Improving effective forces, mean field based methods, and predictions: dedicated measurements

Spokesperson(s):

M. Bender (**CEA/ESNT, CENBG**, bender@nscl.msu.edu),

K. Bennaceur (**CEA/ESNT, IPNL, UCB Lyon 1**, bennaceur@ipnl.in2p3.fr),

S. Péru (**CEA-Bruyères, DAM/DPTA/SPN**, sophie.peru-desenfants@cea.fr).

GANIL contact person : P. Chomaz.

Collaboration :

CEA-Bruyères, DAM/DPTA/SPN: E. Bauge, F. Chappert, J.-P. Delaroche, H. Goutte, S. Hilaire, V. Rotival.

CEA-Saclay, DSM/DAPNIA/SPhN: C. Simenel.

IPN Lyon, UCB Lyon 1: T. Lesinski, J. Meyer.

LPC Caen: D. Lacroix.

NSCL, Michigan State University: T. Duguet.

Université Libre de Bruxelles: P.-H. Heenen.

Abstract:

Methods based on mean field provide a unique and universal approach to the description of many properties of all but the lightest nuclides throughout the table of isotopes. Typical applications range from self-consistent mean-field calculations of bulk properties up to projected configuration-mixing calculations of fission, radiative capture and collective excitation spectra of nuclei exhibiting, for instance, shape coexistence. In this letter, we discuss through several specific examples how such methods can be improved by data collected in SPIRAL 2 experiments.

As the nature of the project given below is purely theoretical, this document is not a letter of intent asking for instrumentation or particular set-up, but a statement of interest regarding certain aspects of the physics and classes of key measurements to be investigated at SPIRAL 2.

Scientific case

Although many efforts are being made to bridge mean field based methods as well as Energy Density Functional (EDF) approaches with more microscopic techniques (*e.g.* effective fields theory), these approaches are still mainly based on phenomenological interactions and parameterized functionals. As a result, the knowledge of data for values of spin, isospin and density far from the condition of the saturation point of symmetric nuclear matter provides crucial constraints for the improvement of the effective forces.

In this context, the wealth of data to be extracted from experiments with rare isotope beams at SPIRAL 2 will provide benchmarks that can be used to test and improve the isospin channel of the effective nucleon-nucleon interaction and the capability of the many-body methods to describe nuclei toward drip lines. As properties of exotic nuclei amplify certain components of the energy functional, data on those systems will help to pin down the relevant degrees of freedom which are strongly entangled. As matter of fact, we believe that several regions of the nuclear chart reachable with the SPIRAL 2 facility provide the opportunity to resolve some of the problems that are currently faced. On the theoretical side, nuclei of particular interest are those located beyond the next major shell closure when going away from the valley of stability. This is the regime where current model predictions tend to diverge. To resolve that problem, we primarily need systematic measurements of masses, radii and spectroscopic properties over a wide range of values of the neutron-to-proton ratio.

Also, it is important to stress that mean field or EDF calculations are far from being in a thoroughly satisfying agreement with the experimental data for all stable nuclei. In this respect, the physics of exotic nuclei will strongly contribute to the understanding of the stable ones. On the other hand, it will also help to reduce the uncertainties on the predictions for even more exotic nuclei that cannot yet be studied in laboratories, but which are needed as inputs to reliable modelling of astrophysical processes (radiative captures), fusion and fission.

Model developments are underway to improve: *i)* the nucleon-nucleon effective force, *ii)* beyond mean field models (GCM formalism and quasi-particle RPA theory breaking spherical symmetry), *iii)* a time dependent beyond mean field model for fission, and *iv)* low energy reaction models for nucleons incident on any nucleus located between drip lines. Down below are enumerated a few classes of experiments the specific character of which would be challenging for our models.

Shell effects and collective properties of even-even nuclei at low excitation energy

There are already many examples for the erosion of shell effects associated with usual magic numbers as one goes towards neutron-rich nuclei. At the same time, many nuclides that have been identified show strong shell effects at other nucleon numbers than the usual magic ones. Many effects can contribute to the disappearance or appearance of shell effects. The most obvious one is a change of the single-particle spectrum due to the evolution of the spin-orbit interaction and of the average central potential with the neutron-to-proton ratio. There are hints that the tensor force, largely omitted so far, might play an important role in that respect. However, a change of the qualitative structure of the many-body state can also mask signatures of magicity without modifying the mean field, as correlations from an increased collectivity can greatly reduce the relative weight of the spherical mean-field state.

