Nuclear Forces from Effective Field Theory

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Workshop of the *Espace de Structure Nucléaire Théorique*

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CEA/SPhN, Orme des Merisiers, building 703, room 135, F-91191 Gif-sur-Yvette Cedex

I. SCIENTIFIC ISSUE

Understanding nuclei from first principles is the ultimate goal of nuclear physics. Recent years have seen a blossoming of "*ab initio*" methods spurred by rapid advances in computer resources. These methods now allow an almost exact calculation of the structure of nuclei up to Carbon from a given nuclear potential, and many extensions to larger nuclei are being actively pursued. The preferred input has been potentials inspired by effective field theory (EFT), which provide a fit to data of similar quality as the best phenomenological potentials while taking into account the symmetries of the underlying theory of strong interactions, QCD.

Nuclear forces must indeed be derived from QCD, but the problem is how: owing to asymptotic freedom and confinement, we cannot yet solve QCD at the characteristic energy scales of nuclear physics. A well-proven strategy to circumvent this limitation is to use low-energy EFTs, which are based on the most general Hamiltonian involving the low-energy fields (nucleons, pions, delta isobars) and symmetries (most importantly, chiral symmetry) of the QCD spectrum. In addition, EFTs must contain an ordering principle — power counting — that allows us to organize the infinite number of interactions according to their impact on low-energy observables. With power counting we can arrange the calculation of physical quantities as power series in terms of a small expansion parameter. The advantage is obvious: at any step in the expansion we can know in advance the error of theoretical predictions, without having to rely on different phenomenological potentials. In addition, depending on the physical problem we are considering, a balance can be achieved between accuracy and computational complexity. With the help of *ab initio* methods, the EFT approach offers the promise of bringing these features to nuclear structure and reactions.

However, the formulation of a consistent nuclear EFT is not a trivial task. The solution of any EFT requires an arbitrary separation between long-range dynamics explicitly contained in a "model space" and short-range dynamics included through the Hamiltonian. An EFT is guaranteed to be consistent with the underlying theory only if it is properly renormalized, that is, if at each order in the expansion it contains enough interactions so that low-energy observables are independent of arbitrary choices such as the size of the model space. The problem is the non-perturbative nature of nuclear forces, manifest in the existence of nuclear bound states and resonances. While standard (that is, perturbative) EFTs are grounded on the well-known systematics of perturbative renormalization, when dimensional analysis works well, non-perturbative EFTs depend in turn on a good understanding of non-perturbative renormalization, a requirement that has not been fulfilled until very recently. Existing EFT-inspired potentials have been constructed using a recipe due to Weinberg, where only the nuclear potential is expanded in a series according to naive dimensional analysis. Unfortunately the corresponding scattering amplitudes, which are obtained by solving a dynamical equation (Schrödinger, Lippmann-Schwinger, *etc.*) and from which observable quantities are extracted, are not properly renormalized. This means the original potential is no longer guaranteed to be equivalent to low-energy QCD.

The purpose of this workshop is to address the question of how to derive a consistent and systematic low-energy expansion of the nuclear potential that produces properly renormalized, and accurate, observables. This is instru-

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mental on the one hand to understand nuclear physics in terms of QCD and on the other to bring all the advantages of the EFT approach to nuclear structure and reaction calculations. However, the challenges facing nuclear EFT are not well-known outside the narrow group of *hard-core* EFT theorists. Therefore, one of main goals of the workshop will be to increase the awareness of the broader nuclear theory community to the issues at stake.

We intend to start the workshop with a couple of lectures reviewing the state of the art. Once we have exposed the problems we face in nuclear EFT, we will plunge into the technical details of how to construct a consistent power counting. We will focus first on two-body forces: while three- (and perhaps four-) body forces are important for attaining high precision, two-body forces are the basic building block of all nuclear physics calculations. The framework to correct Weinberg's approach has been sketched in the literature, but there are aspects that are not well understood and need to be settled, such as the power counting of coupled partial waves and what happens with channels in which the one-pion-exchange potential is repulsive. Thus, another of the main goals of the workshop will be to try to arrive at a definitive solution to these problems.

Exploratory studies of the consistent EFT treatment of two-body forces have in general resulted in a better phenomenological description of the phase shifts than Weinberg counting at the same order in the same channels. Still, we lack a *genuine* EFT potential that describes all low-energy data with a $\chi^2/d.o.f. \sim 1$. Prospects for achieving such goal are good because a previous partial-wave analysis of the Nijmegen group in which a chiral two-nucleon potential was used provided a great description of the two-nucleon scattering data with a number of parameters compatible to that we expect of a consistent EFT of two-nucleon forces. A third goal of workshop is to discuss steps needed to achieve a high-quality fit of two-nucleon data without sacrificing renormalizability.

Of course, we also want to discuss the power counting of few-body forces. In contrast to the situation with two-body forces, where the aim is to close a chapter of nuclear EFT, few-body forces are nearly unexplored theoretical ground. We would like to set out the strategy for finding the correct scaling of the short range operators and, if possible, to make preliminary calculations (*e.g.*, of the triton's binding energy) to show that we are on the right track. This would be the last of the main goals of the workshop.

II. GOALS OF THE WORKSHOP

In summary, the goals of the workshop are

1. to explain to a broader group of physicists the aims of nuclear EFT, what power counting is, why it is important, and the problems we face nowadays in the field.

