Nuclear Forces and the Quantum Many-Body Problem

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1. Challenges for the Nuclear Many-Body Problem

Physical properties, such as masses and life-times, of very short-lived, and hence very rare, nuclei are important ingredients that determine element production mechanisms in the universe. Given that present and proposed nuclear structure research facilities will open significant territory into regions of medium-mass and heavier nuclei, it becomes important to investigate theoretical methods that will allow for a description of medium-mass systems that are involved in such element production. Such systems pose significant challenges to existing nuclear structure models, especially since many of these nuclei will be unstable and short-lived. How to deal with weakly bound systems and coupling to resonant states is an unsettled problem in nuclear spectroscopy. Similarly, a description of larger nuclei using a fully microscopic first principles ("ab initio") approach, starting from the fundamental laws of quantum theory is another unresolved problem in nuclear physics that awaits a satisfactory, computationally tractable, solution.

The aim of this meeting, and its pertinent Institute of Nuclear Theory Program for the fall of 2004, is to shed light on such challenges and particularly on several open questions facing the nuclear few- and many-body problems. In particular, in order to stimulate possible new directions of research, we have singled out five major topics that we feel encompass a number of the open problems in nuclear many-body theory. The program of this meeting reflects hopefully these choices, listed in the following subsections.

1.1. From Free Interactions to Few- and Many-Body Systems

The connection between the so-called free two-body and three-body interactions derived from effective field theory and their applications in few and many-body systems is still an open and unresolved problem in nuclear physics and is crucial to the dialectics of all *ab initio* methods, which start typically with a two-body interaction and eventually a three-body interaction fitted to reproduce low-energy scattering data and properties of selected light nuclei. The contributions from Machleidt, van Kolck, Hammer, Nogga and Phillips deal with many of these issues. How a two-body and/or three-body interaction evolves in a many-body medium is an open problem in nuclear physics, since *e.g.,* a two-body interaction fitted to reproduce phase shifts introduces an off-shell dependence in the medium.

1.2. 'Ab Initio' Many-Body Methods

In order to mover beyond the standard shell model, it will be necessary to identify methods which can complement the shell model for heavier systems and preserve an *ab initio* philosophy. Presently, the Green's function Monte Carlo [1, 2] and the No-Core shell-model [3, 4, 5] approaches offer very precise few and many-body calculations of systems with $A \leq 16$. The Coupled Cluster approaches, inspired from the success in quantum chemistry, have shown a potential for performing similar calculations for nuclei with $A \leq 16$ and $A > 16$, see for example Refs. [6, 7]. Other methods based on Green's function approaches and Block-Horowitz are interesting candidates for 'ab initio' studies, see the contributions of Barbieri [8] and Luu [9].

1.3. Methods for Unstable Systems

It is important to identify and investigate methods that will extend to unstable systems, where we especially face the problem of an increasing single-particle level density and likely resonant states. Presently, there are several attempts at combining shell-model technologies with studies of weakly bound systems. One of the promising approaches is the so-called Gamow shell model, see for example Refs. [10, 11, 12], based on complex scaling techniques developed in quantum chemistry and atomic physics [13].

1.4. Shell Model and Effective Interactions

For heavier systems, one will most likely need to complement the shell model with methods which allow for precise derivations of effective interactions including both two-body and three-body effective interactions. Presently, the shell model with effective two-body interactions based on *e.g.,* perturbative many-body methods, offers a very good description of the excited spectra of several nuclei, see for example the contribution of Brown in this volume. However, this approach faces a number of challenges, as pointed out in the contribution by Barrett, and fails in reproducing binding energies, single-particle energies and basically all known shell closures. Recent Green's function Monte Carlo and No-Core shell-model calculations demonstrate the need of three-body interactions. But for heavier nuclei such calculations are not feasible due to the large dimensionalities involved. One needs, therefore, in parallel more phenomenologically based effective interactions. These play a crucial role since, being fitted to reproduce the available body of data, they may be of great help in clarifying which matrix elements are of importance for shell closures and other features of excited states. The talks by Brown and Otsuka demonstrate the latter, see also Ref. [14]. Another interesting topic is how to match the above *ab initio* methods with extensions of density functional theories, as discussed by Furnstahl and Bender.

