

MONSTRE (**M**odeling **N**uclear **S**tructure and **R**eactions) is a research project sponsored and financed by the National Scientific Committee for Theoretical Physics of the Italian *Istituto Nazionale di Fisica Nucleare* (INFN). MONSTRE gathers several Italian groups working on the theory of nuclear structure and reactions (see [www0.mi.infn.it/monstre](http://www0.mi.infn.it/monstre) for the researchers involved). The main goal of our collaboration is to implement an integrated framework for the physics of atomic nuclei, nuclear reactions, and strongly interacting matter.

In the following, we indicate some lines of development related to our research activity that we deem important for the future of nuclear physics in Europe.

## The Nuclear Equation of State and Collective Modes

Important information obtained from recent astrophysical observations of gravitational waves from neutron star mergers by LIGO/VIRGO, as well as radii measurements of neutron stars by NICER, can be combined with those from nuclear structure and nuclear reaction experiments to provide new constraints on the nuclear Equation of State (EoS).

This large and varied amount of experimental data is accompanied by recent advances in modelling nuclear structure and reactions and astrophysical scenarios. At the present stage, it is important to apply advanced statistical analyses (e.g., comprehensive Bayesian analyses) to the combined astrophysical and terrestrial constraints, making use of the available model predictions, to achieve an improved, multi-verified understanding of the EoS.

Among nuclear structure observables, the properties of giant resonances have represented a very important source of information on the EoS parameters. For example, compressional modes like the monopole resonance provide constraints on the incompressibility of symmetric nuclear matter, while symmetry energy parameters can be constrained by the properties of isovector nuclear states. In order to make significant advances, information on how collective modes evolve far from the stability line is mandatory. This must stem from experimental progress; the commissioning of the radioactive beam facilities plus a set of appropriate detectors (e.g. active targets) are called for. At the same time, the theory must be up-to-date, and Density Functional Theories solvers that can deal with nuclei across the entire chart (including non-spherical and superfluid ones) must be implemented and available.

In this regard, it is important to restore rotational symmetry, which is usually broken in RPA-like methods when applied to deformed systems. Apart from some studies performed in the context of the so-called needle approximation (whose validity has not been demonstrated in realistic studies), this task has never been accomplished in realistic systems. Furthermore, applying projection techniques would enable a more reliable and safer comparison with spectroscopic observables, for which angular momentum is a good quantum number.

## Progress in Heavy-Ion Collisions at Intermediate Energies

Transport theories, which are based on the use of effective interactions, closely linked to the nuclear EoS, are an essential tool to investigate the reaction mechanisms occurring in heavy ion collisions, from Fermi up to intermediate energies, where transient states of nuclear matter in various conditions of density, temperature and charge asymmetry are created. Considerable efforts are currently underway to verify the consistency among the different theoretical approaches and to reduce the model dependence of the predictions of experimental observables in order to derive robust constraints on the EoS.

New experimental and theoretical perspectives open up, related to the study of observables (such as charged pion production in neutron-rich systems) which are primarily sensitive to the initial, pre-

equilibrium stage of the reaction, where nuclear matter is compressed. Also, in collisions between partners having the largest difference in the charge/mass asymmetry, pre-equilibrium gamma-ray emission originating from a collective coherent excitation in the primary composite system could provide, according to the related spectral properties, information on the time and, in some case, on density-variations leading to the multi-fragmentation events in an almost model-independent way.

From the theoretical point of view, the challenge is to reach a consistent prediction of light-particle and meson production in the medium, taking into account the rapid evolution of the nuclear matter states and of the associated mean-field potential. On the other hand, other observables, linked to the features of fragment production, can be exploited to probe the final (low-density) stage of the collision. In this regime clustering effects deserve further investigations, also for their crucial impact on the structure of light nuclei, the properties of the nuclear EoS and the modeling of astrophysical objects.

