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NUCLEAR ISOMERS IN THE HEAVIEST NUCLEI — THE ODD NUCLEON AS A SENSITIVE PROBE OF LOW-LYING NUCLEAR STRUCTURE*

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After the discovery of superheavy nuclei up to ^{294}Og and with the advent of new high-intensity accelerator facilities, more and more details of the nuclear structure of those exotic nuclear systems become accessible. In particular, nuclear structure studies in the vicinity of the deformed shell gaps in the nobelium/fermium region, which were already at the focus of the existing facilities throughout the last two decades, can be extended to a substantially more detailed level. In particular, decay spectroscopy of nuclei with odd particle numbers, which was hitherto hampered by limited beam intensities, will profit from the capabilities of the new facilities. This paper presents some results accumulated for odd-particle (super)heavy nuclei and gives an outlook on research opportunities at future facilities like SPIRAL2 at GANIL. Owing much of my knowledge and scientific passion to one of the main players in the field of superheavy nuclei, Sigurd Hofmann who left us in June 2022, I dedicate my presentation and this article to honor him, his scientific achievements, and his memory.

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1. Dedication

The experimental search for superheavy elements (SHE) was initiated in the sixties of the last century. A seminal event was the conference in Lysekil 1966, where the magic numbers $Z = 114$ and $N = 184$ were proposed by Sobiczewski [1] and Meldner [2].

In the following decades, a substantial effort was put into research programs at institutions all over the globe. For GSI in Darmstadt, Germany, the quest for the next closed proton and neutron shells beyond ^{208}Pb was one of the main topics motivating its foundation [3].

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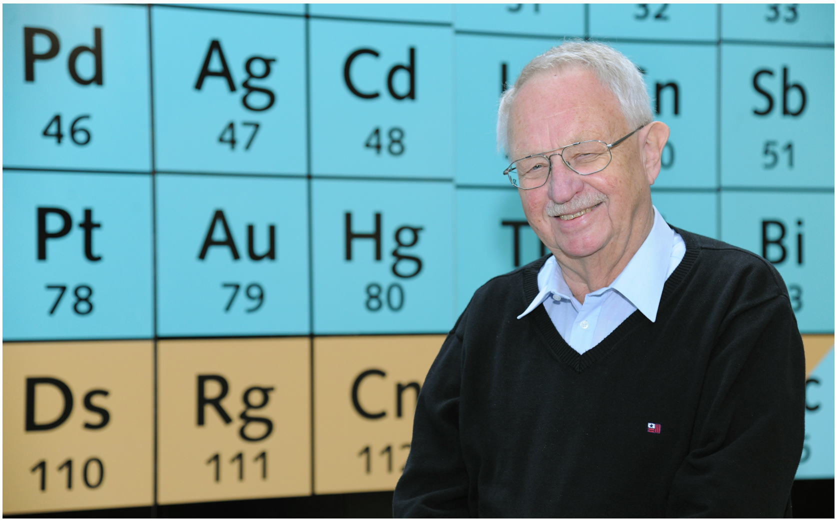

Fig. 1. Sigurd Hofmann — Photo: G. Otto, GSI.

Sigurd Hofmann was part of the SHE research team at GSI's velocity filter SHIP from the very beginning. He saw the first great success with the discovery of elements of $Z = 107$ to 109, bohrium, hassium, and meitnerium, in the early 1980s and he was the leading figure in the discovery of elements of $Z = 110$ to 112, darmstadtium, roentgenium, and copernicium, which became accessible after an upgrade of the separator facility in the 1990s.

Continuous development of the instrumentation and a rigorous dedication to optimization on the basis of the previous achievements was one of the keys to the success in a process in which Sigurd Hofmann played a key role. About a decade after the beginning of this endeavor, the author of this paper had as a young student the outstanding opportunity to become part of it and to profit from the rich know-how accumulated within the SHIP group. After I spent some time abroad, it was Sigurd who brought me back to GSI. In the then following years, I had the pleasure to enjoy and understand the benefit of his rigor in science as well as regarding instrumentation issues what contributed substantially to my professional education. He was certainly one of the most important and influential persons for my personal development in science. In about 20 years of working together, I had met an extraordinary scientist and human being. Despite all controversies which we always kept on the scientific level and discussed with mutual respect based on friendship, I always had a perfect relationship with him on the personal level. There are still many things I would have liked to discuss with him — now it is too late … I owe him a lot as my mentor, teacher, and supervisor — I miss him as a friend.

