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Superheavy nuclei and other exotics – opportunities at SPIRAL2 and S^3

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Abstract. The structure of very heavy and superheavy nuclei (SHN) as well as the location of the next proton and neutron shell closures beyond ^{208}Pb is still one of the most intriguing topics in modern nuclear physics [1]. Worldwide competitive, high beam intensities provided by the accelerator facility SPIRAL2 at GANIL which started operation recently, will cover in future all ions up to uranium thanks to the new injector project NEWGAIN. Combined with the separator-spectrometer installation S^3 [3], it will provide the instrumental prerequisites for an ambitious science program. Apart from SHN/SHE research, the envisaged physics case at S^3 covers, among other, the structure of N=Z nuclei, low energy physics (fundamental properties of the atomic nucleus etc.), interdisciplinary research, atomic physics and reaction studies (fission, deep inelastic reactions etc.). The state of the art of the field is discussed in this paper with an emphasis on the role of the odd particle(s) in odd-even, even-odd and odd-odd nuclei and the consequences for nuclear structure features like K-isomers, trends of single-particle energies as a function of deformation, and the competition of spontaneous fission (SF) and α decay. As an alternative approach to produce heavy and in particular more neutron-rich nuclear species multi-nucleon transfer reactions are briefly discussed as well.

1 Introduction

Heßberger et al. reported recently on the low-lying level structure of ^{243}Es [3]. They proposed a tentative level scheme which is shown in Fig. 2. It illustrades a solution for the puzzle of its quasi-degenerate g.s. configuration, proposing an assigning of the Nilsson configurations $3/2^-[521]$ to the ground state and $7/2^+[633]$ to the next higher state at an excitation energy of about 10 keV. Moreover and surprisingly, we found the $1/2^-[521]$ SPL at only 68(11) keV. Stemming together with $3/2^-[521]$ from orbitals which define the shell gap at sphericity, an energy gap between these two states of $\approx$ 1 MeV, was predicted by models which propose $Z = 114$ with those two states (see e.g. [5]).

The region of SHN promises to offer an ideal laboratory to study the quantum-mechanical properties of nuclear matter and to reveal its still hidden secrets. One of the major reasons for that is that superheavy nuclei (SHN) owe their mere existence to quantum mechanics and the so-called shell effects, as the liquid drop fission barrier vanishes in the fermium-rutherfordium region.The hitherto observed heavier species up to isotopes of tennessine and oganesson with $Z =$ 117 and 118 respectively, give a first impression of exciting, and possibly new and unexpected nuclear structure features to be studied [1]. The new facilities coming presently online like the SHE factory with the new gas-filled separator DGFRS2-2 of JINR/FLNR in Dubna, Russia [6], the RILAC facility of RIKEN in Tokyo/Wako, Japan, with its upgraded high-intensity ion source [7], or the new LINAC of GANIL/SPIRAL2 with its future extension by the new injector NEWGAIN [8] and the conceptually novel separator-spectrometer installation S^3 [9] have the potential to open the door to new element discovery. It will help to extend the detailed structure studies from the nobelium-fermium region and the deformed shell gaps at $Z = 100$ and $N = 152$ to the next heavier ones at $Z = 108$ and $N = 162$ and beyond.

The consequences of nuclear deformation and the here accessible high-J orbitals for single-particle levels (SPLs) are the origin of complex configurations at the interplay of nuclear excitation, stability and decay. In particular, interesting are K isomers, observed up to the heaviest one ^{270m}Ds [10], which is located at the edge of the onset of the descent of deformation towards sphericity [1, 11], following various theory predictions (see e.g. Ref. [12]). Fig. 1 shows all known K isomers for Z≥96. A comprehensive review of isomeric states in SHN is given in Ref. [2].

