BASIC NUCLEAR STRUCTURE FEATURES OF SHN AND PERSPECTIVES AT S^{3*}

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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 such as 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 such as 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 the route towards spherical shell stabilised SHN, have been investigated almost up to the limit posed by the sensitivity of the present-day instrumentation. Precision mass measurements and laser spectroscopy will offer the possibility to study alternative features such as binding energies, charge radii and quadrupole moments. At the magnetic spectrometer VAMOS of GANIL with the recently improved mass resolution and the development of Z identification, deep-inelastic reactions like multi-nucleon transfer can be used to reach more neutron-rich nuclei in the region of light actinides, possibly being extended towards higher Z.

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1. Introduction

Nuclei beyond fermium–rutherfordium owe their existence solely to quantum mechanics, where the fission barrier in a liquid drop approach would vanish, 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.* [1]), 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 [2]. The nuclear structure investigation discussion in this paper will be restricted to decay spectroscopy after separation (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 [3] 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.* [4] and references therein.

Particularly interesting features like K-isomers, can be used to trace the spherical superheavy nuclei (SHN) and to locate the island of stability [5]. 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 nuclei (see figure 4). High intensity accelerators, targets withstanding those high beam intensities and, in particular, actinide targets, 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 and, in particular, the separator-spectrometer setup S^3 [6] presently under construction at the accelerator laboratory GANIL in Caen, France, will offer great perspectives for the field [5]. At this facility, a number of ground breaking experiments are envisaged, including DSAS examining features such as 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 such as Penning traps [7] and multi-reflection time-of-flight spectrometers (MRToF), and laser spectroscopy [8], which give access to basic properties of those heavy nuclei such as binding energies, charge radii and quadrupole moments. The existing facilities such as *e.g.* SHIP with its Penning trap 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, 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, presently being completed at FLNR, and the highly sensitive decay spectroscopy set-up SIRIUS, and low energy branch (LEB) instrumentation.

Some of the recent achievements obtained by DSAS revealing the low-lying nuclear structure of heavy and SHN will be discussed in Section 2. K isomerism occurring for the heaviest deformed nuclear species will be the subject of Section 3. The planned investigation of binary reactions at the spectrometer — γ-ray array combination VAMOS+AGATA will be outlined in Section 4. An outlook showing the opportunities offered in the near future at S^3 will be given in Section 5, showing the perspectives offered by the progress in the development of existing instrumentation, and by the advent of new installations presently under construction like *e.g.* S^3 at SPIRAL2/GANIL.

2. Decay Spectroscopy After Separation — DSAM — for heavy and superheavy nuclei

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 [3] 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. The Nilsson diagram in figure 1 shows the situation for calculated neutron single particle trends in the vicinity of $N = 152$.

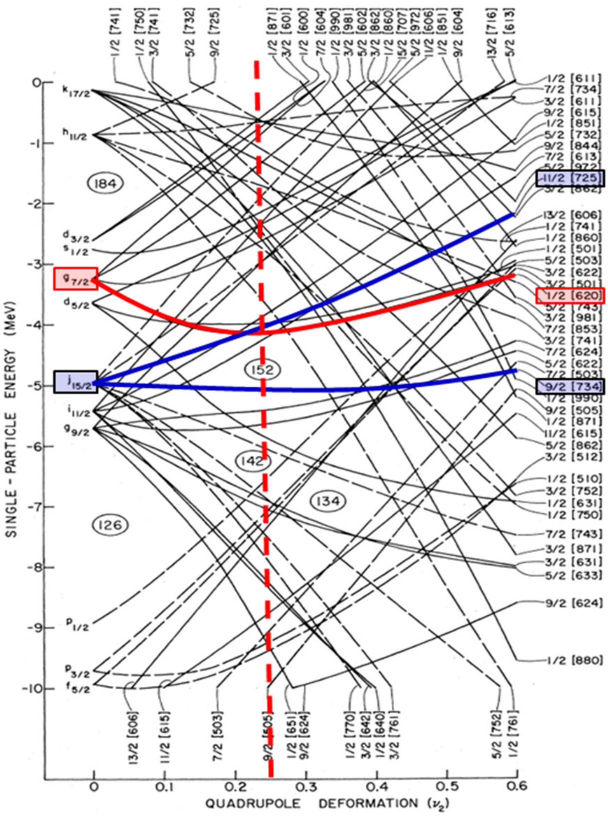

Fig. 1. Neutron single particle energies as a function of quadrupole deformation from a momentum-dependent Woods–Saxon model by Chasman *et al.* [9]; figure was taken from there and adopted as in reference [2].

