**Nuclear Shell Model: structure of exotic nuclei, weak processes and astrophysical issues**

*E. Caurier(1), F. Nowacki(1), K. Sieja(1), N. Smirnova(2), P. Van Isacker(3)*

*(1) IPHC (2) CENBG (3) GANIL*

The shell model is one of the most successful microscopic approaches to understand nuclear spectra and transitions at low energies. The model is based on the diagonalization of a many-body Hamiltonian containing nucleonic kinetic energies and inter-nucleon interactions in a spherically symmetric basis (typically, in the harmonic oscillator basis). For very light nuclei, an A-body problem can be solved in a model space consisting of many harmonic oscillator shells, i.e. almost in the full Hilbert space, and therefore such approaches represent a genuine *ab-initio* formulation of the many-body problem. For heavy nuclei, because of the very large dimensions involved, this is not possible: calculations are done for a few nucleons placed in a few valence space orbitals beyond a closed-shell core. Thus, an effective Hamiltonian and effective transition operators should be constructed and used to provide us with robust expectation values of physical observables.

The recent growth in computation performance and progress in effective interaction theory have preconditioned tremendous success of the shell model in a very precise description of nuclear spectra and decay rates, motivating thus further extensions of the model to more exotic nuclei and heavier nuclei, its foundation from the first principles, as well as numerous interdisciplinary applications.

**Structure and decay of exotic nuclei**

It is already for a few decades that nuclear structure community is focused on the very short lived neutron-rich and proton-rich nuclei, produced and studied nowadays at various radioactive ion beam facilities around the world. The interest is explained by the importance of these nuclei in the life of our Universe - for the formation, explosion and energy generation of the stars.

The description of these nuclei remains a challenge for nuclear theory and the shell model is one of the pioneers in the investigation of the newly discovered nuclei and prediction of not yet observed nuclei.

At the current stage, the following developments are on the way:

* Large-scale calculations in extended model spaces comprising a few oscillator shells to deal with the changing shell structure and the onset of deformation in very neutron-rich nuclei;
* Development of the accurate description of isospin-symmetry breaking using charge-dependent Hamiltonians;
* Construction of fully microscopic interactions for valence-space calculations as a path towards regions where no experimental data are available;
* Development of numerical techniques and state-of-the-art computations;
* Search for additional guidelines and short-cuts using symmetry-based approaches to the nuclear many-body problem.

These developments will provide support to existing and future experimental campaigns at GANIL, ISOLDE, etc.

**Weak-interaction processes and physics beyond the Standard Model**

At present, many-body calculations for nuclear structure are needed to connect experimental particle physics probes and underlying fundamental theories beyond the Standard Model. In particular, the nuclear shell model provides the best precision being thus a unique tool to provide nuclear matrix elements necessary for the tests of the symmetries in weak processes. The efforts are invested mainly in two domains:

* Study of realistic Fermi matrix elements for beta decay between 0+ states or between the mirror states in T=1/2 nuclei, which are used to test the CVC hypothesis and to deduce the Vud matrix element of the Cabibbo-Kabayashi-Maskawa quark-mixing matrix. Calculations of high precision should be performed for a large variety of nuclei with Z=6 to Z=37 and heavier, using precise charge-dependent Hamiltonians.
* Study of the very rare double-beta decay (2νββ and hypothetical 0νββ processes) serving as a probe of the nature of the neutrino and a mean to get the neutrino mass scale. Calculations have to be performed for mid-mass emitters ranging from 48Ca to 136Xe and heaviest 150Nd, and accessible to a shell model description. Such calculations require very large model space (containing all degrees of freedom) well founded effective Hamiltonians and thoroughly elaborated transition operators. In particular, forthcoming developments should concentrate on benchmarking convergence of the ββ matrix elements magnitudes with respect to the size of the valence space.

In addition to the calculation of double-beta decay matrix elements in the framework of the nuclear shell model, it is of interest to relate the results to more phenomenological approaches such as the interacting boson model. With a realistic shell-model Hamiltonian as starting point, a crucial ingredient of the method will be the construction of effective operators, which reflect the truncation from the full shell-model space to the collective subspace and its subsequent mapping to the boson space. This technique was developed for the isospin-invariant version of the interacting boson model, appropriate for lighter nuclei, and should be extended to heavier nuclei where neutrons and protons are in different valence shells.

**Nuclear astrophysics applications: stellar rp- and r-processes and formation of chemical elements**

Nuclear reactions drive the energy generation in the stars, thus their knowledge in stellar environment is crucial in our understanding of our Universe.

Radiative proton-capture reactions - (p,γ), together with the (p,α), (α,γ) and their inverse, play the major role in determining the nucleosynthesis path in novae or X-ray bursts (explosive hydrogen burning). While proton capture on stable nuclei can be estimated from statistical methods, the proton capture on neutron-deficient nuclei is characterized by small reaction Q-values (less than 5 MeV). At such conditions, the level density is relatively low and a few resonances in the vicinity of the proton-separation threshold can significantly contribute to the reaction rate. This resonance contribution, together with the direct contribution to the reaction rate has to be determined from a microscopic approach. The shell model is by far well suited for this task and therefore is exploited nowadays to overwrite the independent-particle model predictions. A precise description of the isospin-symmetry breaking is a great advantage and a need in order to predict unknown experimentally Q-values, resonance energies, proton, alpha or electromagnetic widths of those resonances.

This input is highly awaited for simulations of the X-ray burst or novae events and can be crucial for our understanding of the generated abundances, ejected material and final ashes composition in the neutron star (X-ray burster) or a white dwarf (novae).

Formation of the neutron-rich matter and heavy elements has for long been assigned to the so-called r-process, possibly appearing in type II supernovae and/or kilonovae events (as the recently observed neutron stars mergers). One of the key stages of the astrophysical r-process is the thermal neutron capture with the subsequent gamma decay of the compound state. The description of the decay radiation and level densities of the compound nucleus is therefore crucial to obtain accurate theoretical predictions of the neutron capture rates for astrophysics applications.

While the nuclear shell model is not directly applicable to provide such predictions for around 5000 nuclides necessary to astrophysical modelling, it is the most accurate tool in nuclear structure which can explain in detail the observed structure effects and guide developments of other microscopic or phenomenological models. Recently, it was used successfully to explain the low-energy structure effects in de-excitation dipole strength functions which permitted to improve the existing large-scale QRPA predictions of neutron capture rates. Currently, developments within the QRPA/HFB are carried in order to achieve a fully microscopic description of the gamma decay with correct low-energy behaviour as predicted by the shell model. The challenge for theoretical description of the neutron capture is the most neutron-rich nuclei where due to the low neutron threshold the statistical approach to radiative capture may no longer be applicable and direct capture rates need to be evaluated. Thus the structure input from the nuclear shell model will be applied to test the competition between radiative and direct neutron captures on exotic systems and further precise shell model calculations will provide a benchmark for nuclear models used by default in existing reaction codes (e.g. TALYS).