THE APPLICATION OF CHIRAL FORCES TO THE DEUTERON PHOTODISINTEGRATION PROCESS AT $E_\gamma = 140$ MeV*

V. Urbanevych†, J. Golak, R. Skibiński, H. Witała

M. Smoluchowski Institute of Physics, Jagiellonian University
30-348 Kraków, Poland

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We discuss an application of the nucleon–nucleon chiral potential with the semi-local regularization in momentum space to the deuteron photodisintegration process at the photon energy $E_\gamma = 140$ MeV. We test this new interaction model by comparing results for the differential cross section with data, checking convergence of predictions with respect to the order of chiral expansion and by estimating various theoretical uncertainties. We find that the investigated interaction is promising, however electromagnetic current consistent with the interaction is necessary to describe the data precisely.

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1. Introduction

A new model of nucleon–nucleon (NN) interaction has been derived by the Bochum group and presented in [1]. In this, so-called 'SMS' model, semi-local regularization has been applied directly in momentum space and interaction with chiral expansion up to the fifth order (N^4LO) has been completely built. Moreover, some terms from the sixth order of the chiral expansion have been added to the N^4LO potential giving the most advanced NN chiral interaction (N^4LO+) nowadays. It is expected that the new force will lead to a faster convergence with respect to the chiral order and to weaker dependence on the cut-off parameter compared to the older models of the NN interaction derived within the Chiral Effective Field Theory [2–5]. This has been already confirmed for pure nucleonic systems [6, 7]. In the present work, we extend applications of the SMS chiral model to the electromagnetic processes and specifically we use it to analyze the differential cross section for the deuteron photodisintegration at the incident laboratory photon energy $E_\gamma = 140$ MeV.

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† Corresponding author: `vitalii.urbanevych@doctoral.uj.edu.pl`

2. Theoretical approach

In this contribution, we use the theoretical formalism already presented in Refs. [8, 9] and for details on our approach we refer the reader there. Only some key steps are reminded here.

In order to obtain observables for the deuteron disintegration process, we calculate nuclear matrix elements

$$N^{\mu}_{\rm deu} \equiv \left\langle \Psi^{\rm 2N}_{\rm scatt} \,\middle|\, j^{\mu}_{\rm 2N} \,\middle|\, \Psi^{\rm 2N}_{\rm bound} \right\rangle , \tag{1}$$

of the 2N electromagnetic current $j^{\mu}_{\rm 2N}$ between the final and initial states $|\Psi^{\rm 2N}_{\rm scatt}\rangle$ and $|\Psi^{\rm 2N}_{\rm bound}\rangle$, which represent the proton–neutron scattering state and the deuteron bound state, respectively. We work in the momentum space and the deuteron wave function is a solution of a simple eigenvalue problem. We compute 2N scattering state using the Lippmann–Schwinger equation for the t-operator,

$$t = V + tG_0V , \tag{2}$$

where V and G_0 are the 2N potential and the free 2N propagator, respectively. Taking into account t-operator, $N^{\mu}_{\rm deu}$ can be written as

$$N^{\mu}_{\rm deu} = \left\langle \vec{p}_0 \,\middle|\, (1 + tG_0)\, j^{\mu}_{\rm 2N} \,\middle|\, \Psi^{\rm 2N}_{\rm bound} \right\rangle , \tag{3}$$

where $|\vec{p}_0\rangle$ denotes the eigenstate of the final relative proton–neutron momentum.

Currently, the full form of the current operator (*i.e.* comprising the single-nucleon current (SNC) and the 2N current) consistent with the chiral SMS interaction is not accessible. Since work on the consistent SMS regularization of the electroweak currents is not completed, we use the Siegert theorem in order to take into account some contributions from 2N current on the top of the SNC. Details on this approach are presented in Refs. [10, 11].

3. Results

Figure 1 demonstrates the differential cross section $\frac{{\rm d}^2\sigma}{{\rm d}\Omega}$ for the deuteron photodisintegration for the photon energy $E_\gamma = 140$ MeV. The left panel of Fig. 1 demonstrates the convergence of the predictions with respect to the order of chiral expansion. The predictions at two lowest orders separate from the remaining results clearly showing the necessity to include higher orders contributions to the chiral potential. Starting from the N^{3}LO, the difference between subsequent predictions is quite small what confirms desired convergence pattern also for the studied observable in electromagnetic process.