To illustrate a possible single particle scenario by an instructive example, three single particle levels (SPL) are indicated in figure 1. Here, two SPL, $9/2^-$[734] and $11/2^-$[725], are highlighted, originating from the $j15/2$ shell which is degenerate at sphericity. The $9/2^-$[734] Nilsson level constitutes the g.s. in the $N = 151$ isotones from plutonium to hassium, shown in figure 7 of Ref. [3]. There, experimental values are compared to various microscopic–macroscopic and self-consistent models. As indicated in figure 1, it defines in that region at a deformation of ≈ 0.25 the $N = 152$ shell gap, together with the $11/2^-$[725] SPL. The third highlighted SPL, the $1/2^-$[620], originates from the $g7/2$ shell and crosses the $11/2^-$[725] at the same deformation. It forms the ground state (g.s.) of the $N = 153$ isotones for the same elemental range (see figure 9 in Ref. [3]). Whereas the $11/2^-$[725] SPL has been experimentally determined for the $N = 153$ isotones, it was seen for the $N = 151$ isotones up to now only for ^{255}Rf. The $1/2^+$[620] SPL was measured only for the lighter $N = 151$ isotones up to ^{251}Fm. The observation of both SPLs in ^{253}No is, therefore, a key issue for the determination of their possible crossing and, hence, the confirmation of this peculiar behaviour predicted by theory on the same grounds as the prediction of the neutron shell closure for the spherical SHN at $N = 184$. In a recent DSAS attempt studying levels populated by α decay of ^{257}Rf, only the population of the $7/2^-[743]$ SPL in ^{253}No could be established, in a short run at the velocity filter SHIP at GSI [10].

Apart from α decay, ^{257}Rf has an EC decay branch into ^{257}Lr with branching ratios $b_{\rm EC}$ of 0.094 ± 0.014 and 0.115 ± 0.015 for the g.s. and the isomer decay, respectively [10]. The subsequent α decay then populates the g.s. and excited states in ^{253}Md, providing access to the low-lying structure of this odd-Z even-A isotope. This data is shown together with the at present known experimental nuclear structure information of odd-Z odd-A isotopes in the region from einsteinium to dubnium in figure 2 [2]. An interesting feature here was pointed out by Heßberger *et al.* [11] with the consistent behaviour of the energy difference for the two SPLs $7/2^-[514]$ and $7/2^+[633]$ in einsteinium isotopes and the g.s. deformation of these nuclei, predicted by the microscopic–macroscopic model calculations by Parkhomenko and Sobiczewski [12] (see figure 3).

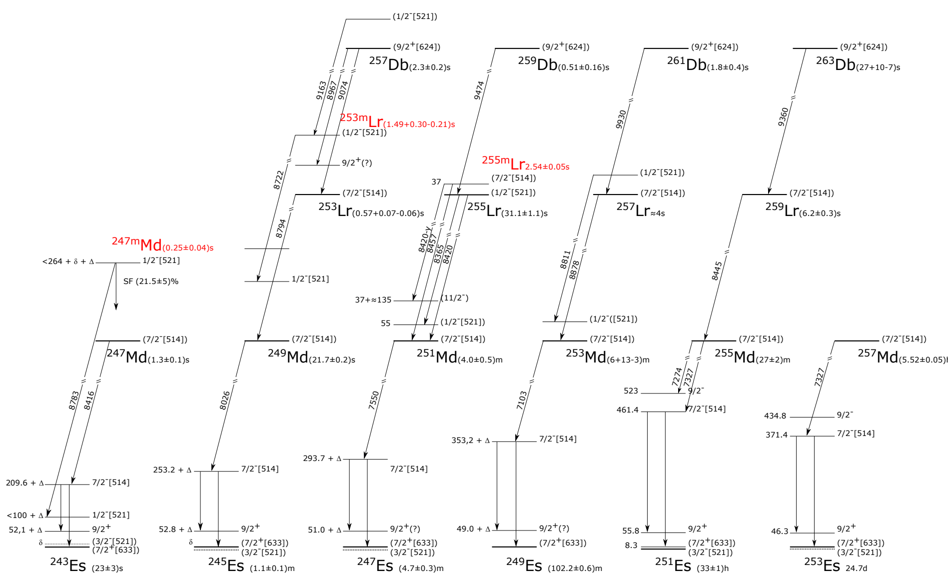

Fig. 2. Decay scheme for odd-Z isotopes from einsteinium to dubnium in the vicinity of the $N = 152$ closed shell. For the origin of the data, see references in [2]. (Figure taken from reference [2].)

