ABSTRACT

These are the proceedings of the international workshop on “Nuclear Dynamics with Effective Field Theories” held at Ruhr-Universität Bochum, Germany from July 1 to 3, 2013. The workshop focused on effective field theories of low-energy QCD, chiral perturbation theory for nuclear forces as well as few- and many-body physics. Included are a short contribution per talk.
1 Introduction

The past decade has witnessed a considerable progress towards understanding nuclear structure and dynamics from first principles. In addition to new experimental results, this is to a large extent related to exciting theoretical developments in this field. On the one hand, rapidly increasing computational resources coupled with sophisticated few- and many-body methods allow nowadays for reliable and accurate nuclear structure calculations for light and medium-mass nuclei. This opens the possibility to relate the properties of the nuclear Hamiltonian to observables in a reliable way without invoking any uncontrollable approximations. On the other hand, significant progress has been reached towards quantitative description of nuclear forces and currents in the framework of chiral effective field theory. Last but not least, first lattice-QCD results for few-nucleon systems have also been reported. The main goal of this workshop was to bring together experimentalists and theorists with expertise in these fields to discuss recent developments and future research directions. More specifically, the workshop focused on effective field theories of low-energy QCD, chiral perturbation theory for nuclear forces as well as few- and many-body physics.

This workshop took place in July 2013 at Ruhr-University Bochum, Germany. It brought together 41 participants whose names, institutions and email addresses are listed below. 34 of them presented results in talks of 35 minutes in length. A short description of their contents and a list of the most relevant references can be found below. We felt that such mini-proceedings represent a more appropriate framework than full-fledged proceedings. Most results are or will soon be published and available on the archive, so this way we can achieve speedy publication and avoid duplication of results in the archive. Below we give the program of the workshop, followed by the list of participants and, finally, by the abstracts of all the talks. The slides of the talks are available at the workshop website http://www.tp2.ruhr-uni-bochum.de/~ndeft13/

We extend our sincere gratitude to the European Research Council (ERC) for the financial support and to Martina Hacke and Peter Druck for the precious help with the administration and organization. We are also grateful to many students of the Institute of Theoretical Physics II and especially to Arseniy Filin, Dmitrij Siemens and Markus Thüramm for their help during the workshop and to the team of the RUB Veranstaltungszentrum for the excellent service. Most important, we thank all the participants for making this an exciting and lively meeting happen.

This workshop was dedicated to Professor Walter Glöckle, an esteemed colleague, advisor and friend of many in our field, who passed away on August 1, 2012.

Evgeny Epelbaum and Hermann Krebs
2 Program

Monday, July 1st, 2013

09:20 Evgeny Epelbaum
(Bochum)
Welcome remarks

Early Morning Session
Chair: Charlotte Elster
09:35 Wayne Polyzou
(Iowa City)
Walter and the relativistic few-body problem
10:10 Henryk Witała (Krakow)
3N reactions with N^3LO chiral force
10:45 Coffee

Late Morning Session
Chair: Charlotte Elster
11:15 Alejandro Kievsky (Pisa)
Scattering states from bound state like wave functions:
The Coulomb case
11:50 Hideki Sakai (Tokyo)
Story of how we started dp scattering experiments at RIKEN
End of Session
Lunch

Early Afternoon Session
Chair: Charlotte Elster
14:00 Hans Pätz gen. Schieck
(Köln)
Spin physics and "polarized fusion"
14:35 Werner Tornow
(Duke, USA)
Are new experiments really needed to advance few-body physics?
Coffee

Afternoon Session
Chair: Dean Lee
15:30 Silas Beane (Bonn)
Nuclear dynamics from lattice QCD
16:05 Veronique Bernard (Orsay)
SU(3) chiral dynamics revisited
Coffee

Late Afternoon Session
Chair: Dean Lee
17:00 Christian Weiss (JLab)
Space-time picture of chiral dynamics with nucleons
17:35 Vadim Baru (Bochum)
Pion production in NN collisions
18:10 Jambul Gegelia (Bochum)
Issues of renormalization in EFT for NN system
End of Session
Tuesday, July 2nd, 2013

**Early Morning Session**
Chair: Evgeny Epelbaum
09:00 Dean Lee (Raleigh) Overview and latest news from nuclear lattice effective field theory
09:35 Ulf-G. Meißner (Bonn/Jülich) Life on Earth – an accident?
10:10 Gautam Rupak (Mississippi State) Nuclear structure and reactions in lattice effective field theory
10:45 Coffee

**Late Morning Session**
Chair: Evgeny Epelbaum
11:15 James Vary (Ames, Iowa) Evolving perspectives on the origins of nuclear structure
11:50 Robert Roth (Darmstadt) From chiral EFT interactions to nuclear structure and back
End of Session
Lunch

**Early Afternoon Session**
Chair: James Vary
14:00 Carolina Romero (TRIUMF) Ab initio many-body calculations of light ion reactions
14:35 Kai Hebeler (Darmstadt) Neutron rich matter from chiral EFT interactions
15:10 Coffee

**Afternoon Session**
Chair: James Vary
15:30 Hans-Werner Hammer (Bonn) Universal properties of halo nuclei
16:05 Daniel Phillips (Athens, USA) Photon interactions with halo nuclei
16:40 Coffee

**Late Afternoon Session**
Chair: James Vary
17:00 Jacek Golak (Krakow) Selected weak interaction processes on the deuteron and \(^3\)He
17:35 Harald Grießhammer (Washington DC) High-accuracy analysis of Compton scattering in chiral EFT: Status and future
End of Session
Workshop Dinner
Wednesday, July 3rd, 2013

Early Morning Session
Chair: Hermann Krebs
09:00 Ashot Gasparyan (Bochum)   Three-Nucleon Force (Theory)
Chiral expansion of the three-nucleon force
09:35 Carlos Schat (Buenos Aires)  Three-nucleon forces in the $1/N_c$ expansion
10:10 Luca Girlanda (Lecce)       Constraining the three-nucleon contact interaction from
                                        nucleon-deuteron elastic scattering
10:45 Coffee

Late Morning Session
Chair: Hermann Krebs
11:15 Kimiko Sekiguchi (Sendai)   Three-Nucleon Force (Experiment)
Exploring three nucleon forces in few-nucleon scattering
11:50 Nasser Kalantar (KVI)       Study of nuclear forces at intermediate energies
12:25 End of Session
12:25 Lunch

Early Afternoon Session
Chair: Henryk Witała
14:00 Andreas Nogga (FZJ)   Hyper-nuclei
Light hypernuclei based on chiral interactions at
next-to-leading order
14:35 Kazuya Miyagawa (Okayama)  The reaction $K^- d \rightarrow \pi \Sigma n$ in the $\Lambda(1405)$ resonance region
15:10 Coffee

Afternoon Session
Chair: Henryk Witała
15:30 Roman Skibinski (Krakow)  Few-Body Electroweak II
The chiral electromagnetic currents applied to the deuteron
and $^3\text{He}$ disintegrations
16:05 Fred Myhrer (Columbia, USA) Muon capture and the connection to the three-nucleon force
16:40 Coffee

Late Afternoon Session
Chair: Henryk Witała
17:00 Charlotte Elster (Athens, USA)  Few-Body IV
Towards $(d, p)$ reactions with heavy nuclei in a Faddeev description
17:35 Stanislaw Kistryn (Krakow) Experimental studies of deuteron-proton breakup at medium energies
18:10 Hiroyuki Kamada (Kyushu) $Nd$ scattering calculation with low-momentum potential
18:45 Hermann Krebs (Bochum)       Concluding remarks
19:00 End of Workshop
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Walter and the relativistic few-body problem

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One of Walter Glöckle’s many interests was to apply few-body methods at relativistic energy scales. At these scales it is possible to probe the short distance properties of the nucleon-nucleon and three-nucleon interactions. These are scales where sub-nucleon degrees of freedom may begin to be relevant. Relativistic methods are also needed for a consistent treatment of particle production and to model reactions involving hypernuclei. Also, because cluster properties generate many-body forces, it is important to understand how these forces interact with conventional many-body forces. Finally, QCD is strongly coupled at these scales and is difficult to control mathematically.

Walter, along with his students and collaborators made a significant amount of scientific progress in the study of relativistic few-nucleon physics. His contributions include relativistic models of interacting nucleons with meson degrees of freedom eliminated[1], construction of realistic relativistic interactions [2], calculations of relativistic effects on the three-nucleon binding energy [3], [4], relativistic effects in proton-deuteron scattering and the interplay of relativistic effects with three-nucleon forces [4], [5], [6], the role of relativity in Y-scaling [7], GeV-scale three-nucleon scattering calculations without partial waves [8] and relativistic spin effects in low-energy calculations of $A_y$[9].

References

[1] Walter Glöckle and L. Müller, Phys. Rev. C23 (1981) 1183-1195.
[2] H. Kamada and W. Glöckle, Phys. Lett. B655 (2007) 119-125.
[3] W. Glöckle, T. S. H. Lee, F. Coester, Phys. Rev. C33 (1986) 709-716.
[4] H. Kamada, W. Glöckle, H. Witała, J. Golak, R. Skibiński, W. Polyzou, Ch. Elster, Mod. Phys. Lett. A24 (2009) 804-809.
[5] H. Witała, J. Golak, W. Glöckle, H. Kamada, Phys. Rev. C71 (2005) 054001.
[6] H. Witała, J. Golak, R. Skibiński, W. Glöckle, H. Kamada, W.N. Polyzou, Phys. Rev. C83 (2011) 044001.
[7] W. N. Polyzou and Walter Glöckle, Phys. Rev. C53 (1996) 3111-3130.
[8] T. Lin, Ch. Elster, W. N. Polyzou, H. Witała, W. Glöckle, Phys. Rev. C78 (2008) 024002.
[9] H. Witała, J. Golak, R. Skibiński, W. Glöckle, W. N. Polyzou, H. Kamada, Phys. Rev. C77 (2008) 034004.
3N reactions with N³LO chiral force

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Comparison of theoretical predictions with data for elastic nucleon-deuteron (Nd) scattering and nucleon induced deuteron breakup clearly shows the importance of the three-nucleon force (3NF). Inclusion of semi-phenomenological 3NF models into calculations in many cases improves the data description. However, some serious discrepancies remain even when 3NF is included.

