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^{270}Ds and its decay products – K-isomers, α-sf competition and masses

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In the period August - October 2010, we investigated the even-even superheavy nucleus ^{270}Ds, employing the reaction ^{64}Ni + ^{207}Pb$\longrightarrow$^{270}Ds. In a first attempt, published in 2001, a total of eight decay chains of type evaporation residue (ER)-α-α-sf (^{270}Ds$\longrightarrow$^{266}Hs ^{262}Sg) was observed. Now, in a period of $\approx$ 40 days of beam on target, we accumulated 25 decay chains of ^{270}Ds, for which we measured in addition to the decay pattern observed in the first experiment, also ER-α-sf and (ER)-α-α-α-sf correlations. For eight of the collected decay chains we detected spontaneous fission of ^{266}Hs. With this we could establish the sf branch of ^{266}Hs. The resulting branching ratio is 0.24$\pm$0.09. More importantly, however, also the searched for K-isomer in ^{266}Hs and the α-decay branch of ^{262}Sg was found. For the latter we detected a total of two α-decays, resulting in a ^{262}Sg α-decay branching ratio of 0.06$\pm$0.04. The observation of this α-decay establishes the missing link to ^{254}No for which a precise mass value employing the Penning trap system SHIPTRAP was measured recently. Using the experimental Q$_\alpha$-values we are now able to provide an experimental mass for the even-even nucleus ^{270}Ds. This is an important parameter for theoretical models which are used to predict masses and binding energies for the heaviest nuclei.

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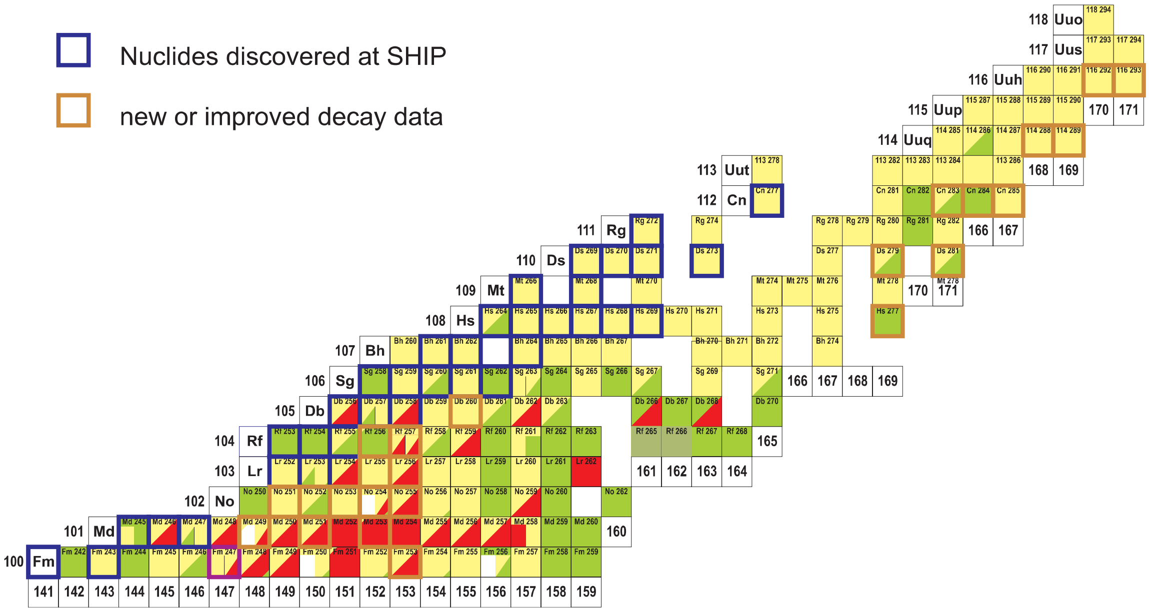

Figure 1: Upper right part of the chart of nuclides summarising the achievements at the velocity filter ship in terms of newly discovered nuclides and progress in spectroscopic data.

