ISOMERIC STATES IN ^{255}Rf, ^{256}Rf AND ^{257}Rf*

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(Received December 11, 2019)

In this work, we present results from the investigations of high-K isomers in ^{255}Rf, ^{256}Rf and ^{257}Rf isotopes produced in ^{50}Ti+^{207}Pb and ^{50}Ti+^{208}Pb reactions. The method of time and position correlation search was used to identify ER–CE–α/SF events in the data. Previously known high-K states in ^{256}Rf and ^{257}Rf were confirmed. A search for high-K isomer in ^{255}Rf was performed for the first time. Observation of ER–CE correlations with a lifetime of ≈ 30 μs indicates the presence of isomeric states also in this isotope.

DOI:10.5506/APhysPolB.51.849

1. Introduction

Detailed spectroscopic studies of nuclei near the deformed shell $N = 152$ serve as a strong tool for investigations of their nuclear structure. High-K isomers are of special interest with respect to the properties of superheavy isotopes as their relative stability against radioactive decay might exceed the lifetime of the ground state (see *e.g.* K isomer in ^{270}Ds [1]). K isomers were identified in many isotopes in this region. At the velocity filter SHIP in GSI Darmstadt, such states were investigated in ^{252}No [2], ^{253}No [3], ^{254}No [4, 5] and ^{255}Lr [6]. The presence of K isomers was reported also in

* Presented at the XXXVI Mazurian Lakes Conference on Physics, Piaski, Poland, September 1–7, 2019.

rutherfordium isotopes ^{254}Rf [7], ^{256}Rf [8, 9] and ^{257}Rf [10]. In ^{255}Rf, so far only one low-lying isomeric state at excitation energy of ≈ 135 keV and a half-life of 50 ± 17 μs was identified via α decay from ^{259}Sg [11].

During our experiment, we produced rutherfordium isotopes ^{255}Rf, ^{256}Rf and ^{257}Rf directly in fusion–evaporation reactions. Statistics of several hundreds nuclei produced for each isotope provided an opportunity for the investigation of isomeric states via internal-conversion electron (CE) and γ-ray spectroscopy. We focused our study on confirmation of previously reported high-K multi-quasi particle states in ^{256}Rf and ^{257}Rf and on the search for high-K states also in ^{255}Rf.

2. Experiment

Experiments aimed at the production of rutherfordium ($Z = 104$) isotopes were carried out at SHIP [12] using pulsed (5 ms beam-on+15 ms beam-off) ^{50}Ti^{8+} beams delivered from the UNILAC. The ^{207}PbS, ^{208}PbS targets had thickness 450 μg/cm^2 and were mounted on a target wheel. ^{208}Pb target was irradiated with beam energies: (a) $E = 241.5$ MeV (excitation energy of the compound nucleus in the middle of the target thickness $E^*_{\mathrm{CN}} = 22.6$ MeV, beam pulse intensity $I = 1.6\,\mathrm{p}\mu\mathrm{A}$, total duration $T = 8.1$ h), and (b) $E = 232$ MeV ($E^*_{\mathrm{CN}} = 15.0$ MeV, $I = 2.0$ pμA, $T = 17.2$ h). In the irradiation of ^{207}Pb target, a beam with $E = 243$ MeV was used ($E^*_{\mathrm{CN}} = 23.4$ MeV, $I = 2.8$ pμA, $T = 33.4$ h).

Reaction products were separated from the primary beam and other undesired nuclei by SHIP and implanted into the focal plane 16-strip position-sensitive silicon detector (STOP). A clover detector was installed close behind the STOP detector for γ- and X-ray detection (for detailed description of the detection setup, see [13]).

For the purposes of CE and γ spectroscopy of possibly present isomeric states, we used the time and position correlations (see details in [14]). We searched for the implantation signal of evaporation residue (ER) in the STOP detector, subsequent CE signal (from the deexcitation of isomeric states) in the same strip (possibly in coincidence with γ-ray signal) followed by α decay or spontaneous fission (SF) at the same position of the STOP detector as the place of ER implantation. Half-lives were evaluated from the time differences (Δt) between the signals (time distributions were treated by the maximum likelihood method described in [15]). We denote such correlations in the text as ER–CE–α and ER–CE–SF.

