Fission hindrances in transfermium nuclei

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Abstract. Very heavy nuclei owe their stability against spontaneous fission to quantum shell effects, which depend on the local density of single-particle states. The height but also the width and the structure of the barrier in multi-dimensional deformation space determine the fission half-lives. Other effects come into play, such as the conservation of quantum numbers and superfluidity or stiffness of the system in the fission process. This is why odd nuclei have longer fission partial half-lives with respect to their even neighbours and also why multi-quasi-particle states, such as high-K states, are thought to be more stable against fission than the ground state. We will report here on two different fission studies carried out with the GABRIELA detector array at the focal plane of the recoil separator SHELS. The first study concerns the fission properties of ^{253}Rf, the most neutron deficient Rf isotope known to date. The second study focusses on a new measurement of the fission hindrance of the known 8^- isomer in ^{254}No.

1 Introduction

The existence of transfermium nuclei is solely due to quantum shell effects, which create a pocket at a given deformation in the potential energy surface of the nucleus and provide a barrier structure against spontaneous fission. These shell effects are clearly observed in the plot of fission partial half-lives of even-even very heavy and super heavy nuclei as a function of neutron number N (see Fig. 10 of ref.[1]), where fission rates are seen to increase drastically on either side of N=152 for the heaviest systems. This is especially visible for the No isotopic chain, where the lifetime drops by 10 orders of magnitude from ^{254}No to ^{250}No. For N≤152, the trend of lifetimes in Rf isotopes follows the one of No isotopes, accelerated by a factor of the order of 10^6 – 10^7. This acceleration is understood as being due to a decline of the second barrier peak in Rf isotopes.

Fission half-lives in odd N/Z systems are known to be much longer than the ones of their even-even neighbours. This fact is theoretically understood, as detailed in Ref. [2]. The conservation of spin on the pathway to fission (and parity in the cases where axial symmetry is not broken) leads to a higher fission barrier by an amount called specialisation energy. The blocking of orbitals by the quasiparticle also lowers pairing energies. This in turn leads to larger collective masses, and therefore to longer fission times. These considerations also apply to multi-quasiparticle states, and in particular to high-K isomers, which are calculated to exhibit a larger stability against fission than the ground state of the same nucleus [3]. Until recently, however, there was no obvious experimental evidence for longer fission times from high-K states than from the corresponding ground state, except for ^{250}No (see Fig. 13 of Ref. [7]). New data on ^{254}Rf [6] and ^{250}No [4, 5] have shown that the fission hindrances ($T_{SF,iso}/T_{SF,gs}$) of high-K isomers in these nuclei are much larger than 1. These new findings cast a doubt on the 3 data points of Ref. [7], which are not lower limits, as pointed out by Clark [8]. In ^{256}Fm, the data comes from the observation of 2 beta-delayed fission events [9] and probably needs confirmation. The data point for ^{262}Rf no longer exists due to a mis-assigned fission activity [1]. Remains the 8^- isomer in ^{254}No, for which a 0.02% fission branch has been reported [10].
So the questions addressed in this talk are related to the limits of the nuclear chart for neutron-deficient Rf isotopes and the fission hindrance of the low-lying $K^\pi=8^-$ isomer in ^{254}No.

2 Experimental Setup

To address the questions of interest, experiments were performed at the FLNR in Dubna, using the GABRIELA de-

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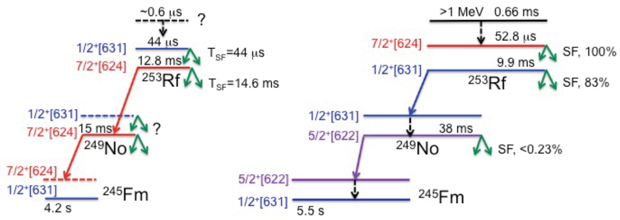

Figure 1. Left: Decay scheme of ^{253}Rf established from data taken at GSI (the figure is adapted from [13]). Right) Decay scheme obtained by compiling the data on ^{253}Rf and ^{249}No collected with GABRIELA and performing a Geant4-assisted analysis (see Ref. [16] for details).

tector setup [11] at the focal plane of the velocity filter SHELS [12]. Intense heavy-ion beams are provided by the U400 cyclotron and are used to produce transfermium nuclei in fusion-evaporation reactions on stable and actinide targets. GABRIELA is composed of an array of Double Sided Silicon-strip Detectors to detect the super heavy nuclei transported by the separator and their subsequent charged particle emissions (alpha particles, fission fragments, internal conversion electrons) and an array of Compton-suppressed Ge detectors to detect the emitted photons and X rays.

