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Low energy electromagnetic processes based on the chiral effective field theory approach*

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Abstract Chiral effective field theory describes the interaction of nucleons and pions in the low-energy regime of QCD. This theory offers a consistent picture of nuclear forces and nuclear current operators. We study the electromagnetic processes based on ChEFT dynamical picture and compare our predictions to results obtained in the conventional framework. In particular, we consider low energy photo-disintegration of the deuteron at different orders of the chiral expansion. We investigate a role of different ingredients in the two-nucleon current operator. For the first time calculations involve consistent contributions from long-range two-pion exchange currents which appear at next-to-leading order of the chiral expansion. We present novel results for cross sections and various polarization observables.

Key words ChEFT, electromagnetic reactions, exchange currents

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1 Introduction

Chiral effective field theory (ChEFT) provides a systematic and model-independent framework to analyze hadron structure and dynamics according to the scheme of the spontaneously broken approximate chiral symmetry of QCD. This approach is a powerful tool for the derivation of the nuclear forces. Exchange vector and axial currents in nuclei have also been studied in the framework of ChEFT. Since the pioneering work of Park et al. [1] heavy-baryon chiral perturbation theory has been applied to derive exchange axial and vector currents for small values of the photon momentum. These calculations employed time-ordered perturbation theory. The resulting exchange vector currents were applied first to analyze radiative neutron-proton capture within a hybrid approach.

ChEFT has been also used to study the electromagnetic properties of the deuteron, elastic Compton scattering on the deuteron and some other reactions [2]. However, no applications to electron or photon inelastic reactions with two or three nucleons at small momentum transfer have been carried out so far. A recent review on the theoretical achievements in this field based on conventional framework can be found in [3]. A strong interest in ChEFT predictions for this type of reactions, especially in view of planned experiments, resulted in the application of this framework to the above-mentioned processes. This requires a consistent derivation of the nuclear Hamiltonian and the electromagnetic current operator for a given few-nucleon system.

In the two-nucleon (2N) system the leading contributions to the exchange current originate from one-pion exchange and are well known. Further contributions to the 2N current operators were recently worked out by Pastore et al. in Ref. [4]. They obtained the electromagnetic 2N current operator using time-ordered perturbation theory. In the present work, on top of simpler ingredients, we apply also the leading two-pion exchange 2N operator from Ref. [5]. This part of the 2N current operator was derived within ChEFT using the method of unitary transformation, consistently with the way in which the nucleon-nucleon (NN) force was obtained earlier [6].

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2 Formalism

The formalism to describe 2N reaction requires the knowledge of the consistent potential and electromagnetic current. The NN potential based on ChEFT is well known up to next-to-next-to-next-to-leading order of the chiral expansion. We will, however, consider only next-to-leading order (NLO) contributions to the 2N current operator and thus confine ourselves with a NLO NN potential. At this order, it contains one- and two-pion exchanges (TPE) as well as various contact interactions [6]

$$V^{\mathrm{NLO}} = V_{\mathrm{cont}} + V_{1\pi} + V_{2\pi}\,. \tag{1}$$

The effective current operator for the 2N system is a sum of the single-nucleon operators $j^{\mu}(i), i=1,2$ and two-nucleon operators of different origin ($j^{\mu}(1,2)$)

$$j^{\mu}_{\mathrm{2N}} = j^{\mu}(1)+j^{\mu}(2)+j^{\mu}_{\pi}(1,2)+j^{\mu}_{2\pi}(1,2)+j^{\mu}_{\mathrm{cont}}(1,2), \tag{2}$$

where the expressions for the single-nucleon and one-pion-exchange (OPE) currents have been known for a long time. In this report, we concentrate on a treatment of the long-range TPE contributions to the 2N current operator derived in Ref. [5]. The TPE current operator given in the momentum space involves the standard loop functions and the three-point functions in a form suitable for numerical calculations.