In the region of the heaviest nuclei, the first K isomers found were typically meta-stable states of even-even isotopes like e.g. ^{254m}No [13] or the above-mentioned ^{270m}Ds. In recent years, K isomers have been reported for even-odd and odd-even nuclei like e.g. ^{255}Rf [14], ^{255}No[15] and ^{249,251}Md [16], respectively. Instead of the even-even isotopes (blue squares in Fig. 1) often 2-quasi-particle excitations across a shell gap create high K-numbers, in odd-mass nuclei (even-odd: orange squares and odd-even: green squares in Fig. 1) those meta-stable states are formed as 3-quasi-particle states. There the high-K values are produced by coupling the 2-quasi-particle excitation to the odd un-paired nucleon. For odd-odd nuclei, however, high-K isomers have not yet been found in this region, despite interesting quasi-particle configurations possibly

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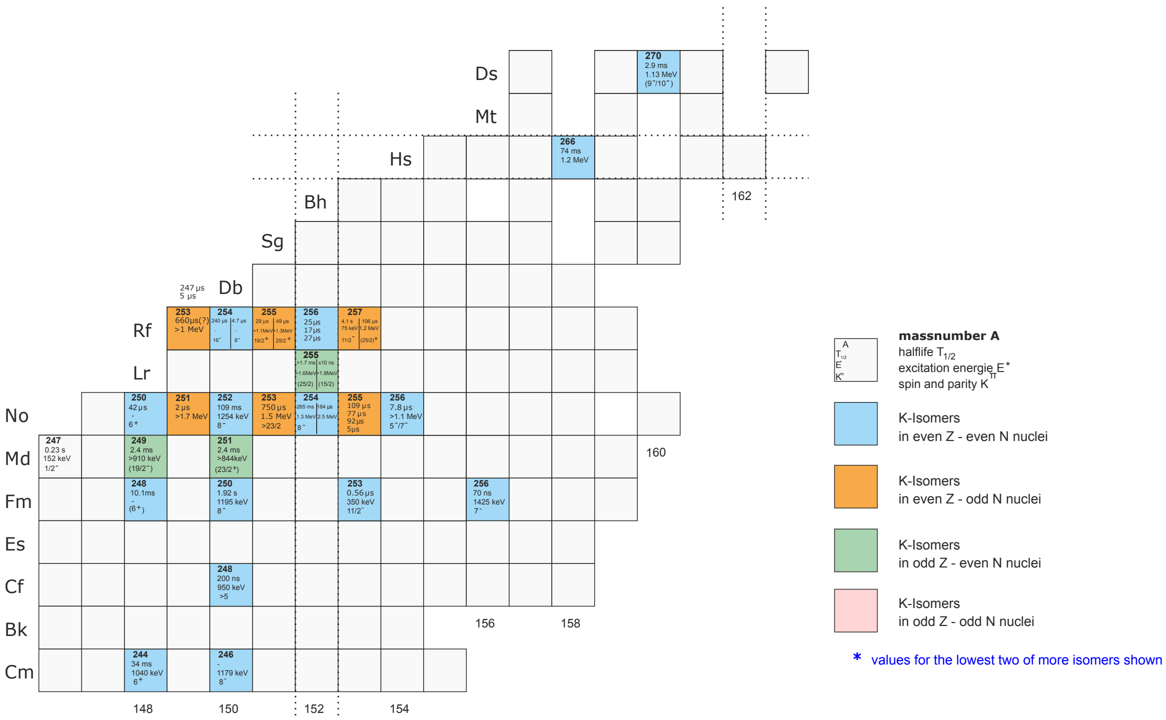

Figure 1. Update of Fig. 43 in Ref. [1]: Summary of K isomers for the heaviest nuclei at and above Z = 96 (Taken from Ref. [2]), including the spin isomer in ^{247}Md.

provided by those species. Nuclei like ^{254}Lr and ^{258}Db, lying close to the shell gaps Z = 100 and N = 152, would be interesting candidates. Supporting this, Hessberger et al. reported two decay activities for the latter [17]. The observation of the low-lying structure of those heavy nuclei provides important input to validate model predictions. A particularly interesting case is ^{247}Md → ^{243}Es decay [3] where low excitation energies and energy differences for single-particle states (SPLs) originating from orbitals which are supposed to define the shell gaps for spherical superheavy nuclei have been observed, with important consequences for theoretical predictions for the next proton and neutron shell closures beyond ^{208}Pb. Beyond delaying substantially the decay of an SPL as discussed for the K-isomers above, the quantum character of such a nuclear state can at the same time have consequences for the competition between fission and α decay for a given single-particle state. Examples which will be discussed here, are ^{247}Md and ^{259}Sg. These observations for ^{247}Md decay to ^{243}Es will be, together with the features of the spin-isomer observed in ^{247}Md (also shown in Fig. 1), subject of the next section. Cases of even-odd nuclei, after this discussion of odd-even cases, will be presented in the following sections with α decay of ^{259}Sg to ^{255}Rf and new results for ^{255}No. Before the outlook towards a promising future at upcoming high-intensity accelerator facilities equipped with efficient new separator-detection installations which concludes this paper, the alternative approach to produce heavy and, in particular, neutron-rich nuclei and the attempts to follow this route will briefly be outlined. Regarding the nuclear structure features a similar discussion as given in this conference proceedings can be found in Ref. [18].

