

Decay properties of ^{257}No , ^{261}Rf , and ^{262}Rf

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In bombardments of ^{244}Pu targets with 114- and 120-MeV ^{22}Ne projectiles we detected 69 α - α correlations linking α decays of ^{261}Rf and ^{257}No . We observed one α peak with $E_\alpha = 8.30 \pm 0.06$ MeV for ^{261}Rf and peaks with α -particle energies 8.07–8.40 MeV for ^{257}No . The half-life of ^{257}No was measured to be 25 ± 3 s. No correlations were found between α decays and subsequent spontaneous fission events, from which we calculated an upper limit of 1.5% for the fission branch of ^{257}No and estimated an upper limit of 3% for the α -decay branch of ^{262}Rf . The cross section of the $^{244}\text{Pu}(^{22}\text{Ne}, 5n)^{261}\text{Rf}$ reaction was measured to be about 4 nb at both ^{22}Ne energies used. We also report on some results from $^{242}\text{Pu} + ^{22}\text{Ne}$ and $^{238}\text{U} + ^{26}\text{Mg}$ bombardments.

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I. INTRODUCTION

The nuclides ^{261}Rf and ^{262}Rf were identified and generally characterized in the discovery experiments (Refs. [1] and [2], respectively). However, more detailed studies of their decay properties are definitely important. First, these nuclides are descendants of neutron-rich α -decaying species with Z, N around the predicted shell closures $Z=108$ and $N=162$ (see, e.g., Refs. [3–6]), whose existence was established in a series of experiments on identification and decay studies of the new nuclides ^{265}Sg , ^{266}Sg , ^{267}Hs , and $^{273}110$ [2,7–9]. Since the identification of such new species is based on establishing genetic links between their α decay and subsequent α or spontaneous-fission (SF) decays of the descendant nuclides, a complete knowledge of the decay properties of the latter facilitates decay-sequence searches and prevents overlooking decay chains from heavier precursors. Second, the $N=157$ – 158 nuclides ^{261}Rf and ^{262}Rf are, by themselves, close to the $N=162$ shell, which can significantly influence their decay properties, especially those of ^{262}Rf [2].

The nuclide ^{261}Rf was characterized [1] to be an α emitter with a half-life $T_{1/2}$ of 65 ± 10 s and the main α -particle energy group at $E_\alpha = 8.28 \pm 0.02$ MeV; its identification was based on physical separation followed by detecting the known 25-s α -decaying daughter, ^{257}No [10,11]. An upper limit of 10% for SF branching in the decay of ^{261}Rf has been reported [1] and an electron-capture (EC) branching of $\leq 10\%$ has been estimated [12] from beta half-life systematics. The isotope ^{261}Rf has been repeatedly used in experiments performed to study the chemical properties of Rf (see, e.g., Refs. [13–15]). More recently ^{261}Rf was produced in on-line gas chromatographic studies of Rf chlorides, in which a new, presumably more accurate $T_{1/2}$ value of 78_{-6}^{+11}

s has been measured [15]. In all of the previous experiments, the ^{261}Rf was produced via the $^{248}\text{Cm}(^{18}\text{O}, 5n)$ reaction with an estimated cross section of about 5 nb [1]. A common feature of these experiments was the use of gas (He)-jet techniques to purge the recoil products from the reaction chamber and transport them to α -counting stations, either with or without chemical processing. Because of Pb and Bi impurities in the targets, α -particle spectra in the E_α range of ^{261}Rf and ^{257}No decays were often [1,15] contaminated by α activities, e.g., from ^{211m}Po , ^{212m}Po , or ^{213}Po .

Another feature which hindered previous experiments is the fact that the α energies of ^{257}No (8.22 to 8.32 MeV [10,11]) overlap those of ^{261}Rf ; this made the two nuclides indistinguishable by α -energy analyses with the experimental techniques used. Although the technique used in Ref. [1] allowed the physical isolation of the daughter α activity on separate detectors, there was no possibility of following the one-to-one correspondence between two consecutive α decays of a particular mother-daughter pair. In Ref. [15], the very fact of detecting α - α correlations of ^{261}Rf to ^{257}No was shown, but true α - α correlations could not be disentangled from random α - α chains produced by genetically unrelated decays from ^{261}Rf and ^{257}No .

