The Two-Nucleon System beyond the Pion Threshold

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Abstract. A model is developed for the hadronic and electromagnetic interaction in the two-nucleon system above pion threshold in the framework of meson, nucleon and \( \Delta \) degrees of freedom. It is based on time-ordered perturbation theory and includes full meson retardation in potentials and exchange currents as well as loop contributions to the nucleonic one-body current. Results for some selected processes are discussed.

1 Introduction

At present, a very interesting topic in the field of medium energy physics is devoted to the role of effective degrees of freedom (d.o.f.) in hadronic systems in terms of nucleon, meson and isobar d.o.f. and their connection to the underlying quark-gluon dynamics of QCD. For the study of this basic question, the two-nucleon system provides an important test laboratory, because it is the simplest system for the study of the nucleon-nucleon interaction, the role of medium effects due to two-body operators and the relevance of off-shell effects, i.e. the change of single particle properties in the nuclear medium. Moreover, the deuteron is of specific relevance as an effective neutron target. Within the present effective description, one is able to obtain a reasonable, though not perfect description of the possible hadronic and electromagnetic reactions in the two-nucleon sector below \( \pi \) threshold. However, for energies beyond \( \pi \) threshold up to the \( \Delta \) region additional complications occur. Present state-of-the-art models should incorporate not only a realistic NN interaction, but also a dynamical treatment of the \( \Delta \) isobar. Moreover, in view of the requirement of unitarity, the various possible reactions should be described within one consistent framework, because they are linked by the optical theorem. In the past, we have started to realize this ambitious project within a retarded coupled channel \( NN - N\Delta \) approach, based on a three-body scattering approach with nucleon, \( \Delta \) and meson degrees of freedom.

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2 The Model

For energies up to the \( \Delta \) region, our model Hilbert space \( \mathcal{H}^{[2]} \) consists of three orthogonal subspaces \( \mathcal{H}^{[2]} = \mathcal{H}^{[2]}_N \oplus \mathcal{H}^{[2]}_\Delta \oplus \mathcal{H}^{[2]}_X \), where \( \mathcal{H}^{[2]}_N \) contains two (bare) nucleons, \( \mathcal{H}^{[2]}_\Delta \) one nucleon and one \( \Delta \) resonance, and \( \mathcal{H}^{[2]}_X \) two nucleons and one meson \( X \in \{ \pi, \rho, \sigma, \delta, \omega, \eta \} \).

Concerning the hadronic part, the basic interactions in our model are \( XNN \) and \( \pi N \Delta \) vertices. Inserting these into the Lippmann-Schwinger equation, one obtains after some straightforward algebra \[3\] effective hadronic interactions acting in \( \mathcal{H}^{[2]}_N \oplus \mathcal{H}^{[2]}_\Delta \) which contain, apart from pion-nucleon loop contributions to the nucleonic self energy, \textit{retarded} one-boson exchange (OBE) mechanisms describing the transitions \( NN \to NN, NN \to N \Delta \) and \( N \Delta \to N \Delta \). Due to the nonhermiticity and nonlocality of a retarded operator, which becomes moreover complex above pion threshold, in most applications the simple static approximation is used by neglecting the energy transfer by the exchanged meson. The corresponding static operators are much easier to handle, but one encounters on the other hand at least two serious problems. Above pion-threshold, unitarity is violated due to the absence of singularities in the static operators. Moreover, in the past it turned out that even the simplest photonuclear reaction, namely deuteron photodisintegration, cannot be described even qualitatively within a consistent static framework \[4, 5\].

In our explicit realization, we use for the retarded \( NN \) interaction the Elster potential \[8\] which takes into account in addition one-pion loop diagrams in order to fulfill unitarity above pion threshold. Therefore, one has to distinguish between bare and physical nucleons (see \[3\] for details). Concerning the transitions \( NN \to N \Delta \) and \( N \Delta \to N \Delta \), we take besides retarded pion exchange static \( \rho \) exchange into account. Moreover, the interaction of two nucleons in the deuteron channel in the presence of a spectator pion (the \( \pi d \) channel) is also considered. This mechanism is necessary for satisfying unitarity, because otherwise no asymptotic free \( \pi d \) state would exist. By a suitable box renormalization \[9\], we are able to obtain approximate phase equivalence between the Elster potential and our coupled channel approach below pion threshold.

