Investigations of the few-nucleon systems within the LENPIC project

**Jacek Golak[1][*], Evgeny Epelbaum[2], Alessandro Grassi[1], Hiroyuki Kamada[3],
Hermann Krebs[2], Patrick Reinert[2], Roman Skibiński[1], Volodymyr Soloviov[1],
Kacper Topolnicki[1], Vitalii Urbanevych[1], Yuriy Volkotrub[1] and Henryk Witała[1]**

1 M. Smoluchowski Institute of Physics, Jagiellonian University, PL-30348 Kraków, Poland
2 Ruhr-Universität Bochum, Fakultät für Physik und Astronomie,
Institut für Theoretische Physik II, D-44780 Bochum, Germany
3 Department of Physics, Faculty of Engineering,
Kyushu Institute of Technology, Kitakyushu 804–8550, Japan

⋆ jacek.golak@uj.edu.pl

Abstract

Results presented in this contribution are obtained within the Low Energy Nuclear Physics International Collaboration (LENPIC). LENPIC aims to develop chiral nucleon-nucleon and many-nucleon interactions complete through at least the fourth order in the chiral expansion. These interactions will be used together with consistently derived current operators to solve the structure and reactions of light and medium-mass nuclei including electroweak processes. In this contribution the current status of the chiral nuclear forces and current operators will be briefly discussed. A special role played by the calculations of nucleon-deuteron scattering will be explained.

1 Introduction

The Low Energy Nuclear Physics International Collaboration (LENPIC) is a project established in 2013 that "aims to develop chiral effective field theory nucleon-nucleon (NN) and three-nucleon (3N) interactions complete through at least fourth order in the chiral expansion (N3LO). Using these new interactions, LENPIC aims to solve the structure and reactions of light nuclei including electroweak observables with consistent treatment of the corresponding exchange currents" [1]. This initiative has brought together physicists from several institutions: Ruhr-University Bochum, Germany, University of Bonn, Germany, Technical University of Darmstadt, Germany, Jagiellonian University, Cracow, Poland, Iowa-State University, USA, Jülich Research Centre, Germany, Kyushu Institute of Technology, Japan, Ohio State University,

USA, Orsay Institute of Nuclear Physics, France, and TRIUMF, Canada. The Co-Spokespersons of this collaboration are Evgeny Epelbaum from Ruhr-University Bochum and James Vary from Iowa State University.

2 Nucleon-deuteron scattering with semi-phenomenological nuclear potentials

Each group involved in the LENPIC project contributes its own expertise. The Cracow-Bochum group had a lot of experience related to investigations of elastic nucleon-deuteron scattering and nucleon-induced deuteron breakup processes. These investigations, based on rigorous solutions of the 3N Faddeev equations in momentum space started in the 1980s and in the 1990s were carried out with the semi-phenomenological (the so-called "realistic") NN forces, which very accurately described the properties of the two-nucleon (2N) system. These were the AV18 [2], CD Bonn [3], NijmI, NijmII, Nijm93 and Reid93 [4] potentials. The results of these studies (see for example Refs. [5,6]) proved that in general predictions for 3N scattering observables agree well with data at the incoming nucleon energies below approximately 30 MeV.

The situation was different at higher energies, where clear discrepancies between the theoretical predictions employing NN forces only and data emerged. For the minimum of the elastic scattering cross section agreement with the data was restored, at least for energies below approximately 140 MeV, when the Tucson–Melbourne [7] or Urbana IX [8] 3N force (3NF) models were added to the 3N Hamiltonian. The parameters of the 3N potentials used in the calculations were chosen to reproduce the experimental triton binding energy [6,9,10]. On the other hand, for many spin observables in elastic nucleon-deuteron scattering (for example the nucleon analyzing power and the deuteron tensor analyzing powers [6,11]) large 3NF effects were predicted, but the available combinations of 2N and 3N forces could not reproduce the data. One of possible reasons for this disagreement between the theoretical predictions and the data could be the nonrelativistic character of the formalism. However, the results obtained within the framework of relativistic Faddeev equation [12,13] revealed only small effects in the cross section. Also elastic scattering polarization observables are only slightly affected by relativity at the considered energies [12,13].

