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ELECTRODISINTEGRATION OF THE DEUTERON NEAR THRESHOLD WITH ALLOWANCE FOR MESON EXCHANGE CURRENTS. RETARDATION EFFECTS

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1 Introduction

At present, the models of MEC in electron - deuteron (e-d) scattering are of great importance for investigating the inner structure of nuclei. This is first of all because investigations of nuclear interactions with external fields at low energies naturally lead to the inclusion of meson exchanges that are responsible for the nuclear forces at long and intermediate distances. Moreover, the allowance for MEC in a nucleus is suitable for investigating the nuclear structure at short distances where the quark degrees of freedom, for instance, begin to appear (see [1]- [12]).

Therefore, the models of MEC are very important for obtaining the natural relation between low energy and relativistic properties of a nucleus.

One of the first investigations of the inelastic e-d scattering with allowance for MEC in a nucleus was related to the thermal np capture [13]. In this case, the calculations of the cross section with allowance for nucleon components in a nucleus, impulse approximation, led to the discrepancy with experimental data. In order to get the realistic description of a nucleus, the inclusion of meson exchange currents was necessary.

The electrodisintegration of the deuteron with allowance for MEC has been discussed in refs. [14] - [22]. There are two general approaches to that problem. One of them has been formulated by Lock, Fabian, Arenhovel, Summer (see refs. [14]-[16]). In these papers a multipole expansion of the $\mid f>$ - final state in the $d \rightarrow \mid f>$ - transition (d denotes the deuteron) has been studied with allowance for MEC. It was shown for the differential cross section that the contribution of MEC allows one to avoid difficulties in the range of $t = 11 - 12 fm^{-2}$, where the calculations only with impulse approximation led to the minimum in contradiction with experimental data. The other approaches are considered in refs.[18]-[22]. In this case, the transition between the deuteron and ${}^1S_0$ - final state has been investigated. It was shown that the contribution of higher partial waves to the final states near the threshold is a negligible correction. In this paper, we shall follow the latter conclusion.

However, the investigations of the retardation effects have not been done yet. The reason is the lack of experimental results at large transfer momenta. In this case the traditional set of meson exchange currents (see fig. 1) was quite enough to get the correct information on the differential cross section in a small region of transfer momenta.

At present, the experimental results on the differential cross section, derived from $ed \rightarrow e'np$ - reaction, are available at transfer momenta up to 1 GeV. This situation is very good for the investigation of structure of the deuteron at short distances with allowance for some exotic effects: relativistic corrections and quark degrees of freedom. In refs [26] - [28] the contribution of the quark admixture with meson exchange currents has been investigated. It was shown that the inclusion of quark currents is very important for explanation of the experimental data. This conclusion strongly depends on the contribution of the meson exchange currents

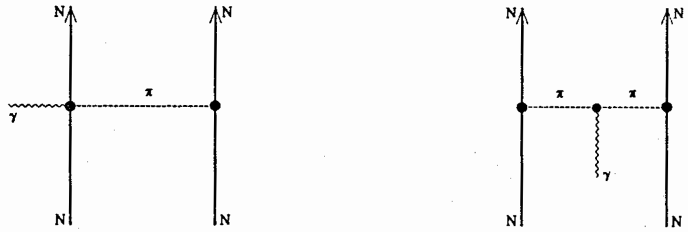

Figure 1: Diagrams of seagull (a) and meson (b) currents

The retardation of meson exchange currents is one of the significant relativistic effects whose investigation still has not been done. It was shown before [25] for the elastic e-d scattering that the inclusion of this current into the structure function $B(q^2)$ has a considerable effect at large transfer momenta. Moreover, for the structure function $A(q^2)$ the contribution of retardation effects makes the agreement with experimental data noticeably worse enabling one to take account of other effects, for instance quark degrees of freedom. That situation provokes the investigation of the deuteron structure when all contributions of the meson exchange currents should be taken into account, including retardation effects.

Our research is devoted to retardation effects in meson exchange currents in the electrodisintegration of the deuteron near threshold.

The retardation current consists of the recoil (RC) and wave function renormalization (WFR) currents (see fig. 2). In ref. [29], the retardation current has been defined. It was shown that the RC and WFR currents cancel out completely in the nonrelativistic limit (up to an order of $O(1/M^2)$). However, in the $O(1/M^3)$ - limit the retardation effects do exist.

In our paper, we have derived the expression for the isovector retardation current ($\vec{J}^R$) up to an order of $O(1/M^4)$ and a general expression for the two - body matrix element with allowance for retardation effects. Theoretical calculations for two kinds of vertex form factors have been done. The calculations with the monopole vertex form factor [19] and with the form factor of $(k^2)^{-3}$ - decreasing at large transfer momenta [30] were investigated. For this case, the expressions for the two - body matrix elements have been derived.

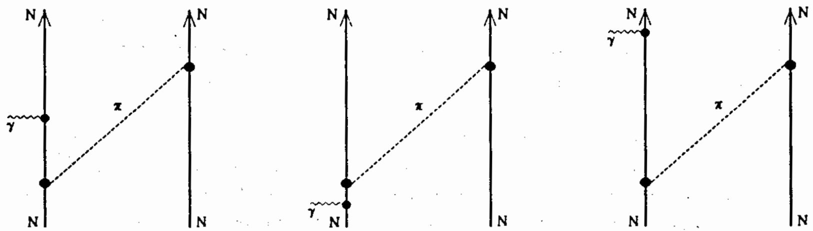

Figure 2: Diagrams of recoil (a) and renormalization (b) currents

The contribution of ρ - meson exchange in MEC with allowance for retardation effects is studied.

Moreover, the radial dependence of the matrix elements with allowance for retardation effects has been investigated. It has been found before in ref. [20] that the meson exchange currents fig.1, dominate if the relative distance between two nucleons is between 1 - 1.4 fm for $t \leq 30 fm^{-2}$. In this case, the influence of retardation effects is studied which is necessary in order to get a realistic picture of the radial dependence at high momentum transfer.