1.5. Computational and Algorithmic Issues

Here one needs to single out important computational and algorithmic developments. The factorization scheme developed by Papenbrock and co-workers is one such candidate which offers a reduction by more than an order of magnitude in dimensionality for shell-model studies. Similarly, the Coupled Cluster approaches allow one to study ground- and excited-state properties of nuclei with dimensionalities beyond the capability of present shell-model approaches, with a much smaller numerical effort when compared to the more traditional shell-model methods aimed at similar accuracies. Furthermore, we feel it is important to stress recent advances in computational science. Parallel technology offers, for example, a totally new paradigm for many-body theories. It is imperative, therefore, to develop methods which are capable of utilizing these advances fully.

In the next section we wish to link the above with present and future challenges from experiments, in order to emphasize our requirements and demands from many-body theories in nuclear physics.

2. Experimental Challenges and Many-Body Methods

Twelve years ago two of us (BRB and JVP) organized a similar three-month program at the INT in Seattle. Back in 1992 we were not in a situation where one could perform almost exact calculations of nuclear systems. At this time, we feel that nuclear many-body theory is now in the position where precise and benchmark calculations can be performed with a given two-body and/or three-body Hamiltonian. For mass $A \leq 16$, the Green's function Monte Carlo approach, the No-Core shell model and recently the Coupled Cluster approaches, represent in principle *ab initio* methods. This offers wide perspectives for studies of various Hamiltonians used in solving the non-relativistic Schrödinger equation. An eventual disagreement with data can then be retraced to our Hamiltonian. The calculations with three-body interactions of Refs. [1, 15] clearly demonstrate this point. Unless a three-body interaction is included, one cannot reproduce the binding energy or some excited states for nuclei with $A \leq 16$.

For stable nuclei, important for the s-process and Big Bang nucleosynthesis, we have typically proton and neutron separation energies S_p and S_n of the order of $S_p \sim S_n \sim 8$ MeV, and the excited states are dominated by an interplay between collective and single-particle degrees of freedom. However, for stable nuclei with $A > 16$, we are not able to describe properties such as shell closures or the binding energy based on a microscopic appproach, unless we employ a fitted two-body interaction in shell-model studies. Well-known cases are the shell-closures in ^{48}Ca or the chain of oxygen isotopes, see Brown's contribution in this volume. We may, however, be able to reproduce several excited states of stable nuclei starting from a perturbative many-body approach, see for example Refs. [16, 17]. It is, on the other hand, difficult to extend such approaches in order to include three-body interactions or go beyond a certain order in perturbation theory. This poses serious challenges to nuclear many-body theories when we move to proton-rich or neutron rich nuclei. Such nuclei have been produced recently or will be studied in the near future. As an example, neutron-rich nuclei, with $S_p \sim 15$ MeV and $S_n \sim 0$ MeV and crucial for the r-process, supernovae and star formation, have been studied extensively in the last years. They exhibit features like halos and resonances which put a strong pressure on existing many-body techniques. How to deal with weakly bound states and an increased number of single-particle degrees of freedom is not easy to account for in present shell-model approaches. Other features like the predictions of new shell-closures and their origin are also properties we would expect a many-body approach to deal with.

Summarizing, it is our firm belief that new developments in many-body theories for nuclear problems should contain as many as possible of the following ingredients:

- It should be fully microscopic and start with present two- and three-body interactions derived from *e.g.,* effective field theory;
- It can be improved upon systematically, e.g., by inclusion of three-body interactions and more complicated correlations;
- It allows for description of both closed-shell systems and valence systems;
- For nuclear systems where shell-model studies are the only feasible ones, viz., a small model space requiring an effective interaction, one should be able to derive effective two and three-body equations and interactions for the shell model;
- It is amenable to parallel computing;
- It can be used to generate excited spectra for nuclei like where many shells are involved (It is hard for the traditional shell model to go beyond one major shell. The inclusion of several shells may imply the need of complex effective interactions needed in studies of weakly bound systems); and
- Finally, nuclear structure results should be used in marrying microscopic many-body results with reaction studies. A very promising method in this direction is the Lorentz transformation method developed by Barnea, Efros, Leidemann and Orlandini, see Ref. [18].

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