Alpha-decay spectroscopy of ^{257}Rf

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The decay properties of the ground state and excited states of ^{257}Rf have been investigated with the detector array GABRIELA at the FLNR, Dubna. The electromagnetic decay of a new excited state in ^{253}No has been observed. The state lies 750 keV above the ground state and is favourably populated in the alpha decay of the low-lying spin isomer of ^{257}Rf . It decays to the $9/2^-$ ground state by an M1 transition and is assigned the $11/2^- [725]$ Nilsson configuration. The presence of this state suggests a possible reinterpretation of the decay of the high-K isomer in ^{253}No .

I. INTRODUCTION

The spectrum of excited states in super heavy nuclei is the result of a delicate balance between the strong Coulomb repulsion between the numerous protons in the nucleus and the properties of the strong force acting between the many nucleons in the system. Following specific states across isotonic and isotopic states chains allows to highlight how the system rearranges itself as neutrons or protons are added to the system and can reveal effects such as changes in the underlying single-particle spectra and coupling with collective phenomena.

Combined prompt and decay spectroscopy by means of alpha, gamma and internal conversion measurements has proven to be a powerful tool to investigate decay patterns of excited nuclear states in transfermium nuclei (see reference [1] for a full review). In this paper, the decay properties of the ground state and isomeric states of ^{257}Rf are investigated using the Si and Ge detector array GABRIELA [3] installed at the focal plane of the Separator for Heavy Element Spectroscopy (SHELS) [2].

II. EXPERIMENTAL DETAILS

To produce ^{257}Rf nuclei, the reaction $^{208}\text{Pb}(^{50}\text{Ti},1n)$ was used at cyclotron beam energies of 240 to 245 MeV. Pb target of thicknesses of 400-450 $\mu\text{g}/\text{cm}^2$ were used. The targets had a 1.5 μm Ti backing and were rotated to withstand the intense flux of ^{50}Ti ions provided by the U400 cyclotron at FLNR, JINR. A total dose of $4.68 \cdot 10^{18}$ incident particles was recorded during the time of the experiment.

The nuclei of interest were separated by SHELS and implanted into the 10x10 cm^2 Double Sided Silicon-strip Detector (DSSD) of the newly upgraded GABRIELA detector array [4]. This detector provides 16384 different pixels for genetic position and time correlations between implantation and subsequent decay events. Surrounding the DSSD, in the upstream direction, 8 smaller-sized DSSDs forming a tunnel were used to detect escaping α particles and fission fragments as well as internal conversion electrons (ICEs). Gamma and X rays were detected with a ring of 4 coaxial Ge detectors and a large clover detector placed just behind the DSSD. The signals from the individual crystals of the clover can be addbacked to gain in high-energy gamma-ray efficiency. All Ge detectors were surrounded by a BGO shield, which provides a flag in case of coincident Ge and BGO events. The signals from all the detectors were time-stamped with a 1 μs clock. The amplification range of the analog electronics was set to detect ICEs and α particles up to 25 MeV on the front and back side of the DSSD.

Energy and efficiency calibration runs for conversion electrons and α particles were performed with ^{50}Ti -induced reactions on standing ^{164}Dy and ^{150}Er targets leading to the production of $^{209\text{m},210\text{m}}\text{Rn}$ and α -emitting Th and Ra isotopes. Ge detectors were calibrated with standard ^{133}Ba and ^{152}Eu sources.

III. RESULTS

The alpha-particle energy spectrum of ^{257}Rf is shown in Fig. 1. Two groups of lines with clearly different lifetimes are visible; one between 8.4 and 8.85 MeV and the other below 8.3 MeV and between 8.9 and 9.1 MeV. They correspond to the emission from the ground state (gs) and a low-lying spin isomer (iso1) respectively [5–9]. The corresponding time distributions are shown in Fig. 2 and the obtained half-lives are given in Tab. I. The half life of iso1 agrees well with the literature

FIG. 1. Spectrum of alpha-particle energies detected in the same pixel as ^{257}Rf nuclei and followed by the characteristic alpha decay of ^{253}No .

values. The half life of the ground state, however, is found to be 1.6 times larger than the evaluated value [10] but consistent with the measurement of Dragojevic et al., [11]. Simulations using the most recently measured half-life value of 5.6 s for the ground state populated indirectly by the alpha decay of ^{261}Sg [8] were carried out to check the possibility that the decaying ground state has an apparent lifetime due to internal decay of iso1. The shape of the time distribution varies quickly with the amount of feeding from the isomer but a shape similar to the measured one can be obtained assuming a 15(5)% feeding from iso1.

TABLE I. Half lives obtained in this work for different states in ^{257}Rf .

Nuclear state	$t_{1/2}$
$^{257,gs}\text{Rf}$	7.1(3) s
$^{257,iso1}\text{Rf}$	4.5(1) s

The alpha decay from the ground state of ^{257}Rf is correlated to the internal decay of the $5/2^+$ isomer [12, 13] at 167 keV above the ground state of ^{253}No . A prominent peak in this group is found at 8778 keV, as previously reported in references [5, 8].

