Nuclear Structure and Reaction Dynamics – WG3

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Introduction

The strong interaction described by quantum chromodynamics (QCD) is responsible for binding neutrons and protons into nuclei and for the many facets of nuclear structure and reaction physics. Combined with the electroweak interaction, it determines the properties of all nuclei in a similar way as quantum electrodynamics shapes the periodic table of elements. While the latter is well understood, it is still unclear how the nuclear chart emerges from the underlying strong interactions. This requires the development of a unified description of all nuclei based on systematic theories of strong interactions at low energies, advanced few- and many-body methods, as well as a consistent description of nuclear reactions.

These developments are closely connected to the existing and new high-intensity stable and radioactive ion beam facilities in Europe, especially conceived to study the structure of exotic nuclei. For instance, the study of nuclear ground- and excited-state properties is vital in revealing the role played by the strong interaction in atomic nuclei and in understanding nuclear structure phenomena and their emergence from fundamental interactions. The fragmentation facility FAIR, the in-flight separator ACCULINNA-2, the low-energy ISOL facilities HIE-ISOLDE, SPES and SPIRAL2, which will provide re-accelerated radioactive ion beams, are being developed and their construction should be vigorously pursued to start the exciting physics programs in the coming decades. Stable beam facilities will continue to perform vital science programmes in the study of exotic nuclei at the extremes of isospin, angular momentum and temperature. In addition, the structure of the heaviest elements will be further explored with high-intensity stable beams at JYFL, GSI, GANIL-SPIRAL2 and JINR-SuperHeavy Elements Factory. The brilliant gamma beams from ELI-NP will open up new perspectives using electromagnetic probes, complementary to the other nuclear physics research facilities. Finally, breakthrough research in theoretical nuclear physics relies on continued access to national and European high-performance computing facilities with leading edge capabilities.

With the development of these new and upgraded facilities, new instrumentation and advanced techniques, Europe will continue to play a leading role in nuclear structure research in the coming decades. These activities will be complemented by experimental programs headed by European teams at leading international facilities outside Europe. The access to new and complementary experiments combined with theoretical advances allows key questions to be addressed such as:

How does the nuclear chart emerge from fundamental interactions?
How does nuclear structure evolve across the nuclear landscape and what shapes can nuclei adopt?
How does the structure change with temperature and angular momentum?
How to unify nuclear structure and reaction approaches?
How complex are nuclear excitations?
How do correlations appear in dilute neutron matter, both in structure and reactions?
What is the density and isospin dependence of the nuclear equation of state?

Nuclear Theory

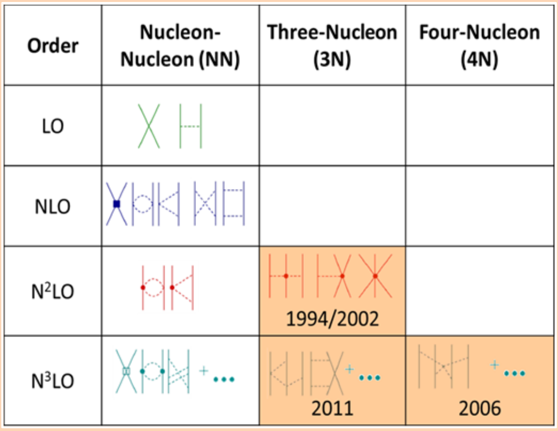
Nuclear theory is entering a precision era with developments in connecting QCD with nuclear structure, great progress towards achieving a unified description of all nuclei and new developments in reaction theory. Reaching the scientific goals involves new challenges in theory that require sustained computational resources as well as the training of the next generation of researchers in nuclear physics across Europe.

How does the nuclear chart emerge from the underlying interactions?

Box 1. Chiral EFT for nuclear forces

The contributions to two-, three- and four-nucleon interactions at successive orders in chiral EFT are shown diagrammatically. The interaction between nucleons (solid lines) is mediated by the exchange of pions (dashed lines), the Goldstone bosons of QCD, which are responsible for the long-range part of strong interactions. The short-range parts of nuclear forces are developed in a general series of contact interactions.

Many-body forces are highlighted including the year they were derived. Three-nucleon (3N) forces, which emerge naturally in EFTs, enter at next-to-next-to-leading order (N^2LO). Moreover, EFTs lead to a hierarchy among many-body interactions.



During the last decade, nuclear structure theory has evolved into a field with a systematic theoretical foundation, with nuclear forces based on QCD and advanced methods to solve the nuclear many-body problem with controlled uncertainties. Effective field theories (EFT) are playing a guiding role in this process, as they reduce the complexity of the underlying QCD theory to the relevant degrees of freedom in a systematic way (see Box 1). While this was first demonstrated for light nuclei, considerable progress in recent years has highlighted that this approach can be extended towards heavier systems.

The era of nuclear structure physics, where EFT of the strong interaction provide an exciting link between experimental and theoretical frontiers, has just started. For strong interactions at low energies, chiral EFT offer a systematic basis for nuclear forces, built on the symmetries of QCD, with controlled expansions of the interactions in the inverse chiral-symmetry breaking scale. Combining EFT with advanced few- and many-body methods opens up a systematic path to investigate nuclear forces and their impact on nuclei and nuclear matter. This provides a link between nuclear structure and matter in stars with the underlying theory, to which it is connected through lattice QCD simulations of few-nucleon systems.

In strongly interacting systems, three-body forces are especially important and have been the target of recent theoretical and experimental work. The calculation of light nuclei required the introduction of three-body forces and they play a key role in universal properties of halo nuclei and their connection to the Efimov effect in ultra-cold atoms. Three-nucleon forces (3N) are a frontier in the physics of nuclei, for shell structure and the evolution to the driplines. Exotic nuclei become increasingly sensitive to 3N forces and other subtle components of nuclear forces, so that experiments with rare-isotope beams provide unique insights into strong interactions. Calculations based on nuclear forces also provide systematic constraints for the properties of nuclear matter in astrophysics. The physics of nuclear forces therefore connects nuclear structure with nuclear astrophysics.

The ongoing exploration of many-body forces is particularly exciting, because at N^3LO, 3N and 4N forces are predicted with many new structures. These have never been applied beyond the lightest nuclei and must still pass experimental precision tests. These developments come in time with the establishment of major nuclear physics facilities, which will give great access to the unexplored regions of the nuclear chart.

The electroweak force plays a crucial role in nuclear physics. Gauge symmetry allows the use of the same EFT expansion to derive electroweak operators that are consistent with the strong interaction. Therefore, the couplings in nuclear forces also largely determine electroweak processes, which provide important consistency tests. Two-body currents, also known as meson-exchange currents, have been recently shown to provide significant contributions to electromagnetic moments and transitions in light nuclei. The exploration of electroweak interactions in nuclei and nuclear matter is therefore emerging as a new area of EFT research.

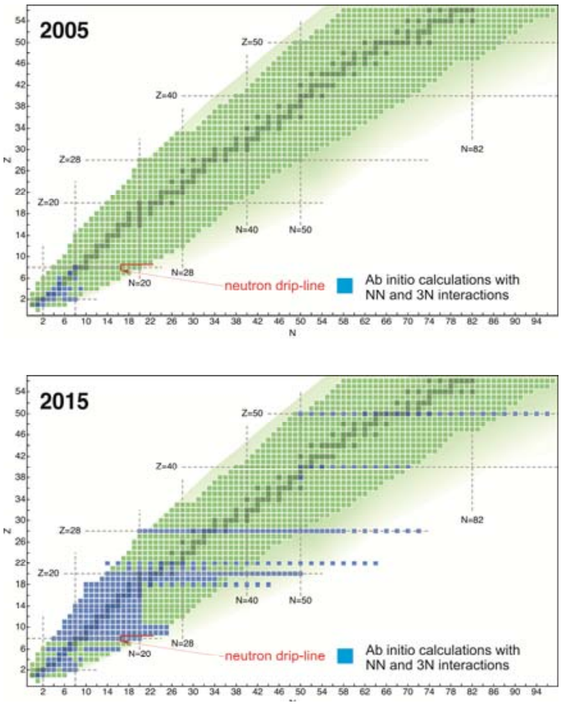
Achieving a unified description of all nuclei

The exploration of nuclear systems proceeds on many fronts employing a range of theoretical nuclear structure methods. Nuclei exhibit all the features of complex many-body systems as they span from one up to about

Box 2. The reach of *ab initio* methods

In recent years, *ab initio* computations of nuclei have advanced tremendously. This progress is due to an improved understanding of the strong interaction that binds protons and neutrons into nuclei, the development of new methods to solve the quantum many-body problem, and increasing computer performance. In the early years of *ab initio* methods progress was approximately linear in the mass number *A* because the computing power, which increased exponentially according to the Moore's law, was applied to exponentially expensive numerical algorithms. In recent years, however, new generation methods, which exhibit polynomial scaling in *A*, have dramatically increased the reach. The figures show the chart of nuclei and the reach of *ab initio* calculations in 2005 (top) and 2015 (bottom). Nuclei for which *ab initio* calculations exist are highlighted in blue. Note that the figure is for illustrative purposes only, and is based on a non-exhaustive survey of the literature.

These recent developments allow the employment of *ab initio* many-body methods to perform dedicated tests of nuclear interactions and to answer what input is required to best constrain nuclear forces.



three hundred nucleons. The individual nucleons interact through the strong and the electromagnetic forces, with intricate details of the interaction driving evolving structures. At the same time, many macroscopic quantities can be understood by concepts similar to those used to describe simple Fermi systems. A particular challenge is therefore to bridge the gaps between different scales in nuclear physics in order to achieve a unified description.

There are essentially three types of approaches to address the bound, resonant, and continuum properties of all known nuclei as well as the properties of nuclear matter. These are the *ab initio* methods, shell model (SM) approaches, and models based on density functional theory (DFT). These are not systematically connected with each other, but rather represent different levels of phenomenology, approximations and predictive power.

The understanding of few-nucleon systems is critical before extending models also to heavier nuclei. In this sense, the solution of the few-nucleon problem is an important starting point for *ab initio* methods and several approaches are being used to explore and constrain nuclear forces in the few-nucleon sector. At the same time, much progress has been made in the development of many-body methods (such as nuclear lattice simulations, quantum Monte Carlo methods, no-core shell model extensions, coupled-cluster methods, the in-medium similarity renormalization group, and Green's function based methods) with a significantly extended reach towards heavier systems (see Box 2). New methods have been developed and successful benchmarking between different approaches has been performed along chains of isotopes. This is particularly important since *ab initio* methods claim to solve the many-body problem without uncontrolled approximations. Such approaches therefore promise to provide quantified theoretical uncertainties. Results from different approaches should agree with each other when starting from the same interactions.

Currently, several approximations have to be invoked to study heavier nuclei. There are renewed efforts to connect rigorously these global methods with nuclear forces based on chiral EFT.

DFT represents the largest class of models, in terms of applicability on the nuclear chart, see Figure 1. In this approach, the energy of a system is expressed as a functional of the various local or non-local densities in all spin and isospin channels including their derivatives. The present energy density functionals (EDF) have relatively simple forms and are fitted to reproduce global properties such as radii and masses across large regions of the nuclear chart. Statistical methods allow determining the correlations among EDF parameters. However, reliable extrapolations are still challenging, in particular to neutron-rich regions. The current thrust of research in nuclear DFT is in proposing, implementing, and testing new forms of EDF that would allow for systematic expansions in the sense of effective theories so successfully applied to studies of nuclear forces.

DFT can be extended to the time-dependent case (Random Phase Approximation and extensions) and to multi-reference DFT in which broken symmetries are restored. Such extensions of DFT are a valuable tool not only to investigate bulk properties but for nuclear spectroscopy as well. Ongoing efforts should also be focused on developing functionals that are increasingly accurate, concerning especially the parts of the functional associated with the neutron-proton asymmetry. Another promising direction is the construction of *ab-initio-based* functionals connected to nuclear forces. In general, the connection between DFT and methods based on many-body perturbation theory should be better elucidated (as is envisaged also in other domains like in condensed matter theory).

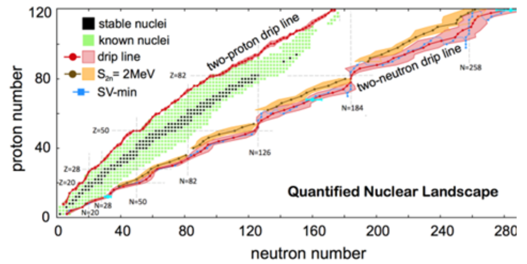


Figure 1. Map of bound even-even nuclei as a function of proton and neutron number Z and N. Drip lines and their uncertainties (red) were obtained by averaging the results of different energy-density functionals.

The shell model corresponds to an effective theory for low-energy excitations considering the nucleus as a closed-shell core with additional interacting valence nucleons. The use of effective valence-space Hamiltonians, including the contributions from configurations outside the model space, reduces the computational cost and enables calculation of properties for large regions in the nuclear chart. Large-scale SM calculations have become a well-established approach to microscopically investigate medium- and heavy-mass nuclei whose description requires very large model spaces with many valence nucleons.

Substantial progress has been made during the last decade in understanding the link between the SM effective Hamiltonian and the underlying nuclear forces. Valence-space Hamiltonians can be derived by means of many-body perturbation theory. It was also recently demonstrated that it is possible to use non-perturbative *ab initio* methods to generate effective interactions for use with SM methods.

At the other extreme of nuclear models are the macroscopic models based on dynamical symmetries, characterised by definite underlying algebraic structures, which have long provided predictions for the properties of nuclei out of reach of microscopic models. Linking symmetry-based descriptions to microscopic theory remains a challenge.

Towards consistent reaction theory

Much of our understanding of nuclei comes from experiments involving nuclear reactions. A proper description of nuclear reactions requires the combination of suitable structure models with an adequate understanding of the reaction mechanism. In addition to their use as a tool to extract structure information, reaction studies have also served to reveal interesting dynamical features as, for example, those derived from the coupling to the breakup channels in reactions involving weakly bound nuclei. In order to properly handle new observables and exotic structures, developments and extensions must be made, both in the treatment of the reaction dynamics as well as on their structure inputs.

The field has realised several advances, including applications of the Faddeev formalism to nuclear reactions induced by light weakly-bound projectiles; successful extensions of continuum coupled-channels methods to four-body reactions involving three-body projectiles such as Borromean nuclei; a more realistic description of the clusters in few-body reaction formalisms, either by including possible collective excitations of these clusters on equal footing with the single-particle excitations (see Figure 2) or by incorporating their microscopic structure (e.g., via the RGM method); improvements of transfer reactions formalisms (e.g., incorporation of non-local interactions, multi-nucleon transfer) and a variety of promising extensions of *ab initio* methods to nuclear reactions.

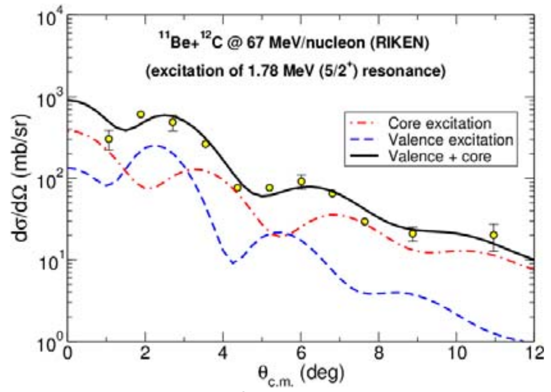


Figure 2. Interplay of valence (halo) versus core excitation mechanism in the resonant breakup of the halo nucleus ^{11}Be on a carbon target in comparison with RIKEN experimental data.

In addition to these novel developments, there has been an intensive activity aimed at re-examining and, when appropriate, upgrading, existing methods, motivated by the new experimental demands and enhanced computational capabilities, thus overcoming constraining approximations of their original formulations. These include the revival of microscopic two-nucleon transfer, inclusive breakup models, and time-dependent Hartree-Fock approaches to fission.

Developments in reaction theory must consider both, the adequate treatment of the reaction dynamics as well as the reliability of the underlying structure models and the effective interactions. With this general scope, several developments would be advisable for the forthcoming years: improvements in effective potentials and better understanding of the need of non-local potentials, developments of dispersive optical model potentials; a more extensive use of microscopic inputs (e.g., transition densities, microscopic overlaps) in reactions calculations; a more accurate treatment of quasi-free breakup reactions; theories for charge-exchange reactions (including double-charge exchange) with a potential use as a tool to extract information on the neutrino-less double-beta decay matrix elements; development of fully quantum-mechanical models for incomplete fusion; further extensions of *ab initio* methods to reactions. Finally, it is desirable to establish an interface of the output of direct reaction codes with the event generators required by the simulation codes used to describe complex detector arrays. This will allow comparing directly the experimental evidence of fragment correlations, in a given setup, with theoretical results.

Computational challenges to reach the scientific goals of nuclear physics

Computational methods play a very important role in nuclear physics research and are already fundamental to the success of key components of present and future experimental programs.

