ON THE MESONIC-EXCHANGE CURRENTS IN THE

PHOTOMESIC REACTIONS

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Abstract

The $\gamma d \rightarrow \pi^{\circ} d$ reaction is analysed in the framework of the relativistic many-body theory with mesonic degrees of freedom explicitly present. It is shown that the mesonic correlations can be grouped into transition operators containing vertices of some elementary reactions between photon, nucleons and pions. The wave function corrections due to meson exchange currents are included in the transition operators and the S-matrix is obtained with the non relativistic deuteron wave function.

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The mesonic exchange currents and their role in nuclear reactions involving photons is nowadays largely discussed. The studies concern not only the static properties of few body nuclei, which are traditionally in the focus of interest [1], but also underline the importance of the mesonic degrees of freedom in understanding reaction processes, like electron-scattering on light nuclei [2,3], electro and photodesintegration reactions, or their inverses [4-10], and meson photoproduction on nuclei [11-12]. Such studies are mostly leading to modifications of nuclear form-factors (see, also refs. 13-17), i.e. to the corrections of the non-relativistic nuclear wave function due to the mesons explicitly present. From the dynamics involved in such modifications, and from its non-relativistic reduction, follows the classification of the mesonic exchange current terms into the pair, pionic, recoil and ,recently introduced [18], wave-function reorthonormalization ones.

In the present note, we shall expose the view, that for the photomesic nuclear processes, the problems connected with mesonic-currents correlations do not end up with the modification of nuclear form-factors. In the framework of the relativistic Green's function theory, with mesonic degrees of freedom explicitly written, the mesonic exchange current effects appear simultaneously in the non-relativistic reduction of the "wave function" and in the "transition operator", and only taking together they give the full account of the correlation effects due to the mesons. Moreover, in the particular case of the coherent photoproduction of pions on deuteron :

$$\gamma + d \longrightarrow \pi^{\circ} + d \qquad (1)$$

we shall see that the rearrangement of these different effects is possible and consequently, within a well defined approximation, the mesonic effects are grouped into vertices representing some elementary reactions between nucleon , photon and pion, all these vertices being parts of "transition operators".

In order to demonstrate this conjecture, we shall describe theoretically the reaction (1) using the variational principle's technique of a renormalized quantum field theory, adopted for the description of nuclear reactions by Klein and Zemach [19] and applied to the study of the deuteron photodesintegration by Pearlstein and Klein [20].

With the use of the general procedure which characterizes this approach (see sec.II of ref. (20)), the Green's function containing two fermions, a pion and a photon, can be written in the form :

$$G_{\mu}(12,\xi,\xi') = \int \Delta \;\; G(12)\; R_{\mu}(12,\xi,\xi')\; G(12)\;\; D_{\mu} \qquad (2)$$

where Δ and D_{μ} are the pion and photon propagators, respectively. The two fermion Green's function, G(12), satisfies the integral equation :

$$G(12) = G_1 G_2 + G_1 G_2 \; I(12) \;\; G(12) \qquad (3)$$

with G_i ($i=1,2$) being the single-fermion propagator and $I(12)$ the interaction kernel. By $R_\mu(12,\xi,\xi')$, one denotes the truncated Green's function, i.e. the "transition operator" for the reaction (1). The integration over the intermediated variables is understood.

The S-matrix, obtained by a suitable ordering of the field operators and by an implementation of the adiabatic hypothesis, reads :

$$S_{\gamma d \to \pi d} = \langle d\, k \,|\, S - 1 \,|\, d\, k'_\mu \rangle =$$

$$= i^3 \int \bar{\chi}_d(12)\; \varphi_k(\xi)\; R_\mu(12,\xi,\xi')\; \chi_d(12)\; A_{k'_\mu}(\xi') \tag{4}$$

where $\varphi_k(\xi)$ and $A_{k'_\mu}(\xi')$ are the pion and photon "wave functions", respectively and $\chi_d(12)$ is the relativistic deuteron amplitude, satisfying the homogeneous integral equation :

$$\chi_d(12) = G_1 G_2\, I(12)\, \chi_d(12) \tag{5}$$

The mesonic degrees of freedom explicitly appear through the interaction kernel $I(12)$ and they have to be treated in an analogous manner both in the $\chi_d(12)$ and in the $R_\mu(12,\xi,\xi')$, i.e. in the same degree of approximation.

