Heavy and super heavy nuclei

Scientific Objectives

Heavy and super-heavy nuclei (SHN), which form the upper end of the chart of nuclei, owe their stability, and for the heaviest systems (Z larger than 104) even their sheer existence, to quantal shell effects. Their study thereby offers unique insights into the quantal nuclear many-body problem. The study of heavy nuclei is not only a theoretical challenge; it is also an experimental one as the production cross sections involved are minute and the experimental methods used to find such needles in the haystack are a “tour de force”. These involve providing and coping with high beam intensities, using exotic targets, manipulating and isolating very rare ions in a huge background of unwanted reaction products and devising the most efficient and versatile detector arrays.

Super-heavy nuclei exhibit a rich phenomenology of excitation and decay modes that are governed by the competition between the short-range strong nuclear interaction, the long-range Coulomb repulsion, surface effects, and the quantal shell structure of single-particle states. Nuclei situated slightly beyond the edges of the presently accessible region are predicted by theory to exhibit new exotic phenomena. There are mainly two specificities of SHN that are responsible for their particular features. First, the large number of positively charge protons in SHN leads to very strong electromagnetic fields that are at the origin of nuclear structure effects that are particular to these nuclei. For example, the competition between the surface energy, which favours compact forms, and the electrostatic force, which prefers extended configurations, leads to so-called Coulomb frustration or redistribution effects, which are expected to produce exotic topologies of nucleonic densities, such as central depressions in the charge distribution. Second, because of the large number of particles, the average density of single-particle levels is much larger in SHN than in lighter systems. This leads to phenomena such as deformed magic numbers with a much larger stabilising effect than what is found for lighter nuclei and the possibility of large shell stabilisation that is disconnected from large gaps in the single-particle spectrum. Both phenomena require a more general perspective on nuclear magicity than the interpretation of light nuclei. Finally, there is no atom without a nucleus, and although the periodic table has an end predicted by quantum electrodynamics at Z=172, the existence of elements beyond Og depends in fine on the stability of the atomic nucleus. This gives a whole other dimension to the study of superheavy nuclei.

*Questions: What theory should observables be compared to? Can the band-heads of deformed odd nuclei be interpreted as single-particle configurations? Which further data are needed to constrain theory and to establish a coherent picture of superheavy nuclei? Are there any special cases, which one could investigate that prove the extent of Coulomb frustration? Or the extent (in N and Z) of the shell-stabilizing effects?*

It is customary to interpret and label the band heads of the presently known SHN in terms of deformed rotors to which one nucleon in some deformed single-particle state is coupled in case of odd nuclei, or two nucleons in case of odd-odd nuclei or excited bands of even-even nuclei. From this, one can then deduce an empirical shell structure in a common single-particle potential. While this intuitive picture describes the gross features of the majority of the observed states, it clearly oversimplifies their structure by neglecting correlations from pairing, core polarization, shape fluctuations, and band mixing. Some of these correlations are partially grasped by self-consistency, but beyond-mean-field models will be needed for a more detailed description and understanding of these states. Shell structure and correlations are in fact intrinsically theoretical concepts, and cannot be individually deduced from data in a unique model-independent way. There also is the possibility that some low-lying excited bands correspond directly to more complex configurations, whose description would again require beyond-mean-field techniques.

Within a given model, the amount of configuration mixing will leave its fingerprint in electromagnetic moments and transition probabilities. Progressing further in this respect involves systematic combined γ and internal conversion spectroscopy, measuring angular distributions and correlations and linear polarization properties of the emitted radiation, measuring lifetimes of excited states and possibly performing Coulomb excitation experiments.

In addition, these past years have seen a number of exciting developments including optical studies of exotic atoms produced at the level of one atom-at-a-time. High-resolution optical measurements of the atomic level structure readily yield fundamental and (nuclear) model-independent data on nuclear ground and isomeric states, namely changes in the size and shape of the nucleus, as well as the nuclear spin and electromagnetic moments. Laser spectroscopy combined with on-line isotope separators and novel ion manipulation techniques provides the only technique for such studies in exotic nuclear systems.