In nuclear theory the research methodology is a combination of both analytical techniques and medium-sized or large-scale computations. In fact, high-performance computing is a critical ingredient to reach the scientific goals of nuclear physics. It allows the tackling of questions that were previously thought to be intractable, and computer-based models enable the numerical exploration of systems that are still inaccessible to experiments.

Recent achievements in DFT (see Figure 1), *ab initio* methods (see Box 2), large-scale SM calculations and reaction modelling are clear examples of current successes for high-performance computing in nuclear physics. This need will continue to increase in the coming decade. Nuclear physics is one of the research fields that will benefit the most from increased efforts to tackle computational challenges through collaborations between different research groups, computer scientists and applied mathematicians. Future investments in computational resources are obviously essential. However, the trend with rapidly evolving hardware architectures requires a parallel development of research software and algorithms. This demand calls for the training of a very diverse workforce that can utilise these new resources and push the frontiers of nuclear theory.

The precision era of nuclear theory

Uncertainty quantification is an important topic in science. In recent years, the need for uncertainty estimates in theoretical calculations has started to be recognised in the nuclear physics community, in particular when claiming predictive power. Reliable theoretical errors make it possible to infer the significance of a disagreement between experiment and theory. The task of assigning uncertainties to theoretical calculations of strongly interacting systems is challenging. An important source of uncertainty in calculated observables arises from the fact that parameters, e.g., the low-energy constants in chiral EFT or those appearing in effective interactions or EDFs, are usually determined by fits to the experimental data. The statistical errors associated to this procedure can be calculated by different methods as exemplified in Figure 3.

A statistical analysis is also a powerful tool to establish correlations between different parameters and determine weakly and strongly constrained parameters. However, in addition to statistical errors, systematic errors arising from the approximate character of physical models or missing aspects of the models have to be considered. The calculation of systematic errors is very difficult and there is no unique strategy for their estimation. However, systematic approaches such as EFT provide hope of also delivering quantified systematic uncertainties. Within this context, it may also be useful to compare the prediction of different models or significantly reduce the statistical errors to acquire information on the quality of the model from the disagreement between theory and experiment. Recent works have been published employing statistical methods and scientific computing to determine the independence of model parameters, parameter uncertainties, and the errors of calculated observables.

New developments in this field will have an impact on our understanding of the structure of nuclei and their reactions. They will be helpful to identify new relevant experiments by revealing what experimental data are crucial to better constrain nuclear theory and to provide information on systems or conditions that are not accessible by experiments.

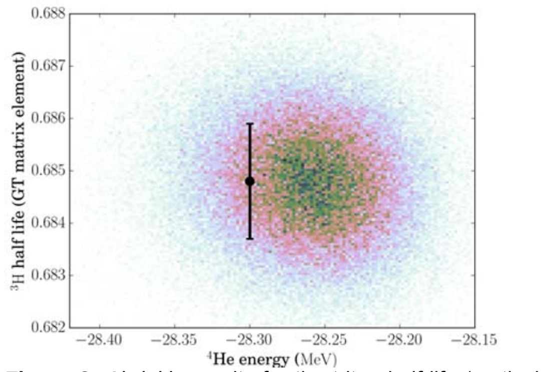


Figure 3. *Ab initio* results for the triton half-life (vertical axis) versus ^{4}He energy (horizontal). These results demonstrate the propagation of statistical theoretical errors to few-nucleon observables. The two-dimensional histogram corresponds to 10^5 computations of the A = 3, 4 systems with statistically sampled low-energy constants in chiral EFT. The marker with error bars represents experiment.

Nuclear physics also plays a vital role in the larger context of fundamental science. Nuclear physics input is required for many important questions in particle-, astro-, and atomic-physics research and in searches for beyond Standard Model physics. At this research frontier, nuclear physics is expected to provide precise measurements or theoretical predictions for relevant observables such as cross sections, masses, or nuclear matrix elements. The ability to associate reliable uncertainties with such predictions is absolutely critical for progress and to reveal the existence of new physics

Training the next generation of researchers in nuclear physics

Strong connections between universities, research laboratories and institutes worldwide are essential in order to create a unique training ground for the future needs of nuclear physics.

Over the last years, the TALENT (Training in Advanced Low-Energy Nuclear Theory) initiative has developed an advanced and comprehensive training for graduate students and young researchers in low-energy nuclear theory. This effort encompasses a broad curriculum that provides the platform for a cutting-edge theory for understanding nuclei and nuclear reactions, available to early-stage researchers in Europe and worldwide. The educational material, generated by experienced teachers, is collected in the form of web-based courses, textbooks and a variety of modern educational resources. It enables smaller university groups to profit from the best expertise available.

TALENT provides students in theory and experiment with a broad background in methods and techniques that can easily be applied to other domains of science and technology. This knowledge is crucial not only for a basic understanding of atomic nuclei, but also for further development of knowledge-oriented industry, from nanotechnology and material science to biological sciences and to high performance computing. As such, TALENT provides interdisciplinary education when it comes to theories and methods

Summary and open issues

Continued efforts to increase the precision and to extend advanced few- and many-body methods to new regions of the nuclear chart, into medium-mass regions away from closed shells and including continuum degrees of freedom are required.

Focused research on constructing improved nuclear EDF that would allow for a precise description of nuclear properties across the nuclear chart, including the spin and isospin channels, restored symmetries, and spectroscopic data is required.

Powerful developments of large-scale SM methods are needed; exploring new regions and valence spaces, advancing novel derivations of effective Hamiltonians and consistent operators and including the coupling with the continuum for weakly bound nuclei.

Increased efforts in nuclear reaction theory are needed to meet new experimental demands. Benchmark calculations of existing reaction models are advised to better establish their limits of validity and identify their limitations.

Sustained progress in nuclear theory requires developing new methods and new ideas supported by employing the most advanced computational tools, access to high-performance computational facilities and by benefiting from increased efforts in training young talent. The successful TALENT graduate training initiative should be supported on a continuous basis.

Nuclear Structure

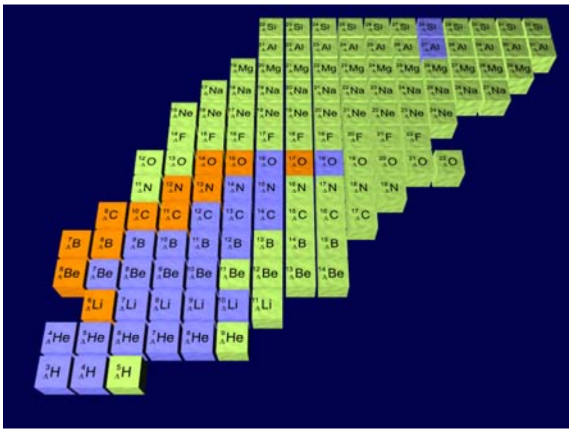
Current nuclear structure research is driven by several fundamental questions: Which are the most important few-body data to constrain nuclear forces? To what extent can the nucleus be described in terms of nuclear shells and how does the shell structure evolve across the nuclear landscape? How can we describe nuclear excitations? What shapes can a nucleus adopt? Do neutron halos and neutron skins exist all over the nuclear chart? What are the origins of clustering in dilute neutron matter? Are there nuclear systems which can be described statistically or present chaotic behaviour?

Which novel few-body data will constrain our understanding of nuclear forces?

Few-body systems continue to provide important observables for testing and constraining nuclear forces and electroweak interactions at low energies. Future topics of interest include explorations of neutron-rich resonances ranging to the extremes of isospin with pure few-neutron systems, novel studies of electroweak reactions with consistent operators, as well as the extension to strangeness with precision experiments for hypernuclei.

Box 3. Hypernuclei

Recently, hypernuclear spectroscopy with heavy ion induced reactions has been successfully performed by the HypHI collaboration at GSI. They have shown that the lifetime of the lightest hypernucleus, ${}^{3}_{\Lambda}H$, is significantly shorter than the Λ-hyperon, also reported by hadron-collider collaborations. A short ${}^{3}_{\Lambda}H$ lifetime has not yet been explained by any theory so far and remains as a puzzle. A signal indicating the existing a neutral strange nucleus, ${}^{3}_{\Lambda}n$ (nnΛ), has been reported, which is still under debate and it requires experimental confirmation. By solving these puzzles with more data on exotic hypernuclei toward nucleon drip-lines, one can deduce essential information on the baryon-baryon interaction under SU(3) including three-body forces Exotic hypernuclei can only be studied with heavy ions at GSI and FAIR. With these experiments, Europe will play an essential role in nuclear physics with strangeness.



Hypernuclear chart expected to be synthesized and studied at GSI and FAIR. Blue boxes indicate known hypernuclei while orange and green coloured boxes show cases to be populated with 10^4 and 10^3 reconstructed events per week, respectively.

Hypernuclei

Understanding of the nuclear force can be extended to the flavoured-SU(3) symmetry by studying hypernuclei, subatomic nuclei with bound hyperon(s). A hyperon is a baryon that includes at least one strange quark. The lightest is the Λ hyperon (usd). Hyperons in hypernuclei can be used as probes of the inside core of nuclei since the hyperon is not subject to the Pauli principle with other nucleons. Hypernuclei close to the stability line have been experimentally studied mainly with induced reactions of meson- and electron-beams. A recent hypernuclei spectroscopic study of ${}^{3}_{\Lambda}H$ is shown in box 3. These studies open a new degree of freedom related to strangeness, which could be combined with exotic nuclei. For instance few-body systems such as 2n+Λ remain to be explained by first principles. These studies, and the present conflicting data is also appealing for the development of completely new experimental techniques.

Resonances in neutron-rich nuclei

Unbound systems of extreme isospin up to pure few-neutron resonances provide novel tests of neutron-neutron interactions and constrain the isospin T = 3/2 component of three-nucleon forces, which is not probed in three-body (nucleon-deuteron) scattering. The resonance energies and widths of the unbound systems can be assessed experimentally by innovative experiments using intense radioactive beams, e.g., by invariant-mass and missing-mass spectroscopy in kinematically complete measurements. Recent pioneering experiments at RIKEN have revealed a very rich field that range from the tetraneutron resonance, to ground-state resonances beyond the neutron dripline, e.g., in the oxygen isotopes to ^{28}O, and to resonant excited states in bound nuclei. On the theoretical side, neutron-rich resonances are extremely challenging, as they require not only an understanding of nuclear forces but also a proper treatment of the continuum.

The properties of unbound systems made of neutrons only are most cleanly related to three-neutron forces. Testing and constraining three-neutron forces is in turn crucial for neutron-rich nuclei and the equation of state of neutron-rich matter, which is key for understanding and predicting properties of neutron stars. In addition, few-neutron resonances are also considered a milestone calculation in lattice QCD, enabling the direct connection of nuclear structure to lattice QCD in the future.

Electroweak reactions

Electromagnetic and weak interactions play a crucial role in nuclear physics. On the theoretical side, gauge symmetry allows the use of the same effective field theory to derive electroweak operators that are consistent with the strong interaction. As a result, the couplings in nuclear forces also determine electroweak processes. This provides important consistency tests for few-body experiments. In particular, effective field theories predict consistent one- and two-body currents, also known as meson-exchange currents. For electro-magnetic reactions, two-body currents have been derived recently and shown to provide significant contributions to electromagnetic processes in few-nucleon systems, e.g., to magnetic moments and B(M1) and B(E2) transitions.

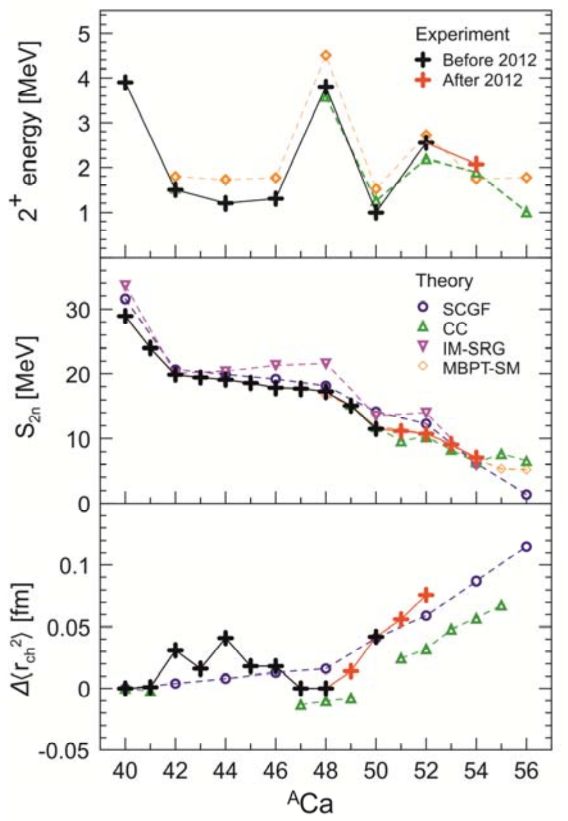
The exploration of electroweak interactions in nuclei is therefore emerging as a new area of effective field theory research. Experimentally, this opens up exciting opportunities for precision tests with electroweak reactions and transitions. This is possible with precision experiments at electron facilities involving stable nuclei, such as the S-DALINAC in Darmstadt, as well with novel experiments involving rare isotopes.

Electroweak interactions can also be exploited to carry out precision studies of nuclear structure. Electron-nucleus scattering experiments have greatly contributed to shed light on the "spectroscopic factor puzzle" (see Box 7), as well as on the long-standing and elusive issue of nucleon-nucleon correlations. More experiments will be needed to acquire additional information which, besides being highly valuable in its own right, is indispensable for the interpretation of the signals detected by accelerator-based searches of neutrino oscillations (see Report of WG5).

Box 4. Structure of Ca isotopes

Standard magic numbers, well established for stable nuclei, fade away in neutron-rich systems where new ones may appear. How do we determine their location? A shell closure cannot be established from a single experimental signature but rather has to emerge from the concurrence of several features, e.g. in energies of the lowest 2^+ excited state, two-nucleon separation energies and charge radii isotopic shifts. Hence, different experiments are typically necessary to assess the evolution of magic numbers, as testified by recent studies of neutron-rich calcium isotopes. Penning-trap measurements at TRIUMF and ISOLDE have extended our knowledge of nuclear masses up to ^{54}Ca (central panel) and pointed to the appearance of a new magic number at *N*=32. More recently, charge radii obtained via laser spectroscopy at ISOLDE (lower panel) weakened this conclusion. In parallel, the measurement of the lowest 2^+ excited state in ^{54}Ca at RIKEN (upper panel) has opened the same debate on *N*=34.

Ab initio calculations (coloured curves) have started to access medium-mass isotopic chains systematically. Comparisons between these calculations and current and future experiments in the region, e.g. up to ^{56}Ca, will help unveil how such magic numbers emerge from underlying complex nucleon dynamics.



How does the shell structure evolve across the nuclear landscape?

The shell model describes the structure of nuclei assuming the nearly independent motion of a few (so-called valence) nucleons in a mean potential generated by all other nucleons (the core). In this framework a few nuclei are interpreted as closed-shell nuclei with magic numbers of nucleons. Their sequence, well known for stable nuclei, is a fingerprint of the properties of the nuclear force. However, it is not universal across the nuclear landscape and magic numbers evolve as a function of the neutron-to-proton ratio. Different facets of nuclear forces have been revealed to play a role in the nuclear structure evolution across the nuclear landscape. Despite continuous efforts, the picture of this evolution is far from being established, both experimentally and theoretically.

Exploration towards the drip lines

Basic observables such as the energies of the first excited state, masses and beta-decay half-lives are used to explore nuclear structure in new regions of the nuclear landscape using radioactive beams with intensities down to typically few particles per second. This information is obtained by combining different techniques at ISOL and fragmentation facilities, as illustrated for the case of the Calcium isotopic chain along which new subshell closures at N=32,34 are under debate (see Box 4). The exploration of new regions of the nuclear landscape has been a world-leading program in Europe and will continue with a revitalised competitiveness in the coming decades after the completion of ongoing RIB facility projects. In particular, the regions of possible closed-(sub) shell nuclei ^{48}S, ^{60}Ca and ^{100}Sn should be investigated, using the unique facilities that will exist in Europe. The use of decay and mass spectrometry at FAIR will enable the very neutron-rich nuclei with atomic number larger than 60 to be studied, opening an entire unexplored region of the nuclear landscape, beyond and above ^{132}Sn and ^{208}Pb. The measurement of the first accessible observables (e.g. 2^+ energy, lifetime) should be complemented by more detailed investigations requiring intense low-energy beams.

In recent years, several physics programs using European detectors have been initiated at the Radioactive Isotope Beam Factory in Japan where currently the most neutron-rich nuclei are accessible today. These fruitful international collaborations lead to worldwide unique physics results such as the beta-decay and spectroscopy of *r*-process nuclei, the in-beam gamma spectroscopy of key neutron-rich nuclei such as the doubly magic ^{78}Ni and the spectroscopy of the most exotic nuclei beyond the limits of nuclear binding. The use of the spin-orientation obtained in two-step projectile fragmentation allowed nuclear moment studies of microsecond isomeric states in exotic nuclei very far from stability. These activities should continue in the coming years.

