OFF-SHELL EFFECTS IN ELECTROMAGNETIC INTERACTION WITH BOUND NUCLEONS

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Off-energy-shell effects in one- and two-nucleon photoabsorption are studied in the reaction $\gamma\,{}^3He \to pd$ at intermediate energies. The calculations are carried out with the ^{3}He wave functions for the Bonn and Paris potentials.

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1. INTRODUCTION

Uncertainties due to the off-shell effects in the cross section of the electron scattering off a bound nucleon were discussed in 1,2. Large efforts were made to understand the role of the off-shell effects in the production of electron-positron pairs in the virtual Compton scattering on the proton 3, the proton-proton bremsstrahlung 4, the Compton scattering on the nucleon 5, the deuteron photo- 6 and electrodisintegration 7-8, the elastic scattering of electrons off ^{3}He 9, the two-body ^{3}He photodisintegration 10,11. Detailed discussion of the problems in the theory of EM interaction with the off-shell particles and references to previous work can be found in 12,13.

Articles 14-15 contribute to the theory of EM interaction with off-mass-shell particles. The origin of the off-energy-shell (OES) effects in the framework of the theory with the on-mass-shell particles can be clarified within approach 16,17,18 based on Fukuda-Sawada-Taketani-Okubo transformation. OES modifications were introduced into the single-nucleon current in 19,20,21-22. Two-body interaction currents taking into account OES corrections were constructed in 23 using model 24 of the pion-exchange currents (πEC). It was shown 25,26 that due to the OES effects the relative role of the two-nucleon mechanisms generated by the pion exchange could be visibly reduced in $\gamma^3\mathrm{He} \to \mathrm{pd}$ at $\mathrm{E}_\gamma \square 200\,\mathrm{MeV}$.

Mechanisms of ^{3}He photodisintegration and proton-deuteron radiative capture are intensively studied both below 27-28 and above 29,30,31,32,33-34 the pion production threshold. A considerable progress has been made, in particular, in the region of photon energies $\mathrm{E}_\gamma \square 140\,\mathrm{MeV}$, where the interaction currents and rescattering effects were treated simultaneously 35 -36. The meson exchange currents (MEC) were demonstrated to bring important contributions to the differential cross sections and the polarization observables.

The interaction currents are included implicitly in 37-38 via the extended Siegert theorem and explicitly in 39,40,41,42,43,44,45-46. While rescattering in the pd-system has been taken into account in 47-48, investigations 49,50,51,52,53-54 have been performed in the plane-wave approximation. The techniques to treat the MEC in calculations with the exact solutions of the Faddeev-like equations for the initial and final states have been elaborated in 55. Approach 56 is based on the multipole and partial-wave decompositions. A distinguishing feature of 57,58,59,60,61 is the use of vector variables following 62,63.

Aim of the present report is to improve and to detail model of πEC 64 that embodies the OES corrections. Other purpose of the paper is to study influence of the OES effects in one- and two-nucleon photoabsorption on observables in the reaction $\gamma\,{}^3He \to pd$ taking advantage on the precise numerical solutions of the Faddeev equations for the 3N bound state obtained in 65-66 with the realistic NN potentials.

2. MODEL OF THE NUCLEAR CURRENT

In the present calculations we take into account one- and two-nucleon contributions to the nuclear current $J_\mu(x) = J_\mu^{[1]}(x) + J_\mu^{[2]}(x)$, where

$$J^{[1]}(x) = \sum_{\alpha} J(x;\alpha) \quad \text{and} \quad J^{[2]}(x) = \sum_{\alpha<\beta} J(x;\alpha\beta).$$

