence of the D-wave on the total cross-section, in the case of small energies, was revealed. However, the disagreement between the theory and the experiment appears in describing the total cross-section of the d(d, γ)^{4}He process in the case where the deuteron energy exceeds 4 MeV [13]. It was supposed that this disagreement can be removed by the contribution of other transitions and the 2$^+$ resonance accounting.

There are some features of the mentioned theoretical works that should be noted. Uppermost, they are of a nonrelativistic nature in the case where the matrix element is defined by the overlap integrals of wave functions. As a result, a number of parameters, which define the form of potentials, are added to the theory. Consequently, the quantitative estimations strongly depend on the structure of effects. Moreover, these estimations are false on broader energy intervals. Nonrelativistic computations account for this. Thus, the importance of nonrelativistic corrections still be unresolved. In addition, all mentioned calculations were done without regard for the gradient invariance requirement. This led to different results for different choices of the EM field calibration.

[4] Using the detailed balancing principle.

[5] Such as a binding energy or charge radius.

[6] With the isotopic spin $T = 0$.

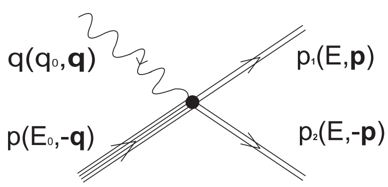

Fig. 1. ^{4}He(γ,d)d process in the center-of-mass system

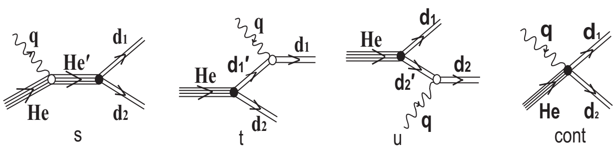

Fig. 2. Set of diagrams for the ^{4}He$(\gamma, d)d$ reaction

That is why, nowadays, an unambiguous and consistent theory that is able to describe all the data set concerning the ^{4}He(γ,d)d reaction is absent.

In our approach, the gradient-invariance requirement ensuring was assured by the other choice of the reaction mechanism: the contact diagram supplements the well-known field-theory row. This diagram involves many-particle effects, including the EM interaction with the "strong interaction carriers". In addition, the constructed amplitude satisfies the fundamental principle of the gradient-invariance irrespective of the explicit form of the disintegration form-factors or of their number.

To describe the cross-section of the process ^{4}He(γ,d)d, it is convenient to use spiral amplitudes, which were obtained in a Cartesian coordinate system, when the γ-quantum momentum is directed along z-axis and the first deuteron momenta is situated in the xOz plane. First, we define the matrix

$$R_{\lambda_\gamma,\lambda'_\gamma} = \sum_{\{\lambda\}} M^{\lambda_\gamma}_{\lambda_1,\lambda_2}\rho_{\lambda_\gamma,\lambda'_\gamma} M^{*\lambda'_\gamma}_{\lambda_1,\lambda_2}, \tag{1}$$

where $M^{\lambda_\gamma}_{\lambda_1,\lambda_2}$ are spiral amplitudes of the ^{4}He(γ,d)d process, $\lambda_\gamma, \lambda_1$, and λ_2 are helicities of a γ-quantum and the first and second deuterons, respectively, and $\rho_{\lambda_\gamma,\lambda'_\gamma}$ is the polarization density matrix of a γ-quantum.

The differential cross section of the ^{4}He(γ,d)d process in the case where a γ-ray is polarized in an arbitrary way in the center-of-mass system (see Fig. 1) is

$$\frac{\partial\sigma}{\partial\Omega} = \frac{1}{2(8\pi W)^2}\frac{|\mathbf{p}|}{|\mathbf{q}|}\mathrm{Sp}R, \tag{2}$$

where

$$W = q_0 + E_0 = 2E.$$

Using Eq. (1) and the explicit form of a photon polarization density matrix, we obtain

$$\mathrm{Sp}R = \sum_{\lambda_1,\lambda_2} M^1_{\lambda_1,\lambda_2} M^{1*}_{\lambda_1,\lambda_2} + 2\mathrm{Re}(M_{1,1}M^*_{-1,-1} +$$

$$+ M_{1,-1}M^*_{-1,1} - M_{1,0}M^*_{-1,0} - M_{0,1}M^*_{0,-1} + \frac{1}{2}|M_{0,0}|^2).$$