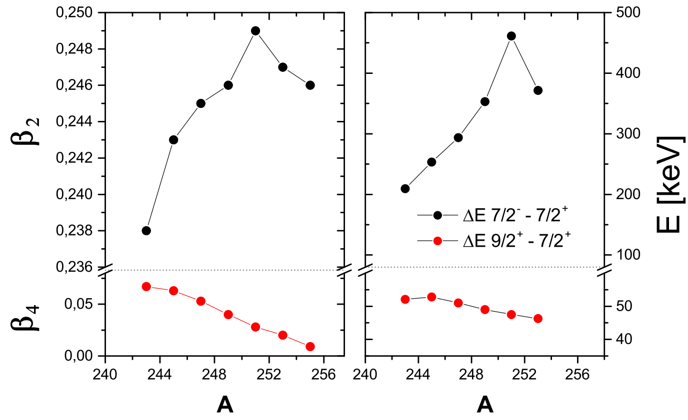

Fig. 3. Comparison of the energy differences of the lowest levels in the isotopes ^{243}Es to ^{253}Es (see figure 2) with quadrupole and hexadecapole deformation obtained by a macroscopic–microscopic model calculation [12]. See also Heßberger *et al.* [11]. (Figure taken from reference [2].)

3. *K* isomerism in heavy and superheavy nuclei

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 [13].

The heaviest nucleus for which such an isomeric state has been observed is ^{270}Ds [14]. Recently, such a state has been reported also for its α decay daughter ^{266}Hs [15]. 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 stabilized 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 localize the long sought for *island of stability* of SHN. Table 2 in Ref. [5] lists as an update of the table of known K-isomers in even–even nuclei in heavy and SHN from [16] the known K isomeric states in the region from curium to darmstadtium. A summary of observed K-isomers in that region is shown in figure 4. An outlook into the expectations for higher Z and the next deformed neutron shell gap is given by Prassa *et al.* [17]. 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.

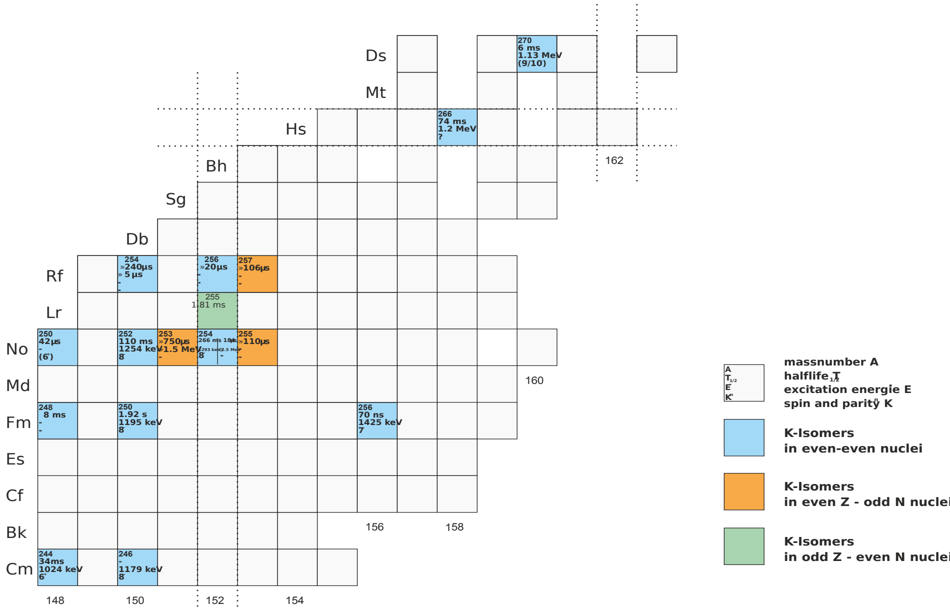

Fig. 4. Excerpt of the chart of nuclides indicating the K-isomers observed for heavy nuclei in the region $Z \geq 96$. Half-life, decay energy, spin and parity values are given for K-isomers only. (Figure and caption are taken from reference [2].)

