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LLNL-TR-729382

Report on INT Program INT-17-1a

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April 19, 2017

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Report on

INT Program INT-17-1a

Toward Predictive Theories of Nuclear Reactions Across the Isotopic Chart

February 27 - March 31, 2017

and

Workshop on

Nuclear Reactions: A Symbiosis between Experiment, Theory and Applications

March 13-16, 2017

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Overview

The purpose of the 5-week program was to bring together physicists from the low-energy nuclear structure and reaction communities to identify avenues for achieving reliable and predictive descriptions of reactions involving nuclei across the isotopic chart. The 4-day embedded workshop focused on connecting theory developments to experimental advances and data needs for astrophysics and other applications.

Theory Program

Weeks 1–2 and 4–5 focused primarily on theoretical aspects of nuclear reactions. We followed the standard INT program format of one or two daily (morning) talks and afternoon discussions. The afternoon meetings, which were well attended, consisted of a mix of pre-selected short contributions (determined based on participant interests) and less-structured discussions, guided by issues raised during the morning talks. A working web site, which we produced prior to the program, was used to solicit and gather participant input.

Throughout the program, we pursued two essential goals:

- Determine strategies for expanding current *ab initio* nuclear structure and reaction descriptions towards medium-mass nuclei;
- Determine strategies for moving towards microscopic theories of heavy nuclei to achieve increasingly more predictive descriptions of the structure and reactions of heavy nuclei.

Recent years have seen exciting new developments and progress in nuclear reaction theory that allow us to move towards a description of exotic systems and environments, providing deeper insights into the dynamics of the nuclear many-body system, and setting the stage for new discoveries. Using the most advanced supercomputer facilities, solutions based on first-principle approaches to scattering and nuclear reactions for light nuclei have become feasible. These *ab initio* approaches have demonstrated considerable success in applications to fusion reactions and astrophysics for light nuclei. The methods provide a simultaneous description of both bound and scattering states. They also carry predictive power, which is critical for studying short-lived isotopes inaccessible by experiment.

We heard a number of presentations on recent developments in the resonating group method and no-core shell model, coupled-cluster theory, the Gamow shell model, a Faddeev-Yakubovsky equations approach, *ab initio* Green's function method, halo and cluster effective field theory for weakly-bound systems, and in lattice effective field theory. We learned that we are close to seeing a numerical solution of the Faddeev-Yakubovsky equations for the five-body $n + \alpha$ system. There has been impressive progress in many-body methods, with calculations being carried out for select medium mass and heavy nuclei (such as ^{208}Pb), and benchmark calculations demonstrating their accuracy for nuclear bulk properties. These developments make it possible to distinguishing between different NN (and 3N) interactions and motivate the search for reliable interactions. The need to critically examine how to best approach nuclear interactions was a theme discussed several times during our program.

In the effort to apply the lessons learned from *ab initio* approaches to the structure of and reactions with heavier systems, effective field theories (EFT) are seen to play an important role, as presentations on pion-less EFT, halo (cluster) EFT, and lattice EFT talks demonstrated. EFT approaches enable one to identify the relevant degrees of freedom and provide a framework for improving the descriptions via well-defined expansion schemes. Symmetry-adapted methods, which organize the model space in a manner consistent with dominant parts of the Hamiltonian, similarly offer computational advantages and the possibility to introduce physics-driven truncation methods.

Reaction theory is needed to describe elastic and inelastic scattering processes, the fusion of nuclei, as well as transfers of nucleons or groups of nucleons between projectile and target. The complexity of the problem requires the elimination of possible reaction channels from explicit consideration to arrive at a (usually few-body) problem which can be computed exactly. A consequence of this reduction to a set of manageable channels, the introduction of effective interactions (often referred to as optical potentials) is mandatory. In the past decade effective interactions in the form of phenomenological optical potentials received much attention.