We report here on our experiments (presented preliminarily in Ref. [9]) in which we used the technique of kinematic separation to isolate the $Z=104$ recoils from transfer-reaction products, to implant the separated recoils in a position-sensitive silicon detector, and to observe, for individual α -decay events of ^{261}Rf , a subsequent time- and position-correlated α -decay event of its genetically related daughter ^{257}No . Another goal of our experiments was to discover the α -decay branch of the even-even nuclide ^{262}Rf [2] by searching for time and position correlations between α decays of ^{262}Rf and subsequent SF events from its short-lived spontaneously fissioning daughter ^{258}No .

The first unambiguous identification of the spontaneously

*Deceased.

TABLE I. Summary of the bombardments of ^{244}Pu , ^{242}Pu , and ^{238}U with ^{22}Ne and ^{26}Mg beams. Here W is the average target thickness, E is the beam energy in the middle of the target, E^* the excitation energy of the compound nucleus, D the total beam dose, and σ the production cross section (with an estimated accuracy of a factor of ~ 2) for the indicated nuclide.

Target	W (mg cm^{-2})	Ion	E (MeV)	E^* (MeV)	D ($\times 10^{18}$)	Nuclide	σ (nb)
^{244}Pu	0.41	^{22}Ne	114	46	3.1	^{261}Rf	4.4
			120	51	2.1	^{261}Rf	3.8
^{242}Pu	0.30	^{22}Ne	114	45	3.8	^{259}Rf	1.7
						$^{260}\text{Rf}^a$	0.9
^{238}U	0.28	^{26}Mg	134	46	0.45	$^{260}\text{Rf}^a$	0.24
			140	51	1.7	^{259}Rf	1.1
^{238}U	0.25	^{22}Ne	117	51	1.3	^{255}No	200 ^b

^aTentative assignment is based on literature data [12].

^bA cross section value from Ref. [20] corrected by applying the nuclear data from Ref. [12] regarding the EC branchings in the decays of ^{255}No and ^{251}Fm .

fissioning isotope ^{262}Rf was reported in Ref. [2]; it was observed as the α -decay daughter of ^{266}Sg . From time intervals for six detected α -SF correlation chains linking α decays of ^{266}Sg with subsequent SF decays of ^{262}Rf , the total half-life of the ground state of ^{262}Rf was measured to be $1.2_{-0.5}^{+1.0}$ s, 25 times longer than a tentative value of 47 ms ascribed to ^{262}Rf previously [16]. The stability of ^{262}Rf against SF decay proved to be higher by a factor of 10^2 – 10^3 than that of several nuclides with lower Z or N values, such as ^{258}Fm , ^{262}No , or ^{256}Rf (see also Ref. [17]). This significant stability increase for ^{262}Rf is due to a strong effect of the shell closures $N=162$ and $Z=108$. The observation of α decay of ^{262}Rf would yield important information for improving predictions of masses, shell corrections, and radioactive decay properties of unknown heavy nuclei including those in the vicinity of $N=162$ and $Z=108$. The detection of α decay of ^{262}Rf would also allow the unequivocal identification of ^{258}No , which is reported to be a spontaneously fissioning nuclide with $T_{1/2}=1.2\pm 0.2$ ms [12,18].

II. EXPERIMENTAL TECHNIQUE

To produce ^{262}Rf and ^{261}Rf we used the complete fusion reaction $^{244}\text{Pu}+^{22}\text{Ne}$ followed by the evaporation of four or five neutrons from the compound nucleus ^{266}Rf . Beams of ^{22}Ne projectiles were delivered by the Dubna U400 cyclotron. We chose ^{22}Ne bombarding energies of 114 and 120 MeV, resulting in excitation energies of the compound nucleus ^{266}Rf of about 46 and 51 MeV, respectively. Three plutonium targets (98.6% ^{244}Pu , 1.1% ^{242}Pu , and 0.3% ^{240}Pu) with average areal densities of 0.41 mg cm^{-2} ^{244}Pu and a total area of 11.7 cm^2 were arranged on a wheel whose rotation was synchronized to the 150-Hz frequency of the cyclotron so that a target was exposed to the ~ 2.2 -ms beam macropulse during each 6.7-ms beam cycle. The targets were electrodeposited on 0.70 mg cm^{-2} Ti substrates and covered with a $30\text{-}\mu\text{g cm}^{-2}$ carbon layer. For calibration purposes, we performed a bombardment of ^{238}U with ^{22}Ne projectiles.

A summary is given in Table I, which also shows results of $^{242}\text{Pu}+^{22}\text{Ne}$ [19] and $^{238}\text{U}+^{26}\text{Mg}$ [9,19] bombardments (see below).

