Effective field theory of nuclear forces and the many-body problem

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I. SCIENTIFIC ISSUE

One of the long-term goals of nuclear physics is to understand the emergence of nuclear structure and reactions from the underlying theory of strong interactions, quantum chromodynamics (QCD). However, calculations with the degrees of freedom of quarks and gluons are so complicated, owing to the large strong coupling constant, that their forbiddingly high costs make it impossible in the foreseeable future to apply QCD directly and ubiquitously to low-energy nuclear physics. A feasible path is represented by effective field theories (EFTs), which rely on effective degrees of freedom and interactions and ensure that such effective features reproduce those of QCD. In spite of the considerable work on EFTs and their application to nuclear structure and reactions calculations, some fundamental unresolved issues still exist. As detailed below, one of the main problems concerns the EFT power counting and its consequences on many-body approaches for nuclear systems. With the present project we aim to address such issues and propose a task-force on an EFT formulation of nuclear structure and reactions that will involve researchers at Saclay, Orsay and the visit of Professor Bingwei Long from Sichuan University, China.

The central idea of EFTs is to construct an expansion in powers of the small ratio of light mass scales that are relevant to nuclear physics to heavy scales where quarks and gluons are relevant. The details of QCD are parametrized by the coefficients of the expansion, which could eventually be obtained from comparison with QCD results but are for now fitted to few-nucleon data. The starting point, which has been extensively studied and well established, is an effective Lagrangian that incorporates hadronic degrees of freedom such as pions and nucleons and has all the

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symmetries of QCD, including chiral symmetry. While employing low-energy degrees of freedom and implementing symmetries is hardly a novel idea for nuclear physics (or any other field of physics), this "Chiral EFT" offers an organizing principle under which a systematic approximation can be achieved. Referred to as power counting, this organizing principle is much more than merely a bookkeeping that labels different terms in effective Lagrangians: it must quantify reliably the theoretical uncertainties at any given order. Moreover, power counting is the direct consequence of the renormalization group flow of QCD into the infrared, low-energy "Chiral EFT": without it, the long-sought connection of the EFT description with QCD is lost.

Chiral EFT has been recognized as the starting point for the *ab initio* methods that are being rapidly developed in the nuclear theory community worldwide —including the powerful self-consistent Gorkov-Green's function (SCGGF) approach being pursued at Saclay. Unfortunately, however, existing chiral potentials have been found to be based on an incorrect power counting. The power counting used in the original development of Chiral EFT was proposed by S. Weinberg and assumes naive dimensional analysis (NDA), which states that the dimensionful coefficients that parametrize multi-nucleon short-range interactions are suppressed by inverse powers of the breakdown mass scale of Chiral EFT, e.g., the rho-meson mass. For systems having only one, or several closely clustered heavy mass scales, and where perturbation theory can be used, NDA is correct since no other scale is available to compose a dimensionful parameter. However, this is not the case for nuclear forces. The strength of one-pion exchange (OPE) is characterized by a light mass scale ~ 100 MeV, which is analogous to the inverse Bohr radius of the Coulomb potential. Now with two scales from both ends of the mass hierarchy, one is no longer certain about how a dimensionful coefficient would scale. Recent investigations on nucleon-nucleon scattering, carried out by some of the applicants, offered new ideas on how a consistent power counting should be constructed.

An outstanding issue is how this consistent power counting can be applied beyond the two-nucleon system in cutting-edge *ab initio* A-body methods, in particular SCGGF theory. In the consistent power counting, interactions coming in at leading order have to be treated non-perturbatively but proper renormalization requires that corrections are treated in perturbation theory. This raises questions regarding state-of-the-art many-body methods whose good performances are largely attributed to their non-perturbative character, i.e. to their ability to resum infinite sets of diagrams built from 2N and 3N interactions taken as a whole. Consequently, unexplored questions of renormalization and power counting within the A-nucleon sector ($A \gg 2$) force us to revisit the current implementation scheme of, e.g., SCGGF theory. In particular, one needs to envision a differentiated treatment of the various pieces making up EFT interactions depending on the chiral order they come into play. In doing so, important aspects of power counting related to the proper ordering of few-body forces as A increases could be addressed.

II. GOALS OF THE PROJECT

The goals of the project are (a) to extend the analysis of power counting from the two-nucleon to the few- and many-nucleon systems, (b) to discuss how to implement these ideas in concrete calculations and (c) to review the reasons leading to the existence of different power counting schemes in the two-nucleon sector and whether they can be solved by looking at the larger picture provided by the A-nucleon systems. Specifically, we aim to answer the following questions

1. Why different theoretical tools lead to different power-counting schemes in the two-nucleon system? Can any of them be eliminated based on pure theoretical considerations rather than the quality of the fit?

2. How to investigate the counting of contact three-nucleon forces? Given the difficulty of analytic calculations, a numerical method needs to be developed, preferably based on available many-body calculation frameworks.

3. How should SCGGF calculations be modified to handle interactions generated by the correct power counting?

Addressing the latter point in particular will act as a jump-start for a new collaboration that is meant to lead to full-fledged numerical tests based on modified SCGGF calculations.

III. SELECTED REFERENCES

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4. B. Long, C.J. Yang, Phys. Rev. C **85**, 034002 (2012)
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Leading chiral three-nucleon forces along isotope chains in the calcium region

IV. SCHEDULE

The project involves the visit of Professor Bingwei Long to Saclay for four weeks. His expertise will be highly beneficial for all the points raised above. In particular, he will engage specific discussions on nucleon-nucleon scattering with M. Pavón Valderrama and U. van Kolck and on the implementation of the new power counting in A-body *ab initio* structure calculations with T. Duguet, M. Pavón Valderrama, V. Somà and U. van Kolck.

A detailed schedule of his visit includes

1. May 5th to May 9th - Discussions on the current state and problems of chiral interactions
2. May 12th to May 15th - Discussions on how to perform A-body calculations based on a consistent power counting
3. May 16th - Half-a-day workshop on *Effective field theory of nuclear forces and the many-body problem*
4. May 19th to May 28th - Further discussions and work on A-body calculations

V. WORKSHOP

On May 16th, a half-day workshop will be dedicated to introducing interested nuclear experimentalists and theoreticians to the challenges and perspective related to the application of effective field theories to many-nucleon systems. Informal discussions with the audience will provide us with additional insights that we will make use of in the remaining of the project.

- 09h30-09h45 *Welcome*
- 09h45-11h00 B. Long: *Renormalization and power counting of chiral nuclear forces*
- 11h00-11h15 *Break*
- 11h15-12h30 V. Somà: *Towards many-body calculations on the basis of a consistent chiral power counting*
- 12h30-13h30 *Lunch*