In order to write down the amplitude of the process ^{4}He(γ,d)d, we follow the approach described in [2]. In that paper, the problem of ensuring the gradient invariance of the amplitude was solved by choosing the following reaction mechanism: the contact diagram was added to the known field-theoretic row. This diagram takes multiparticle effects into account, including the electromagnetic interaction with the "carriers of strong interaction". Rooting from this approach, the amplitude, which satisfies the principles of the relativistic and gradient invariances, was determined by the sum of contact and pole diagrams, which are shown in Fig. 2.

The matrix element pole part of these diagrams is characterized by two electromagnetic vertices (γ^4He $\to$ ^{4}He), (γd $\to$ d) and the strong one – (^{4}He $\to$ dd). The explicit form of these vertices can be obtained by the use of the Argonne [22] or Urbana parametrization. To obtain these vertices within the Urbana parametrization, we used data from [23]. The following parametrization of the functions A^{00}_{dd} and A^{22}_{dd} is possible:

$$A^{00}_{dd}(|\mathbf{p}|) = a1 + a2 * |\mathbf{p}| + a3 * |\mathbf{p}|^2 +$$

$$+ a4 * |\mathbf{p}|^3 + a5 * |\mathbf{p}|^4,$$

$$A^{22}_{dd}(|\mathbf{p}|) = b1 + b2 * |\mathbf{p}| + b3 * |\mathbf{p}|^2 +$$

$$+ b4 * |\mathbf{p}|^3 + b5 * |\mathbf{p}|^4,$$

where the parameters $a1 = 316.51$, $a2 = 0.48\times$ $\times 10^{-3}, a3 = -0.0138$, $a4 = 0.543 \times 10^{-4}$, $a5 =$ $= -6.21 \times 10^{-8}$; $b1 = -0.0272$, $b2 = 0.373 \times 10^{-2}$, $b3 = 0.117 \times 10^{-3}$, $b4 = -0.6847 \times 10^{-6}$, $b5 =$ $= 9.696 \times 10^{-10}$. Figure 3 shows the functions $A^{00}_{dd}(|\mathbf{p}|)$, $A^{22}_{dd}(|\mathbf{p}|)$, and $N_{dd}(|\mathbf{p}|)$, where the solid lines represent the approximation of real values that are marked as dots.

In view of the expressions for vertices [22], we estimated the following matrix elements corresponding to the pole s-, t-, and u-channel diagrams:

$$M^{(s)} = e\varepsilon_\mu(2p+q)^\mu \frac{1}{s-m_{\rm He}^2} U_\rho^*(p_1)U^{*\sigma}(p_2) \times$$
$$\times\, G_\sigma^\rho(p;p_1,p_2),$$
$$M^{(t)} = e_1\varepsilon_\mu F_\beta^{\mu\rho}(q,p_1',p_1)\frac{1}{t-m_d^2}U_\rho^*(p_1)U^{*\sigma}(p_2)\times$$
$$\times\, G_\sigma^\beta(p;p_1',p_2),$$
$$M^{(u)} = e_2\varepsilon_\mu F_\sigma^{\mu\beta}(q,p_2',p_2)\frac{1}{u-m_d^2}U_\rho^*(p_1)U^{*\sigma}(p_2)\times$$
$$\times\, G_\beta^\rho(p;p_1,p_2'),$$

where $s=(q+p)^2$, $t=(p_1-q)^2$, $u=(p_2-q)^2$ are the Mandelstam variables, m_d and $m_{\rm He}$ are the deuteron and helium nucleus masses, respectively, and $p'=p+q$.

