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# $^4He(\gamma,d)d$ and $^3He(\gamma,p)d$ reactions in nonlocal covariant model

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**Abstract.** Photonuclear reaction research is of great interest to obtain information about the structure of nuclei. The investigation of structural effects requires certain insights into the reaction mechanisms, that have to be identified on the basis of the fundamental principles of covariance and gauge invariance. The major achievement of the chosen model is the ability to reproduce the cross-section dependence using the minimal necessary set of parameters. We analyze the two-particle disintegration of $^3He$ nuclei by photons. Our interest was raised by the fact that $^3He$ is the simplest many-particle system which admits an exact solutions. We also consider the process $^4He(\gamma,d)d$. This process comes at the expense of the quadrupole absorption of γ-rays, while the dipole transition is suppressed. This property is a consequence of the isospin selection as well as the identity of the particles in the final state. Obtained results describe the energy range from threshold (20 MeV) to 140 MeV. Therefore, the model mentioned in the paper has the peculiarity to be valid not only for the low-energy regime, but also for higher energies. Present paper is devoted to determine the roles of different reaction mechanisms and to solve problems above.

## 1 Introduction

All the most important theoretical results obtained in the micro-world studies are strongly limited by the framework of the local quantum-field approach. In papers [3,4] the possibility to involve the non-local matter fields into the standard quantum electrodynamics (QED) was generated. Different observed characteristics of the various photodisintegration reactions ($d(\gamma,p)n$, $^4He(\gamma,p)T$, $^4He(\gamma,n)$ $^3He$) were calculated [5, 6] on the basis of this approach.

The $^4He(\gamma,d)d$ reaction data was carefully described in papers [6,7]. Therefore, we only make a short overview of this process here. The $^4He(\gamma,d)d$ process is characterized by the following fact: the electric dipole moment is suppressed and the process realizes mostly due to a quadrupole γ-ray absorption. This property is caused by the isospin selection and by the identity of the particles in the final state.

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The two-particle $^3He$ splitting reaction has been attracting the attention of theoreticians and experimentalists for a sufficiently large period of time. The interest was caused by the fact that $^3He$ is the simplest "many-particle" system. Moreover, this system admits an exact solution. Also, $^3He$ has simple electromagnetic (EM) interaction, therefore the perturbation theory is applicable.

The early theoretical works [1,2] are describing the structure of three-nucleon systems with the help of phenomenological wave functions or with the help of Fadeev equation solutions with simple non-realistic potentials. This approach is acceptable only for low-energy processes, while the approach we use is good for much bigger energies also. It's interesting that research of the processes with photons and electrons were held separately. Despite the fact that in this work we present the results only for reactions with photons, the developed approach gives the possibility to calculate the reactions with photons and electrons simultaneously.

Therefore, despite the numerous theoretical researches, we have a number of unsolved questions about the photodisintegration of three-nucleon systems. Thus, in some papers there is no maximum of differential cross section at $\theta = 90°$ and $E_\gamma \sim 11 MeV$, whose value due to experimental data is 90-120$\mu b/sr$. For example, in paper [8] $\frac{d\sigma}{d\Omega}(\theta = 90°)_{max} \leq 80\mu b/sr$. In other papers, the description of the differential cross section maximum is made with the help of final state interaction (FSI). Assuming these conclusions, we can state about the important role of FSI. But in paper [10], accounting only pole set of diagrams and the contact part, a $\frac{d\sigma}{d\Omega}(\theta = 90°)_{max} \sim 100\mu b/sr$ was achieved. It is a very interesting fact, because in the energy range of differential cross section maximum $E_\gamma \sim 11MeV$ the dependence of *NN*-interaction isn't valuable for calculation.

These facts inspired us to make an independent calculations for the reactions $^4He(\gamma, d)d$ and $^3He(\gamma, p)d$.

## 2 $^3He(\gamma, p)d$ and $^3He(\gamma, p)d$ reactions

We consider reaction $T + \gamma \rightarrow p + d$, where $T(T_0, \boldsymbol{T})$ is 4-momentum of target nucleus $^3He$ with mass $m_T$, $p(p_0, \boldsymbol{p})$ – detected nucleon with mass $m_N$, $d(d_0, \boldsymbol{d})$ – remnant core, the deuteron with mass $m_d$.