Evaporation residues (EVR's) recoiling out of the ^{244}Pu targets were separated in flight from beam particles and various transfer-reaction products by the Dubna Gas-filled Recoil Separator, described in Ref. [21]. To set the field B of the separator's dipole magnet for $Z=104$ EVR's, we used prior measurements [2,7,19,21] of the average charge states for slow EVR's with $Z=89$ – 104 moving in 0.7 Torr of hydrogen, cf. Fig. 1 in Ref. [7]. The average charge states of Rf and No isotopes were calculated to be 1.9, 2.6, and 2.2 for EVR's produced in the $^{242,244}\text{Pu}+^{22}\text{Ne}$, $^{238}\text{U}+^{26}\text{Mg}$, and $^{238}\text{U}+^{22}\text{Ne}$ reactions, respectively. The separated EVR's passed through a time-of-flight (TOF) measurement system composed of two (start and stop) multiwire proportional chambers in a 1.5-Torr pentane-filled module and were implanted in a position-sensitive detector (PSD) array composed of three $40\times 40\text{-mm}^2$ silicon *Canberra Semiconductor* detectors, each with four 40-mm high $\times 9.7$ -mm wide strips. We obtained horizontal (x) positions for the reaction products from the 12 strips and vertical (y) positions from the 40-mm high resistive layer of the detectors. Top and bottom or y -position signals from each strip were divided into a signal for α or implant events (~ 1 – 14.5 MeV) and a signal for SF events (~ 20 – 250 MeV). We also recorded the energy of the α /implant events; we determined the total energy of SF events by off-line summing of their y -position signals. With each detected energy event, we also recorded the strip number, TOF information, the time in μs from the beginning of each beam pulse to either α or implant or SF events, and the running time in 0.1-ms intervals. The dead time of the electronics system was $\approx 7 \mu\text{s}$. The data were acquired in list mode.

Alpha-energy calibrations were performed periodically using α emitters produced in the $^{197}\text{Au}+^{22}\text{Ne}$ reaction. Most of the strips had α -energy peak full width at half maximum (FWHM's) of about 50–60 keV. By using known event se-

quences from the calibration reactions, we measured the FWHM y -position deviation Δ_{pos} to be 1.2 mm (3% of the strip height) for α - α sequences; for α -SF sequences we expected a similar FWHM Δ_{pos} value. The FWHM Δ_{pos} value for Rf EVR- α and EVR-SF correlations was estimated to be ≈ 6 mm due to the low measured energies of the EVR's.

We determined the detection efficiency of ^{216}Ac EVR's produced in the complete fusion reaction $^{197}\text{Au} + ^{22}\text{Ne}$, the product of the $3n$ evaporation channel. Comparing the total number of ^{216}Ac α particles and the observed number of EVR's correlated with them, we measured the EVR detection efficiency to be $\approx 75\%$. In this case, the initial ^{216}Ac EVR energy of 11 MeV was reduced to ~ 5 MeV at implantation due to losses in the target, hydrogen gas and the TOF module. In the $^{244}\text{Pu} + ^{22}\text{Ne}$ reaction the initial EVR energy of 9.5 MeV was reduced to ~ 2.5 MeV of implantation energy. Furthermore, due to the pulse-height defect of the PSD array, most of the signals from the $Z=104$ implants were reduced below the detection threshold set at ~ 1 MeV.

To test the collection efficiency of the separator, we performed a model bombardment of ^{238}U with ^{22}Ne , detecting the known nuclei $^{254,255,256}\text{No}$ [12] implanted in the PSD. In the α -energy range of 7.60–8.34 MeV, covering the known α spectrum of ^{255}No , we detected a total of 1708 α 's during out-of-beam periods. We observed about 110 correlated α - α pairs of the $^{254}\text{No} \rightarrow ^{250}\text{Fm} \rightarrow ^{246}\text{Cf}$ chain in which mother α decays with $E_{\alpha 1} = 7.97$ –8.18 MeV were followed by daughter α decays with $E_{\alpha 2} = 7.31$ –7.52 MeV. The half-life of the daughter α activity was calculated to be 23^{+16}_{-8} min [22] in agreement with the literature value of 30 ± 3 min [12] for ^{250}Fm . From this we estimated that α decays of ^{254}No , the product of the $6n$ evaporation channel, resulted in about 290 detected α 's in the range of 7.60–8.34 MeV. We also detected 38 α 's in the α -energy range of 8.34–8.50 MeV belonging to the product of the $4n$ evaporation channel, ^{256}No . By comparing the detected yield of ^{255}No with that calculated from the cross section value of Ref. [20], corrected by applying more recent nuclear data [12] on the EC branchings in the decays of ^{255}No and ^{251}Fm , the collection efficiency was determined to be $(5.4^{+1.4}_{-1.2})\%$. Yields of the products of the $4n$ - and $6n$ -evaporation channels relative to that of the $5n$ channel were calculated to be $0.016^{+0.004}_{-0.002}$ and $0.14^{+0.10}_{-0.05}$, respectively, in agreement with the results given in Ref. [20].