Fig. 3 shows the Compton-suppressed γ ray spectrum observed in coincidence with alpha particles emitted by implanted mother nuclei as well as the correlations with the subsequent alpha decay of the daughter nuclei. Three lines are assigned to the decay of excited states in ^{253}No as they are clearly correlated to the subsequent characteristic alpha decay of ^{253}No between 8 and 8.1 MeV : 750, 283 and 63 keV. The 91 keV line observed by Streicher et al., [8] is present in the left panel of

FIG. 2. Logarithmic time distributions of the alpha-particle groups shown in Fig. 1, blue for iso1 and red for the ground state. The solid lines are the fitted exponential decay curves. The dashed line is the result of simulations of the ground state decay assuming feeding from iso1. See text for details

Fig. 3, but it is not found to be correlated to the α decay of ^{253}No . No evidence for the 557 keV transition reported by Hessberger et al., [14] is observed. The 63 keV transition is fed by the alpha decay of iso1 and is in line with the energy reported for the $11/2 \rightarrow 9/2$ transition in the ground state rotational band [15, 16]. The 750 keV transition is new. The state emitting the 750 keV transition is also populated by iso1. From the few counts at the expected K and LMN internal conversion peak positions in the tunnel detectors, the 750 keV transition is found to have a total conversion coefficient $\alpha_{tot}=0.30(24)$, which indicates it is of M1 character. The 283 keV transition is populated by the alpha decay of the ground state of ^{257}Rf . As already reported in reference [8], the distribution of alpha-particle energies in coincidence with this transition is large, which indicates feeding from higher-lying states and summing effects with atomic processes [17]. Three counts are observed in the energy range of the LMN conversion peak of the 283 keV transition which translates into a conversion coefficient $\alpha_{LMN+}=0.3(2)$. The K conversion of the 283 keV line could not be disentangled from possible contributions from unobserved low-energy transitions, however, the LMN conversion coefficient suggests an E2 character.

IV. DISCUSSION

From Q value considerations, the decay scheme of Fig. 4 can be constructed. The spin of the ground state of ^{253}No has been firmly established from a measurement of its hyperfine splitting [18]. The spin assignments have been deduced from the measured (or previously known in the case of the 167 keV transition [8, 13]) multipolarities and taking into account the available low-lying single-particle states. Configuration assignments have been made on the basis of systematics. With the present data, it is not possible to determine unambiguously the spin of the state at 450 keV

FIG. 3. Left: Compton-suppressed and add-backed γ -ray energy spectrum observed in coincidence with alpha particles emitted by implanted mother nuclei. Right: same as on the left but as a function of daughter alpha-particle energies.

excitation energy. Given the available single-particle states around the Fermi level and the decay trends observed in the isotone ^{251}Fm [19], the spin $1/2$ has been assigned, which could correspond either to the $1/2^+[620]$ or $1/2^+[631]$ Nilsson states.

The $11/2^-$ state at 750 keV is assigned the $11/2^-[725]$ configuration, as, with the $9/2^-[734]$ orbital, it is the only available negative parity single-neutron level around the Fermi surface. Its excitation energy reflects the splitting of the $j_{15/2}$ shell, from which both it and the $9/2^-[734]$ ground state emanate. The $11/2^-$ state in $N=151$ isotones decreases in excitation energy as Z increases, as a fine structure alpha decay study places it at ~ 600 keV in ^{255}Rf [20]. A similar trend is observed in $N=153$ isotones, where the $11/2^-$ state steadily decreases in excitation energy from ^{251}Cf onwards to become the ground state in ^{259}Sg . This behaviour is explained by theoretical calculations using the Nilsson-Strutinsky approach based on a Woods-Saxon model [21] and arises because of changes in deformation.

Interestingly, a weak 750 keV transition has been observed in the decay of the $674 \mu\text{s}$ high-K isomer in ^{253}No [22–24]. Since some of the high-energy lines observed in the decay of this isomer have been seen at the target position in a prompt spectroscopy experiment [25], the decay of the isomer must go through an intermediate structure, which emits promptly the aforementioned transitions. An intermediate structure based on the coupling of the odd $9/2^-$ neutron to a 2-quasiproton 3^+ excitation was put forward in reference [23]. Given the present data, a different scenario can be constructed. Indeed, by building a rotational band on top of the $11/2^-$ state of Fig. 4, with a similar sequence as the one reported by Rissanen in ^{257}Rf [9], most of the high-energy gamma lines seen in the decay of the isomer (at 614, 703, 714, 779 and 802 keV) can be reinterpreted as decays from members of the $11/2^-$ band to states of the ground state band. This scenario is in part supported by the fact that the $11/2^-$ state is predicted to carry a significant octupole phonon content [26], which could explain why the decay occurs all through the band.

FIG. 4. Proposed decay scheme of ^{257}Rf . The alpha-particle energies populating the different states have a 5 keV uncertainty, except for the 8490 keV line, which is affected by summing and has an uncertainty of ~ 15 keV.

V. CONCLUSION

The properties of the alpha decay of ^{257}Rf have been re-investigated with the GABRIELA detection setup. The half-lives extracted for the 2 known alpha-emitting states have been measured. The half-life of the low-lying spin isomer is in agreement with previously-published values, while the one of the ground state is found to be significantly higher. This fact can be attributed to feeding of the ground state from the isomer. The alpha decay has revealed a significant branch from the spin isomer in ^{257}Rf to a new $11/2^-$ state in ^{253}No , which decays by an M1 transition to the $9/2^-$ ground state. This decay path has the same Q value as other branches observed to the first excited state of the ground state rotational band and the ground state itself, giving confidence in the established decay scheme. The possible implication of the $11/2^-$ state in decay of the known high-K isomer in ^{253}No has been discussed. This scenario, however, needs verification with a dedicated investigation as the complete decay scheme from the isomer needs to be established.

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