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APPROACHING THE ISLAND OF STABILITY — WALKING ON FIRM GROUNDS*

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Dedicated to the late Professor Adam Sobiczewski

The research in the field of superheavy elements started in the sixties of the last century triggered by the prediction of a region of enhanced nuclear stability at the next closed proton and neutron shells beyond ^{208}Pb. Adam Sobiczewski was one of the first predicting proton and neutron numbers for these shell closures at $Z = 114$ and $N = 184$, respectively. In the following decades, extensive efforts led to the synthesis of isotopes of elements up to $Z = 118$ in a fruitful competition of the leading laboratories in the field with FLNR/JINR in Dubna, Russia, LBNL in Berkeley, USA, GSI in Darmstadt, Germany and most recently RIKEN in Wako (Tokyo), Japan. Beyond the synthesis of new elements and isotopes, substantial activities were dedicated to nuclear structure studies, laying the basis for the understanding of this exotic nuclear matter. In-beam spectroscopy as well as decay spectroscopy after separation (DSAS) together with the support by theory have the potential to lay the basis for a successful approach of the so-called *island of stability*, the firm grounds, the creation of which had been started by pioneers like Adam Sobiczewski in the beginning of the second half of last century. In this paper, some of the achievements mainly of DSAS will be presented, with an emphasis on the guidance by theory and the work of Adam Sobiczewski, to whom this paper is dedicated.

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1. Introduction

The synthesis of new elements has reached up to $Z = 118$ with IUPAC recently assigning the naming rights for the elements 113, 115, 117 and 118 to groups at the FLNR and at RIKEN [1–4], resulting in the completion of the seventh row of Mendeleyev's periodic table with the new entries nihonium (Nh), moscovium (Mc), tennessine (Ts) and oganesson (Og).

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Nuclei beyond fermium–rutherfordium owe their existence solely to quantum mechanics effects what makes them an ideal laboratory to study the strong nuclear interaction by in-beam methods as well as decay spectroscopy after separation (DSAS) [5].

To enable successful experiments, a solid theoretical background is essential and mandatory. Effective guidelines were provided by the manifold features of superheavy nuclei (SHN) studied by Adam Sobiczewski. Shell correction energies are possibly the most instructive as they indicate the possible location of the island of stability [6] as can be seen from Fig. 1, where also the additional stability for the region of deformed nuclei around $Z = 108$ is clearly visible. Yet, also binding energies and masses [7], decay [8] and nuclear structure properties of SHN [9, 10], and fission barriers [11] are some of the features investigated by Adam Sobiczewski and his collaborators. In the 1960s, he was one of the first to predict the possible location of the next closed shells beyond ^{208}Pb with $Z = 114$ and $N = 184$ [12]. Nonetheless, his model predictions are still guiding us nowadays in the endeavour to eventually set foot on the island of stability of SHN.

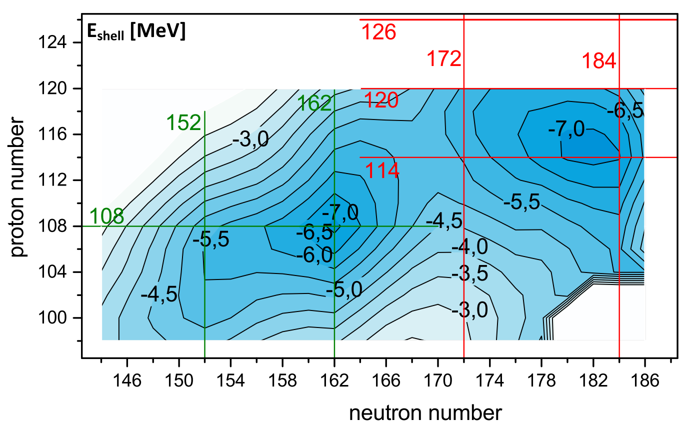

Fig. 1. Shell correction energies in the SHN region calculated in a macroscopic–microscopic model approach by Sobiczewski [6]. Two regions of enhanced stability are visible near the deformed ^{270}Hs and spherical ^{294}Fl nuclei. (Figure and caption taken from [5].)