Various approaches are used to derive a construction for the one-nucleon current $J(x;\alpha)$ (for discussion see, e.g., 67,68,69,70-71. The current of interest can be obtained from the expression for the matrix element

$$\langle p'|J^\mu(0;\alpha)|p\rangle = \bar{u}'(p')\Gamma^\mu \bar{u}(p), \tag{1}$$

where p^μ and p'^μ are momenta of the nucleon with the label α, for instance, $p^\mu = \left(E_{\vec{p}}, p\right)$. The spin indices are omitted for brevity. For the nucleons on the mass shell, i.e., $p_\mu{}^2 = E_p^2 - p^2 = M_N^2$, and $p_\mu'^2 = M_N^2$ the γNN vertex function Γ^μ has the form 72-73

$$\Gamma^\mu(p',p) = F_1\left((p'-p)_\lambda^2\right)\gamma^\mu + \\ + \frac{1}{2M_N} F_1\left((p'-p)_\lambda^2\right) i\sigma^{\mu\nu}(p'-p)_\nu, \tag{2}$$

where $\sigma^{\mu\nu}$ denotes the commutator of the γ-matrices and M_N is the nucleon mass. The vertex function depends on the Dirac and Pauli form factors (FFs), F_1 and F_2, with the arguments belonging to the space-like region since for the on-mass-shell nucleons $(p'-p)_\mu^2 \le 0$.

Taking into account that the spinors $u'(p')$ and $u(p)$ obey the Dirac equation one can get a representation of current (1),(2) that is convenient for the use in the calculations with the nuclear wave functions expressed in terms of the two-component Pauli spinors.

Following 74-75 we keep the arguments of the EM FFs as $(p'-p)_\mu^2 = (E_{\vec{p}'} - E_{\vec{p}})^2 - (p'-p)^2$. As far as three-momentum is conserved in the intermediate states within the framework of the theory with the nucleons on the mass shell, one has $(p'-p)_\mu^2 = (E_{\vec{p}'} - E_{\vec{p}})^2 - Q^2$. The vector $(p'-p)^\mu$ cannot be replaced by the four-momentum transfer $Q^\mu = (\omega, Q)$ in the general case since $E_{\vec{p}'} - E_{\vec{p}} \ne \omega$.

The current is expanded in powers of (p/M_N). For example, the lowest order in (p/M_N) for the Fourier transform of the charge density reads

$$\left\langle p' \left| \rho^{[1]}(\vec{Q}) \right| p \right\rangle = \\ = \delta(\vec{p}' + \vec{p} - \vec{Q}) F_1((E_{\vec{p}+\vec{Q}} - E_{\vec{p}})^2 - \vec{Q}^2). \qquad (3)$$

For the next terms in the (p/M_N) expansion of the one-body current we refer, e.g., to 76,77-78.

One can decompose the arguments of the FFs

$$(p'-p)_\mu^2 = -Q^2(1 - (n \cdot (p'+p)/(2M_N)) + \ldots), \qquad (4)$$

where the unit vector $n = Q/|Q|$. Nevertheless, we retain the arguments in the form of Eq. (4) to derive the expressions for the two-body currents.

Approximating $(p'-p)_\mu^2 \approx -Q^2$ we get the prescription of Ref. 79, where the nonrelativistic limit of the Dirac current was suggested to include the FFs $F_i(-Q^2)$.

It is worth noting that constructions for the one-body current 80 that are obtained with the help of the Foldy-Wouthuysen transformation applied to the Dirac equation for a nucleon in an external EM field contain $F_i(Q_\mu^2)$.

Two-nucleon interaction currents satisfy the continuity equation $[V, \rho^{[1]}] = Q \cdot J^{[2]}$, where V is the nucleon-nucleon potential. We restrict our treatment by the contributions to the current $J^{[2]}$ generated by the pion exchange. The respective part of the potential is given by the one-pion-exchange interaction. For the matrix elements one has

$$\left\langle p'_\alpha p'_\beta \left| V(\alpha\beta) \right| p_\alpha p_\beta \right\rangle = \delta(k_\alpha + k_\beta) V(\tfrac{1}{2}(k_\alpha - k_\beta); \alpha\beta),$$

where

$$V(k;\alpha\beta) = -\sigma(\alpha) \cdot k_\alpha\, \sigma(\beta) \cdot k_\beta\, v_\pi(k)\, \tau(\alpha) \cdot \tau(\beta), \qquad (5)$$

$$v_\pi(k) = \frac{1}{2\pi^2} \frac{f_{\pi NN}^2}{m_\pi^2} \frac{1}{m_\pi^2 + k^2} F_{\pi NN}^2(k^2), \qquad (6)$$