3. Results from ^{50}Ti+^{208}Pb reaction

We detected many ER–CE–α and ER–CE–SF correlations in each of the first two irradiations of ^{208}Pb target, designated for the production of

^{256}Rf and ^{257}Rf. We based the assignment of correlations to ^{256}Rf or ^{257}Rf on their decay properties (the third member in the chains). ^{256}Rf decays dominantly by SF ($b_{\mathrm{SF}} = 97\%$ [16]) with $T_{1/2} = 6.2 \pm 0.2$ ms [17]. In ^{257}Rf, two long-lived states with $T_{1/2} = 5.5 \pm 0.4$ s and 4.9 ± 0.7 s, dominantly α decaying, were reported in [16, 18]. Thus, in the case of ^{256}Rf, we searched for ER–CE–SF and in the case of ^{257}Rf for ER–CE–α correlations. The energy conditions were set as 100–250 MeV for SF and 8400–8800 and 8900–9200 keV for α particles (according to known α-decay energies for ^{257}Rf). We also used time differences between signals from CE and SF or CE and α decay to support the identification of isotopes according to their half-lives.

We assigned all 24 detected ER–CE–SF events to ^{256}Rf and all 66 detected ER–CE–α events to ^{257}Rf, according to the CE–SF and CE–α time distributions, shown in Fig. 1 (c) and (d). We excluded a contribution from other isotopes considering production possibilities and expected decay properties. Time differences between ER and CE from ER–CE–SF and ER–CE–α correlations are shown in Fig. 1 (a) and (b). Activities with half-lives of 18 ± 5 μs and 105 ± 15 μs are clearly separated from the random correlations (part of the $\log_{10}(\Delta t)$ distributions is missing due to the 20–25 μs

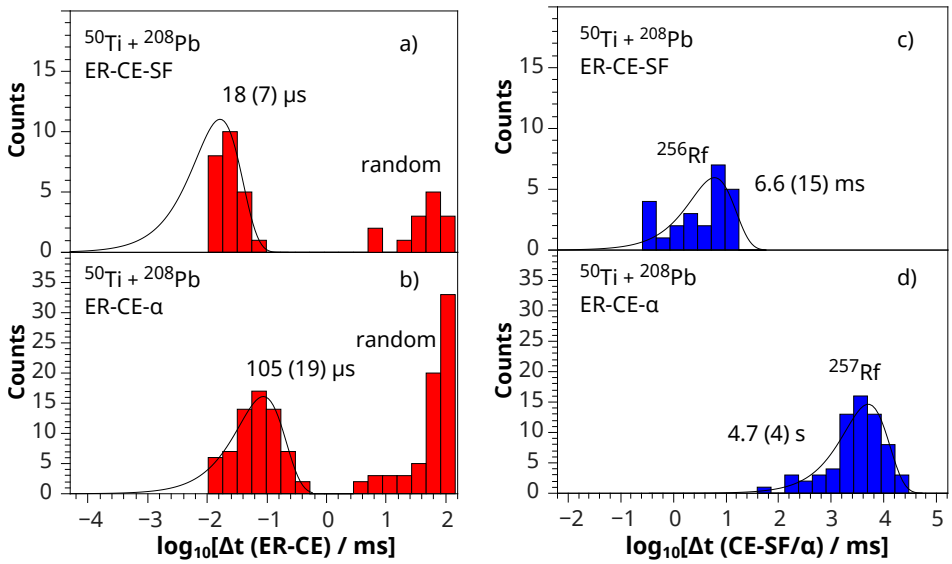

Fig. 1. Distribution of the time differences between ER–CE and CE–SF/α from the ER–CE–α and ER–CE–SF correlations detected in the irradiation of ^{208}Pb target. (a) Δt(ER–CE) from ER–CE–SF, (b) Δt(ER–CE) from ER–CE–α, (c) Δt(CE–SF) from ER–CE–SF, (d) Δt(CE–α) from ER–CE–α correlations. Data below 25 μs are missing due to the dead time of the data acquisition system. Half-lives of observed activities evaluated from the time distributions are stated.

dead time of the data acquisition system). The energy spectra of CEs from ER–CE–SF(^{256}Rf) and ER–CE–α(^{257}Rf) correlations are shown in Fig. 2 (a) and (b). Some of the CE were in coincidence with γ-ray signals as shown in Fig. 2 (d) and (e).

