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Nuclear structure of superheavy nuclei – state of the art and perspectives (@ S^3)

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Abstract. Decay spectroscopy is a powerful tool to study the low lying nuclear structure of heavy and superheavy nuclei (SHN). Single particle levels and other structure features like K isomerism, being important in the fermium-nobelium region as well as for the spherical shell stabilized SHN, can be investigated. The new separator-spectrometer combination S^3, presently under construction at the new SPIRAL2 facility of GANIL, Caen, France, together with the high intensity beams of SPIRAL2's superconducting linear accelerator (SC LINAC), will offer exciting perspectives for a wide spectrum of nuclear and atomic physics topics. The installation is designed to employ nuclear physics methods like decay spectroscopy after separation or atomic physics methods like laser spectroscopy and mass measurements. The nuclear physics studies will include particle and photon correlation studies, attacking the open questions in the field, which have been revealed in earlier studies at facilities like e.g. GSI in Darmstadt, Germany, with the velocity filter SHIP and the gas-filled separator TASCA, the cyclotron accelerator laboratory of the University of Jyväskylä, Finland, with RITU and its numerous auxiliary detection set-ups, and FLNR/JINR in Dubna with the DGFRS and VASSILISSA/SHELS separators.

1 Introduction

Heavy nuclear systems in the region of the chart of nuclides starting at fermium and extending towards the predicted area of shell stabilized superheavy nuclei (SHN) owe their existence to quantum mechanical effects only. A liquid drop of a system with more than 100-104 protons becomes unstable against fission mainly due to the repulsive Coulomb force created by the high density of the many positive charges in the limited volume of the nucleus. Quantum mechanic 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, to an ideal laboratory to study in detail the quantum mechanic nature of the strong nuclear interaction which is responsible for this. The experimental tools for their investigation are traditionally decay spectroscopy after separation (DSAS) and since the end of the last millennium more and more in-beam spectroscopy, made possibly by major advances in detection technology and signal processing by so called digital electronics [2].

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While in-beam nuclear structure studies will not be discussed here, some 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, and an outlook will be given in section 4, showing the perspectives offered by the progress in the development of existing instrumentation and by the advent of new installations presently under construction like the Superconducting Separator Spectrometer S^3 at SPIRAL2/GANIL.

