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Toward Predictive Theories of Nuclear Reactions Across the Isotopic Chart: Web Report

J. E. Escher, J. Blackmon, C. Elster, K. Launey,
D. Lee, N. D. Scielzo

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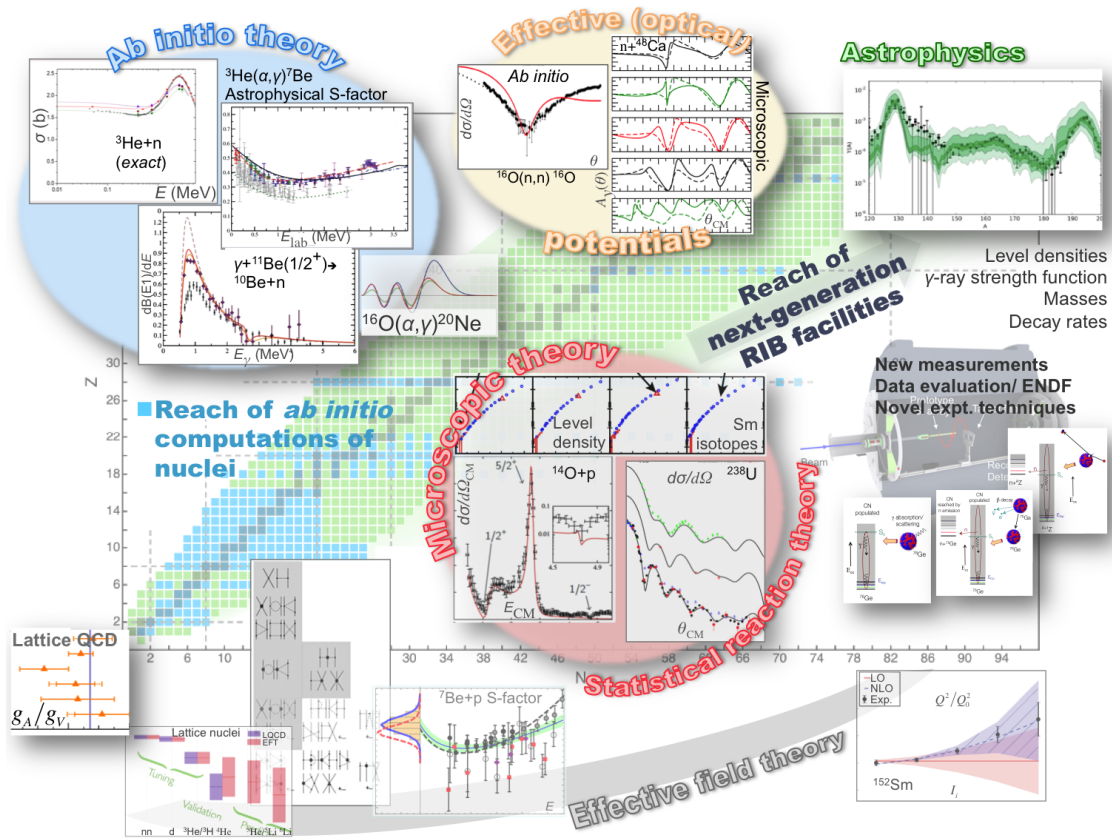
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Report on
 INT Program INT-17-1a
Toward Predictive Theories of Nuclear Reactions Across the Isotopic Chart
 February 27 - March 31, 2017
 and
 Workshop on
Nuclear Reactions: A Symbiosis between Experiment, Theory and Applications
 March 13-16, 2017

J.E. Escher, K.D. Launey, J. Blackmon, Ch. Elster, D. Lee, and N.D. Scielzo



Recent years have seen exciting new developments and progress in nuclear structure theory, reaction theory, and experimental techniques, that allow us to move towards a description of exotic systems and environments, setting the stage for new discoveries. 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.

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. A recurring theme throughout the program was the desire to produce reliable predictions rooted in either *ab initio* or microscopic approaches. 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 foreseeable 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.

Highlights from the program include:

***Ab initio* theory** – Using the most advanced supercomputer facilities, solutions based on first-principle approaches to scattering and nuclear reactions for light nuclei have become feasible. Successful applications to fusion reactions and astrophysics have been reported, e.g., the $^{11}\text{C}(p,\gamma)^{12}\text{N}$ *S*-factor. We learned that we are close to seeing a numerical solution of the Faddeev-Yakubovsky equations for the five-body $n + \alpha$ system, and that *ab initio* theories have aggressively pushed toward intermediate- and medium-mass nuclei, with selected heavy nuclei beyond, reaching as far as ^{208}Pb . Benchmark calculations have demonstrated the accuracy of different approaches for nuclear bulk properties. *Ab initio* methods that build upon physically relevant modes in nuclei have been shown to offer computational advantages and the ability to capture important characteristic, such as alpha-clustering and deformation. These developments make it possible to inform the 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.