Comprehensive spectroscopy

A detailed understanding of nuclear structure demands the combination of several measurements, which often require beam intensities of 10^4 particles per second or more. Particle spectroscopy of bound and unbound states from nucleon transfer reactions offer information on the quantum numbers of the populated states and their nature in terms of neutron or proton excitations. Transition probabilities from lifetime measurements or Coulomb excitation, as well as electric and magnetic moments, add crucial information on the wave functions of individual states.

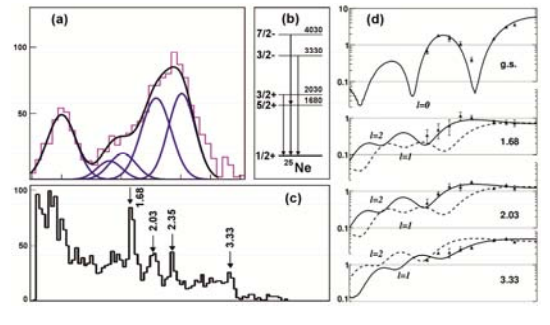


Figure 4. Particle and gamma spectroscopy of ^{25}Ne from the one-neutron transfer ^{24}Ne*(d,p)*^{25}Ne at 10.6 MeV/nucleon at GANIL/SPIRAL1. (a) Excitation energy (counts / 190 keV) fitted with (b) observed levels in ^{25}Ne defined by (c) gamma-ray energy (counts / 40 keV), resulting in (d) differential cross sections (mb/sr *vs* laboratory angle).

Low-energy nucleon transfer reactions enable in principle a quantitative study of single-particle energy migration as well as the investigation of intruder states and core-excited states as a function of isospin. The medium and heavy mass regions should be uniquely accessed at new generation ISOL facilities producing intense radioactive ion beams from the fission of ^{238}U at rates larger than 10^{12} fissions per second, and reaccelerated to optimum energies of about 10 MeV/nucleon. Such spectroscopic studies would require an efficient combination of high-granularity particle detection with light-particle identification capabilities and high-resolution gamma spectrometers, as illustrated in the proof-of-principle case shown in Figure 4. As key perspectives, the evolution of the hole and single-particle states along the tin isotopes will be studied in detail near and beyond the doubly closed-shell nucleus ^{132}Sn, while first detailed spectroscopic data should be collected in the region of the doubly magic nucleus ^{78}Ni.

Laser spectroscopy techniques are planned to be used for nuclear moment studies in these regions, e.g. at ISOLDE and SPIRAL2/DESIR while techniques allowing spin/parity determination of both ground and excited states are presently being developed at ALTO. Nuclear moments, spins and charge radii of ground and excited nuclear states are indeed among the key experimental observables providing information on the composition and the purity of the nuclear wave function. Charge radii give information on the proton distribution in the nuclei and, indirectly, insight to the neutron distribution when measured along isotopic chains. Electric quadrupole moments are the closest experimental approach to the shape of a nuclear state. Although the magnetic dipole moments are considered as fingerprints of the single-particle properties of the nuclei they can as well provide information on the interplay between single-particle and collective degrees of freedom especially for presumed-collective states as in even-even nuclei.

Depending on the location in the nuclear chart, strong correlations redistributing protons and neutrons across closed shells may result in lowering strongly “unnatural” configurations, in some cases even inverting the regular and the (often deformed) intruder configuration. This can give rise to unexpectedly low-lying states, which can lead to configuration and shape coexisting structures.

Important cases to study will be the region of neutron rich iron and chromium isotopes towards ^{60}Ca, where a so-called Island of Inversion has been evidenced but not completely characterised, neutron-rich nickel isotopes beyond N=50 and tin isotopes beyond N=82.

The structure of nuclei with N=Z is expected to exhibit unique features due to the reinforced coherent contribution of protons and neutrons at the Fermi energy. In particular, the role of neutron-proton T=0 pairing in the region of ^{100}Sn is to be understood. Properties of mirror systems will contribute further to the study of isospin symmetry. SPIRAL2/S3 would be one of the key facilities for investigating proton-neutron interactions along the N=Z line both for ground and excited states. In addition to γ-ray spectroscopy studies (including moments measurements and laser spectroscopy), “deuteron” transfer cross sections should open new insight in the study of neutron-proton Cooper pairs.

Up to now, almost all transfer transition matrix elements have been obtained from the projectile ground state. The development of new experimental techniques to measure pickup or stripping from short lived to very short lived states, from µs to ps, should provide a new dimension to the study of nuclear structure with high intensity radioactive beams and with isomeric beams.

Recent developments of nuclear moment studies of excited states with picosecond lifetimes, populated in Coulomb excitation, can provide high-accuracy results using well defined charge states (H-like or alkali-like). This approach could provide indispensable information on the interplay between single-particle and collective properties of light exotic nuclei.

Single- and few-nucleon transfer reactions as a mean for spin-orientation are presently being investigated and might provide a way for nuclear moment studies of isomeric states with post-accelerated ISOL beams.

The development of a consistent formalism including the treatment of the reaction mechanism and the nuclear structure from the same Hamiltonian with controlled uncertainties is a long term objective for medium-mass nuclei which should be pursued vigorously since it may lead to new avenues to an in depth understanding of the nuclear many-body problem. Improving our description of the direct reaction mechanisms will require their systematic study as a function of incident energy from a few to hundreds of MeV/nucleon.

Heavy and superheavy elements

The stability and existence of superheavy elements derive from the shell correction energy. Understanding the structure and stability of heavy elements therefore requires the study of the underlying shell structure. The question of the next magic numbers beyond Z=82 for protons and N=126 for neutrons, namely the location and extension of the fabled “Island of Stability” of nuclei with possibly very long half-lives is still open. The predicted shell-correction energy (which can be linked to the level density and degeneracy of the single-particle states at these particle numbers) varies smoothly over a wide range of nucleon number but depends on the theoretical approach used. It has been shown that the stability of heavy nuclei is also influenced by *deformed* shell closures, particularly at Z=100, 108 and N=152, 162.

The vast majority of level assignments are derived from α or β-decay spectroscopy, sometimes combined with coincident γ-ray or conversion-electron data. A few reference points around Cm-Cf were established by transfer reaction data. In the coming years, focus should be given to direct mass and nuclear spin measurements, which are extremely rare in the heaviest elements. Optical methods, previously restricted to macroscopic samples, are advancing to access nuclei produced on-line. Current spin assignments can thus be confirmed, providing the required anchor points for decay spectroscopic data. These studies demand the highest-intensity stable beams, as the nuclei of interest cannot be produced in any other way.

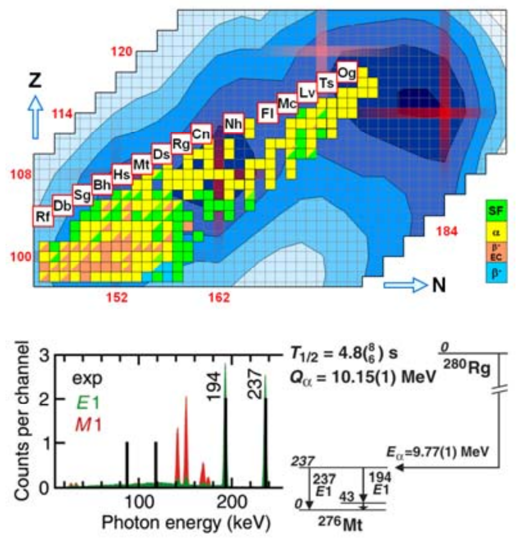


Figure 5 (top) The chart of nuclides in the region of the heaviest elements. The blue contours are calculated shell correction energies in MeV according to a macroscopic-microscopic model. The "island of stability" is located near Z=114 and N=184, indicated in red. The magic numbers Z=120 / N=172 as they alternatively follow from relativistic mean field model calculations are also indicated, along with the deformed shell closures at N=152,162 and Z=100,108. Experimentally observed nuclei are indicated as coloured boxes. (Bottom left): Experimental photon spectrum (black) observed in coincidence with α particles assigned to ^{280}Rg in the study of element 115 decay chains from the ^{48}Ca+^{243}Am reaction measured at GSI; simulated spectra for the level scheme are shown with the assumed E1 (M1) transitions in green (red). (Bottom right) Proposed level scheme, based on the combined data from experiment and simulations.

Knowledge on high-spin and isomeric states from in-beam studies complements information from decay experiments and is obtained by coupling large arrays of germanium detectors to efficient recoil separators. Technical advances have pushed the spectroscopic limit to Z=104, facilitating in-beam studies at the 10 nb level. In-beam studies yield information on the moments of inertia (and indirectly the pairing interaction), alignment effects, deformation and stability as a function of excitation energy and spin. Future studies require further development in γ ray and conversion-electron spectroscopy, in conjunction with improved and new recoil separators (e.g. S3, MARA) designed for higher efficiencies and greater background suppression to push the spectroscopic limit even further.

Detailed spectroscopic studies can constrain nuclear structure theory, but only indirectly shed light on the high-Z limit of the nuclear chart (Figure 5). The heaviest element currently known has Z=118. Thus to directly explore the limits of nuclear stability, a priority in the coming years will be production of new elements, firstly those with Z=119 and 120. Such experiments should be guided by refined nuclear reaction and structure theory, and represent a main driving force for the development of stable beams with the highest possible intensities. The possibility to directly determine Z of the heaviest known nuclei was demonstrated recently in pioneering studies of the element 115 decay chains with the TASISpec setup at GSI Darmstadt and is of high priority, as is that for A determination, for which complementary instrumentation is being built.

Indirect evidence is emerging on the importance of electron capture decay in the heaviest elements, a decay mode that cannot currently be directly detected. Promising results have also been obtained by the analysis of reaction time distributions, pointing towards to production of Z=120,124 elements.

Novel techniques such as calorimeter-based detectors (already established in other fields) should thus be developed. Chemical methods can serve as Z-separators providing ideally clean samples for further studies. The coupling of chemistry apparatus to recoil separators has allowed Fl (Z=114) to be reached. Faster techniques for studying heavier elements are currently being developed. Chemical studies also probe the influence of relativistic effects caused by the high Z. The volatility and reactivity of single atoms and molecules can be studied. Novel approaches will also allow measuring the stability of chemical compounds, broadening the range of experimentally accessible observables. Technical advances such as optical methods, yield information on atomic level schemes or the first ionisation potential of elements produced at higher rates.

How complex are nuclear excitations?

Coupling between nucleons and core-excitations

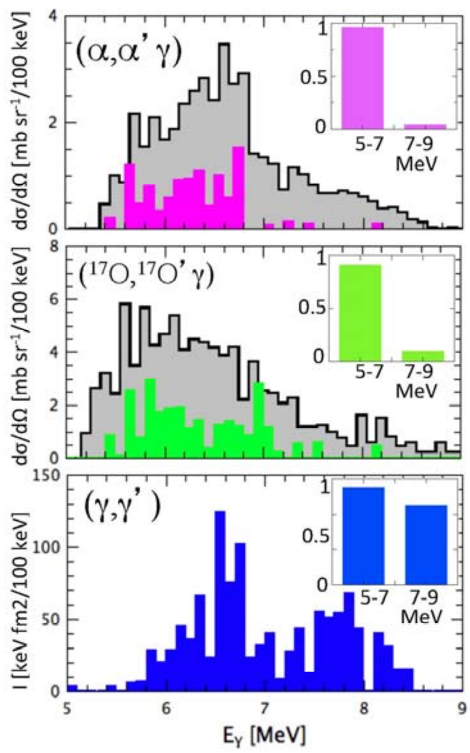
The interplay between single particle excitations and collective responses of the nucleus generates a multifaceted scenario of nuclear excitations, which can be studied in their simplest form in systems made of one valence particle and a doubly magic core. Here, long range correlations, such as couplings between particle and excitations of the core (phonons in particular) are major sources of partial occupancies of nucleonic orbitals (as evidenced by knock out and transfer reactions), they are doorways to the damping of resonance excitations and were also found to impact the Gamow Teller strength function in the β-decay of closed-shell systems. ^{49}Ca and ^{133}Sb are archetypal of these phenomena: γ-spectroscopy studies at LNL and ILL have shown that their valence neutron and proton couple to both collective and non-collective excitations of the ^{48}Ca and ^{132}Sn cores, resulting in fast changes of the wave function composition with spin. Coulomb excitation and transfer studies of odd-Cu/Co isotopes (one proton from the Ni core) performed at ISOLDE, LNL etc., across N=40, have also shown how the robustness of semi-magic shell closure, moving towards exotic regions, can be monitored through studying the properties of particle-core coupled states, in strong complementarity with spectroscopy studies of single particle states. These isotopes are a natural forefront for *ab-initio* nuclear structure theory that aims at investigating the spectral function for nucleon attachment and removal in large semi-magic isotopic chains. Data around doubly magic (^{132}Sn, ^{78}Ni, ^{100}Sn) and semi-magic shell closure (Ca, Ni, Sn) will therefore be pivotal to further improve our knowledge of nuclear interactions.

From a broader perspective, the emergence of simple and repetitive patterns in the excitation energy and gamma-decay spectra along isotopic chains, e.g., in terms of competition between magnetic and electric transitions, can be used to trace the evolution of the system in the energy-spin-isospin phase space. By profiting of recent progress in isotopic identification achieved in GANIL, both prompt and delayed gamma spectroscopy becomes possible for more than hundreds neutron-rich nuclei from a single fissioning system. AGATA and EXOGAM, as well as new setups under development at the intense neutron-beam facility at ILL, will be the workhorses of this field.

Box 5. Pygmy Resonances

In neutron-rich systems, the neutron excess is expected to form a skin, often assumed to oscillate outside the proton-neutron core: this results in a concentration of E1 strength in the region around the particle binding energy (< 10 MeV) - the Pygmy Dipole Resonance. Experiments are ongoing for few exotic nuclei above separation-energy threshold, using advanced and complex setups at fragmentation facilities, while stable systems, below threshold, have been largely investigated by different probes – from photons, high energy protons and alphas and heavy ions at intermediate energies. A quite complex nature of pygmy states has been evidenced, as in the case of ^{124}Sn where isoscalar and isovector states seem to co-exist in the same energy region, and the character of these excitations appears to be hybrid, with mixture of compressional or non-collective character.

New experiments are envisaged to better clarify the features of the low-lying dipole strength with neutron excess and the existence of pygmy states of other multipolarities, E2 in particular. At ISOL facilities, inelastic scattering at 10-15 MeV/nucleon in inverse kinematics will shed light on the nature of the pygmy resonance below particle threshold, while exclusive measurements based on the detection of high resolution γ rays and particle decay at intense gamma-beam facilities, such as ELI-NP, will pin down the fine structure of the entire resonance response in stable systems, shedding light on damping mechanisms.



γ–decay spectra from the pygmy resonance in ^{124}Sn, as measured with α scattering at 34 MeV/A (top, KVI data), heavy ion at 20 MeV/nucleon (middle, AGATA at LNL) and γ scattering (bottom, Darmstadt data). Coloured histograms give the strength resolved in individual transitions, with energy-integrated relative intensities (insets).

Giant Resonances

Giant Resonances are an extreme manifestation of collective excitations, involving a large fraction of constituent nucleons. They provide information on bulk properties of nuclei and their measurement in exotic systems is extremely challenging and limited so far to a handful of cases. The full isoscalar and isovector responses (protons vibrating in phase/out of phase with neutrons) have started to be investigated with innovative techniques, like the MAYA active target setup at GANIL, and the R^3B-LAND setup at GSI. This will allow a systematic study of key quantities, like compressibility and its impact on the nuclear equation of state of neutron-rich matter (see section on the Nuclear Equation of State). Owing to their complex nature and their influence on reaction rates in the astrophysical r-process, collective excitation modes are under intense scrutiny in a number of stable and exotic systems, by various experimental techniques.

The problem of collectivity in spin, spin-isospin modes is also very crucial. The quenching of M1 and Gamow Teller decays is of paramount importance in astrophysics, β-decay and double-β decay studies, and information over wide range of masses and deformations is expected in coming years. Low-energy isovector excitations with mixed proton-neutron symmetry will also be extensively investigated in exotic systems, where they are very sensitive to the effective restoring forces between protons and neutrons in the valence shell. In stable systems, these features will be ideally investigated at ELI-NP, together with a variety of elementary collective excitations: quadrupole shape vibrations, double scissors mode, rotational states built on the scissors mode, the M2 twist mode, spherical/deformed octupole vibrations, as well as hexadecupole vibrations and Pygmy (see Box 5).

What shape can nuclei take?

The shape is one of the most intriguing properties of the nucleus. Spherical shapes are most natural in the vicinity of double shell closures. In the regions lying away from doubly magic nuclei different nuclear shapes, with dominance of quadrupole symmetric forms, are competing and may coexist in the same nucleus at low excitation energy. In even-even systems, fingerprints of shape coexistence are low-lying 0^+ excited states associated with deformations different from the ground state. A systematic search for such states from two-nucleon transfer and/or electron conversion is particularly relevant in regions where configuration coexistence at low-energy is expected or partially evidenced.

