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Challenging nuclear structure of the heaviest – opportunities at S^3

Dieter Ackermann[1,*] on behalf of the S^3 collaboration

[1]Grand Accélérateur National d'Ions Lourds – GANIL, CEA/DRF-CNRS/IN2P3, Bd. Becquerel, BP 55027, F-14076 Caen, France

Abstract. After more than half a century of research addressing the synthesis and nuclear structure of superheavy nuclei (SHN) a boost for its progress is expected from the advent of new instrumentation. An order of magnitude in beam intensity increase is envisaged to be provided by new powerful accelerators like the new DC280 cyclotron at the SHE factory of FLNR/JINR or the superconducting linac at SPIRAL2 of GANIL. In addition new ion-optical installations like the separator-spectrometer set-up S^3 with two complementary detection systems SIRIUS and LEB will provide a substantial sensitivity increase for classically pursued routes like decay spectroscopy after separation (DSAS), and alternative and complementary methods like high precision mass measurements and laser spectroscopy. Decay spectroscopy has proven in the past to be a powerful tool to study the low lying nuclear structure of heavy and superheavy nuclei. Single particle levels and other structure features like K isomerism, being important in the fermium-nobelium region as well as for tracing deformation towards spherical shell stabilised SHN, have been investigated almost up to the limit posed by the sensitivity of present-day instrumentation. Precision mass measurements and laser spectroscopy will offer the possibility to study alternative features like atomic and nuclear binding energies, nuclear charge radii and quadrupole moments.

1 Achievements in SHN research and challenges

Nuclei beyond fermium-rutherfordium owe their existence solely to quantum mechanics. In that region of the chart of nuclei the fission barrier derived from a macroscopic liquid drop approach would vanish [1], which gives rise to the nuclear physicists definition of a superheavy nucleus (SHN). These quantum mechanics features, often referred to as shell effects and taken into account as shell corrections in so called microscopic-macroscopic models (see e.g. [2]), lead to a modification of the nuclear potential which is the basis for the extension of the chart of Segré to high Z and A. This makes these nuclei, in turn, an ideal laboratory to study the strong nuclear interaction by in-beam methods as well as decay spectroscopy after separation (DSAS) [3]. The nuclear structure investigation discussion in this paper will be restricted to DSAS of these deformed nuclei in the region Z=100-112 and N=152-162. These studies have the potential to provide links to the next heavier spherical closed shell nuclei, by investigating single particle levels [4] close to the fermi energy which according to some models play a major role in defining the spherical shell gaps in the region of the so-called *island of stability*. For in-beam spectroscopy which gives access to nuclear structure at higher spins like e.g. rotational bands, we refer to the recent review by Theisen et al. and references therein [5].

Particularly interesting features like K isomers, can be used to trace the spherical superheavy nuclei (SHN) and to locate the island of stability [7]. A number of cases have been found in the region of fermium isotopes and beyond mainly for isotopes of all even-Z elements up to darmstadtium (Z=110) apart from seaborgium (Z=106), but also for some even-odd and odd-odd nuclei. High intensity accelerators, targets withstanding those high beam intensities and, in particular, actinide targets [8], efficient in-flight separators and spectrometers, and highly efficient detectors with fast electronics are the essential ingredients for the success of the field. The new SPIRAL2 facility with the separator-spectrometer set-up S3 [6] presently under construction at the accelerator laboratory GANIL in Caen, France, will offer great perspectives for the field [7]. At this facility a number of ground breaking experiments are envisaged, including DSAS examining features like the single particle structure, deformation and the search for K-isomers for those exotic nuclear species.

The experimental tools employed in the field, composed of highly efficient and selective separators and spectrometers combined with highly sensitive detection arrays for particles and photons, are recently complemented by alternative approaches with precision mass measurements, using devices like Penning traps [9] and Multi-Reflection Time of Flight Mass Spectrometers (MR ToF MS), and laser spectroscopy installations [10], which give access to basic properties of those heavy nuclei like binding energies, charge radii and quadrupole moments. The existing facilities like e.g. SHIP with its Penning trap set-up SHIPTRAP and the gas-filled separator TASCA at GSI in Darmstadt, Germany, RITU and the MARA set-up at the cyclotron laboratory of the University of Jyväskylä,