3 Fission stability of Rf isotopes

The most neutron-deficient Rf isotope known to date is ^{253}Rf. To produce it, we used the 2-neutron evaporation channel of the fusion reaction between ^{50}Ti ions and the atoms of an isotopically enriched ^{204}Pb target. A few months after our experiment, GSI published a paper [13], in which they confirmed the existence of 2 fission activities in this nucleus (it was not clear from Ref. [14] whether the longer-lived activity was from the production of ^{256}Rf on contaminants of the target). They also could observe a small alpha branch to the newly discovered ^{249}No [13, 15, 16]. On the basis that fission from a low-K state occurs faster than from a high-K state, the faster fission activity was assigned to the 7/2+[624] neutron configuration, while the longer-lived state was assigned the 1/2+[631] configuration, following the systematics of N=147 isotones. In our experiment, we collected a factor 10 more data. The lifetimes of the 2 fission activities were found to be in agreement with the GSI values. We also confirm the existence of an alpha decay branch to ^{249}No. What we also observed was the internal decay of an isomer, which has to be a high-K isomer given its measured excitation energy of more than 1 MeV. This internal decay is followed by the shorter-lived fission activity of ^{253}Rf. This finding leads us to change the assignments made in Ref. [13], and also the decay scheme of ^{253}Rf to ^{249}No, as shown in Fig. 1.

The relative excitation energies of the $7/2^+$ and $1/2^+$ states in ^{253}Rf could not be measured, but given the decreasing trend of the $1/2^+[631]$ state in N=149 isotones (see Fig. 6 of Ref. [18]) , it is likely that the $1/2^+$ is the ground state in ^{253}Rf, in which case the $7/2^+$ state must not be more than $\approx$ 15 keV above the ground state in order to be isomeric. If, on the other hand, the $1/2^+$ is not the ground state, it must lie within less than 100 keV from the 7/2+ state. This leads to very a unique situation: the existence of 2 nearly degenerate states in the same nucleus, with very different fission properties.

The known fission half-lives of No and Rf isotopes are resumed in FIg. 2. The drop of 6-7 orders of magnitude in spontaneous fission half-lives in going from No to Rf isotones continues in ^{253}Rf and extrapolating further, one can conclude that the ground state of the next even Rf isotope (^{252}Rf) will probably be very close to the limit of stability of an atom and that if the ground state of ^{251}Rf has the same configuration as ^{249}No, it should be accessible to experiments. The difference in fission half-lives between the 2 close-lying neutron configurations in ^{253}Rf can be understood with the help of some preliminary axial calculations using the BSkG2 Skyrme parametrisation [19]. These show that the $7/2^+$ orbital follows closely the Fermi level all the way to scission, while the $1/2^+$ orbital, undergoes many avoided crossings and moves away from it. This should lead to a larger specialisation energy and could therefore explain the factor $\approx$250 difference in fission time. Of course, a full microscopic calculation, including the triaxial degree of freedom, with pairing and proper treatment of the avoided crossings is required to confirm the difference, but this is quite challenging and requires more computer time.

4 Fission from the 8^- isomer in ^{254}No

The ^{254}No nucleus is the most investigated nucleus in the transfermium region [10, 20–22]. Two isomers are known; a low-lying 264 ms 8^- state, which decays to an intermediate 3^+ band and to the ground state band and a higher-lying shorter-lived state, which decays to the lower-lying isomer and whose spin and parity are still under debate (in the level scheme established by the Berkeley group [22], a spin 16 has been assigned to the 184 μs isomer). In Ref. [10], one can find a value for the fission branch from the 8^- state, but it should be mentioned that the corresponding number of fission events was obtained by correcting for the contribution of the fission of the ground-states of ^{254}No and ^{252}No (produced on ^{206}Pb contaminants in the target). No fission has been observed from the short-lived isomer. In order to verify the fission hindrance of the low-lying isomer, we performed a long irradiation of an enriched 340 μg-thick ^{208}PbS target (99.57% ^{208}Pb, 0.01% ^{206}Pb) with an intense beam of ^{48}Ca. A total beam dose of 4.2 10^{18} was measured and close to 1 million full-energy alpha particles corresponding to the decay of ^{254,255}No were observed (more details on the experiment can be found in Refs. [23, 24]).