## Advancing *Ab initio* Nuclear Theory

*Ab initio* studies of many-nucleon systems have grown drastically in their reach along the Segrè chart, so that it is now possible to compute energies and radii of Sn and Pb isotopes with controlled approximations. Despite the polynomial scaling of the number of configurations accepted, a wall in mass number and precision is still encountered, and it is mandatory to investigate new strategies to include higher configurations that are beyond the present limitations. Possible approaches are:

a) The Gorkov self-consistent Green's function method (SCGF) broke new ground for open shells isotopes, effectively extending the reach of *ab initio* theory from a few closed shell to hundreds of semi-magic isotopes. Current applications, however, are still limited to the second order truncations in the algebraic diagrammatic expansion [or ADC(2)]. An extension to the ADC(3) truncation will provide considerably higher accuracy to evaluate direct interactions with neutrino and to study collective responses and the evolution of shell model near the driplines. This goal is under implementation for finite nuclei, and it will rely on a configuration sampling approach similar to The Configuration Interaction Monte Carlo method (CIMC).

b) The CIMC demonstrated the possibility of sampling momentum space configurations in pure neutron matter and reached accurate diffusion MC results. CIMC allows us to exploit both two- and three-nucleon chiral interactions with non-locality in momentum representation derived from Effective Field Theory, that were previously beyond the reach of Quantum MC. The CIMC is to be extended to symmetric nuclear matter.

c) Artificial neural networks have proven to be a flexible tool to approximate quantum many-body states in condensed matter and chemistry problems. Variational Monte Carlo computations based on neural-network quantum states (NQS) have proven to outperform state-of-the-art diffusion Monte Carlo results, avoiding limitations related to the fermion sign problem. Calculations of nuclei up to  $^{16}\text{O}$  have been recently carried out. Applications to infinite nucleonic matter and nuclei as large as  $^{40}\text{Ca}$  are within reach on current-generation supercomputers, while larger systems will be possible once Exascale computers are deployed. In addition to their ground-state and low-lying excited states properties, NQS promise to access the real-time dynamics of atomic nuclei. Accessing the latter is critical for studying fission, heavy-ion fusion, as well as lepton-nucleus scattering processes.

*Ab initio* results in specific systems can also be used to constrain other approaches which are less computationally demanding. Energy density functionals (EDFs) are now routinely used to predict properties of ground and excited states of nuclei throughout the nuclear chart. However, current EDF implementations are almost completely based on phenomenology and have not been anchored to the

fundamental theory of nuclear interaction. Phenomenological functionals become uncertain whenever there is lack of accurate experimental data from where to extrapolate. A potentially successful strategy—that led to the extremely accurate EDFs for many-electron systems—is to reconstruct the functional based on a thorough analysis of metadata from ab initio computations.

## Unified View of Nuclear Structure and Reactions

The structure of exotic isotopes depends on a complex interplay of shell structure and collective modes that can evolve in a dramatic way, moving away from the valley of stability and toward the drip lines. Much needs to be understood, both in regard to the structure itself and in regard to the response to external probes, so that one can learn about and predict the properties of the ~3000 isotopes yet to be discovered far from the valley of stability.

Basic spectroscopic information is obtained from the analysis of one-nucleon transfer and knock-out reactions based on optical potentials. The latter are usually derived with (semi-) phenomenological approaches. Crucial breakthroughs may be obtained from a consistent theoretical description of structure and reactions based on ab initio theory.

Recent attempts at first principle computations of optical potentials have produced only partially satisfying results. The efforts and know-how that allowed recent achievements in the calculation of the ground states of heavy nuclei should now be directed toward refining ab initio simulations of elastic scattering, which represents an inherently different problem. With the present-day computational power, is it conceivable to carry out reliable computations of spectroscopic overlaps and elastic scattering up to energies of about 100 MeV/A for medium mass isotopes, based on the direct computation of the nuclear self-energies in SCGF theory or by inversion of the one-nucleon Green's function. In any case, the game-changing step is not simply an increase in computational power but rather the introduction of innovative ways for sampling and controlling the dynamical degrees of freedom that are probed by the reaction dynamics.