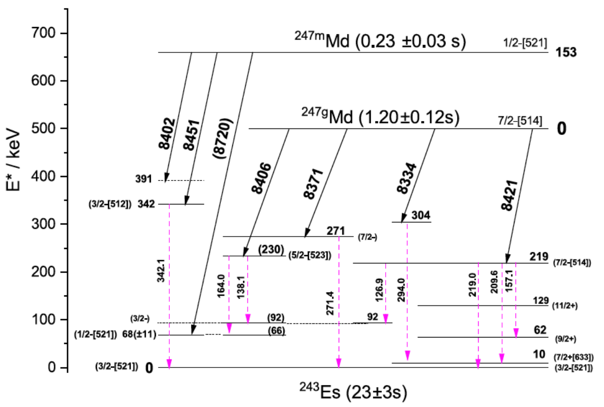

Figure 2. Proposed tentative decay scheme of ^{247}Md. Half-lives for ^{247gs,247m}Md are from [3], half-life of ^{243}Es is taken from [4]. Alpha transitions are represented by full lines, γ transitions by dashed lines. (Figure and caption are taken from Ref. [3].)

2 Decay spectroscopy of the heaviest nuclei

Decay spectroscopy after separation (DSAS) is a powerful tool for studying low-lying structure of the heaviest nuclear species and during the last two decades a number of exciting features have been observed in the region around the deformed shell gaps $Z = 100$ and $N = 152$ [1]. Initially breaking nucleon pairs in even-even nuclei by quasi-particle excitations provided access to the single-particle structure in the vicinity of the Fermi surface. Experimental excitation energies and the observed order of excited