The matrix element, which corresponds to the contact diagram, is presented in the integral form:

$$M^{(c)} = e\varepsilon_\mu U_\rho^*(p_1)U^{*\sigma}(p_2)\times$$
$$\times\left(\int\limits_0^1 \frac{d\lambda}{\lambda}\frac{\partial}{\partial q_\mu} e_1 G_\sigma^\rho\,(p'-q\lambda;p_1-q\lambda,p_2) + \right.$$
$$\left. + \int\limits_0^1 \frac{d\lambda}{\lambda}\frac{\partial}{\partial q_\mu} e_2 G_\sigma^\rho\,(p'-q\lambda;p_1,p_2-q\lambda)\right).$$

In the above-mentioned model, the full amplitude of the process ^{4}He$(\gamma,{\rm d})$d is determined by the following sum: $M^{(s)}+M^{(t)}+M^{(u)}+M^{(c)}$. A differential and total cross-sections were calculated by the substitution the full amplitude into Eq. (2).

Figure 4 shows the angular dependence of the differential cross section of the process ^{4}He$(\gamma,{\rm d})$d at photon energies in the lab system $E_\gamma = 40$ MeV in the case where a γ-quantum is linearly polarized. The qualitative description of the experimental angular distribution was obtained: the correct location of the cross-section minimum at $\upsilon = 90°$ and maxima at $\upsilon = 45°$, and 135°.

The quadrupole transition can be investigated by analyzing the differential cross-section at angles $\upsilon = 0°$, 90°, and 180°. The thorough study of the nature of the dipole transition will be presented in the following section.

3. ^{4}He$(\gamma,{\rm p})$T and ^{4}He$(\gamma,{\rm n})^3$He Reactions

To estimate the differential cross-section of the processes ^{4}He$(\gamma,{\rm N})$T, where N is a nucleon (either p or n) and T is either ^{3}He or ^{3}H, we have to write down the corresponding matrix element. It equals

$$M = e\varepsilon_\mu \bar{u}(N)\sum_{i\,=\,s,t,u,c} M^{\mu(i)}\nu(T),\, \nu(T) = C\bar{u}^T(T),$$

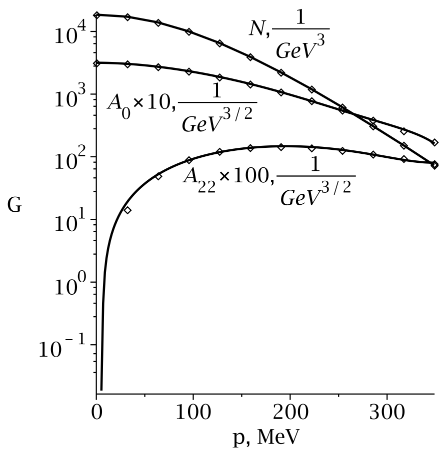

Fig. 3. S-, D-waves, and the momentum distribution approximation for the Urbana function

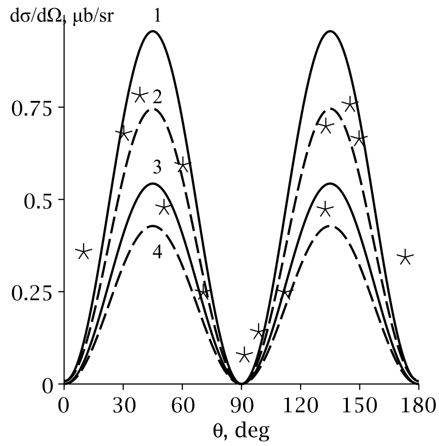

Fig. 4. ^{4}He$(\gamma,{\rm d})$d differential cross section at $E_\gamma = 40$ MeV, solid lines take the contact part into account, dash lines don't take the contact part into account, curves *1, 2* were calculated, by using the Argonne parametrization, curves *3, 4* were calculated, by using the Urbana parametrization, and * – experimental data [24]