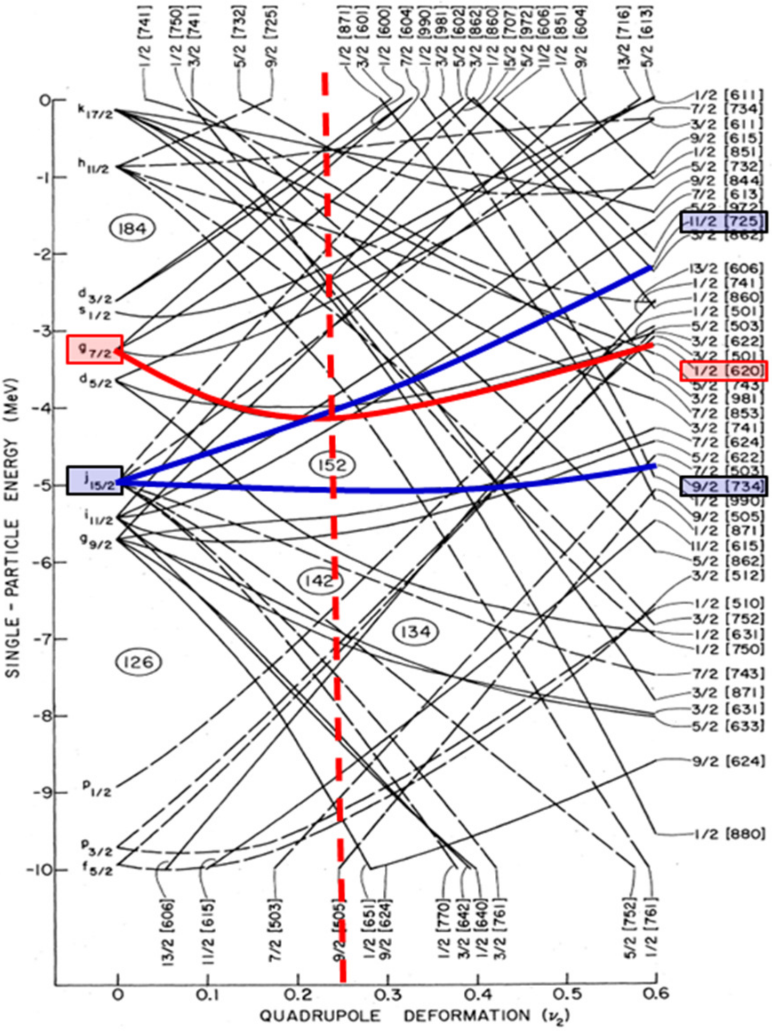

Figure 1. Neutron single particle energies as a function of quadrupole deformation from a momentum-dependent Woods-Saxon model by R.R. Chasman et al. [3]; figure was taken from there and adopted as in reference [2].

2 Systematic study of nuclear structure features

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] summarized the recent achievements of DSAS for isotonic chains in the vicinity of the closed neutron subshell N=152 in a region ranging form fermium to meitnerium. In particular, the N=151 and 153 isotones with one hole in and one particle more than the subshell closure, respectively, are well suited to trace single particle levels which are important for the predicted spherical shell gaps. This can be seen in the Nilsson diagram in figure 1.