p_α is the momentum of the α-th nucleon, $k_\alpha = p'_\alpha - p_\alpha$, $k_\alpha = p'_\alpha - p_\alpha$, $f_{\pi NN}$ is the pseudovector πN coupling constant, m_π is the pion mass, $\sigma(\alpha)$ $(\tau(\alpha))$ denotes the Pauli vector in the spin (isospin) space of particle α. For the πNN FF $F_{\pi\text{NN}}(k^2)$ we use the parametrization in the monopole form $F_{\pi\text{NN}}(k^2) = (\Lambda_\pi^2 - m_\pi^2)/(\Lambda_\pi^2 + k^2)$, where Λ_π is the cut-off parameter.

To meat the requirements imposed by the continuity equation, when the charge density is chosen in the form of Eq. (3) and NN interaction is given by Eq. (5), pion exchange currents should consist 81 of the following terms

$$J(\vec{Q};\alpha\beta) = J^{iv}(\vec{Q};\alpha\beta) + J^{iv'}(\vec{Q};\alpha\beta) + J^{is}(\vec{Q};\alpha\beta),$$

where $J(\vec{Q};\alpha\beta)$ is the Fourier transform of the current $J(x;\alpha\beta)$, the isovector currents $J^{iv}(\vec{Q};\alpha\beta) \sim$ $\sim \mathrm{i}[\tau(\alpha) \times \tau(\beta)]_z$, $J^{iv'}(\vec{Q};\alpha\beta) \sim \tau_z(\alpha), \tau_z(\beta)$ and the isoscalar current $J^{is}(\vec{Q};\alpha\beta) \sim \tau(\alpha) \cdot \tau(\beta)$. For the current

$$\left\langle \vec{p}'_\alpha \vec{p}'_\beta \left| J(\vec{Q};\alpha\beta) \right| \vec{p}_\alpha \vec{p}_\beta \right\rangle = \\ = \delta(\vec{k}_\alpha + \vec{k}_\beta - \vec{Q}) J(\vec{p}'_\alpha, \vec{p}'_\beta, \vec{p}_\alpha, \vec{p}_\beta; \alpha\beta),$$

the leading (p/M_N) order can be derived form the corresponding expressions 82.

In the case when the approximation $(p'-p)_\mu^2 \approx -Q^2$ is used for the arguments of the EM FFs, model 83 yields

$$J(Q;\alpha\beta) = J^s(Q;\alpha\beta) + J^\pi(Q;\alpha\beta), \qquad (7)$$

with

$$J^{s,\pi}(p'_\alpha, p'_\beta, p_\alpha, p_\beta; \alpha\beta) = J^{s,\pi}(k_\alpha, k_\beta; \alpha\beta) \qquad (8)$$

like the original currents. The seagull and pion-in-flight currents are

$$J^s(\vec{k}_\alpha, \vec{k}_\beta; \alpha\beta) = \mathrm{i}[\tau(\alpha) \times \tau(\beta)]_z F_1^{\mathrm{v}}(-Q^2) \times \\ \times (-\vec{\sigma}(\alpha)\vec{\sigma}(\beta) \cdot \vec{k}_\beta\, v_\pi(k_\beta) + \vec{\sigma}(\beta)\vec{\sigma}(\alpha) \cdot \vec{k}_\alpha\, v_\pi(k_\alpha)) \qquad (9)$$

and

$$J^\pi(\vec{k}_\alpha, \vec{k}_\beta; \alpha\beta) = \mathrm{i}[\tau(\alpha) \times \tau(\beta)]_z F_1^{\mathrm{v}}(-Q^2) \times \\ \times (\vec{k}_\alpha - \vec{k}_\beta)\vec{\sigma}(\alpha) \cdot \vec{k}_\alpha\, \vec{\sigma}(\beta) \cdot \vec{k}_\beta \times \qquad (10) \\ \times (v_\pi(k_\beta) - v_\pi(k_\alpha))/(k_\alpha^2 - k_\beta^2).$$