III. RESULTS AND DISCUSSION

A. Production and decay properties of ^{261}Rf and ^{257}No

The production of ^{261}Rf in the $^{244}\text{Pu} + ^{22}\text{Ne}$ reaction was clearly observed in the energy spectra of α particles detected at both bombarding energies used. The group of α particles with $E_{\alpha} \approx 8.20$ –8.40 MeV from α decays of ^{261}Rf and ^{257}No was the only α group in the E_{α} range ≥ 7.6 MeV. Since the α -particle spectra measured at the bombarding energies 114 and 120 MeV were rather similar, in Fig. 1 we show the sum energy spectrum of α particles detected by the whole PSD array during the entire measurement time of 260

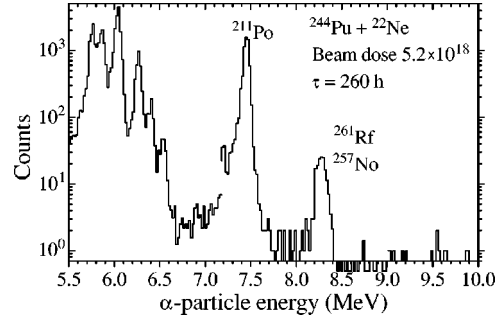


FIG. 1. Sum energy spectrum of α particles detected out of beam in the $^{244}\text{Pu} + ^{22}\text{Ne}$ reaction at the bombarding energies 114 and 120 MeV.

h. Note that most α particles with E_{α} below 7.6 MeV (e.g., ^{211}Po) originate in the decays of long-lived activities produced in the $^{197}\text{Au} + ^{22}\text{Ne}$ reaction used for calibrations, rather than from reactions with impurities in the targets.

We conducted an off-line search for correlated α - α event pairs with both α particles detected out of beam in the α -energy range $E_{\alpha} \geq 7.6$ MeV within the time window $\Delta t = 1800$ s; the y -position deviations between two α events were required to be within 1.2 mm. At the bombarding energy 120 MeV we observed 17 correlated α - α pairs in which mother α decays with $E_{\alpha 1} = 8.22$ –8.41 MeV were followed within time intervals of 0.4–181 s by daughter α decays with $E_{\alpha 2} = 8.07$ –8.37 MeV. At the bombarding energy 114 MeV we observed 25 pairs of α events with $E_{\alpha 1} = 8.25$ –8.36 MeV and $E_{\alpha 2} = 8.21$ –8.40 MeV, correlated within time intervals of 0.2 to 129 s. No α - α correlations were found in the Δt range of 181–1800 s, with the exception of one α - α pair with $E_{\alpha 1} = 8.83$ MeV, $E_{\alpha 2} = 8.09$ MeV, and $\Delta t = 223$ s, which was observed at the bombarding energy 114 MeV and we attribute to the α -decay chain of ^{259}Rf produced in reactions with the 1.1% admixture of ^{242}Pu in the ^{244}Pu target material. From our observations, it follows that the number of α - α pairs from genetically unrelated α -decay events of ^{261}Rf and ^{257}No is less than 0.1 within the time window of 200 s, which should be compared with the observed total of 42 α - α chains formed by genetically linked α decays of these two nuclides. A total of 245 single out-of-beam α events detected in the E_{α} range of 8.06–8.42 MeV is in good correspondence with the number of 252 single α events from ^{261}Rf and ^{257}No expected on the basis of the 42 observed α - α correlations. The correlation times measured for the 42 α - α chains give a maximum-likelihood half-life of 25 ± 4 s for ^{257}No .