Spectacular progress has been made in studying shape coexistence in unstable Si/Mg, Kr/Rb/Sr/Zr, Po/Pb/Hg and Rn/Ra isotopes. Various experimental probes, e.g., γ-ray and conversion-electron spectroscopy, Coulomb excitation, lifetime measurements and laser spectroscopy, have been used with both stable and radioactive ion beams. Notable examples are ^{32}Mg, $^{72\text{-}76}$Kr, $^{96\text{-}98}$Sr and ^{182}Hg, studied at ISOLDE and SPIRAL1. This encourages further detailed studies of shape coexistence far from the stability, aiming at a mapping of this phenomenon along the nuclear chart.

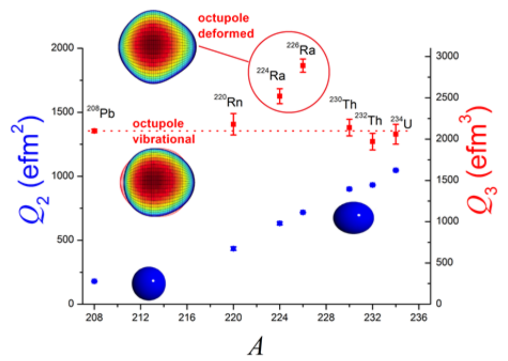


Figure 6. The evolution of shapes in the A > 220 nuclei measured at ISOLDE is well described by quadrupole and octupole moments. While ^{220}Rn shows an octupole vibrational character, similar to ^{208}Pb and heavier Th and U systems, ^{224,226}Ra give evidence for static octupole deformation in the intrinsic frame

A peculiar manifestation of the coexistence of shapes are shape isomers, arising from the existence of additional deep local minima in the nuclear potential energy, calculated as a function of shape parameters. The most known manifestation of shape isomers are fission isomers in actinides, however, this phenomenon is predicted in many regions of the nuclear chart, based on microscopic-macroscopic approaches. For example in the neutron rich Ni isotopes, these predictions are strongly supported by state of the art shell model calculations, encouraging future investigation at radioactive beams facilities.

New (dynamical) symmetries are also being searched for in nuclear matter. The description of higher-order deformation of nuclei, resulting from octupole, or hexadecapole symmetries, remains an experimental challenge. Recently, major progress has been obtained in the investigations of octupole correlations in Rn and Ra chains (see Figure 6): Coulomb excitation experiments at ISOLDE have given firm evidence of static octupole deformation in

[224,226]Ra. This helps to constrain candidates for experimental studies of the atomic electric-dipole moment (EDM) that would indicate CP violation and, in consequence, the existence of physics beyond the standard model. Octupole correlations still remain to be understood in the Xe, Te and Ba isotopes both close to ^{100}Sn and beyond N=82, where theory predicts extended region of deformation. From a broader perspective, the understanding of the octupole degree of freedom in nuclear matter is of general interest as it can also be used for the description of clusters in nuclei, evaporation of heavy fragments and asymmetric fission processes.

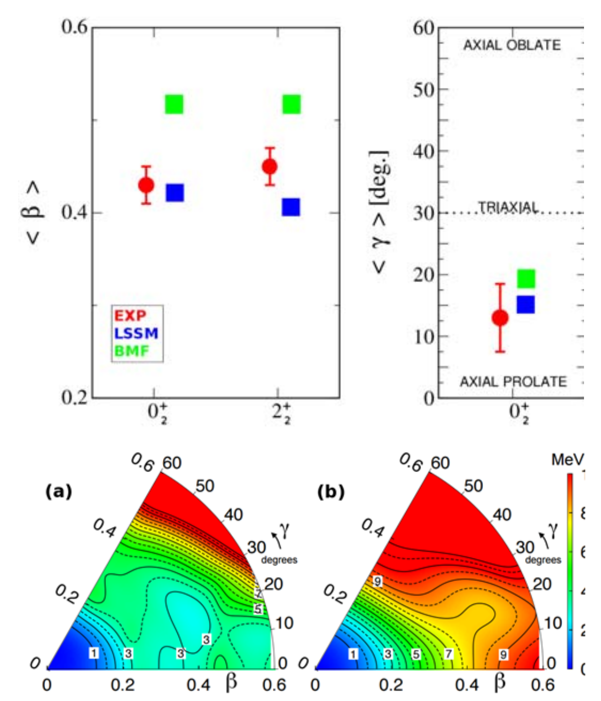


Figure 7. Coulomb excitation of ^{42}Ca was used to measure for the first time static quadrupole moments of the superdeformed states and to extract the quadrupole shape parameters (β,γ) (top figure). The experimental results, providing firm evidence for coexistence of spherical and (slightly triaxial) superdeformed structures in ^{42}Ca, are supported by the state-of-art shell model (panel a; blue squares) and beyond mean field (panel b; green squares) calculations. They bring decisive information about shape evolution close to doubly-magic nuclei. The potential of Coulomb excitation as a tool to study superdeformation has been demonstrated for the first time and opens up new vistas for future studies at next generation RIB facilities.

Superdeformed (SD) nuclear shapes are a major facet of nuclear structure. SD states become yrast at high spin, but their decay to normal deformation proceeds through highly excited states in the quasi-continuum. This transition from an ordered to a chaotic and back to an ordered regime remains to be fully understood. In general, the properties of the warm rotation, both in normal and SD systems, need to be further detailed, and can be used as a tool to pin down the onset of chaoticity in terms of fragmentation of rotational γ-ray strength with increasing excitation energy. In light nuclei, SD states can be interpreted as multiparticle-multihole excitations across spherical shell gaps. The very first AGATA experiment at LNL provided firm experimental evidence for (triaxial) superdeformation in ^{42}Ca, see Figure 7.

Triaxial nuclei also remain a challenge to understand particularly in the rare earth region where rotational structures are observed to ultra-high spin (I>60ħ). A consistent picture between experiment and theory of the shape, spin and excitation energy of these bands required further experiments with the high efficiency gamma spectrometers (e.g. AGATA).

Even more elongated, so-called hyperdeformed (HD) shapes are predicted in neutron-rich nuclei, but direct evidence still remains to be found in reactions populating nuclei at the highest possible spin. Nuclei are furthermore expected to undergo a Jacobi shape transition under such extreme conditions. Search for new regions of SD and HD in moderately neutron-rich isotopes will have to make use of fusion-evaporation reactions induced by intense neutron-rich radioactive beams which will be provided by the ISOL facilities in the future. Advanced implementation of highly efficient γ-ray arrays, such as AGATA, that can collect high multiplicity data, used often with specific ancillary detectors and separators, will be key instruments for these investigations.

How do neutron halos and skins evolve across the nuclear chart?

Halo nuclei exhibit, in some of their states, a wave function which extends well beyond the core of the nucleus. They represent a unique quantum phenomenon in nuclear systems. A rule of thumb defines a halo when the nucleon probability in the region forbidden by classical mechanics exceeds 50%. P-wave neutron halos have recently been claimed to appear in very neutron-rich Ne and Mg isotopes although this is not yet firmly proven and should be further explored through exclusive measurements. Halos in short-lived excited states still have to be found. For medium mass nuclei, the appearance of a halo is controversial and today no data supports the existence of the phenomenon. Neutron skins, corresponding to a neutron density distribution larger than the proton one at the surface of the nucleus, have triggered numerous studies and efforts. In stable nuclei they have been investigated using various probes and skins thicker than 0.5 fm were observed in light neutron-rich nuclei. Thick neutron skins and halos have not yet been detected in medium-mass nuclei, since the heaviest halo nucleus claimed so far is ^{31}Ne. A systematic study of neutron skins would open the way to map out its evolution and the occurrence of low-density neutron matter as a function of proton number.

To reach the most neutron rich nuclei in which halos and thick neutron skins could be observed, probes sensitive to low production rates should be further developed. A systematic study of the evolution of the neutron skin thickness along isotopic chains (for example the $^{126-138}$Sn isotopes) would be possible via indirect neutron and proton-removal cross sections at intermediate energies. This indirect method has the advantage of allowing a first estimate of the neutron skin thickness down to low intensities of few 10 particles per second, although it would require benchmarks to quantify the reaction-model uncertainties. The use of low-energy antiprotons produced at CERN to populate antiprotonic atoms with unstable nuclei is being considered and should be a unique way to produce very neutron-rich exotic nuclei. This will give access to undiscovered regions of the nuclear chart where it will be possible to examine the existence of halos and neutron skins by studying the tail content of their nuclear densities.

An ultimate characterisation of new halos and thick neutron skins throughout the nuclear chart would require the ability to measure accurately the density distributions of both the protons and the neutrons. Our basic knowledge on the nuclear charge distributions was established on the stable nuclei using electron elastic scattering. Electrons of 400-800 MeV provide the ideal spatial resolution scale of about 0.5 fm to study charge distributions.

Observables **Deduced quantity**	**Reactions**	**I [s^{-1}]** **L [cm^{-2}s^{-1}]**
r.m.s. matter radii	*(p,p) at small q*	I =10^4 (light)
Matter density with 3 parameters ρ_m	*(p,p) 2nd min.*	I = 10^{5-6} (medium-heavy)
r.m.s. charge radii	*(e,e) at small q*	L: 10^{24} (light)
Charge density with 2 parameters ρ_{ch}	*(e,e) first min.*	10^{24-28} (light-heavy)
Charge density with 3 parameters ρ_{ch}	*(e,e) 2nd min.*	10^{26-29} (medium-heavy)
Neutron skin from ρ_m and ρ_{ch}	**(p,p) and (e,e)**	***(p,p)*** **: I=10^6/s** **e: L=10^{28} 10^{29}**

Table 1. Accessible information from proton and electron elastic scattering off nuclei for fixed target kinematics for typical intensities I and luminosities L, respectively.

Robust insight into the nuclear matter distribution can be obtained by proton elastic scattering. The nuclear interaction is sensitive to both the neutron and proton density distributions. By use of density and energy dependent microscopic potentials to calculate the *(p,p)* cross sections, matter density distributions can be extracted by comparison between calculations and data. Provided the proton distributions are known from *(e,e)*, the neutron densities can be inferred. Sensitivities up to three-parameter proton and neutron distributions, i.e. beyond the radius and diffusiveness, are realistic with unstable ions. A complete picture of nucleon distributions inside a nucleus can be achieved by combining *(e,e)* and *(p,p)* scattering in different momentum transfer regimes.

Ion-electron colliders represent a crucial innovative perspective in nuclear physics to be pushed forward in the coming decade. They would require the development of intense electron machines to be installed at facilities where a large variety of radioactive ions can be produced. As illustrated in Table 1, the profile of the proton density distributions (3-parameter Fermi) would require luminosities of 10^{28} cm^{-2}s^{-1}. Then, to infer the neutron-skin density from the matter density, proton elastic scattering requires beam intensities of 10^6 particles per second. As a long term goal, such facilities would allow *(e,e'X)* inelastic scattering with selectivity to the transferred angular momentum, *(e,e'f)* electro-fission with detection of both fragments, and ultimately *(e,e'p)* quasi-free scattering studies with radioactive ions.

How do nucleon correlations appear in dilute neutron matter?

It is well known that correlations play a major role in the nucleus, although their precise origin and evolution with binding energy and isospin still remain to be explored.

Nuclear pairing is the most obvious manifestation where the spatial and momentum correlations between pairs of nucleons yields enhanced binding energy and tip the balance between a nucleus being bound or not, fissile or fissionable, with a corresponding imprint on the nuclear structure. The existence of different types of nucleon pairing, T=0 or T=1, and the spin-dependence of the nuclear force provides a rich spectrum of correlated structures with a sensitivity to the spin alignment of the nucleons with a fundamental link to the underlying exchange processes. It is speculated, but not yet proven, that a condensate of n-p T=0 pairs may develop in heavy self-conjugate nuclei close to ^{100}Sn.

At the neutron drip-line the effects of neutron-neutron correlations are manifest in the Borromean nature of ^{6}He, ^{8}He, ^{11}Li and ^{14}Be. The origin of di-neutron spatial correlations and their persistence in heavier nuclei remain challenging to observe. Similarly, on the proton-rich side ^{10}C may be thought of as four-fold-Borromean system composed of ^{4}He+^{4}He+p+p. In this particular instance the very high binding energy of the α particle is playing a driving role.

When the decay threshold of cluster, e.g. alpha, is reached, the nucleus has the opportunity to transform its internal energy into the binding energy of the cluster and the nuclear structure may reach a form, which asymptotically approximates a free cluster and core. Such nuclear states are embedded in the continuum, and as such coupling to the continuum is likely to have a significant influence in the appearance of the cluster states whose nature is imprinted in the continuum (see Figure 8). Cluster correlations are also an important feature in heavier nuclei. Recent generalised relativistic functional calculations predict a significant alpha cluster at the surface of heavy nuclei with a more pronounced effect in neutron-rich nuclei. A systematic search from alpha quasi-free scattering or transfer along isotopic chains should be pursued in the coming years. The surface α clustering affects the correlation of the neutron skin thickness of heavy nuclei with the density dependence of the symmetry energy.

From the experimental perspective, there are still significant gaps in our knowledge. Often the precision for testing new theories is not met. For example, the precise characterisation of phase-shifts in low energy and resonant scattering, electromagnetic transitions or in weak decay properties. This is particularly true for continuum properties either of excited states of bound nuclei or for systems beyond the drip-lines. A coordinated experimental program to measure moments, transition strengths, (decay) widths, and determine the complete spectroscopy of nuclear systems is essential. In the particular case of electromagnetic decays from unbound states with branching of 10^{-2}-10^{-4} compared with the dominant particle decay channel, large gamma spectrometers are necessary to reach the desired sensitivity. Selective reaction mechanisms, using both radioactive and high intensity stable beams, must be employed to enhance the formation and sensitivity to cluster structures in nuclei.

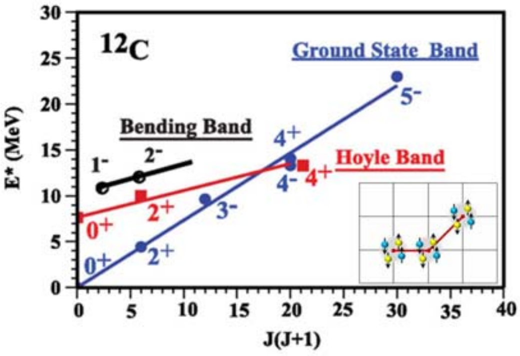


Figure 8. Spectroscopy of ^{12}C. Recent measurements of high excited 2^+ and 4^+ states associated with rotational states built on the Hoyle intrinsic state configuration are consistent with a three alpha structure, in agreement with state-of the-art *ab initio* lattice calculations (inset).

For the study of clusters, key nuclei might include: ^{12}C (particularly the spectroscopy above the alpha-decay threshold, including the Hoyle-state), molecular nuclei such as ^{9}Be and ^{9}B (where it is believed that neutrons and protons may be exchanged between cluster cores), drip-line nuclei from the helium to oxygen isotopes, and alpha-particle states above decay thresholds.

When reaching the limits of existence the coupling between bound nuclear states and the continuum may also lead to new decay modes. At the proton drip line, one- and two-proton emissions have been discovered that enable the validity of nuclear models to be tested beyond the drip line. The dynamics of the emitted protons provide an insight into the pairing and the tunnelling in nuclear matter. For this purpose, the angular correlations between the two protons have to be measured precisely. Up to now, such studies have been done partially in ^{45}Fe and the combination of high intensity secondary beams at the drip line provided by new generation fragmentation facilities. One difficulty with two-proton radioactivity lies in the fact that the correlations between the emitted protons are somehow washed out by the Coulomb interaction. It would be therefore interesting from a theoretical point of view to observe similar two-neutron decays from ground states or from isomeric states close to the neutron drip line.

How does nuclear structure change with temperature?

Investigating properties of nuclear systems as a function of intrinsic excitation energy (temperature) is crucial for studying nuclear structure beyond a pure mean field description. From the ground state up to the particle separation energy, the weakening of pair correlations of protons and neutrons (Cooper pairs) boosts the level density exponentially. Around the neutron binding energy, an almost fully chaotic behaviour leaves a fingerprint on the nearest-neighbour spacings of neutron resonances. Neutron-resonance and capture data, from e.g. the n-ToF group at CERN, reveal very important information in this energy regime.

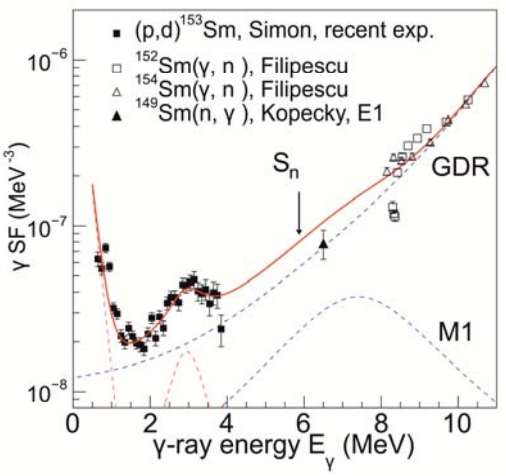


Figure 9. Low-lying γSF structures in Sm isotopes: the strength at < 1 MeV and the scissors resonance at 2-4 MeV, may change the (n,γ) reaction rates by 2-3 orders of magnitude for very neutron-rich Sm isotopes relevant to *r*-process nucleosynthesis.