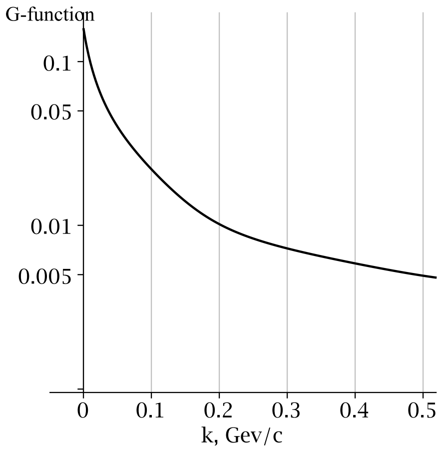

Fig. 5. Energy dependence of a G-function

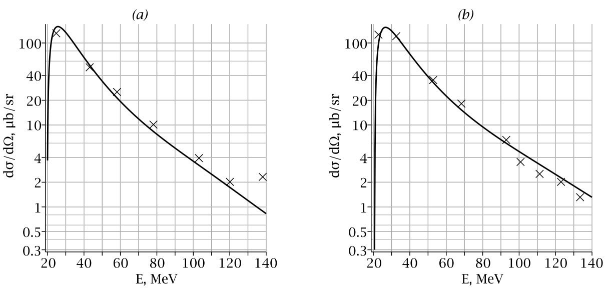

Fig. 6. Dependence of the differential cross section ^{4}He(γ, p)T (a) and ^{4}He$(\gamma, \mathrm{n})^3$He (b) on the photon energy at angles $\upsilon = 90°$. $\times$ – experimental data [25]

where:

$$M^{\mu(s)} = e\frac{(p+p')^\mu}{s-m_{\mathrm{He}}^2}G^{(s)}\gamma_5,$$

$$M^{\mu(t)} = j^{\mu(t)}\frac{(\hat{N}'+m_{\mathrm{N}})}{t-m_{\mathrm{N}}^2}G^{(t)}\gamma_5,$$

$$M^{\mu(u)} = G^{(t)}\gamma_5\frac{(\hat{T}'-m_{\mathrm{T}})}{u-m_{\mathrm{T}}^2}j^{\mu(u)},$$

$$M^{\mu(c)} = \int_0^1 \frac{d\lambda}{\lambda}\frac{\partial}{\partial q_\mu}\{z_{\mathrm{N}}G[-k_{st}^2] + z_{\mathrm{T}}G[-k_{su}^2]\}\gamma_5,$$

$\mathrm{q}, \mathrm{p}, \mathrm{N}$, and T are 4-momenta of a γ-quantum, ^{4}He, a nucleon, and a nucleus T, respectively. Electromagnetic currents were defined in a standard way: $j^{\mu(t)} = (z_{\mathrm{N}} + k_{\mathrm{N}}\hat{k})\gamma^\mu$, $j^{\mu(u)} = (z_{\mathrm{T}} + k_{\mathrm{T}}\hat{k})\gamma^\mu$, where $z_{\mathrm{N}}(z_{\mathrm{T}})$ and $k_{\mathrm{N}}(k_{\mathrm{T}})$ are the charge and the anomalous magnetic moment of a particle $N(T)$; z_{H} is the charge of ^{4}He.

The relative four-momenta that characterize the vertex ^{4}He $\rightarrow$ NT in the pole diagrams are as follows:

$$k_s = N - \frac{(Np')}{p'^2}p' = \frac{(Tp')}{H'^2}p' - T,$$

$$k_t = k_s - \frac{(Tp')}{p'^2}q, \quad k_u = k_s + \frac{(Np')}{p'^2}q.$$

The quantities $k_{st}(\lambda)$ and $k_{su}(\lambda)$ are defined as

$$k_{st}(\lambda) = k_s - \lambda\frac{(Tp')}{p'^2}q, \quad k_{su}(\lambda) = k_s + \lambda\frac{(Np')}{p'^2}q.$$

The vertex functions $G^{(i)} \equiv G(-k_i^2)$, $(i = s, t, u)$ depend on the appropriate four-momentum. They describe the virtual collapse of ^{4}He into NT and, due to the relativistic invariance, depend on the square of the relative four-momentum.