4. Binary reactions — an alternative approach

Despite the recent success in synthesis of new elements culminating in the detection of decay chains assigned to element 118 oganesson [18], the perspectives to push the applied reaction scheme of fusion–evaporation even further are rather limited. In particular, neutron-rich actinides and transfermium isotopes cannot be produced in complete fusion reactions due to the lack of sufficiently neutron-rich projectile–target combinations. An alternative method to produce neutron-rich heavy systems has been proposed by Zagrebaev *et al.* [19, 20], with the employment of deep-inelastic collisions of heavy nuclei. In an early chemistry experiment, Schädel *et al.* [21] could observe the production of isotopes from Pu to Fm in a cross-section range from mbar to nbarn for the reaction ^{238}U+^{238}U. The neutron-rich part of these isotope chains reaches into close vicinity of the $N = 152$ sub-shell closure. Predictions of the Langevin model by Karpov *et al.* [22] suggest for this reaction that multi-nucleon transfer could populate nuclei having additional 5 nucleons, protons and neutrons, with a cross section of about 1 μbarn in the final exit channel, which would correspond for the uranium isotopic chain to ^{243}U, being one neutron short of 152. This would open those isotopes for in-beam nuclear structure studies at the large solid angle magnetic spectrometer VAMOS in combination with the multi-detector γ-tracking array AGATA. The mass resolution of $\Delta A = 1/500$, recently achieved for VAMOS [23], together with a Z identification by X-rays should provide the necessary identification in A and Z to extend the use of isotope-tagged γ-ray spectroscopy further towards $N = 152$. In a recent investigation of the reaction ^{136}Xe+^{238}U at the combination of the magnetic spectrometer PRISMA at LNL and AGATA, Birkenbach *et al.* could establish a rotational band up to 20–24 $\hbar$ for ^{240}U [24]. The heaviest uranium isotope, ^{242}U, for which the first 2^+ state is known, is two neutrons away from $N = 152$ [25]. An experiment to study the reaction ^{238}U+^{238}U has been accepted by the GANIL Program Advisory Committee (PAC) and is planned to be carried out in the nearest future at VAMOS+AGATA. To extend the reach of this type of measurements to higher Z, heavier actinide targets like *e.g.* ^{248}Cm [26] are needed.

5. Outlook: 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 [27]. The planned intensities for the two envisaged construction phases are listed in Ref. [2, 27]. 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.

The community of scientists interested in exploiting the capabilities of the SC LINAC-S^3 facility for SHN/SHE research has developed and presented its scientific program to be pursued in various letters of intent. A summary is given in Table I [2, 5]. The possible features to be studied by this initiative for the various heavy and superheavy nuclei range from evaporation residue (ER) cross-section measurements to detailed spectroscopy topics such as K isomerism, α fine structure or 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.* references [18, 28]), due to the precise prediction capabilities for atomic transitions by theory.

TABLE I

Proposed nuclei for "day 1" experiments at S^3 and for the phase 1++ when an injector with the capability to prepare ions with $A/Q = 6$ or 7 will be available at the SC LINAC presently under construction at the SPIRAL2 facility of GANIL. Courtesy of the S^3 Collaboration. (Table and caption are taken from reference [2].)

Nuclide	Reaction	Feature	Reference x-section [pbarn] (ER)	Rate [h^{-1}]	No. of events per 7 days
^{254}No	^{48}Ca+^{208}Pb	K-isomer	2×10^6	6×10^4	6×10^7
^{256}Rf	^{50}Ti+^{208}Pb	K-isomer	17×10^3	550	540.000
^{266}Hs	^{64}Ni+^{207}Pb	ER	15 (^{270}Ds)	0.34	285
^{266m}Hs	^{64}Ni+^{207}Pb	K-isomer	15 (^{270}Ds)	0.01	12.5
^{270}Ds	^{64}Ni+^{207}Pb	ER	15	0.45	380
^{270m}Ds	^{64}Ni+^{207}Pb	K-isomer	15 (^{270}Ds)	0.22	190
^{262}Sg	^{64}Ni+^{207}Pb	α-decay	15 (^{270}Ds)	0.02	25
^{276}Cn	^{70}Zn+^{207}Pb	K-isomer	0.5 (^{277}Cn)*	0.01	12.5
^{288}Mc	^{48}Ca+^{243}Am	ER	10	0.3	300
^{288}Mc	^{48}Ca+^{243}Am	L X-rays	10	1.8**	1800**

*As no experimental value is known for ^{276}Cn the one for ^{277}Cn is given, assuming a similar situation as for ^{270}Ds/^{271}Ds.
**Esimate from the L/K X-ray detection efficiency ratio in a lighter system and the assumption of the observation of 1 K X-ray in 23 decay chains from [29].

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 such as isomeric states and β-delayed fission. In addition, a low-energy set-up including a gas stopping cell, laser spectroscopy instrumentation and a multi-reflection time-of-flight spectrometer (MRToF) will be used to study nuclei in the $N = Z$ region as well as the heaviest nuclear species. 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.

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