The γ-ray strength function (γSF), see Figure 9, together with the nuclear level density (NLD), are crucial for several fields of science and applications, being related to fundamental properties of the structures and dynamics of heated nuclear quantum systems. At low spins, the γ-decay channel plays a pivotal role in estimating reaction rates for the nucleosynthesis in extreme astrophysical environments. This concerns in particular (n, γ) reaction rates (see Figure 9), as well as our understanding of neutron capture in fusion processes for energy production, and for the design and modelling of next-generation nuclear power plants.

By moving towards more and more exotic systems, the continuum domain takes over at lower excitation energies due to a rapidly decreasing nucleonic threshold, and, for super-heavy nuclei, a lowering of the fission barrier. The γ-decay strengths will have a stronger coupling to the particle decay channel and to the occurrence of chaos that may spread the particle widths over many states. Fundamental questions concerning the quasi-continuum remain, such as the transition to chaos and the validity of the Brink-Axel hypothesis stating that the γSF only depends on the γ energy. Experimental and theoretical effort is required to attack these challenges in the next decade.

Finally, the temperature degree of freedom also offers the possibility of investigating the restoration of one of the most important symmetries in the atomic nucleus, namely isospin, which is broken - at the percent level - by the Coulomb interaction. At high temperature, isospin symmetry is partially restored, due to the short decay time of the compound system. This can be probed, in a unique way, by the γ-decay properties of the Giant Dipole Resonance in the hot compound nucleus. The isospin impurity at zero temperature can be also deduced, as recently shown in the heavy N=Z nucleus ^{80}Zr. Heavier systems, close to ^{100}Sn, will be within reach with intense beams which, combined with the use of powerful γ-ray detector arrays, offers a unique opportunity to elucidate changes in the system with intrinsic excitation energy, opening new venues in exotic nuclei.

Summary and open issues

To face the challenges of nuclear structure, correlations and dynamics, cutting-edge facilities and instrumentation are essential.

A high priority should be given to the full completion of the international radioactive ion beam facilities in Europe, NUSTAR @ FAIR and HIE-ISOLDE, SPES and SPIRAL2. Adequate funding and human resources for a timely operation of these facilities and instrumentation should be provided.

In parallel, strong support is needed for new initiatives that will pave the way for the long-term future of nuclear physics, including: (i) an enhanced integration of the ISOL facilities HIE-ISOLDE, SPES and SPIRAL2 under the EURISOL Distributed Facility (DF) initiative with the goal of a future ISOL-based European large-scale facility for nuclear science and applications, (ii) an upgrade of the EURISOL project and technical design.

We also strongly support the development of storage rings for in-ring physics with high priority both at low energy as the storage ring planned at HIE-ISOLDE and the HESR of FAIR and related NuSTAR programs which will provide unique physics opportunities in Europe.

AGATA is a unique and world-leading device for high-resolution gamma-ray spectroscopy for nuclear structure studies. A timely completion of the AGATA gamma-ray spectrometer is strongly recommended.

Smaller scale accelerator facilities in Europe play a crucial role in the joint effort of understanding nuclear structure. These need the necessary support for their development and operation to keep them keeping at the highest international level.

Reaction Dynamics

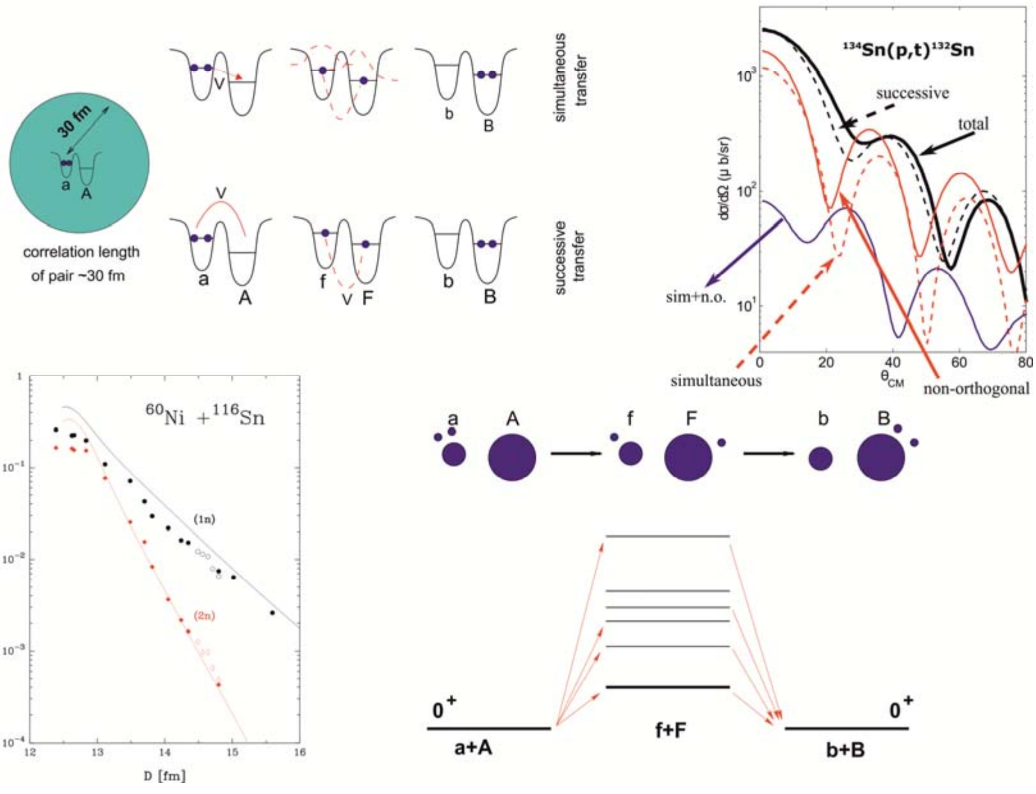
Investigation of correlations by means of transfer and knockout reactions

The pairing interaction induces particle-particle correlations that are essential in defining the properties of finite quantum many body systems in their ground and neighbouring states. These structure properties may influence in a significant way the evolution of the collision of two nuclei, i.e. the effects of pair correlations affect a variety of nuclear processes. In this sense, two-nucleon transfer constitutes the key probe in the study of pairing in nuclei, see Box 6.

Box 6: Two particle transfer reactions as a tool to study pairing correlations.
The comparison of experimental absolute cross sections with a suitable microscopic reaction theory provides insights on nucleon-nucleon correlations. Modern implementations of two-nucleon transfer formalisms have proven to be able to account for the absolute neutron pair transfer cross sections within their experimental errors. State-of the art examples are given for ^{132}Sn+p (top-right panel) and for ^{60}Ni+^{116}Sn (bottom-left panel). The scenario of the simultaneous and sequential mechanisms of the transfer of two nucleons is schematically presented in top-left panels, where inside of the pair correlation length (blue shaded area) the interaction (mean field) potentials and the non-zero overlap of the wave functions are drawn.

Many reaction paths arising from the simultaneous and sequential mechanisms have to be included, as displayed on bottom-right panel with the schematic representation of the two-neutron transfer, from the incoming to outgoing channels, through intermediate channels. The sequential contribution turns out to be dominant. Indeed, the large correlation length of the nucleon Cooper pair, ensures that pairing correlations are maintained during the transfer process, also in the case of sequential transfer.

It will be important to investigate how and to what extent these structure properties influence the evolution of the collision of two nuclei, keeping in mind the importance of the connection between reaction and structure aspects. Such studies are particularly relevant for nuclei far from the stability valley where correlations may play an important role in stabilising the system by increasing their binding energy.



The search of signatures of pairing has been mainly attempted via the measurement of two-particle transfer channels, in particular, via the extraction of enhancement coefficients, defined as the ratio of the actual cross section to the prediction of models using uncorrelated states. Such enhancement factors should provide a direct measurement of the correlation of the populated states. Admittedly, in the description of the observed cross sections, structure and reaction have to be treated simultaneously. Thus, to conclude about the effect of correlations, the absolute experimental cross sections have to be compared with the calculation of the absolute value of two-nucleon transfer cross sections. This requirement has motivated the re-examination of microscopic theories, which incorporate neutron-neutron correlations in the reaction mechanism, and their implementation in flexible codes. Despite this success, the extension of these microscopic theories to two-nucleon transfer processes involving both protons and neutrons is also needed.

From the experimental side, the decisive contribution came from the study of reactions in which a correlated pair of nucleons is added or removed from the nucleus as in the (t,p) or (p,t) reactions, for neutron transfers, or (^{3}He,p) for proton-neutron transfers, and also with high–energy knock-out reactions. More recently, pair correlations have been probed in heavy ion collisions, where transfers of different nucleon pairs can be studied simultaneously. Such studies are especially relevant for future investigations with radioactive beams and it is important that new, high quality data are collected.

Modelling fusion

Nuclear fusion involves the collision of two quantum many-body systems that coalesce to form a “hot” fused nucleus following full dissipation of their relative kinetic energy. Experimentally, the challenge is to identify the processes that trigger dissipation as the two nuclei approach one another, determine their evolution with the collision energy, and quantify their influence on fusion. Theoretically, the challenge lies in how to incorporate dissipation into models that retain the essential quantum many-body nature of the colliding nuclei.

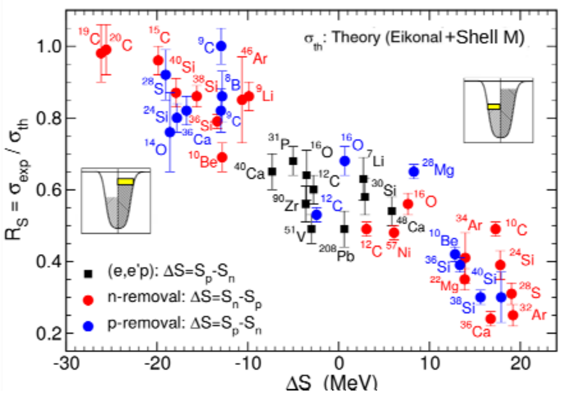
For light weakly-bound nuclei (e.g. ^{6,7}Li, ^{9}Be) recent experimental results have corroborated the suppression of the above-barrier fusion cross sections (25-40%) relative to single-channel or simple coupled-channels predictions. Although the effect has been attributed to the coupling to two-body breakup channels into ^{2}H, ^{3}H and ^{4}He clusters, recent exclusive breakup measurements indicate that the reactions causing breakup are more

Box 7: Toward the solution of the “spectroscopic factor puzzle”

One-nucleon removal cross sections are systematically overestimated by reaction calculations based on the combination of the eikonal reaction theory with standard shell-model (SM) spectroscopic factors. Further, the ratio between the experimental and theoretical cross sections (R_s) decreases monotonically as a function of the difference in separation energies $|S_p$-$S_n|$, becoming smaller and smaller as the separation energy of the removed nucleon becomes larger. This behaviour has been attributed to a reduction of the spectroscopic factors for deeply bound orbits due to several kinds of correlations not accounted for by the conventional SM.

Nucleon-removal reactions, some using fragmentation, used in these studies are inclusive with respect to the state of the residual nucleus. Consequently, the theoretical cross sections are calculated by summing the contribution to all (predicted) bound final states of the mass A-1 residue, as predicted by the SM calculations. Therefore, the observed behaviour might indicate some inadequacy of the SM calculations to correctly predict the single-particle strength leading to bound states. This interpretation is consistent with the fact that recent transfer experiments, leading to definite final states of the residual nucleus, do not show this suppression. In addition, the fact that part of the discrepancy is due to an inadequate understanding of the nucleon-removal reaction dynamics cannot be ruled out. Consequently, new developments and alternative models for these reactions (maybe avoiding the eikonal approximation) would be desirable to cross-check these results.

In parallel, quasi-free breakup experiments of the form *(p,pN)*, using inverse kinematics, have been put forward as a promising alternative to knockout reactions, since they are expected to probe deeper parts of the wave-function of the removed nucleon. The models to describe these processes, such as the DWIA method, while used extensively in the 1970s -80s with stable nuclei, are now being re-examined and upgraded by several groups.



diverse than commonly assumed. These works postulate transfer-induced breakup as a significant contributor of fusion suppression.

At sub-barrier energies, the situation seems to be less clear and continues to be a matter of debate (Figure 10). Just below the barrier, the data point toward an enhancement of the fusion cross section with respect to single-channel prediction. However, at deep sub-barrier energies, a hindrance with respect to the coupled-channels prediction has been reported and several interpretations provided, from a possible inner pocket in the ion-ion potential, to a transition from a two-body regime to a one body regime.

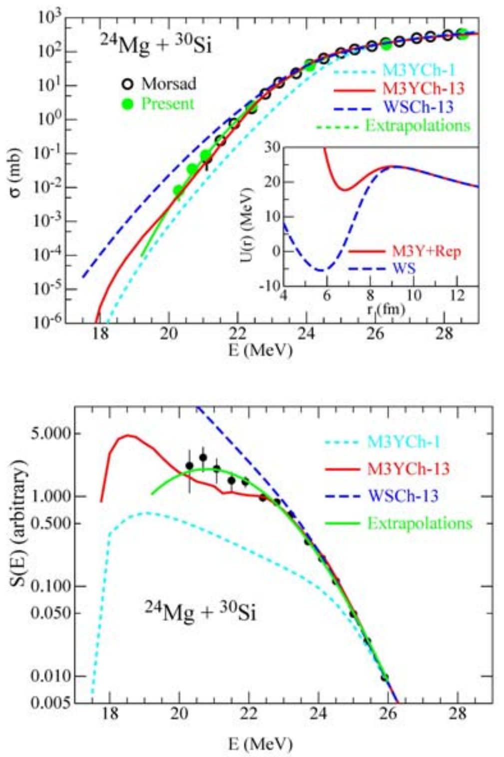


Figure 10. The phenomenon of heavy-ion fusion hindrance at deep sub-barrier energies. The excitation function (top) and the astrophysical S-factor (bottom), together with coupled-channels calculations performed with different potentials (see inset) and different number of channels. Thanks to the development of detection systems it has been possible to extend fusion excitation functions to low energies. The suppression of the fusion probability at these low energies was explained in terms of the saturation properties of nuclear matter (the inclusion of a repulsive core in the nuclear potential). Therefore such studies have a direct impact on the description of the astrophysical processes by providing more reliable recipes for extrapolation of the relevant cross sections and reaction rates into the temperature range of interest.

The behaviour of the heavy-ion fusion cross sections at extreme low energies has a direct impact on the description of the astrophysical process. In many cases, the cross-section measurements in the critical energy windows are still unattainable in the laboratory, and thus extrapolations to lower energies must be used in simulations, which will be strongly influenced by the fusion hindrance.

The recent revival of transfer reaction studies benefited from the construction of the detector arrays, reaching unprecedented efficiency and resolution (such as PRISMA, VAMOS, EXOGAM and AGATA). Their high selectivity provided a new body of valuable more exclusive data for binary reactions, with clear selection of all needed experimental observables like Z, A and energy (transfer induced fission, deep inelastic reactions...). For example, the advent of large solid angle magnetic spectrometers, and their coupling to the large gamma arrays are already demonstrating high efficiency and selectivity.

Interfacing structure with reaction observables

The extraction of physically meaningful information from reaction observables requires, in addition to an adequate modelling of the reaction dynamics, the use of realistic structure models and a proper understanding on how the structure information can be single-out from the reaction dynamics. It has become clear that the structure models used for a number of reaction calculations are often too simplistic.

In the light region of the nuclear chart, it has become apparent that the strict few-body picture, which proved to be very useful to understand the structure and reactions of weakly-bound nuclei, is sometimes inadequate and core excitations/polarisations are indeed needed for a correct description of the data. Along the same lines, recent studies on one- and two-nucleon *knockout* reactions have shown that the inclusion of microscopic overlaps obtained from ab-initio calculations, including 3-body forces, provides improved results as compared with the conventional shell-model inputs.

Accessing structures beyond the proton/neutron driplines

Many nuclear reactions produce nuclei beyond the proton or nucleon driplines: transfer, knockout, quasi-free *(p,pN)* breakup processes, fission, etc. Reaction theory can help to extract information from these processes (e.g. resonances, virtual states, E1 strengths, etc).

It has been demonstrated that with the proper selection of the colliding systems and reaction energy, the nucleon exchange can lead to the population of neutron-rich nuclei, in the region of the nuclear chart with the challenging aspects in the nuclear structure behaviour. The recent revival of transfer reaction studies benefited from the construction of the new generation detector arrays, reaching an unprecedented efficiency and selectivity. One of the promising tools for the production of the neutron-rich heavy nuclei is the use of the multinucleon transfer reactions at energies close to the Coulomb barrier. These nuclei, which are relevant for the r-process, play a critical role for predictions of the synthesis of the heaviest elements, whose origin in the universe remains one of the greatest unanswered questions of modern physics. By using heavy-ion fusion reactions the study of the nuclear structure has been extended to regions of very high angular momentum and large excitation energies. In the heavy-ion transfer reactions close to the Coulomb barrier, the transfer process maximises the transferred angular momentum to allow a good matching between the orbital angular momentum of the involved states, and this leads to the strong population of the yrast states in the final nuclei. On the other side, the excitation and transfer processes are mediated by the well-known single-particle form factors for the fermion degrees of freedom and by the collective form factors for the vibrational or rotational modes. This makes such reactions suitable for studies of the important couplings (fermion-fermion, fermion-boson).