It is also should be noted that, in the case where $G^{(s)} = G^{(t)} = G^{(u)} = \mathrm{const}$, we have $M^{\mu(c)} = 0$. Therefore, the sum of pole diagrams is a gauge-invariant quantity.

We parametrize our vertex function on the basis of work [23]. This step allows us to determine all necessary quantities. Figure 5 shows the parametrization of G as a function of the relative momentum of fragments.

As soon as all quantities were defined, we made calculations and compared them with experimental data without changing any previously fixed variables. Figure 6 shows the dependence of the differential cross-section ^{4}He(γ, N)T on the photon energy at the angle $\upsilon = 90°$(E is a photon energy in the lab system). The obtained data fits well experimental ones. According to the results, the standard row of pole amplitudes should be supplemented with an additional mechanism, namely the regular part of the amplitude, to better describe the processes under study. Practically at all photon energies, the regular part is essential.

Figure 7 presents six pairs of the angular spectra at fixed energies. The experimental angular distributions are well described by this model in any considered energy interval.

In Fig. 8, the solid line indicates the dependence of the total cross sections for the reactions ^{4}He(γ, N)T on the photon energy in the interval from 20 to 44 MeV taking all the diagrams into consideration. The dash-dotted and dotted lines describe the account for pole diagrams and the regular one, respectively.