2. Introduction

When the liquid drop fission barrier vanishes in the fermium–rutherfordium region, only the stabilization by quantum-mechanical effects allows the existence of the observed heavier species. This makes the region of SHN an ideal laboratory to study the quantum-mechanical properties of nuclear matter.

Among the nuclear structure features to be studied in the field of superheavy nuclei (SHN) [4], nuclear deformation and single-particle levels (SPLs) with complex configurations are the most intriguing in the interplay of nuclear excitation, stability, and decay. In particular interesting are K isomers observed up to the heaviest one, ^{270m}Ds [5], which is located at the edge of the onset of the descent of deformation towards sphericity [4, 6], following various theory predictions (see *e.g.* Ref. [7]). Figure 2 shows all known K isomers for $Z \geq 96$.

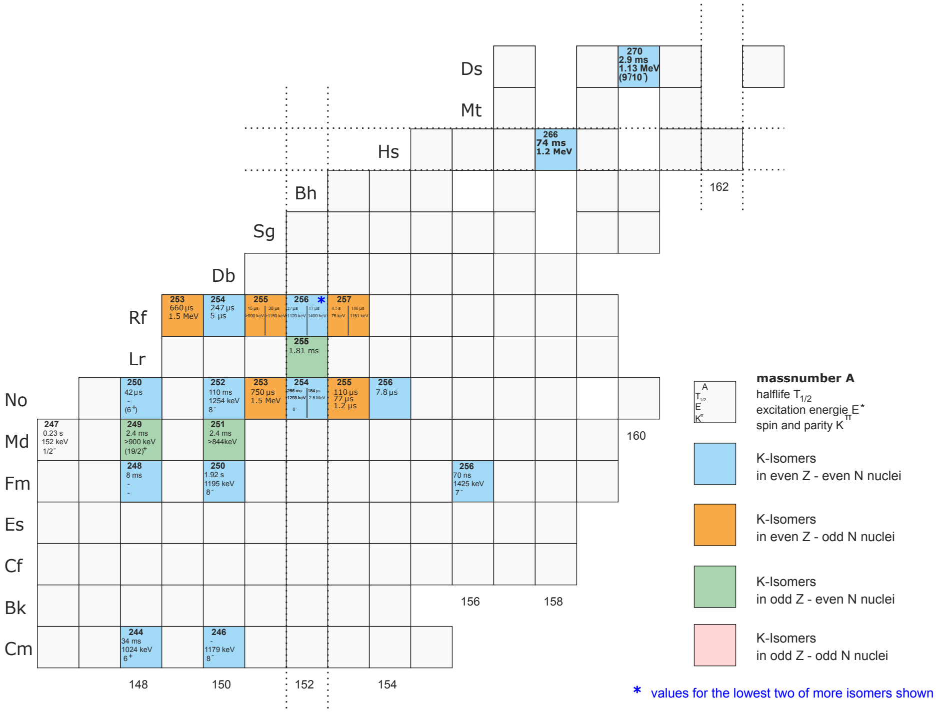

Fig. 2. (Color online) Update of Fig. 43 in Ref. [4]: Summary of K isomers for the heaviest nuclei at and above $Z = 96$.

The first K isomers found in the region of the heaviest nuclei were typically meta-stable states of even–even isotopes such as *e.g.* ^{254m}No [8] or the above-mentioned ^{270m}Ds. More recently, cases for even–odd and odd–even nuclei have been reported with *e.g.* ^{255}Rf [9], ^{255}No [10], and ^{249,251}Md [11], respectively. While for the even–even isotopes (blue/light gray squares in Fig. 2) often 2-quasi-particle excitations across a shell gap lead to high-K numbers, the meta-stable states in odd-mass nuclei (even–odd: orange/dark gray squares and odd–even: green/gray squares in Fig. 2) are formed as 3-quasi-particle states, where high-K values are produced by 2-quasi-particle excitation coupled to the odd un-paired particle. No high-K isomer has yet been assigned to odd–odd nuclei in this region, possibly providing interesting quasi-particle configurations. Nuclei in the vicinity of shell gaps such as ^{254}Lr and ^{258}Db, lying close to $Z = 100$ and $N = 152$, would be interesting candidates. For the latter, two decay activities have been reported [12]. The observation of low excitation energies for single-particle states (SPLs) originating from orbitals which are supposed to define the shell gaps for spherical superheavy nuclei provide an important input to validate theoretical predictions, like in the case of the $^{247}\mathrm{Md} \rightarrow {}^{243}\mathrm{Es}$ decay [13].