We heard that efforts to determine effective interactions (optical model interactions) from *ab initio* methods are still in the early stages and have seen limited success. Accurately-predicted matter radii are known to be crucial for producing correct diffractive patterns in differential cross sections. Collectivity and cluster degrees of freedom were seen to pose challenges to current *ab initio* approaches, but are important for producing accurate predictions. For heavier nuclei, methods based on density-functional and (Q)RPA approaches are being employed to obtain microscopic potentials for the calculation of scattering observables, for both spherical and deformed nuclei. The importance of obtaining *ab initio* and microscopic effective inter-cluster interactions was highlighted, as these can provide guidance for developing a new generation of phenomenological optical-model interactions, which should be dispersive and nonlocal.

An important objective of nuclear theory is to achieve reliable predictions for reactions involving heavy isotopes away from stability, e.g. those produced in r-process nucleosynthesis. In the past, phenomenological approaches (describing the bulk properties of nuclei and using parameterizations fitted to data for stable isotopes) were widely used as input for statistical (Hauser-Feshbach) calculations for heavy nuclei. The past decade has seen a move towards the use of microscopic approaches for calculating required nuclear structure input (discrete levels, level densities, gamma-ray strength functions, fission barriers, etc.), optical models, as well as pre-equilibrium descriptions. Developments in this area were discussed during the program, including calculations based on (Q)RPA calculations with finite-range interactions, multi-phonon descriptions, and shell-model Monte-Carlo methods. It was stressed that replacing older phenomenological models by such microscopic descriptions is crucial for allowing for more controlled extrapolations to very exotic isotopes. In addition, possible observations of non-statistical effects, the question of energy averaging, and a new method to describe fission in an approach that goes beyond the traditional phenomenological approach involving a simple fission barrier model without resorting to computationally-challenging microscopic generator-coordinate methods, were discussed.

Experimental facilities involving radioactive ion beams and dramatically-improved multi-physics simulation capabilities provide new challenges and opportunities. Nuclear theory must address phenomena from laboratory experiments to stellar environments, from stable nuclei to weakly-bound and exotic isotopes. Expanding the reach of theory to these regimes requires a comprehensive understanding of the reaction mechanisms involved as well as detailed knowledge of nuclear structure. We discussed breakup effects and multi-step processes in inelastic scattering and transfer reactions. It became obvious that properly including these higher-order effects in the reaction theories is crucial for interpreting experiments, both for extracting structure information and for determining cross sections indirectly.

A recurring theme throughout the program was the desire to produce reliable predictions rooted in either *ab initio* approaches or, at least, microscopic methods, with realistic interactions. At the same time it was recognized that some applications involving heavy nuclei away from stability, e.g. those involving fission fragments, may need to rely on simple parameterizations of incomplete data for the forseable future. The goal here, however, is to subsequently improve and refine the descriptions, moving to phenomenological, then microscopic approaches. There was overarching consensus that future work should also focus on reliable estimates of errors in theoretical descriptions.

Workshop

The embedded workshop was coordinated by J. Blackmon (LSU), N. Scielzo (LLNL), and J. Escher (LLNL). While the overall program aimed at a better integration of the complementary theory efforts, the workshop incorporated the experimental measurements that will serve as crucial tests of the predictive power of theory. The workshop also explored the nuclear data needs for astrophysics and other applied areas, and a topic of discussion was how to better integrate experimental and theoretical efforts to improve data libraries.

A workshop format was adopted that combined a series of talks and opportunities for discussions. Several longer (50 min) talks provided overviews over various experimental facilities and theoretical approaches, and a larger number of shorter (30 min) talks added more details and additional perspectives. At the end of each morning and each afternoon session, a discussion, co-led by an experimentalist and a theorist, provided an opportunity to make connections and to view the presentations in a larger context. Feedback from participants indicates that the discussion sessions were viewed as very valuable.

We had overviews on the experimental progress at the NSCL/FRIB, TRIUMF, and Argonne National Lab. The ability to study the properties of exotic nuclei will significantly improve in the near future with the new facilities coming to these laboratories, which promise not only substantial improvements in the breadth and intensity of radioactive ion beams, but also multi-user capabilities that could substantially increase the volume and impact of the experimental data. Looking to the future, several proposed upgrades to FRIB could further extend the scientific reach by implementing higher beam energies, a harvesting capability for long-lived isotopes, and an ISOL capability.