At low energies the prominent examples were found for the vector analyzing power in elastic Nd scattering and for the neutron-deuteron (nd) breakup cross sections in neutron-neutron (nn) quasi-free-scattering (QFS) and symmetric-space-star (SST) geometries. Since both these configurations depend predominantly on the S-wave nucleon-nucleon (NN) force components, these cross section discrepancies have serious consequences for the nn \(1S_0\) force component. A stronger \(1S_0\) nn force is required to bring theory and nn QFS data to agreement. The increased strength of the \(1S_0\) nn interaction could make the nn system bound.

At energies above \(\approx 100\) MeV current 3NF’s only partially improve the description of cross section data and the remaining differences indicate the possibility of relativistic effects. We extended our relativistic formulation of 3N Faddeev equations to include also 3NF. New results show that relativistic effects based on relativistic kinematics and boost effects of the NN force play an important role in building up the magnitude of 3NF effects.

One of the reasons for the above disagreements could be a lack of consistency between 2N and 3N forces used or/and omission of important terms in the applied 3NF. The Chiral Effective Field Theory approach provides consistent 2N and 3N forces. Recently the chiral 3NF at N³LO was derived. At this order 3NF consists of long range parts with the \(2\pi\)-exchange, \(1\pi-2\pi\) and ring terms and a short-range contributions \(2\pi\)-contact and relativistic corrections of order \(1/m\). This is supplemented by \(1\pi\)- and 3N- contact terms. First results obtained with that N³LO force without relativistic corrections show that it does not provide explanation for the low energy \(A_y\) puzzle.

References

[1] H. Witala and W. Glöckle, Phys. Rev. C83 (2011) 034004.
[2] H. Witala et al., Phys. Rev. C83 (2011) 044001.
[3] V. Bernard et al., Phys. Rev. C77 (2008) 064004.
[4] V. Bernard et al., Phys. Rev. C84 (2011) 054001.
Scattering states from bound state like wave functions:
The Coulomb case

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An application of the integral relations derived in Ref. [1] is discussed. To this end we give the generalization of the integral relations to the case in which more than one channel is open.

\[ B_{ij} = -\frac{m}{\hbar^2} \langle \Psi_i | H - E | F_j \rangle \]
\[ A_{ij} = \frac{m}{\hbar^2} \langle \Psi_i | H - E | \tilde{G}_j \rangle \]
\[ R^{2nd} = A^{-1} B. \]  

(1)

with \( R^{2nd} \) the second order estimate of the scattering matrix whose eigenvalues are the phase shifts and the indices \((i,j)\) indicate the different asymptotic configurations accessible at the specific energy under consideration. Consider \( p - d \) scattering at \( E_{lab} = 3 \) MeV in \( J = 1/2^+ \) state, the scattering matrix is a \( 2 \times 2 \) matrix. Using the AV18 potential, phase-shift and mixing parameters calculated using the PHH expansion, are given in Table 1. It is possible to solve an equivalent problem with a screened Coulomb potential and then use the integral relations to extract the scattering matrix corresponding to the unscreened problem [2]. This has been done using Eq. 1 and the results are given in Table 1 using \( r_{sc} = 50 \) fm and \( n_{sc} = 5 \) [3]. We observe a complete agreement between the two procedures.

Table 1: Phase-shift and mixing parameters for \( p - d \) scattering at \( E_{lab} = 3 \) MeV using the AV18 potential. Results using the PHH expansion (second column) and using the integral relations (last column).

| \( p - d \) | Int. Rel. |
| --- | --- |
| \(^4D_{1/2}\) | -3.563° | -3.562° |
| \(^2S_{1/2}\) | -32.12° | -32.12° |
| \( \eta_{1/2^+} \) | 1.100° | 1.101° |

References

[1] P. Barletta, C. Romero-Redondo, A. Kievsky, M. Viviani, and E. Garrido Phys. Rev. Lett. 103, 090402 (2009).
[2] A. Kievsky, M. Viviani, P. Barletta, C. Romero-Redondo, and E. Garrido Phys. Rev. C81, 034002 (2010).
[3] A. Kievsky, EPJ Web of Conferences 3, 01002 (2010).
Story Behind the Launch of Deuteron-Proton Scattering Experiments at RIKEN; How It All Started.

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It all started with the construction of the polarized ion source (PIS) for deuteron. Around 1990, we decided to pursue spin-isospin physics by using a polarized deuteron beam. The research topics considered at the time were the $(\vec{d},^2\text{He})$ reaction for the $\beta^+$ Gamow-Teller (GT) response study or the $(\vec{d},\vec{d}')$ reaction for the double GT giant resonance search. To this end we proposed the construction of PIS at the RIKEN Ring Cyclotron facility.

The construction was finished in 1992. Before starting experiments, absolute magnitudes of vector and tensor polarizations of the deuteron beam had to be measured for polarimetry. Considering the merit and demerit, we chose the $\vec{d}+p$ elastic scattering.

We measured for the first time the precise complete set of analyzing powers ($A_y, A_{xx}, A_{yy}, A_{xz}$) for the $\vec{d}+p$ scattering at 270 MeV, of which I was very proud, and we submitted the results to Physics Letters B (PLB). However, it was turned down! Both referees pointed out that the cross section data were not the state-of-the-art. Indeed the data fluctuated over scattering angle beyond the statistical errors. This was because we were interested in the deuteron polarimetry and did not pay much attention to the cross sections. According to the suggestion of the PLB Editor, we remeasured the cross sections with improved equipment, to reduce the systematic errors. With the new data the paper was accepted and published [1]. This was the beginning of our involvement in the three-nucleon-force (3NF) study.

Soon after, rigorous Faddeev calculations with 3NF became available from the Bochum group [2] and naturally the collaboration between Bochum group and us followed. The first outcome of the collaboration appeared in [3], where the 3NF effects were clearly shown in the angular region with the minimum cross section.

Since then, extremely fruitful collaborations have been developed. Our recent activities are described at this conference by Kimiko Sekiguchi.

We would like to thank Walter Gröckle for his continuous support and encouragement. Without them, we would not have achieved such excellent results.

References

[1] Sakamoto, Sakai et al., Phys. Lett. B 367 (1996) 60.
[2] Witala et al. Phys. Rev. Lett. 81 (1998) 1183.
[3] Sakai et al. Phys. Rev. Lett. 84 (2000) 5288.
Spin Physics and “Polarized Fusion”

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Low-energy fusion reactions, especially the four- and five-nucleon reactions, are not only important for big-bang nucleosynthesis, but are the main reactions considered for energy production in future reactors, either with magnetically (TOKOMAKS such as ITER) or inertially confined plasmas (e.g. laser facilities such as NIF). The primary research goal is to reach energetic break-even, before useful reactors can be implemented, but spin-polarized fuel might speed-up progress.

The use of polarized particles as fusion fuel has long been considered \[1\] and it is undisputed that for the \[\text{d} + ^3\text{H} \rightarrow n + ^4\text{He} + 17.58 \text{MeV} \] (1) and \[\text{d} + ^5\text{He} \rightarrow p + ^4\text{He} + 18.34 \text{MeV} \] (2) reactions the reaction rates can be enhanced by up to a factor 1.5 by polarizing the reacting nuclei. In addition, the polarization can be used to control particle emission directions and thus save structure materials. For a number of reasons the neutron-less reaction (2) is preferred but needs higher incident energy and is accompanied by neutrons from the \[\text{d} + \text{d} \rightarrow n + ^3\text{He} + 3.268 \text{MeV} \] (3) reaction. This and \[\text{d} + \text{d} \rightarrow p + ^3\text{H} + 4.033 \text{MeV} \] (4) are energy-producing reactions in their own right, but are less efficient.

The proposal of suppressing these DD neutrons by polarizing the deuterons in the \(S=2\) (quintet) state has incited many conflicting theoretical predictions as well as attempts to parametrize the existing experimental data, see e.g. \[3\] whereas a spin-correlation experiment has never been attempted \[2\]. It is clear that – due to the very low energies (10 - 100 keV) – such an experiment is difficult and lengthy and requires sophisticated spin-polarization techniques, but is being planned by the \textit{PolFusion} collaboration \[4, 5\]. The reaction mechanism of the two reactions is very complicated and requires up to 16 complex T-matrix elements (\(S-, P-, \text{and D-waves are important}\)) and is therefore also interesting in itself. The low-energy data situation is rather poor, and better theoretical predictions for all (polarization) observables are urgently needed.

References

[1] R.M. Kulsrud \textit{et al.}, Phys. Rev. Lett. \textbf{49}, 1248 (1982).
[2] H. Paetz gen. Schieck, Eur. Phys. J. A \textbf{44}, 321 (2010).
[3] S. Lemaître, H. Paetz gen. Schieck, Ann. Phys. (Leipzig) \textbf{2}, 503 (1993).
[4] K. Grigoriev \textit{et al.}, Proc. 19th Int. Spin Physics Symposium (SPIN2010), Jülich, J. of Phys. IOP Conf. Series \textbf{295}, 012168 (2011).
[5] H. Paetz gen. Schieck, Few-Body Syst. DOI 10.1007/s00601-012-0485-0 (2012).
Are New Experiments at Low Energies Really Needed to Advance Few-Body Physics?

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The reason for raising the question given in the title is the possibility that experimental facilities capable of producing low-energy hadron and photon beams will not be available anymore in the foreseeable future. Here, ”low-energy” refers to incident beams of up to about 50 MeV. Even if some existing facilities survive, or new ones come on-line, it will be very difficult to obtain beam time for few-body physics experiments. Funding agencies keep saying ”You have been doing this already for too long” and they continue with the question stated in the title. In this talk I give arguments and show examples for the A=2 to A=4 few-body systems that new experiments are needed

A) If there exist observables of ”special theoretical interest” for which the existing experimental results are contradictory.

B) If only one measurement exists for an observable of ”special theoretical interest”.

C) If experimental results are not available at all for observables which are of ”special theoretical interest”.

In general, the agreement between data and few-nucleon calculations at low energies is very satisfactory. I consider this observation as a real success story. However, there is still the need to definitely resolve existing discrepancies between experimental data for a few observables, like neutron-neutron quasi-free scattering. In addition, a few new observables should definitely be measured, for example:

a) The analyzing power in neutron-³H elastic scattering.

b) Observables which are sensitive to the off-shell behavior of the NN interaction, for example, neutron-proton bremsstrahlung.

c) Some polarized spin-spin observables.

d) A full set of Wolfenstein parameters at a few energies.