With such statistics, the fission events from the ground state as well as from the 8^- state can be isolated from all other possible sources of fission by selecting specific decay paths. In the case of the ground state fission, we demand that the implanted ions first undergo the characteristic decay of the long-lived isomer of ^{254}No. The time of the subsequent decays is shown as a function of decay energy

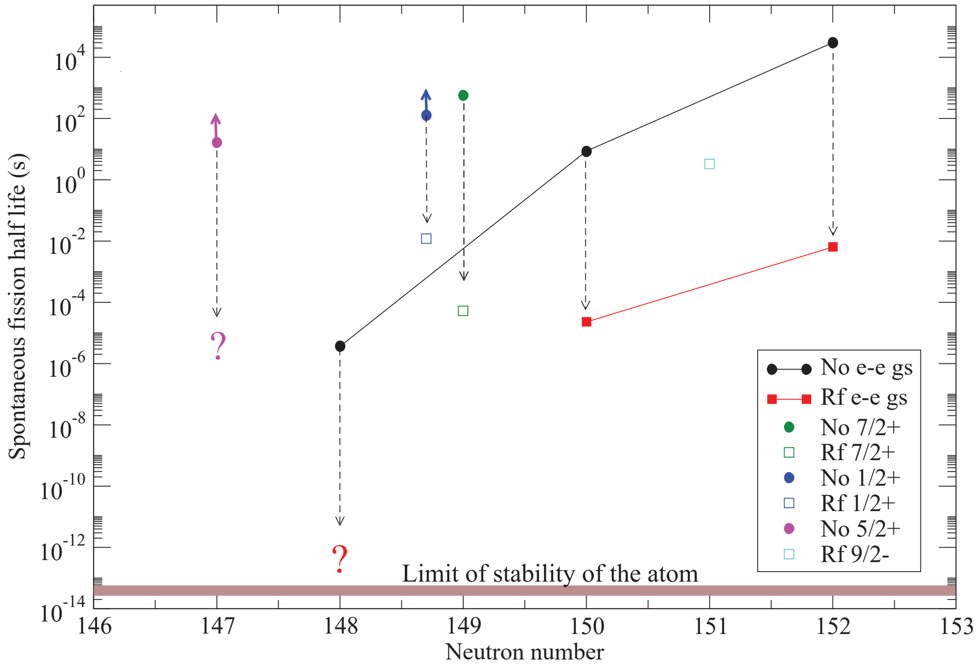

Figure 2. Fission half-lives of No (circles) and Rf (squares) isotopes as a function of neutron number. The spins and parities for the odd-N cases are given in the legend. In the case of ^{253}Rf (N=149), the data points are drawn at N=148.5 and 149 for clarity. The typical formation time of an electronic shell ($\approx 10^{-14}$ s) is shown and denotes the limit of stability of an atom.

in the top left panel of Fig. 3. The characteristic alpha decay of ^{254}No (highlighted in red) and the ground-state fission at large amplitude (surrounded by the blue box) are clearly visible. From the ratio of fission to alpha-decay events, a fission branch of 1.61(8) 10^{-3} could be extracted, which is in good agreement with previous measurements. The ground state half-life can be measured by fitting the time distribution of the alpha-decay events highlighted in red, as shown in the bottom left panel of Fig.3.
Now if we demand that the decay flux first go through the higher-lying isomer, the subsequent decay of the 8^- isomer is cleanly isolated in the correlation plot on the top right panel of Fig. 3. The signals arising from the isomeric cascade of internal conversion electrons and accompanying fluorescence and auger emissions are seen at low ADC channel values between 1 ms and 4 s (y-axis values of 10 and 22 respectively in the top right panel of Fig.3). In the similar time interval at large amplitudes, where one expects the isomeric fission events, no counts are observed in the corresponding blue box. The absence of fission events gives an upper limit of 2.26 10^{-5} for the fission branch of the 8^- isomer. The half-life of the isomeric decay is obtained by fitting the time distribution of the events highlighted in red with a 3-component fit, as shown in the bottom panel of Fig. 3. With the measured fission branches and half-lives, the fission hindrance of the isomer is found to be greater than 0.37, which is ~9 times larger than the previously established value.

