Scientific motivations and impact for nuclear physics for suggested program with title:

Nuclear Hamiltonians for Advancing Nuclear Physics and Beyond

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A sound theoretical description of nuclear forces is pivotal for understanding many important physical observables over a wide range of energy scales and densities. A few examples include: few-body physics where there exists exciting experimental evidence for exotic few-neutron resonances [1]; nuclear-structure observables (e.g. exotic decays, radii, ground-state and separation energies) in the medium- to heavy-mass region of the nuclear chart, in particular towards the driplines [2–5], which set the nucleosynthesis path far away from stability probed at the FRIB facility; and astrophysical phenomena, such as properties of neutron stars and neutron-star mergers [6–8], that receive strong interest due to the observations of gravitational waves from compact stellar objects. A systematic and precise theory for nuclear Hamiltonians is crucial to providing accurate predictions for these systems with sound estimates of theoretical uncertainties, and will enable meaningful comparisons of theoretical calculations with experimental data and astrophysical observations.

Within the last two decades, significant progress in nuclear physics has been made possible, in part, due to the algorithmic and theoretical development of powerful ab initio many-body methods and their combination with modern interactions from chiral effective field theory (EFT) [9–11]. The many-body methods amount to different approximate solutions of the many-body Schrödinger equation and include, e.g., quantum Monte Carlo methods, the no-core shell model, the coupled-cluster method, the self-consistent Green's function method, and the in-medium similarity renormalization group. With increasing computational power and continuous development of such methods, increasingly larger parts of the nuclear chart are accessible to ab initio calculations. We have entered an era of precision nuclear physics where many-body uncertainties can be better controlled and often accounted for in a systematic way. The development of reduced-order models (emulators) [12–14] based on eigenvector continuation [15–17] pave the way for sophisticated Bayesian inference methods to estimate the uncertainties of theoretical predictions. The remarkable agreement between predictions of different many-body approaches is very encouraging [6]. Overall, the tremendous methodical progress in recent decades means that uncertainties from the nuclear Hamiltonians are increasingly important to quantify since they dominate over uncertainties arising from the many-body methods.

Modern nuclear Hamiltonians are derived within chiral EFT, which is constrained by the symmetries of the fundamental theory, quantum chromodynamics (QCD). In contrast to phenomenological interactions, chiral EFT provides an organized expansion scheme in powers of momenta that promises a systematic way to improve nuclear interactions order by order. Assuming that the chiral expansion is controlled and at least asymptotic, i.e., if it obeys a sound power counting scheme that arranges different interaction mechanisms according to their relative importance, this allows for the estimation of meaningful theoretical uncertainties in nuclear theory predictions which may also provide a statistical interpretation [18]. Most of the current chiral Hamiltonians are constructed within Weinberg power counting, which is based on naive dimensional analysis of the interaction potential. However, there exist several relevant and foundational questions regarding renormalization and the power-counting scheme in chiral EFT [19, 20]. Furthermore, to develop nuclear forces for precision nuclear physics requires a detailed discussion of several additional topics that currently persist. This involves questions regarding how to learn the low-energy constants of chiral EFT from data [21–24], the practical role of the regularization scheme [25], possibilities for exploiting reduced-basis methods to leverage computationally expensive many-body calculations [26], how to best exploit the advantages of Bayesian methods for model mixing [27] and experimental design [28], and possible paths of matching nuclear interactions to lattice QCD simulations [29–35].

A reoccurring question in the field is why some interactions, even though adjusted to reproduce similar data, work better than others for particular observables across the nuclear chart. This question is related to several open challenges pertaining to the (chiral) Hamiltonians used in ab initio many-body methods: uncertainty quantification for interactions, the regularization scheme and scale dependence, the possibility of identifying an ideal set of observables to constrain Hamiltonians, and uncertainty quantification due to approximations made when solving the many-body Schrödinger equation. These open questions and topics reflect shortcomings in modern nuclear Hamiltonians which can lead to sizable uncertainties for nuclear observables of interest for next-generation experiments and astrophysical observations. Currently, the systematic uncertainties of the nuclear Hamiltonian are the main limitation for making accurate predictions for, e.g., neutron matter and saturation properties of nuclear matter [36–38], the nuclear symmetry energy and its density dependence, nuclei up to the medium-mass region [39], nuclear energy levels far away from stability, the location of nuclear driplines, electroweak currents [40] and reactions, such as those relevant for ab initio nuclear matrix elements for neutrinoless double-β decay [41, 42] and neutrino-nucleus scattering for Deep Underground Neutrino Experiment (DUNE) [35]. These uncertainties must be quantified or at least estimated. Clearly, any uncertainty in nuclear physics will propagate and impact predictions for astrophysics, e.g., for the structure and the mass-radius relation of neutron stars, simulations of supernovae and neutron-star mergers, nucleosynthesis and the r-process path, gravitational waves, as well as searches for beyond Standard Model physics, such as the search for Majorana neutrinos and direct detection of dark matter.