Only then it may eventually be justifiable to let Few-Body Physics at low energies become a purely theoretical discipline.
Nuclear Dynamics from Lattice QCD

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Nuclear physics is a vast field, whose phenomenology has been explored for decades through intense experimental and theoretical effort. However, the quantitative connection between nuclear physics and the basic building blocks of nature, quarks and gluons, whose interactions are encoded in QCD, are only now beginning, using lattice QCD (LQCD) methods. The first predictions for nuclear physics from LQCD are for the hyperon-nucleon interaction [1]. These interactions determine, in part, the role of the strange quark in dense matter, such as that found in astrophysical environments. Calculations of phase shifts, performed at a heavy pion mass of $m_\pi \sim 390$ MeV have been extrapolated to the physical pion mass using chiral effective field theory (EFT). The interactions determined from QCD are consistent with those extracted from hyperon-nucleon experimental data within uncertainties. The scattering lengths and effective ranges that describe low-energy nucleon-nucleon scattering have been calculated in the limit of SU(3)-flavor symmetry at the physical strange-quark mass using LQCD [2].

The values of the scattering parameters, in the $^1S_0$ and $^3S_1$ channels are, in a sense, more natural at $m_\pi \sim 800$ MeV where both satisfy $a/r \sim +2.0$, than at the physical pion mass where $a(^1S_0)/r(^1S_0) \sim 8.7$ and $a(^3S_1)/r(^3S_1) \sim +3.1$. The relatively large size of the deuteron compared with the range of the nuclear forces may persist over a large range of light-quark masses, and therefore might be a generic feature of QCD. The $^1S_0$-channel, by contrast, is finely tuned at the physical light-quark masses and it remains to be seen over what range of masses this persists. Finally, the existing LQCD data for the quark-mass dependence of nuclear binding has been used, together with EFT methods, to show that the cross sections for scalar-isoscalar WIMP-nucleus interactions arising from fundamental WIMP interactions with quarks do not suffer from significant uncertainties due to enhanced meson-exchange currents [3].

References

[1] S. R. Beane, E. Chang, S. D. Cohen, W. Detmold, H. -W. Lin, T. C. Luu, K. Orginos and A. Parreno et al., Phys. Rev. Lett. 109, 172001 (2012) [arXiv:1204.3606 [hep-lat]].
[2] S. R. Beane, E. Chang, S. D. Cohen, W. Detmold, P. Junnarkar, H. W. Lin, T. C. Luu and K. Orginos et al., arXiv:1301.5790 [hep-lat].
[3] S. R. Beane, S. D. Cohen, W. Detmold, H. -W. Lin and M. J. Savage, arXiv:1306.6939 [hep-ph].
SU(3) chiral dynamics revisited

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The analysis of the fermion determinant in terms of Dirac eigenvalues shows that two particularly interesting order parameters of the spontaneous breaking of chiral symmetry, the quark condensate and the meson decay constant in the chiral limit, are dominated by the infrared extremity of the Dirac spectrum. This leads to a parametric suppression of the three-flavor condensate namely:

\[ \Sigma(3) < \Sigma(2), \quad F^2(3) < F^2(2) \]  

Interesting questions thus are: how strong this suppression is and what the consequences are. To address them we have studied meson properties such as spectrum, decay constants and \(K_{\ell3}\) form factors on one hand \([1]\) and topological quantities \([2]\), the topological susceptibility and the fourth cumulant, on the other hand in the framework of resummed \(\chi PT\) \([3]\). Such a scheme reorders the chiral series allowing for a numerical competition between leading order and next to leading order terms. Performing a fit to data from two lattice collaborations \([4]\), \([5]\) the emerging picture for the pattern of chiral symmetry breaking is marked by a strong dependence of the observables on the strange quark mass and thus a significant difference between chiral symmetry breaking in the \(N_f = 2\) and \(N_f = 3\) chiral limits. This result impacts the chiral extrapolation of lattice data, in particular it can affect the determination of the lattice spacing as discussed in \([2]\). Furthermore, for hierarchies of light-quark masses close to the physical situation, the fourth cumulant has a much better sensitivity than the topological susceptibility to the three-flavour quark condensate. Also a combination of the topological susceptibility and the fourth cumulant is able to pin down the three flavour condensate in a very clean way in the case of three degenerate quarks.

References

[1] V. Bernard, S. Descotes-Genon and G. Toucas, JHEP 1101 (2011) 107.
[2] V. Bernard, S. Descotes-Genon and G. Toucas, JHEP 1206 (2012) 051; JHEP 1212 (2012) 080.
[3] S. Descotes-Genon, N. H. Fuchs, L. Girlanda and J. Stern, Eur. Phys. J. C 34 (2004) 201.
[4] S. Aoki et al. [PACS-CS Collaboration], Phys. Rev. D79 (2009) 034503.
[5] C. Allton et al. [RBC-UKQCD Collaboration], Phys. Rev. D78 (2008) 114509; P.A. Boyle et al., Phys. Rev. Lett. 100 (2008) 141601; [arXiv:1004.0886].
Space-time picture of chiral dynamics with nucleons

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We explore chiral dynamics with nucleons in the space–time picture based on the partonic (or light-front) formulation of relativistic systems. The electromagnetic form factors are expressed in terms of frame–independent densities of charge and magnetization in transverse space (see [1] for a review). The chiral component of nucleon structure is identified as the region of transverse distances \( b = O(M_{\pi}^{-1}) \) and can be studied systematically using chiral EFT methods. We compute the peripheral transverse charge and magnetization densities in the leading–order approximation and study their properties (large–distance behavior, heavy–baryon expansion, role of intermediate \( \Delta \) isobars, chiral vs. non-chiral contributions) [2], [3]. We demonstrate the equivalence of the Lorentz-invariant formulation of chiral EFT and the time-ordered formulation using light–front wave functions. The time–ordered formulation provides a simple “mechanical” interpretation of the nucleon’s chiral component and explains the relative magnitude of the peripheral charge and magnetization densities. The space-time picture of chiral dynamics described here offers new perspectives on peripheral nucleon structure and basic properties of the chiral expansion. It connects chiral dynamics with the nucleon’s quark/gluon structure (generalized parton distributions) probed in peripheral high-energy scattering processes [4], [5].

References

[1] G. A. Miller, Ann. Rev. Nucl. Part. Sci. 60, 1 (2010).
[2] C. Granados and C. Weiss, arXiv:1308.1634 [hep-ph].
[3] M. Strikman and C. Weiss, Phys. Rev. C 82, 042201 (2010).
[4] M. Strikman and C. Weiss, Phys. Rev. D 80, 114029 (2009).
[5] M. Strikman and C. Weiss, Phys. Rev. D 69, 054012 (2004).
Pion production in nucleon-nucleon collisions

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The proper treatment of $NN \rightarrow NN\pi$ within chiral EFT requires taking into account the intermediate momentum scale, $p \approx \sqrt{m_\pi m_N}$ with $m_\pi$ and $m_N$ being the pion and nucleon masses [1]. Given this modification, the application of chiral EFT to s-wave pion production in the $pp \rightarrow d\pi^+$ channel at next-to-leading order (NLO) [2], revealed good agreement with experimental data. In contrast, for s-wave pion production in the channel $pp \rightarrow pp\pi^0$, all operators at LO and NLO are strongly suppressed [1]. Therefore, it is not a surprise that the relative importance of chiral loops with explicit nucleon and $\Delta(1232)$ degrees of freedom at $N^2$LO in $pp \rightarrow pp\pi^0$ is significantly enhanced compared to $pp \rightarrow d\pi^+$ [3].

The study of pion production in $pn \rightarrow d\pi^0$ provides access to charge symmetry breaking (CSB) phenomena [4-6]. CSB in $pn \rightarrow d\pi^0$ is caused predominantly by the strong contribution to the proton-neutron mass difference [3]. Therefore, studying CSB in $pn \rightarrow d\pi^0$ allows one to extract separately the important low-energy parameters – strong and electromagnetic contributions to the proton-neutron mass difference – in analogy to a recent determination of the s-wave $\pi N$ scattering lengths from pionic atoms [7]. Another important application would be to verify the connection provided by chiral symmetry between pion production and other low-energy few-nucleon reactions. Specifically, p-wave pion production can be used to pin down the $(\bar{NN})^2\pi$ low-energy constant (LEC) [8,9]. Apart from $NN \rightarrow NN\pi$, this LEC contributes to the 3N force, to electroweak processes and to reactions involving photons. Recent measurements of $\bar{pp} \rightarrow (pp)\pi^0$ and $\bar{pn} \rightarrow (pp)\pi^-$ at COSY provide the database for the extraction of this LEC [10].

References

[1] C. Hanhart, Phys. Rept. 397 (2004) 155.
[2] V. Lensky et al., Eur. Phys. J. A 27 (2006) 37.
[3] A. A. Filin et al., Phys. Rev. C 85 (2012) 054001; arXiv:1307.6187 (2013).
[4] U. van Kolck et al., Phys. Lett., B 493, 65 (2000).
[5] A. Filin et al., Phys. Lett. B 681 (2009) 423.
[6] A. K. Opper et al. Phys. Rev. Lett., 91, 212302 (2003).
[7] V. Baru et al., Phys. Lett. B 694 (2011) 473; Nucl. Phys. A 872 (2011) 69,
[8] C. Hanhart et al., Phys. Rev. Lett. 85 (2000) 2905.
[9] V. Baru et al., Phys. Rev. C 80 (2009) 044003.
[10] S. Dymov et al. [ANKE Collaboration], arXiv:1304.3678 [nucl-ex].
**Issues of renormalization in EFT for the NN system**

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In calculations of physical quantities in low-energy effective field theory (EFT) of few nucleons \([1]\), one usually interchanges the order of calculating quantum corrections and the non-relativistic expansion. Generally, to perform a proper non-relativistic expansion, one has to first evaluate the observable of interest based on a Lorentz-invariant effective Lagrangian. The calculation of quantum corrections (i.e. loop diagrams) requires regularization (\(\Lambda\)) and renormalization. Resulting finite physical quantities can then be expanded in inverse powers of the nucleon mass (\(m\)). On the other hand, in non-relativistic formulations of EFT, one first expands the Lorentz-invariant effective Lagrangian in powers of \(1/m\). The calculation of quantum corrections based on the \(1/m\)-expanded Lagrangian again requires regularization and renormalization and leads to renormalized quantities being represented as series in \(1/m\). Generally, the expansion in \(1/m\) and calculation of quantum corrections are non-commutative. However, the difference (“error”) can be compensated by adding terms to the \(1/m\)-expanded EFT Lagrangian \([3]\). Due to non-commutativity of \(1/m\) and \(1/\Lambda\) expansions in loop integrals and nonperturbative nature of the problem at hand, an infinite number of compensating terms are to be taken into account in the NN sector already at leading order (LO). At least in some cases, these contributions play a crucial role and hence cannot be dropped \([1]\). Possible solutions to this problem include keeping \(\Lambda \lesssim m\) (see e.g. \([2]\)) and using the original Lorentz invariant Lagrangian without interchanging the \(1/m\)-expansion and the calculation of loop contributions. The last approach has been formulated and applied at LO in Refs. \([5-7]\).