*Question:* While the elements with atomic numbers Z=113, 115, 117 and 118 have recently been assigned to the periodic table of the chemical elements, completing the seventh row, there is no direct proof of their atomic number and their chemical properties yet. How can we improve on this and unambiguously identify the nuclear charge of the heaviest SHN? How do relativistic effects affect the architecture of the periodic table? How can we extend the nuclear chart both in Z and N, thereby also extending the periodic table?

The lifetime of known SHN is governed by the competition between α decay and spontaneous fission. Since Qα values depend on the difference in binding energy between the initial and final nuclei, the theoretical systematic errors present in the masses cancel each other out, leading to fairly robust estimates. The difference between experimental and theoretical Qα values is typically several hundred keVs, which is often sufficient to provide indications on the identity of the parent nucleus, in the absence of direct experimental evidence. Cross bombardments have been used to corroborate (Z, A) assignments but some decay chains are controversial and fine structure α decay can often blur the picture in the odd cases. The non-observation of other decay modes (e.g. EC) could explain the unusual properties of some observed activities. Furthermore, in odd-Z or odd-A cases, it may be the case that the preferential α decay branch observed when the nucleus is populated directly, is not the same as when it is populated by α decay of the mother nucleus. Low-threshold and efficient detection systems sensitive to γ and X-ray decays need to be developed in a systematic way, especially for the synthesis experiments. Ways to tag on beta decay should also be investigated. In-flight sensitivity to A and fast transport systems are required, especially when going up in Z, as lifetimes are predicted to be quite short. Isomeric excited states, created by configurations with high *K* are regarded to be a general feature for SHN, some of them being longer-lived than the ground state. While there are only a few such cases known for isomers of lighter nuclei, for superheavies this might be much more systematic. This has the potential to provide new possibilities in terms of synthesis and spectroscopic study of new isotopes, or even new elements, close to the shores of the “sea of instability”.

As fusion-evaporation as a production scheme is limited to rather neutron deficient nuclei, methodological development is mandatory. The exploitation of more exotic target materials is definitely to be pursued, though it faces challenges concerning procurement and handling (e.g. radioprotection) and promises limited progress. The use of actinides is essential for any progress to higher Z and A, for both synthesis and spectroscopy. Alternative production schemes are demanded, beyond the challenging use of pxn or αxn evaporation reactions, hampered by low cross sections and technical challenges like a e.g. a reduced transmission in a 0-degree separator due to the larger momentum spread for α evaporation channels. The employment of deep inelastic reactions like multi-nucleon transfer (MNT) on heavy actinide targets, and their potential to reach more neutron-rich species are presently widely discussed in the community. Predictions and first tests for lighter systems promise interesting production cross section for neutron-rich species, and justify the hope that MNT is a potentially a new route towards the proton and neutron numbers predicted by the various models for the spherical superheavy nuclei – the “island of (enhanced) stability”.

The predicted long lifetimes for those SHN ask for identification methods beyond the genetic evaporation residue (ER)-α-SF correlations. The construction of those decay chains relies on short decay times (and position measurements) to correlate the chain members. Few- or even single-event precision mass measurements in Penning traps or multi-reflection time-of-flight mass spectrometers (MRToF MS) are possible methods to establish the atomic mass of the reaction products, while X-ray detection of excited states (e.g. isomers surviving separation) could provide their Z identification.

Concerning Z-identification of the SHN produced in 48Ca-induced reactions on actinide targets up to 294Og, systematic measurements employing lighter calcium or less rare 46-50Ti projectiles could bridge the gap between those and the SHN which are connected to known (α-decaying) SHN. Other projectile-target combinations using silicon or sulphur isotopes have also been discussed.

In all the above-mentioned cases, it is a challenge for theory to develop predictive models for the production of SHN that can guide future experimental research. Systematic reaction studies leading to less heavy systems should be performed to constrain the models and decrease the extrapolation exercise. The totally unknown territory of super-heavy neutron-rich nuclei is enormous. As there is currently no way to synthesize superheavy neutron-rich systems, all information on these nuclei, also relevant for the understanding of the astrophysical r-process that in one way or other ends there, must come from theoretical predictions.