The TPE four-current operator consists of many terms $j^{\mu} = (j^0, \vec{j}\,)$ and quite generally can be written as

$$\begin{aligned} j^0 &= \sum_{\boldsymbol{\alpha}=1}^{5}\sum_{\boldsymbol{\beta}=1}^{8} f_{\boldsymbol{\alpha}}^{\boldsymbol{\beta} S}(\vec{q}_1,\vec{q}_2)T_{\boldsymbol{\alpha}}O^{\boldsymbol{\beta} S}, \\ \vec{j} &= \sum_{\boldsymbol{\alpha}=1}^{5}\sum_{\boldsymbol{\beta}=1}^{24} f_{\boldsymbol{\alpha}}^{\boldsymbol{\beta}}(\vec{q}_1,\vec{q}_2)T_{\boldsymbol{\alpha}}\vec{O}^{\boldsymbol{\beta}}, \end{aligned} \tag{3}$$

where $\vec{q}_i \equiv \vec{p}\,' - \vec{p}$ is the momentum transferred to nucleon i, T_{α} is the 2N isospin operator, $O^{\beta(S)}$ and $\vec{O}^{\boldsymbol{\beta}}$ are the (momentum dependent) spin operators in the 2N space, $f_{\boldsymbol{\alpha}}^{\boldsymbol{\beta} S}$ and $f_{\boldsymbol{\alpha}}^{\boldsymbol{\beta}}$ are scalar functions. They do not contain any free parameters. Further information about these operators can be found in Ref. [5].

In the 2N current operator which we use in our present calculations, the contact terms in (2) are missing and we focus on the role of the TPE part. Due to their isospin structure they do not contribute to elastic electron-deuteron scattering. It is then natural to study photo-disintegration of the deuteron. We choose a chiral potential V_{2N} consistent (in its TPE part) with the current operator and generate the deuteron bound state, $|\Psi_{\mathrm{bound}}\rangle$, and the proton-neutron (pn) scattering $|\Psi^{\mathrm{pn}}_{\mathrm{scatt}}\rangle$ state in order to obtain the nuclear matrix element N^{μ} from which all observables can be calculated:

$$N^{\mu} \equiv \langle \Psi_{\mathrm{scatt}} | j^{\mu}_{\mathrm{2N}} | \Psi_{\mathrm{bound}} \rangle. \tag{4}$$

We use the solution of the Lippmann-Schwinger equation, $t = V_{\mathrm{2N}} + tG_0V_{\mathrm{2N}}$, in order to write N^{μ} as

$$N^{\mu} = \langle \vec{p}_0 \,|\, (1+tG_0)\, j^{\mu}_{\mathrm{2N}} \,|\, \Psi_{\mathrm{bound}} \rangle, \tag{5}$$

where G_0 is the free 2N propagator and $\vec{p}_0$ is the relative pn momentum in the final state.

We work in momentum space and employ standard partial wave decomposition (see for example Ref. [7]) of our chiral potential. Thus we have to represent the TPE current operator in the same form. To this end we first prepare all the spin and isospin matrix elements using Mathematica and then calculate the resulting fourfold angular integrals (6) on the parallel supercomputer IBM Blue Gene/P of the Jülich Supercomputing Centre (JSC).

$$\begin{aligned} &\langle p'(l's')j'm';t'm_{t'}|j^{\mu}_{\alpha\beta}|p(ls)jm;tm_t\rangle = \\ &\int \mathrm{d}\hat{p}' \int \mathrm{d}\hat{p} \sum_{m_l'}\sum_{m_l} C(l's'j';m_{l'},m'-m_{l'},m') \times \\ &Y^{*}_{l'm_{l'}}(\hat{p}')C(lsj;m_l,m-m_l,m)Y_{lm_l}(\hat{p}) \times \\ &f^{\beta}_{\alpha}(\vec{q}_1,\vec{q}_2)\langle t'm_{t'}|T_{\alpha}|tm_t\rangle\langle s'm'-m_{l'}|O^{\beta}|sm-m_l\rangle. \end{aligned} \tag{6}$$