This work was supported by the DFG (GE 2218/2-1) and the Georgian Shota Rustaveli National Science Foundation (grant 11/31).

**References**

[1] S. Weinberg, Phys. Lett. B251 (1990) 288.
[2] E. Epelbaum et al., Rev. Mod. Phys. 81, 1773 (2009).
[3] J. Gegelia and G. Japaridze, Phys. Rev. D 60, 114038 (1999).
[4] E. Epelbaum and J. Gegelia, Eur. Phys. J. A 41, 341 (2009).
[5] E. Epelbaum and J. Gegelia, Phys. Lett. B 716, 338 (2012).
[6] E. Epelbaum and J. Gegelia, arXiv:1210.3964 [nucl-th].
[7] E. Epelbaum and J. Gegelia, arXiv:1301.6134 [nucl-th].
Overview and Latest News
from Nuclear Lattice Effective Field Theory

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This talk begins with an overview of the theoretical methods and numerical algorithms used in nuclear lattice effective field theory. This includes a description of chiral effective field theory regulated on the lattice [1], [2], [3], scattering phase shifts on the lattice using spherical wall boundaries [4], and Monte Carlo simulations using Euclidean time projection and auxiliary fields [5].

The remainder of the talk presents recent results on the spectrum of carbon-12 [6], the structure and rotations of the Hoyle state [7], [8], preliminary new results on nuclei up to $A = 28$, and the spectrum and structure of oxygen-16.

References

[1] B. Borasoy, E. Epelbaum, H. Krebs, D. Lee and U. -G. Meißner, Eur. Phys. J. A 31, 105 (2007).
[2] B. Borasoy, E. Epelbaum, H. Krebs, D. Lee and U. -G. Meißner, Eur. Phys. J. A 35, 343 (2008).
[3] E. Epelbaum, H. Krebs, D. Lee and U. -G. Meißner, Eur. Phys. J. A 41, 125 (2009).
[4] B. Borasoy, E. Epelbaum, H. Krebs, D. Lee and U. -G. Meißner, Eur. Phys. J. A 34, 185 (2007).
[5] D. Lee, Prog. Part. Nucl. Phys. 63, 117 (2009).
[6] E. Epelbaum, H. Krebs, D. Lee and U. -G. Meißner, Phys. Rev. Lett. 104, 142501 (2010).
[7] E. Epelbaum, H. Krebs, D. Lee and U. -G. Meißner, Phys. Rev. Lett. 106, 192501 (2011).
[8] E. Epelbaum, H. Krebs, T. A. Lähde, D. Lee and U. -G. Meißner, Phys. Rev. Lett. 109, 252501 (2012).
Life on Earth – an accident?

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The Hoyle state is considered a prime example for the \textit{anthropic principle}, that states that the fundamental parameters of all interactions are constrained by the requirement that carbon-oxygen based life could have been formed. Carbon is formed in hot stars via the triple-alpha process and this requires an $0^+$ excited state in $^{12}\text{C}$ close to the $3\alpha$ threshold, the so-called Hoyle state. This state could be described \textit{ab initio} for the first time using nuclear lattice simulations \cite{1}. In this framework, one can address the question: how much fine-tuning in the fundamental parameters of QCD+QED (the part of the Standard Model underlying nuclear physics) is allowed to still have a sufficient production of the life-essential elements? This requires the knowledge of the quark mass dependence of the nuclear forces as addressed to next-to-next-to-leading order in chiral EFT in Ref. \cite{2}. Based on this, one can study the ground and excited state energies of the nuclei appearing in the $3\alpha$-process, see Refs. \cite{3}, \cite{4}. We find strong evidence that the physics of the $3\alpha$-process is driven by $\alpha$-clustering, and that shifts in the light quark mass at the $\sim 2 - 3\%$ level are unlikely to be detrimental to the development of life. Tolerance against much larger changes cannot be ruled out at present, given the relatively limited knowledge of the quark mass dependence of the two-nucleon S-wave scattering parameters. Lattice QCD is expected to provide refined estimates of the scattering parameters in the future. Further, variations of the fine-structure constant $\alpha_{\text{EM}}$ up to $\pm 2.5\%$ are consistent with the requirement of sufficient carbon and oxygen production in stars.

References

[1] E. Epelbaum, H. Krebs, D. Lee and U.-G. Meißner, Phys. Rev. Lett. \textbf{106} (2011) 192501 \texttt{[arXiv:1101.2547 [nucl-th]]}.

[2] J. C. Berengut, E. Epelbaum, V. V. Flambaum, C. Hanhart, U.-G. Meißner, J. Nebreda and J. R. Pelaez, Phys. Rev. D \textbf{87} (2013) 085018 \texttt{[arXiv:1301.1738 [nucl-th]]}.

[3] E. Epelbaum, H. Krebs, T. A. Lähde, D. Lee and U.-G. Meißner, Phys. Rev. Lett. \textbf{110} (2013) 112502 \texttt{[arXiv:1212.4181 [nucl-th]]}.

[4] E. Epelbaum, H. Krebs, T. A. Lähde, D. Lee and U.-G. Meißner, Eur. Phys. J. A \textbf{49}:82 (2013) \texttt{[arXiv:1303.4856 [nucl-th]]}.
Nuclear Structure and Reactions in Lattice Effective Field Theory

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Nuclear structure and reactions play an important role in low-energy nuclear astrophysics where constraints on fundamental physics can be placed. There is also renewed experimental interest in properties of nuclei that populate areas in the nuclear chart far from the valley of stability. Nuclear theory is needed for extrapolation of experimental data to the low-energy regime relevant to nuclear astrophysics. Ab initio calculation becomes important when parameters necessary for constraining the nuclear theory are not known experimentally. This is the case [1], for example, for \(^7\)Li\((n, \gamma)\)^8\(\text{Li}\) and \(^7\)Be\((p, \gamma)\)^8\(\text{B}\). Thus there is a physics need for ab initio calculations. Further, microscopic calculations based on chiral perturbation theory (\(\chi\)PT) can act as the bridge between nuclear properties and first principle Quantum Chromodynamic (QCD) calculations in lattice gauge theories. Lattice effective field theory (EFT) calculations are particularly attractive as it systematically combines \(\chi\)PT rooted in QCD with the powerful numerical lattice methods [2]. However, there has been no general method for calculating reactions on the lattice.

I present a general method for calculating radiative capture reactions \(a(b, \gamma)c\) where \(a, b, c\) are generic nuclei [3]. The basic idea involves calculating an effective two-body Hamiltonian for scattering the nuclei \(a\) and \(b\) using an adiabatic Euclidean time projection, and using this Hamiltonian to calculate the capture reactions on the lattice. We test the method by calculating the adiabatic Hamiltonian for fermion-dimer and quartet channel neutron-deuteron scattering. Calculation of the capture reaction using a two-body Hamiltonian on the lattice is demonstrated by considering \(p(n, \gamma)d\). We use the two-point retarded Green’s function to calculate the capture reaction where we introduce an infrared regulator to systematically suppress the finite volume corrections on the lattice. Finally, I present some new calculations of neutron matter equation of state that updates the results from Ref. [4] using an improved lattice EFT Hamiltonian.

References

[1] G. Rupak and R. Higa, Phys. Rev. Lett. 106 (2011) 222501.
[2] D. Lee, Prog. Part. Nucl. Phys. 63 (2009) 117.
[3] G. Rupak and D. Lee, Phys. Rev. Lett. 111 (2013) 032502.
[4] E. Epelbaum et al., Eur. Phys. J. A 40 (2009) 199.
Evolving perspectives on the origins of nuclear structure

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The overarching problem of nuclear theory is to use all the fundamental interactions of the Standard Model to describe and predict nuclear phenomena. The “ab initio” approach to nuclear structure, in which one solves the nuclear many-body problem with interactions based on Chiral Effective Field Theory (EFT), is a key step in this direction and it is emerging as a validated and predictive theory with quantified uncertainties.

Among the many recent successes to mention, the successful description of the suppressed beta decay of $^{14}\text{C}$ as rooted in the role of the chiral three-nucleon interaction stands as a particularly interesting achievement [1]. Historically, many-body theory with realistic nucleon-nucleon interactions alone had been unsuccessful in achieving the required suppression. It emerged that this decay is sensitive to subtle changes in the spin-dependent components of the nuclear Hamiltonian that were successfully described only with the addition of the three-nucleon interaction. Additional advances in both structure and reactions have been reviewed recently [2], [3].

Progress to date allows us to demonstrate certain limitations of currently available Hamiltonians from Chiral EFT. This motivates a new generation of efforts to derive and implement improved Hamiltonians. A large-scale collaboration (LENPIC) is getting underway with these goals in mind.

Many challenges for microscopic many-body theory of nuclei remain including the need for a detailed description of cluster structure in nuclei as well as other collective motions. We also aim to extend ab initio microscopic many-body theory to heavier nuclei than those currently addressed. We have entered an era where large-scale calculations are required as well as continued collaborations between physicists, applied mathematicians and computer scientists.

This work is supported by the US DOE SciDAC program through the NUCLEI collaboration, by the US DOE Grants No. DE-SC-0008485 (SciDAC/NUCLEI) and No. DE-FG02 87ER40371 as well as by the US NSF Grant No. 0904782.

References

[1] P. Maris, J. P. Vary, P. Navrátíl, W. E. Ormand, H. Nam and D. J. Dean, Phys. Rev. Lett. 106, 202502 (2011) [arXiv:1101.5124 [nucl-th]].

[2] B. R. Barrett, P. Navrátíl and J. P. Vary, Prog. Part. Nucl. Phys. 69 (2013) 131.

[3] P. Maris and J. P. Vary, Int. J. Mod. Phys. E., (in press).
New Horizons in Ab Initio Nuclear Structure Theory

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Low-energy nuclear theory has entered an era of ab initio nuclear structure and reaction calculations based on input from QCD. One of the most promising paths from QCD to nuclear observables employs Hamiltonians constructed within chiral effective field theory (EFT) as starting point for precise ab initio studies. However, the full inclusion of chiral two- plus three-nucleon (NN+3N) interactions in exact and approximate many-body calculations beyond the few-body domain poses a challenge.