*e-mail: Dieter.Ackermann@ganil.fr

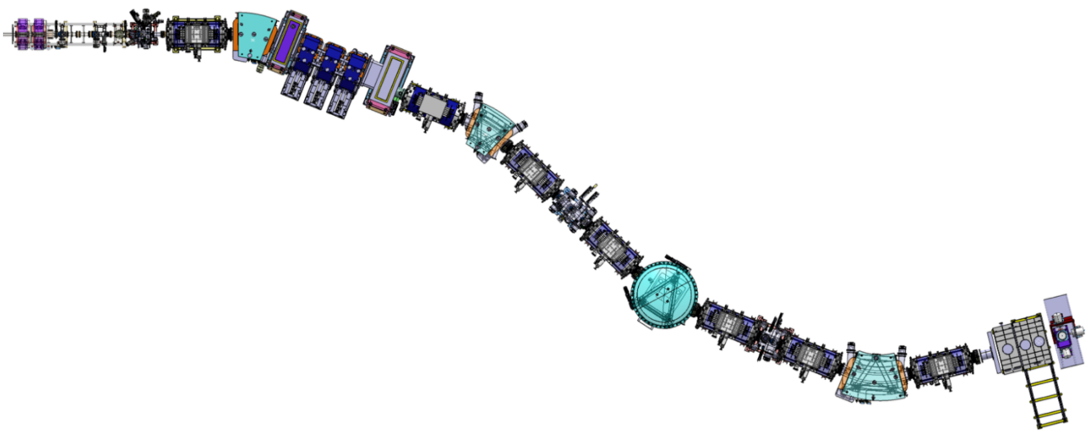

Figure 1. Technical drawing of the arrangements of the ion optical components of S^3, consisting of three magnetic dipoles, one electric dipole, a room-temperature quadrupole triplet and seven super-conducting multiplets (SMT), in a QQQ-MD-QQQ-QQQ-MD-QQQ-QQQ-ED-QQQ-QQQ-MD-QQQ configfuration [6].

Finland, SHELS (former VASSILISSA) at FLNR/JINR in Dubna, Russia or BGS at LBNL, will soon be joined by the Superconducting Separator-Spectrometer set-up S^3 of SPIRAL2 at GANIL in Caen, France. This new facility will profit from high beam intensities similar to the ones expected from the new DC280 cyclotron of the SHE-factory, in operation since recently at FLNR/JINR, and the highly sensitive decay spectroscopy set-up SIRIUS, and low energy branch (LEB) instrumentation.

In a special issue of Nuclear Physics A in 2015, volume 944, all major topics concerning the field of superheavy element (SHE) research have recently been reviewed. Asai and collaborators [4] summarised the recent achievements of DSAS for isotonic chains in the vicinity of the closed neutron subshell N=152 in a region ranging from fermium to meitnerium. A general problem to investigate single particle states is the admixture of other components to the initial and final states for which transitions are observed. In regions of low level density, however, the single-particle character is enhanced. Moreover, a spin and parity assignment is supported by the selectivity provided by transition selection rules in stepwise construction of level schemes, built on states for which quantum numbers are known. A more realistic picture can be achieved by employing models which take into account correlations beyond the single particle picture by coupling to the relevant configurations which involve e.g. vibrational states. In particular, the N=151 and 153 isotones with one hole in and one particle more than the sub-shell closure, respectively, are suited to trace single particle levels which are important for the predicted spherical shell gaps.

Deformation, as present in the region of deformed shell stabilised nuclei around Z = 100 to 108 and N = 152 to 162, gives rise to a class of metastable states at high values of K. The K quantum number is defined by the projection of the total spin, i.e. the sum of the nuclear spin and the orbital angular momenta of quasiparticle states excited in the nucleus, on the symmetry axis of a deformed nucleus. In cases of high K numbers, isomeric states can be caused by a large difference in angular momentum and possibly opposite parity of the isomeric state and the next available state into which the isomer can decay. Such isomeric states have been predicted for the whole region of deformed heavy and superheavy nuclei [11].

The heaviest nucleus for which such an isomeric state has been observed is ^{270}Ds [12]. Recently such a state has been reported also for its α decay daughter ^{266}Hs [13]. For both nuclei the isomeric state is longer lived than the g.s., a feature which is rarely occurring in atomic nuclei. As the necessary precondition for the formation of K isomers is nuclear deformation, their development towards increasing Z can be used to trace deformation towards the predicted spherical shell stabilised SHN for which it should vanish. Together with the nuclear structure information gained from the respective implications of the involved quasiparticle states which form those metastable states, this can be used to develop and adjust theoretical model predictions to eventually localise the long sought for *island of stability* of SHN. Table 2 in ref. [7] lists as an update of the table from [14] of known K-isomers in even-even nuclei in heavy and SHN in the region from curium to darmstadtium. An outlook into the expectations for higher Z and the next deformed neutron shell gap is given by V. Prassa et al. [15]. Employing Energy Density Functional (EDF) calculations, they predict a particular pattern for high K states in N=162 isotopes with respect to their neighbours for isotopic chains from rutherfordium to darmstadtium. For those the low lying neutron single-particle states predicted at excitation energies below 1 MeV for the neighbours are elevated to higher energies. The resulting low energy gap is a feature which should observable experimentally.

2 Opportunities at S^3

As the heart of the new SIRAL2 facility at GANIL in Caen, France, a high intensity super conducting linear accelerator (SC LINAC) is presently under construction with specifications which respond to the need of highest intensities [16]. The planned intensities for the two envisaged construction phases are listed in ref. [3, 16]. The superconducting separator spectrometer (S^3) set-up [6] combined with the decay spectroscopy detection array SIRIUS (Spectroscopy and Identification of Rare Isotopes Using S^3) in combination with the high intensity beams from SC LINAC will be one of the most powerful facilities for SHN/SHE research worldwide together with the SHE Factory presently under construction at JINR/FLNR.