The conclusion from all these studies was that the discrepancies observed at higher energies, which persisted even when the Tucson–Melbourne or Urbana IX 3NF models were included in the calculations, called for better models of the 3NF (with a richer spin structure) and consistence between the 2N and 3N potentials. This could be achieved only within the chiral effective field theory.

3 Nucleon-deuteron scattering with chiral nuclear potentials

In [14] for the first time that consistency was realized when low energy 3N scattering was investigated with chiral next-to-next-to-leading order (N2LO) 2N and 3N forces. Later in Refs. [15, 16] precise 2N potentials were derived at next-to-next-to-next-to-leading order (N3LO) of the chiral expansion. They reproduced experimental phase-shifts [17,18] in a wide energy range and almost equally well as the semi-phenomenological 2N potentials. The corresponding N3LO 3N force contributions were derived in Refs. [19,20]. They do not involve any unknown parameters. The large number of terms in the 3NF at N3LO required a new automatized method of their partial-wave decomposition [21–23]. The two free parameters of the 3N potential at N2LO were fixed to reproduce the triton binding energy and the nucleon-
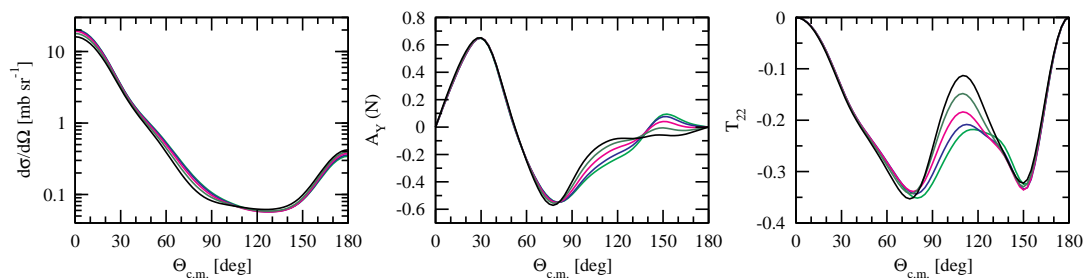
Figure 1: The differential cross section $d\sigma/d\Omega$ (left panel), the nucleon analyzing power $A_y(N)$ (middle panel) and the deuteron tensor analyzing power T_{22} (right panel) for elastic nucleon-deuteron scattering at the laboratory nucleon energy $E=$ 200 MeV as a function of the center of mass nucleon scattering angle $\theta_{c.m.}$ calculated with the chiral N4LO 2N potential [25, 26] employing the local coordinate-space regularization. The five lines show predictions obtained with five different regulator values $R=$ 0.8, 0.9, 1.0, 1.1 and 1.2 fm.

deuteron doublet scattering length. Both the 2N and 3N forces required regularization, which in this first generation of the chiral forces was realized by simple non-local partial wave independent regulators, applied in momentum space. Unfortunately, the use of such non-local regularization was the source of finite-cutoff artefacts in the results for higher-energies elastic nucleon-deuteron scattering [24]. These artefacts appear for *all* non-locally momentum-space regularized 2N potentials and are a major obstacle to employing such forces in 3N continuum calculations.

A new improved generation of 2N chiral potentials prepared up to next-to-next-to-next-to-next-to-leading order (N4LO) [25, 26] employed a local coordinate-space regularization of the one- and two-pion exchange contributions to the 2N force. The change leads to a significant reduction of the finite-cutoff artefacts for high energy observables, especially for the differential cross section. This effect is shown in Fig. 1 and should be compared with Fig. 12 from Ref. [24]. (Note that further significant reducion of the finite cutoff artefacts, also for the polarization observables, is achieved in the calculations employing the newest chiral NN potentials from Ref. [30] described below.) These findings are consistent with the ones obtained in the two-nucleon sector [25, 26, 30].