Our recent breakthroughs enable ab initio calculations for ground states and spectra of nuclei throughout the p- and lower sd-shell with full 3N interactions using consistent Similarity Renormalization Group (SRG) transformations and the Importance-Truncated No-Core Shell Model (IT-NCSM) [1], [2]. In this ab initio framework we are studying, e.g., the ground-state properties and spectroscopy along the Carbon and Oxygen isotopic chains and demonstrate the predictive power of chiral Hamiltonians [2]. The same NN+3N Hamiltonians can be applied for the ab initio description of medium-mass nuclei, e.g. in Coupled Cluster Theory [3], [4] or in the In-Medium SRG [5], [2]. These calculations clearly demonstrate that the frontier of ab initio nuclear structure theory is rapidly moving towards heavier nuclei, which were completely out of reach a few years ago. Another new direction is the ab initio description of p-shell hypernuclei, which was the domain of phenomenological calculations so far. With the advent of hyperon-nucleon interactions from chiral EFT and the advances in many-body methods ab initio calculations of ground states and spectroscopy of single-Λ hypernuclei are now possible throughout and beyond the p-shell.

As these developments show, the horizon for ab initio nuclear structure theory has changed dramatically over the past few years, offering exciting perspectives for QCD-based nuclear structure physics in the coming years.

Supported by the DFG through SFB 634, by the Helmholtz International Center for FAIR, and by the BMBF through BMBF-FSP 302 and 06DA7047I.

References

[1] R. Roth, et al.; Phys. Rev. Lett. 107, 072501 (2011).
[2] H. Hergert, et al.; Phys. Rev. Lett. 110, 242501 (2013).
[3] S. Binder, et al.; Phys. Rev. C 87, 021303(R) (2013).
[4] R. Roth, et al.; Phys. Rev. Lett 109, 052501 (2012).
[5] H. Hergert, et al.; Phys. Rev. C 87, 034307 (2013).
Ab initio many-body calculations of light-ion reactions

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The ab initio no-core shell model/resonating group method (NCSM/RGM) introduced in Refs. \cite{1,2} is a technique capable of describing both structure and reactions in light nuclear systems. This approach combines a microscopic cluster technique with the use of realistic inter-nucleon interactions and a consistent microscopic description of the nucleon clusters.

The method has been introduced in detail for two-body clusters and has been shown to work efficiently in different systems \cite{1-4}. In this work we discuss recent advances of the method which include its coupling with the NCSM into a new approach called no-core shell model with continuum (NCSMC) with results for 7He resonances \cite{5}. We also present the first results after the inclusion of chiral three-nucleon forces in the calculations and its effect in the nucleon-4He scattering phase shifts \cite{6}. Finally, we introduce three-body cluster configurations and provide, for the first time within an ab initio framework, the correct asymptotic behaviour for the three-cluster wave functions. We present the results obtained for 6He within a 4He(g.s.)+n+n basis for the ground and continuum states \cite{7}.

Acknowledgments: Prepared in part by LLNL under Contract DE-AC52-07NA27344. Support from the NSERC Grant No. 401945-2011, U.S. DOE/SC/NP (Work Proposal No. SCW1158), the DFG through SFB 634, the Helmholtz International Center for FAIR and the BMBF(06DA7074I) is acknowledge.

References

\cite{1} S. Quaglioni and P. Navrátil, Phys. Rev. Lett. 101 (2008) 092501.
\cite{2} S. Quaglioni and P. Navrátil, Phys. Rev. C 79 (2009) 044606.
\cite{3} P. Navrátil and S. Quaglioni, Phys. Rev. Lett. 108 (2012) 042503.
\cite{4} P. Navrátil, R. Roth, and S. Quaglioni, Phys. Lett. B 704 (2011) 379.
\cite{5} S. Baroni, P. Navrátil, S. Quaglioni, Phys. Rev. C 87 (2013) 034326.
\cite{6} G. Hupin, J. Langhammer, P. Navrátil, S. Quaglioni, A. Calci, R. Roth, in preparation (2013).
\cite{7} S. Quaglioni, C. Romero-Redondo and P. Navrátil, in preparation (2013).
Neutron rich matter from chiral effective field theory interactions

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Chiral effective field theory (EFT) offers a systematic expansion of nuclear forces well suited to meet the calculational challenges of neutron-rich matter, which span the extremes from universal properties at low-densities to the dense matter in neutron stars. The development of novel Renormalization Group (RG) methods make it possible to study various properties of matter within many-body perturbation theory [1]. Very recently these results have been validated for the first time using Quantum Monte Carlo calculations based on chiral EFT interactions [2]. Our current efforts aim at improving the treatment of chiral three-nucleon (3N) forces by employing interactions which have been evolved consistently within the Similarity RG [3].

Based on our microscopic neutron matter results up to densities around nuclear saturation, we were able to derive model-independent constraints on the nuclear equation of state at higher densities using only constraints from neutron star mass observations and causality [4].

Neutron matter also provides a powerful laboratory for testing chiral EFT power counting at relevant nuclear densities, since only long-range 3N forces contribute at next-to-next-to-leading order (N^2LO) [1] and there are no new parameters for 3N and four-nucleon interactions at next-to-next-to-next-to-leading order (N^3LO). In Ref. [5] we presented the first complete N^3LO calculation of the neutron matter energy, including contributions from 3N and 4N forces. We find large contributions from 3N forces at N^3LO, which indicates that a chiral EFT with explicit delta degrees of freedom might be more efficient.

References

[1] K. Hebeler and A. Schwenk, Phys. Rev. C82 (2010) 014314.
[2] A. Gezerlis et al., arXiv:1303.6243 [nucl-th].
[3] K. Hebeler, Phys. Rev. C85 (2012) 021002(R); K. Hebeler and R. J. Furnstahl, Phys. Rev. C87 (2013) 031302(R).
[4] K. Hebeler et al., Phys. Rev. Lett. 105 (2010) 161102; K. Hebeler et al., Astrophys. J., 773 (2013) 11.
[5] I. Tews et al., Phys. Rev. Lett. 110 (2013) 032504; T. Krüger et al., arXiv:1304.2212 [nucl-th].
Universal Properties of Halo Nuclei

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Halo Effective Field Theory (EFT) exploits the separation of scales between a tightly bound core and loosely bound valence nucleons in halo nuclei. Low-energy observables are described in a controlled expansion in the ratio \( R_{\text{core}}/R_{\text{halo}} \) of the scales characterizing core and halo [1]. While ab initio approaches try to predict nuclear observables from a fundamental nucleon-nucleon interaction, halo EFT essentially provides model-independent relations between different nuclear observables. Coulomb effects and electromagnetic currents can be included in a straightforward way.

In this talk, we discuss recent results on the charge and matter form factors of halo nuclei. We review the universal properties and structure of one-neutron (1n) and 2n halo nuclei, focusing on their form factors and radii [2]. In particular, we highlight recent work by Acharya et al. [3] on the implications of a recent matter radius measurement for the binding energy and existence of excited Efimov states in \(^{22}\text{C}\). Moreover, we discuss the extension of the electromagnetic structure calculations in halo EFT to 2n halo nuclei using a trimer auxiliary field formalism and its application to the charge form factors and radii of \(^{11}\text{Li}\), \(^{14}\text{Be}\) and \(^{22}\text{C}\) [4]. Finally, we present results from a recent investigation of Efimov physics in the Calcium isotope chain [5]. This study combined \(n^{-60}\text{Ca}\) S-wave scattering phase shifts from state of the art ab initio coupled cluster calculations using chiral interactions with halo EFT to obtain the properties of \(^{62}\text{Ca}\). In particular, correlations between different observables in the \(n^{-61}\text{Ca}\) and \(^{62}\text{Ca}\) systems were predicted and evidence of Efimov physics in \(^{62}\text{Ca}\) was provided.

References

[1] C.A. Bertulani, H.-W. Hammer and U. Van Kolck, Nucl. Phys. A 712 (2002) 37 [arXiv:nucl-th/0205063]; P.F. Bedaque, H.-W. Hammer and U. van Kolck, Phys. Lett. B 569 (2003) 159 [arXiv:nucl-th/0304007].
[2] D. L. Canham and H.-W. Hammer, Eur. Phys. J. A 37 (2008) 367 [arXiv:0807.3258 [nucl-th]].
[3] B. Acharya, C. Ji and D. R. Phillips, Phys. Lett. B 723 (2013) 196 [arXiv:1303.6720 [nucl-th]].
[4] P. Hagen, H.-W. Hammer and L. Platter, arXiv:1304.6516 [nucl-th].
[5] G. Hagen, P. Hagen, H.-W. Hammer and L. Platter, arXiv:1306.3661 [nucl-th].
EFT for photon interactions with halo nuclei

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“Halo EFT” contains core and neutron degrees of freedom, and is built on the scale hierarchy $R_{\text{core}} \ll R_{\text{halo}}$. This theory can be used to analyze the Coulomb dissociation of one-neutron halos. In $^{19}$C $R_{\text{core}}/R_{\text{halo}} \approx 0.4$, and fitting the N$^2$LO Halo EFT amplitude for the Coulomb dissociation of $^{19}$C to experimental data allows accurate values for the $^{18}$C effective-range parameters to be extracted.

The $^{11}$Be nucleus has shallow $1/2^+$ and $1/2^-$ states. We used data on the $^{11}$Be levels and the B(E1) of the $1/2^+$ to $1/2^-$ transition to fix LO EFT parameters. We then predicted the Coulomb dissociation spectrum of $^{11}$Be at LO. At next-to-leading order an additional parameter associated with the asymptotic normalization coefficient (ANC) of the $1/2^+$ state enters. It can be adjusted to obtain a good description of data on the low-energy dB(E1)/dE spectrum.

One may instead employ ANCs obtained in ab initio calculations as input to Halo EFT. We have done this in the case of the reaction $^7\text{Li} + n \rightarrow ^8\text{Li} + \gamma$. We need 7 ANCs in order to fix the LO parameters of the theory that are pertinent to radiative neutron capture into the $^8\text{Li}$ ground and first-excited states. Our LO result for the threshold ground-state capture cross section is about 30% below the data. The ratio of ground-to-excited-state capture is within 1% of the experimental result, and we also obtain a good result for the ratio of capture from different spin channels. This is in contrast to a previous EFT calculation, which made simplifying assumptions about the reaction dynamics.

p-wave 2n halos are also now being addressed in Halo EFT. A LO calculation of $^6\text{He}$ using the power counting of Ref. shows that a three-body force is necessary at LO in this system. A similar conclusion, but using a different approach and a different $^4\text{He}$-n amplitude, was reached in Ref.