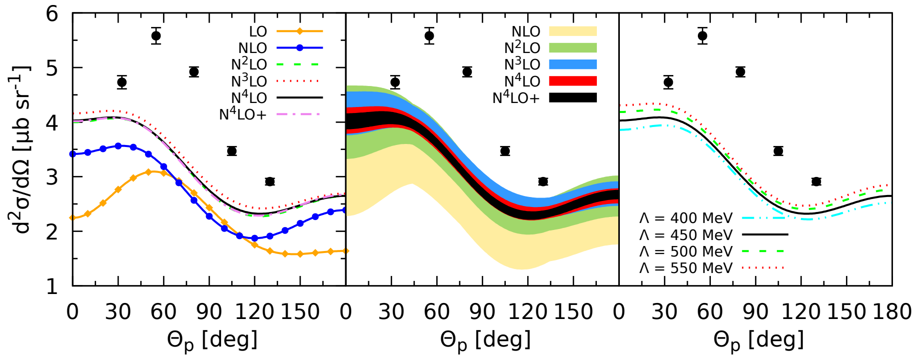

Fig. 1. The differential cross section $\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega}$ for the deuteron photodisintegration as a function of the proton scattering angle θ_p in the center-of-mass frame for the photon energy $E_\gamma = 140$ MeV. The left plot demonstrates predictions from various orders of chiral expansion with the cut-off parameter $\Lambda = 450$ MeV. The middle panel shows truncation errors with respect to the order of chiral expansion. The dependence of predictions on the cut-off parameter at the fifth chiral order (N^4LO) is presented in the right plot. Data points are from [12].

That also means that one should not expect large contributions from the higher order forces. This statement is in agreement with the magnitude of truncation errors presented in the central panel of Fig. 1. The bands seen in this panel show the uncertainty of the predictions at given order due to neglecting contributions to the chiral interaction above this order. To estimate magnitudes of the truncation errors, we use the same prescription as in Ref. [9].

Figure 1 presents also (in the right panel) N^4LO predictions on the investigated cross section obtained with the different values of the regulator parameter Λ. The observed dependence on the regularization parameter is weak, however, the spread of predictions is bigger than the magnitude of the truncation error at N^4LO shown in the central panel. Only restriction to the two central values of Λ: 450 MeV and 500 MeV, which delivers the best description of the NN data, makes the regulator dependence of predictions comparable to the truncation uncertainty. It is also worth mentioning that the regulator dependence shown in Fig. 1 is much weaker than the regulator dependence observed for the chiral forces with the nonlocal regularization, see, for example, Refs. [8, 13].

The description of experimental data taken by De Sanctis *et al.* [12] is unsatisfactory, and the discrepancy between our predictions and the data amounts to 20%–30%. At this, relatively high energy, the meson exchange currents as well as relativistic corrections can play an important role. While this work is not focused on the properties of the electromagnetic current operator, it is interesting to find out how big is the impact of two-body currents on the studied cross section. In Fig. 2 we compare the predictions (at N^4LO, $\Lambda = 450$ MeV) already shown in Fig. 1 with results based only on the single nucleon current. Applying the Siegert theorem, changes the predictions by factor 3–4 and moves them towards the data. It seems reasonable to expect that the remaining gap between predictions and the data will be, to a great extent, reduced by using a complete two-body current consistent with the interaction.

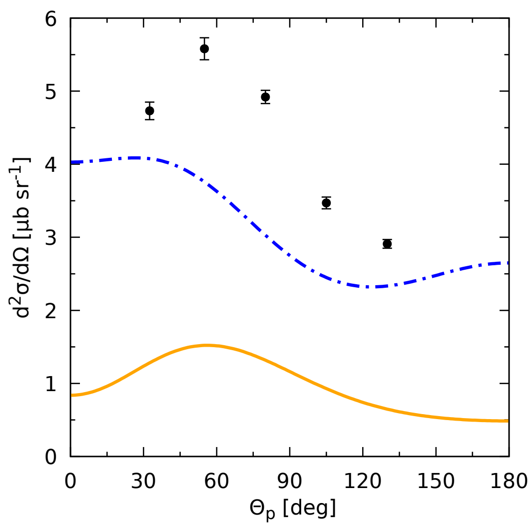

Fig. 2. The same $\frac{d^2\sigma}{d\Omega}$ differential cross section as in Fig. 1. The dash-dotted curve represents predictions obtained with the chiral SMS interaction at N^4LO and the cut-off parameter $\Lambda = 450$ MeV. The two-body current contributions have been included via the Siegert theorem. The solid curve represents predictions with the same potential but using only the single-nucleon current operator. Experimental data are taken from [12].

4. Summary

We have presented an application of the chiral SMS NN potential [1] to the deuteron photodisintegration process at the photon energy $E_\gamma =$ 140 MeV. Results of our calculations reveal a good convergence with respect to the chiral order and a moderate dependence on the cut-off parameter. It has been also shown that, at the investigated energy, the two-body electromagnetic current has a big impact on the deuteron photodisintegration cross section. The remaining discrepancy between our predictions based on the

Siegert approach and the data makes the deuteron photodisintegration reaction extremely useful for future detailed investigations of the 2N currents derived within the Chiral Effective Field Theory.

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