Meson retardation in deuteron photodisintegration above 
\(\pi\)-threshold \(^\dagger\)

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Abstract

Photodisintegration of the deuteron above \(\pi\)-threshold is studied in a coupled channel approach including \(N\Delta\)- and \(\pi d\)-channels with pion retardation in potentials and exchange currents. A much improved description of total and differential cross sections in the energy region between \(\pi\)-threshold and 400-450 MeV is achieved.

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I. INTRODUCTION

Despite its long history, photodisintegration of the deuteron is still a very intensely studied process. In the past decades, large efforts were made in order to understand this simplest photonuclear reaction. At energies below \(\pi\)-threshold, where the theory is based on realistic \(NN\)-interaction models and corresponding exchange currents, the agreement between theory and experiment is quite satisfactory \(^2\). On the contrary, in the \(\Delta\)-resonance region where the \(\Delta\)-excitation is dominant, the situation is much

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less well settled (for a review see [1]). None of the models developed so far such as the
diagramatic approach of Laget [1], the framework of nuclear isobar configurations in
the impulse approximation [5], the unitary three-body model [3] and the coupled channel
approach (CC) [7,8] is able to describe in a satisfactory manner the experimental data
over the whole ∆-resonance region [9,10]. In the impulse approximation [5] and also in
the CC approach of [7], several parameters were adjusted in order to fit the total cross
section whereas in the three-body model of [3] and in the coupled channel approach of
[8] all free parameters were fixed in advance by fitting NN- and πN-scattering, and π-
photoproduction on the nucleon. Consequently, no adjustable parameters remained for
deuteron photodisintegration. However, it turned out that both approaches considerably
underestimated the total cross section in the ∆-region by about 20-30% [3,8]. Another
failure was the wrong shape of the differential cross section which was flatter than the
experimental one and which developed a more and more pronounced dip around 90°
with increasing energy. Also the photon asymmetry was not well described, especially at
photon energies above 300 MeV [3,8].

One of the crucial points in these calculations is the question of how to fix the γNΔ-
coupling $G_{ΔN}^{M1}(E_Δ)$ in the $M1 NΔ$-current

$$\vec{j}_{ΔN}^{M1}(E_Δ, \vec{k}) = \frac{G_{ΔN}^{M1}(E_Δ)}{2M} \tau_{ΔN,0} i \vec{σ}_{ΔN} × \vec{k}, \quad (1)$$

where $E_Δ$ is the energy available for the internal excitation of the Δ and $\vec{k}$ the momen-
tum of the incoming photon. While in the impulse approximation and also in [4] the
whole $P_{33} M1$-strength was interpreted as Δ-excitation strength, the more sophisticated
approaches [3,8] have determined $G_{ΔN}^{M1}$ by fitting the $M1+(3/2)$-multipole of pion photo-
production on the nucleon including nonresonant Born terms, resulting in a smaller $G_{ΔN}^{M1}$
and consequently a smaller photodisintegration cross section. The Born terms contribut-
ing to the (3,3)-channel are the crossed $N$-pole and π-pole graphs. When embedded into
the two-nucleon system, these Born terms become part of the recoil and the π-meson cur-
rent, respectively (Fig. [1]). In static calculations, however, the recoil current is not present
due to its cancellation against the wave function renormalization current [11]. A similar, but less serious problem arises in the treatment of the pion pole diagrams compared to the meson current of static MEC. It had already been conjectured in [8] that this inconsistent treatment of pion exchange may lead to the observed underestimation of the total cross section in their coupled channel approach, because by incorporating the Born terms effectively into an increased $M1 \Delta$-excitation strength a satisfactory agreement with the data could be achieved.

In the present paper, we have overcome these shortcomings by including for the first time in a coupled channel approach complete retardation in the $\pi$-exchange contributions to potentials and MECs. This retardation is not approximated by keeping only the leading order contribution of a $p/M$-expansion in the $\pi NN$-propagators as was done for example in [12,13]. We furthermore consider the intermediate $\pi d$-channel in order to ensure all unitarity constraints up to the $2\pi$-threshold.

II. THEORETICAL FRAMEWORK

In our framework, the Hilbert space is subdivided into three orthogonal spaces $H = H_N \oplus H_\Delta \oplus H_Q$ [14]. $H_N$ consists of two nucleons only, in $H_\Delta$ one of the nucleons is replaced by a $\Delta(1232)$-isobar, and $H_Q$ contains at least one meson besides two baryons. $H_Q$ is then eliminated by introducing effective operators in $H_N \oplus H_\Delta$ using the projection operator technique.