We are proposing a five-week program (four weeks of regular program and one week of a focused workshop) at the Institute for Nuclear Theory for the year 2025 with the goal of bringing together field theorists, specialists in the construction of nuclear Hamiltonians, experts in many-body calculations of systems ranging from nuclei to nuclear matter, and experts in lattice QCD calculations for nuclear physics, with the goal of actively working together on overcoming the shortcomings of modern nuclear Hamiltonians, to identify possible future pathways and novel constraints that can be used to build nuclear Hamiltonians for advancing nulear physics and beyond.

The program, in particular, will consist of the following themes:

- Theme 1: *Current limitations of nuclear Hamiltonians*
  Current nuclear Hamiltonians are limited in several ways. It is unclear up to which densities/momentum scales chiral Hamiltonians remain applicable. Chiral EFT is a low-momentum expansion, and so there must be a point at which the relevant momentum scale in a nuclear system (for example, uniform nuclear matter) is too large to trust the expansion. However, at what values of density or nucleus size or scattering energy this takes place is difficult to know a priori and Bayesian inference is believed to be a tool well suited to address these questions. In addition, nuclear interactions are limited by necessary truncations of both the chiral expansion and the Hilbert space. In this context, the inclusion of additional degrees of freedom, e.g., the Δ isobar, may be crucial. We would like to address these limitations to highlight the major sources of uncertainty and to identify the most promising ways forward. In this theme, we will involve experimentalists to further emphasize shortcomings in present nuclear theory.

- Theme 2: *Constraining nuclear forces with few- and many-body observables*
  Recently, it has been observed that fits of low energy constants in the EFT description of the nuclear force most likely require necessary input from many-body observables. It is however not clear which observables form an "ideal" set to constrain nuclear interactions. We would like to discuss methods for identifying key observables that nuclear Hamiltonians are most sensitive to and that next-generation Hamiltonians necessarily need to reproduce. We will discuss under which conditions such an approach can be regarded as a systematic EFT given the sensitivity of predictions to fit observables. Clearly, it will be pivotal to discuss computational and statistical methods for performing global sensitivity analyses of low-energy constants in complex nuclei as well as how to incorporate models for theoretical error estimates in the objective and likelihood functions.

- Theme 3: *Improving nuclear forces with novel fitting strategies and higher orders in chiral EFT*
  There is a tremendous effort in the community to construct nuclear interactions at higher orders in the expansion. While two-body interactions are available at N^{4}LO and partially at N^{5}LO, three-body interactions are only available at a subleading order (N^{3}LO). It has been argued that subleading three-body contact interactions may be crucial to solve the A_y puzzle and improve the description of nuclei. Besides, nuclear lattice EFT offers a way to improve nuclear interactions by providing access to e.g., α-α scattering data, if the continuum limit is within reach. Fitting nuclear forces using Bayesian inference, which by design easily offers a statistically meaningful interpretation of the posterior distributions of coupling constants, may be necessary to construct next-generation interactions. We plan on assessing the optimal ways of constructing nuclear interactions for future applications. A key question will be how to mitigate computationally expensive components, e.g. many-body observables, using emulators. We will encourage computational physicists/statisticians to contribute to this theme in particular.

- Theme 4: *Improved power-counting schemes*
  Several modified power-counting schemes have been presented throughout the years that attempt to solve the shortcomings of Weinberg power counting. The main question remains, how the many-body community can explore the effects of such modified power-counting schemes in nuclei heavier than the α particle? Besides the apparent lack of infrastructure for easily transferring matrix elements, several

other problems, of a more technical nature, appear upon attempting to solve the nuclear many-body Schrödinger equation. For example, in some versions of modified power-counting schemes, spurious bound states appear in certain nucleon-nucleon partial-waves. This may present a difficulty for a set of many-body methods that converge to the lowest energy state for a given Hamiltonian. Another problem is the analysis of high-cutoff potentials, which are usually too hard to be treated in most many-body methods. We will discuss these modified power-counting schemes and identify clear ways forward to implementing and assessing these schemes using presently available many-body methods. We will also discuss finding simple, or well-understood, benchmark systems to analyze renormalization, regularization, and power-counting strategies.

- Theme 5: *Constraining nuclear forces from lattice QCD calculations*
  There is the prospect of using inputs and constraints from lattice QCD to construct nuclear interactions. For example, lattice QCD may provide access to systems that cannot be reached experimentally, or can only be reached with extreme difficulty. These could be pure neutron systems, hyperonic systems, or short-distance contributions to exotic nuclear processes such at the neutrinoless double-β decay. We plan on addressing clear paths forward to map nuclear interactions and currents to calculations in lattice QCD and to identify the most promising systems to match. Ideas such as matching directly energy eigenvalues of few-nucleon systems in a finite volume obtained from lattice QCD and from many-body methods given nuclear Hamiltonians will be explored. Additionally, the prospect of using Euclidean finite-volume matrix elements in order to tune the low-energy constants of the EFT characterizing response of light nuclear systems to external probes will be discussed. On the computational side, critical discussions will be devoted to evaluating the resource requirement and the reach of current methods and algorithms for precision studies of light nuclei at the physical values of quark masses. New technologies in generating more efficiently nuclear correlation functions and more robust fitting and energy-extraction strategies from noisy data will be discussed.