In order to get the truncated Green's function with the boson fields present, one adds to the original Lagrangian new terms containing the external photon ($J^\mu(x)$) and pion ($K(x)$) sources. The closed expressions are obtained by functional derivations of the original Green's function with respect to these sources which are switched off at the end of the calculation. The Green's function $G_\mu(12,\xi,\xi')$ is given by the expression :

$$i^3 G_\mu(12,\xi,\xi') = \left.\frac{\delta^2 G(12)}{\delta K(\xi)\, \delta J^\mu(\xi')}\right|_{K=J^\mu=0} \tag{6}$$

By applying the rule of functional derivation, which we shall write symbolically as, say $\frac{\delta}{\delta K} = \Delta \frac{\delta}{\delta\phi}$, (ϕ being the pion field, A_μ the photon field), we have :

$$i^3 G_\mu(12,\xi,\xi') = \int \Delta\ G(12) \Big\{ \frac{\delta \Delta^{-1}}{\delta A_\mu} \Delta \frac{\delta G^{-1}(12)}{\delta\phi} - \frac{\delta^2 G^{-1}(12)}{\delta\phi\, \delta A_\mu}$$

$$+ \frac{\delta G^{-1}(12)}{\delta A_\mu} G(12) \frac{\delta G^{-1}(12)}{\delta\phi} + \frac{\delta G^{-1}(12)}{\delta\phi} G(12) \frac{\delta G^{-1}(12)}{\delta A_\mu} \Big\} G(12)\, D_\mu \tag{7}$$

In deriving the above expression we have used the identities of the type $\frac{\delta\Lambda}{\delta A_\mu} = -\Delta \frac{\delta\Delta^{-1}}{\delta A_\mu} \Delta$, which serve for defining the vertex operators. The comparison between Eqs. 7) and 2) shows that the truncated Green's function can be easily identified as the bracket expression in Eq. 7).

For further elaboration, one used Eq. 3) and observes that the truncated Green's function can be written in a form of a series with respect to the interaction kernel I(12). Retaining the 0^{th} and the 1^{st} order terms of this development only, one gets :

$$R_\mu(12,\xi,\xi') \simeq R_\mu^{(0)}(12,\xi,\xi') + R_\mu^{(1)}(12,\xi,\xi') \tag{8}$$

$$R_\mu^{(0)} = \Big\{ \Big(\Gamma_{\gamma\pi}\, \Delta\, \Gamma_{\pi N}^{(1)} + \Gamma_{\gamma N}^{(1)} G_1 \Gamma_{\pi N}^{(1)} + \Gamma_{\pi N}^{(1)} G_1 \Gamma_{\gamma N}^{(1)} + \Gamma_{\gamma\pi N}^{(1)} \Big) G_2^{-1} + \Gamma_{\gamma N}^{(1)} \Gamma_{\pi N}^{(2)} \Big\} + \Big\{ 1 \rightleftarrows 2 \Big\} \tag{8a}$$