In this paper, I focus on the achievements of DSAS in the next section. In Section 3, I will discuss K isomerism with the example of ^{270}Ds and its decay products, being predicted for the whole region of deformed heavy and superheavy nuclei from fermium to copernicium (see *e.g.* Ref. [13]). I conclude in Section 4 with an outlook towards possible future progress in the field, expected from the new facilities presently under construction like the SHE factory at FLNR/JINR in Dubna, Russia, or at the new separator-spectrometer set-up S^3 at SPIRAL2/GANIL in Cean, France.

2. Decay spectroscopy after separation — DSAS — for heavy and superheavy nuclei

In a special issue of *Nuclear Physics A* **944**, (2015), all major topics concerning the field of superheavy element (SHE) research have been reviewed. Asai and collaborators [14] summarised the recent achievements of DSAS for isotonic chains in the vicinity of the deformed neutron shell gap $N = 152$ in a region ranging from fermium to meitnerium. 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 2 shows the situation for calculated neutron single-particle trends in the vicinity of $N = 152$.

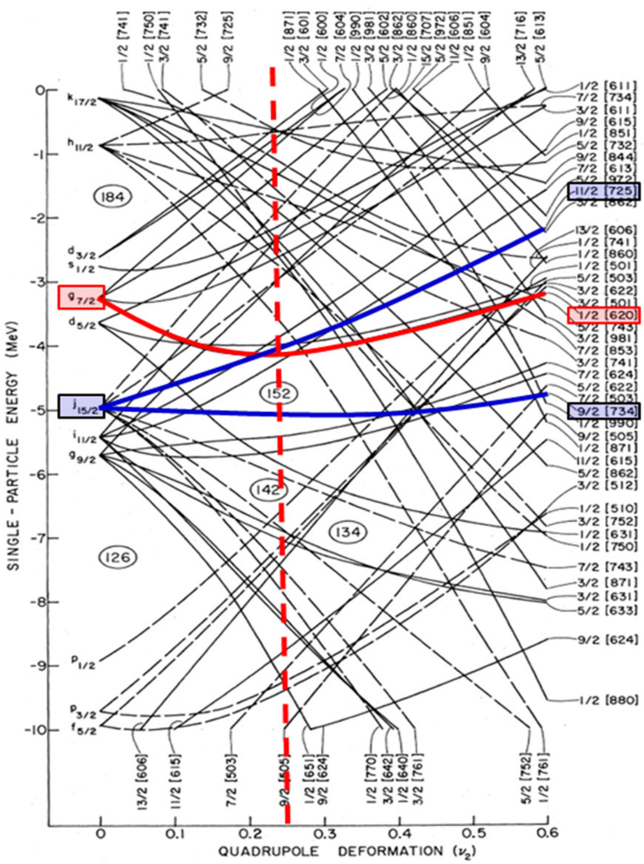

Fig. 2. Neutron single-particle energies as a function of quadrupole deformation from a momentum-dependent Woods–Saxon model by Chasman *et al.* [15]; figure was taken from [15] and adopted as in Ref. [5].