3 Results

We present preliminary results for the deuteron photo-disintegration process at the photon laboratory energy of 60 MeV. We calculated the following observables: the differential cross section, the deuteron tensor analyzing powers, the photon analyzing power and the outgoing proton polarization. The results are shown in Fig. 1. The plots show contributions from the different parts of the 2N current. Note that the results depend on the two cut-off parameters present in the chiral potential. While the first cut-off parameter Λ appears in the regulator function for the Lippmann-Schwinger equation, the second parameter $\tilde{\Lambda}$ is defined in the spectral function regularization (SFR) and denotes the ultraviolet cut-off value in the mass spectrum of the two-pion-exchange potential. The bands reflect the dependence of the results on variations of Λ and $\tilde{\Lambda}$. The cut-off values vary between 450 and 600 MeV for Λ and between 500 and 700 MeV for $\tilde{\Lambda}$. For these choices we followed Ref. [8]. We show also some reference results obtained with the phenomenological AV18 potential [9] and the corresponding exchange currents. We see that in all observables the 2N current operator plays an important role and that a restriction to the single nucleon current operator would be unjustified. In particular, for the deuteron tensor analyzing powers we see quite a good agreement between the very reliable AV18 potential prediction and our chiral results.

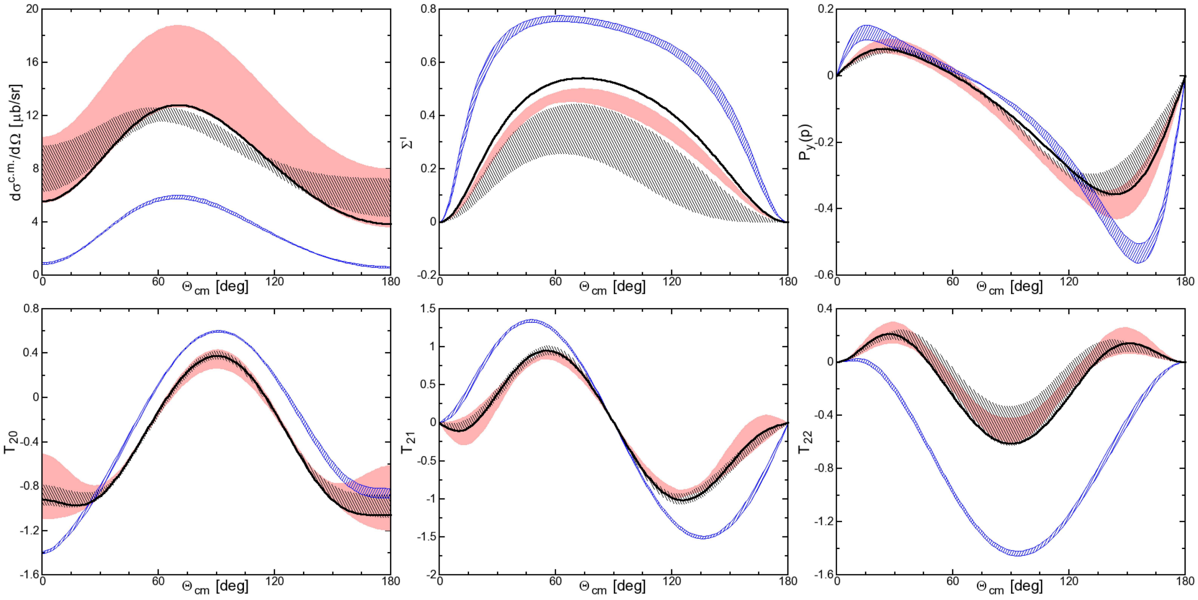

Fig. 1. (color online). The preliminary results for the unpolarized cross section and selected polarization observables in the deuteron photo-disintegration process at the photon laboratory energy of 60 MeV displayed as functions of the nucleon emission angle. The solid black line is for the standard calculation based on the AV18 potential, the blue band covers results obtained with the single-nucleon current only, the grey band represents predictions based on the single-nucleon and OPE parts, and the pink band contains additionally TPE parts.

4 Summary and outlook

We applied TPE current densities, recently derived within the framework of ChEFT, to the description of deuteron photo disintegration and compared different contributions to the chiral 2N current operator for the unpolarized cross section and several polarization observables. Our dynamical framework is in development. Consistent short-range contact and other higher-order terms in the 2N current operator are still missing. Such a consistent framework will be used to analyze electromagnetic processes with two and three nucleons.

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