For our reaction differential cross section in the center of mass system is expressed as follows:

$$\frac{d\sigma}{d\Omega_N} = \frac{1}{(8\pi W)^2} \left|\overline{\mathfrak{M}}\right|^2; (1)$$

where $W$ – the total system energy. Matrix element is determined by the well-known expression:

$$\mathfrak{M} = \varepsilon^\mu J_\mu(p; d; T); (2)$$

and $\varepsilon^\mu \varepsilon^*_{\mu'} = -\frac{1}{2} g^\mu_{\mu'}$. The incorporating of the EM field into the bound system of strongly interacting particles was made using the field-theoretic technique. We obtained the following structure of nuclear current:

$$J_\mu(p; d; T') = e\bar{u}(p) \sum_i T^{(i)}_{\mu\nu} u(T') U^{*\nu}(d); (3)$$

where $e$ is elementary charge, $\bar{u}(p)$ and $u(T')$ are the spinor fields, and $U^{*\nu}(d)$ is vector field. Index $i$ runs through the values $i = (s, t, u, c)$. We mark diagrams for the $^3He$ pole ($s-$ chanel),proton pole($t-$chanel), deutron pole($u-$chanel) and the contact part($c-$chanel). Obviously,$U_{\nu'}(d)U^{*\nu}(d) = -(g^\nu_{\nu'} - \frac{d_{\nu'}d^\nu}{m_d^2})$. Amplitudes $T^{(i)}_{\mu\nu}$ are defined for each channel separatly[4].

On the basis of the calculations, we obtained the dependence of the differential cross section from the photon energy and the angle $\theta$. Due to the fact that the only undetermined parameters are the form factors $A(-k_i^2); B(-k_i^2)$ we made several evaluations. First, we have chosen constant form factors for the model calculations. Therefore we obtained a standard form of the differential cross section. The assumption of the contact diagram in the matrix element didn't change the cross section. The reason is

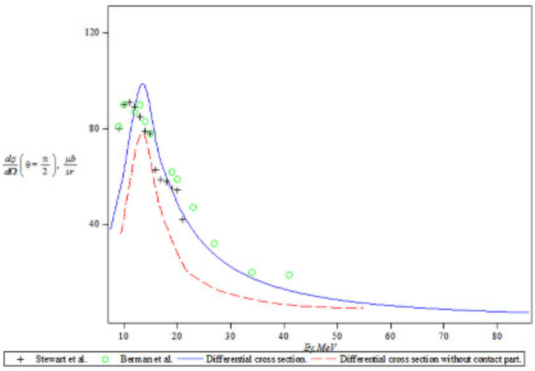


**Figure 1.** Dependence of differential cross section $^3\boldsymbol{He}(\boldsymbol{\gamma},\boldsymbol{p})\boldsymbol{d}$ at θ=90° of photon energy.

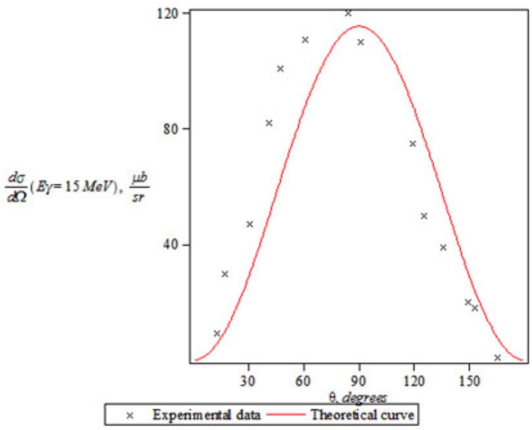


**Figure 2.** Differential cross section of angel θ.

that only accounting of the dynamics at the vertex of the strong interaction gives a significant contribution into the reaction cross section. The explicit form of reaction form-factors was taken from [10].