2 Model

According to ref. [29], the investigation of the interaction between the external electromagnetic field and deuteron will be performed in the framework of the effective operator model. If the nucleus is the meson - nucleon system, the complete wave function Ψ contains a nucleon as well as meson components. We shall eliminate meson degrees of freedom from the complete wave function Ψ. This transformation leads to the new wave function, ϕ which is expressed in terms of positive nucleons, and defines the effective interaction operators through the meson and nucleon variables. It has been shown in ref. [29] that a transformation like that can be expressed in the following way

$$\Psi = J(\eta J^+ J\eta)^{-1/2}\phi. \tag{1}$$

Here,

$$<\Psi \mid \Psi> = <\phi \mid \phi> = 1. \tag{2}$$

Thus, starting from the exact Schrodinger equation for the complete wave function Ψ

$$H\Psi = E\Psi, \tag{3}$$

we reduced it to the effective Schrodinger equation given by

$$(T_N + V_{eff})\phi = E\phi, \tag{4}$$

where T_N is the nucleon kinetic energy, V_{eff} is the effective nucleon potential:

$$V_{eff} = (\eta J^+ J\eta)^{-1/2} J^+ H J (\eta J^+ J\eta)^{-1/2} - \eta H_0 \eta. \tag{5}$$

Here, H_0 is the free Hamiltonian, η is the projection operator into the nucleon states, J has the following form:

$$J = 1 + F, \tag{6}$$

where

$$F = \sum_i F_i + \sum_{i,j} F_{i,j} + ... \tag{7}$$

with

$$F_i = \frac{\Lambda}{E_0 - H_0} H_I(i)\eta + ...,$$
$$F_{i,j} = \frac{\Lambda}{E_0 - H_0} H_I(i) \frac{\Lambda}{E_0 - H_0} H_I(j)\eta + ... \tag{8}$$

Here, H_I is the meson nucleon interaction, $\Lambda = 1 - \eta$, i and j are nucleon indices. E_0 denotes the free energy of the nucleon. The external electromagnetic operator $\vec{J}_{em}$ has reduced to the effective operator $\vec{J}^{eff}_{em}$ in the following way:

$$< \Psi \mid \vec{J}_{em} \mid \Psi > = < \phi \mid \vec{J}^{eff}_{em} \mid \phi >, \tag{9}$$

where

$$\vec{J}^{eff}_{em} = (\eta J^+ J\eta)^{-1/2} J^+ \vec{J}_{em} J (\eta J^+ J\eta)^{-1/2}. \tag{10}$$

The electromagnetic operator $\vec{J}_{em}$ has the following form:

$$\vec{J}_{em} = \vec{J}^N + \vec{J}^{NM} + \vec{J}^{M_1 M_2}. \tag{11}$$

$\vec{J}^N$ is the electromagnetic current of a nucleon, $\vec{J}^{NM}$ is the meson - nucleon current, $\vec{J}^{M_1 M_2}$ is the meson electromagnetic current.

The equation for $\vec{J}^{eff}_{em}$ can be derived from (10) as follows:

$$\vec{J}^{eff}_{em} = \vec{J}^I + \vec{J}^S + \vec{J}^M + \vec{J}^R. \tag{12}$$

Here, $\vec{J}^I$ is the impulse approximation (I), $\vec{J}^S$ stands for the seagull current (S), fig. 1 a), $\vec{J}^M$ denotes the mesonic current (M), fig. 1 b), $\vec{J}^R$ is the retardation current (R) fig. 2. The individual contributions of currents are expressed in the following way (see [21], [23], [24]):

$$\vec{J}^I = iG^v_M(t) \frac{\vec{\sigma}_1 \times \vec{q}}{4M} \tau^1_3, \tag{13}$$

$$\vec{J}^S = iF^v_1(t) \frac{f^2}{4\pi m^2_\pi} (\vec{\tau}_1 \times \vec{\tau}_2)_3 \left(\frac{\vec{\sigma}_2(\vec{\sigma}_1 \cdot \vec{k}_1)}{m^2_\pi + \vec{k}^2_1} - \frac{\vec{\sigma}_1(\vec{\sigma}_2 \cdot \vec{k}_2)}{m^2_\pi + \vec{k}^2_2} \right), \tag{14}$$

$$\vec{J}^M = iF^v_1(t) \frac{f^2}{4\pi m^2_\pi} (\vec{\tau}_1 \times \vec{\tau}_2)_3 \frac{(\vec{\sigma}_1 \cdot \vec{k}_1)(\vec{\sigma}_2 \cdot \vec{k}_2)}{(m^2_\pi + \vec{k}^2_1)(m^2_\pi + \vec{k}^2_2)} (\vec{k}_1 - \vec{k}_2). \tag{15}$$

For the retardation effects we derived:

$$\vec{J}^R = \vec{J}^A + \vec{J}^B \tag{16}$$

with

$$\vec{J}^A = -iG^v_M(t) \frac{f^2}{32\pi M^2 m^2_\pi} \frac{1}{\omega^4} (i(\vec{\tau}_1 \times \vec{\tau}_2)_3 + \tau^2_3)(\vec{\sigma}_1 \cdot \vec{k}_2)(\vec{\sigma}_1 \times \vec{q})(\vec{q} \cdot \vec{k}_2)(\vec{\sigma}_2 \cdot \vec{k}_2), \tag{17}$$

$$\vec{J}^B = -F^v_1(t) \frac{f^2}{32\pi M^2 m^2_\pi} \frac{1}{\omega^4} (i(\vec{\tau}_1 \times \vec{\tau}_2)_3 + \tau^2_3) \vec{k}_2 (\vec{\sigma}_1 \cdot \vec{k}_2)(\vec{q} \cdot \vec{k}_2)(\vec{\sigma}_2 \cdot \vec{k}_2). \tag{18}$$

Here, $f^2/4\pi = 0.08$, M is the nucleon mass, m_π denotes the pion mass, $\vec{k}_{1,2} = \vec{p}'_{1,2} - \vec{p}_{1,2}$ ($\vec{p}_{1,2}$, $\vec{p}'_{1,2}$ are the initial and final momenta of two nucleons), ω is the pion energy,

$$G^v_M(t) = \frac{G^v_M(0)}{(1 + t/m^2_0)^2}, \tag{19}$$

$$F^v_1(t) = \frac{1}{(1 + t/m^2_0)^2} \frac{1}{1 + t/4M^2} (1 + G^v_M(0) \frac{t}{4M^2}). \tag{20}$$

Here, $G^v_M(0) = 4.706$, $m^2_0 = 18.23 fm^{-2}$ (see [19]).