Much interest is attached to the study of states beyond the neutron or proton drip-line. This is the object of several experimental investigations in light nuclei, in particular via the invariant mass method, which require a good treatment of the continuum for a theoretical interpretation and for a quantitative computation of the energy and width of the observed resonant states, as well as for particle decay. Such data represent a severe test for models aiming at a comprehensive treatment of structure and reactions, like the continuum shell model, or many-body treatments that need to deal with important renormalization processes including bound and continuum states. The comparison of the energy and width of resonances observed in (d,p) and (p,d) reactions represents an important test for the energy dependence of ab initio optical potentials.

## Nuclear Physics and Fundamental Symmetries

Nuclear physics has a long record of important contributions to the testing of Standard Model and to the probing of new physics beyond it.

Neutrinoless double-beta ( $0\nu\beta\beta$ ) decay is a weak process in which two neutrons inside a nucleus transform into two protons with no neutrinos emitted. The existence of  $0\nu\beta\beta$  decay is uncertain and motivates strong experimental and theoretical efforts because it would prove that neutrinos are Majorana rather than Dirac particles and could be used to constrain the neutrino mass. One of the main sources of systematic uncertainties is associated with the nuclear matrix elements (NMEs) connecting

the wave functions of the parent and granddaughter nuclei in double beta decay. Efforts should be made to reduce these uncertainties.

Microscopic models in which no fitted parameters are introduced, such as the quenching factor of the axial coupling constant, are particularly valuable and should be improved. In this respect, it is important to investigate the renormalization of spin- and spin-isospin-dependent operators, arising from the effects of electromagnetic and electro-weak two-body currents and their impact on the so-called “quenching problem” affecting, for instance, the gyromagnetic factors and the axial coupling constant  $g_A$ .

It may be interesting to focus on observables related to  $0\nu\beta\beta$  NMEs. Interesting perspectives in this direction are provided by the study of second-order electromagnetic transitions emitting two photons and charge-exchange modes excited by heavy ion-induced reactions. Recent shell-model calculations have shown the existence of a good linear correlation between the double charge-exchange Gamow-Teller and the  $0\nu\beta\beta$  NMEs. More efforts are needed to reach a comprehensive description of the underlying reaction mechanism, especially in the case of double charge-exchange reactions. Experimental studies of  $\gamma\gamma$  decay for some selected Double Isobaric Analog State may be also relevant to reduce the uncertainty in  $0\nu\beta\beta$  analyses.

Current- and next-generation accelerator neutrino experiments are aimed at measuring neutrino properties, including their masses, oscillation parameters and CP-violating phase, with unprecedented accuracy. These experiments use nuclei in their detectors to significantly enhance the event rate. Hence, the proper interpretation of experimental data requires accurate theoretical calculations of neutrino-nucleus scattering cross sections with quantified uncertainties. Over the past decade, ab-initio calculations of neutrino- $^{12}\text{C}$  cross sections have been performed within the Green's Function Monte Carlo method. Major theoretical progress is required to reach  $^{16}\text{O}$  and  $^{40}\text{Ar}$  nuclei, which will be utilized by the Hyper-Kamiokande and DUNE experiments. The auxiliary-field diffusion Monte Carlo and the self-consistent Green's function methods can both reach  $^{16}\text{O}$  and  $^{40}\text{Ar}$ . Developments are in order to include consistent Hamiltonians and electroweak current operators and to accommodate in these approaches integral-transform techniques, such as the Lorentz and the Laplace transform.

Measurements of atomic parity violation and parity-violating elastic scattering in stable nuclei should be encouraged and fostered by NuPECC. These experiments provide fundamental tests of the Standard Model via the measurement of the nuclear weak charge (weak-mixing angle) and of the weak charge density, respectively. We note that the weak charge density in nuclei give direct access to the neutron distribution, a very elusive and very basic property of the atomic nucleus.