One of the most important atomic properties governing an element’s chemical behaviour is the energy required to remove its least-bound electron, referred to as the first ionization potential. For the heaviest elements, this fundamental quantity is strongly influenced by relativistic effects, which lead to unique chemical properties. Laser spectroscopy on an atom-at-a-time scale can probe the optical spectrum of neutral superheavy atoms near the ionization threshold. Those measurements can provide a stringent benchmark for state-of-the-art many-body atomic modelling that considers relativistic and quantum electrodynamics effects and paves the way for high-precision measurements of atomic properties of elements only available from heavy-ion accelerator facilities. Conversely, high-precision atomic many-body calculations are needed for the planning and evaluation of laser spectroscopy experiments on the lighter superheavy elements.

*Questions: What does* α *decay tell us about shape changes/transition and pairing? How to construct fully microscopic theories for*  *decay and fission?*

Theory predicts that with the synthesis of heaviest presently known nuclei the limit of the chart of nuclei has been pushed into a transitional region where ground-state shapes change from strongly prolate deformed through γ-soft and oblate shapes towards spherical configurations when approaching the end of the major proton and neutron shells. It can be expected that nuclei in this region will exhibit shape coexistence, similar to what is observed for lighter nuclei around spherical shell closures. Because of Coulomb frustration effects, for SHN there is the possibility of low-lying configurations with more exotic shapes than what is found for light nuclei. As the nuclear matrix element for  decay is reduced when the shapes of initial and final states are different, any change of shape between these nuclei will leave its fingerprint in a deviation of the empirical relation between -decay lifetimes and Q values. Similarly, a situation with shape coexistence can lead to preferred decays into excited states of the final nucleus. For odd and odd-odd nuclei, this effect will be interwoven with the additional hindrance effects related to transitions between different configurations at the same shape.

While phenomenological models of -decay in general well describe data and extrapolate similarly into the unknown, setting up a fully microscopic theory of  decay remains a formidable challenge for theory,

Contrary to the case of decay, predictions for spontaneous fission lifetimes of heavy nuclei often differ by many orders of magnitude when compared to experiment and also among each other. Among the reasons are large differences in predictions for heights and widths of fission barriers among models, and drastic approximations made when calculating the lifetimes. Efforts towards a consistent microscopic modelling of fission half-lives are underway, but even the most advanced numerical calculations have to make many idealizing assumptions to remain feasible. There are many fundamental open questions that need to be answered by theory, for example concerning the relevant collective degrees of freedom along the fission path, and the coupling of collective and single-particle degrees of freedom. From a computational point of view, the construction of a predictive and reliable microscopic model of the fission of heavy elements is a challenge in many respects. Having such a model for the fission of superheavy nuclei is also of prime importance for the reliable modelling of the astrophysical r-process.

*Questions: Fission defines the limits of existence for heavy nuclei. Are fission barrier heights the relevant property to characterise the stability against fission?*

Superheavy nuclei exhibit many decay channels that compete one with another. Their region of existence in the chart of nuclei, however, is ultimately limited by fission. This is quite different from lighter nuclei, where nuclear existence is in most cases limited by nucleon emission.

While stability against particle emission is trivially characterized through separation energies, the situation is much more complicated for fission. The fission barrier as such is a theoretical construct that cannot be directly measured. Also, the height of the energy barrier is only one among many other factors determining the lifetime. They all also depend on the excitation energy and the quantum numbers of the fissioning state. Fission barriers as extracted from experiment, however, are the parameters of a model adjusted to describe more complex data, often scanning large intervals in excitation energy for an unknown range of quantum numbers. It therefore remains an unanswered question how to connect experimentally deduced fission barriers with calculated ones.

More direct observables related to the fission process are the mass and kinetic energy distributions of the fragments. While kinetic energies can be obtained from the standard focal plane detector setups, mass distributions require dedicated setups. Could new detectors and digital pulse shape analysis be developed to perform Z and A identification of the heavy fragments at the focal plane of recoil separators or at dedicated decay stations?