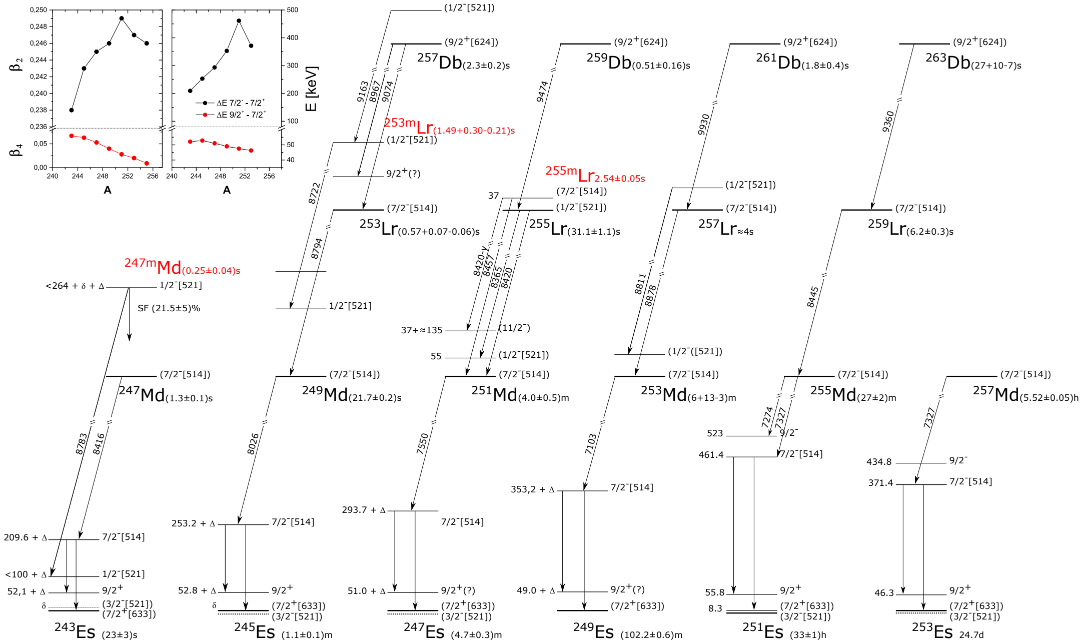

Figure 2. Decay scheme for odd-Z isotopes from einsteinium to dubnium in the vicinity of the N=152 closed shell. For the origin of the data see references in [2]. For the ground state (g.s.) assignment for ^{243}Es, the presentation of Antalic et al. has been chosen who propose two possible scenarios [5]. For the shown case with the $\pi 7/2^+[633]$ Nilsson level being the g.s, δ would be the excitation energy of the $\pi 3/2^-[521]$ level and Δ=0. For the opposite assignment Δ would be the excitation energy of the $\pi 7/2^+[633]$ state. For the other einsteinium g.s. assignments the representation of [6] has been adopted here. Insert (top left): Comparison of the energy differences of the lowest levels in the isotopes ^{243}Es to ^{253}Es (see main part of this figure 2) with quadrupole and hexadecapole deformation obtained by a macroscopic-microscopic model calculation [7]. See also Heßberger et al. [8]. (Figures and captions are taken from reference [2])

To illustrate this by an instructive example, three single particle levels (SPL) are indicated in figure 1. Two of them originate from the j15/2 shell which is degenerate at sphericity. The 9/2⁻[734] Nilsson level constitutes the ground state (g.s.) in the N =151 isotones from plutonium to hassium, shown in figure 7 of ref. [4], where 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 1/2⁻[620] SPL, originating

Table 1. Update of the table of known K-isomers in even-even nuclei in heavy and SHN from [10] as given in [11]. (Table and caption are taken from reference [2])

nucleus	K^π	$T_{1/2}$	E_x	detected decay	configuration	reference
^{244}Cm	6^+	34 ms	1.040 MeV	γ	$5/2^+[622]_\nu \otimes 7/2^+[624]_\nu$	[12, 13]
^{246}Cm	8^-	-	1.179 MeV	γ	$7/2^+[624]_\nu \otimes 9/2^-[734]_\nu$	[14]
^{248}Fm	(6^*)	$\simeq$8 ms	-	γ		[15, 16]
^{250}Fm	8^-	1.92 s	1.195 MeV	γ	$7/2^+[624]_\nu \otimes 9/2^-[734]_\nu$	[17]
^{256}Fm	7^-	70 ns	1.425 MeV	γ,SF	$7/2^+[633]_\pi \otimes 7/2^-[514]_\pi$	[18]
^{250}No	(6^+)	42 μs	-	SF,γ?	$(5/2^+[622]_\nu \otimes 7/2^+[624]_\nu)$	[19]
^{252}No	8^-	110 ms	1.254 MeV	γ	$7/2^+[624]_\nu \otimes 9/2^-[734]_\nu$	[20]
^{254}No	8^-	266 ms	1.293 MeV	γ	$7/2^-[514]_\pi \otimes 9/2^+[624]_\pi$	[21, 22]
	8^-	263 ms	1.297 MeV	γ	$9/2^-[734]_\nu \otimes 11/2^-[725]_\nu$	[23]
^{254}No	-	184 μs	$\simeq$2.5 MeV	γ	-	[21, 22]
	-	184 μs	2.928 MeV	γ	-	[23]
^{254}Rf	6,7	5 μs	$\simeq$? MeV	IC^1	2-quasiparticle	[24]
^{254}Rf	6,7	240 μs	$\simeq$? MeV	IC^1	4-quasiparticle	[24]
^{256}Rf	6,7	25 μs	$\simeq$1.12 MeV	IC^1	-	[25]
^{256}Rf	10^+	17 μs	$\simeq$1.4 MeV	IC^1	$(9/2^-[734]_\nu \otimes 11/2^-[725]_\nu)$	[25]
^{256}Rf	-	27 μs	2.2 MeV	IC^1	-	[25]
^{266}Hs	-	74 ms	$\simeq$1.2 MeV	α	-	[11, 26]
^{270}Ds	9^-,10^-	6 ms	$\simeq$1.13 MeV	α	$11/2^-[725]_\nu \otimes 7/2^+[613]_\nu$ $11/2^-[725]_\nu \otimes 9/2^+[615]_\nu$	[11, 27, 28]

[1] detection by electrons from internal conversion

from the g7/2 shell and crossing the latter at the same deformation, forms the g.s. of the N=153 isotones for the same elemental range (see figure 9 in reference [4]). 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, making the observation of both SPLs in ^{253}No 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 [9].