These data should be understood within dynamical models (semiclassical as well as quantum) of heavy-ion collisions. Since all the reaction channels (quasi-elastic and deep inelastic scattering, quasi fission, fusion-fission) are substantially coupled and overlap with each other, a model should consider the evolution of the nuclear system from the configuration of two well-separated nuclei approaching each other in the entrance channel and up to formation of final fragments. One of the key but still unanswered questions here is the role of the shell effects influencing the dynamics of nucleus-nucleus collisions.

Accessing extreme deformations and rare fission modes

Photofission measurements with high-brilliance quasi-monochromatic gamma beams at ELI-NP will open the possibility for highly selective investigation of extremely deformed nuclear states in light actinides and can be used to better understand the landscape of the multiple-humped potential energy surface (PES) in these nuclei. While the appearance of a deep superdeformed minimum in the PES of the nucleus has been observed experimentally and described theoretically long time ago, the existence of a third extremely deformed hyperdeformed (HD) minimum in the PES is a long-standing problem in nuclear physics that still awaits its solution. One experimental approach to investigate extremely deformed collective and single particle nuclear states in light actinides is based on the observation of transmission resonances in the prompt fission cross section (Figure 11). By observing transmission resonances caused by resonant tunnelling through excited states in the third minimum of the potential barrier as a function of the energy allows us to identify the excitation energies of the HD states.

The capabilities of the gamma beams in terms of high spectral density and narrow bandwidth of the next-generation facility ELI-NP will allow for the identification of sub-barrier transmission resonances in the fission decay channel with integrated cross- sections down to $\Gamma\sigma \sim 0.1$ eV·b, where Γ is the resonance width.

High intensity quasi-monochromatic gamma beams at ELI-NP will be used for the first time to search for rare fission modes such as true ternary fission. Nuclear fission accompanied by light charge particle emission will be studied. As ternary particles are released close to the scission point they provide valuable information about the scission point and fission dynamics. The use of linearly polarised gamma beams has the advantage to fix the geometry of the fission process and facilitate a detailed study of it. These studies aim at unrevealing the mechanism of ternary particles emission and its connection to the deformation energy, spectroscopic factors or formation of heavier clusters.

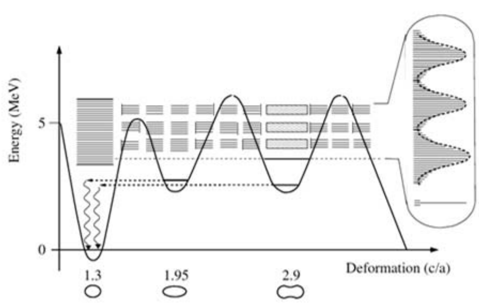


Figure 11. Schematic description of the occurrence of transmission resonances in prompt fission through a triple humped fission barrier.

Summary and open issues

The complicated scenario unveiled by recent near-barrier exclusive breakup measurements calls for a better understanding of the processes responsible for the fusion suppression, and their mutual influence. One of the challenges here is the simultaneous inclusion of the different competing channels affecting fusion (transfer, collective excitations, breakup, etc.) and their coupling with the relative motion. From the theoretical point of view this task is hindered by the fact that traditional reaction models tend to emphasise particular degrees of freedom, e.g. transfer, breakup, collective excitations, etc.

It is of timely interest to deepen our understanding of incomplete fusion, including the development of a fully quantum mechanical model for this process, which goes beyond the present classical and semiclassical models.

Improvements on the nucleus-nucleus potential used in fusion calculations would be desirable, replacing the simplified usual diabatic potential with parabolic approximation of deformation dependence.

Recent experimental findings call for a deeper understanding of the heavy-ion fusion hindrance at extreme low energies, including the development of more reliable methods for extrapolation of the relevant cross sections and reaction rates into the temperature range of interest.

Time Dependent Hartree Fock calculations, whose feasibility has benefit from the use of modern HPC, need to be systematically applied to various phenomena: transfer, deep-inelastic, fission, fusion. The incorporation of correlations beyond mean field would be a natural and advisable step forward in these studies.

A more widespread use of dynamical models (semiclassical as well as quantum-mechanical) is needed taking into account the coupling among relevant reaction channels (quasi-elastic and deep inelastic scattering, quasi fission, fusion-fission) and considering the evolution of nuclear system from the configuration of the two well-separated nuclei approaching each other in the entrance channel and up to formation of final fragments in the exit one.

It is important to improve our understanding on the interplay and relative importance of different degrees of freedom taking place in nuclear reactions, namely, collective excitations, rearrangement channels and breakup. These studies should improve our comprehension of the nuclei in the so-called island of inversion, where *weak-binding* and *deformation* coexist.

Particle correlations in different kinds of breakup processes (including knockout and quasi-free (*p,pN*) reactions) are usually assumed to contain information on the structure of the colliding nuclei. However, this structure information may be entangled with the reaction mechanism. It would be desirable to clarify the connection between the reaction dynamics and the structure information that can be actually accessed from these experimental observables (Box 7).

Due to its potential implications, it is advisable to investigate the possibility of extracting information on the neutrinoless double-beta decay matrix elements by means of double-charge exchange reactions. Since, at present, no exact microscopic reaction theory exists for these reactions, for example they treat exchange terms approximately, an upgrade of existing formalisms is required.

The Nuclear Equation of State

Introduction

The equation of state (EoS) of infinite nuclear matter describes the relation, $E(T,\rho)$, between the energy per nucleon, E, temperature, T, and nucleon density ρ. The EoS plays a key role in reaction mechanisms and in collective excitations of nuclear systems. These are generally composed of two distinct fermions, neutrons (n) and protons (p). Hence, the isospin asymmetry $\delta=(\rho_n-\rho_p)/(\rho_n+\rho_p)$ is also crucial in determining the properties of nuclear matter. Distinct phenomena are predicted to occur whether symmetric ($\delta=0$) or asymmetric ($\delta\neq0$) nuclear systems are investigated. The top panel on Figure 12 shows a schematic view of the phase diagram of nuclear matter on the temperature-isoscalar density ($\rho=\rho_n+\rho_p$) plane. The occurrence of phase transitions for systems in the spinodal instability region has been the focus of several investigations both experimentally, with heavy-ion collision studies, and theoretically by means of transport model calculations. The less explored EoS for asymmetric nuclear matter, $E(\rho,\delta)$ with $\delta\neq0$, is described as the sum of a symmetric term ($\delta=0$) and an isospin asymmetry term: $E(\rho,\delta)=E(\rho,\delta=0)+S(\rho)\times\delta^2$. The relevant effects of the so-called symmetry energy, $S(\rho)$, with its density dependence around and away from saturation density ρ_0=0.16 fm^{-3}, represent the main goal of present heavy-ion collision studies at several laboratories. The bottom panel of Figure 12 displays different theoretical predictions of the density dependence of the symmetry energy. Heavy-ion collisions at intermediate energies have provided some range of constraints on S(ρ), as indicated by the shaded green area on the figure. Since uncertainties still exist, extensive studies are performed around saturation densities, $\rho \approx \rho_0$, as well as at sub-saturation ($\rho < \rho_0$) and supra-saturation ($\rho > \rho_0$) densities.

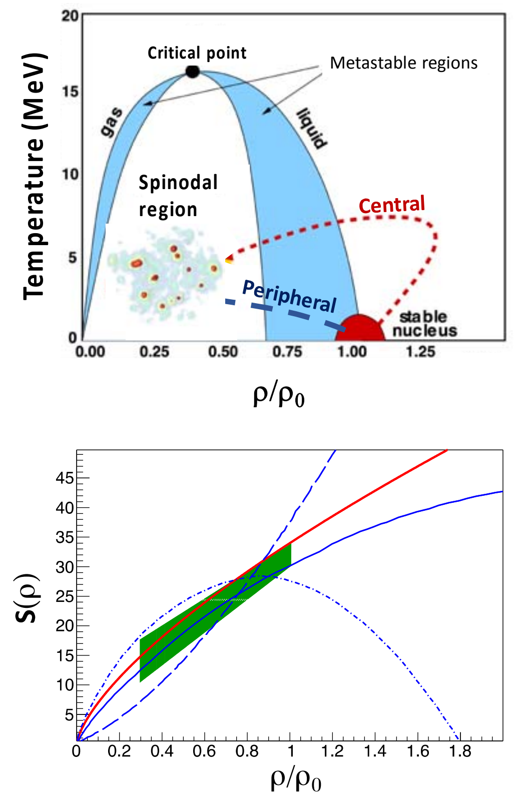


Figure 12. Top: Spinodal instability region of the nuclear EoS on the temperature-density plane. Dashed lines indicate paths followed by systems produced in heavy-ion collisions. Bottom: Schematic density dependence of the symmetry energy which could be predicted by theoretical calculations (lines) and present status of constraints provided by heavy-ion collision measurements.

As in ordinary matter, collective properties such as phase transitions and collective vibrations around saturation density, are directly linked to the effective interaction acting between its components. Moreover, nuclear forces and nucleon-nucleon correlations induce clustering phenomena in matter at low densities, $\rho < 1/10\rho_0$, playing an important role in core collapse supernovae and neutron stars. Such dilute state of nuclear matter can be accessed at the late stage of heavy-ion collisions. Nuclear physicists as well as astrophysicists are engaged in investigating the EoS.

It has been found that few-body fits have not sufficiently constrained three-nucleon force contributions around nuclear saturation. The accurate reproduction of binding energies and radii of finite nuclei simultaneously with the main properties of nuclear matter saturation point therefore remains one of the main challenges in *ab initio* calculations. Various solutions to this problem have been proposed, ranging from short-range correlations and Pauli blocking effects to the inclusion of many-body forces and the in-medium optimisation of nuclear forces.

The density dependence of the equation of state: incompressibility and symmetry energy

The EoS is governed by the incompressibility of nuclear matter, K_∞, and the density dependence of the symmetry energy, S(ρ). Both quantities can be extracted or extrapolated from experimental data on heavy-ion collisions and collective nuclear excitations, both in stable and exotic systems. The incompressibility of nuclear matter is defined as the curvature of energy per particle at the saturation density ρ_0. It cannot be directly measured, but it has to be extrapolated from experimental data on finite systems studied either with heavy-ion collisions or with reactions probing collective vibrations around saturation density for stable and exotic nuclei. In the case of heavy-ion collisions, measurements of in-plane and out-of-plane collective flow of protons, neutrons, clusters and kaons in Au+Au collisions at 100 MeV<E/A<10 GeV per nucleon, when compared with transport model simulations, have led to incompressibilities K_∞ between 210 and 300 MeV. However, more extensive and precise investigations on K_∞ are performed by extrapolating it from collective oscillation of nuclei around saturation density, studied in a series of measurements on an extended range of masses and isotope chains. There are two modes of vibrations which directly couple to nuclear incompressibility. These are the Isoscalar Giant Monopole Resonance (ISGMR) and the Isoscalar Giant Dipole Resonance (ISGDR). The centroid energies of these resonances can be translated into the value of finite nuclear incompressibility K_A, by means of comparisons to theoretical models. Systematics measurements performed over a wide range of masses and isotopes allows the incompressibility K_∞ for infinite nuclear matter to be deduced. Most experimental attempts consist of inelastic scattering of alpha particles at E/A<200 MeV on a range of heavy target nuclei (Ni, Zr, Pb, etc.). Such experiments are difficult as they involve measurement of the outgoing particle at 0^o. In the past, measurements have been performed on a few medium heavy and heavy stable nuclei but the results are far from consistent. The value of K_0=240±10 MeV, obtained from experiments on ^{90}Zr, ^{144}Sm and ^{208}Pb, appears to be consistent with heavy-ion collision data on collective flow. However, such incompressibility values would lead to an overestimated value of the centroid energies of giant resonances in Sn and Cd isotopes. In order to resolve such discrepancies and improve our understanding of nuclear compressibility, giant resonances for various nuclei and isotopes of the same element extending into the unstable region of the nuclear chart should be measured. This, in turn, faces the problem of measuring these observables with the use of radioactive beams in inverse kinematics reactions where the light-ion probe would be the target. The best light particle probe to study ISGMR and ISGDR is isoscalar alpha particle at energies around 100-200 MeV/nucleon. In inverse kinematics with radioactive beams, this would mean that recoil alpha particles with energies below 1 MeV in order to come close to 0^o in the centre of mass of the reaction, need to be measured. This difficult task can be achieved either by impinging radioactive ions on a light target in a ring environment in which the low-energy recoil easily emerges from the ultra-thin target, or by sending the beam into an active target acting as the detector of the low-energy recoil particles. High quality measurements will be possible with the new generation of radioactive ion beam facilities, which will provide large number of unstable nuclei with high intensities to the community.

The density dependence of the Symmetry Energy

The density dependence of the symmetry energy, S(ρ), needs to be explored with beams of nuclei over a wide range of N/Z (and thus δ) asymmetries. Nuclear structure and dynamics probes are sensitive to the strength $S_0=S(\rho_0)$, and the slope, $L \propto dE/d\rho|_{\rho_0}$, around saturation density, $\rho=\rho_0$. These quantities govern ground state and excited state properties of nuclei, collective excitations, such as the Pygmy Dipole Resonance (PDR, Box 5), and neutron/proton transport phenomena in heavy-ion collisions. The S_0 and L parameters also govern the dominant baryonic contribution to the pressure in neutron stars affecting their inner crust and radii. Thus investigations on nuclear properties as well as astrophysical observations and calculations need to provide consistent constraints on S(ρ). The results on ranges of S_0 and L values, as they are obtained by different techniques in nuclear physics and astrophysics, are displayed in Figure 13. Regardless the moderate agreement between different results, it will be important to achieve consistent descriptions of the density dependence of the symmetry energy from laboratory measurements as well as astrophysical observations, possibly reducing uncertainties originating from both experimental accuracy and model dependencies.

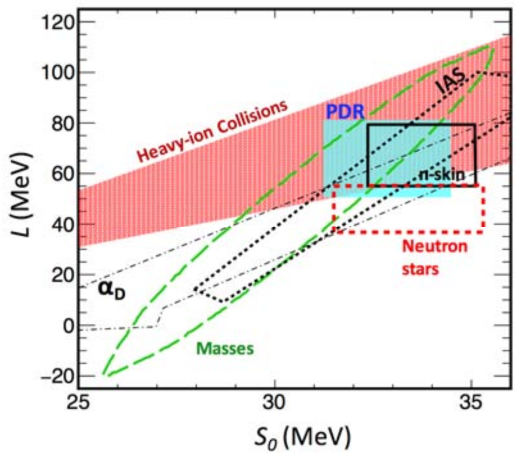


Figure 13. Ranges of strength, S_0, and slope, L, of the symmetry energy at saturation density, determined from different investigations in nuclear physics and astrophysics.

Investigations around saturation densities

The symmetry energy at saturation density is well known in the liquid-drop model and it affects significantly the binding energy of nuclei, the neutron skin thickness δR_{np} (i.e. the difference of the neutron and proton rms radii in heavy neutron rich nuclei), and excited state properties such as the energies to isobaric analogue states (IAS) and collective excitations. Experimental measurements explore a range of observables that are sensitivity to the symmetry energy. Among them we mention: measurements of the difference of binding energy per nucleon, ΔB/A, between even-even isotope pairs of different elements; the Lead-Radius Experiment (PREX) at the Jefferson Laboratory to determine the δR_{np} of ^{208}Pb to about 1% accuracy by means of parity-violating electroweak asymmetry in the elastic scattering of polarised electrons from ^{208}Pb targets; proton elastic scattering, on ^{58}Ni and ^{204,206,208}Pb isotopes; measurements of the energy of isobaric analogue states (IAS) in a number of nuclei. Some results obtained from these measurements range in the different areas indicated on Figure 13.

The Giant Dipole Resonance (GDR), in which all protons vibrate against all neutrons, is a clear probe of the symmetry energy around saturation density. In particular, the nuclear polarisability α_D (defined as the $1/\omega^2$-weighted integral of the photo-absorption cross section) and the strength of the Pygmy Dipole Resonance are connected with the symmetry term of the nuclear EOS. The "slope" parameter L can be deduced due to its links to the energy-weighted sum rule (EWSR) exhausted by the PDRs and to the neutron-skin thickness.

A precise measurement of the nuclear polarizability requires detailed studies of the photo-absorption cross section, representing a challenging task in exotic systems. The dipole polarisability in ^{68}Ni, has been recently extracted at GSI using Coulomb excitation in inverse kinematics at the R^{3}B-LAND setup (see Figure 12).