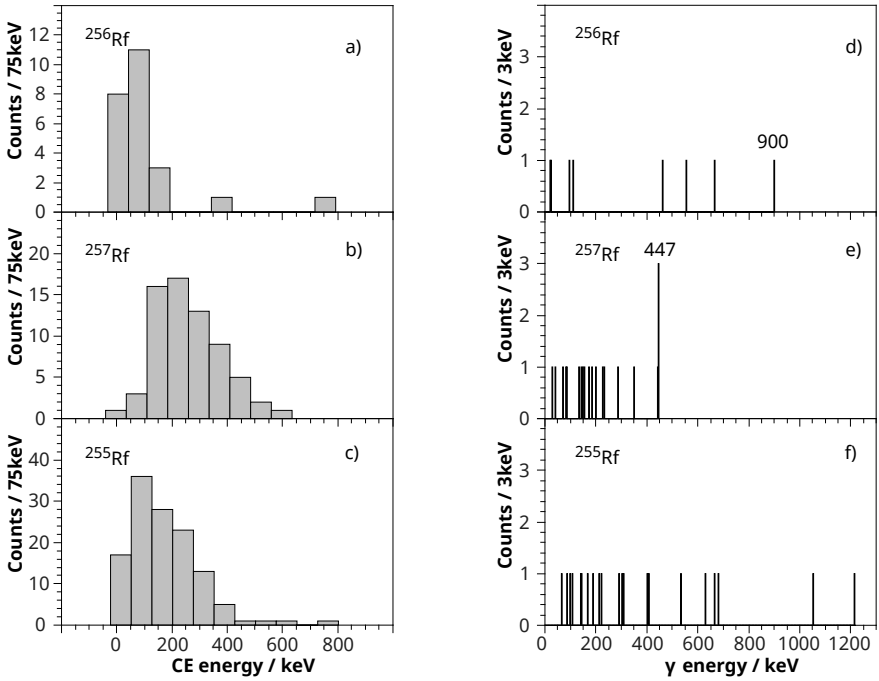

Fig. 2. Left: Energy spectra of CEs from the ER–CE–α and ER–CE–SF correlations for (a) ^{256}Rf, (b) ^{257}Rf and (c) ^{255}Rf. Right: Energy spectra of γ rays in coincidence with CE for (d) ^{256}Rf, (e) ^{257}Rf and (f) ^{255}Rf.

4. Results from ^{50}Ti+^{207}Pb reaction

About thousand α decays of ^{255}Rf were detected during the irradiation of ^{207}Pb target. In order to search for possible isomeric states, the data were treated in the same way as for ^{256}Rf and ^{257}Rf described in Sec. 3. The branching ratio for ^{255}Rf was reported as $b_{\mathrm{SF}} = 0.52 \pm 0.06$, $b_\alpha = 0.48 \pm 0.06$ [19] with a half-life of 1.68 ± 0.09 s [20], thus we searched for both ER–CE–α and ER–CE–SF correlations. The energy conditions were set as 100–250 MeV for SF and 8650–9500 keV for α particles (according to α-decay energies for ^{255}Rf [19]).

We detected 80 ER–CE–SF and 54 ER–CE–α correlations. The time distributions for the CE–SF and CE–α are shown in Fig. 3 (c) and (d). They correspond to the half-life of ^{255}Rf. In the case of CE–SF, a small contri-

bution of ^{256}Rf, which was produced via $1n$ evaporation channel, is present within 0–35 ms. Therefore, we excluded all the ER–CE–SF correlations in the range of 0–35 ms from further studies. Time differences between ER and CE from ER–CE–SF and ER–CE–α correlations are shown in Fig. 3 (a) and (b). In both cases, we observed activities with half-life of ≈ 30 μs well separated from random correlations. The energy spectrum of CE from these correlations is shown in Fig. 2 (c) and energy spectrum of coincident γ rays in Fig. 2 (f).

