INT Workshop Proposal:

Chiral EFT: New perspectives

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Requested Length and Season:

5 days, Preferred Season: Fall 2024, Alternative: Spring 2024

We, the group of organizers submitting this proposal, have read the instructions & INT code of conduct (https://sites.google.com/uw.edu/int/announcements/code-of-conduct) and we hereby agree to these terms.

Justification for a 4th organizer: The workshop brings together expertise from four different subcommunities: EFT, potential models, ab initio methods, and fundamental symmetries. To have a representation of researchers belonging to all these fields and design a balanced and well-thought agenda for the workshop, we felt the need for a larger organizational team.

Motivation and Context

We are at a dramatic point when nuclear theory has an opportunity to shine and impact other areas: Recent advances in astrophysics and particle physics now require nuclear input at precision levels not seen before.

The challenge for the nuclear theory community is to go beyond uncontrolled models and approximations, a task of notorious difficulty given the complexity of the strong interactions at low energies. Since the renormalization failure of pion theories in the 1950s, nuclear interactions have been constructed mostly on a phenomenological basis from two-body data, without the benefit from our understanding of strong interactions at higher energies, represented by quantum chromodynamics (QCD). A significant difficulty has been the solution of the many-body problem and the determination of consistent few-body forces and currents. The development of effective field theories (EFTs) and "*ab initio*" many-body methods (AIMs) over the last three decades or so has provided an exquisite description of many nuclear observables, but also exposed significant problems.

AIM calculations typically start with potentials obtained from the most comprehensive, but also most difficult, nuclear EFT — Chiral EFT. The most popular approach follows the original prescription by Weinberg, where the nuclear potential is expanded in the same way as amplitudes in Chiral Perturbation Theory, and the truncated potential at some order is solved for exactly to produce nuclear amplitudes. Unfortunately it is now known that this approach produces unrenormalized nuclear amplitudes, as did the simpler pion theories of the 1950s. The choice of regularization procedure, which should be arbitrary, instead incorporates physics and results no longer provide a model-independent description of data (from either experiment or lattice QCD). Proper renormalization requires a reevaluation of the assumptions made about the expected size of short-range interactions. Short-range interactions appear at lower orders than expected on the basis of Weinberg's prescription and the increasingly singular nature of subleading interactions requires (distorted-wave) perturbation theory. These ingredients are well-established properties of other nuclear EFTs such as Pionless and Halo/Cluster EFTs.

Moreover, AIMs have reached such a level of sophistication that they now expose various shortcomings of the interactions they use as input. A cornucopia of refined numerical AIMs has appeared over the last couple of decades, such as Effective-Interaction Hyperspherical Harmonics, No-Core Shell Model, Coupled Cluster, Green's Function Monte Carlo, Auxiliary-Field Diffusion Monte Carlo, Self-Consistent Green's Function, In-Medium Similarity Renormalization Group, and Nuclear Lattice EFT. AIMs make diverse improvable approximations, and mutual benchmarking has shown that they are at the point where their results can test their dynamical input up to medium-mass nuclei. As a consequence there is a growing awareness of the limitations of potentials and currents obtained from Chiral EFT. Among other problems detected in chiral potentials: nuclei beyond the alpha particle are unstable at LO; a good description of light nuclei only emerges at high orders, mostly through the delicate adjustment of short-range interactions rather than pion exchange; high-order potentials fail to simultaneously describe light and medium-mass nuclei; and nuclear matter does not saturate within the expected range of applicability of the theory until three-body forces are included at subleading orders. All these problems are not inconsistent with the need for a reorganization of interactions in Chiral EFT.

Most of the progress addressing these issues has been incremental, as practitioners from the various subcommunities address their own difficulties separately. These difficulties are significant. The singularity of even one-pion exchange demands a perturbative treatment in higher partial waves, and how to match this expansion with the momentum expansion is unclear. Current AIMs are designed to solve for a given potential essentially exactly regardless of the method used for potential construction, and require substantial redesign to deal with perturbatively small subleading orders. Even though, once renormalization has been achieved, cutoffs need not be much larger than the EFT breakdown scale, the very test of renormalizability in numerical calculations requires wide cutoff variation and thus large model spaces. The relative importance of two-pion exchange and few-body forces is still not firmly established, and their apparent phenomenological importance has not yet found power-counting justification.

We believe we can only rise above incremental improvements by bringing together a group of experts of the various subcommunities — EFT, nuclear forces, AIMs, “users” — all committed to this research program.

Impact for Nuclear Physics

One of the fundamental goals of nuclear physics is to understand its emergence from the dynamics of quarks and gluons, as described by QCD. EFTs, whose construction is guided by the symmetries of QCD, provide a hierarchy of permissible interactions, hence allowing for an estimation of systematic uncertainties given some “power counting” rules. AIMs then extend the reach of EFT predictions by solving the nuclear many-body problems based on the EFT potentials, and should, in principle, allow confronting data all the way to heavy nuclei.

In a consistent implementation of EFTs through AIMs, renormalization at each order requires the values of a finite number of parameters. Unfortunately these parameters are not always accessible to experiment. A well known example is that in hypernuclear physics, where the amount of data from lattice QCD (albeit at unphysical pion masses) is already comparable to those from experiment. Even more critical are the parameters needed for some astrophysical applications and the the test of “fundamental” symmetries, for example, the various sources of time-reversal violation via dimension-six operators in the Standard Model EFT, which can only be disentangled in future measurements of nuclear electric dipole moments if their short-range contributions in Chiral EFT can be obtained from lattice QCD.

An even more urgent case is neutrinoless double-beta decay (NDBD). Renormalization of Chiral EFT (and of Pionless EFT alike) requires a short-range parameter at leading order — the same type of argument that shows the inconsistency of Weinberg’s prescription for the strong-interaction potential. With a reasonable guess for this parameter, various AIM calculations have shown that it gives a significant contribution to NDBD matrix elements, which are needed for the very planning and interpretation of NDBD experiments. We must know this parameter for the same regulator employed in the strong part of the calculation.

The urgent need for a more consistent implementation of Chiral EFT is by no means limited to NDBD. New constraints on the equation of state of dense matter have emerged from neutron-star mergers and are expected to improve significantly over the next years. The properties of dense matter depend crucially on the behavior of pions. While chiral potentials are now routinely used in calculations, pion propagation in matter depends on the interactions of pions with at least two nucleons, which are poorly constrained. One example is the "two-nucleon sigma term" — a four-nucleon-field operator that breaks chiral symmetry explicitly and thus couples to an even number of pions. If one-pion exchange is treated nonperturbatively, as in most calculations, the two-nucleon sigma term is a LO interaction, but it is usually neglected.

Thus, improving Chiral EFT addresses not only the last Standard Model frontier — controlling strong interactions at low energy — but also paves the way for the quantification of physics beyond the Standard Model.

Other Items

Please see web form.