The quantum character of a nuclear state can lead to a substantial delay as discussed for the K isomers above, but it can at the same time have consequences for the competition between fission and α decay for a given single-particle state. This will be discussed in the following for the two examples of ^{247}Md and ^{259}Sg. The ^{247}Md decay to ^{243}Es is revealing the low-lying level structure of the decay daughter with consequences for the predictions of the next proton shell closure beyond ^{208}Pb. This will be, together with the features of the spin-isomer observed in ^{247}Md (also shown in Fig. 2), subject of the next section. After that, the odd–even cases with α decay of ^{259}Sg to ^{255}Rf and new results for ^{255}No will be presented, before the outlook towards a promising future at upcoming high-intensity accelerator facilities equipped with efficient new separator-detection installations will conclude this paper.

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

In a recent publication, Heßberger *et al.* [13] could construct the low-lying level structure of ^{243}Es. The proposed level scheme is shown in Fig. 3. Among others, we could solve the puzzle of its quasi-degenerate g.s. configuration, assigning the Nilsson configurations $3/2^-[521]$ to the ground state and $7/2^+[633]$ and an excitation energy of about 10 keV to the next higher state [13]. In addition, we found the $1/2^-[521]$ SPL at only 68(11) keV. This contradicts an energy gap between this state and $3/2^-[521]$ of ≈ 1 MeV, predicted by models which propose $Z = 114$ with those two states stemming from orbitals which define the shell gap at sphericity (see *e.g.* [14]). As a conclusion, $Z = 114$ is most likely not the next proton shell closure.

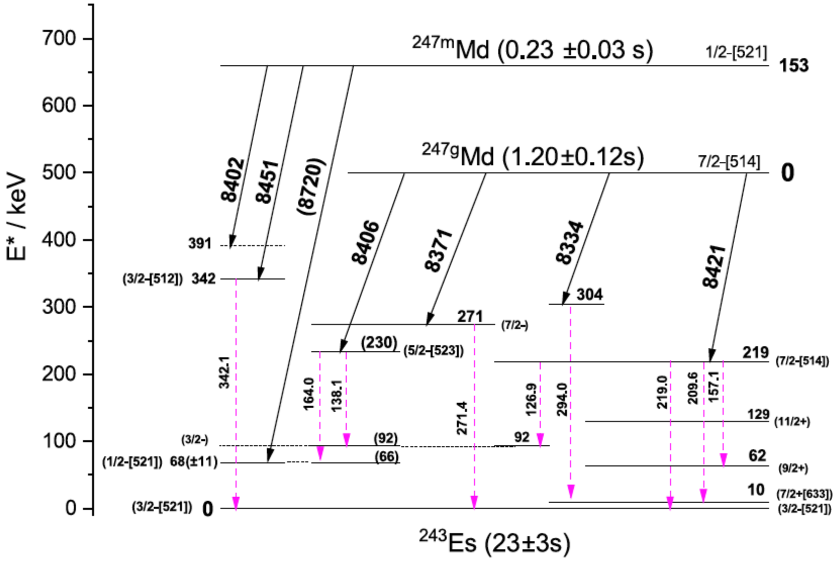

Fig. 3. Proposed tentative decay scheme of ^{247}Md. Half-lives for ^{247g,247m}Md are from [13], the half-life of ^{243}Es is taken from [15]. Alpha transitions are represented by full lines, γ transitions by dashed lines. (Figure and caption are taken from Ref. [13].)

For the SF-branching ratios, we report $b_{\mathrm{SF}} = 8.6 \times 10^{-3}(10)$ for $^{247\mathrm{gs}}$Md with $7/2^{-}[514]$ and $b_{\mathrm{SF}} = 8.6 \times 0.20(2)$ for ^{247m}Md with $1/2^{-}[521]$. The strong g.s. fission hindrance is attributed to its complex quantum properties, for which the Nilsson models predict a steep increase in SPL energy with increasing deformation, a feature which is known as specialization energy. A discussion of the specialization energy and the dependence of the fission barrier on the spin for superheavy nuclei can be found in Ref. [16], where Ćwiok *et al.* discuss the single-particle structure of the heaviest nuclei with $95 \leq Z \leq 111$ and $149 \leq N \leq 162$ using a Nilsson–Strutinsky approach with an average Woods–Saxon potential.