An extension of model (7), (9), (10) can be cast into the form

$$J_{OS}(\vec{Q};\alpha\beta) = \\ = J_{OS}^{s,mi}(\vec{Q};\alpha\beta) + J_{OS}^{\pi,mi}(\vec{Q};\alpha\beta) + J_{OS}^{\pi,md}(\vec{Q};\alpha\beta). \qquad (11)$$

The currents

$$J_{OS}^{s,mi}(\vec{Q};\alpha\beta) = \mathrm{i}[\tau(\alpha) \times \tau(\beta)]_z \times \\ (-\vec{\sigma}(\alpha)\vec{\sigma}(\beta) \cdot \vec{k}_\beta\, F(\alpha) v_\pi(k_\beta) + \qquad (12) \\ + \vec{\sigma}(\beta)\vec{\sigma}(\alpha) \cdot \vec{k}_\alpha\, F(\beta) v_\pi(k_\alpha)),$$

$$
\begin{aligned}
J_{OS}^{\pi,mi}(Q;\alpha\beta) = {} & \mathrm{i}[\tau(\alpha)\times\tau(\beta)]_z \times \\
& \times (k_\alpha - k_\beta)\,\sigma(\alpha)\cdot k_\alpha\,\sigma(\beta)\cdot k_\beta \times \\
& \times (F(\alpha)v_\pi(k_\beta) - F(\beta)v_\pi(k_\alpha))/(k_\alpha^2 - k_\beta^2)
\end{aligned}
\qquad (13)
$$

satisfy the continuity equation with the charge density (3) and NN interaction (5). According to 84 one can reckon these currents among “model independent” ones since the structure of the currents is determined by the requirement of current conservation entirely. The EM FFs appear in the expressions for the currents in the superposition

$$
\begin{aligned}
F(\alpha) = {} & \tfrac{1}{2}(F_1^V((E_{\vec{p}'_\alpha} - E_{\vec{p}'_\alpha - \vec{Q}})^2 - \vec{Q}^2) + \\
& + F_1^V((E_{\vec{p}_\alpha + \vec{Q}} - E_{\vec{p}_\alpha})^2 - \vec{Q}^2)),
\end{aligned}
$$

where F_1^V is the isovector FF of the nucleon.

The transverse current

$$
\begin{aligned}
J_{OS}^{\pi,md}(Q;\alpha\beta) = {} & \mathrm{i}[\tau(\alpha)\times\tau(\beta)]_z \times \\
& \times (k_\alpha - k_\beta)_{transv}\,\sigma(\alpha)\cdot k_\alpha\,\sigma(\beta)\cdot k_\beta \times \\
& \times \tfrac{1}{2}(F(\alpha) - F(\beta))(v_\pi(k_\beta) + v_\pi(k_\alpha))/(k_\alpha^2 - k_\beta^2)
\end{aligned}
\qquad (14)
$$

is not constrained by the continuity equation and is in a certain sense “model dependent”. The r.h.s. of Eq. (14) contains the transverse component of the vector defined as $\vec{A}_{transv} = [n\times[\vec{A}\times n]]$. One has $J_{OS}^{\pi,md}(Q;\alpha\beta) = 0$ when the arguments of the EM FFs are taken to be $-Q^2$ or Q_μ^2.

Current (14) is introduced with the aim to compensate the singularity in $(J_{OS}^{\pi,mi}(Q;\alpha\beta))_{transv}$ that springs from the factor $1/(k_\alpha^2 - k_\beta^2)$. As a result one has

$$
\begin{aligned}
(J_{OS}^{\pi,mi}(Q;\alpha\beta) + {} & J_{OS}^{\pi,md}(Q;\alpha\beta))_{transv} = \\
= {} & \mathrm{i}[\tau(\alpha)\times\tau(\beta)]_z\,\tfrac{1}{2}(F(\alpha) + F(\beta))\times \\
& \times (k_\alpha - k_\beta)_{transv}\,\sigma(\alpha)\cdot k_\alpha\,\sigma(\beta)\cdot k_\beta \times \\
& \times (v_\pi(k_\beta) - v_\pi(k_\alpha))/(k_\alpha^2 - k_\beta^2),
\end{aligned}
\qquad (15)
$$

where $(k_\alpha - k_\beta)_{transv} = 2(k_\alpha - n(n\cdot k_\alpha))$. Expression (15) is free from singularities similar to Eq. (10).