The new NN potentials [25, 26] were employed by LENPIC members in few-nucleon and many nucleon systems [27–29]. Results for several few-nucleon observables obtained with the NN potentials alone show clear discrepancies between theoretical predictions and experimental data. These discrepancies are much larger than the estimated truncation uncertainty and agree with the expected magnitude of 3NF contributions. Unfortunately, the implementation of a consistent regulator in coordinate space proved to be very difficult for the 3N potentials beyond N2LO, so in Ref. [31] the consistent investigation of nucleon-deuteron scattering as well as ground and low-lying excited states of nuclei with $A \leq 16$ was performed only up to N2LO. One of the important questions posed in that study was the determination of the low-energy constants c_D and c_E, specifying the 3NF at N2LO. On top of the experimental triton binding energy, which provides a connection between these two parameters, an observable from nucleon-deuteron scattering is necessary to fix the c_D and c_E values. The very precise experimental data for the proton-deuteron differential cross section at the proton laboratory energy of 70 MeV from Ref. [32] was chosen, taking into account the theoretical uncertainty from the truncation of the chiral expansion.

Calculations described in Ref. [33] showed additionally that combining N4LO NN potentials with the N2LO 3NF regularized in the same way leads to similar 3NF effects in nucleon-deuteron scattering as found with semi-phenomenological nuclear forces. In particular, the

application of these forces did not explain the low energy A_y puzzle [33]. For a detailed comparison of these chiral potential based predictions to data we refer the reader to Ref. [33].

The latest generation of the chiral 2N potentials, introduced in Ref. [30], employs a momentum-space version of the local regulator. These potentials developed up to the so-called "N4LO+" version are currently the most precise chiral interactions on the market. They reach at least the same accuracy in reproducing NN scattering data below the pion production threshold as the phenomenological high-precision potentials but with a significantly smaller number of adjustable parameters.

In a very recent paper [34] the study of Ref. [31] was updated and nucleon-deuteron scattering observables were analyzed using the newest chiral NN potentials of Ref. [30] in combination with consistently regularized N2LO 3N forces. The former way of estimation of truncation uncertainties was replaced by a Bayesian approach. The results for elastic nucleon-deuteron scattering observables confirmed predictions based on the coordinate-space version of the local regulator and agree within errors with experimental data. Additionally they indicated that a precise description of neutron-deuteron scattering below pion production threshold would require 3N forces (at least) at the N4LO level, see [35–37] for some work along this line.

In this contribution, in some measure by definition, we restrict ourselves to the nuclear forces developed within the LENPIC project. But we are of course aware of the important contributions made by other groups. Here we only mention the Moscow (Idaho)-Salamanca group [38] results, the nuclear forces constructed by Piarulli et al. [39, 40], by Ekström et al. [41, 42] and a very recent family of potentials intended for nuclear structure calculations [43]. For a more general discussion of the recent chiral models of the nuclear interactions we refer the reader to Ref. [34].

4 Electroweak processes

Electroweak processes are also of interest to the LENPIC project. They require single-nucleon and many-nucleon electromagnetic and axial current operators, which are derived consistently with the nuclear forces. Although electromagnetic and axial currents have been worked out in chiral effective field theory completely up through N3LO [44–47] using the method of unitary transformation and employing dimensional regularization for loop integrals, they are not yet regularized and thus cannot be used in practical calculations together with the nuclear forces employing the coordinate- or momentum-space regularization.

That is why we studied various electroweak processes: muon capture on ^{3}He and ^{3}H [48, 49], (anti)neutrino scattering off ^{3}He and ^{3}H [50, 51] and pion radiative capture in ^{3}He and ^{3}H [52] exactly in the same framework as electron scattering on ^{3}He and ^{3}H and photodisintegration of ^{3}He and ^{3}H [53], using the semi-phenomenological AV18 [2] potential and the single nucleon current, including additionally in some cases 3NF and 2N current effects. We not only provided realistic predictions for all the above mentioned reactions but argued that all these processes should be studied within LENPIC using the consistent nuclear forces and current operators. Some of the calculated observables will be used to fix the low-energy constants in the chiral electromagnetic and axial currents.