1. Introduction

Four decades after the first prediction of the "island of stability" of SHE in the late sixties of the last century [1] its localisation seems almost in reach with experimental indications up to a Z of 118 [2, 4, 3]. The two approaches cold and hot fusion, have yielded the synthesis of a large number of isotopes in the region of highest Z and A. At GSI cold fusion reactions have been employed to produce elements up to Z=112 [2], whereas the heaviest nucleus for this approach has been synthesized at RIKEN in the reaction ^{70}Zn + ^{209}Bi [5]. In ^{48}Ca induced reactions on actinide target nuclei decay patterns have been observed at Dubna which were assigned to the production of nuclei spanning the more neutron rich area from ^{266}Rf to ^{294}118. Some of these results for decay chains assigned to isotopes of the elements Z = 112, 114 and 116 have been confirmed independently at the velocity filter SHIP at GSI [6, 7], at the Berkeley gas-filled separator BGS at LBNL [8], and at the gas-filled separator TASCA at GSI [9]. Beyond the successful synthesis of heavy nuclei, the high beam intensities nowadays available, together with the advanced particle and γ detector set-ups allow for detailed nuclear structure investigations for heavy and superheavy nuclei like ^{252,254}No[10, 11] and ^{270}Ds [12] which will be discussed in this paper. In addition fast SHE chemistry, e.g. at the gas-filled separator TASCA[13], and precision mass measurements in the penning trap system SHIPTRAP complete the experimental means available at GSI. As one of the highlights in the field of heavy and superheavy nuclei the masses of the nobelium isotopes ^{252,253,254}No were measured with high precision at SHIPTRAP [14]. An overview of the achievements at the velocity filter SHIP is summarised in Fig. 1.

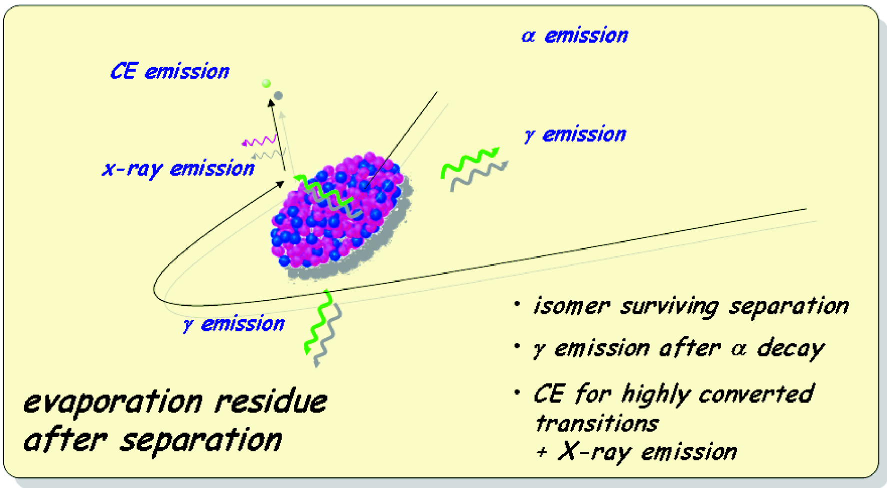

Figure 2: Features which can be accessed by decay spectroscopy after separation by means of particle, γ-ray and X-ray detection.

2. Nuclear Structure Features of Heavy and Superheavy Elements

There are two complementary approaches to explore the structure of heavy and superheavy nuclei. A comprehensive review of nuclear structure investigations for heavy actinide and trans-actinide nuclei has been published by M. Leino and F.P. Heßberger [15]. Inbeam studies using a γ-spectroscopy set-up at the target position yield access to the high spin region of nuclear excitation in heavy ion collisions. They suffer from high background rates from the target which limits the beam current. Decay spectroscopy after beam separation yields access to low lying states, populated by α-decay or below isomeric states, only. It is, however, almost background free due to separation and decay coincidences, and the full intensities of high current accelerators can be used. The UNILAC accelerator together with the velocity filter SHIP and the decay spectroscopy setup is among the most efficient setups for studies of this type worldwide. A similar detector array called TASISPEC [16] is in use at the focal plane of TASCA.