For photodisintegration we need the outgoing $NN$-scattering wave with total energy $E$ which can be expressed as

$$|NN^{(-)}\rangle = \left[1 + G_0^N(z)T_{NN}(z) + G_0^\Delta(z)T_{\Delta N}(z)\right]|NN\rangle, \quad z = E - i\epsilon. \tag{2}$$

The $T$-matrix obeys a coupled integral equation of Lippmann-Schwinger type

$$T_{NN}(z) = V_{NN}(z) + \bar{V}_{NN}(z)G_0^N(z)T_{NN}(z) + \bar{V}_{NN}(z)G_0^\Delta(z)T_{\Delta N}(z), \tag{3}$$

$$T_{\Delta N}(z) = \bar{V}_{\Delta N}(z) + \bar{V}_{\Delta N}(z)G_0^N(z)T_{NN}(z) + \bar{V}_{\Delta N}(z)G_0^\Delta(z)T_{\Delta N}(z). \tag{4}$$
Here, $G_0^N(z)$ denotes the free $NN$-propagator and $G_0^\Delta(z)$ the dressed $N\Delta$-propagator, which depends on the bare $\Delta$-mass $M_0^\Delta$ and the complex, energy dependent $\Delta$-self energy $\Sigma_\Delta$ taken from the dynamical model of Tanabe and Ohta (model A in \[15\]).

The various effective driving potentials $\tilde{V}_{XX'}$ with $X, X' \in \{N, \Delta\}$ in Eqs. (3) and (4) consist of two terms (Fig. 2)

\[
\tilde{V}_{XX'}(z) = V_{XX'}(z) + V_{XX'}^{\pi d}(z),
\]

incorporating respectively the usual boson-exchange mechanism and the formation of an interacting $NN$-pair with deuteron quantum numbers and a pion as a spectator (denoted for simplicity by $\pi d$). In static applications, we have chosen for $V_{NN}(z)$ the realistic, energy independent Bonn-OBEPR model \[16\], whereas for the inclusion of full $\pi$-retardation we have used an improved version of the energy dependent Bonn-OBEPT model developed by Elster et al. \[17\] which contains besides retarded operators also self energy diagrams calculated within a simple Lee model \[18\].

For $V_N^\Delta$ and $V_\Delta^N = V_N^{\pi \Delta}$, we have constructed corresponding static and retarded $\pi$- and $\rho$-exchange potentials, taking for the $\pi NN$- and $\pi N\Delta$-form factors the ones of the full Bonn potential \[16\]. The $\rho NN$- and $\rho N\Delta$-regulator masses are fixed by fitting the $^1D_2$ $NN$-partial wave which is of crucial importance for deuteron photodisintegration because of its strong coupling to the dominant $^5S_2(N\Delta)$ partial wave. The diagonal interaction $V_{\Delta\Delta}$ in $\mathcal{H}_\Delta$ consists of the 'forward' and 'backward' going pion diagrams as depicted in Fig. 2. For its $\pi N\Delta$-vertex, the form factor of \[15\] is used.

We now turn to the discussion of $V_{XX'}^{\pi d}$, which was studied in \[6\] but not included in \[8\]. From the corresponding diagram of Fig. 2 it is obvious that $V_{XX'}^{\pi d}$ can be written as

\[
V_{XX'}^{\pi d}(z) = V_{X'Q}G_0^{\pi NN, stat}t_{QQ}^{\pi d}(z)G_0^{\pi NN, stat}V_{QQ'} ,
\]

where $V_{X'Q}$ is the nonrelativistic $NN\pi$- or $N\Delta\pi$-vertex, respectively. The free $\pi NN$-propagator $G_0^{\pi NN, stat}$ is taken in the static limit and $t_{QQ}^{\pi d}(z)$ denotes the $NN$-scattering amplitude in $Q$-space describing an intermediate off-shell $NN$-state with the quantum
numbers of the deuteron and a pion as spectator. The amplitude \( t_{QQ}^{\pi d}(z) \) is obtained from the Lippmann-Schwinger equation

\[
t_{QQ}^{\pi d}(z) = v^{\pi d} + v^{\pi d} G_0^{\pi d}(z) t_{QQ}^{\pi d}(z) ,
\]

where \( G_0^{\pi d} \) denotes the free \( \pi d \)-propagator. It can be solved easily by assuming a separable form for the driving term \( v^{\pi d} \)