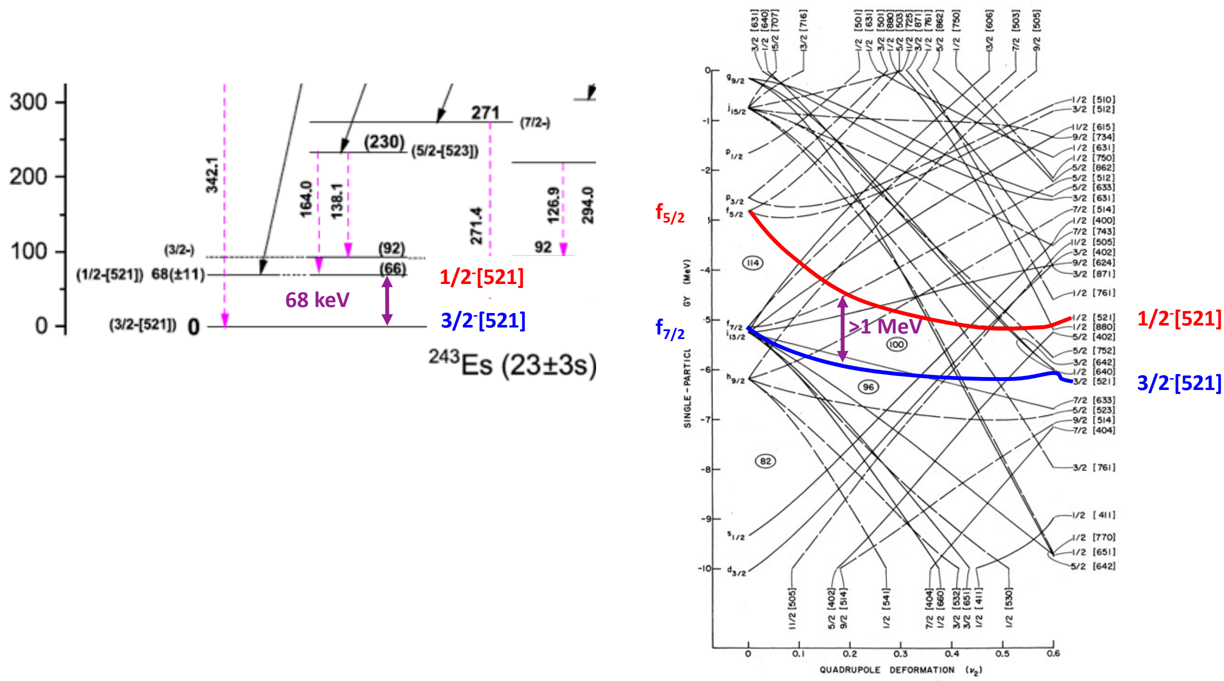

Figure 3. Indication that Z = 114 is probably not the next proton shell closure beyond ^{208}Pb by comparison of the excitation energy difference for the two proton Nilsson levels 1/2[521] and 3/2[521] in the experimentally obtained low-lying level structure of ^{247}Md with $E^{*} = 68$ keV, shown in an excerpt from Fig. 2 (left panel) and the Nilsson diagram from Ref. [5] (right panel) with ≈ 1 MeV in a wide range of deformation.

states were compared to model calculations, helping to develop theory towards more and more reliable predictions for those nuclear species at the limits of stability at highest Z. Extending the investigations to DSAS of nuclei with odd-proton or odd-neutron numbers, hence including the coupling of the unpaired nucleon in the ground state (g.s.) and quasi-particle excitations, provides access to the formation of more complex configurations and their particular properties, one of them being the formation of high-K isomers. From those findings even conclusions for the next proton and neutron shell closure beyond ^{208}Pb can be inferred, as will be discussed in the next subsection 2.1 for the odd-even nucleus ^{247}Md and its α-decay daughter ^{243}Es (for the proposed level scheme from Ref. [3] see Fig. 2). There also the competition between α decay and fission (SF) and the consequences for nuclear stability, dependent on the quantum mechanical structure of those decaying states, will be illustrated. The following subsections present recent results obtained for the even-odd nuclei, ^{259}Sg and its α-decay daughter ^{255}Rf (subsection 2.2), and ^{255}No(subsection 2.3). For the latter, the formation of high-K-isomers is favored by the access to high-J orbitals around the Fermi energy of the two protons above the $Z = 100$ proton shell gap and the neutron above the $N = 152$ neutron shell gap.

This discrepancy of two orders of magnitude in the energy difference strongly contradicts the prediction of $Z = 114$ as the next proton shell closure. This is illustrated in Fig. 3, where for easier comparison the respective SPLs are highlighted in an excerpt from the ^{247}Md level scheme (Fig. 2) as well as in the respective Nilsson diagram taken from Ref. [5].

2.1 The low-lying level structure in ^{243}Es and the competition of fission and α decay in ^{247}Md

Concerning the competition of SF and α decay, we report SF-branching ratios $b_{SF} = 8.6\times10^{-3}(10)$ for $^{247g.s.}$Md with $7/2^{-}[514]$ and $b_{SF} = 0.20(2)$ for ^{247m}Md with $1/2^{-}[521]$. We attribute the strong g.s. fission hindrance to its complex quantum properties, for which Nilsson models predict a steep increase in SPL energy with increasing deformation. This feature is known as specialization energy. In Ref. [19] a discussion of the specialization energy and the dependence of the fission barrier on the spin for superheavy nuclei can be found. There, using a Nilsson-Strutinsky approach with an average Woods-Saxon potential, Cwiok et al. discuss the single-particle structure for the heaviest nuclei with 95 ≤Z≤111 and 149≤N≤162 .

2.2 Even-odd nuclei: ^{259}Sg and its daughter ^{255}Rf

Antalic et al. reported for ^{259}Sg a similar effect as discussed in the previous section regarding the fission-α decay competition [20]. There we observed α decay from both, the $11/2^{-}[725]$ g.s. with a half-life of 402(46) ms as well as from the $1/2^{-}[620]$ first excited state with $T_{1/2} = 226(27)$ ms, while SF was observed with $T_{1/2}$ =

299(147) ms. Consequently, fission occurs most probably only from the first excited state, while it is hindered by the effect of the aforementioned specialization energy for the g.s. due to the more complex quantum mechanical configuration.