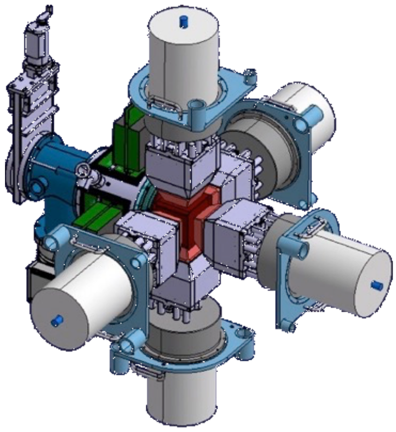

Figure 2. Technical drawing of the mechanical arrangement for the DSAS detection array SIRIUS, consisting of a Double-sided Si Strip Detector (DSSD), surrounded by silicon detectors with an adopted pad structure for the detection of α particles escaping from the the implantation detector, fission fragments and conversion electrons (CE), surrounded by large-volume germanium detector for γ ray detection

The community of scientists interested in exploiting the capabilities of the SC LINAC-S^3 facility for SHN/SHE research has over the years developed their envisaged research topics in various letters of intent. The possible features for the various heavy and superheavy nuclei range from evaporation residue (ER) cross section measurements to detailed spectroscopy topics like K isomerism, α fine structure, or γ, conversion electron (CE) and X-ray spectroscopy. The latter has the potential of settling the still open question of Z identification for the heaviest nuclei produced in ^{48}Ca induced reactions for the first time at the FLNR (see e.g. reference [17, 18]), due to the precise prediction capabilities for atomic transitions by theory. A summary of the collected ideas together with a description of the facility and the state of the art of the development at that time can be found in [19].

The detection instrumentation of two complementary set-ups in the focal plane of S^3 consists of the particle and photon detection array for DSAS, SIRIUS and the S^3 Low Energy Branch (LEB) for precision mass measurements and laser spectroscopy. SIRIUS is composed of a combination of a box-like arrangement of silicon detectors in a thin aluminium housing which is transparent for γ radiation and can be surrounded by an array of large volume Ge detectors. Tracker detectors in beam direction before the Si array serve for veto and time-of-flight purposes. Fig. 2 shows an overview of the set-up. Apart from allowing for the investigation of K-isomers, isotopic and isotonic trends of low lying nuclear excitations by exploiting γ-electron-α/fission and X-ray coincidences, SIRIUS is also an ideal tool to study delayed processes like isomeric states and β-delayed fission. The S^3 LEB consists of a combination of a gas-stopping cell, various ion guides, a laser spectroscopy installation and a Multi-Reflection Time-o-Flight Mass Spectrometer (MRTof MS), which can be combined with additional particle and photon detectors. It will be used to study nuclei in the N=Z region as well as the heaviest nuclear species.The major components of the LEB mounted as an almost complete set-up in a test laboratory at LPC Caen, is shown in Fig. 3.

In a farer future the synthesis and investigation of, also so far unknown, highest-Z systems is envisaged, for which the earlier experiments will establish the fundament. A necessary prerequisite for his type of research is a new injector for the SC LINAC with the capability to accelerate ions with an A/Q ratio of 7 which will allow for the treatment of ions up to uranium. The present A/Q = 3 injector causes efficiency losses for ion masses beyond 40 to 50.

In a recent meeting of the S^3 community in June 2018 the day one experimental campaign at S^3 has been discussed in further detail. In preparation of this meeting a call for so-called pre-proposals, providing a detailed scientific and technical discussion of realistically feasible experiments, was launched. It resulted in the submission of eleven projects for both focal plane instrumentation arrangements. For an appealing S^3 "day 1" program the five most promising submissions, concerning scientific excellence, feasibility and uniqueness, were chosen. The resulting projected campaigns comprise for the LEB, apart from mass measurements and laser spectroscopy in lighter nuclei in the A = 80 to 100 region, high-resolution in-gas laser spectroscopy and deformation studies for various actinides, and the investigation of fundamental properties of nuclei in the vicinity of the deformed shell gaps at Z = 100 and N = 152. For SIRIUS the exploration of the limits of stability in the vicinity of the proton drip line in the fermium-nobelium region, the search for new heavy isotopes, the more detailed investigation of known and the search for new isomeric states, and the investigation of odd-Z nuclei are the building blocks of this envisaged first DSAS campaign at S^3.

The laboratories primarily involved in this work are: Grand Accélérateur National d'Ions Lourds (GANIL), Institut de Recherche sur les Lois Fondamentales de l'Univers (CEA, IRFU), Institut de Physique Nucléaire d'Orsay (IPNO), Institut Pluridisciplinaire Hubert Curien (IPHC), Centre de Sciences Nucléaires et de Sciences de la Matière (CSNSM), Argonne National Laboratory (ANL), KU Leuven, Laboratoire de Physique Corpusculaire de Caen (LPC), and the Institut des NanoSciences de Paris (INSP).

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Figure 3. Photograph of the S^3 LEB set-up as presently mounted in a test laboratory at LPC Caen. The MRToF MS set-up in the left foreground is completed by the laser spectroscopy arrangement in the background of the picture.

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