References

[1] H.-W. Hammer, these mini-proceedings.
[2] B. Acharya and D. R. Phillips, Nucl. Phys. A 913, 103 (2013).
[3] H.-W. Hammer and D. R. Phillips, Nucl. Phys. A 865, 17 (2011).
[4] K. M. Nollett and R. B. Wiringa, Phys. Rev. C 83, 041001 (2011).
[5] X. Zhang, K. Nollett, and D. R. Phillips, in preparation.
[6] G. Rupak and R. Higa, Phys. Rev. Lett. 106, 222501 (2011).
[7] P. F. Bedaque et al., Phys. Lett. B 569, 159 (2003).
[8] C. Ji, Ch. Elster, and D. R. Phillips, in preparation.
[9] J. Rotureau and U. van Kolck, Few Body Syst. 54, 725 (2013).
Selected weak interaction processes on the deuteron and $^{3}$He

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In 1992 Walter Saake, a student of Prof. Walter Glöckle, prepared his master thesis \cite{Saake1992}, in which he studied numerical properties of the three-nucleon (3N) bound state and some weak transitions between the $^{3}$H and $^{3}$He nuclei. We now calculate selected decay rates for the muon-deuteron and muon-$^{3}$He atoms as well as the $ft$-value for the triton beta decay. We use the single nucleon current operator without and with relativistic corrections. We employ a new method to deal with partial wave decomposition (PWD) of the current operator and show that for the two-nucleon (2N) system PWD can be totally avoided \cite{Topolnicki2012}. We plan to include 2N current operators as given for example in Refs. [3-8]. We do hope that the framework under construction can be a useful tool for constructing a consistent treatment of forces and current operators within the chiral effective field theory.

References

\cite{Saake1992} W. Saake, master thesis, Ruhr-Universität, Bochum, (1992), unpublished.
\cite{Topolnicki2012} K. Topolnicki et al., Few-body Syst., DOI 10.1007/s00601-012-0479-y
\cite{Marcucci2002} L. E. Marcucci, Ph.D. thesis, Old Dominion University, (2002),
http://www.df.unipi.it/~marcucci/
\cite{Marcucci2001} L. E. Marcucci et al., Phys. Rev. C63 (2001) 015801.
\cite{Ando2002} S. Ando et al., Phys. Lett. B533 (2002) 25.
\cite{Marcucci2011} L. E. Marcucci et al., Phys. Rev. C83 (2011) 014002.
\cite{Marcucci2012} L. E. Marcucci et al., Phys. Rev. Lett. 108 (2012) 052502.
\cite{Shen2012} G. Shen et al., Phys. Rev. C86 (2012) 035503.
High-accuracy analysis of Compton Scattering in $\chi$EFT

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Compton scattering from protons and neutrons provides important insight into the structure of the nucleon. A new extraction of the static electric and magnetic dipole polarisabilities ($\alpha_{E1}$ and $\beta_{M1}$) of the proton and neutron from a new statistically consistent database taking into account all published elastic data below 300 MeV in Chiral Effective Field Theory finds (in units of $10^{-4}\text{fm}^3$):

proton $^1$: $\alpha_{E1}^{(p)} = 10.7 \pm 0.4(\text{stat}) \pm 0.2(\text{Baldin}) \pm 0.3(\text{theory})$
$\beta_{M1}^{(p)} = 3.1 \mp 0.4(\text{stat}) \pm 0.2(\text{Baldin}) \mp 0.3(\text{theory})$

neutron $^2$: $\alpha_{E1}^{(n)} = 11.1 \pm 1.8(\text{stat}) \pm 0.4(\text{Baldin}) \pm 0.8(\text{theory})$
$\beta_{M1}^{(n)} = 4.2 \mp 1.8(\text{stat}) \pm 0.4(\text{Baldin}) \pm 0.8(\text{theory})$

Special care has been taken to reproducibly justify a theoretical uncertainty of $\pm 0.3$ from the most conservative of several estimates of higher-order terms. Within the statistics-dominated errors, the proton and neutron polarisabilities are thus identical, i.e. no isospin breaking effects of the pion cloud are seen, as predicted by Chiral EFT. An explicit $\Delta(1232)$ is particularly important for deuteron Compton scattering above about 90 MeV as measured at SAL and MAXlab. For few-nucleon systems like the deuteron and $^3\text{He}$, consistency arguments dictate that the $NN$ and $NNN$ rescattering states must be included for a correct Thomson limit. In view of ongoing and planned efforts at HI-$\gamma S$, MAMI and MAXlab, single- and doubly-polarised observables with linearly or circularly polarised photons on both unpolarised deuterons are important. Several observables can be used to extract not only scalar nucleon polarisabilities, but also the so-far practically un-determined spin polarisabilities. These parametrise the stiffness of the nucleon’s low-energy spin degrees of freedom in electro-magnetic fields, i.e. the optical activity of the nucleon.

Supported by US DoE DE-FG02-95ER-40907 and the Sino-German CRC 110.

References

[1] J. A. McGovern, D. R. Phillips and H. W. Grießhammer: Europ. J. Phys. A49 (2013) 12 [arXiv:1210.4104 [nucl-th]].
[2] H. W. Grießhammer, J. A. McGovern, D. R. Phillips and G. Feldman: Prog. Part. Nucl. Phys. 67 (2012), 841 [arXiv:1203.6834 [nucl-th]].
[3] H. W. Grießhammer: Europ. J. Phys. A in press [arXiv:1304.6594 [nucl-th]].

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Chiral expansion of the three-nucleon force

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A precise, quantitative description of the three-nucleon forces (3NFs) is needed to understand nucleon-deuteron elastic and breakup scattering (in particular the $A_y$-puzzle) and to improve ab-initio nuclear structure calculations. We describe the calculation of the long-range contributions to the 3NF up to next-to-next-to-next-to-leading order ($N^4$LO) in the $\Delta$-less chiral EFT framework. The long-range topologies do not involve free parameters except for the low-energy constants (LECs) which have been extracted from $\pi N$ scattering using the same theoretical framework. To study convergence of the chiral expansion, we worked out the most general operator structure of a local isospin-invariant 3NF which involves 89 independent operators. We proposed a set of 22 operators which can serve as a basis and give rise to all 89 structures in the 3NF upon making permutations of the nucleon labels. Using this operator basis, we compared the strength of the corresponding profile functions in configuration space for individual topologies at various orders in the chiral expansion. We observe a good convergence for the longest-range $2\pi$-exchange topology which clearly dominates the 3NF at distances of the order $r \gtrsim 2$ fm. The intermediate-range $2\pi-1\pi$ exchange and ring diagrams provide sizable corrections at $r \sim 1$ fm and contribute to those 12 profile functions which vanish for the $2\pi$ exchange. As expected, we found that $N^4$LO corrections to the intermediate-range topologies are numerically large and in most cases dominate over the nominally leading $N^3$LO terms. This can be traced back to the role played by the $\Delta(1232)$ isobar whose excitations provide an important 3NF mechanism. For the intermediate-range topologies, first effects of the $\Delta$ appear at $N^4$LO through resonance saturation of the LECs $c_2$, $c_3$ and $c_4$. The importance of the $\Delta$ isobar is reflected in the large values of these LECs which are responsible for large $N^4$LO corrections we observe. Our preliminary results in the $\Delta$-full approach demonstrate indeed a better convergence pattern for the 3NF. We also observe that some 3NF operators receive sizable contributions from double $\Delta$-excitation graphs. Such contributions are absent in the $\Delta$-less $N^4$LO potential, which may indicate that the $\Delta$-full approach is more efficient.

References

[1] H. Krebs, A. Gasparyan, E. Epelbaum, Phys. Rev. C 85, 054006 (2012).
[2] H. Krebs, A. Gasparyan E. Epelbaum, Phys. Rev. C 87, 054007 (2012).
Three-nucleon forces in the $1/N_c$ expansion

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We present a complete classification of all the spin-flavor structures that can contribute to three-nucleon forces and power count them in $1/N_c$. Including all independent momentum structures, a complete basis of operators for the three-nucleon force is given explicitly up to next-to-leading order in the $1/N_c$ expansion. We also show that the expansion is in a power series in $1/N_c^2$. This summarizes recent findings that have been presented in Ref. [1].

In the context of nuclear forces the $1/N_c$ expansion was first used to study the central part of the NN potential by Savage and Kaplan [2], and then to analyze the complete potential, classifying the relative strengths of the central, spin-orbit and tensor forces, by Kaplan and Manohar [3]. To obtain the results mentioned above we extended these analyses of the two-nucleon force to the case of the three-nucleon force (3NF).

In particular, we find that at leading order in $1/N_c$ a spin-flavor independent term is present, as are the spin-flavor structures associated with the Fujita-Miyazawa three-nucleon force. Modern phenomenological three-nucleon forces like the Urbana potential [4] are thus consistent with this $O(N_c)$ leading force, corrections to which are suppressed by $1/N_c^2$.

We obtain another interesting result if we restrict our basis to a subset of time-reversal even operators: we find a total of 80 operators that constitute the most general basis for a local 3NF. In a recent paper [5] the authors needed a basis of 89 operators to obtain the most general contribution of a local 3NF. An important subject for future investigation is the relation between the two sets of operators, and a determination of the minimal basis of operators for a general, local 3NF.