Similarly, the basic electromagnetic interactions consist of baryonic and mesonic one-body currents as well as vertex and Kroll-Rudermann contributions \[4, 5\]. These currents are, together with the \( \pi NN \) vertex, the basic building blocks of the corresponding effective current operators. The latter contain beside the ordinary spin-, convection- and spin-orbit currents full retarded pionic meson exchange currents and electromagnetic loop contributions, where the latter can be interpreted as off-shell contributions to the baryonic one-body current \[8\]. Moreover, static \( \rho \) MEC as well as \( \Delta \) MEC contributions are taken into account. It can be shown \[8\] that concerning the pionic part gauge invariance is fulfilled in leading order of \( 1/M_N \). This is a consequence of the fact that the hadronic pion-nucleon loop contributions, the retarded \( \pi \)-exchange contribution to the NN interaction, the electromagnetic loop contributions, and the \( \pi \) MEC are based on the same \( \pi NN \) vertex.
3 Results

The hadronic $\Delta$ parameters and the M1 $\gamma N \Delta$ coupling are simultaneously fitted to the $M_{1+}(3/2)$ multipole of pion photoproduction on the nucleon, to the $P_{33}$ channel of pion-nucleon scattering and to the $1D_2$ channel of nucleon-nucleon scattering [3, 4]. In Fig. 1, our results for the $1D_2$ phase shift and inelasticity are depicted. We obtain a good description at least up to about $T_{lab} = 800$ MeV. This is of particular relevance for deuteron photodisintegration where the most important contribution to the unpolarized cross section in the $\Delta$ region comes from the $1D_2$ channel. Concerning the other partial $NN$ waves, the overall description is only fairly well [3]. Therefore, we have started to construct from scratch an interaction model whose parameters are fitted to the phase shifts and inelasticities of all relevant $NN$ partial waves for energies up to about 1 GeV. However, as of yet we have not found a parameter set which would lead to a considerable improvement. One reason for this failure may be the fact that our effective baryon-baryon model is basically a one-boson exchange model which does not take into account more complicated mechanisms like the crossed two-pion-exchange. Moreover, the $\pi N$ interaction has to be improved. Forthcoming studies on that topic are essential, especially for clarifying the role of final state interactions (FSI) in hadronic and electromagnetic breakup reactions on the deuteron for energies beyond the $\pi$ threshold.

As next, we discuss very briefly deuteron photodisintegration. The starting point of our consideration is the static approach of Wilhelm et al. [7] which is based on the Bonn-OBEPR potential [10]. Similar to our present approach, there is no free parameter in the calculation of the photodisintegration process in [7]. As is evident form Fig. 2, Wilhelm et al. clearly fail in describing the data. One obtains a considerable underestimation of the cross section in the $\Delta$ peak. Moreover, a dip structure around $90^\circ$ occurs at higher energies which is not present in the data. This feature is also present in other static approaches like the unitary three-body model of Tanabe and Otha [6]. On the other hand, these

![Figure 1](image-url).

**Figure 1.** Phase shift $\delta$ and inelasticity $\rho$ for the $1D_2 NN$-channel in comparison with experiment (solution SM97 of Arndt et al. [11]) for two potential models: dash-dotted curve: static approach, based on the Bonn-OBEPR potential [10], full curve: retarded approach. See [3] for further details.
Differential cross section of deuteron photodisintegration for two photon energies $k_{lab}$ as function of the c.m. proton angle $\theta_p$: dotted curve: result of Wilhelm et al. in static approach, full curve: retarded approach of [4]. Offshell contributions to the nucleonic one-body current are included, too [5]. Experimental data from [12] (●), [13] (open box) and [14] (○).