5 Conclusion and perspectives

To conclude, the fission properties of 2 states in ^{253}Rf have been revisited, giving insights into the properties of even more neutron-deficient Rf isotopes and providing a new tool to probe the spectrum of single-particle states as a function of elongation. The fission of the 8^- state in ^{254}No has been searched for in a dedicated high-statistics run but no evidence for it could be found. Fission from a high-K state has therefore yet to be confirmed. The continued development of high-sensitivity and high-spectroscoppic-quality set-ups at various facilities around the world should allow to extend these studies to heavier systems.

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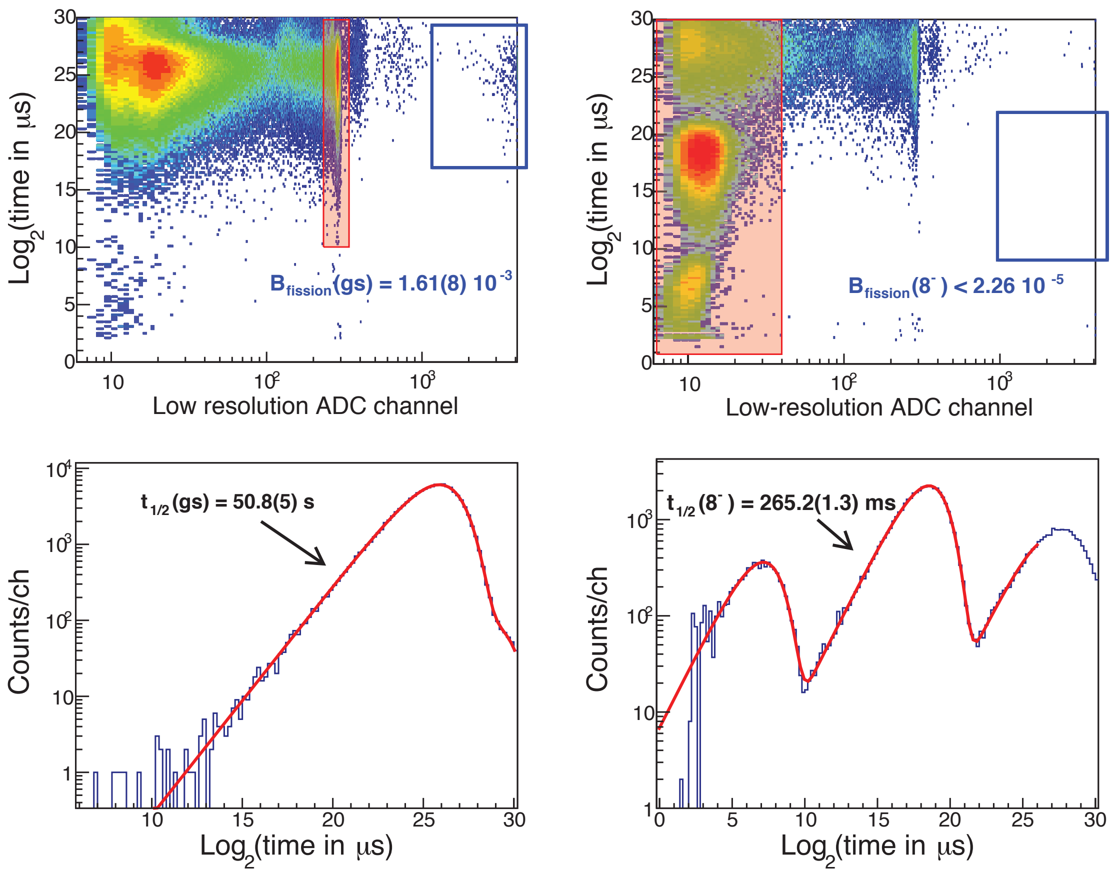

Figure 3. Top left) Time distribution of decay events following the decay of the 8^- isomer in ^{254}No as a function of low-resolution ADC channel. In this particular instance, the low-resolution amplification range of the DSSD ADCs allowed to measure energies up to ∼100 MeV. Top right) Same as on the left, but for decay events which follow the detection of the short-lived isomer of ^{254}No. Bottom panels) Projection onto the time axis of the shaded areas in the corresponding top panels. The solid lines represent multi-component fits to the resulting time distributions. In particular, due to the existence of short-lived isomers in cascade in ^{255}No [24, 25], the characteristic decay of the $11/2^-$ state of ^{255}No appears in the right panel between x-axis values of 3 and 10 (8 μs-1 ms) and needs to be accounted for in the fit of the time distribution. The extracted fission branches and half-lives of the ground-state (left) and 8^- isomeric state (right) are indicated in the corresponding panels. See text for more details.

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