As the representation

$$
\begin{aligned}
(J_{OS}^{\pi,mi}(Q;\alpha\beta))_{long} = {} & \mathrm{i}[\tau(\alpha)\times\tau(\beta)]_z \times \\
& \times n/|Q|\,\sigma(\alpha)\cdot k_\alpha\,\sigma(\beta)\cdot k_\beta \times \\
& \times (F(\alpha)v_\pi(k_\beta) - F(\beta)v_\pi(k_\alpha))
\end{aligned}
$$

indicates, the longitudinal component of current (13) has no singularities either. For any vector one has $A_{long} = n(n\cdot A)$.

Currents (10) and (15) have much in common. On the other hand, feature (8) is lost in model of πEC (11)-(15) consistent with charge density (3). If the arguments of the EM FFs in (11)-(15) are substituted by Q_μ^2, constructions 85 for the πEC will be recovered.

3. RELATIVE ROLE OF THE OFF-ENERGY-SHELL EFFECTS IN THE ^{3}He TWO-BODY PHOTODISINTEGRATION

To study the role of the OES effects in the reaction $\gamma + {}^3\mathrm{He} \rightarrow p + d$ the construction of convection and spin currents (CC and SC) from 86,87 and model (7)-(10) of πEC are used. For the nucleon EM FFs the dipole parametrization and the scaling rule 88,89 are taken. The calculations have been performed with the Bochum – Cracow wave functions (WFs) for 3N bound state obtained 90-91 for the Bonn and Paris potentials. The rescattering effects in the final pd-state are neglected. The reaction amplitudes are computed within approach 92, 93,94 that allows us do not apply any multipole decompositions for the nuclear current.

As is demonstrated in Fig. 1, the OES corrections in the nuclear current affect the differential cross section σ at $E_\gamma > 175\,\mathrm{MeV}$, compensating contributions of the πEC and decreasing the σ values. At $E_\gamma \sim 200\,\mathrm{MeV}$, variations of the cross section due to OES effects and changes caused by increase of the cut-off parameter Λ_π from 750 MeV/c up to 1.2 GeV/c are of the same order in magnitude. The observed dependencies indicate importance of treatment of the OES effects.

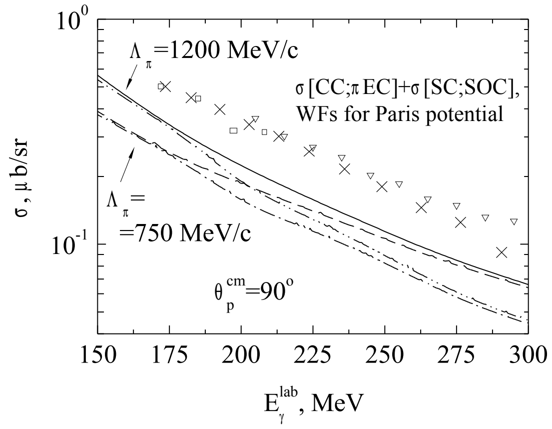

Fig. 1. *Energy dependences of the differential cross section for $\gamma\,{}^3He \rightarrow pd$. Influence of the off-energy-shell effects is displayed by the dash-dotted and dash-dot-dotted curves. The experimental points ″, C and ▯ are taken from 95,96 and 97, respectively*

The detailed analysis reveals that the substitution $(\mathrm{p'} - \mathrm{p})_\mu^2 \rightarrow -\mathrm{E}_\gamma^2$ in the arguments of the nucleon EM FFs is not a very rough approximation. Nevertheless, The substitution is not well justified at forward and backward angles θ_p of proton emission. It should be stressed, that in studying the processes with real photons the EM FFs of nucleons are usually taken at point $Q_\mu^2 = 0$.