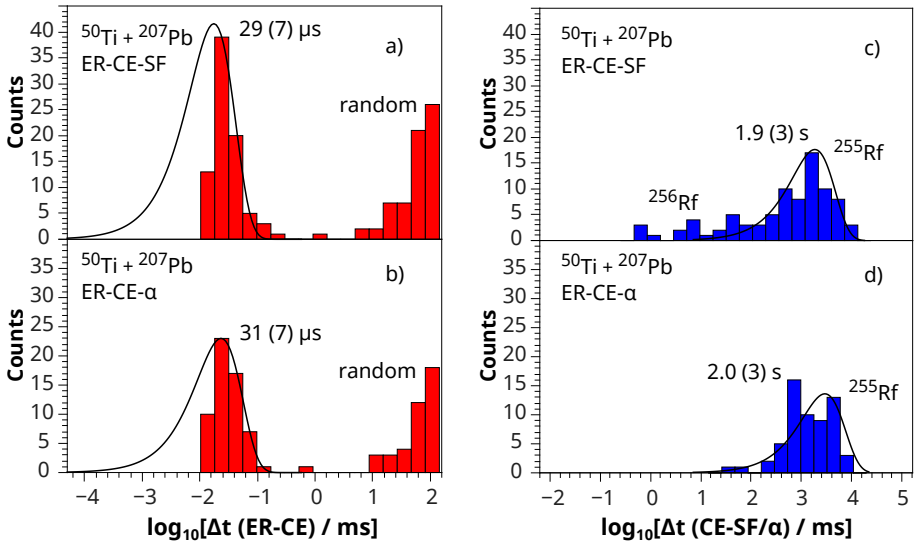

Fig. 3. The same as in Fig. 1, but from the irradiation of ^{207}Pb target.

5. Discussion

Our results are in a good agreement with previously reported high-K isomers in ^{256}Rf [8, 10] and ^{257}Rf [10]. The half-lives of 18 ± 7 and 105 ± 19 μs agree within the uncertainties with reported values of 27 ± 5 and 106 ± 6 μs, respectively. In the energy spectra of γ rays in coincidence with CE, we observed one count at 900 keV, which was the energy of the dominant γ line in the decay of the ^{256}Rf K isomer in [8]. For ^{257}Rf, we identified 4 counts in the 447-keV peak observed as dominant in [10].

For ^{255}Rf, we observed a total of 125 ER–CE–SF or ER–CE-α correlations with ER–CE half-life of ≈ 30 μs, broad CEs energy distribution (up to 800 keV) and several CEs in coincidence with γ rays. Our results are in contrast with the previously reported $5/2^+[622]$ single-particle isomer [11], where CE energy spectrum formed one narrow peak at ≈ 105 keV and CEs were not in coincidence with γ rays. Therefore, our observations indicate new high-energy high-K isomer(s) in ^{255}Rf.

6. Conclusion

In our study, we confirmed the presence of high-K isomers in ^{256}Rf and ^{257}Rf isotopes which were reported in previous studies [8, 10]. Half-lives ($18\pm 7\,\mu$s for ^{256}Rf and $105 \pm 19\ \mu$s for ^{257}Rf) were in agreement with published data; also the dominant γ transitions were observed. In ^{255}Rf, where so far only a single-particle isomer was known, we observed new isomer(s) with half-life of $\approx 30\ \mu$s, broad CE energy distribution and also several CEs in coincidence with γ rays. More details on new isomers in ^{255}Rf can be found in [21].

This work was partly supported by the Slovak Research and Development Agency (contract No. APVV-14-0524) and by the Slovak grant agency VEGA (contract No. 1/0532/17).

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