The extracted dipole polarisability yields a neutron-skin thickness of 0.17(2) fm, and an extrapolated value for ^{208}Pb in agreement with existing experimental and theoretical estimates. The GSI experiment pioneered innovative techniques, paving the way to future investigations in neutron rich systems along isotopic chains. The existing results on PDR studies have led to quite stringent constraints on the slope $L\approx 64.8\pm 15.7$ MeV and strength $S_0\approx 32.3\pm 1.3$ MeV.

Investigations away from saturation densities: heavy-ion collisions

Heavy-ion collisions between N/Z-asymmetric nuclei represent the only terrestrial means to explore the equation of state and the symmetry energy away from saturation densities. The intermediate energy regime (E/A=20-100 MeV) explores nuclear matter at sub-saturation density ($\rho<\rho_0$), while relativistic beam energies (100 MeV<E/A<1 GeV) allow probing supra-saturation densities (up to $\rho\approx 2\rho_0$). The hot and compressed systems evolve with time under the effect of nuclear and Coulomb forces. Microscopic transport models provide simulations of such evolution, with specific density functionals of the symmetry energy, $S(\rho) \propto (\rho/\rho_0)^\gamma$, that are plugged-in as input parameters. Then the γ parameter defines the stiffness of such density dependence.

Sub-saturation densities

The dashed lines in Figure 12 schematically show the paths followed by a finite nuclear system produced in a collision at intermediate energies. The red and blue colours refer to central and peripheral collisions, respectively. In the first case, the system undergoes a strong compression stage accompanied by an increase of temperature. Then nuclear matter may expand towards the spinodal instability region at sub-saturation densities, $\rho<1/3\rho_0$, and finite temperatures where a liquid-gas phase coexistence may occur.

Such collisions have been extensively studied with the INDRA and CHIMERA 4π detectors at GANIL and INFN-LNS, respectively. The results obtained from studying multifragmentation phenomena, collective flow, fragment emission time-scales, fluctuations analyses, bimodality and calorimetric measurements have increased our understanding of phase transitions and the EoS. The availability of beams over a wide range of N/Z asymmetries allows investigation of the effect of isospin asymmetry on phase transitions. In particular, "isospin distillation" has been observed: due to the symmetry potential pushing neutrons towards low density regions, the gas phase is expected to be more neutron-rich ($N_{gas}>>Z_{gas}$) than the liquid phase ($N_{liq}\approx Z_{liq}$). Such phenomenon has been studied by measuring light fragment (Z=3-7) production in ^{112,124}Sn+^{58,64}Ni collisions with the 4π Chimera detector at the INFN-LNS. The future availability of the FAZIA array, equipped with new digital pulse-shaping technologies, will allow extending high isotopic resolution even to heavier isotopes with Z>20, providing unique constraints on the symmetry energy effects with liquid-gas phase transitions.

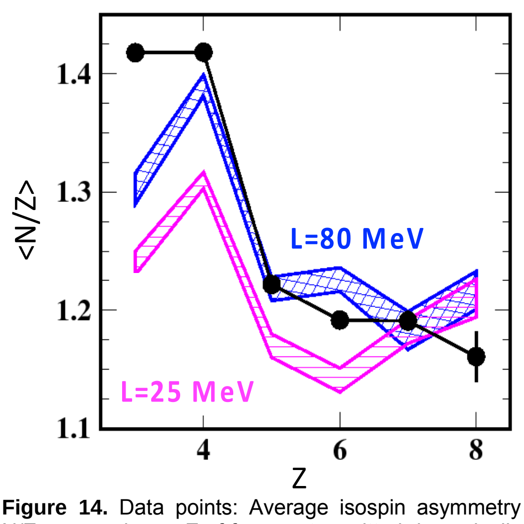


Figure 14. Data points: Average isospin asymmetry N/Z versus charge Z of fragments emitted dynamically from the neck region in ^{124}Sn+^{64}Ni at E/A=35 MeV. Coloured bands: results of Stochastic Mean Field simulations with different density dependences of the symmetry energy (corresponding to L=25 and 80 MeV).

Important probes of the symmetry energy arise from the pre-equilibrium emission of neutrons and protons, exploring their energies and emission time-scales. Such measurements are important and require implementation of neutron detection into existing charged particle detectors (INDRA, FAZIA, CHIMERA, GARFIELD).

In peripheral collisions the quasi-projectile (QP) and quasi-target (QT) partners exchange nucleons through a low-density neck region. During this phenomenon two mechanisms, namely *isospin drift* and *isospin diffusion*, depend directly on the symmetry energy. Isospin drift consists of a net migration of neutrons towards the low density neck region. This mechanism is therefore due to the existence of a density gradient in the system and is governed by the slope L of the density dependence of the symmetry energy at $\rho=\rho_0$. A study of isospin drift in ^{124}Sn+^{64}Ni peripheral collisions at E/A=35 MeV has been carried out with the 4π Chimera detector at INFN-LNS. The average N/Z of dynamically emitted neck fragments over a wide range of charges Z (data points in Figure 14) has been compared with Stochastic Mean Field (SMF) calculations and has led to a slope values $L\approx 80$ MeV for the density dependence of the symmetry energy . Isospin diffusion occurs when the colliding projectile and target nuclei have different N/Z asymmetries, as in the case of ^{124}Sn+^{112}Sn mid-peripheral collisions. The N/Z-gradient driven exchange of neutrons and protons ends when the interacting projectile and target re-separate, thus depending on reaction times. In this case, the strength S_0 of the symmetry energy at $\rho=\rho_0$ mostly affects such mechanism. Isospin diffusion has been investigated by studying the QP decays in N/Z-asymmetric reactions with the INDRA array at GANIL. Comparisons with SMF predictions, have led a density dependence of the symmetry energy, $S(\rho) \propto (\rho/\rho_0)^\gamma$ with γ=1. Such studies may be affected by discrepancies arising from different transport model approaches (mean-field models, molecular dynamics models, etc.). Efforts to achieve a consistent description of symmetry energy effects in different models will represent a priority to improve existing constraints on the nuclear EoS.

In peripheral reactions, the evolution of hot quasi-projectiles during its decay may lead to the observation of interesting phenomena possibly indicating the existence of boson condensation in hot nuclei. Similar studies have been recently performed on the ^{40}Ca+^{40}Ca reaction at E/A=35 MeV with a novel experimental approach where the VAMOS magnetic spectrometer has been coupled to the INDRA 4π array. Light particle emission allows deducing densities and temperatures of the decaying hot QP at different excitation energies, as it is shown in Figure 15. Densities extracted from bosons (deuterons and alphas) result to be higher than those extracted from Fermions (protons). This result demonstrates the rich structure of dilute and hot density nuclear matter and has been interpreted as first possible signal of Boson Condensation and Fermi Quenching in the decay of hot nuclei.

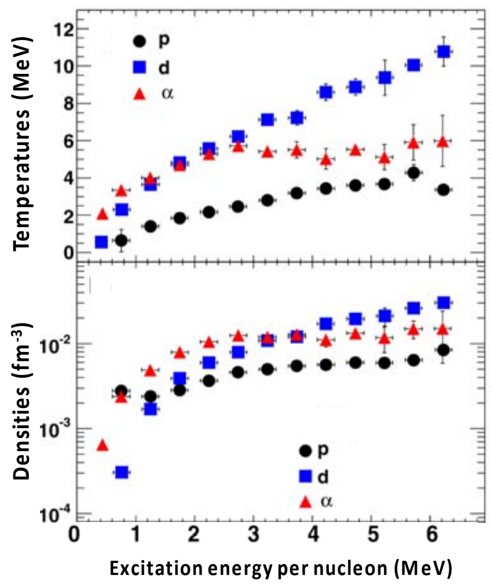


Figure 15.Tempertaures and partial densities probed by different particle species (protons, deuterons and alphas) as a function of excitation energies of quasi-projectile decay in peripheral ^{40}Ca+^{40}Ca collisions at E/A=35 MeV.

Interplays of EoS and structure properties

The interplay between reaction mechanisms and structure properties can manifest itself with phenomena such as alpha clustering, theoretically predicted to affect the low density behaviour of the nuclear EoS. Clustering plays a key role even at low energies, E/A=8-16 MeV, where an interplay between fast pre-equilibrium and relaxed equilibrated thermal emissions exists. Reactions ^{16}O + ^{65}Cu at E=265 MeV and ^{19}F + ^{62}Ni at E=304 MeV, producing the same compound nucleus but induced by projectile nuclei with (in the case of ^{16}O) and without (in the case of ^{19}F) alpha-clustering structure, have been studied at INFN-LNL with the GARFIELD detector and the RingCO array. The different alpha structure properties of projectile nuclei is reflected on the measured shape of their energy spectra. Such phenomena may be important near the drip–lines, with interesting future perspectives offered by the future SPES, HIE-ISOLDE and SPIRAL2 facilities.

Supra-saturation densities

At beam energies E/A>200 MeV heavy-ion collisions produce systems at densities as high as twice saturation density, $\rho \approx 2\rho_0$. The elliptic flow of nucleons as well as meson (pions and kaons) production carry information about the density dependence symmetry energy $S(\rho)$. Experimental measurements of the elliptic flow of protons and neutrons in Au+Au collisions at E/A=400 MeV have been successfully attempted with the LAND-CHIMERA-KRATTA experiment at GSI. Thanks to the capability of LAND to detect both neutrons and protons, constraints on the slope of the symmetry energy at saturation density have been obtained, $L \approx 72 \pm 13$ MeV.

At energies E/A>300 MeV/nucleon, the relative yields of positive and negative pions, $\pi^+/\pi-$, as a function of their kinetic energies is also expected to lead to important information about $S(\rho)$. Attempts to measure $\pi^+/\pi-$ ratios with FOPI at GSI have led to conflicting conclusions on the symmetry energy when experimental results have been compared with different transport model predictions. Discrepancies arise from the difficulty in treating pion production and their absorption and re-scattering in the nuclear medium. In contrast to pions, kaons are mainly produced at high densities during the early stage of the collision and are essentially free of subsequent reabsorption effects, promising to provide more stringent probes of the symmetry energy.

Summary and open issues

The symmetry energy can be accessed in heavy-ion collisions by measuring energy spectra and correlation functions for neutron and proton pairs. To this purpose, neutron detection would need to be integrated into existing charged-particle detector arrays. Neutron detection remains still important at relativistic energies and will benefit from the availability of the NeuLAND system at GSI.

The study of how structure and clustering evolves with density needs to be pursued by measuring high resolution resonance decays and particle-particle correlations in heavy-ion collisions. Such evolution of microscopic properties is predicted by theory and requires experimental campaigns to be extensively explored.

The EoS is important to study the opacity of the neutrinosphere to outgoing neutrinos in Core Collapse Supernovae. Both experimental and theoretical nuclear dynamics investigations should reinforce synergic efforts with astrophysics community involved in supernovae simulations.

Efforts to improve the predicting power of transport models are necessary to progress in equation of state studies with heavy-ion collisions and should be encouraged. It will be important to achieve a quantitative consistency in predictions of the same observables provided by different models will be important.

Pion π^+/π and Kaon K^+/K^0 yield ratio, as well as neutron/proton elliptic flow measurements in collisions at FAIR energies, should be pursued as the only means to better constraint the supra-saturation density dependence of the symmetry energy, still largely uncertain. In this respect, radioactive beams at FAIR will represent a unique opportunity to enhance symmetry energy effects in experimental measurements.

Facilities and instrumentation

Accelerator/Reactor facilities

Radioactive beam facilities

During the past 30 years, the first generation of radioactive beam (RIB) facilities based on the complementary methods, in flight separation (GANIL and GSI) and ISOL approach (ISOLDE and SPIRAL1) have enabled tremendous progress in the study of exotic nuclei to be made and stimulated the efforts to build new radioactive ion beam facilities. Both in flight separation and ISOL approach, combined with different post-processing of the radioactive nuclei, will form the pillars of the RIB facility network in Europe.

FAIR will be the European flagship facility for the coming decades. The unique accelerator and experimental facilities will allow for a large variety of unprecedented fore-front research in physics and applied science. The main thrust of FAIR research focuses on the structure and evolution of matter on both a microscopic and on a cosmic scale, deepening our understanding of fundamental questions. Prior to the commencement of the modular start version of FAIR, the upgraded GSI facility will continue to perform a science programme and instrumentation commissioning in a phase 0 of FAIR. The urgent completion of FAIR, the Super-FRS and NUSTAR@FAIR, are of utmost importance for the community. In the interim period it is vital that a high-level research programme and use of the new detectors for FAIR at GSI continues using the existing beams and facilities.

The ultimate ISOL facility in Europe will be EURISOL for which an extensive R&D program and a design study has been carried out proposing that it will consist of a high energy and power superconducting linear accelerator. Prior to EURISOL the EURISOL DF project aims at integrating the ongoing efforts and developments at the major ISOL facilities of HIE-ISOLDE, SPES and SPIRAL2, the planned ISOL@MYRRHA facility, and the existing JYFL and ALTO facilities. EURISOL DF will use the synergies and complementarities between the various facilities to build a programme of research to bridge the gap between present facilities and EURISOL.

An IGISOL facility for production of exotic neutron-rich nuclei using brilliant gamma beams is being designed at ELI-NP. The energy distribution of the gamma beams can be tuned such to optimally cover the energy region of the giant dipole resonance of fissile target nuclei making it an ideal tool to induce their photofission. The IGISOL technique allows for the extraction of the isotopes of refractory elements, which do not come out from standard ISOL targets.

Stable ion beam and other techniques

High quality beams at moderate intensities (10^6-10^8 pps) and over a wide range of energies (ranging from few MeV's up to few GeV's per nucleon) are presently available at several European laboratories, playing a key role in structure studies (with particle and γ spectroscopy) and in nuclear dynamics to explore the isospin dependence of the nuclear equation of state. Very intense stable ion beams (SIB) are used to study superheavy element (SHE), rare phenomena relevant for nuclear astrophysics, nuclear structure at low, medium and high spin, exotic shapes, decay modes, clustering and collective motion in nuclear systems, nuclear ground state properties (masses, charges and moments) and near barrier transfer and fusion reactions. These challenges are championed by the ECOS initiative that supports such facilities to address challenges in searching for the limits of nuclear existence towards the n- and p-drip lines, as well as towards the regime of SHE, with beams at intensities as high as 10^{12}-10^{13} pps. The present and future SIB facilities include, the LINAG at GANIL, the UNILAC and future cw-linac at GSI, the ALTO facility at IPN Orsay, the accelerators at JYFL-Jyväskylä, KVI-CART-Groningen, LNL-Legnaro and LNS-Catania. The NUMEN project at INFN-LNS will lead to an increase of the superconducting cyclotron power from 100 W to 10 kW, that will allow the study of double charge- exchange reactions and measure matrix elements needed to study the double beta decay in neutrino related researches. Finally, the ECOS initiative is supporting other projects such as LINCE-Andalusia still in the R&D and elaboration phase in order to be the next generation high intensity stable ion beam facility.

Intense neutron beams provide a unique opportunity for studies of neutron induced reactions and for applications. The ILL reactor in Grenoble is the world brightest continuous neutron source, feeding about 40 state-of-the art instruments. This includes the high resolution spectrometer GAMS, the fission fragment recoil separator LOHENGRIN, and the multi-detector setup FIPPS, at which a rich γ-spectroscopy program is foreseen, following neutron induced fission and neutron capture reactions on a large variety of targets. At CERN, the n_TOF facility produces neutrons by a pulsed beam of proton on a Pb spallation target. An intense wide neutron spectrum is created, with energies from a few MeV to several GeV. The workhorse of the facility is the Total Absorption Calorimeter, a 4π segmented array made of 42 BaF2 scintillators. At LICORNE, IPN-Orsay, monoenergetic, kinematically focused, neutron beams, with energies 0.5-4 MeV are produced by bombarding hydrogen-rich targets with intense ^{7}Li beams. Experimental campaigns make use of a modular setup based on Ge detectors coupled to large volume scintillators and detectors for fission products. In GANIL, the Neutron For Science facility will soon provide intense 1-40 MeV pulsed neutron beams produced from protons and deuterons accelerated by the LINAG on a converter.

Other accelerator based probes are also important for nuclear physics research in Europe. The Extreme Light Infrastructure - Nuclear Physics (ELI-NP) project is one of the three pillars of the pan-European ELI project aiming at the use of extreme electromagnetic fields for nuclear physics research. The characteristics of the photon will allow new sensitivity to be reached, that is needed to approach a virgin science field at the frontier between the strong field QED and nuclear physics. Laser driven nuclear physics will explore possibilities of ion acceleration with solid state density bunches, giving the opportunities of producing very neutron rich nuclei in fission-fusion reactions or studying nuclear reaction rates and isomers production in laser plasma. Applications of photon beams in nuclear energy, medicine, space science, industrial radioscopy and tomography are also planned.

Europe has many smaller-scale facilities that are mostly associated with and/or run by Universities. They keep their importance in training and education of the next-generation researchers as well development and testing of new instruments and techniques. In some cases, the presence of unique instrumentation and the availability of a large variety of stable beams, combined with easy access, offers the possibility of forefront research in some specific areas of nuclear structure and some applied nuclear physics activities, such as medical imaging.