Figure 1 shows the dependence of differential cross section $^3He(\gamma,p)d$ at $\theta = 90°$ of photon energy. Blue solid line represents the evaluation, using the pole part and the contact part of diagram. Red dashed line represents the evaluation without contact diagram. Obviously, we have a good match with experimental data only if we take into account all diagrams: the pole set and the contact one. Experimental data are taken from [1].

Figure 2 shows the dependence of differential cross section $^3He(\gamma,p)d$ at photon energy 15 MeV of angle $\theta$. Experimental data are taken from [1].

Now, we briefly consider the reaction $^4He(\gamma,d)d$. The $^4He(\gamma,d)d$ 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 a quadruple $\gamma$ −ray absorption. Therefore, this channel helps to study the nature of a quadrupole transition.

The matrix elements, corresponding to the appropriate diagram are defined as follow:

$$M^{(s)} = e\varepsilon_\mu \frac{(2p+q)^\mu}{s - m_{nucl}^2} U_\rho^*(p_1) U_\sigma^*(p_2) G_{\rho\sigma}(p'; p_1, p_2); \ (4)$$

$$M^{(t)} = e_1 \varepsilon_\mu F_{\beta\rho}^\mu(q, p_1', p_1) \frac{1}{t - m^2} U_\rho^*(p_1) U_\sigma^*(p_2) G_{\beta\sigma}(p; p_1', p_2); \ (5)$$

$$M^{(u)} = e_2 \varepsilon_\mu F_{\beta\rho}^\mu(q, p_2', p_2) \frac{1}{u - m^2} U_\rho^*(p_1) U_\sigma^*(p_2) G_{\beta\rho}(p; p_1, p_2'); (6)$$

$$M^{(c)} = e\varepsilon_\mu U_\rho^*(p_1) U_\sigma^*(p_2) \times$$

$$\times \int_0^1 \frac{d\lambda}{\lambda} \frac{\partial}{\partial q^\mu} \left[ e_1 G_{\rho\sigma}(p' - q\lambda; p_1 - q\lambda, p_2) + e_2 G_{\rho\sigma}(p' - q\lambda; p_1, p_2 - q\lambda) \right]; \ (7)$$

Fig. 3 shows a differential cross section angular dependence of the process $^4He(\gamma,d)d$ at photon energies in lab system $E_\gamma = 40$MeV for the case when a $\gamma$ −quantum is linearly polarized. A qualitative description of the experimental angular distribution was obtained: the correct location of the cross-section minimum at $\theta = 90°$ and maximums at $\theta = 45°, 135°$.

## 3 Conclusions

Present paper contains the results of covariant investigation of the reaction of the two-particle splitting of $^3He$. We have briefly described the results for $^4He(\gamma, d)d$. The role of contact diagram was investigated. It was shown that only accounting contact diagram provides an adequate agreement with the experimental data. Moreover, we claim that only the accounting of the dynamics at the vertex of the strong interaction gives a significant contribution into the reaction cross section. An exact conservation of the total nuclear current was achieved. We plan to carry out the calculations of the reaction $e + {}^3He \to e' + p + d$ on the basis of developed approach.

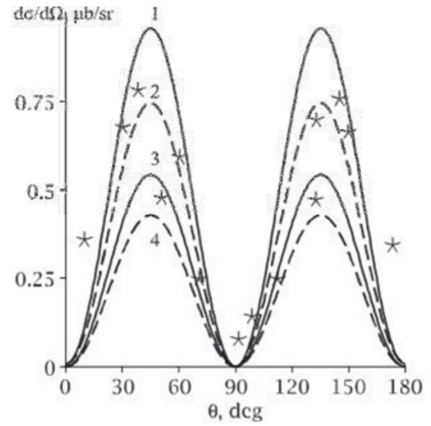


**Figure 3.** $^4\boldsymbol{He(\gamma, d)d}$ differential cross section at $\boldsymbol{E_\gamma = 40}$MeV, solid lines take into account a contact part, dash lines don't take into account a contact part, curves 1, 2 were calculated using the Argonee parametrisation, curves 3, 4 were calculated using the Urbana parametrisation, * - experimental data [9]

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