In order to get the realistic properties of the two - nucleon system the extension structure of nucleons at short distances has to be taken into account. In this case, the bare πNN vertex has to be parametrized by the vertex form factor $K_\pi(k)$. We shall investigate two parametrization forms of the vertex form factor. The first one is the monopole vertex form factor. According to ref. [19], we have

$$K_\pi(k) = \frac{\Lambda^2_\pi - m^2_\pi}{\Lambda^2_\pi + k^2}. \tag{21}$$

The second parametrization ensures the monopole behavior at small k^2 that is usually used in the low - energy reactions and $(k^2)^{-3}$ decrease at large k^2 that is assigned to quantum chromodynamics [30]

$$K_\pi(k) = \frac{1}{(1 + k^2/\Lambda^2_{1,\pi})(1 + k^4/\Lambda^4_{2,\pi})}. \tag{22}$$

We shall investigate different values of the cut-off parameters related to the rms of the nucleon: 0.48 fm and 0.7 fm. Here, $\Lambda_\pi = 1.25$ GeV or 0.85 GeV, respectively. The detailed analysis of the rms was done in ref. [19]. The cut-off parameters $\Lambda_{1,\pi} = 0.99$ GeV, $\Lambda_{2,\pi} = 2.58$ GeV were determined in ref. [30]. The calculations with vertex form factor (22) were made with the following renormalization of the coupling constant f:

$$f = f(1 - \frac{m^2_\pi}{\Lambda^2_\pi}). \tag{23}$$

3 Matrix elements

Due to ref. [19], the differential cross section for the $d \to {}^1S_0$ - transition has the form

$$\frac{d^2\sigma}{d\Omega d\omega} = \frac{16}{3}\alpha^2\frac{k_f^2}{\vec{q}^2}\frac{KM}{t^2}sin^2\frac{1}{2}\theta((k_i + k_f)^2 - 2k_ik_fcos^2\frac{1}{2}\theta) \mid < {}^1S_0 \parallel T_1^{Mag} \parallel d > \mid^2, \quad (24)$$

$k_{i(f)}$ is the initial (final) momentum of the electron, $\vec{q}$ is the vector of momentum transfer, t stands for the four momentum transfer. Momentum K is related to the relative energy E_{np} of the np system in the following way

$$E_{np} = \frac{K^2}{M}. \quad (25)$$

The relationship between kinematical quantities is given by

$$\mid \vec{q} \mid = \sqrt{\frac{((M_n + M_p + E_{np})^2 - M_d^2 + t)^2}{4M_d^2} + t}, \quad (26)$$

where M_n, M_p and M_d are the neutron, proton and deuteron mass, respectively.

$$k_f = \frac{-\omega + \sqrt{\omega^2 + t/sin^2\frac{1}{2}\theta}}{2}. \quad (27)$$

Here, $\omega = \epsilon_i - \epsilon_f$ ($\epsilon_{i(f)}$ is the initial (final) energy of the electron). The magnetic multipole T_1^{Mag} is expressed through the isovector current operator $\vec{J}_{em}^{eff}$ as follows:

$$T_1^{Mag}(q) = \int j_1(qx)\vec{Y}_{111}^M(\Omega_x)\cdot\vec{J}_{em}^{eff}d\vec{x}. \quad (28)$$

In term of $\vec{J}^I$ the one-body matrix element is

$$\begin{aligned} < {}^1S_0 \parallel T_{1,1-body}^{Mag} \parallel d > &= i\frac{q}{2M}G_M^v(t)\frac{1}{\sqrt{2\pi}}\int_0^\infty (j_0(\frac{1}{2}qr)u(r)u_0(r) - \\ &- j_2(\frac{1}{2}qr)\sqrt{\frac{1}{2}}w(r)u_0(r))dr. \end{aligned} \quad (29)$$

Here $u(r)$, $w(r)$, $u_0(r)$ are S, D waves of the deuteron and wave function of the ${}^1S_0$ - state, respectively. If the relative coordinate $r \to \infty$, then

$$u_0(r) \to \frac{1}{K}sin(Kr + \delta_0). \quad (30)$$

The equations for the matrix elements related to the two-body currents have the following expressions: for the seagull current

$$\begin{aligned} < {}^1S_0 \parallel T_{1,S}^{Mag} \parallel d > &= iF_1^v(t)2\sqrt{\frac{2}{\pi}}\frac{f^2}{4\pi m_\pi^2}\int_0^\infty \frac{e^{-m_\pi r}}{r^2}(1 + m_\pi r)j_1(\frac{1}{2}qr)(u(r) + \\ &+ \sqrt{\frac{1}{2}}w(r))u_0(r)dr, \end{aligned} \quad (31)$$

mesonic current

$$\begin{aligned} &< {}^1S_0 \parallel T_{1,M}^{Mag} \parallel d >= i\frac{1}{6}qF_1^v(t)2\sqrt{\frac{2}{\pi}}\frac{f^2}{4\pi m_\pi^2} \times \\ &\times \int_0^\infty(((\frac{d^2}{dr^2} + \frac{2}{r}\frac{d}{dr})t_0 + (\frac{d^2}{dr^2} + \frac{5}{r}\frac{d}{dr} + \frac{3}{r^2})t_2)u(r)u_0(r) + \\ &+ ((\frac{d^2}{dr^2} - \frac{1}{r}\frac{d}{dr})t_0 + (\frac{d^2}{dr^2} + \frac{2}{r}\frac{d}{dr} - \frac{6}{r^2})t_2)\sqrt{\frac{1}{2}}w(r)u_0(r))dr, \end{aligned} \quad (32)$$

