The two-nucleon system in the $\Delta$ region including full meson retardation †

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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 $NN$ scattering and deuteron photodisintegration are presented.

I. 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 nuclear system for the study of the nucleon-nucleon interaction. Moreover, the role of medium effects due to two-body operators and the role of offshell effects, i.e. the change of single particle properties in the nuclear medium, can be investigated most precisely.

State-of-the-art models for describing hadronic and electromagnetic reactions on the two-nucleon system up to the $\Delta$ region should incorporate – among other things – a dynamical treatment of the $\Delta$ isobar. Moreover, gauge invariance and unitarity should be fulfilled at least approximately. Within a unitary model, the various possible reactions cannot be treated independently, because they are linked by the optical theorem. For example, for energies up to the two-pion threshold the forward Compton scattering amplitude is related via

$$\text{Im} T(\gamma d \rightarrow \gamma d; \theta = 0) \sim \sigma_{\text{tot}}(\gamma d \rightarrow NN, \pi d, \pi NN)$$

(1)

to the sum of the cross sections of photodisintegration and coherent and incoherent pion photoproduction. Therefore, all reactions on the two-nucleon system should be described within one consistent framework. In the past years, we have started to realize this ambitious project within a retarded coupled channel $NN/N\Delta$-approach based on three-body scattering theory with nucleon, $\Delta$ and meson degrees of freedom [1–5].

II. THE MODEL

In order to motivate why retardation should be taken into account above pion threshold, let us consider an arbitrary two-body meson-exchange operator like the ordinary one-pion exchange potential. In time-ordered perturbation theory, the propagation of the intermediate $\pi NN$ system is described by the retarded propagator $G_0^{\text{ret}}(E + i\epsilon) = (E + i\epsilon - H_0)^{-1}$, where $E$ is the invariant energy of the system and $H_0$ denotes the kinetic Hamilton operator for the intermediate $\pi NN$ system. Due to its nonhermiticity, nonlocality and the existence of singularities above pion threshold, an exact treatment of $G_0^{\text{ret}}$ is quite complicated. Therefore, in most practical applications a low energy approximation, the so-called static limit is used by neglecting the energy transfer between the nucleons by the pion. The corresponding propagator $G_0^{\text{stat}}$ is much easier to handle. One encounters on the other hand at least two serious problems. Above pion-threshold, unitarity is violated due to the absence of singularities in $G_0^{\text{stat}}$. 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 [6–8].

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For incorporating retardation, the mesons generating the nucleon-nucleon interaction and the meson-exchange currents have to be treated as explicit degrees of freedom. Therefore, the model Hilbert space consists then 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 the desired retarded one-boson exchange (OBE) mechanisms describing the transitions $NN \rightarrow N\Delta$, $NN \rightarrow N\Delta$ and $N\Delta \leftrightarrow N\Delta$. This strategy of starting with vertices as basic interaction terms in the enlarged Hilbert space $\mathcal{H}[2]$ has the advantage that no inconsistencies occur. In this context, note especially that the vertices are hermitean. On the other hand, if one started with a retarded OBE as basic interaction in $\mathcal{H}[2]^N \oplus \mathcal{H}[2]^{\Delta}$, one would loose hermiticity and therefore the solid grounds of quantum mechanics.

In our explicit realization, we use for the parametrization of the retarded $NN$ interaction the Elster potential [3] 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 $NN \rightarrow N\Delta$ and $N\Delta \leftrightarrow N\Delta$, we take besides retarded pion exchange static $\rho$ exchange into account. Moreover, the interaction of two nucleons in the deuteron channel in presence of a spectator pion (the so-called $\pi d$ channel) is also considered. By a suitable box renormalization [3], 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 [3,4]. 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 current 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 [3,4]. Moreover, static $\rho$ MEC as well as $\Delta$ MEC contributions are taken into account. It can be shown [3,4] that concerning the pionic part gauge invariance is fulfilled in leading order of $1/M_N$.

III. 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, the $P_{33}$ channel in pion-nucleon scattering and the $^1D_2$ channel in nucleon-nucleon scattering [3,4]. In Fig. [3], 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. Concerning the other partial $NN$ waves, the overall description is fairly well but needs some further improvement in the future [3,4]. Therefore, at present we are constructing from scratch an improved hadronic interaction model whose parameters are fitted to the phase shifts and inelasticities of all relevant $NN$ scattering partial waves for $T_{lab}$ energies up to about 1 GeV.

As next, we discuss very briefly deuteron photodisintegration. The starting point of our consideration is the static approach of Wilhelm et al. [3] which is based on the Bonn-OBEPR potential [3]. Similar to our present approach, there is no free parameter in the calculation of the photodisintegration process in [3]. As is evident from 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. On the other hand, these problems in the differential cross section vanish almost completely in a retarded approach [3,4]. 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, and which need further consideration [3,4].

IV. OUTLOOK

A very interesting topic to be studied in the future is the exploration of the spin asymmetry of the total cross section on the nucleon which determines the GDH-sum rule [15,16] and which is at present under
investigation experimentally [17]. Due to the lack of a free neutron target, a measurement on the deuteron is of specific significance because it may serve as an effective neutron target. However, the extraction of the neutron contributions relies on the basic assumption that final state interactions and MEC can be neglected and that proton and neutron contribute incoherently. First, still preliminary results show that these assumptions are quite crude. 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 $S_{11}$ resonance should be taken into account if one wants to consider higher energies.

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FIG. 1. Phase shift $\delta$ and inelasticity $\rho$ for the $^1D_2$ NN-channel in comparison with experiment (solution SM97 of Arndt et al. [1]) 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.

FIG. 2. Differential cross section of deuteron photodisintegration for two photon energies $k_{\text{lab}}$ as function of the c.m. proton angle $\theta_p$: dotted curve: result of Wilhelm et al. in static approach [7], 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] (○).