To illustrate a possible single-particle scenario by an instructive example, three single-particle levels (SPL) are highlighted in figure 2 — $9/2^-[734]$, $11/2^-[725]$ and $1/2^+[620]$ — showing in particular the crossing of the latter two at a deformation of $\beta_2 \approx 0.25$. While the macroscopic–microscopic models, and in particular also the calculations by Parkhomenko and Sobiczewski (see also figures 6 and 7 in Ref. [10]), show all three SPLs, the self-consistent models miss the $11/2^-[725]$ state. This SPL has been experimentally determined for the $N = 153$ isotones, but it was seen for the $N = 151$ isotones up to now only for ^{255}Rf. The observation of the $11/2^-[725]$ state in ^{253}No is a key issue for the determination of the possible crossing, predicted by theory on the same grounds as the prediction of the neutron shell closure at $N = 184$. In a recent DSAS attempt of 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 [16]. Figure 3 [5] shows the at present known experimental nuclear structure information of odd-Z odd-A isotopes in the region from einsteinium to dubnium. An interesting feature here was pointed out by Heßberger *et al.* [17] 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 macroscopic–microscopic model calculations

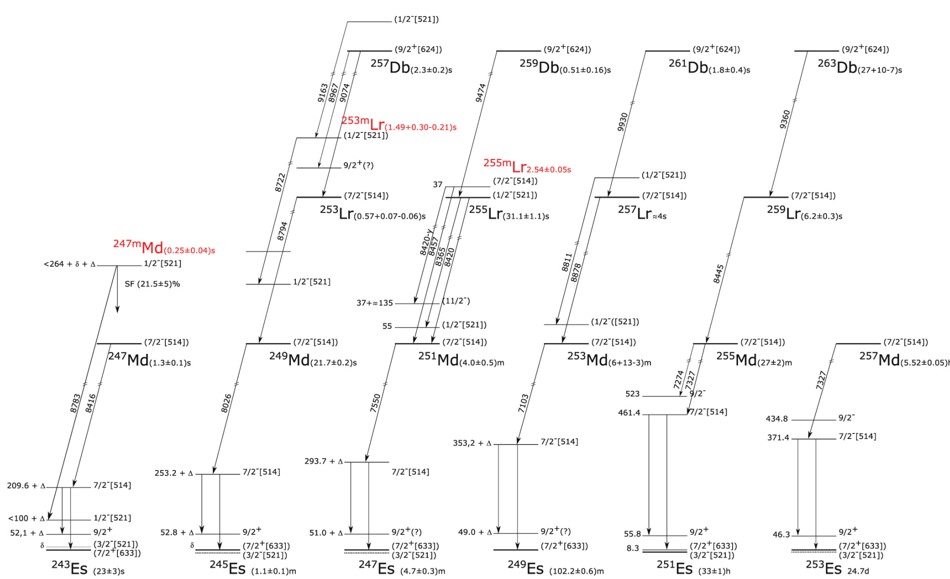

Fig. 3. Decay scheme for odd-Z isotopes from einsteinium to dubnium in the vicinity of the $N = 152$ closed shell. For the origin of the data, see references in [5]. (Figure taken from Ref. [5].)

of Parkhomenko and Sobiczewski [9] (figure 4). Here again, the predictions of Sobiczewski and his collaborators guide us to a deeper understanding of nuclear structure tracing deformation towards heavier nuclei. Deformation is the necessary precondition for nuclear matter to form a certain class of meta-stable states, so-called K-isomers which will be discussed in the next section.

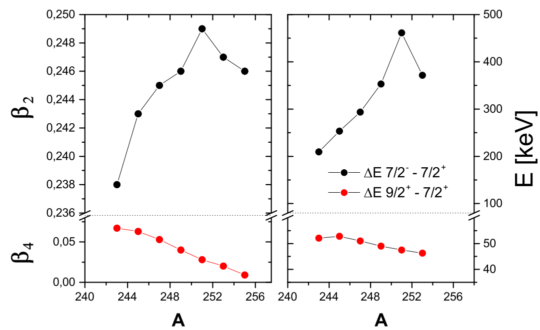

Fig. 4. Comparison of the energy differences of the lowest levels in the isotopes ^{243}Es to ^{253}Es (see the main part of figure 3) with quadrupole and hexadecapole deformation obtained by a macroscopic–microscopic model calculation [9]. See also Heßberger *et al.* [17]. (Figure taken from Ref. [5].)