References

[1] D. R. Phillips and C. Schat, arXiv:1307.6274 [nucl-th].
[2] D. B. Kaplan and M. J. Savage, Phys. Lett. B 365, 244 (1996).
[3] D. B. Kaplan and A. V. Manohar, Phys. Rev. C 56, 76 (1997).
[4] S. C. Pieper, V. R. Pandharipande, R. B. Wiringa and J. Carlson, Phys. Rev. C 64, 014001 (2001).
[5] H. Krebs, A. Gasparyan and E. Epelbaum, Phys. Rev. C 87, 054007 (2013).
Constraining the three-nucleon contact interaction from nucleon-deuteron elastic scattering

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None of the presently available models of the three-nucleon (3N) interaction leads to a satisfactory description of bound and scattering states of $A = 3$ systems. It seems natural to ascribe the above situation to the fact that these models include a very small number of adjustable parameters, compared to the two-nucleon interaction case. Moreover, the main discrepancies arise at very low energy, as in the case of the proton vector analyzing power $A_y$ in $p - d$ scattering. At such low energies, much smaller than $M_\pi$, the interactions among the three nucleons are effectively of contact nature. We therefore propose to include the subleading 3N contact terms, which contain two powers of nucleon momenta and are unconstrained by chiral symmetry. By using all constraints from discrete and space-time symmetries we arrived at a set of 10 independent operators, and parametrized the potential in terms of 10 LECs, $E_1,...,E_{10}$ [1]. The basis of operators has been chosen such that most terms in the potential can be viewed as an ordinary interaction of a pair of particles with a further dependence on the coordinate of the third particle. In particular, the terms proportional to $E_7$ and $E_8$ are of spin-orbit type, and, as already suggested in the literature [2], have the right properties to solve the $A_y$ puzzle. Limiting ourselves to contact interactions, we thus have 11 LECs, a leading one $E = c_E/(F^4\pi\Lambda)$, and ten subleading ones $E_i = c_E^{3N}/(F^4\pi\Lambda^3)$, with adimensional quantities $c_{E,3N} \sim O(1)$, according to naive dimensional analysis. With the above 3N potential, used in conjunction with the AV18 two-nucleon interaction, we obtain the $p - d$ phaseshifts using the HH method [3], and compare to the phaseshift analysis (PSA) [4]. We observe a strong sensitivity to $c_E, e_8^{3N}$ and $e_{10}^{3N}$, and fit them (for a given $\Lambda = 500$ MeV) to reproduce the P-waves $^4P_{1/2}, ^4P_{3/2}$ and $^4P_{5/2}$ (particularly important for the $A_y$ problem), finding natural values of the LECs but a large $\chi^2$. This may be due to the optimistic experimental errorbars of the energy-independent PSA [4]. Work is in progress to optimize the fitting procedure and explore the sensitivity to $\Lambda$.

References

[1] L. Girlanda, A. Kievsky and M. Viviani, Phys. Rev. C 84 (2011) 014001.
[2] A. Kievsky, Phys. Rev. C 60 (1999) 034001.
[3] A. Kievsky et al., J. Phys. G 35 (2008) 063101.
[4] A. Kievsky et al., Nucl. Phys. A 607 (1996) 402.
Exploring Three Nucleon Forces in Few Nucleon Scattering

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Experimentally, one must utilize systems with more than two nucleons \( A \geq 3 \) to explore the properties of three nucleon forces (3NFs). Three nucleon scattering is one of the most promising tools, because this system provides a rich set of energy dependent spin observables and cross sections. In 1998 two theory groups incorporated 3NFs in elastic nucleon–deuteron \( (Nd) \) scattering at intermediate energies \( (E \gtrsim 60 \text{ MeV/nucleon}) \), and they suggested that the difference found in the cross section minima is the signature of 3NF effects \[1\], \[2\]. Since then we have extensively performed experimental studies of intermediate–energy \( pd \) and \( nd \) scattering at RIKEN and RCNP \[3\], \[4\], providing precise data for cross sections and a variety of spin observables. Recently we have extended the measurements at the new facility of RIKEN RI beam factory \[5\] where polarized deuteron beams are available up to 400 MeV/nucleon.

The results of comparison between elastic scattering data and the state–of–the–art Faddeev calculations based on realistic nucleon–nucleon forces plus \( 2\pi \)–exchange 3NFs are summarized as follows; (i) A clear signature of 3NFs is identified in the cross section minimum for \( Nd \) elastic scattering. (ii) The polarization observables are not always described by adding the 3NFs, indicating defects of spin dependent parts of 3NFs. (iii) As going to higher incident energies \( (\gtrsim 200 \text{ MeV/nucleon}) \) the serious discrepancies between the data and the calculations appear at the backward angles, which are not remedied even by including the 3NFs. Some significant components are missing in the higher momentum transfer region.

As the next step of experimental study of few nucleon scattering it should be interesting to extend the measurements to \( 4N \) scattering systems, which are the first step from few to many body systems, and to obtain \( 3N \) scattering data at higher energies to investigate higher momentum components of nuclear forces.

References

[1] H. Witala et al., Phys. Rev. Lett. 81 (1998) 1183.
[2] S. Nemoto et al., Phys. Rev. C 58(1998) 2599.
[3] For example, K. Sekiguchi et al., Phys. Rev. C 65 (2002) 034003; ibid. 79 (2009) 054008; Phys. Rev. Lett. 95 (2005) 162301.
[4] K. Hatanaka et al., Phys. Rev. C 66 (2002) 044002; Y. Maeda et al., ibid. 76 (2007) 014004.
[5] K. Sekiguchi et al., Phys. Rev. C 83 (2011) 061001.
Study of nuclear forces at intermediate energies

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At KVI and many other laboratories, various combinations of high-precision cross sections, analyzing powers, spin-transfer and spin-correlation coefficients have been measured at different incident proton or deuteron beam energies between 100 and 200 MeV for a large range of scattering angles. These measurements have been performed for elastic and break-up reactions as well as for the radiative-capture process. Calculations based on two-body forces only do not describe the data sufficiently. The inclusion of three-body forces improves the discrepancies with the data significantly. However, there are still clear deficiencies in the calculations [1].

The question that arises when looking at the bulk of the data and the remaining discrepancies which are sometimes sizable [2] is: what are the sources of the lack of understanding of the three-nucleon systems? Considering the fact that the calculations are numerically exact, the only remaining possibility is our understanding of the nuclear force itself. Although there is a lot of progress in producing consistent nuclear potentials within the framework of effective field theories, one has to look deeper into this problem. In fact, one can argue that part of the problem in the nuclear potentials, presently on the market, is that they all use experimental observables primarily from elastic nucleon-nucleon scattering. In that way, the sensitivity to the off-shell effects of these potentials could be masked. These off-shell properties should show up again in the calculations of observables in three-body systems. Precise measurements of nucleon-nucleon bremsstrahlung process have also presented major disagreements with the potential model calculations in the past [3], [4]. The only complication in this process is the presence of the electromagnetic operator. Recent developments in effective field theories indicate that this operator will be under control soon. Once this is the case, it is mandatory to revisit the bremsstrahlung process and see whether one understands this process as well alongside the three-nucleon system.

References

[1] N. Kalantar-Nayestanaki, E. Epelbaum, J.G. Messchendorp and A. Nogga, Rep. Prog. Phys. 75 (2012) 016301 and references therein.
[2] A. Ramazani-Moghaddam-Arani et al., Phys. Rev. C78 (2008) 014006.
[3] M. Mahjour-Shafiei et al., Phys. Rev. C70 (2004) 024004 and references therein.
[4] M. Mahjour-Shafiei et al., Phys. Lett. B632 (2006) 480.
Light hypernuclei based on chiral interactions at
next-to-leading order

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Chiral perturbation theory is an important tool to develop consistent two- and
more-baryon interactions based on the symmetries of Quantum Chromo Dynamics. Here, we discuss predictions for the binding energies of the light hypernuclei \(^{3}\Lambda\)H, \(^{4}\Lambda\)He and \(^{4}\Lambda\)H based on chiral hyperon-nucleon interactions \(^1\). These calculations are based on leading and next-to-leading order chiral hyperon-nucleon (YN) interactions \(^2, \(^3\). We briefly introduce these interactions and their description of the YN low energy data. Then we use the Faddeev-Yakubovskiy technique of Ref. \(^4\) to obtain first predictions for light hypernuclei based chiral interactions at next-to-leading order. The charge-symmetry breaking of \(^4\Lambda\)He and \(^4\Lambda\)H is studied in some detail.

References

[1] J. Haidenbauer, U.-G. Meißner, and A. Nogga, in preparation.
[2] H. Polinder, J. Haidenbauer, and U.-G. Meißner, Nucl. Phys. A 779 (2006) 244.
[3] J. Haidenbauer, S. Petschauer, N. Kaiser, U.-G. Meißner, A. Nogga, W. Weise, Nucl. Phys. A 915 (2013) 24.
[4] A. Nogga, H. Kamada, and W. Glöckle, Phys. Rev. Lett. 88 (2002) 172501.
The present work investigates the reaction $K^-d \to \pi \Sigma n$. It is motivated by a corresponding proposal for an experiment at the J-PARC 50-GeV proton synchrotron whose primary goal is to study the mass and width of the $\Lambda(1405)$ resonance. As in Ref. [1], we take into account single and two-step processes owing to $\bar{K}N \to \pi \Sigma$ rescattering and evaluate the $\pi \Sigma$ invariant mass spectrum in the $\Lambda(1405)$ resonance region.

A similar calculation was already performed by Jido et al. [3]. We scrutinize the results of Ref. [3], [4] avoiding some of the approximations introduced in those articles. In addition, we consider elementary $\bar{K}N-\pi \Sigma$ amplitudes generated from different interaction models, namely besides the one of the Oset-Ramos model employed in [3], [4] also those of a coupled-channel meson-exchange interaction [6], [7] that likewise predicts two poles in the region of the $\Lambda(1405)$ resonance. We find that the $\pi \Sigma$ invariant mass spectra are suppressed by the deuteron wave function and the fall-off of the $nK^-p$ Green’s function, and show no clear peaks below the $nK^-p$ threshold for both potentials.

However, as is pointed out in Ref. [1], one cannot rule out the possibility that peaks would be generated by the inclusion of all rescattering processes summed up to infinite order and one should rather rely on Faddeev-type approaches. Now we continue our study in that direction, and preliminary results incorporating in addition $\bar{K}N$ rescattering suggest that the truncation of the multiple scattering series adopted so far could be inadequate.

References

[1] K. Miyagawa, J. Haidenbauer, Phys. Rev. C 85 (2012) 065201; Few-Body Syst. 2013, DOI 10.1007/s00601-013-0657-6.
[2] S. Ajimura et al., [http://j-parc.jp/NuclPart/pac_0907/pdf/Nouni.pdf](http://j-parc.jp/NuclPart/pac_0907/pdf/Nouni.pdf)
[3] D. Jido, E. Oset, T. Sekihara, Eur. Phys. J. A 42 (2009) 257.
[4] D. Jido, E. Oset, T. Sekihara, [arXiv:1207.5350](http://arxiv.org/abs/1207.5350) [nucl-th].
[5] E. Oset, A. Ramos, C. Bennhold, Phys. Lett. B 527 (2002) 99.
[6] A. Müller-Groeling, K. Holinde, J. Speth, Nucl. Phys. A 513 (1990) 557.
[7] J. Haidenbauer, G. Krein, U.-G. Meißner, L. Tolos, Eur. Phys. J. A 47 (2011) 18.
The chiral electromagnetic currents applied to the deuteron and $^3$He disintegrations

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The Chiral Effective Field Theory delivers a systematic way to describe the nucleon-nucleon as well as the three nucleon interactions [1]. This formalism has been extended to electromagnetic interactions and the nuclear electromagnetic current has been derived in [2], [3]. Up to NLO many different topologies contribute to the electromagnetic current what results in many momentum dependent spin-isospin operator structures. Inclusion of electromagnetic currents into few-body calculations in a scheme of [4], [5] requires their partial wave decomposition. The efficient, semi-automatized method of such decomposition was proposed in [6] for two- and three-body operators and applied to the electromagnetic currents in [7].