\[
v^{\pi d} = \frac{V_{NN}(E^{\pi d})|d\pi; \vec{q} \rangle \langle d\pi; \vec{q} \mid V_{NN}(E^{\pi d})|d\pi; \vec{q} \rangle}{\langle d\pi; \vec{q} \mid V_{NN}(E^{\pi d})|d\pi; \vec{q} \rangle} \quad \text{with} \quad E^{\pi d} = \frac{q^2}{4M} + \sqrt{m_\pi^2 + q^2} ,
\]

where \( |d\pi; \vec{q} \rangle \) denotes a free \( \pi d \)-state with relative momentum \( \vec{q} \). This ansatz for \( v^{\pi d} \) satisfies for any realistic \( NN \)-potential \( V_{NN} \) the Schrödinger equation for the \( \pi d \)-state

\[
G_0^{\pi d}(E^{\pi d}) v^{\pi d} |d\pi; \vec{q} \rangle = |d\pi; \vec{q} \rangle .
\]

Since the parameters of the realistic \( V_{NN} \) are fitted to deuteron properties and \( NN \)-scattering phases without explicit coupling to the \( N\Delta \) and \( \pi d \)-channels, we have to apply a box-renormalization \([14]\)

\[
V_{NN}(z) \rightarrow V_{NN}(z) - \tilde{V}_{N\Delta}(2M) G_0^{\Delta}(2M) \tilde{V}_{N\Delta}(2M) - V_{NN}^{\pi d}(2M)
\]

in order to ensure an approximate phase equivalence in the presence of these additional channels.

Now we turn to the e.m. part of our model. Above \( \pi \)-threshold, the \( \Delta \)-excitation is the most important photoabsorption mechanism, which is described by the current operator in Eq. \([11]\) neglecting small E2 contributions. As mentioned above, \( G_{\Delta N}^{M_1}(E_{\Delta}) \) is an energy dependent and complex coupling which is fitted to the experimental \( M_{1+}(\frac{3}{2}) \)-multipole of pion photoproduction on the nucleon. It contains besides the bare \( \gamma N\Delta \)-coupling contributions from nonresonant pion rescattering. The full pion photoproduction amplitude \( t_{\pi \gamma}(E_{\Delta}) \) in the \((3,3)\)-channel can be written as

\[
t_{\pi \gamma}^{\pi}(E_{\Delta}) = t_{\pi \gamma}^{B}(E_{\Delta}) - \frac{\gamma_{\Delta}^{\pi} \cdot \vec{j}_{\Delta N}^{M_1}(E_{\Delta}, \vec{E})}{E_{\Delta} - M_{\Delta}^{\pi} - \Sigma_{\Delta}(E_{\Delta})} ,
\]

5
where $t^{B}_{\pi\gamma}(E_{\Delta})$ is the nonresonant Born amplitude. While in \cite{8} an effective $\gamma N\Delta$-coupling $G^{M_{1+}}_{\Delta N}(E_{\Delta})$ and the model of \cite{14} for the bare $\Delta$-mass $M_{\Delta}^0$, the $\Delta$-self energy $\Sigma_{\Delta}$ and the $\Delta\pi N$-vertex $v_{\Delta}^\dagger$ has been used, we follow here the work of Tanabe and Ohta (model A in \cite{15}) in which an explicit evaluation of the half-off-shell Born amplitude in the $M_{1+}(3/2)$-multipole has been performed.

Furthermore, concomitant with the construction of the effective interactions, we have derived the corresponding effective two-body charge and current density operators which fulfil current conservation (for details, see \cite{19}). These $\pi$-retarded MECs contain besides the usual vertex-, meson- and contact-MECs the recoil current and charge densities and a couple of additional two-body operators which vanish identically in the static limit. Whereas the latter ones yield only very small contributions which can be safely neglected, the recoil contributions turn out to be quite important (see discussion below). They do not appear in static approaches due to their cancellation against the wave function renormalization contributions \cite{11}, which have their origin in the renormalization of the baryonic states when eliminating the mesonic wave function components. This concept breaks down beyond the $\pi$-threshold if full $\pi$-retardation is considered since the $\pi NN$-component can be on-shell. Therefore, we do not orthonormalize and no wave function renormalization contributions appear. Consequently, the recoil current and charge densities have to be included.