The workshop also included shorter talks on specific experimental topics, and in most sessions we succeeded in pairing experimental and theoretical talks on the same topic (e.g. on indirect determination of cross sections), which lead to productive discussions. Major scientific themes included the structure of light exotic nuclei that are accessible by *ab initio* theory, the improved nuclear physics input that is needed to interpret the ever-increasing number of astrophysics observations, how to improve the treatment of the continuum, how to better constrain neutron capture on radioactive nuclei, and what measurements will have the most impact on theoretical developments.

The theoretical and experimental developments required to address the nuclear properties needed for astrophysics involve a large number of unstable nuclei. In some cases, the increased intensity of reaccelerated beams of short-lived nuclei will allow direct measurements of the reactions of interest, such as (p,γ) reactions of importance for understanding the rp-process. However, for most reactions needed for nuclear astrophysics and applications, direct measurement will remain inaccessible due to beam or target limitations. For these cases, indirect approaches which depend on a close interplay of experimental observables and reaction theory are needed.

In some cases, collecting data under different conditions, such as determining spectroscopic factors and ANCs at different beam energies, could provide additional information to limit the model dependence of the interpretation. It was recognized that important open questions about the limitations of these approaches remain. For example, how good is mirror symmetry and how large of an uncertainty do we assign results which rely on this symmetry? Broad resonances remain a challenge, both for measurements and for theoretical descriptions. How well do we understand the evolution of statistical properties of nuclei, such as the low-energy behavior of the photon strength function or the pygmy dipole resonance, as we move away from the valley of stability? How do we best account for the differences between the conditions present in indirect measurements and those relevant to the quantity we are interested in?

A recurring theme throughout the workshop centered around how to best make connections between theory and experiment. Questions discussed included how to best disseminate information (logistics of databases and their maintenance), which quantities are the most appropriate for comparisons, and reliable estimation (and reporting) of uncertainties.

Administrative Aspects of the Program

We had a total of 72 participants at the program, 43 of whom also attended the workshop. The majority of the participants were, as expected, theorists (57), but we also had a good number of experimentalists (15). Among the participants were several scientists from the astrophysics, national lab, and nuclear data communities. The program represented all demographics of the physics community. Three of the four organizers were female, as were 13 out 72 participants. Furthermore, 5 out of 72 participants were from under-represented minority groups. The participation was also diverse geographically, with participants who are now working or studying in nine different countries. This includes the United States (50), Belgium (2), Canada (4), Czech Republic (1), France (7), Germany (4), Israel (1), Italy (2), and the United Kingdom (1). The program attracted a mix of scientists at different stages in their careers, from students and postdocs to senior members and retirees. Our discussion sessions benefited from this diverse mix, as lessons learned from much earlier work were considered along with very recent results.

Participant feedback and organizer perception of the interaction point towards a generally well-received program. We found the participants quite engaged in the many (29) scheduled discussion sessions and observed interactions between subsets of the low-energy nuclear community that do not often cross paths. We were told about new projects and collaborations that were started during this program. We had a number of participants for whom this program was the first experience with the INT, and their responses were uniformly positive.

First and foremost, the overall environment created by the INT staff and faculty deserves credit for contributing to the success of the program. The streamlined, extremely well-run organization and the very capable and friendly staff allowed not only the participants, but also the organizers, to be fully involved in the scientific aspects of the program. Funding provided to participants was another crucial factor, as it enabled participants to attend longer than otherwise possible or even to attend at all. Furthermore, the availability of desk space during the regular program, as well as spaces for small-group discussions was important.

We found the catered coffee breaks during the workshop useful, for facilitating interactions as well as for replenishing energy. The availability of coffee throughout the day and cookies in the afternoon helped as well.

We had a number of students attending who, we believe, benefitted from the program. It would be good to allow, in the future, a small portion of the program funds to be used to support selected, advanced graduate students.