$$t_l = \int_0^1 \frac{e^{-\alpha r}}{\alpha}j_l(\frac{1}{2}\eta qr)d\eta, \quad (33)$$

where

$$\alpha = \sqrt{m_\pi^2 + \frac{1}{4}q^2(1 - \eta^2)}, \quad (34)$$

retardation effects

$$\begin{aligned} &< {}^1S_0 \parallel T_{1,R}^{Mag} \parallel d >= iG_M^v(t)\frac{q^2}{40\pi^{\frac{5}{2}}}\frac{f^2}{M^2m_\pi^2} \times \\ &\times \int_0^\infty u_0(r)(j_1(\frac{1}{2}qr)(\frac{1}{\sqrt{2}}u(r)19I_1(r) + \\ &+ w(r)\frac{1}{10}(-13I_1(r) - 8I_3(r))) + j_3(\frac{1}{2}qr)(\frac{1}{\sqrt{2}}u(r)11I_3(r) + \\ &+ w(r)\frac{1}{10}(7I_1(r) - 28I_3(r))))dr. \end{aligned} \quad (35)$$

The radial functions $I_l(r)$ are given by

$$I_l(r) = \int_0^\infty k^5 j_l(kr)\frac{K_\pi^2(k)}{(k^2 + m_\pi^2)^2}dk. \quad (36)$$

The inclusion of the vertex form factor arises an important problem, namely the current conservation law. It has been shown before that in the case of point-like nucleons with allowance for seagull and meson currents the gauge invariance is insured [24].

$$i(\vec{k}_1 + \vec{k}_2) \cdot \vec{J} + (\vec{\tau}_1 \times \vec{\tau}_2)_3 (V_\pi(k_2) - V_\pi(k_1)) = 0. \tag{37}$$

Here $\vec{J} = \vec{J}^S + \vec{J}^M$ and

$$V_\pi(k) = -\frac{f^2}{m_\pi^2} \frac{(\vec{\sigma}_1 \cdot \vec{k})(\vec{\sigma}_2 \cdot \vec{k})}{m_\pi^2 + k^2} \tag{38}$$

is the pion potential without factor $(\vec{\tau}_1 \cdot \vec{\tau}_2)$. If the vertex form factor is used, the meson exchange currents have to be reduced to the form which insures the current conservation law. For the seagull current we have

$$\vec{J}^S = iF_1^v(t) \frac{f^2}{4\pi m_\pi^2} (\vec{\tau}_1 \times \vec{\tau}_2)_3 \left(K_\pi^2(k_1) \frac{\vec{\sigma}_2(\vec{\sigma}_1 \cdot \vec{k}_1)}{m_\pi^2 + \vec{k}_1^2} - K_\pi^2(k_2) \frac{\vec{\sigma}_1(\vec{\sigma}_2 \cdot \vec{k}_2)}{m_\pi^2 + \vec{k}_2^2}\right). \tag{39}$$

In the case of meson current, the available equation is given by

$$\vec{J}^M = -iF_1^v(t) \frac{f^2}{m_\pi^2} (\vec{\tau}_1 \times \vec{\tau}_2)_3 (\vec{k}_1 - \vec{k}_2)(\vec{\sigma}_1 \cdot \vec{k}_1)(\vec{\sigma}_2 \cdot \vec{k}_2) \frac{1}{k_1^2 - k_2^2} \left(\frac{K_\pi^2(k_1)}{k_1^2 + m_\pi^2} - \frac{K_\pi^2(k_2)}{k_2^2 + m_\pi^2}\right). \tag{40}$$

In the Breit system where $q_0 = 0$, the continuity equation for the retardation current has the following form:

$$\vec{q} \cdot \vec{J}^R = \vec{q} \cdot \vec{J}^B. \tag{41}$$

However, we have obtained that the matrix element (35) is independent of $\vec{J}^B$, which makes the calculations with allowance for retardation effects gauge independent when the $d \to {}^1S_0$ - transition is studied. According to ref.[19], meson exchange currents defined in (39), (40) lead to the following transformations of matrix elements; for monopole form (21) and seagull current:

$$\frac{e^{-m_\pi r}}{r^2}(1 + m_\pi r) \to \frac{e^{-m_\pi r}}{r^2}(1 + m_\pi r) - \frac{e^{-\Lambda_\pi r}}{r^2}(1 + \Lambda_\pi r) - \frac{\Lambda_\pi^2 - m_\pi^2}{2} e^{-\Lambda_\pi r}. \tag{42}$$

Meson current:

$$\frac{e^{-\alpha r}}{\alpha} \to \frac{e^{-\alpha r}}{\alpha} - \frac{e^{-\lambda r}}{\lambda} - \frac{\Lambda_\pi^2 - m_\pi^2}{2} e^{-\lambda r} \frac{1 + \lambda r}{\lambda^3}, \tag{43}$$

where

$$\lambda = \sqrt{\Lambda_\pi^2 + \frac{1}{4} q^2 (1 - \eta^2)}. \tag{44}$$

For the parametrization (22) we derived: In the case of the seagull current:

$$\begin{aligned}
\frac{e^{-m_\pi r}}{r^2}(1 + m_\pi r) \to & \frac{\Lambda_1^4 \Lambda_2^8}{(\Lambda_1^2 - m_\pi^2)^2 (\Lambda_2^4 + m_\pi^4)^2} \times \\
\times & \left(\frac{e^{-m_\pi r}}{r^2}(1 + m_\pi r) - \frac{(\Lambda_2^4 + m_\pi^4)^2}{(\Lambda_1^4 + \Lambda_2^4)^2} \left(\frac{e^{-\Lambda_1 r}}{r^2}(1 + \Lambda_1 r) + \frac{\Lambda_1^2 - m_\pi^2}{2} e^{-\Lambda_1 r} + \right.\right. \\
+ & \left.\left. \frac{\Lambda_1^2 - m_\pi^2}{\Lambda_1^4 + \Lambda_2^4} 4\Lambda_1^2 \frac{e^{-\Lambda_1 r}}{r^2}(1 + \Lambda_1 r)\right) + \frac{(\Lambda_1^2 - m_\pi^2)^2 (\Lambda_2^4 + m_\pi^4)}{\Lambda_2^4 (\Lambda_2^4 + \Lambda_1^4)^2} \left(\frac{1}{r^2} - \frac{1}{r^2} \frac{d}{dr}\right) Z\right),
\end{aligned} \tag{45}$$