Novel techniques like transfer-induced fission and similar surrogate reactions offer a more detailed picture of the fission dynamics giving access to observables like the competition of symmetric and asymmetric fission, multi-chance fission and their dependence on the experimentally established excitation energy. Systematic studies of the heaviest reachable fissioning nuclei have the potential to develop a deeper understanding of the fission process and the fission barriers involved.

*Questions: Which spectroscopic observables can one obtain? Is there any hope to do Coulomb excitation or inelastic electron scattering on (the lightest) superheavies in order to probe their deformation, in particular for even-even nuclei for which laser spectroscopy cannot provide quadrupole moments? How to relate charge radii to the predicted central depression in a model-independent way?*

To better constrain nuclear models in the region of SHN, new high-quality data on bulk and spectroscopic properties of superheavy systems are needed. It is particularly important to learn more about single-particle states, the role of pairing correlations, and the different shapes and excitation modes of the heaviest nuclei. Key observables such as energy, spin, parity, static and dynamic moments and charge radii of nuclear states are accessible via nuclear spectroscopy and hyperfine atomic spectroscopy techniques. The existence of isomers facilitates the study of the structure of these superheavy nuclei, since the decay of these metastable states gives a characteristic signal that is easily detectable and that populates states that are often inaccessible by other methods. In addition, *K*-isomers with their pre-condition of deformation are an interesting tool to trace the transition from the deformed SHN around Z=108 and N=152 to162 towards the spherical SHN predicted at higher Z and A, and to probe model prediction. As electron scattering off superheavy nuclei is a very challenging task, a simpler possibility to obtain at least a first insight into the effect of Coulomb frustration on density distributions would be to try to establish firm correlations between the central depression of the density and simpler observables within nuclear models.

Requirements for nuclear and atomic spectroscopy:

Given the extremely low production cross-sections and exploratory measurements, long beam times are required for these types of studies. Intense heavy and light ion beams are needed to maximize production and give access to new unknown nuclei. In order to separate the nuclei of interest from the other reaction products, efficient separators, with high rejection and short flight times are required. Mass sensitivity, either in-flight (like planned at S3) or after separation, is beneficial.

Search for new superheavy elements (SHE) is only possible in installations where there is a will to devote several months of beam time per year to a research program on SHN. In the coming years, only dedicated facilities such as SHE factory in Dubna, sRILAC in RIKEN and cw-linac in Darmstadt will have a chance to see new SHE. Could we foresee over several years a dedicated SHE program on the new LINAC and S3 in GANIL?

To perform hyperfine structure studies, prior knowledge of ionisation schemes is mandatory and requires additional, often long, irradiation times. Spectral resolutions of 100 MHz and fast and efficient transport systems should allow to extend the region of accessible nuclei to optical spectroscopy like it is planned with the REGLIS setup at S3.

For nuclear decay spectroscopy, sensitivity to all potential decay modes is crucial and requires an instrumentation that has low noise, is fast and has a large dynamic range. Compact detector arrays are being built at many facilities around the world (at S3 and S3-LEB, SHELS, TASCA, AGFA, FIONA…). Pulse shape analysis methods could probably aid in reducing background, enhance detector sensitivity and aid in particle identification.

For detection of prompt emissions at the target position, efficiency and count rate capabilities are important as well as the combination of γ and conversion electron spectroscopy. SAGE is the only multidetector, which meets this last criterion. Access to additional observables such as lifetimes, linear polarization, total energy and multiplicity is not yet always possible nowadays, but should become standard with the advent of ~3-4 tracking arrays such as AGATA. Lifetime measurements from plunger devices and Coulomb excitation require the use of inverse kinematics for these very heavy systems, while the use charge plungers (such as the one recently commissioned at MARA) requires further testing and simulations. Lifetime measurements of states populated by α decay can also be performed in a dedicated multi-electrode tower inside penning traps (such as MLL trap). In order to investigate the nucleonic density distributions of SHN, electron scattering experiments would be the way to go – however, this would require an electron-superheavy ion collider.

In all these cases, simulations of the setups and their response to typical decay cascades are required and geant4 or other simulation packages need to evolve and to be tested to accommodate physical processes beyond Z=99-100.