- *Theme 6: The role of new computational strategies in low-energy nuclear physics*
  Given that many aspects of the low-energy nuclear-physics program, from lattice QCD to ab initio nuclear many-body studies, involve large-scale computations, and given the importance of precise and accurate computations in advancing the field, the community has been constantly exploring ways to go beyond established computing paradigms to expedite computations. A more near-term paradigm is machine learning, whose applications in both lattice QCD and in nuclear many-body problem have emerged in recent years. A potentially longer-term solution is quantum computing, which uses fundamentally different strategies compared with classical computing. It requires extensive algorithmic development and benchmarking for nuclear-physics applications, a line of research that has been growing in recent years. This research has further promoted studies of the role of quantum entanglement in low-energy nuclear physics, has led to better understanding of the effectiveness (or lack) of certain classical-computing methods in studies of nuclei, and has provided insights into the interplay between symmetries of the nuclear Hamiltonian and the entanglement properties of the resulting states. We aim to bring experts in these areas to further discuss opportunities and challenges.

The structure of the program will be as follows: During the first two program weeks, we will mostly address themes 1-3. The workshop will happen during week 3. The last two program weeks will address themes 3-5. Theme 6 will be blended in all weeks. This will allow us to avoid full compartmentalization of the themes into individual weeks and allows us to maximize the overlap of scientists from different subfields while still maintaining coherence. The overlap will be maximal during the workshop week.

A virtual INT program with similar themes was organized in the spring of 2021 by the same organizers. From the feedback that we received, we gathered that the community responded very well to our efforts to both acknowledge the successes of current approaches and to confront their shortcomings. The multifaceted perspectives of the participants were collected in a dedicated anthology (edited by the organizers) [43], with a total of 18 contributions from 42 program attendees. These perspectives represented the unchanged reflections of a vibrant and engaged community of researchers on the status of theoretical research in low-energy nuclear physics, the challenges ahead, and new ideas and strategies to make progress in nuclear structure and reaction physics, effective field theory, lattice QCD, quantum information, and quantum computing. From this collection, the usefulness of a dedicated in-person meeting to carefully discuss and review these matters in detail is clear. As a result, a longer in-person program in Seattle appears timely in 2025, particularly given the INT's unique set-up for programs, not fully available in other nuclear physics institutes (e.g., open and flexible formats that foster interactions, office space, strong community of local nuclear theory faculty and post-docs, etc).

During the last program, we realized that further opening up our program to engage a larger fraction of the community at early career stages is particularly useful to guarantee a lasting impact. With this in mind, we have added a fifth Early-Career Osrganizer (Joanna Sobczyk, JGU Mainz) to this proposal who is a postdoctoral researcher. Dr. Sobczyk is an accomplished junior researcher in the field and provides complementary experience related to the physics topics addressed in the program. This will improve and widen the scope of our program and provide the Early-Career Organizer a great opportunity to co-organize a program with international visibility.

It is crucial that the program provides sufficient time for the participants to be working on the identified issues and solutions directly at the INT. It is important to us that the suggested program has a "hands-on" component that allows to directly test suggestions. We will not plan for more than one talk (1 hour) per day (or two short and related talks that are back to back) in the morning, and will conduct a longer discussion session immediately after the talk(s). The discussion session will be led by one of the organizers or an expert participant. During the discussion session, we will give participants, in particular early-career scientists, the chance to informally present a couple of slides and discuss results and ideas of interest to the program. This approach keeps the talk load light but allows us to take into account a wider range of perspectives. This leaves the afternoons free for participants to continue with informal discussions and collaborations and to think at a deeper levels about the issues and ideas presented in the morning. We will attempt to have short talks from experimental and computational colleagues to provide additional perspectives on the points made in the program.

To summarize, we expect our program to have a transformative impact on nuclear physics. During previous workshops and programs we have seen that there is a strong interest in the nuclear-physics community in improving nuclear Hamiltonians to give reliable predictions for nuclear and exotic systems, ranging from neutron stars to neutron-rich nuclei, and nuclei relevant for the BSM searches, e.g. neutrinoless double-β decay. An accurate and reliable description of these systems is crucial to understand next-generation experiments and astrophysical observations in the near future and it is important to revisit these issues regularly to assess the progress and roadblocks in the community. We envision to develop a unified approach to nuclear interactions that involves input from all parts of the community and may enable next-generation precision calculations of nuclear observables that are reliable and provide well-understood systematic uncertainties. This will be of wide interest also to other communities, like high-energy physics or astrophysics.

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