2.1 Decay Spectroscopy after Separation

Detailed understanding of nuclear structure and its development in the vicinity of closed shells, in regions of deformation and towards higher Z is a necessary ingredient for a successful progress in the synthesis of new heavy elements. Possible trends in single particle levels are the most sensitive probe for the formation of low level density, and eventually the appearance of shell gaps. Decay spectroscopy of α-emitters after separation is a powerful tool to study their daughter products or isomeric states via α fine structure or α-γ spectroscopy by ER-α or ER-α-γ coincidence measurements. Here the fusion reaction products are after separation implanted into a Si detector for residue and α detection, which is combined with a high resolving γ-ray detector array. Fig. 2 shows the features which can be investigated by such a set-up. This method is very clean compared to in-beam studies because of the effective shielding from target background due to its spatial separation and the effective cleaning by the ER-α coincidence technique. It is highly efficient because of the favourable close geometry of the α and γ detectors. Due to the source at rest it has the further advantage of the absence of any γ-ray Doppler shift or broadening which yields, with a moderate crystal size and a moderate granularity of the Ge-detector, a nevertheless high efficiency in case of the SHIP set-up of up to 15%. For TASISpec values of up to $\approx$ 40% can be reached [17].

2.2 *K*-Isomers

Among the most interesting features is the observation of *K*-isomeric states (see e.g. [18, 19]). Xu et al., employing configuration constrained potential energy surface calculations (PES), predict *K*-isomers to be a general feature of prolate deformed nuclei in the region for $Z>100$ at low excitation energies ($\approx$ 1-2 MeV) for even-even isotopes [20]. A table of *K*-isomers in even-even isotopes in that region is given in ref. [21]. We could recently establish and/or confirm such states in the isotopes ^{252,254}No [22]. The heaviest nucleus where such a state was found is ^{270}Ds [12]. *K*-isomers were found also in even-odd and odd-even isotopes in this region like e.g. ^{251}No [22], ^{253}No [23], ^{255}No [24], and ^{255}Lr [25, 26]. Xu et al. pointed out that high-spin *K*-isomerism has consequences for the fission barrier and α-decay, which could lead to a higher stability and longer lifetimes of the isomer as compared to the ground state (g.s.) for a certain class of superheavy nuclei. Examples for such an isomer-g.s. lifetime inversion are ^{250}No [27] and the here investigated ^{270}Ds [12].

2.2.1 K-Isomers in ^{252}No and ^{254}No

For ^{252}No and ^{254}No the ground-state band structure had been investigated in pioneering experiments at ANL and JYFL [21]. For ^{254}No two isomeric states were observed in decay spectroscopic studies [28, 29]. The first was placed at an excitation energy of 1293-1297 keV. Its half-life was determined to be 180 μs. For the second isomeric state both groups estimated $\approx$ 2.5 MeV but disagreed on the spin assignment. In both publications four-quasipaticle configurations are proposed for this state with $K^{\pi} = 16^{+}$ [28] and 14^{+} [29]. In a recent measurement at SHIP we could establish the band structure between the two isomers as well as its link to the ground state rotational band [30]. We measured a half-life for this second isomeric state of 198(13) μs. For ^{252}No we observed a new K-isomer with a half-life of 110 ± 10 ms at an excitation energy of 1254 keV [10]. Beyond the spin and parity assignment of this isomer we could also establish a detailed decay scheme including a side band below the isomeric state and its connection to the ground state rotational band.

2.2.2 ^{270}Ds and its Decay Products

In the experiment reported in ref. [12] we observed in the reaction ^{64}Ni + ^{207}Pb a total of 8 decay chains consisting of evaporation residue(ER)-α-α-sf correlations all of which attributed to the production of ^{270}Ds followed by the sequential emission of two α-particles leading two the daughter ^{266}Hs and the granddaughter ^{262}Sg which eventually decayed by spontaneous fission. For the ^{270}Ds α decay we assigned to the observed two groups of decay times the half-lives of $6.0^{+8.2}_{-2.2}$ ms and 100^{+140}_{-40} μs, respectively. The α decay energy of the shorter lived g.s. was 11.03 ± 0.05 MeV, whereas for the longer lived isomer we observed α particles with 10.95 ± 0.02 MeV, 11.15 ± 0.02 MeV and 12.15 ± 0.05 MeV. For the daughter ^{266}Hs the observed eight decay times were consistent with a single half-life of $2.3^{1.3}_{-o.6}$ ms with an α energy of 10.18 ± 0.02 MeV. There was no clear indication of a K-isomeric state which would be in line with the expectations from the