We also searched for correlated α - α event pairs from the $^{261}\text{Rf} \rightarrow ^{257}\text{No} \rightarrow ^{253}\text{Fm}$ chain, in which only one of the two α events was detected out of beam. To avoid a contribution from random α - α correlations, in this case we required the y -position deviations between the two α events to be within 0.5 mm; the search was made within the time window $\Delta t = 500$ s. The α energies were allowed to vary between 8.00–8.70 MeV and 8.00–8.50 MeV for out-of-beam ^{261}Rf - and ^{257}No -like members of α - α chains, respectively. For in-beam events, the corresponding α energy ranges were restricted to 8.22–8.41 MeV and 8.19–8.40 MeV, thus limit-

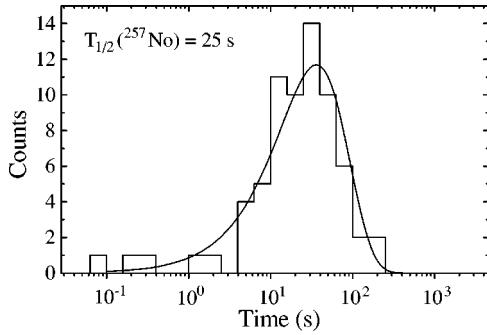


FIG. 2. Sum distribution of time intervals from correlated $^{261}\text{Rf} \rightarrow ^{257}\text{No} \rightarrow ^{253}\text{Fm}$ α - α pairs. The calculated distribution for $T_{1/2} = 25$ s is also shown.

ing the E_α values to those observed for ^{261}Rf and ^{257}No from the 41 α - α chains with both α events detected out of beam (with the exception of a single correlation including a ^{257}No event with $E_\alpha = 8.07$ MeV). As a result of the above-described selection, we observed an additional 27 α - α correlations in which α events with $E_{\alpha 1} = 8.24$ – 8.40 MeV were followed within time intervals of 0.08–192 s by daughter α decays with $E_{\alpha 2} = 8.19$ – 8.38 MeV. From the correlation times measured for these 27 α - α chains, we obtain a half-life value of 20_{-5}^{+6} s for ^{257}No . Two α - α pairs with correlation times above 300 s were found, indicating a possible presence of a few random pairs among the above 27 α - α correlations.

In Fig. 2 we show the distribution of time intervals from all of the 69 α - α correlations. In general, the distribution of the measured decay times fits the decay pattern of a single activity; however, three events in Fig. 2 show decay times of 0.08, 0.21, and 0.38 s, which are several hundred times shorter than expected from the ^{257}No lifetime. This observation might hint at the existence of a much shorter-lived state in ^{257}No decaying with similar α -particle energies, although the limited statistics do not allow more conclusive statements. Considering all of the measured decay times, we calculate a half-life of 25 ± 3 s for ^{257}No , in agreement with the accepted value of 25 ± 2 s [12].

The α -particle energy spectra of ^{261}Rf and ^{257}No based on the observed 69 genetically linked α decays of these two nuclides are plotted in Fig. 3. The correlation technique used in our work made it possible to measure for the first time the α -energy spectrum of ^{261}Rf without any contribution from α decays of its daughter. The measured α -particle energy spectrum of ^{261}Rf is relatively narrow and can be well fitted by a single Gaussian curve with a standard deviation $\sigma = 33$ keV, centered at $E_\alpha = 8.30$ MeV; from calibrations we estimated the averaged α -energy peak σ value to be 27 ± 6 keV. Our data (see Fig. 3) show no α -decays which correspond to the 8.52-MeV α events of ^{261}Rf , one observed by the GSI group in one of two $Z = 112$ decay sequences [23] and one reported from chemistry experiments with ^{265}Sg [24].

The α -particle energy spectrum that we measured for decays of ^{257}No is in good agreement with the α -energy pattern observed for this nuclide in previous experiments [11]. As shown in Fig. 3, this spectrum can be fitted by the sum of three Gaussian curves with $\sigma = 28$ keV, defining the three

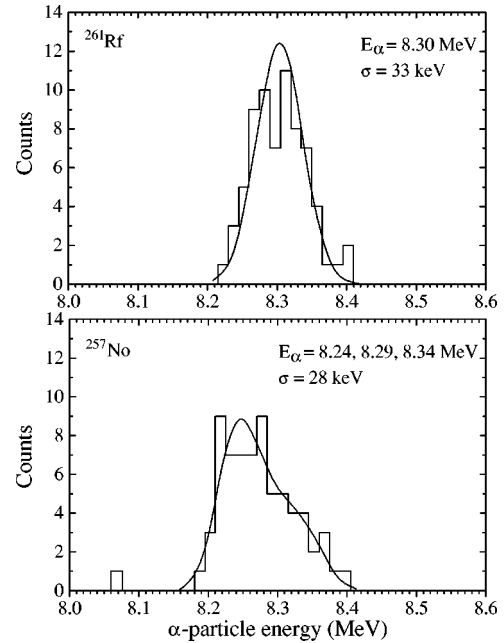


FIG. 3. Experimental α -particle spectra of ^{261}Rf and ^{257}No based on the genetically linked α decays with corresponding fitted spectra.

main α groups of ^{257}No with $E_\alpha = 8.24$, 8.29, and 8.34 MeV, with relative intensities of 55, 26, and 19%, respectively, according to Ref. [11]. One α -decay event was detected with $E_\alpha = 8.07$ MeV, implying the existence of a weak α group of ^{257}No ; this 8.07-MeV α event followed a preceding 8.34-MeV α event from ^{261}Rf by 0.38 s. Note that lower α -particle energies of ^{257}No , down to $E_\alpha = 8.11$ MeV, were also observed in experiments [2,17], although using detectors with poorer energy resolution.