(see talks by B. Barrett, A. Calci, T. Dytrych, G. Hagen, K. Launey, R. Lazauskas, D. Lee, P. Navratil, N. Nevo Dinur, and S. Quaglioni)

Effective field theory (EFT) – EFT approaches are seen to play an important role to provide a framework for improving nuclear descriptions via well-defined expansion schemes and identifying the relevant degrees of freedom, as demonstrated by presentations on, e.g., pionless EFT, halo (cluster) EFT, and EFT for deformed nuclei. Most models rely on available experimental data, but recent efforts focus on calculating model parameters within another theoretical framework, e.g., *ab initio* structure calculations provide input to halo EFT. Similarly, computational advantages have been noted in methods that can provide a separation of scales, such as a renormalization group evolution.

(see talks by P. Capel, E.A. Coello Prez, R. Furnstahl, C. Ji, T. Papenbrock, D. Phillips, G. Rupak, U. van Kolck)

Effective inter-cluster interactions (EICI) or optical potentials – 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. As a consequence of this reduction to a set of manageable channels, the introduction of effective interactions (often referred to as optical potentials) is mandatory. To date, these have been available and widely used in the form of phenomenological optical potentials.

Remarkable progress has been reported on *ab initio* EICI, but these methods are still in the early stages of development and have suggested that, to produce reliable EICI, the *ab*

initio structure models, from which the EICI are derived, need to reproduce matter radii and to properly take into account collectivity/clustering degrees of freedom. 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 EICI was highlighted, as these can be used in few-body reaction calculations and provide guidance for developing a new generation of phenomenological optical-model interactions, which should be dispersive and nonlocal.

(see talks by G. Blanchon, W. Dickhoff, L. Hlophe, J. Holt, A. Idini, F. Nunes)

Microscopic many-body approaches and statistical reaction theory – 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 program featured recent developments in the framework of microscopic approaches for calculating reaction observables or the required nuclear structure input, such as level densities, gamma-ray strength functions, fission barriers, as well as optical models and pre-equilibrium descriptions. Approaches employing (Q)RPA calculations with finite-range interactions, multi-phonon descriptions, and shell-model Monte-Carlo methods, as well as the Gamow shell model, were discussed. It was stressed that replacing older phenomenological models by such microscopic descriptions is crucial for allowing for 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. It became obvious that properly including higher-order effects in the reaction theories, such as breakup effects and multi-step processes in inelastic scattering and transfer reactions, is crucial for interpreting experiments, both for extracting structure information and for determining cross sections indirectly.

(see talks by G. Bertsch, I. Thompson, J. Escher, D. Baye, Y. Alhassid, M. Płoszajczak, C. Brune, A. Bonaccorso, N. Tsoneva, L. Jin, N. Auerbach, M. Dupuis, G. Potel Aguilar)

Workshop “Nuclear Reactions: A Symbiosis between Experiment, Theory and Applications”

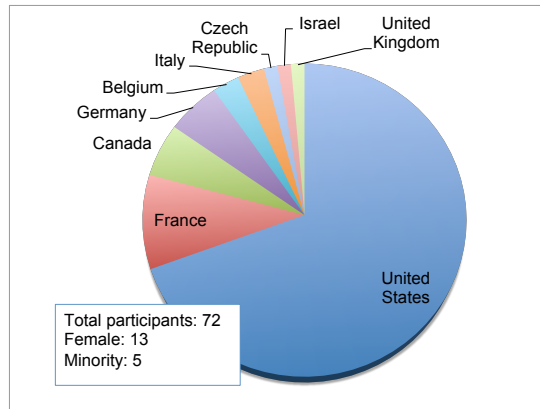
A recurring theme throughout the workshop centered around how to best make connections between theory and experiment, as well as experimental measurements that will serve as crucial tests of the predictive power of theory. Questions discussed included how to best disseminate information (logistics of databases and their maintenance), which quantities are the most appropriate for comparisons, and reliable estimation (and reporting) of uncertainties.

Overviews of nuclear physics facilities and research programs – these included NSCL/FRIB, TRIUMF, and ANL and other universities and national laboratories. With new facilities coming online, the ability to study the properties of exotic nuclei will significantly improve in the near future. These facilities promise not only significant 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.

Open questions – Major scientific themes included the structure of light exotic nuclei that are accessible by *ab initio* theory, 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. It was recognized that, 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. Other important open questions remain: For example, how good is mirror symmetry and how large of an uncertainty do we assign to 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?

Astrophysics and data libraries – The theoretical and experimental developments required to address the nuclear properties needed for astrophysics involve a large number of unstable nuclei. Improved nuclear physics input is needed to interpret the ever-increasing number of astrophysics observations. 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. Nuclei on the nucleosynthesis paths that will remain unmeasured, will have to rely on theoretical predictions. Another topic of discussion was how to better integrate experimental and theoretical efforts to improve data libraries.



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.