INT Program Proposal:

Effective Field Theories and the Many-Body Problem

Organizers:

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Motivation and Context

The goal of this proposed three-month workshop is to tie together the recent success stories in the nuclear many-body problem at different nucleon number A. For the purposes of this proposal, we consider three broad communities:

- Effective field theories (EFTs) and few-body systems ($A = 0 - 4$): We have seen the development of nuclear EFTs, both pionful and pionless, that incorporate QCD symmetries and allow systematic expansions of nuclear observables in powers of momenta. In addition, a related approach has been popular in the last couple of years, where the renormalization group is used to generate low-momentum potentials.
- General many-body theories (MBTs) for light and medium nuclei ($A = 4 - 60$ or 70): Here we group together a wide variety of computational approaches that, nonetheless, share broad overlaps. Examples include the interacting shell model (which further includes the no-core shell model and the Tokyo Monte Carlo shell model), Green's-function Monte Carlo, and coupled clusters. Recent improvements in computers and algorithms now allow one to address many-body basis spaces with dimensions of 10^{7-9}. For light nuclides ($A \leq 16$) one has nearly exact calculations of bound states starting from good quality NN and NNN interactions. New developments in auxiliary field path integrals may extend the applicability of these technique as well.
- Density functional theory (DFT) for heavy nuclei ($A \gg 60$). By simple limits of computers MBTs cannot systematically address heavy nuclides. Therefore one turns to mean-field (density-functional) theory and its extensions. There are a variety of different phenomenological approaches, such as Skyrme, Gogny, and the relativistic meson-exchange models.

There have been a few, preliminary attempts to marry the elegance of EFTs to the power of recent many-body calculations, but significant conceptual and language barriers exist. We wish to provide a forum where these obstacles can be breached, and cross-pollination pushed much farther.

Such efforts will have important ramifications beyond the immediate few-and-manybody-theory communities. Reaccelerated beams of exotic nuclei will both test and require theory in new regimes. Reactions of astrophysical interest require reliable calculations, and a very important many-body problem for nuclear astrophysics —e.g., in supernovae and neutron stars— is the nuclear matter equation of state. An ongoing SCIDAC project is to obtain a Universal Nuclear Energy Density Functional, validated by many-body theory and tuned by effective interactions. Finally, this discussion cuts across physics disciplines: in the 1980s, accurate density functionals for quantum chemistry were developed with the aid of Monte Carlo simulations and are now widely used; our discussions could benefit from bringing in experts from the quantum chemistry community. There has also been recent exciting progress in applying

EFT, MBT, and DFT to cold atomic gases which we expect to be an important topic during the program.

The Proposed Program

In contrast to previous programs that have focused on EFT for few-nucleon systems or on many-body methods, we hope to bring together the various communities. A list of potential participants can be found below. One of our major objectives is to overcome the barriers for interactions among practitioners of the various approaches. The goal is for EFT experts to go away with a good idea of what MBT and DFT practitioners need and can or cannot use, and for MBT and DFT practitioners to understand what EFTs can (currently) provide. For example, the form of few-body interactions is given by EFT; however, in shell-model calculations, arbitrary two-body interactions can be used (without restriction on locality or momentum dependence), but interactions that use a fractional power of the density are a tremendous challenge; Green's function Monte Carlo requires local interactions and find few-body interactions burdensome, and so on. We the proposers already know from our experience that lack of common language across subdisciplines presents a barrier to cross-pollination.

We will follow the standard format of daily talks and afternoon informal meetings. In addition, we plan focused activities. The program will begin a series of tutorials for the three communities: EFT, MBT, and DFT. Representative speakers will lay out cores issues, with a focus on what each can and cannot do, and provide written/webbased introductions that can be referred to through the program. We also will have "refresher" lectures throughout the program, one afternoon at the beginning of each week, to welcome incoming participants and to help clarify and sharpen concerns and needs. The organizers will seek to keep the program on track by reminding the participants of the Big Framework and the Three Big Questions, which themselves will evolve and be sharpened, through these refresher sessions. We suggest one or two one-week formal workshops emphasizing cross-disciplinary issues in cold atomic gases and quantum chemistry.

The Big Framework of the program: We note that all three communities restrict the many-body degrees of freedom–cutoffs in momentum or position space for EFTs, cutoffs in cluster correlations (for example) in MBTs, and placing the weight of correlations in the energy functional for DFTs. *Can we have a unified framework for systematic and controlled reduction of the degrees of freedom for these disparate disciplines? How do we transplant information about reduced degrees of freedom from one community to another?*

We apply the Big Framework to each of the three communities as Three Big Questions:

Big Question #1: How do EFTs evolve with A, and can we at some point extrapolate smoothly?

- How far in A (and density) can one push the pionless EFT? Could it be that it holds for nuclear matter?

- The main current issues for the pionful EFT are power counting and convergence; the many-body aspect is the size and form of few-body forces, including the role of the delta isobar.

- How can we calculate with EFT for A ≥ 4?

Big Question #2: How can we put the many-body dependence of EFTs in a tractable form into MBTs?

- So far, MBT methods have used EFT potentials as input in the same manner as phenomenological ones. Is there a more efficient/correct way to marry EFT and MBTs? For example, treating corrections to the leading potential in perturbation theory; defining the EFT directly within the discrete small SM spaces; etc.
- How can we improve the many-body methods? For example, how does one derive simultaneous effective operators (for electron scattering, beta decay, etc.) along with the interaction itself? Can we justify approximations or selection of certain contributions (such as done, e.g., in the coupled-cluster method) with an EFT power counting?
- It is known in EFTs that choice of the off-shell matrix elements of the two-body interaction affects the three-body (and higher order) interaction. Can this be exploited to either minimize, or put into a form convenient for MBT and DFT, the three/many-body interaction?
- It will be useful and important to understand how EFT error estimates (from leading order, next-to-leading order, etc.) propagate to MBT calculations. An EFT-style error analysis for MBT would be helpful to the community.

Big Question #3: How can we use EFTs to constrain DFTs?

- Constraining the nuclear equation of state from fits of energy functionals to ordinary or even extraordinary nuclei (i.e., unstable neutron-rich) involves uncontrolled extrapolations at present. At low densities, where the pionless EFT is applicable, there are close connections to cold atoms physics. At higher densities inadequately constrained many-body forces are a serious concern. EFT might provide much-needed controlled extrapolations and theoretical error bars.
- Since DFT can be cast in the form of an effective action approach, it is immediately compatible with EFT in principle. In practice there are many implementation issues, such as how to do power counting for the energy functional for a given EFT.
- What are the possible EFTs for nuclear matter? For example, are nucleon-only degrees of freedom adequate? What is the role of pions and chiral symmetry? Can we write an EFT around the Fermi surface? Does Pauli blocking make the

EFT (more?) perturbative, as suggested by work with low-momentum potentials? Is there a covariant EFT that can explain and improve the successes of “relativistic mean field” phenomenology, which is a form of DFT?

Suggested Participants (list of names)