Problems in the differential cross section vanish almost completely in a retarded approach [4, 5]. However, some discrepancies in polarization observables like the linear photon asymmetry $\Sigma$ or the polarization $P_y(p)$ of the outgoing proton are still present [4, 5]. It is known that polarization observables may be sensitive to small reaction mechanisms which are suppressed in the unpolarized cross section. Therefore, we assume that the failure of our model in describing $\Sigma$ and $P_y(p)$ may be attributed to the present treatment of the hadronic interaction which needs to be improved as has been outlined above.

A very interesting topic is the exploration of the spin asymmetry of the total cross section of the nucleon and light nuclei which determines the GDH-sum rule [15, 16]

$$I_{GDH} = \int dk \frac{\sigma^P(k) - \sigma^A(k)}{k} = 4\pi\kappa^2 \frac{e^2}{M^2 S}$$

and which is at present under investigation experimentally [17]. In (1), $\sigma^{P/A}(k)$ denotes the total photoabsorption cross section on a target with mass $M$, spin $S$ and anomalous magnetic moment $\kappa$ with the photon spin parallel (antiparallel) to the target spin.

Due to the lack of a free neutron target, a measurement of the GDH-sum rule on the deuteron is of specific significance because it has been suggested in the past that one can measure the spin asymmetry of the total photoabsorption cross section of the neutron by using light nuclei like the deuteron. This would rest on the assumptions that (i) the polarized deuteron constitutes an effective polarized neutron target and (ii) one has to suppose that the spin asymmetry on the deuteron is dominated by the quasi free pion-production, so that binding and FSI effects from the presence of the spectator nucleon can be neglected, resulting in an incoherent sum of proton and neutron contributions.

However, both assumptions are questionable. First of all, due to the existence of the $D$ state component in the deuteron wave function, even in a
Figure 3. Preliminary result for the spin asymmetry on the deuteron within our retarded approach as a function of the photon energy $k_{lab}$ in the laboratory frame. The dotted curve shows the result within a simple spectator approach. In the dashed-dotted curve, hadronic backscattering mechanisms are added. In the full curve, additional two-body meson exchange currents are taken into account. A part of the Born term contributions in pion production has been neglected.

completely polarized deuteron target, the neutron is not completely polarized. With respect to the second assumption, one has to recall that, in contrast to the nucleon case, for the GDH-integral on the deuteron also the energy region below $\pi$ threshold has to be taken into account due to the existence of the breakup channel $\gamma d \rightarrow NN$ which is absent in the photoabsorption on a free nucleon. As has been pointed out in [18], there exists a strong anticorrelation between pion production and photodisintegration, because the latter reaction yields a very large negative contribution to the GDH-integral in (1) near the breakup threshold. This fact explains at least partially the large difference between the GDH-value on the deuteron ($I_{d}^{GDH} = 0.65 \, \mu b$) and the sum of the GDH-value on proton and neutron yielding 438 $\mu b$. Moreover, the effect of final state interactions in $\pi$ production on the deuteron cannot at all be neglected [19] so that a simple spectator model picture is not appropriate for the evaluation of the spin asymmetry on the deuteron.

Due to these facts, it is obvious that an extraction of the neutron amplitude from the deuteron reaction cannot be performed in a model independent manner. Nevertheless, the experimental investigation of the GDH-sum rule on the deuteron is very important because the measurement of the spin asymmetry is for itself of great interest since it will give us much more detailed information on the underlying dynamics than just the unpolarized cross section. Therefore, it may serve in the future as a stringent test for existing models (see for example Fig. 3) in the two-nucleon sector.
4 Outlook

In the future, we plan to apply the present model to other reactions, especially electrodisintegration. Conceptually, we have to improve our hadronic interaction model. Moreover, additional d.o.f. like the Roper, the $D_{13}$ and the $S_{11}$ resonances should be taken into account if one wants to consider higher energies.

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