We are interested in testing the asymmetry dependence of the effective force through the evolution of collective properties of nuclei at low excitation energy along isotopic chains, especially for neutron rich nuclei with a neutron number approaching or crossing magic numbers. In this respect we hope to have available new systematic measurements for 2^+ and 4^+ level energies, reduced transition probabilities $B(E2,0^+\rightarrow2^+)$ or $B(E2,2^+\rightarrow0^+)$ and quadrupole moments $Q(2^+)$ for neutron rich Sr, Kr, Zn, Sn and Cd isotopes. Similar observable measurements near the proton drip line would be critical to challenge our predictions for even-even nuclei with proton number Z between Z = 50 and Z = 82.

Evolution of shell effects at the upper end of the chart of nuclei

Pining down spectroscopic properties of deformed transfermium nuclides around ^{270}Hs will contribute significantly to the understanding of the structure of nuclei at the upper end of the nuclear chart. The comparison of data with theory on the evolution of moment of inertia in rotational bands, of one-quasiparticle spectra in odd-A nuclei and of two-quasiparticle and higher K-isomers in even-even nuclides will help to pin down the shell structure at sphericity. This is necessary to achieve a better understanding of the shell structure around the "island of stability" that is expected for super heavy elements.

Evolution of pairing correlations

While most nuclear properties are modified by the presence of pairing correlations, there are very few observables which are specifically sensitive to the details of the effective pairing interaction close the valley of beta stability. On the other hand, it has been demonstrated that the properties of very exotic nuclei (which are often still beyond the scope of SPIRAL 2 but which are of astrophysical interest) are very sensitive to details of the effective pairing interaction. Notably, most pairing interactions deliver a reasonable description of pairing gaps in nuclei around the valley of stability, but differ strongly when extrapolated beyond the next major shell closures. For example, accurate mass measurements and the extraction of the pairing gaps up to ^{140}Sn would already provide valuable information to discriminate between existing effective pairing interactions.

Very exotic medium and heavy mass nuclei located at the neutron drip-line may develop neutron skin with unusual diffuseness sensitive to pairing properties. This is predicted to be the case for isotopes having a neutron Fermi energy surrounded by low-angular momentum orbitals at the neutron drip-line. Most favorable cases correspond to weakly-bound near spherical nuclei with an $l = 0$ or 1 state close to the Fermi energy. This is predicted to be the case for heavy Cr isotopes, which might be reachable with SPIRAL 2.

Systematic of excitation spectra at low energy

The low-energy excitation spectrum of even-even nuclei also reflects the underlying shell structure; hence, the systematic behavior of the lowest collective excitations, their spectroscopic and transition moments provide complementary information to understand the evolution of shell structure. Isomeric states represent opportunities to study excitation spectra of exotic nuclei since they allow easier population and identification of rotational bands.

Giant resonances in exotic nuclei

Giant monopole, dipole and quadrupole resonances in exotic nuclei provide key information about properties of asymmetric nuclear matter, i.e. its incompressibility or effective masses. For example, precise measurements of the giant monopole mode in ^{100}Sn and ^{132}Sn would provide benchmarks regarding the evolution of the incompressibility with asymmetry. Such measurements, however, might be on the edge of what can be done with the SPIRAL 2 facility. Apart for this specific example, giant resonances can also bring new constraints on the EDF through the discovery of exotic collective modes and anomalies or new structures in the strength functions. Of course, the evolution of collectivity in weakly-bound nuclei with a more diffuse surface is a fascinating topic by itself.

Pygmy resonances: E1 and M1 dipole strength distributions

The study of pygmy resonances is one among the hot topics in nuclear physics. Improving our knowledge of their properties will help mapping the E1 and M1 strength distributions in the vicinity of the binding energy of the last neutron. Conversely these strength distributions govern the amount of radiative capture of low energy neutrons. Our interest is in having experimental information on pygmy resonance properties in neutron rich nuclei for which the strength is expected to grow. One way to access such experimental information in stable nuclei and direct kinematics has been and still is using ^{3}He beam (the Oslo University group method). This method can be used in inverse kinematics as well, by bombarding an ^{3}He target with radioactive beams. If this method is feasible at SPIRAL 2, we would be interested in having new information on pygmy resonances for neutron rich Zr isotopes from reaction between incident neutron rich Sr isotopes with an ^{3}He target. Such data would help testing QRPA predictions. Once validated, these model predictions will improve the modelling of neutron radiative capture cross sections for neutron rich nuclei populated in sequential reactions, for instance in the r-process simulations.

Prompt fission fragment properties

Kinetic energy and multiplicity of neutrons emitted in prompt fission gives access to excitation energy of fragments at scission. We are very much interested in such data on prompt neutron emission by each pair of light and heavy fission fragments for several heavy systems formed in fusion-fission reactions. Then we will be able to explore the dependence of such properties over Z and N so as to challenge our microscopic model predictions for scission configurations. The modellling of the decay of the fragments produced at these scission configurations can then predict neutron multiplicities and spectra to be compared with experiment.