Fig. 4 shows the tentative decay scheme constructed from the observed ^{259}Sg α decay: a), containing a low 50-μs isomeric 5/2$^+$[622] Nilsson level at an excitation energy of $E^* \approx 135$ keV. This is consistent with the $N = 151$ isotone systematics, where this state is observed with similar properties throughout the whole sequence [21].

Populating ^{255}Rf by the reaction ^{207}Pb(^{50}Ti, 2n)^{255}Rf P. Mosat et al. observed two high-K isomers at an excitation energy range above 900 keV. This is obviously not accessible to the ^{259}Sg α decay. As shown in Fig. 6 a), a possible configuration for these high-K states can be deduced as $1/2^-[521]\pi \oplus 9/2^+[624]\pi \oplus 9/2^-[734]\nu \rightarrow K = 19/2^+$ with $\Delta K = 5$ from the single-particle configuration of ^{255}Rf .

2.3 Even-odd nuclei: ^{255}No

Considering conversion electrons (CEs) emitted by the ^{255}No evaporation residues (ERs), we revisited recently earlier taken data for ^{255}No, [15]. Using ER–CE_1(–CE_2)(–γ) correlations, we could establish the presence of three high-K isomers in this even-odd nobelium isotope. In Fig. 5, the tentative level scheme of ^{255}No is shown with approximate excitation energies E^*, and possible spin and parity assignments. For the connection of the higher lying

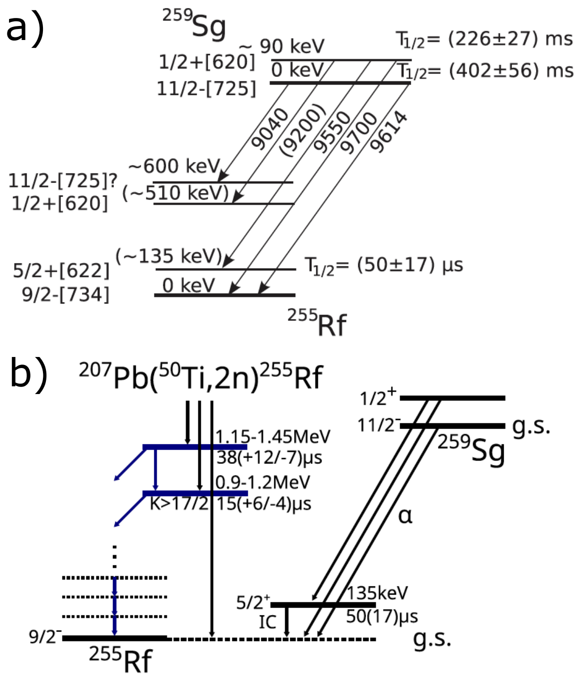

Figure 4. a) Suggested decay scheme for α decay of ^{259}Sg. (Figure taken from Ref. [20].) b) Proposed decay scheme of the K isomers in ^{255}Rf, populated in the reaction ^{207}Pb(^{50}Ti, 2n)^{255}Rf (left) and in the α decay of ^{259}Sg (right). (Figure and caption taken from Ref. [14].)