4. Even–odd nuclei: ^{259}Sg and its daughter ^{255}Rf

A similar effect as discussed in the previous section regarding the fission-α decay competition was reported by Antalic *et al.* [18] for ^{259}Sg. While we observed α decay from both, the $11/2^{-}[725]$ g.s. with a half-life of 402(56) ms as well as from the $1/2^{-}[620]$ first excited state with $T_{1/2} = 226(27)$ ms, SF was observed with $T_{1/2} = 299(147)$ ms. This is indicating that fission occurs most probably only from the first excited state, while it is hindered for the g.s. with the more complex quantum mechanical configuration by the effect of the aforementioned specialization energy.

The tentative decay scheme constructed from the observed ^{259}Sg α decay is shown in Fig. 4 (a), containing a low 50-μs isomeric $5/2^{-}[622]$ Nilsson level at an excitation energy of $E^* \approx 135$ keV. This is in line with the $N = 151$ isotone systematics starting from ^{245}Pu, where this state is observed with similar properties throughout the whole sequence [17].

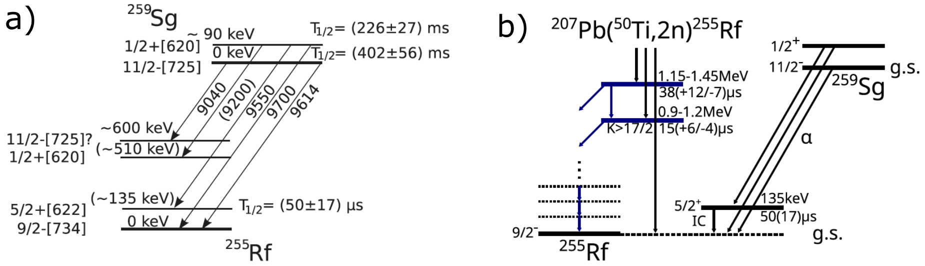

Fig. 4. (a) Suggested decay scheme for α decay of ^{259}Sg. (Figure taken from Ref. [18].) (b) Proposed decay scheme of the K isomers in ^{255}Rf, populated in the reaction ^{207}Pb(^{50}Ti, $2n$)^{255}Rf (left) and in the α decay of ^{259}Sg (right). (Figure and caption taken from Ref. [9].)

In the direct population of ^{255}Rf by the ^{207}Pb(^{50}Ti, $2n$)^{255}Rf reaction, Mosat *et al.* [9] observed two high-K isomers at an excitation energy range above 900 keV which is obviously not accessible for the ^{259}Sg α decay. 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 as shown in Fig. 5 (a).

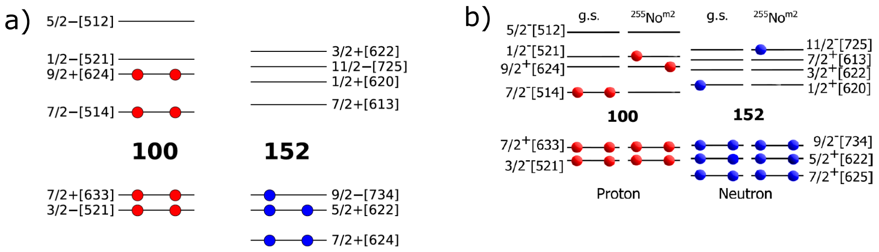

Fig. 5. (a) Single-particle levels for protons (left) and neutrons (right) in ^{255}Rf, calculated in Ref. [14] with nuclear deformations taken from Ref. [19]. The neutron level 5/2+[622] was placed according to experimental results from Ref. [18]. The ground-state configuration is shown. (Figure and caption taken from Ref. [9].) (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. [14] with nuclear deformations taken from Ref. [19]. The neutron Nilsson levels $1/2^{+}[620]$, $3/2^{+}[622]$, and $5/2^{+}[622]$ were placed based on the experimental results from Refs. [20–22] and [18], respectively. (Figure and caption taken from Ref. [10].)