where

$$\begin{aligned}
Z = & e^{-r\frac{\Lambda_2}{\sqrt{2}}} \left(l_1 \left(a cos\left(r\frac{\Lambda_2}{\sqrt{2}}\right) - b sin\left(r\frac{\Lambda_2}{\sqrt{2}}\right)\right) + \right. \\
+ & \left. l_2 \left(a sin\left(r\frac{\Lambda_2}{\sqrt{2}}\right) + b cos\left(r\frac{\Lambda_2}{\sqrt{2}}\right)\right)\right),
\end{aligned} \tag{46}$$

$$\begin{aligned}
l_1 &= \frac{r\sqrt{2}}{8\Lambda_2} + \frac{\Lambda_2^2}{2(\Lambda_2^4 + m_\pi^4)} + \frac{\Lambda_2^2}{(\Lambda_2^4 + \Lambda_1^4)} + \frac{1}{2\Lambda_2^2}, \\
l_2 &= \frac{r\sqrt{2}}{8\Lambda_2} - \frac{m_\pi^2}{2(\Lambda_2^4 + m_\pi^4)} - \frac{\Lambda_1^2}{(\Lambda_2^4 + \Lambda_1^4)}, \\
a &= \Lambda_2^2(\Lambda_2^4 - \Lambda_1^4 - 2m_\pi^2 \Lambda_1^2), \\
b &= 2\Lambda_2^4 \Lambda_1^2 + m_\pi^2 \Lambda_2^4 - m_\pi^2 \Lambda_1^4.
\end{aligned} \tag{47}$$

The transformation for the meson current has the following expression:

$$\frac{e^{-\alpha r}}{\alpha} \to -\frac{\Lambda_1^4 \Lambda_2^4}{4} \left(f_1 \frac{e^{-\alpha r}}{\alpha} - f_2 \frac{e^{-\lambda r}}{\lambda} - f_3 \frac{1 + \lambda r}{2\lambda^3} e^{-\lambda r} + (f_4 cos(\theta r) + f_5 sin(\theta r)) e^{-\beta r}\right) \tag{48}$$

with

$$f_1 = \gamma_1, \quad f_2 = \gamma_1 + \gamma_2 - \gamma_3, \quad f_3 = -\gamma_4,$$

$$f_4 = \frac{\beta(\gamma_2 - \gamma_3) + \theta(\gamma_5 + \gamma_6)}{\beta^2 + \theta^2} + \frac{\varphi_1 \gamma_7 + \varphi_2 \gamma_8}{\frac{q^4}{16}(1 - \eta^2)^2 + \Lambda_2^4},$$

$$f_5 = \frac{\beta(\gamma_6 + \gamma_5) + \theta(\gamma_3 - \gamma_2)}{\beta^2 + \theta^2} + \frac{\varphi_1 \gamma_8 - \varphi_2 \gamma_7}{\frac{q^4}{16}(1 - \eta^2)^2 + \Lambda_2^4}. \tag{49}$$

Here

$$\gamma_1 = -\frac{4\Lambda_2^4}{(\Lambda_1^2 - m_\pi^2)^2 (\Lambda_2^4 + m_\pi^4)^2},$$

$$\begin{aligned}
\gamma_2 = & \frac{2}{(\Lambda_1^4 + \Lambda_2^4)^3 (\Lambda_2^4 + m_\pi^4)^2} (\Lambda_2^4 (\Lambda_2^4 (\Lambda_1^2 (3\Lambda_1^2 + 9m_\pi^2) - \\
- & (3\Lambda_2^4 + m_\pi^4)) + \Lambda_1^2 (\Lambda_1^2 (\Lambda_1^2 (2\Lambda_1^2 + 5m_\pi^2) + 3m_\pi^4) + \\
+ & 5m_\pi^6)) + \Lambda_1^6 m_\pi^6),
\end{aligned}$$

$$\begin{aligned}
\gamma_3 = & -\frac{2}{(\Lambda_1^4 + \Lambda_2^4)^3 (\Lambda_2^4 + m_\pi^4)} (\Lambda_2^4 (\Lambda_1^2 (3\Lambda_1^2 + 3m_\pi^2) - \\
- & \Lambda_2^4) - \Lambda_1^6 m_\pi^2),
\end{aligned}$$

$$\gamma_4 = \frac{4\Lambda_2^4}{(\Lambda_1^4+\Lambda_2^4)^2(\Lambda_1^2-m_\pi^2)},$$

$$\begin{aligned}\gamma_5 &= \frac{2}{\Lambda_2^2(\Lambda_1^4+\Lambda_2^4)^3(\Lambda_2^4+m_\pi^4)^2}(\Lambda_2^4(\Lambda_2^4(\Lambda_1^2(\Lambda_1^2(3\Lambda_1^2 - \\ &- 3m_\pi^2)+(7\Lambda_2^4+3m_\pi^4))+4\Lambda_2^4 m_\pi^2+2m_\pi^6)- \\ &- \Lambda_1^4(\Lambda_1^2(m_\pi^4+3\Lambda_1^2 m_\pi^2)+3m_\pi^6))-\Lambda_1^8 m_\pi^6),\end{aligned}$$

$$\gamma_6 = 2\frac{\Lambda_2^2(\Lambda_2^4(3\Lambda_1^2+m_\pi^2)-\Lambda_1^4(3m_\pi^2+\Lambda_1^2))}{(\Lambda_1^4+\Lambda_2^4)^3(m_\pi^4+\Lambda_2^4)},$$