$$\begin{aligned} R_\mu^{(1)} = {} & \Gamma_{\gamma\pi}\, \Delta\, \frac{\delta I(12)}{\delta \phi} + \Big(\Gamma_{\gamma N}^{(1)} G_1 + \Gamma_{\gamma N}^{(2)} G_2 \Big) I(12) \Big(G_1 \Gamma_{\pi N}^{(1)} + G_2 \Gamma_{\pi N}^{(2)} \Big) \\ & + \Big(\Gamma_{\gamma N}^{(1)} G_1 + \Gamma_{\gamma N}^{(2)} G_2 \Big) \frac{\delta I(12)}{\delta \phi} + \frac{\delta I(12)}{\delta A_\mu} \Big(G_1 \Gamma_{\pi N}^{(1)} + G_2 \Gamma_{\pi N}^{(2)} \Big) \\ & + \Big(\Gamma_{\pi N}^{(1)} G_1 + \Gamma_{\pi N}^{(2)} G_2 \Big) I(12) \Big(G_1 \Gamma_{\gamma N}^{(1)} + G_2 \Gamma_{\gamma N}^{(2)} \Big) \\ & + \Big(\Gamma_{\pi N}^{(1)} G_1 + \Gamma_{\pi N}^{(2)} G_2 \Big) \frac{\delta I(12)}{\delta A_\mu} + \frac{\delta I(12)}{\delta \phi} \Big(G_1 \Gamma_{\gamma N}^{(1)} + G_2 \Gamma_{\gamma N}^{(2)} \Big) \\ & + \frac{\delta^2 I(12)}{\delta \phi\, \delta A_\mu} \end{aligned} \tag{8b}$$

The symbols used are $\Gamma_{\pi N}^{(i)} = -\frac{\delta G_i^{-1}}{\delta \phi}$ for the pion-nucleon vertex, $\Gamma_{\gamma\pi} = -\frac{\delta \Delta^{-1}}{\delta A_\mu}$ for the photon-pion vertex, $\Gamma_{\gamma N}^{(i)} = -\frac{\delta G_i^{-1}}{\delta A_\mu}$ for the photon-nucleon vertex and $\Gamma_{\gamma\pi N}^{(i)} = \frac{-\delta^2 G_i^{-1}}{\delta A_\mu\, \delta \phi}$ for the photon-pion-nucleon vertex. The analytical forms of their momentum dependences are to be found from the chosen interaction Lagrangian.

The graphical representation of $R_\mu^{(0)}$ (Eq. 8a) is given in Fig. 1). The term (I) which contains the full T-matrix of the photoproduction of a pion on a single nucleon will serve for the reconstruction of the impulse approximation. Notice, the second row of the figure : throughout the paper, the circle is used to denote the full T-matrix of the corresponding elementary process. Also, for all the graphical representations of the constituents of $R_\mu\,(12,\xi,\xi')$, the external lines are used not to represent the propagators, but only to indicate the nature of the interaction. The term (II) is disconnected and corresponds to a process in which one nucleon absorbs photon and the second emits pion.

For the evaluation of $R_\mu^{(1)}$ (Eq. 8b), one has to precise the form of the interaction kernel I(12). We shall restrict ourselves to the study of the one-pion exchange interaction. The generalization to a linear superposition of one-boson-exchange graphs is straightforward and permits to relate the exposed theory to the study of a nucleon-nucleon potential.

By using

$$I\,(12) = \Gamma_{\pi N}^{(1)}\ \Delta\ \Gamma_{\pi N}^{(2)} \qquad (9)$$

$R_\mu^{(1)}$ (Eq. 8b) can be written as a sum of four terms referred by A, B, C and D which are graphically shown in Fig. 2). In the same figure, one finds also a meaning of a possible regroupment of these terms. $R_\mu^{(1)}$ (A) serves for the reconstruction of the full T-matrix for the elementary process of double pion photoproduction on a nucleon with a subsequent absorption of one pion by other nucleon, while $R_\mu^{(1)}$ (B) is to be used to represent the full T-matrix of a photoproduction of a pion by one nucleon and its rescattering by the other one. The reason of the separation of

$R_\mu^{(1)}$ (C) lies in the fact that it is a part of the T-matrix of both processes just mentioned, but in the derivation of Eq.(8b) with the interaction kernel given by Eq. (9), it appears only once. The separation of $R_\mu^{(1)}$ (D) is dictated by the $(1 \rightleftarrows 2)$ nucleon symmetry.