5. Even–odd nuclei: ^{255}No

Recently, we revisited earlier taken data, considering conversion electrons (CEs) emitted by the ^{255}No evaporation residues (ERs) formed in the production reaction ^{48}Ca + ^{208}Pb [10]. On the basis of ER–CE$_1$(–CE$_2$)(–γ) correlations, the presence of three high-K isomers in this even–odd nobelium isotope could be established. The tentative level scheme of ^{255}No with the approximate location in excitation energy E^*, and possible spin and parity assignments is shown in Fig. 6. Here, also alternative scenarios are shown for the connection of the higher lying ^{255m2}No and ^{255m3}No to ^{255m1}No, the lowest in E^* of the three isomers. In Fig. 5 (b), a possible assignment for ^{255m2}No is illustrated on the basis of SPL configurations showing the g.s. and possible proton and neutron single-particle excitations leading to a 21/2$^+$ configuration. For a more detailed discussion of these findings, see Ref. [10].

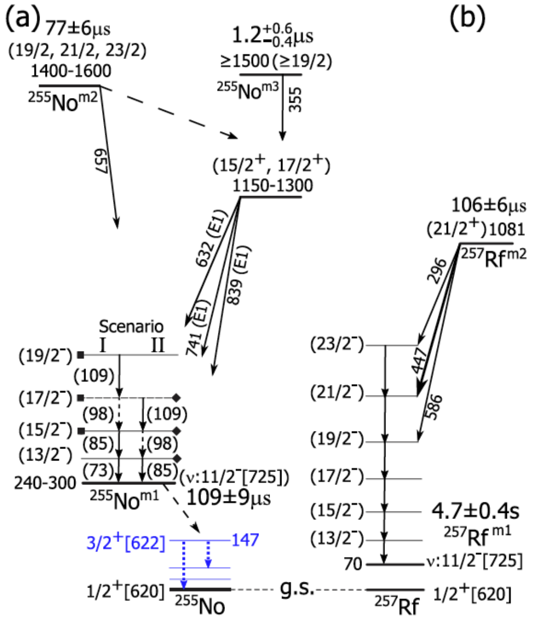

Fig. 6. (Color online) (a) Tentative decay scheme of isomeric states in ^{255}No. The gray/blue dotted lines represent previously observed levels and transitions [22]. Dashed lines indicate only tentative assignments. Roman numerals and rectangles at the end of horizontal lines correspond to different scenarios, where various members of the 11/2$^-$[725] rotational band are populated via the 632-, 741-, and 839-keV transitions (see Ref. [10], Sec. IVB). (b) Decay scheme of the isotonic neighbor ^{257}Rf [24]. Energies are in keV. (Figure and caption taken from Ref. [10].)

In an independent experiment, the same nucleus has been investigated 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 Kessaci [23] at the University of Strasbourg, France, and it is expected to be published soon in *Physical Review C*.

6. Odd particle nuclear systems and new opportunities at SPIRAL2/S^3 — an outlook

The unpaired nucleon in the quantum configuration of a nucleus with odd particle numbers, protons and/or neutrons, of very heavy and superheavy nuclei has proven to be a sensitive probe for the quantum character of nuclear matter, testing in this region of the Segrè chart, in particular, nuclear structure of highest K due to the predominance of SPLs with large spin values.

While already a significant amount of data has been collected in the nobelium–fermium region for even–odd and odd–even (proton–neutron) nuclear systems, more detailed information would be needed to follow the trends of SPLs towards the next closed proton and neutron shells at the so-called "island of stability" of spherical superheavy nuclei. In particular, K isomers which need for their formation, apart from the hindrance-driving spin/parity and energy conditions, a discrete deformation of the nucleus, are expected to be powerful indicators to trace the development from deformation towards sphericity.

For the odd–odd systems with the potential to populate rich varieties of states with complex quantum configurations, data is still very scarce. In these systems up to date, no K isomer has been observed, while quasiparticle excitations of those proton–neutron configurations have the potential to produce high-spin values.

The expected complexity, on the other hand, demands the accumulation of substantial amounts of data, which can be provided only by the new facilities with the highest beam intensities, which are starting operation — like the SHE Factory 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 at GANIL in Caen, France. At SPIRAL2, the separator-spectrometer installation S^3 [25] will be equipped with versatile detection instrumentation, allowing a wide spectrum of experimental approaches from decay spectroscopy after separation (DSAS) [4] to laser spectroscopy and precise mass measurement at the low-energy branch of S^3 [26].

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