We searched for correlated α -SF events with out-of-beam α particles in the energy range $E_\alpha \geq 7.6$ MeV and SF events detected both out of beam and in beam. No correlations were found within the time window $\Delta t = 1000$ s. The y -position deviations between α and SF events were required to be within 1.2 mm. On the basis of the total number of α particles with $E_\alpha = 8.06$ – 8.42 MeV and 42 observed α - α correlations of ^{261}Rf and ^{257}No , we calculated a 68% confidence level upper limit of 1.5% for the SF branch of ^{257}No .

B. Spontaneous-fission activities from the $^{244}\text{Pu} + ^{22}\text{Ne}$ reaction and ^{262}Rf decay

In the reaction $^{244}\text{Pu} + ^{22}\text{Ne}$ we detected 239 out-of- and in-beam SF events at the ^{22}Ne energy of 114 MeV and 303 SF events at 120 MeV. Analyzing the EVR-SF correlation time distributions, we singled out two short-lived activities. At both energies a SF activity with $T_{1/2} = 1.4_{-0.2}^{+0.3}$ ms was observed, being the source of about 45 events at the ^{22}Ne energy of 114 MeV and of about 42 events at 120 MeV. Another SF activity, with $T_{1/2} = 26_{-6}^{+10}$ ms, contributed ~ 12 and ~ 22 events at 114 and 120 MeV, respectively. These numbers do not represent the complete contribution from the corresponding activities since the detection efficiency of

EVR's was less than 100%. The wide distribution of these events on the detector area also hints that the total yield of observed activities could be higher.

One of the probable sources of the 1.4-ms SF activity is ^{258}No produced in the $\alpha 4n$ -emission channel. Note that recently the product of an $\alpha 3n$ channel, ^{259}No , was observed in this reaction with the cross section in the range of 6.4–3.1 nb [25] corresponding to the ^{22}Ne bombarding energies of 110.9–129.2 MeV. However, the average measured energy of the 1.4-ms recoils appeared to be two times higher than expected for ^{258}No , ~ 2.3 MeV, which means ~ 5 -MeV implantation energy. The spontaneously fissioning isomer ^{244m}Am produced in transfer reactions could possibly contribute to this activity but, as it will be shown below, we did not observe noticeable yield of a similar pn -transfer product — the isomer ^{242m}Am in the $^{242}\text{Pu} + ^{22}\text{Ne}$ reaction. One of the probable sources of 26-ms SF activity is spontaneous fission of ^{260}Rf , a $6n$ -evaporation product, especially at the ^{22}Ne energy of 120 MeV (see Sec. III C). Contributions from the decays of hypothetical spontaneously fissioning $Z=104$ isomers cannot be excluded; the above assignments remain somewhat speculative.

To probe the α -decay branch of the even-even nuclide ^{262}Rf we searched for correlations between α decays of ^{262}Rf and subsequent SF events from its short-lived spontaneously fissioning daughter ^{258}No . The theoretical Q_α value for ^{262}Rf of ≈ 8.25 MeV [3] corresponds to a partial α -decay half-life of approximately 200 s. For potential ^{262}Rf decays, we considered the α -energy range $E_\alpha = 7.8$ – 8.5 MeV, which corresponds to the partial α -decay half-life range of 10–3000 s [3]. We found no α -SF correlations with α particles and SF events detected both out-of- and in-beam within the time window of 10 s.

The low implantation energy of $Z=104$ EVR's in the PSD (see Sec. II) prevented us from distinguishing SF events of 1.2-s ^{262}Rf and determining its yield directly from the EVR-SF correlation data. To estimate the yield of ^{262}Rf we used experimental ratios of $5n$ - and $4n$ - evaporation cross sections measured at the ^{22}Ne bombarding energies close to the $4n$ -evaporation maximum in the reactions $^{236,238}\text{U} + ^{22}\text{Ne}$ [26,20], $^{242}\text{Pu} + ^{22}\text{Ne}$ (present work), and $^{248}\text{Cm} + ^{22}\text{Ne}$ [2]. From these data, we assumed the $4n$ -evaporation cross section to be half of that of the $5n$ channel at the ^{22}Ne energy of 114 MeV. Using these assumptions and estimating that 113 SF events from ^{262}Rf occurred, we set the 68% confidence level upper limit at 3% for the α -decay branch of ^{262}Rf . Both the low α branching and the predominance of SF in the decay of $^{262}104$ (and all other even-even Rf isotopes) is a very definite prediction of theory [3–5].