Simultaneously with the development of truncated Green's function, one has to carry out the non-relativistic reduction of the deuteron amplitude, given by Eq. (5). It is natural that this reduction has to be done in the same spirit as the one applied for the truncated Green's function, namely by using a sort of development with respect to the interaction kernel I(12). The full non relativistic i.e. Schrödinger wave-function for deuteron in which all the meson effects are covered by a nuclear potential, corrected by a term linear with respect to I(12), serves for this purpose. One writes :

$$\chi_d(12) \simeq \varphi_d + \psi(I(12)) \tag{10}$$

The Schrödinger wave function, φ_d , (named further as "large" component of the wave function) is obtained from Eq. (5) :
α) by retaining only the positive energy parts of the fermion fields,
β) by using the static limit of the interaction kernel and
γ) by taking the non-relativistic expressions for the one-particle propagators. In the ref. (20), the corrected term, $\psi(I(12))$ (further called the "small" component) was obtained via the Breit equation by relaxing the conditions β) and γ).

Within the approximations used to derive Eqs. (8) and

(10), the 0^{th} and the 1^{st} order terms with respect to I(12) of the S-matrix, (Eq. 4), read :

$$S_{\gamma d\to\pi d} \simeq S^{(o)}_{\gamma d\to\pi d} + S^{(1)}_{\gamma d\to\pi d} \qquad (11)$$

$$S^{(o)}_{\gamma d\to\pi d} = \int \varphi^*_k(\xi)\, \varphi^*_d\, R^{(o)}_\mu\, \varphi_d\, A_{k'_\mu}(\xi') \qquad (11a)$$

$$\begin{aligned} S^{(1)}_{\gamma d\to\pi d} = &\int \varphi^*_k(\xi)\, \varphi^*_d\, R^{(1)}_\mu\, \varphi_d\, A_{k'_\mu}(\xi') + \\ &+ \int \varphi^*_k(\xi)\, \varphi^*_d\, R^{(o)}_\mu\, \Psi(I(12))\, A_{k'_\mu}(\xi') + \\ &+ \int \varphi^*_k(\xi)\, \Psi^*(I(12))\, R^{(o)}_\mu\, \varphi_d\, A_{k'_\mu}(\xi') \end{aligned} \qquad (11b)$$

One immediately sees that $S^{(0)}_{\gamma d\to\pi d}$ term is the usual impulse approximation corrected by the contribution of the disconnected diagram of Fig. 1. The last two terms of $S^{(1)}_{\gamma d\to\pi d}$, in which the "large"and "small" components of the wave function are mixed, refer to the situation in which the pion exchange is either antecedent or postcedent to the interaction vertices of $R^{(0)}_\mu$. As it is shown in the graphical equation for $R^{(1)}_\mu$ (A) and $R^{(1)}_\mu$ (B) (Fig. 2), the same structure have those terms (with the impulse approximation vertex for $R^{(1)}_\mu$ (A) and with the disconnected vertices for $R^{(1)}_\mu$ (B)), needed to complete the T-matrices of the corresponding elementary processes. With this conjecture, which might be proved analytically, the above S-matrix is equal to the contributions of six terms, diagramatically shown in Fig. 3. The double arrow line is used to represent the non-relativistic deuteron wave function. We conclude, that in distinction to the Watson multiple-scattering theory, containing impulse and pion-rescattering contributions [21], new terms appear, whose nature reflects the mesonic-exchange contributions. The obtained mesonic "transition operators" include the effect of the wave-function corrections and have to be calculated with the deuteron Schrödinger wave function.

In the resonance regions, one should expect the greatest contribution for (a), (b) and (c) graphs. We have already calculated [21] the impulse approximation together with the pion-rescattering contribution. A crude estimation of the graph (c) alone, in the energy region of the first pion-nucleon resonance and for backwards angles shows that it contributes for about 3%. This suggests that the interference effects might be important. Unfortunately, the $\gamma N \to N\pi\pi$ reaction is much less known than $\gamma N \to \pi N$ and $\pi N \to \pi N$ reactions. Detailed calculations of the whole S-matrix are in progress.