Apart from α decay, ^{257}Rf has an EC decay branch into ^{257}Lr with branching ratios b_{EC} of 0.094±0.014 and 0.115±0.015 for the g.s. and the isomer decay, respectively [9]. 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 from DSAS 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. [8] 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 [7] (insert in figure 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

Table 2. Beam intensities expected for the SC LINAC of SPIRAL2, taken from [31].

ion	intensity [pμA] $A/Q = 3$	intensity [pμA] $A/Q = 6$ or 7
^{16}O	216	375
^{19}F	57	50
^{36}Ar	35	40
^{40}Ar	5.8	30
^{48}Ca	2.5	15
^{58}Ni	2.2	10
^{84}Kr	0	20
^{124}Sn	0	10
^{139}Xe	0	10
^{238}U	0	2.5

in angular momentum and possibly 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 [29].

The heaviest nucleus for which such an isomeric state has been observed is ^{270}Ds [27]. Recently such a state has been reported also for its α decay daughter ^{266}Hs [11, 26]. 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 1 lists the known K isomeric states in the region from curium to darmstadtium [11]. As an example energy density functional (EDF) calculations predict a particular pattern for high K states in N=162 isotopes with respect to their neighbours for isotopic chains from rutherfordium to darmstadtium [30].

4 Technical development and perspectives

The success of DSAS relies on the major instrumentation, necessary to perform this type of investigations: high intensity heavy ion accelerators, and efficient and selective separators combined with comprehensive particle and photon detection systems. High beam intensities require additional effort for target development in order to make them withstand the increased energy deposit [32]. The study of heavy and superheavy nuclei is pursued in various laboratories which possess such instrumentation. For the separation, gas-filled separators are employed as well as vacuum devices. Examples for the latter are the velocity filter SHIP of the GSI Helmholtzzentrum in Darmstadt, Germany [33], the Separator for Heavy ELement Spectroscopy SHELS at FLNR/JINR in Dubna, Russia [34], the fragment mass analyzer FMA at ANL in Argonne, U.S.A. [35], or the separator-spectrometer set-up S^3 presently being built at the SPIRAL2 facility of GANIL [36]. An alternative separation type are the generally more compact gas-filled separators like e.g. TASCA at GSI [37], DGFRS at FLNR/JINR [38], RITU at the cyclotron laboratory of the University of Jyväskylä in Finland [39], GARIS at RIKEN in Tokyo, Japan [40], BGS at the LBNL in Berkeley, U.S.A. [41], and AGFA presently under construction at ANL in Argonne, U.S.A. [42].

The major aim of future facilities is dictated by the ever lower cross sections for the investigation of ever heavier system both, in terms of the synthesis of new heavy elements as well as for extending

Table 3. 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}]	# 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)[1]	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 [2]	1800[2]

[1] 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

[2] 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 [46]

nuclear and atomic structure studies (in-beam and DSAS). The detailed knowledge of atomic and nuclear properties like binding energies, ionisation potentials and atomic excitation levels, as well as the single particle and collective nuclear excitations are essential for a successful progress towards the eventual localization for the next proton and neutron shell closures. But the foremost important aim is the understanding of the strong interaction, promising a detailed insight into fundamental physics.

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 this need of highest intensities [31]. The planned intensities for the two envisaged construction phases are listed in table 2. The superconducting separator spectrometer (S^3) set-up [36] combined with the decay spectroscopy detection array SIRIUS (Spectroscopy and Identification or 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 [43, 44].

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 3 [2, 11]. 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 like 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. reference [43, 45]), due to the precise prediction capabilities for atomic transitions by theory.

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. In addition, a low energy set-up including a gas stopping cell, laser spectroscopy instrumentation and a multi-reflection time-of-flight spectrometer (MR ToF) will be used to study nuclei in the N=Z region as well as the heaviest nuclear species. In a farther future the synthesis and investigation of, also so far unknown, highest-Z systems is envisaged, for which the earlier experiments will establish the basis.

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