2. to discuss power counting for the two-nucleon EFT potential from different perspectives (renormalization-group analysis, perturbative renormalizability, scaling properties of short-range operators) and resolve the discrepancies among the different approaches (for example, the correct ordering of short-range operators in the presence of repulsive tensor forces and in coupled channels).

3. to investigate whether we can achieve a high-precision ($\chi^2/d.o.f. \sim 1$) description of two-nucleon scattering data at next-to-next-to-leading order in nuclear EFT.

4. How do we extend the previous ideas to three-body forces? What do we predict for the triton?

Useful references

- "Determination of the chiral coupling constants c(3) and c(4) in new pp and np partial wave analyses",
  M.C.M. Rentmeester, R.G.E. Timmermans, and J. J. de Swart, Phys. Rev. C **67** (2003) 044001.

- "Renormalization of one-pion exchange and power counting",
  A. Nogga, R.G.E. Timmermans, and U. van Kolck, Phys. Rev. C **72** (2005) 054006.

- "Power counting with one-pion exchange",
  M.C. Birse, Phys. Rev. C **74** (2006) 014003.

- "Subtractive renormalization of the NN interaction in chiral effective theory up to next-to-next-to-leading order: S waves",
  C.-J. Yang, Ch. Elster, and D.R. Phillips, Phys. Rev. C **80** (2009) 044002.

- "Perturbative renormalizability of chiral two pion exchange in nucleon-nucleon scattering",
  M. Pavón Valderrama, Phys. Rev. C **83** (2011) 024003.

- "Renormalizing chiral nuclear forces: triplet channels",
  B. Long and C.J. Yang, Phys. Rev. C **85** (2012) 034002.
- "Short-range nuclear forces in singlet channels",
  B. Long and C.J. Yang, Phys. Rev. C **86** (2012) 024001.
- "Infinite-cutoff renormalization of the chiral nucleon-nucleon interaction at N3LO",
  Ch. Zeoli, R. Machleidt, D.R. Entem, arXiv:1208.2657.
- "Nucleon-nucleon interactions from dispersion relations: Elastic partial waves",
  M. Albaladejo, J.A. Oller, Phys. Rev. C **84** (2011) 054009.
- "Improved method for partial-wave decomposition of two-pion exchange three-nucleon force",
  R. Lazauskas, Few-Body Syst. **46** (2009) 37.
- "Universal correlations in pion-less EFT with the resonating group model: three and four nucleons",
  J. Kirscher, H.W. Griesshammer, D. Shukla, and H.M. Hofmann, Eur. Phys. J. A **44** (2010) 239.
- "Application of complex-scaling method for few-body scattering",
  R. Lazauskas and J. Carbonell, Phys. Rev. C **84** (2011) 034002.

III. LIST OF LECTURERS

There will be three introductory lectures to explain the problems we are trying to solve to a wider audience

- M.C. Birse, U. of Manchester, England (mike.birse@manchester.ac.uk),
  "Renormalization-Group Analysis of the Two-Nucleon System with Pions"
- D.R. Phillips, Ohio U., Athens, USA (phillips@phy.ohiou.edu),
  "Chiral Nuclear Forces: An Overview"
- R.G.E. Timmermans, Rijksuniversiteit Groningen, Netherlands (timmermans@kvi.nl),
  "Connections Between Chiral Forces and the Nijmegen Partial-Wave Analysis"

IV. LIST OF SPEAKERS

The list of speakers for the more technical program is

- D.R. Entem, Universidad de Samalanca, Salamanca, Spain, (entem@usal.es),
  "Infinite Cut-off Regularization of Chiral Nucleon-Nucleon Forces"
- H. Grießhammer, George Washington U., Washington D.C., USA (hgrie@gwu.edu),
  "Resonating Group Method and EFT Forces"
- R. Lazauskas, IPHC, Strasbourg, France (rimantas.lazauskas@iphc.cnrs.fr),
  "Electromagnetic and weak observables in few-nucleon system using hybrid EFT approach"
- B. Long, JLab, Newport News, USA (bingwei@jlab.org),
  "Two-Nucleon System in Singlet Channels"
- J.A. Oller, Universidad de Murcia, Murcia, Spain (oller@um.es),
  "NN interactions from chiral symmetry and the dispersive N/D method including two-pion exchange"
- M. Pavón Valderrama, IPN, Orsay (pavonvalderrama@ipno.in2p3.fr),
  "Perturbative Renormalizability and Power Counting in the Two-Nucleon System"
- C.-J. Yang, U. of Arizona, Tucson, USA (cjyang@email.arizona.edu),
  "Two-Nucleon System in Triplet Channels"

V. TENTATIVE PROGRAM

March 4	March 5
09h00 Introduction (Duguet)	–
09h15 Phillips	09h15 Oller
10h15 Timmermans	10h15 Entem
11h15 **Break**	11h15 **Break**
11h45 Birse	11h45 Discussion (Valderrama)
12h45 **Lunch**	12h45 **Lunch**
14h00 Valderrama	14h00 Lazauskas
15h00 Yang	15h00 Grießhammer
16h00 **Break**	16h00 **Break**
16h30 Long	16h30 Discussion (Duguet)
17h30 Discussion (Van Kolck)	17h30 **End**
18h30 **End+Dinner**	–

We would like to mention that some of the speakers will be available for discussion in Saclay for the whole week. They are H. Grießhammer, B. Long, D.R. Phillips, R.G.E. Timmermans and C.-J. Yang.