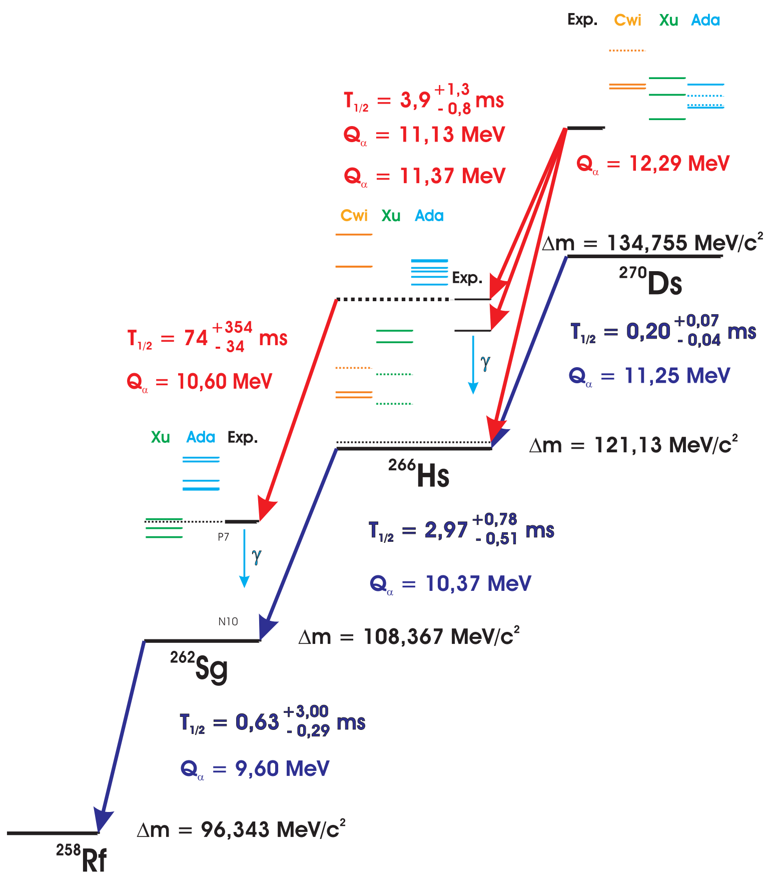

Figure 3: Proposed decay and level scheme for ^{270}Ds and its decay products on the basis of our observations including the new data. The shown Q_α values and half-lives are still somewhat preliminary. Final values will be published elsewhere. The experimental decay scheme is compared levels obtained from Hartree-Fock-Bogoliubov (HFB - Cwi) [12, 33], configuration constrained potential energy surface (PES - Xu) [34] and two center shells model (TCSM - Ada) [35] calculations.

theoretical predictions of the existence of *K* isomers in the whole region of deformed heavy and superheavy nuclei.The last member of the decay chain decays by fission with a half-life of $6.9^{+3.8}_{-1.8}$ ms and a total kinetic energy of the fission fragments of 222 ± 10 MeV. From the measured α decay energies and times we could construct various decay paths from ^{270}Ds down to ^{262}Sg which were consistent with the calculated level scheme [31].

In a second experiment we accumulated 25 decay chains of ^{270}Ds, for which we observed in addition to the decay pattern observed in the first measurement, ER-α-α-sf, also ER-α-sf and (ER)-α-α-α-sf correlations. For eight of them we detected spontaneous fission of ^{266}Hs, confirming its expected sf branch. The resulting branching ratio is 0.24 ± 0.09, including the 8 events from the first run. Also the searched for α decay branch of ^{262}Sg was found. We detected a total of two α decays, resulting in a α-decay branching ratio of 0.06 ± 0.04. The observation of this α-decay establishes the missing link to ^{254}No for which we recently produced a precise mass value using the Penning trap system SHIPTRAP [14]. Using the experimental Q_α-values, including the one for ^{258}Rf reported in [32], we are now able to provide an experimental mass for the whole decay chain