Requirements for nuclear theory:

Because of the unfavourable scaling of the computational cost of other more microscopic methods with system size, energy density functional methods will remain the main pillar of the consistent modelling of superheavy nuclei for many years to come, in particular concerning fission and dynamics. It is therefore of prime interest to push these models to maximum performance for applications on superheavy nuclei. On their most basic level of self-consistent mean-field calculations, these models offer an intuitive interpretation of the properties of heavy nuclei in terms of deformed shapes and shells. Beyond-mean-field techniques such as symmetry restoration and configuration mixing can then be used to respect selection rules for transitions and to describe correlations related to fluctuations in shape and other degrees of freedom. Over the years it has become clear that the performance of the presently used forms of energy functionals cannot be systematically improved further. Simultaneously, it has been realized that the formalism of beyond-mean-field methods imposes constraints on the form of functionals, which are not respected by the majority of the existing ones. Identifying a suitable and computationally efficient form of energy functional that offers all relevant degrees of freedom is a crucial task for the further advancement of the modelling of all nuclei, not just superheavy ones. In parallel, it is desirable to systematically use symmetry-unrestricted configurations to study the potential role of exotic shapes and the role of the orientation of angular momenta of excited states relative to the nuclear shape. At present this is rarely done, mostly for reasons of computational cost of performing such calculations and human investment needed to update the solvers for all presently used types of energy functionals. Similarly, it is highly desirable to systematically perform beyond-mean-field calculations based on such symmetry-unrestricted configurations, which at present is only done for exceptional cases. Besides the fundamental questions concerning the suitable form of energy functional that need to be answered, this requires further developments in efficient algorithms. The improvement of these methods to the description of fission half-lives is a sub problem of the much larger on-going quest for a predictive theory of fission dynamics for arbitrary initial conditions. At the extreme limit of the nuclear chart, the predictions of the single particle structure of SHE strongly depends on the quality of the models and the precision of the experimental anchor points used to set the potentials or the parameters of the functionals. The influence of the uncertainties of these experimental inputs on the theoretical predictions should also be studied.

There is, however, also an interest in developing and testing novel ideas for the efficient separation of relevant from less relevant degrees of freedom in ab-initio-based microscopic theories with the overall goal of reducing their numerical cost such that they will become available at least for benchmark calculations of very heavy systems. One possible and promising route is to profit from the same use of symmetry breaking and restoration that is at the core of energy density functional methods, with the difference that the symmetry-breaking configurations would already be correlated states. Besides offering valuable insight into our understanding of large nuclei from first principles, having such tools can be used to connect the parameterization of energy density functionals to the first principles of the strong interaction and the quantal many body problem.

Strategy

1. Push the program at SHELS to the limits of the instrument
2. Upgrade GABRIELA for L-X-rays measurement and full digital operation
3. Search for new SHE within international collaborations
4. Continue to develop a multi-nucleon transfer program (at VAMOS, ANL, Dubna and Riken) with identification of all produced isotopes
5. Start the program on S3-SIRIUS & LEB with competitive beams
6. Build AGATA 3-4  or GRETA in order to gain 1-2 orders of magnitude in cross section for prompt spectroscopy studies (over JUROGAM-RITU or GAMMASPHERE-AGFA)
7. Perform complete decay spectroscopy and measurement of branching-ratios for available nuclei with SIRIUS (needs several months of beam time per year)
8. Measure barrier distributions for SHE reaction of interest as it was done at RIKEN
9. Systematic measurement of excitation functions in the available systems coupled to any performed experiment
10. Develop target backings and target systems (S3 actinide target station, spoke-less rotating targets such as the one developed by IPHC for JUROGAM) compatible with expected intensities for SHE program and push S3 to Z=110-112
11. Bridge the gap between cold and hot fusion around Z=110
12. Develop A/Q=7 and high intensity metallic beams
13. Push SIRIUS towards Z = 118 for spectroscopy and LEB to Sg for moment and charge radii + mass measurements with MR-ToF-MS
14. Transfer transactinides to DESIR for Penning trap measurements.