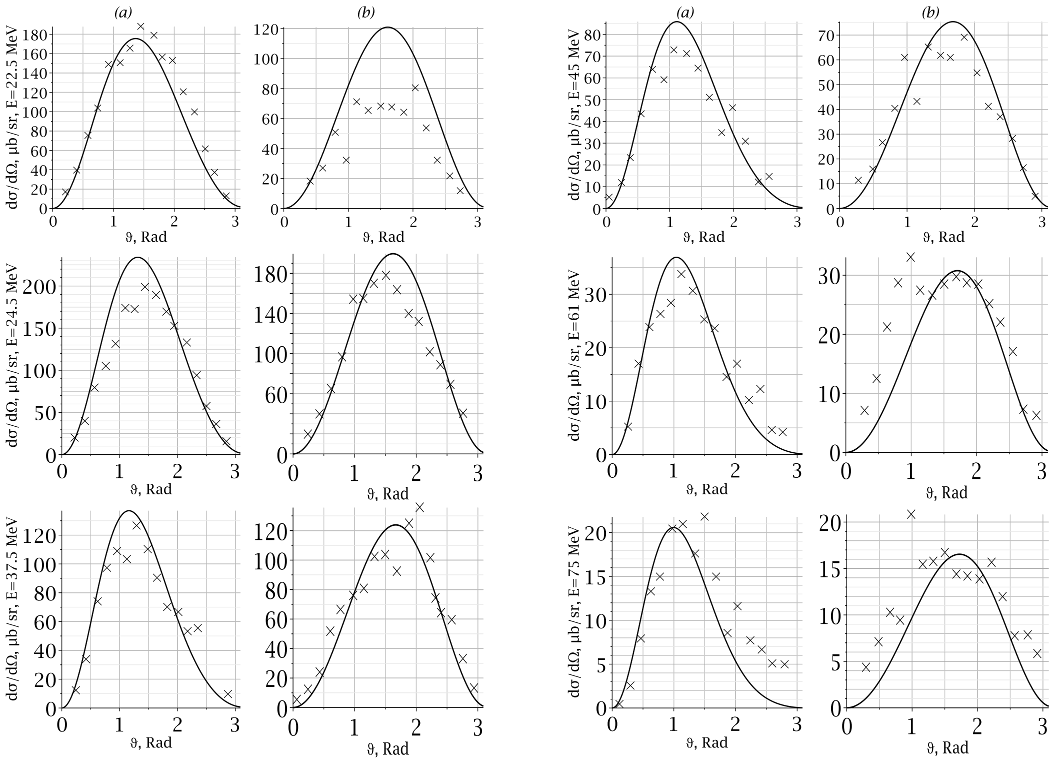

Fig. 7. Angular dependence of the differential cross sections for the reactions ^{4}He(γ, p)T (a) and ^{4}He$(\gamma, \mathrm{n})^3$He (b) in the energy interval from $E_\gamma = 22.5$ to 75.0 MeV. $\times$ – experimental data [25]

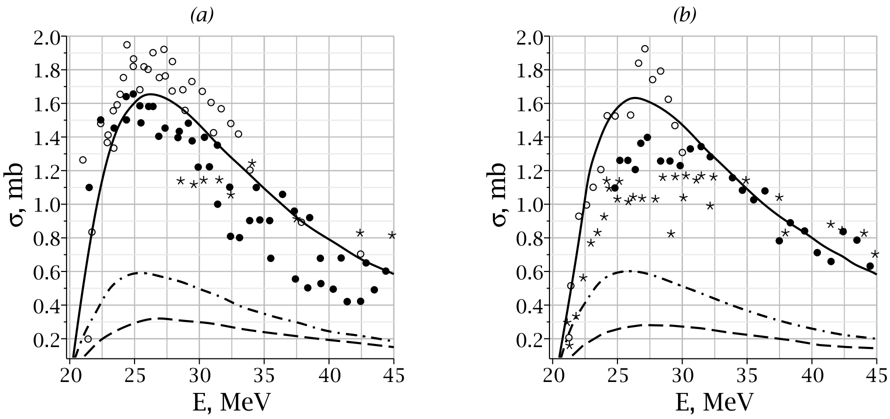

Fig. 8. Dependence of the total cross sections for the reactions ^{4}He(γ, p)T (a) and ^{4}He$(\gamma, \mathrm{n})^3$He (b) on the photon energy in the interval from 20 to 44 MeV. Experimental data are from [26]

It is evident that the required agreement with experimental data can be achieved only if we consider both inputs. Accounting only the pole diagrams does not provide an adequate description of experimental data.

4. Conclusion

We have attained the high-quality theoretical description of the two-particle photodisintegration processes of He-4, using a minimal number of parameters. The performed calculations and comparisons with experimental results have shown that a generalization of the Feynman rules for the description of photonuclear processes works well. The alternative approach to the theory describing the electromagnetic processes in compound systems allowed us to reproduce the results without any problems. The special role was given to the construction of the regular part of the amplitude, which determines the gauge-closed matrix element. This means that the structure of the matrix element has been adapted to the description of various processes. These elements satisfy the requirements of covariance and the fundamental requirement of gauge symmetry.

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ДВОЧАСТИНКОВЕ ФОТОРОЗЩЕПЛЕННЯ ^{4}He: ^{4}He$(\gamma, d)d$, ^{4}He$(\gamma, p)T$, ^{4}He$(\gamma, n)^3$He

Р е з ю м е

Підраховано диференціальний перетин реакцій двочастинкового фоторозщеплення ^{4}He, використовуючи коваріантну діаграмну техніку та концепцію ядра як елементарної частинки. Єдиним функціональним параметром була структурна вершинна функція, яка описує "колапс" ядра ^{4}He на нуклони-залишки. Взаємодія реальних фотонів визначалась значенням зарядів частинок, в той час як електромагнітні форм-фактори було підраховано у фотонних точках. Закони збереження енергії-імпульсу та заряду протягом взаємодії було виконано за рахунок властивості невіддільності електричного заряду від маси елементарної частинки. Таким чином, вимога калібрувальної симетрії виконувалась автоматично. Коваріантна амплітуда процесу дорівнювала сумі полюсних діаграм та регулярної частини, яку було додано щоб задовольнити вимогу збереження електромагнітного току.