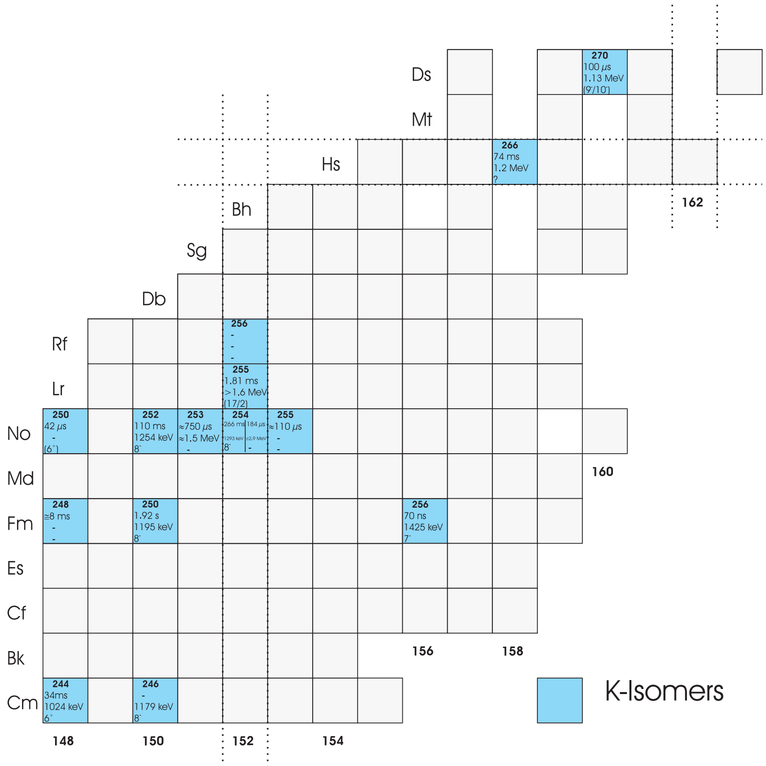

Figure 4: Excerpt of the chart of nuclides indicating the *K*-isomers observed for heavy nuclei in the region Z>96 and the decay chain for the proposed reaction ^{64}Ni + ^{207}Pb. Half-life, decay energy, spin and parity values are given for *K*-isomers only

up to the even-even nucleus ^{270}Ds for the first time. This is an important parameter for theoretical models which are used to predict masses and binding energies for the heaviest nuclei. In addition to the g.s. to g.s. α decay of ^{270}Ds, we observed decays from the *K*-isomer into excited states of the daughter ^{266}Hs. One of these populates the newly discovered *K*-isomer in the daughter ^{266}Hs, which we tentatively assign due to a more then one order of magnitude longer decay time of 105 ms and an approximately 200 keV higher α-decay energy. In addition a γ ray of 332 keV was observed in coincidence with this α decay, proving that an excited state in ^{262}Sg was populated in this decay. In Fig. 3 we show a level scheme which has been constructed on the basis of both experiments. It is compared to model calculations in terms of Hartree-Fock-Bogoliubov (HFB) [12, 33], configuration constrained potential energy surface (PES) [34] and two center shells model (TCSM) [35] calculations. The shown Q_α values and half-lives are still somewhat preliminary. The final results of this analysis will be published elsewhere. Fig. 4 shows a section of the chart of nuclides, for Z = 96 to 100, showing the currently established *K*-isomers in that region.

summarises in an excerpt of the chart of nuclides for Z = 100 to 110 the up to now established *K*-isomers in the that region.

3. Outlook: Towards the Island of Stability

Low cross sections, the advances in nuclear structure investigations, reaction mechanism studies, chemistry and SHE synthesis experiments with a steadily increasing demand for higher beam intensities, more sensitive and more sophisticated detection set-ups and new methods determine the road map for future SHE investigations. Intensity increase is one of the major issues in this context. The presently pursued upgrade of the UNILAC accelerator at GSI, consisting of a new 28 GHZ ECR source and a new RFQ injector providing an order of magnitude higher beam current, is only a first step towards a dedicated continuous wave (CW) accelerator which would increase the beam intensity by a factor of four already by extending the 25% UNILAC duty cycle to 100%. Additional increases due to the advanced accelerator technology can be expected. Improvement of the detection system in terms of higher efficiencies is as mandatory as the employment of additional measurement parameters. Mass determination and X-ray spectroscopy would be extremely helpful for a final A and Z identification for the hot fusion reaction products. Finally the predicted spherical shell stabilised SHN are far in the neutron rich region, not accessible to stable beams. Rare isotope facilities like the project FAIR at GSI do not (yet) provide sufficient beam intensities of the required radioactive beam species, but offer possibilities for systematic studies in terms of nuclear structure investigations as well as isospin dependent reaction mechanism studies. Given a certain development potential, in the far future even synthesis experiments might be envisioned. In conclusion, the roadmap towards spherical shell stabilized nuclei is laid out. The challenges are obvious. It is up to us to take them on.

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