The chiral electroweak current operators are generally not expected to be used to analyze results of experiments, where electromagnetic and weak probes transfer a lot of energy and large momenta to a nuclear system. (See, however, recent predictions for elastic electron-deuteron scattering in Ref. [54].) That is why first of all we plan to apply chiral currents to low-energy photodisintegration processes and muon capture from the lowest atomic orbits, where the energy and momentum transfers are naturally limited. Calculations based on chiral forces and currents will be important for the results of electron scattering experiments planned
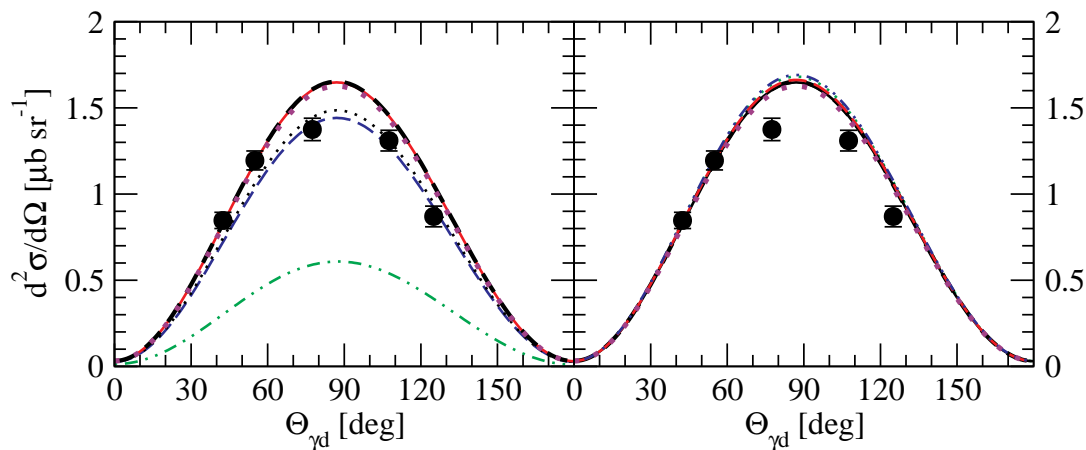
Figure 2: The differential cross section $d^2\sigma/d\Omega$ for the $n + d \rightarrow \gamma + {}^3$H reaction at the neutron laboratory energy E_n= 9 MeV as a function of the center-of-mass angle $\Theta_{\gamma d}$ between the initial deuteron and final photon momenta obtained with the chiral NN potential [25, 26] and the Siegert theorem [53]. In the left panel various lines show predictions from Ref. [57] with the fixed cut-off parameter R= 0.9 fm at various orders of chiral expansions: LO (double-dotted-dashed green), NLO (dashed blue), N2LO (dotted black), N3LO (solid red) and N4LO (thick dashed black). In the right panel the lines show N4LO predictions for various cut-off parameter values R: 0.8 fm (dotted green), 0.9 fm (thick dashed black), 1.0 fm (solid black), 1.1 fm (dashed red) and 1.2 fm (double-dotted-dashed blue). In both cases we added our predictions based on the AV18 NN potential [2], represented in the two panels by the thick violet dotted curve. The data are from Ref. [58].

at the MESA accelerator in Mainz, Germany.

Despite the lack of the electroweak currents consistent with the newest chiral nucleon-nucleon potentials, electromagnetic processes with real photons were studied in Ref. [55] using the Siegert theorem. In this way we could include implicitly certain types of many-nucleon contributions in the nuclear current operator. The results obtained with the potentials employing the local coordinate-space regularization turned out to be very promising, revealing a very weak dependence of predictions on the cutoff parameter and providing a good data description.

As an example, we show in Fig. 2 our predictions from Ref. [57] for the differential cross section $d^2\sigma/d\Omega$ for the $n + d \rightarrow \gamma + {}^3$H reaction at the neutron laboratory energy E_n= 9 MeV. The left panel of Fig. 2 shows a fast convergence of the results with respect to the chiral order for the fixed regulator value of R= 0.9 fm and the right panel demonstrates a weak dependence on the regulator value at N4LO. Additionally the N4LO results agree very well with the predictions based on the AV18 potential and, most importantly, with the data [58].

5 Conclusion

The reader should be aware that in this contribution we restricted ourselves to the the few-nucleon part of the LENPIC project. Equally important are the investigations of many-nucleon systems performed within LENPIC [28,31,60,61], which put the current models of the nuclear forces to stringent tests.

All the studies mentioned in this contribution yielded very promising results and demonstrate the high quality of the newest chiral NN potentials [30]. Also the studies including the

consistently regularized N2LO 3N force are very encouraging [34]. It is, however, very clear that these efforts should be extended at least to N3LO, which requires inclusion of the consistently regularized 3N force and many-nucleon current contributions [56, 59]. Work along these lines is in progress by the LENPIC Collaboration.

Acknowledgements

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