The approximated expressions can be factorized taking the EM FF out from the nuclear overlap integrals. This transformation allows one to explain an observation that the cross section asymmetry coefficient Σ for the reaction $\gamma + {}^3He \rightarrow p + d$ with linearly polarized photons is insensitive to the OES effects at least under the conditions when the πEC play an important role. Really, since the polarization observables, in particular, the photon asymmetry, are given by a ratio of quadratic forms of the amplitudes, they do not depend on the OES modifications of the nuclear current introduced in the factorized form both in the numerator and in the denominator.

To assess the relative role of the OES effects we demonstrate in Fig. 2 dependence of the differential cross section and the beam asymmetry on the number N_α of the partial-wave component of the 3N bound state wave function included in the calculations and on the choice of the nucleon-nucleon potential.

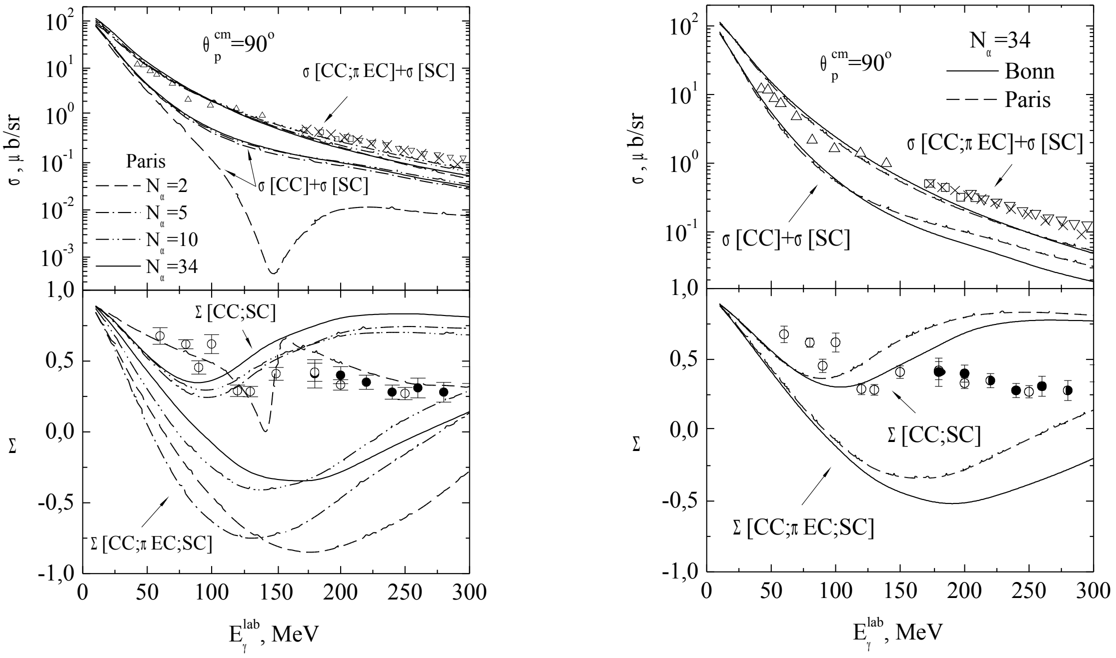

__Fig. 2.__ Energy dependences of the differential cross section for $\gamma\, ^3He \rightarrow pd$ and the asymmetry coefficient for the reaction with linearly polarized photons. Results of the calculations with the Bochum-Cracow WFs for the Bonn and Paris potential are shown. The experimental points □, , □, □, and . are taken from 98,99,100, 101,102-103 and 104, respectively

As is seen from the Fig. 2, the differential cross section $\sigma\,[CC;\pi EC]+\sigma\,[SC]$ is not strongly affected by the WF components when $N_\alpha > 2$, i.e., by the P-, D-, etc. partial waves. The sensitivity of the cross section to the choice of the WFs substantially decreases when πEC are taken into account. In this situation the variation of σ due to OES effects should not be neglected. To reduce the discrepancies between the result of the calculations and the data, especially for the beam asymmetry Σ, the three-nucleon mechanisms of photoabsorption and the rescattering in the final state are to be included.

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