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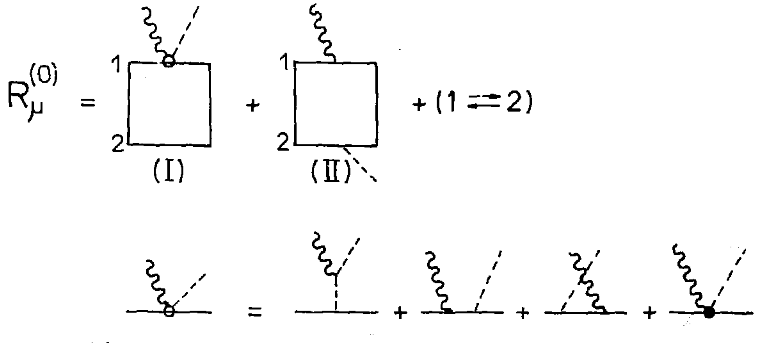

Fig. 1

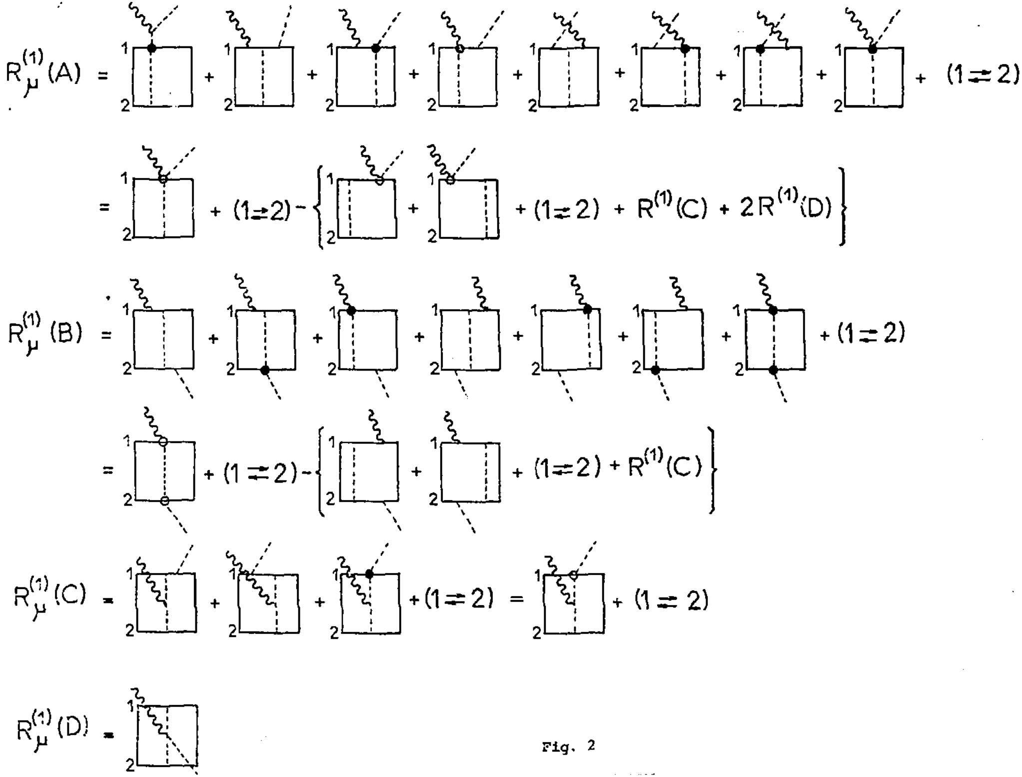

Fig. 2

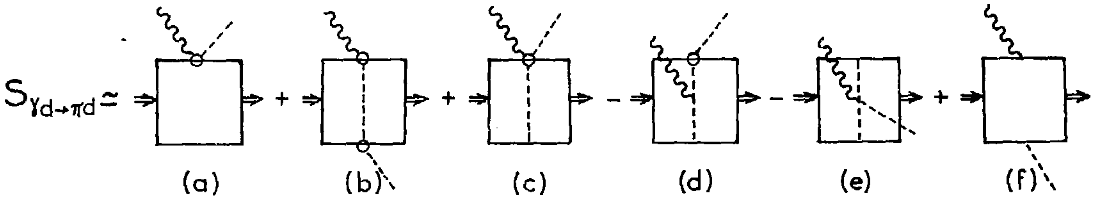

Fig. 3