Instrumentation

Separators, spectrometers and associated detection for nuclei identification

The production of exotic nuclei is closely linked to the availability of separators and spectrometers in order to select and identify the nuclei or reactions of interest.

One method that is used is in high-energy radioactive ion production in which the primary heavy-ion impinge on a light and thin target. The projectile or fission fragments can be separated in-flight within some hundred nanoseconds. The in-flight separation offers the possibility to have momentum resolving powers of up to 20,000 and it provides isotopically pure or cocktail beams and it can provide fully-stripped ions up to uranium. The Super-FRS at FAIR will be the most powerful in-flight separator for exotic nuclei up to relativistic energies (~1GeV/nucleon). A novel development is high-resolution spectroscopy of hypernuclei, exotic atoms and nucleon resonance studies in exotic nuclei using hadron spectrometers at the central focal plane of the separator.

Recently, in collisions at the energies near the Coulomb barrier, the isotopic identification of fission fragments has been achieved using VAMOS++ at GANIL, and identification of both transfer binary fragments using PRISMA and kinematic coincidence arm at LNL. The use of the inverse kinematics make possible to exploit the unique performances of these spectrometers in terms of resolution and efficiency. A good isotopic separation enables the importance of secondary processes (like fission and evaporation), which may significantly modify the production yields in the heavy mass region, to be investigated. These findings will be exploited for nuclear structure studies of neutron-rich nuclei by means of prompt-delayed γ-ray spectroscopy. In addition, exploitation of the gas-filled separator RITU at JYFL continues to provide new insights into the structure of neutron deficient and heavy nuclei.

Fusion-evaporation reactions are mainly used to produce neutron deficient nuclei toward the proton drip line and SHE and are used with efficient velocity filters (such as SHIP) or gas filled separators (such as TASCA, RITU). The challenge is to develop new separators able to handle very high intensities such as S3 installed in the experimental areas of the superconducting LINAC of Spiral2. It is designed for in-flight transmission and purification of rare reaction products combining a momentum selection plus a mass selection.

Within the ISOLDE approach, intense beams of exotic nuclei are extracted from ion sources at low energy (30-60 keV) although they are accompanied by a strong contamination of nuclei closer to the stability. Purification techniques are then mainly based on isobar separators. The actual challenge is to reach resolving power in the range of 20,000 (DESIR-HRS@SPIRAL2). Alternatively a selection based on the chemical element (laser ionisation) can be done but this is not available for all elements. Another technique based on the use of devices like new Penning traps or multi-reflection time-of-flight mass separators are currently under development to increase the resolving power by one or two orders of magnitude. Isomer separation has been demonstrated at GSI using an MR-TOF-MS opening the possibility to produce pure isomeric beams. A new and important approach concerns the hybrid systems like the FRS Ion-Catcher combining gas cells with in-flight separators providing ISOL-type beams of short lived nuclei.

Detectors for structure and dynamic studies

Gamma Detectors

The workhorse for high resolution gamma spectroscopy are arrays based on Ge detectors, have now reached the frontier of efficiency and sensitivity with AGATA, which will be the first 4π gamma-ray spectrometer solely built from Ge detectors. Being fully instrumented with digital electronics it exploits the novel technique of gamma-ray energy tracking. AGATA has been successfully operated since 2009 at LNL, GSI and GANIL, taking advantage of different beams and powerful ancillary detector systems.

AGATA has been successfully coupled to charged particles detectors (DANTE, LYCCA), high energy γ-ray scintillators (HECTOR, ELENA), magnetic spectrometers (PRISMA, VAMOS++) and the fragment separator (FRS). In the future, AGATA will benefit from the increased selectivity of ancillary detectors currently developed in the framework of new facilities (SPIRAL2, SPES, FAIR). AGATA will be coupled to the next generation of neutron detectors NEDA (see Figure 16), to the charged particle detector DIAMANT and MUGAST, developed for ISOL facilities, and the high energy γ-rays scintillator of PARIS and the fast timing detectors of FATIMA, opening new avenues in the detailed description of the nuclear structure and nuclear reaction mechanisms. In conjunction with site-specific beams, particle separators and spectrometers a full exploitation of AGATA's capabilities will become possible.

At FAIR, the high-purity Germanium Array DEGAS will be a key instrument for Decay Spectroscopy (DESPEC) project, which will allow high-resolution spectroscopy from alpha, beta, proton, neutron and isomeric decays of exotic nuclear species. It will employ electrical cooling of the cryostats and it will be surrounded by an active shielding shell.

A number of Ge arrays, most based on conventional anti-Compton shield principle, are available in European Laboratories, contributing to carry on a rich gamma spectroscopy program in conjunction with ancillary detectors (e.g., EXOGAM (GANIL), GALILEO (LNL), JUROGAM (JYFL), MINIBALL (ISOLDE), ORGAM/NuBall (Orsay), ROSPHERE (Bucharest), ELIADE (ELI-NP), EAGLE (Warsaw)).

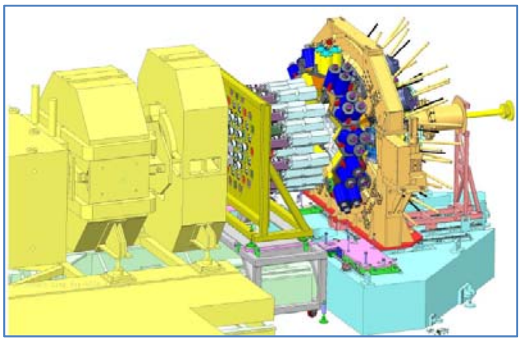


Figure 16. The AGATA array at GANIL, coupled to the NEDA neutron detectors at forward angle and detectors from the neutron wall array at 90°in front of the VAMOS spectrometer.

Scintillator detectors still cannot compete with Ge in terms of energy resolution, even with the use of new materials (e.g., $LaBr_3$:Ce). However, in all physics cases where time resolution, efficiency for medium and high energy gamma rays, and fast charged particles identification are needed, scintillators arrays are commonly used. In Europe, several scintillator arrays exist or are under development: they can work in standalone configuration or in complex setups comprising different type of detection systems. Arrays of smaller size (few inches) scintillators are employed for lifetime measurements, in the ps to ns range (e.g. FATIMA), while large volume detectors are ideal for high energy γ-rays (e.g., HECTOR+, ELIGANT-GN, PARIS, OSCAR), fast charged particles and γ rays (CALIFA and CEPA).

Particle Detectors

Future challenges in nuclear structure and dynamics require charged particle detectors capable of identifying particles, and to measure their energy and emission angle with the highest precision. Nuclear dynamics studies profit from powerful 4π or large area detector systems such as Chimera, Indra and the combined array GARFIELD+RCO, operating at INFN-LNS, GANIL and INFN-LNL laboratories, respectively. Charge and mass identification is attained by means of energy loss, time of flight and pulse-shape measurements in different detector materials, including silicon, inorganic scintillators and gas detectors. Direct reactions aimed at precise spectroscopic measurements require high energy and angular resolution. These features are encountered in double-sided silicon detectors equipping extensively used arrays such as MUST2, Tiara and Charissa. New generation arrays are under construction to address the most ambitious technical challenges with future radioactive and stable beam facilities. Notable examples are the FAZIA array for nuclear dynamics at intermediate energies (made of high uniformity nTD silicon detectors and CsI(Tl) crystals), and the GASPARD and TRACE 4π and highly segmented nTD silicon strip and pad arrays, to be used in coincidence with γ-ray detectors. These systems are characterised by digital and high speed pulse-shape capabilities, with charge and mass identification over a wide dynamic range (4 GeV for particle charges Z~1-50, in FAZIA, and 50-200 MeV for Z=1-2, in GASPARD and TRACE). Low energy identification thresholds are ensured, an important feature at RIB facilities. Digital pulse-shape technologies are also implemented in the silicon strip and CsI(Tl) FARCOS detector, at INFN-LNS, for multi-particle correlation measurements and they are successfully used in the KRATTA array, in experiments at both low and very high beam energies. A fast reset ASIC coupled to a stack of double sided Si detectors has been realised for AIDA, the implantation detector for DESPEC at GSI/FAIR.

Calorimetric low temperature detectors (Bolometers) offer excellent opportunities within the NuSTAR project owing to their excellent energy resolution and linearity for heavy ion detection.

Neutron Detectors
There exists efficient detectors for slow neutrons and for high-energy (above 100 MeV) neutrons, whereas neutrons in the range of a few MeV's still present a challenge. Very specialised instrumentation exists for experiments taking place at reactors and spallation neutron sources. For low-energy reactions the focus is on efficiency, on the capability to distinguish neutrons from other radiations, such as γ rays, and for detector arrays on eliminating cross-talk between modules. Several improved specification arrays are being constructed at the moment (e.g. NEDA). For high-energy reactions neutron arrays are an essential and integral part of complete kinematics setups, one clear example being NeuLAND for the R^3B setup**.**

Active Targets
Gaseous detectors are well-suited for the study of the most exotic nuclear species thanks to their efficiency and versatility. When used as vertex trackers, thick targets can be employed (as target and detector) without loss of resolution, in particular for low-energy particles. Large interest in these devices has grown worldwide over the last few years, with a number of instruments being built. Progress has been made especially with the increase of their dynamic range, by using various mechanical and electronic methods. Another key development has been in dedicated digital read-out electronics, handling the large number of pads present in some of the detectors. In Europe, recent efforts on developing a new generation of active targets concentrated around ACTAR TPC, the GANIL-based versatile active target and TPC chamber, from which projects for more specialised detectors have originated. The physics scope of these instruments is broad, including direct reactions (elastic and inelastic scattering, one and two-neutron transfer), resonant reactions, inelastic scattering with low-momentum transfer and, exotic decay modes. Active targets are planned at the forthcoming RIB facilities of HIE-ISOLDE, SPES, SPIRAL2 and FAIR.

Hadron spectrometers
Novel detection and measurement schemes are presently under development for new experiments exploring nucleon resonances and strangeness in exotic nuclei as well as mesic atoms. Different options (e.g. solenoid-type or dipole magnet based systems) for meson and light hadron identification and spectroscopy (by tracking and time-of-flight measurements) are under development. It is planned to use these detectors for invariant mass spectrometry together with the high-momentum resolution capabilities of high-energy spectrometers like FRS or Super-FRS. This is an emerging field, which will open up new degrees of freedom for exotic nuclei research.

Storage rings
Storage rings are well-established instruments in atomic, nuclear and high-energy physics and with them quite remarkable discoveries were achieved. The combination of the fragment separator FRS and the experimental storage ring ESR of GSI was the first incarnation of experiments with radioactive beams in storage rings. This, together with new technical features like electron cooling of heavy ions, provided unprecedented physics opportunities and novel results. Despite the challenging techniques and instrumentation, the obvious potential for basic science prompted plans and developments at many other facilities worldwide. Today, a major activity is the construction of the storage-ring complex at GSI/FAIR. At HIE-ISOLDE, there are plans to install a storage ring, which will be the first of its kind at an ISOL facility, thus underlining the pioneering role of Europe in this domain. It will open new possibilities in atomic, nuclear, nuclear astrophysics and neutrino physics. The CERN Scientific Policy Committee strongly supports the physics case.

With respect to in-flight separation and storage rings for high beam energies, the construction of FAIR is underway and awaits its completion. At the Collector Ring (CR), where secondary ion beams undergo stochastic pre-cooling, direct mass measurements of extremely short-lived nuclei (down to half-lives of the timescale of microseconds) far off stability can be performed with high accuracy using Isochronous Mass Spectrometry (ILIMA). The New Experimental Storage Ring (NESR) serves several precision experiments with exotic ions and antiprotons. It will be equipped with stochastic, electron and laser cooling and comprise several straight sections for dedicated detector systems and internal targets (including an eA-collider with a counter-propagating multi-MeV electron beam) for a variety of experiments including very low-energy experiments (like direct reactions). As novel features at FAIR, the implementation of storage-rings will enable measurements of hadronic scattering at low momentum transfer

(EXL), electron scattering off exotic nuclei (ELISE) and fission studies with radioactive beams (ELISE). In an intermediate stage, the existing ESR of GSI and the new high-energy storage ring HESR, which is part of FAIR modular start version, will provide unprecedented and world unique opportunities. In particular, the highly-relativistic beams (gamma up to ~6) accelerated in the HESR synchrotron, open up a new domain, never before explored with radioactive beams.

Traps and Lasers

Atomic physics precision techniques have been used for decades to extract information of nuclear levels and the rapid introduction during recent decades of novel techniques for ion manipulation has given new physics possibilities.

Laser ionisation sources are increasingly favoured for production of ISOL beams due to their significantly enhanced selectivity. Apart from decreasing the level of contaminants it also, in favourable cases, allows "in-source" physics to be performed, such as the recent measurement of the ionisation potential of the rare element astatine.

Laser spectroscopic measurement on ionic or atomic beams and mass measurements in ion traps yield the state-of-the-art information on nuclear masses, radii and moments and are therefore implemented at many radioactive beam facilities worldwide. The techniques are being continuously refined, with ISOLDE leading the scene in Europe. Recent additions include a cooler-buncher that increased the sensitivity of collinear fluorescence spectroscopy by two to three orders of magnitude, the development of a dedicated collinear resonance ionization spectroscopy beamline which further improved the sensitivity with another two orders of magnitude, and the installation of a multi-reflection time-of-flight mass spectrometer that allowed mass measurements of the Ca-chain at ISOLDE all the way out to ^{54}Ca.

In-gas-jet resonance ionisation spectroscopy is the latest addition to this family of techniques, combining the efficiency of in-source method with an enhanced resolution thanks to the reduction of Doppler broadening. Such a set-up is planned for research on elements around and beyond uranium at the S3 facility of SPIRAL2.

Technical Innovations

Electronics - The new detection setups in nuclear structure research pose a number of challenges on the associated read-out electronics including a large number of channels, large dynamic ranges, low noise and high energy and timing resolution, and high throughput. Digitisation of signals has become the norm for most detectors, complemented with high-density front-end electronics based on Application-Specific Integrated Circuits, multiplexing of the signals and solutions for back-end electronic based on existing standards from Telecommunications Computing Architecture. The trend is towards triggerless systems and time-stamped signals.

Several dedicated systems have been developed, while only few flexible systems with a wider scope exist (FEBEX and GET are two notable examples). For the future, the development of a common platform allowing the integration of the various existing and planned detection spectrometers is one of the objectives of the EURISOL DF.

Scintillators - The last few years have seen fast developments in scintillator detectors owing to the availability of i) new scintillation materials, ii) high efficiency photocathodes, iii) new photo-sensors, iv) new configurations or designs and v) fast high bits digitisers.

Some materials are nowadays well established ($LaBr_3$:Ce), some are in an advanced state of test or already used (CeBr3:Ce or SrI2) and some are still in the prototypal phase (CLYC, GYGAG, CLLB or CLLC). In addition, the development of super-bialkali photocathodes (SBA and HBA) and the impressive evolution of SiPMT granted scintillation detectors better performances, immunity to magnetic fields and imaging features.

Summary and open issues

Radioactive ion beam facilities

In flight separation and ISOL approach will form the pillars of the RIB facilities network in Europe.

The urgent completion of FAIR, the Super-FRS and NUSTAR@FAIR, are of utmost importance for the community.

EURISOL is the long term goal that will ensure unique physics opportunities. In the meantime it is important that the development of the existing intermediate major facilities (Spiral2, HIE-ISOLDE and SPES) in the framework of the EURISOL-DF are supported.

In addition to the efforts to develop existing in-flight and ISOL facilities and build new ones, a large variety of state-of-the-art instrumentation has to be constructed for their optimal exploitation

Stable ion beam facilities

The long-term goal for a new dedicated high-intensity stable ion beam facility in Europe is recommended as an important future project. The ECOS initiative is playing a key role in preparing this project and in providing a network among the existing stable beam facilities.

Very high-intensity stable-ion beams from the high-power LINAG of the SPIRAL2, and the new super-conducting cw-linac under construction at GSI are of high importance, especially for out of beam studies of extremely rare nuclei, such as superheavy elements.

Other smaller scale facilities, often university based, have to be supported for their specific programmes, for the development of new instruments and also for providing education and training of next generation researchers.

Instrumentation

One of the strength of the European community is the development of powerful detectors, the flagship being the gamma detector AGATA that has been used since 2010 at LNL, GSI and GANIL. The timely completion of the full AGATA spectrometer is of highest importance to address the exciting science programme at both the stable and radioactive beam facilities.

Recommendations

We recommend efforts towards a universal description of nuclear structure to provide bridges between the ab-initio, shell model and EDF methods are developed.

The exciting science program for nuclear structure, reactions and equation of state requires the development of stable and radioactive facilities. We recommend the urgent completion of FAIR and the development of the major facilities within EURISOL-DF.

The urgent completion of FAIR, the Super-FRS and NUSTAR@FAIR, are of utmost importance for the community. In the interim period it is vital that a high-level research programme and use of the new detectors for FAIR at GSI continues using the existing beams and facilities

A strength of the European community is the development of powerful detectors and instrumentation. The timely completion of the full AGATA spectrometer is of highest importance to address the exciting science programme at both the stable and radioactive beam facilities.