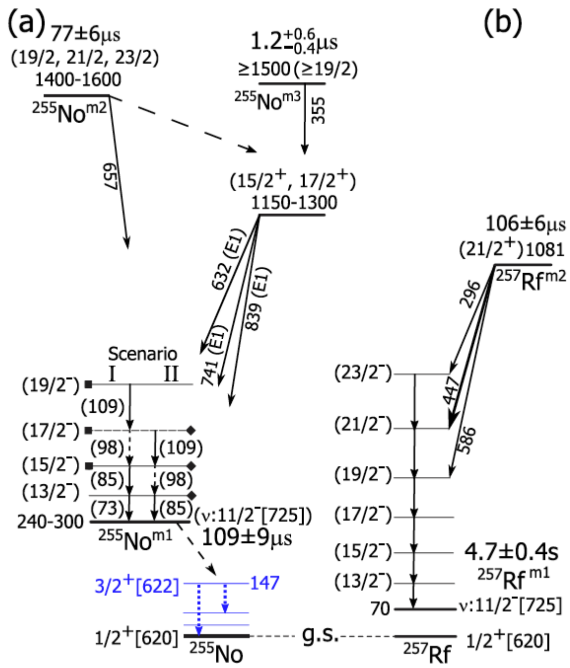

Figure 5. (a) Tentative decay scheme of isomeric states in ^{255}No. Blue dotted lines represent previously observed levels and transitions [22]. Dashed lines indicate only tentative assignments. Roman numerals and rectangles at the end of horizontal lines correspond to different scenarii, where various members of the 11/2$^-$[725] rotational band are populated via the 632-, 741-, and 839-keV transitions (see Ref. [15], Sec. IVB). (b) Decay scheme of the isotonic neighbor ^{257}Rf [23]. Energies are in keV. (Figure and caption taken from Ref. [15].)

^{255m2}No and ^{255m3}No to the lowest in E^* of the three isomers ^{255m1}No, alternative scenarii are shown. A possible assignment for ^{255m2}No is illustrated in Fig. 6 b), based on SPL configurations showing the g.s. and possible proton and neutron single particle excitations leading to a 21/2$^+$ configuration. A more detailed discussion of these findings can be found in Ref. [15].

The same nucleus has been investigated in an independent experiment at the velocity separator SHELS of the Flerov Laboratory of Nuclear Reactions, FLNR/JINR in Dubna, Russia. This investigation is part of the Ph.D. thesis of K. Kessaci [24] at the University of Strasbourg, France. It is expected to be published soon in Physical Review C.

3 Multi-nucleon transfer - an alternative approach to produce heaviest neutron-rich nuclei

Heavy neutron-rich species, i.e., neutron-rich actinides and trans-fermium isotopes, and, in particular, SHN on the so-called *"island of stability"*, cannot be produced by fusion-evaporation reactions with projectile-target combinations of stable isotopes. An alternative method to produce neutron-rich heavy systems has been proposed by Zagrebaev et al. [28, 29], with the employment of deep-inelastic collisions of heavy nuclei. In an early

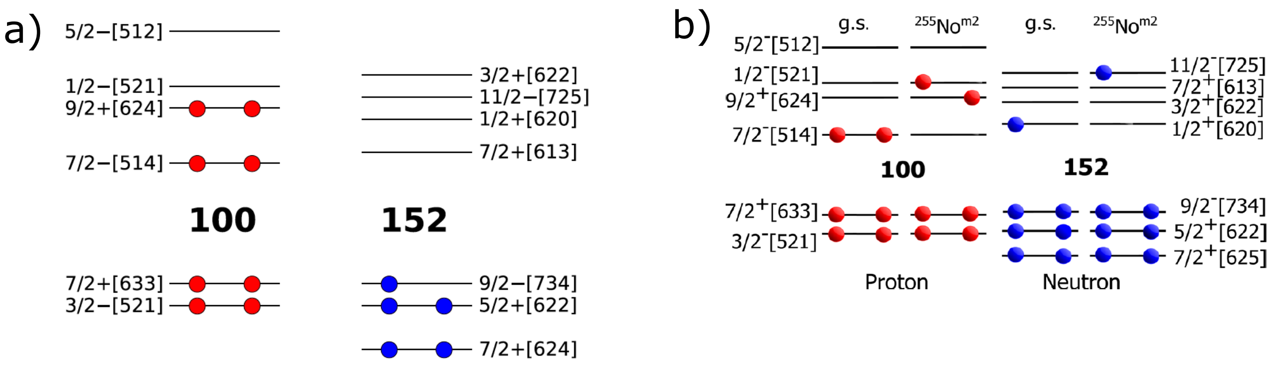

Figure 6. a) Single-particle levels for protons (left) and neutrons (right) in ^{255}Rf, calculated in Ref. [5] with nuclear deformations taken from Ref. [25]. The neutron level 5/2+[622] was placed according to experimental results from Ref. [20]. The ground-state configuration is shown. (Figure and caption taken from Ref. [14].) b) Ground-state configuration of ^{255}No and tentative ^{255m2}No 3-qp configuration. Given single-particle levels for protons and neutrons were calculated in Ref. [5] with nuclear deformations taken from Ref. [25]. The neutron Nilsson levels $1/2^+$[620], $3/2^+$[622], and $5/2^+$[622] were placed based on the experimental results from refs. [22, 26, 27] and [20], respectively. (Figure and caption taken from Ref. [15].)

chemistry experiment, Schädel et al. [30] could observe the production of isotopes from Pu to Fm in a cross-section range from mbarn to nbarn. The most promising reaction using available nuclides, following the predictions of the Langevin model approach, was found to be ^{238}U+^{248}Cm [31].