The group of LBNL, Berkeley, studied the reaction $^{244}\text{Pu} + ^{22}\text{Ne}$ by using the gas-jet technique coupled with a rotating wheel system [27]. No α decays correlated with SF from ^{258}No were observed and an upper limit of 0.8% for the α -decay branch of ^{262}Rf was set. It should be noted that the authors of Ref. [27] assigned all the 200 observed SF events with an apparent half-life $T_{1/2} = 2.1 \pm 0.2$ s and maximum production cross section of ~ 0.7 nb at $E(^{22}\text{Ne}) = 114.4$ MeV to the ground-state decay of ^{262}Rf on the basis of excitation

function measurements. Mass and kinetic-energy distributions of coincident fission fragments were measured. The possible interfering SF background, which would raise the reported α -decay branch limit, was considered to be low enough to ascribe all the observed fission activity to ^{262}Rf .

C. Production of Rf isotopes in the $^{242}\text{Pu} + ^{22}\text{Ne}$ and $^{238}\text{U} + ^{26}\text{Mg}$ reactions

We also studied the production of the Rf isotopes in the reactions $^{242}\text{Pu} + ^{22}\text{Ne}$ and $^{238}\text{U} + ^{26}\text{Mg}$, resulting from the same compound nucleus ^{264}Rf . One of the aims of these experiments was to compare production and detection rates of the Rf nuclides in these two reactions in order to choose between the ^{22}Ne - and ^{26}Mg -induced reactions for the synthesis of new Sg isotopes. The ^{22}Ne beam energy was chosen to correspond to the maximum of the $4n$ evaporation channel excitation function, and the two bombarding energies of ^{26}Mg ions were chosen to be close to the expected maxima of the $4n$ and $5n$ evaporation reactions. Correlation data and fission activities from these experiments are summarized in Table II.

The well-known isotope ^{259}Rf [12], the product of the $5n$ -evaporation channel, was identified by detecting 17 out-of-beam α - α correlations with ^{255}No decays in the reaction $^{242}\text{Pu} + ^{22}\text{Ne}$ and 5 α - α correlations in the $^{238}\text{U} + ^{26}\text{Mg}$ reaction. In the last case, due to higher EVR detection efficiency, we also observed 22 EVR- α correlations of ^{259}Rf . Measured cross sections of the $5n$ -evaporation channel for both these reactions are listed in Table I. Even at the lower bombarding energy, corresponding to the maximum of the $4n$ -evaporation channel, the cross section of the $^{242}\text{Pu}(^{22}\text{Ne}, 5n)^{259}\text{Rf}$ reaction is larger than that of the $^{238}\text{U}(^{26}\text{Mg}, 5n)^{259}\text{Rf}$ reaction at its expected peak by a factor of approximately 1.5.

In both reactions we observed SF activities. We could single out 22 fission events correlated with preceding EVR's in the $^{242}\text{Pu} + ^{22}\text{Ne}$ experiment and 4 such events in the $^{238}\text{U} + ^{26}\text{Mg}$ reaction which show an identical half-life of about 20–30 ms. After the end of the $^{242}\text{Pu} + ^{22}\text{Ne}$ experiment, off-line measurements were performed to look for long-lived α activities implanted in the detectors. From the upper limit for ^{242}Cm production, we estimated the possible contribution from the 14-ms isomer ^{242m}Am to be three SF events or less. Thus the observed 20–30-ms SF activity could be tentatively assigned, based on literature data [12], to the spontaneous fission of ^{260}Rf , the $4n$ -evaporation product. In the reaction $^{242}\text{Pu} + ^{22}\text{Ne}$, no correlations were found between out-of-beam α particles with $E_\alpha = 8.25$ – 8.60 MeV characteristic of ^{256}No [12,28] and preceding α events with $E_\alpha \geq 7.6$ MeV within a time interval of 100 s. An upper limit of 20% follows for the α -decay branch of ^{260}Rf .