In Ref [7] the deuteron and $^3$He photodisintegrations were studied with different parametrizations of the chiral nuclear potential at N$^2$LO [1]. The electromagnetic current was constructed from the single-nucleon current, the one-pion exchange current and the leading two-pion exchange currents at NLO. The resulting predictions for the deuteron photodisintegration show, in general, good agreement with the data and with the predictions based on AV18 interaction at photon energies below 70 MeV. While at higher energies and for the differential cross section the band which originates in different parametrizations of chiral forces becomes broad, for the polarized observables this band remains reasonably narrow.

For the $^3$He photodisintegration the width of bands grows with the increasing photon energy what do not allow for quantitative conclusions above $E_\gamma=20$ MeV. This points that the short-range meson exchange currents at NLO have to be included in the future theoretical analysis.

References

[1] E.Epelbaum, Prog. Part. Nucl. Phys. 57 (2006) 654.
[2] S.Köling et al., Phys. Rev. C80 (2009) 045502.
[3] S.Köling et al., Phys. Rev. C84 (2011) 054008.
[4] J.Golak et al., Phys. Rept. 415 (2005) 89.
[5] R.Skibiński et al., Eur. Phys. J. A24 (2005) 31.
[6] J.Golak et al., Eur. Phys. J. A43 (2010) 241.
[7] D.Rozpędzik et al., Phys. Rev. C83 (2011) 064004.
Muon capture connecting to the three-nucleon force

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The rate of muon capture in a muonic hydrogen atom is calculated in heavy-nucleon chiral perturbation theory (HB$\chi$PT) up to next-to-next-to leading order where corrections due to the QED and the proton-size effect are included. Since the low-energy constants (LECs) involved are determined from other independent sources of information, the theory has predictive power. For the hyperfine-singlet $\mu p$ capture rate $\Gamma$, our calculations [1], [2], [3] give $\Gamma = 713 \pm 4 \pm 2 \pm 1 \text{s}^{-1}$, where the uncertainties are due to the (historical) variations in the values of $g_A$, $g_{\pi NN}$ and the proton axial radius $\langle r_A^2 \rangle$, respectively. The estimated next order HB$\chi$PT correction is about 1%. The value quoted is in excellent agreement with the experimental value [4].

The MuSun Collaboration [5] is measuring the muon capture on deuteron. Given the accuracy of HB$\chi$PT, Ref. [5] aims at determine an unknown two-nucleon-pion LEC which also enters the chiral three-nucleon potential as well as the reaction $pp \rightarrow NN\pi$ [6]. Furthermore, this LEC also affects, e.g., the primary $pp$ solar fusion reaction and $\nu d$ reactions which were used to determine the solar neutrino flux at the Sudbury Neutrino Observatory. See the muon capture review [7] and recent theoretical work [8].

References

[1] S. Ando, F. Myhrer and K. Kubodera, Phys. Rev. C 63 (2000) 015203.
[2] U. Raha, F. Myhrer and K. Kubodera, Phys. Rev. C 87 (2013) 055501.
[3] S. Pastore, F. Myhrer and K. Kubodera, in prepraration.
[4] V.A. Andreev et al. Phys. Rev. Lett. 110 (2013) 012504.
[5] V.A. Andreev et al. arXiv:1004.1754[nucl-ex].
[6] V. Baru, invited talk at this workshop.
[7] P. Kammel and K. Kubodera, Annu.Rev.Nucl.Part.Sci. 60 (2010) 327.
[8] L.E. Marcucci et al. Phys. Rev. Lett. 108 (2012) 052502; Adam et al. Phys. Lett. B 709 (2012) 93; Y.-H. Song et al. to appear.

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Towards (d,p) reactions with Heavy Nuclei in a Faddeev Description

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Current interest in nuclear reactions, in particular with rare isotopes, concentrates on their reactions with neutrons. In order to facilitate the study those reactions, indirect methods using deuterons, like (d,p) reactions must be used. Those may be viewed as three-body reactions and described with Faddeev techniques. Here the three-body Hamiltonian governing the dynamics contains the nucleon-nucleon force describing the deuteron, and phenomenological neutron- and proton-nucleus optical potentials, which in turn are fit to a large body of elastic scattering data force between the neutron (proton) and the nucleus.

The application of momentum space Faddeev techniques to nuclear reactions has been pioneered in Ref. [1], and successfully applied to (d,p) reactions for light nuclei. However, when extending these calculations to heavier nuclei [2], it becomes apparent that techniques employed for incorporating the Coulomb interaction in Faddeev-type calculations of reactions with light nuclei can not readily be extended to the heaviest nuclei. Therefore, a new formulation for treating (d,p) reactions with the exact inclusion of the Coulomb force as well as target excitation was formulated in Ref. [3]. This new approach relies on a separable representation of the interparticle forces.

We present a separable representation of complex optical potentials suited to be employed in momentum space Faddeev type calculations of (d,p) reactions [4]. They are a generalization of the Ernst-Shakin-Thaler scheme in such a way that they fulfill the reciprocity theorem.

References

[1] A. Deltuva, A. Fonseca, Phys. Rev. C79, 0144606 (2009).
[2] F. Nunes, A. Deltuva, Phys. Rev. C84, 034607 (2011); N. Upadhyay, A. Deltuve, F. Nunes, Phys. Rev. C85, 054621 (2012).
[3] A. Mukhamedzhanov, V. Eremenko, A. Sattarov, Phys. Rev. C86, 034001 (2012).
[4] L. Hlophe, Ch. Elster, R.C. Johnson, N. Upadhyay, F.M. Nunes, G. Arbanas, V. Ermenko, J.E. Escher, I.J. Thompson, in preparation.
Experimental Studies of Deuteron-Proton Breakup at Medium Energies

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Exact modeling of all details of the few-nucleon system dynamics is a crucial prerequisite for reaching full understanding of the nuclear interactions. Thorough studies of three-nucleon (3N) systems have led to a conclusion that a proper description of the experimental data cannot be achieved with the use of nucleon-nucleon (NN) forces alone. This indicates a necessity of including additional dynamics: subtle effects of suppressed degrees of freedom, introduced by means of genuine three-nucleon forces (3NF), or, for a long-time neglected, Coulomb force.

Those findings would not be possible without a strong improvement of the experimental methods. New generation experiments in the middle-energy region employing high-resolution, multi-detector arrangements, provide data of unprecedented accuracy - see e.g. reviews \[1\] and \[2\]. The ways of exploiting all advantages of such precision measurements are demonstrated by discussing a sample experiment of the $^1\text{H}(\bar{d},pp)n$ breakup reaction at 130 MeV \[3\]. The project, carried out at KVI, Groningen, The Netherlands and FZ Jülich, Germany, provided very abundant data set - around 4500 points for cross section and around 800 data points for each of the five analyzing powers (vector $A_x$, $A_y$ and tensor $A_{xx}$, $A_{yy}$, $A_{xy}$).

Confronting the experimental data with the theoretical predictions shows the sensitivity of the cross sections to 3NFs and to Coulomb force effects, while there is no sensitivity of the deuteron vector analyzing powers to any additional dynamics beyond the NN forces. The behavior of the tensor analyzing powers is rather complicated, showing discrepancies between the calculations and the experimental data which must be considered as indications of deficiencies in the spin part of the assumed models of the 3NFs. Studies of the discrepancies as a function of different kinematical variables, extended over a range of several beam energies, might provide signposts for improvements in the modeling of 3N system dynamics.

References

[1] K. Sagara, Few-Body Syst. 48 (2010) 59.
[2] N. Kalantar-Nayestanaki \textit{et al.}, Rep. Prog. Phys. 75 (2012) 016301.
[3] St. Kistryn, E. Stephan, J. Phys. G: Nucl. Part. Phys. 40 (2013) 063101.
Nd scattering calculation with Low-momentum potential

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The low-momentum nucleon-nucleon potentials (LMNN) have been developed [1] by a renormalization unitary transformation from realistic potentials. The LMNN potential has a parameter Λ which restricts upper limit of momentum space. Using the LMNN potential the binding energies of triton and alpha particle were calculated [2] to investigate the dependence of Λ in few-nucleon system. The study showed that a choice Λ ≥ 5 fm⁻¹ is necessary to obtain the original binding energies.

Although in the case of the similarity renormalization group method, recent studies [3] prove that, inclusion of an induced three-body force arising from effects of many-body complex and the truncated 2-body space, brings them back to the original binding energies even under the choice Λ ≤ 2.3 fm⁻¹. This is a good situation for the chiral effective field theory (χEFT) whose cut-off parameter has been taking the choice 2.3 ≤ Λχ ≤ 3.0 fm⁻¹. Because the three-body force of χEFT is consistently built up with the two-body force, the three-body force already contains the above-mentioned induced part.

We calculated the Nd scattering observables at E=10 and 135 MeV using the LMNN potential. The similar paper is already published [4], however, we recalculated them by using our LMNN potential. Even if Λ was set to 3.0 fm⁻¹ and the induced three-body force was not included, only a small change was seen in almost all the scattering observables.

References

[1] S. K. Bogner et al., Phys. Rep. 386 (2003) 1.
[2] S. Fujii, E. Epelbaum, H. Kamada, R. Okamoto, K. Suzuki and W. Glöckle, Phys. Rev. C70(2004) 024003; A. Nogga, S. K. Bogner and A. Schwenk, Phys. Rev. C70 (2004) 061002(R).
[3] E. D. Jurgenson et al., Phys. Rev. C 87 (2013) 054312; K. A. Wendt, Phys. Rev. C 87 (2013) 061001(R).
[4] A. Deltuva, A. C. Fonseca, S. K. Bogner, Phys. Rev. C 77 (2008) 024002.