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 quasi-particle states excited in the nucleus, on the symmetry axis of a deformed nucleus. In cases of high K numbers typically for low excitation energy at ≈ 1 MeV and below, 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 [18]. Recently, such a state has been also reported for its α-decay daughter, ^{266}Hs, in a continuation of the original study [19, 20], where 25 new decays were collected, in addition to the 8 chains observed in the first measurement. For both nuclei, the isomeric state is longer lived than the g.s., a feature which is rarely occurring in atomic nuclei. The original level assignment of the observed decays is shown in figure 5, taken from [21]. The construction of this level scheme had been performed on the basis of calculations performed by members of Sobiczewski's group [22, 23] and by

Ćwiok [24]. The new data will, to some extend, help to refine the understanding of decay details. It revealed, however, new questions which can eventually only be attacked with improved instrumentation, like the ones presented briefly in the next and last section.

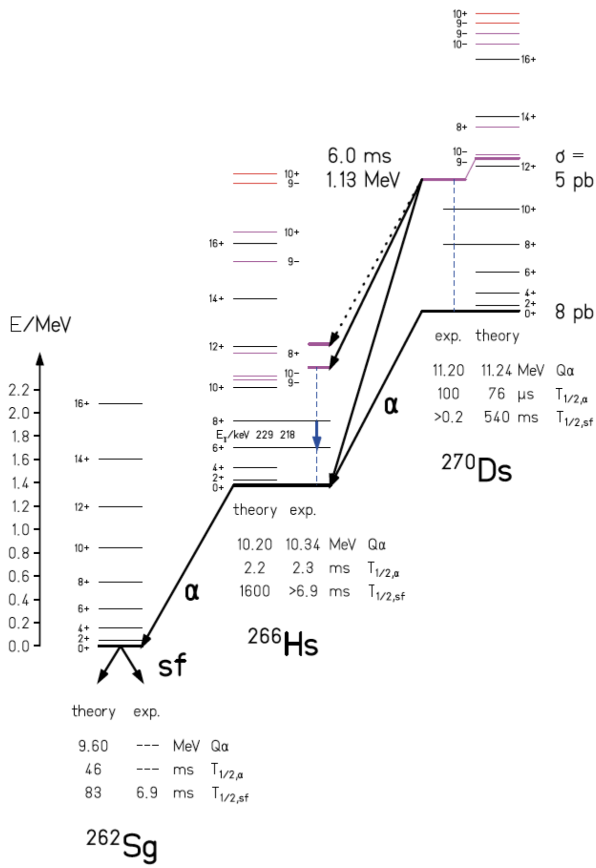

Fig. 5. Original level scheme for the decay of ^{270}Ds and its decay products constructed on the basis of the data of Ref. [18] and theory input for the rotational levels [23], low-lying high K two-quasi-particle states [24]. (Figure taken from Ref. [21].)

4. Outlook: new facilities

To successfully continue the path which had been initiated more than half a century ago by Adam Sobiczewski and his colleagues from theory and experiment, substantial efforts are presently put into the construction of new accelerator facilities, providing beam intensities which will be an order of magnitude higher than the present state-of-the-art. At Dubna, the new SHE

Factory equipped with the high-intensity cyclotron DC280, new separators and improved detection equipment is expected to start operation in 2019 [25] with the major scope to extend the periodic table beyond $Z = 118$, recently established by the FLNR.

At the new SPIRAL2 facility of GANIL in Caen, France, a high intensity superconducting linear accelerator (SC LINAC) is presently under construction with specifications which also respond to the need of highest intensities [26]. It will be equipped with the superconducting separator spectrometer (S^3) set-up [27] combined with the decay spectroscopy detection array SIRIUS (Spectroscopy and Identification of Rare Isotopes Using S^3). 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 Refs. [5, 28]. The possible features to be studied 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.* Refs. [1, 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 like isomeric states in general 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 fundament.

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