Progress in the theoretical understanding of asymmetries is also required to provide atomic parity violation experiments with more reliable nuclear weak charge distributions for the analysis of the experimental data. A mild tension between the parity-violating longitudinal asymmetry in  $^{208}\text{Pb}$  and  $^{48}\text{Ca}$  has been found when analyzed with several theoretical models and observations. The scenario is much worst for the transverse asymmetry in  $^{208}\text{Pb}$ , because no theoretical model is presently able to describe this quantity. To shed light on this topic will have also a clear impact on important features of the nuclear effective interaction and hence on the nuclear equation of state.

Reaching the proton drip line in heavy isotopes with novel experimental techniques will give access to the study of a variety of mirror nuclei with neutron to proton asymmetries larger than available nowadays. This will enhance the effect of isospin symmetry breaking (ISB) in the nuclear medium, which is poorly known but may entail relevant consequences in particle physics, nuclear structure, and astrophysical contexts. Hence, it will be instrumental to foster the theoretical study of ISB in the medium by lattice QCD, ab-initio models, interacting shell model and DFT.

## Clustering and Alpha Correlations

The quantitative microscopic understanding of clustering represents a major open problem in nuclear structure. The phenomenology of clusters and nuclear molecules is relatively well-known, for example, in  ${}^6\text{Li}$ ,  ${}^7\text{Li}$ ,  ${}^7\text{Be}$ ,  ${}^{12}\text{C}$  as well as in several unstable nuclei, but a theory that merges single-particle aspects with clusters still stymies the efforts of theorists. Cluster structures and molecular states that are known to exist, especially among light nuclei, do not emerge systematically from first-principle approaches based on individual nucleons and taking fully into account the Pauli principle. Until very recently, cluster states were thought to occur only close to separation thresholds, but now, thanks in particular to powerful predictions of algebraic models, it is clear that geometric point-group symmetries play a crucial role in determining a portion of the low-energy spectrum as, for example, in  $N\alpha$  nuclei like  ${}^{12}\text{C}$ ,  ${}^{16}\text{O}$  and  ${}^{20}\text{Ne}$ .

The study of  $\alpha$ -like correlations ("quartets") induced by the proton-neutron pairing force is of crucial importance also in heavy  $N=Z$  nuclei. These investigations can now be pursued close to the proton drip line in the mass region  $A\sim 100$ . This region is considered one of the focal points of nuclear structure, with  ${}^{100}\text{Sn}$  beta-decay exhibiting the largest Gamow-Teller strength measured to date and a superallowed alpha-decay observed in the  $N=Z$  chain  ${}^{108}\text{Xe} \rightarrow {}^{104}\text{Te} \rightarrow {}^{100}\text{Sn}$ . The spectroscopic properties of  $N=Z$  nuclei around  $A=100$  are, however, little known. Carrying a systematic experimental investigation of these exotic nuclei would favour the comprehension of their structure by making it possible to analyze the phenomenon of nuclear quartetting also in regions far from the line of beta stability.

It should be stressed that reactions involving clusterized nuclei, like cluster transfer, break up and fusion reactions are essential to reveal the underlying molecular structures and symmetries.

## New Perspectives Opened by Quantum Computing Technology

In the past five years, the development of Quantum Computing (QC) testbeds has seen very rapid progress, partly due to the effort of medium-large industrial companies. More and more researchers have started devoting their effort to developing QC-based algorithms aiming to exploit a possible quantum advantage in the study of many-body problems. While it is still quite hard to give a reliable perspective on the process that might lead to QC being a standard protocol in the study of nuclear structure and reactions, the current state of the art suggests that a coherent effort should be started in this direction.

In the short-term perspective, the use of Variational Quantum Eigensolvers, adaptable to both digital quantum machines and D-Wave type machines, seems to be a promising way to possibly accelerate standard many-body techniques for nuclear structure studies.

On a longer-term perspective, the capability of QC to efficiently implement the real-time evolution of a quantum state suggests that there might be a promising path towards the simulation of nuclear reactions, starting from processes involving light nuclei. In the short term, given the complexity of the problem and the very large depth of quantum circuits involved, this might require the use of non-conventional techniques, like the implementation of custom gates via optimal control.