Besides the $\pi$-MECs and the corresponding Siegert operators, our model includes the usual nucleonic one-body current and as most important relativistic contribution (besides retardation) the spin-orbit current. Because the $\rho$-mass is rather large, retardation in the $\rho$-MEC is expected to be rather unimportant and therefore not considered in this work. Concerning the $N\Delta\pi$-MEC, we include retardation in the corresponding recoil part, whereas, due to their minor importance, the contact-, meson- and vertex-contributions are taken in the static limit. Since the pion production model of Tanabe and Ohta \cite{15} effectively incorporates $\omega$-exchange, we include in addition the leading order $\rho\pi\gamma$- and
III. RESULTS

In the numerical evaluation we have included all multipoles and scattering waves up to \( L = 4 \) and \( j = 4 \). Retardation in the meson-, vertex-, contact- and \( \rho \pi \gamma/\omega \pi \gamma \)-currents is only included up to \( L = 2 \). For the higher multipoles the static limit has been adopted, because inclusion of retardation effects there does not show significant effects on observables. We start the discussion of deuteron photodisintegration with the total cross section shown in Fig. 3. Similar to [8,9], the static calculation (without \( \pi d \)-channel and \( \rho \pi \gamma/\omega \pi \gamma \)-MECs) considerably underestimates the data (dotted curve). However, the \( \gamma N \Delta \)-coupling of [15] used in our approach is somewhat larger than the one used by Wilhelm et al., so that the discrepancy between our static calculation and experiment is not as dramatic as in [8,9]. The reduction of the cross section by the inclusion of retardation in the hadronic interaction (dash-dotted curve) is, however, overcompensated if retardation in the \( \pi \)-MECs is added, of which the recoil contributions turn out to be the most important ones. This destructive interference of retardation in potential and recoil current corresponds to the cancellation of wave function renormalization and recoil current in the static limit. However, here remains a net effect leading to a significant increase. The cross section is further enhanced by inclusion of the \( \pi d \)-channel and the \( \rho \pi \gamma/\omega \pi \gamma \)-MECs (by about 8% respectively 3% at 260 MeV) so that the complete calculation (full curve) agrees quite well with the experimental data over the whole energy range.

Concerning the role of the \( \pi d \)-channel in \( NN \)-scattering, its influence on the inelasticity of the \( ^1D_2 \)-channel is similar to [8]. However, in contrast to our result of a slight enhancement, the \( \pi d \)-channel leads in [8] to a reduction of the cross section in \( \gamma d \to pn \), the reason for which we are presently investigating.

In Figs. 4 and 5, we show differential cross sections and photon asymmetries for various energies. Whereas now the differential cross section is in satisfactory agreement with the
data, we slightly underestimate the absolute size of the asymmetry. In contrast to [8] we
are able to reproduce quite well the shape of these two observables also at higher energies,
in particular the dips in the angular distributions have disappeared.

In conclusion, we have demonstrated that a CC approach including $N\Delta$- and $\pi d$-
channels with full pion retardation in potentials and exchange currents is able to remove
almost quantitatively the still existing discrepancies between theory and experiment in
deuteron photodisintegration in the $\Delta$-region. Further improvements of our model should
include relativistic contributions to internal dynamics and currents whereas boost effects
are expected to be small [20]. Furthermore, a realistic $N N$-interaction is desirable which
includes isobar degrees of freedom in a coupled channel approach from the beginning so
that no box renormalization procedure is necessary. The success of our model in $\gamma d \rightarrow N N$
encourages us to study retardation in related e.m. processes on the deuteron in the near
future, like $\pi$-photoproduction and electrodisintegration.

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FIGURES

FIG. 1. The Born terms contributing to the $M_{1+}(3/2)$-multipole amplitude of pion photoproduction (upper part) and their correspondence in the recoil and pion-MECs in deuteron photodisintegration (lower part).

FIG. 2. Graphical representation of the hadronic interaction of Eq. (5) with $X, X' \in \{N, \Delta\}$.

FIG. 3. Total cross section for $\gamma d \rightarrow pn$ as a function of photon energy $E_\gamma$ in comparison with experiment \cite{9,10}. Dashed: static calculation of Wilhelm et al. \cite{9}; dotted: static OBEPR-calculation in our approach; dash-dot: retardation switched on in the hadronic part only, but static MECs; full: complete calculation including $\pi d$-channel and $\rho \pi \gamma/\omega \pi \gamma$-MECs.
FIG. 4. Differential cross sections for various energies in comparison with experiment [9,10].

Notation of the curves as in Fig. 3.

FIG. 5. Photon asymmetry $\Sigma$ for various energies in comparison with experiment [9,21,22].

Notation of the curves as in Fig. 3.