$$\gamma_7 = -\frac{\Lambda_2^4(m_\pi^2+2\Lambda_1^2)-\Lambda_1^4 m_\pi^2}{(\Lambda_1^4+\Lambda_2^4)^2(m_\pi^4+\Lambda_2^4)}, \quad \gamma_8 = \frac{\Lambda_2^2(\Lambda_1^2(2m_\pi^2+\Lambda_1^2)-\Lambda_2^4)}{(\Lambda_1^4+\Lambda_2^4)^2(m_\pi^4+\Lambda_2^4)},$$

$$\beta = \frac{1}{\sqrt{2}}((\frac{1}{16}q^4(1-\eta^2)^2+\Lambda_2^4)^{\frac{1}{2}}+\frac{1}{4}q^2(1-\eta^2))^{\frac{1}{2}},$$

$$\theta = \frac{1}{\sqrt{2}}((\frac{1}{16}q^4(1-\eta^2)^2+\Lambda_2^4)^{\frac{1}{2}}-\frac{1}{4}q^2(1-\eta^2))^{\frac{1}{2}},$$

$$\varphi_1 = \frac{\frac{q^2}{4}(1-\eta^2)\beta-\Lambda_2^2\theta}{\beta^2+\theta^2}+\frac{q^2}{4}(1-\eta^2)r, \quad \varphi_2 = \frac{\frac{q^2}{4}(1-\eta^2)\theta+\Lambda_2^2\beta}{\beta^2+\theta^2}+\Lambda_2^2 r. \tag{50}$$

4 Results and Discussion

Calculations of the differential cross section have been done with the relative energy of the np system E_{np} = 1.5 MeV and angle of scattering $\theta = 155^0$ with the use of wave functions of the Paris potential [31].

First of all we present the calculations of the matrix elements for the individual contributions of MEC making use of the vertex form factor (21) and cut-off parameter Λ_π= 1.25 GeV.

It is seen from fig.3 that the seagull current dominates in the region $t < 30 fm^{-2}$. Then, the retardation current, curve 4, begins to appear so that at $30 < t < 35 fm^{-2}$ the situation is determined by the competition of the seagull current and retardation effects. The contribution of the meson current is small in comparison with the seagull and retardation currents.

Figure 4 shows the calculations of the matrix elements as a sum of individual contributions of MEC with allowance for the retardation current. Here, we consider

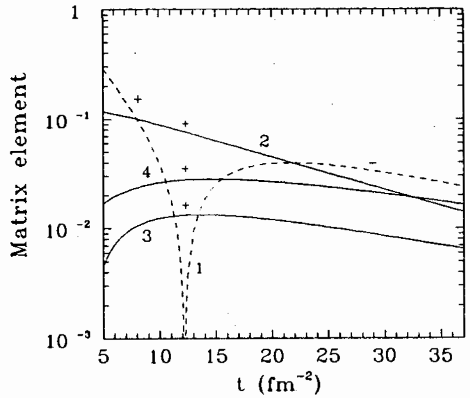

Figure 3: The dashed line 1 is the impulse approximation, 2 is the seagull current, 3 is the meson current, 4 is the retardation effects. The calculations were made with the vertex form factor (21) and Λ_π = 1.25 GeV

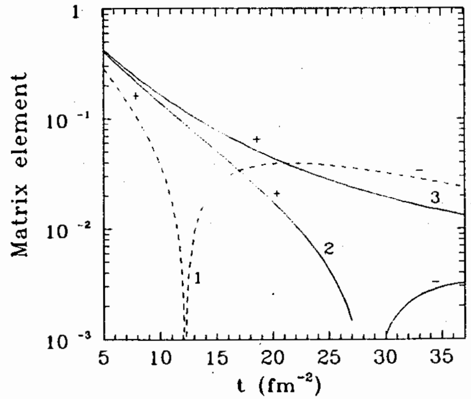

Figure 4: The dashed line 1 is the impulse approximation, 2 is the inclusion of MEC contributions (I+S+M), 3 is the inclusion of MEC with allowance for retardation effects (I+S+M+R). The calculations were made with the vertex form factor (21) and Λ_π = 1.25 GeV

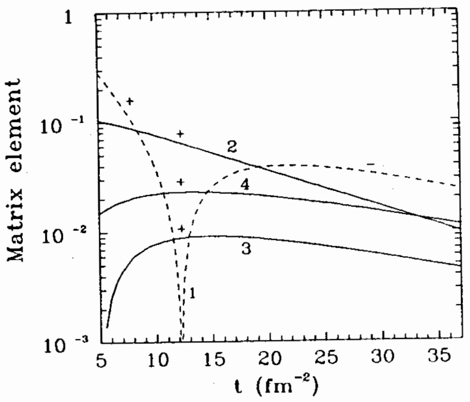

Figure 5: The notation is as in fig. 3. The calculations were made for the $\Lambda_\pi = 0.85$ GeV

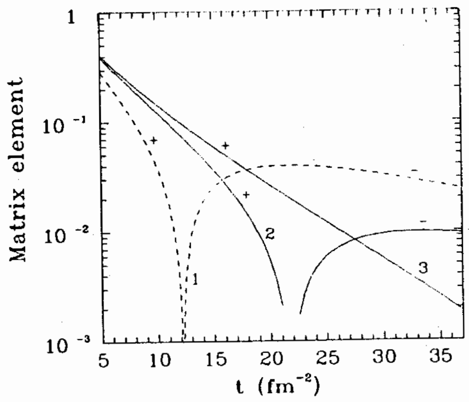

Figure 6: The notation is as in fig. 4. The calculations were made for the $\Lambda_\pi = 0.85$ GeV

the influence of the retardation effects. It is seen that the retardation effects, curve 3, that begin to appear at $t > 10 fm^{-2}$, are very noticeable at large momentum transfer.

Thus, the final result is determined by the retardation effects which increasing of the matrix element (curve 3) and eliminating the minimum dependence of the preceding calculations (curves 1, 2).