To prepare the exploration of the lighter actinides' nuclear structure, an attempt to study MNT production probabilities of neutron-rich isotopes close to the $N = 152$ deformed neutron shell gap was recently undertaken at the magnetic spectrometer VAMOS++ [32] coupled to the germanium detector array AGATA [33] and the X-ray detection system ID-Fix, employing the reaction ^{238}U+^{238}U [34]. Due to low statistics, the population of transfer channels could not be observed with a sufficient number of counts to extract recoil-γ correlations for other than the elastic channel. The search for population of transfer channels by recoil-γ correlations was not successful. All mass-gated γ spectra are dominated by the tail of the distributions of the ^{238}U rotational band transitions, leaking into the respective lighter and heavier mass gates. In an earlier investigation, the reaction ^{136}Xe+^{238}U had been studied at the combination of the magnetic spectrometer PRISMA at LNL, Legnaro, Italy, and the γ-ray detection array AGATA, where a rotational band could be established up to 20-24 $\hbar$ in ^{240}U [35]. The heaviest uranium isotope, ^{242}U, for which the first 2^+ state is known, is two neutrons away from $N = 152$ [36]. A continuation of these efforts is presently being discussed, using similar experimental set-ups with the above mentioned instrumentation at GANIL and LNL, exploiting efficiency upgrades and more stable beam condition that will allow the accumulation of sufficient amounts of data.

4 Summary and outlook – odd particle SHN, perspectives at SPIRAL2/S^3 and n-rich nuclei via MNT

Nuclei with odd nucleon numbers are becoming more and more accessible for the heaviest nuclear species, providing a sensitive probe to investigate single particle properties of SHN. The quantum configuration of the unpaired nucleon in very heavy and superheavy nuclei with odd proton and/or neutron numbers have the potential to reveal basic properties of the quantum character of nuclear matter in this extreme region of the Segrè chart. In particular, the nuclear structure of highest K becomes accessible due to the predominance of SPLs with large spin values. In the past decade, a significant amount of data has been collected in the nobelium-fermium region for even-odd and odd-even (proton-neutron) nuclear systems. To extend our knowledge in order to eventually set foot on the "island of stability" of spherical superheavy nuclei, more detailed information would be needed to follow the trends of SPLs towards the next closed proton and neutron shells. K-isomers play a decisive role here. Apart from the hindrance-driving spin/parity and energy conditions, K isomers, owing their existence to a discrete deformation of the nucleus, are expected to be powerful indicators to trace the development from deformation towards sphericity. One of the next steps will be the investigation of odd-odd systems, for which data is still very scarce. Their potential to populate rich varieties of states with complex quantum configurations promises new insights. In these heavy systems, up to date, no K-isomer has been observed, while quasi-particle excitations of those proton-neutron configurations have the potential to produce high spin values.

The basis for a successful progress and the accumulation of substantial amounts of data are the new facilities with highest beam intensities, which are presently starting operation like the SHE Factory [6] of FLNR/JINR, Dubna, Russia, being upgraded like the linear accelerator RILAC at RIKEN, Tokyo, Japan, being envisioned for some not too far future like the HELIAC project at GSI/FAIR, Darmstadt, Germany, or are presently coming online like the SPIRAL2 LINAC facility and S^3 at GANIL in Caen, France. The separator-spectrometer installation S^3 [9] at GANIL/SPIRAL2 will be equipped with versatile detection instrumentation. The decay spectroscopy setup SIRIUS and the S^3 Low Energy Branch (S^3LEB) are powerful tools to attack a wide spectrum of experimental approaches from decay spectroscopy after separation (DSAS) [1] to laser spectroscopy and precise mass measurement [37, 38].

MNT seems to provide an alternative approach to reach into regions of the Segré chart of at least modestly heavy neutron-rich nuclei. Its application is discussed in the context of future developments, including possibly production schemes of exotic beams.

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