In both reactions a few SF events can be attributed to a shorter-lived activity, with a half-life of ~ 0.1 ms. The 19 SF events observed in the reaction $^{238}\text{U} + 140\text{-MeV } ^{26}\text{Mg}$ show a half-life of 12_{-2}^{+4} ms and a production cross section of 0.3 nb. Their most probable source is the product of the $6n$ -evaporation channel, ^{258}Rf [12], although a contribution from ^{260}Rf cannot be excluded.

TABLE II. Summary of observations from $^{242}\text{Pu}+^{22}\text{Ne}$ and $^{238}\text{U}+^{26}\text{Mg}$ reactions.

Reaction	Projectile energy (MeV)	Number of correlated events ^a	Measured half-life	Assignment
$^{242}\text{Pu}+^{22}\text{Ne}$	114 ^b	17 α - α	$3.2^{+1.6}_{-0.9}$ min	$^{259}\text{Rf} \rightarrow ^{255}\text{No} \rightarrow ^{251}\text{Fm}$
	114 ^b	22 EVR-SF	21^{+17}_{-9} ms	$^{260}\text{Rf}^c \rightarrow$
$^{238}\text{U}+^{26}\text{Mg}$	134 ^b	4 EVR-SF	28^{+39}_{-13} ms	$^{260}\text{Rf}^c \rightarrow$
	140	22 EVR- α	$2.5^{+1.1}_{-0.7}$ s	$^{259}\text{Rf} \rightarrow$
	140	5 α - α	$5.1^{+3.8}_{-1.6}$ min	$^{259}\text{Rf} \rightarrow ^{255}\text{No} \rightarrow ^{251}\text{Fm}$
	140	19 EVR-SF	12^{+4}_{-2} ms	$^{258}\text{Rf}^c \rightarrow$

^aThe detection efficiencies of the Rf EVR's were about 30% in the reaction $^{242}\text{Pu}+^{22}\text{Ne}$ and 60% in the $^{238}\text{U}+^{26}\text{Mg}$ reaction (due to higher EVR initial and, consequently, implantation energy).

^bA detector array of six Si(Au) detectors of 3-cm high \times 2-cm wide without position sensitivity was employed for these irradiations.

^cTentative assignments of EVR-SF sequences are based on literature data [12].

IV. CONCLUSION

In bombarding ^{244}Pu targets with 114- and 120-MeV ^{22}Ne projectiles, we detected 69 α - α correlations linking α decays of ^{261}Rf and ^{257}No . The correlation technique used in our work made it possible to measure the α -energy spectrum of ^{261}Rf without any contribution from the α decays of its daughter. We observed a single α peak with $E_\alpha = 8.30 \pm 0.06$ MeV for ^{261}Rf . The half-life of ^{257}No was measured to be 25 ± 3 s. The cross section of the $^{244}\text{Pu}(^{22}\text{Ne}, 5n)^{261}\text{Rf}$ reaction was estimated to be about 4 nb at both ^{22}Ne energies. The α -particle energies of 8.19 to 8.40 MeV that we measured for ^{257}No are in agreement with the pattern observed for this nuclide in previous experiments. One α -decay event of ^{257}No was detected with $E_\alpha = 8.07$ MeV; this implies the existence of a weak α group of ^{257}No . No correlations were found between α decays with $E_\alpha \geq 7.6$ MeV and subsequent spontaneous fission events, from which we calculated an upper limit of 1.5% for the spontaneous-fission branch of ^{257}No and estimated an upper limit of 3% for the α -decay branch of ^{262}Rf .

In all three reactions studied we observed several SF activities that we could not assign to specific nuclides. Our earlier experiments on the synthesis of ^{266}Sg established unambiguous assignment of the ground-state SF decay of ^{262}Rf following the α decay of the mother nucleus. Similar experiments can produce lighter even-even Rf isotopes that may be

the origin of some of the unidentified SF activities reported here. Since both ^{262}Sg and ^{264}Sg are expected to have significant α -decay branches [3–5], their α decay should lead to the even-even daughters ^{258}Rf and ^{260}Rf , which are assigned to short-lived SF activities. The new Sg isotopes could be produced, e.g., in complete fusion reactions $^{242,244}\text{Pu}+^{25,26}\text{Mg}$ or $^{246,248}\text{Cm}+^{22}\text{Ne}$ with evaporation of four, five, and probably six neutrons. These experiments will allow the first identification of the ^{258}Rf and ^{260}Rf using decay sequences that are correlated in position and time. The decay properties of these nuclides are important for investigating trends in properties of the $Z=104$ and 106 isotopes with neutron numbers increasing towards $N=162$.

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