In figs.5 and 6 we show the calculations of the same matrix elements but with $\Lambda_\pi = 0.85$ GeV. In this case, the behavior of individual contributions at high transfer momenta is somewhat different. Here, the inclusion of retardation effects, in contrast with the previous result, decreases the final curve 3 in the range of $t > 27 fm^{-2}$ which is below the result with allowance for the seagull and meson currents (see fig.6).

Figures 7, 8 show the calculations of matrix elements with rapidly decreasing form factor (22). Here, the situation is close to the preceding results with certain differences at high transfer momenta that do not need special comments.

The results for the differential cross section are shown in fig. 9.

First of all we have to note that the calculation of MEC with allowance for the retardation effects with the slowly decreasing vertex form factor and cut-off parameter $\Lambda_\pi = 1.25$ GeV (curve 5) destroys the agreement with experimental results in the region of $t > 12 fm^{-2}$.

The inclusion of $\Lambda_\pi = 0.85$ GeV, curve 2, leads to the more positive result which is not in contradiction with experimental data.

Curves 3 and 4 (see (23)) show the calculations of the same differential cross section but with the rapidly decreasing vertex form factor (22). In this case, in contrast with the monopole vertex form factor, one gives the negative results which are in contradiction with experimental data in the region of $t > 14 fm^{-2}$.

It is seen that the calculations are very sensitive to the choice of the parametrization form of the vertex form factor and cut-off parameters.

Further, we shall estimate the influence of the ρNN-currents on the cross section of electrodisintegration. Following ref. [19] we determine the strong ρNN-vertex and cut-off parameter Λ_ρ. Here, $g^2_{\rho NN}/4\pi = 0.55$, $\Lambda_\rho = 1.5$GeV. Figure 10 shows the role of ρ - meson in MEC with allowance for retardation effects. It is seen (curves 2, 3) that the ρ - meson contribution is essential when the only seagull and meson currents are used. However the inclusion of retardation effects (curves 4, 5) leads to the noticeable decrease of the ρ - meson contribution at high transfer momenta.

It is to be noted that the selection of the strong ρNN-vertex and cut-off parameter Λ_ρ is a special problem the investigation of which will be undertaken in subsequent publications.

Now let us consider the radial dependence of the matrix elements on the choice of momentum t. In accordance with ref. [20], redefine matrix element for the M1-transition in the following way:

$$< {}^1S_0 \parallel T_1^{Mag} \parallel d > = i\frac{q}{\sqrt{2\pi}} \int_0^\infty \eta(r,t) dr. \tag{51}$$

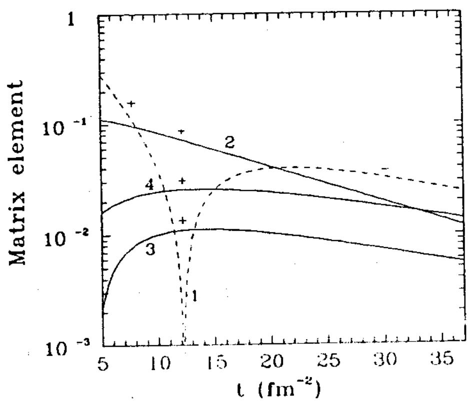

Figure 7: The notation is as in fig. 3. The calculations were made for the vertex form factor (22) and $\Lambda_\pi = 1.25$ GeV (see (23))

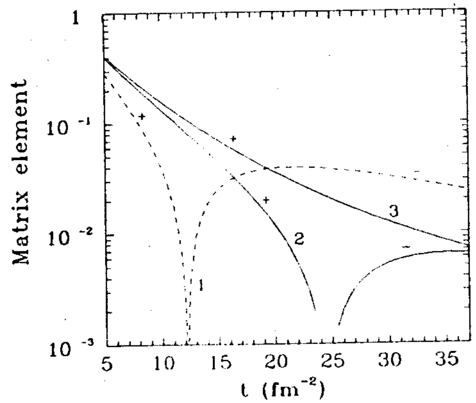

Figure 8: The notation is as in fig. 4. The calculations were made for the vertex form factor (22) and $\Lambda_\pi = 1.25$ GeV (see (23))

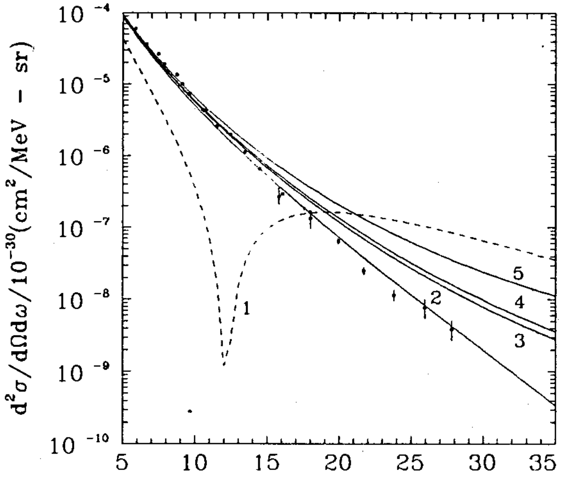

Figure 9: Differential cross section. The dashed line 1 is the impulse approximation, 2 is the calculation with the vertex form factor (21), and $\Lambda_\pi = 0.85$ GeV, 3,4 are the calculations with the vertex form factor (22) with $\Lambda_\pi = 0.85$ GeV and $\Lambda_\pi = 1.25$ GeV, respectively (see (23)), 5 is the calculation with the vertex form factor (21) and $\Lambda_\pi = 1.25$ GeV. The experimental data from ref. [32], [33]

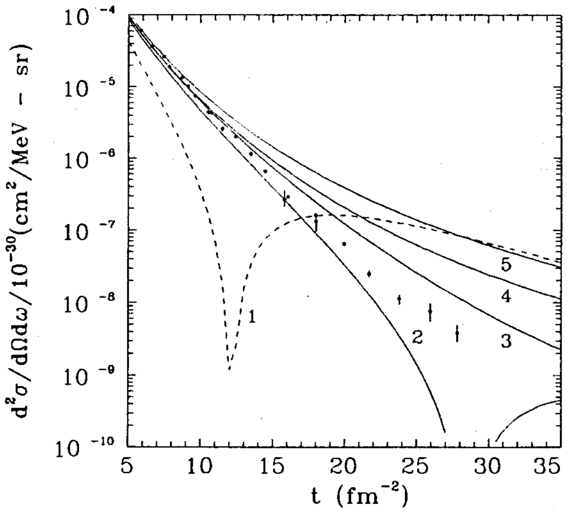

Figure 10: Differential cross section. The dashed line 1 is the impulse approximation, 2 is the inclusion of MEC contributions (I+S+M) with π - exchange, 3 is the inclusion of MEC contributions (I+S+M) with π and ρ - exchanges, 4 is the inclusion of MEC with allowance for retardation effects (I+S+M+R) with π -exchange, 5 is the inclusion of MEC with allowance for retardation effects (I+S+M+R) with π and ρ - exchanges. The calculations were made with the vertex form factor (21), $\Lambda_\pi = 1.25$ GeV and $\Lambda_\rho = 1.5$ GeV. The experimental data from ref. [32], [33]

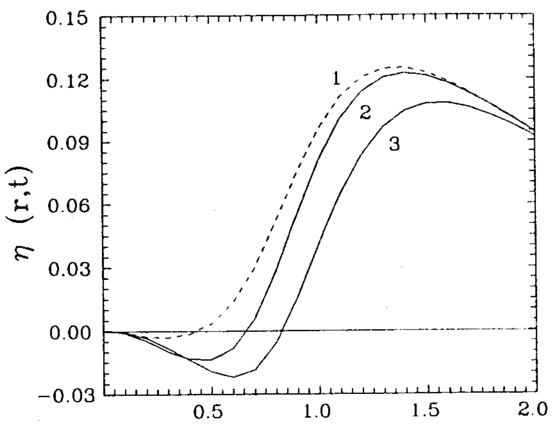

Figure 11: The dashed line 1 is the calculation for point particles. 2 is the inclusion of MEC with allowance for retardation effects (S+M+R) and Λ_π = 1.25 GeV. 3 is the inclusion of MEC with allowance for retardation effects (S+M+R) and $\Lambda_\pi = 0.85$ GeV. The calculations were made with the vertex form factor (21) and $t = 0 fm^{-2}$

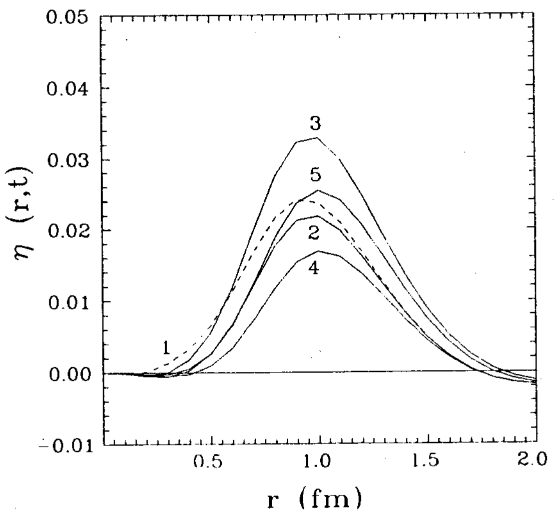

Figure 12: The dashed line 1 is the calculation for point particles. 2 is the inclusion of MEC (S+M), 3 is the inclusion of MEC with allowance for retardation effects (S+M+R). Here, Λ_π = 1.25 GeV. Calculations 4, 5 are the same as 2, 3, but for Λ_π = 0.85 GeV. The calculations were made with the vertex form factor (21) and $t = 30 fm^{-2}$

We shall devote the following discussion to the radial function $\eta(r,t)$. Figures 11, 12 show the calculations of the radial function $\eta(r,t)$ for the vertex form factor (21) with $\Lambda_\pi = 1.25$ GeV and $\Lambda_\pi = 0.85$ GeV for momenta transfer $t = 0 fm^{-2}$ and $t = 30 fm^{-2}$.

First of all we have to emphasize that if $t = 0 fm^{-2}$, the retardation effects are absent (curves 2, 3). In this case, curves 2 and 3 are absolutely identical to the calculation without the retardation current.

The total result dominates in the range of relative distances of about 1.4 fm for $\Lambda_\pi = 1.25$ GeV and 1.5 fm for $\Lambda_\pi = 0.85$ GeV.

However, the retardation effects are more manifest in the calculations at large transfer momenta.

Comparing the result obtained with allowance for the retardation effects fig. 12 (curve 3, 5) with the analogous calculation with the use of the seagull and meson currents, curve 2 and 4, we see that the retardation effects give a considerable contribution at $t = 30 fm^{-2}$. Here, the considered set of meson exchange currents dominates in the range of about 1 fm, which is not in contradiction with the previous result of ref.[20].

5 Conclusion

The investigation of the electrodisintegration of the deuteron near threshold with allowance for the retardation effects in MEC allows us to make the following conclusions:

1. All the contributions of meson exchange currents should be taken into account including the retardation effects.

2. It is very important to take the retardation effects into account at large transfer momenta ($t > 12 fm^{-2}$).

3. The calculations are very sensitive to the choice of the value of the cut-off parameters and are strongly dependent on the vertex form factors.

4. The influence of the ρ - meson contribution in MEC is noticeably decreasing when the retardation effects are taken into account.

5. The meson exchange currents dominate when the relative distance between two nucleons is of about 1 - 1.5 fm ($t < 30 fm^{-2}$).

6. Generally speaking, the calculations of the differential cross section with allowance for the retardation effects at large transfer momenta give the situation where other degrees of freedom are to be taken into account.

7. Moreover, for the analysis not only the inclusion of different degrees of freedom, but also the structure of NN interaction is of great importance. For this case the calculations within the "exact" nonphenomenological potentials modelling NN interaction as a result of the exchange by different mesons are of particular interest. The Bonn potential [34] can serve as an example of these potentials. The theoretical calculations of the electrodisintegration with the use of the Bonn potential will be the subject of our future investigation.

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