Electromagnetic decays of excited states in ^{261}Sg ($Z = 106$) and ^{257}Rf ($Z = 104$)

J. S. Berryman,[1] R. M. Clark,[1] K. E. Gregorich,[1] J. M. Allmond,[2] D. L. Bleuel,[3] M. Cromaz,[1] I. Dragojević,[1,4] J. Dvorak,[1] P. A. Ellison,[1,4] P. Fallon,[1] M. A. Garcia,[1,4] S. Gros,[1] I. Y. Lee,[1] A. O. Macchiavelli,[1] H. Nitsche,[1,4] S. Paschalis,[1] M. Petri,[1] J. Qian,[1] M. A. Stoyer,[3] and M. Wiedeking[3]

[1]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

[2]*Department of Physics, University of Richmond, Virginia 23173, USA*

[3]*Lawrence Livermore National Laboratory, Livermore, California 94551, USA*

[4]*Department of Chemistry, University of California, Berkeley, California 94720, USA*

(Received 31 March 2010; published 29 June 2010; corrected 16 August 2010)

An isomeric one-quasineutron state, likely based on the [725]11/2$^-$ Nilsson level, was identified in ^{261}Sg by its decay via internal conversion electrons. The state has an excitation energy of ≈200 keV and a half-life of $9.0^{+2.0}_{-1.5}$ μs. ^{261}Sg has the highest Z and A of any nucleus in which the electromagnetic decay of an isomeric state was observed to date. A separate experiment was performed on the α daughter nucleus of ^{261}Sg, namely ^{257}Rf. Spectroscopy of delayed γ rays and converted electrons from ^{257}Rf resulted in the identification of a K isomer at an excitation energy of ≈1125 keV with a half-life of 134.9 ± 7.7 μs. The spin of the isomeric state is tentatively assigned $I = 21/2, 23/2$ and the state likely decays to a rotational band built on the [725]11/2$^-$ Nilsson level via a $\Delta K = 5$ or 6 transition. The present results provide new information on excited states in the transactinide region, which is important for testing models of the heaviest elements.

DOI: 10.1103/PhysRevC.81.064325 PACS number(s): 21.10.Tg, 23.20.Lv, 23.35.+g, 27.90.+b

I. INTRODUCTION

Superheavy nuclei should fission instantaneously due to the Coulomb repulsion between protons. However, nuclear shell effects provide added stability due to energy gaps in the single-particle level ordering at particular "magic" numbers of protons and neutrons. The spherical shell closures beyond ^{208}Pb remain a matter of considerable theoretical debate. The microscopic-macroscopic models with various parametrizations of the nuclear potential predict magic numbers at $Z = 114$ and $N = 184$ [1]. Meanwhile, relativistic and nonrelativistic nuclear mean-field calculations yield a proton magic number ranging from $Z = 120$ to 126 and a neutron magic number ranging from $N = 172$ to 184 [2,3]. The heaviest element whose existence has been confirmed has $Z = 114$ [4,5], with further experiments suggesting the observation of elements up to $Z = 118$ [6]. The production cross sections for the superheavy elements drop rapidly with proton number and are on the order of a few pb for element 114 [4,5,7]. Recently, it has become possible to take a different approach to understanding the behavior of the heaviest nuclei by making detailed spectroscopic studies of shell-stabilized nuclei in the vicinity of deformed subshell gaps at $Z \approx 100$ and $N \approx 152$ (^{252}Fm) [8]. Nuclei in the region of $Z \approx 100$ may have cross sections up to a few μb and therefore are far easier to access experimentally. Prolate deformation drives down single-particle orbitals from above the predicted $Z = 114$ and $N = 184$ gaps, which can intrude close to the Fermi surface in the transfermium region. Such experimental data are essential for testing the models that differ in their predictions for the superheavy elements.

The particular interest of this study is the decay of isomers, excited metastable states of atomic nuclei. Isomers with high angular momentum are found in deformed nuclei near ^{252}Fm ($Z = 100$, $N = 152$). Isomers in this region, both single and multiquasiparticle (qp) states, may involve nucleon orbitals with high K values, where K is the quantum number describing the projection of the total angular momentum on the symmetry axis. Electromagnetic decays from these states can involve large changes of K and such transitions can become hindered, leading to the metastability. One can learn about single-particle structure, pairing correlations, and excitation modes in the heaviest nuclei by identifying such isomers and studying their decay to states with lower excitation energy. In this article, we report on the first observation of isomerism in ^{261}Sg and provide new information on the K isomerism in ^{257}Rf.

II. EXPERIMENTAL DETAILS

Two separate experiments were performed at the 88-Inch Cyclotron of the Lawrence Berkeley National Laboratory using the Berkeley Gas-filled Separator (BGS) [9]. The ^{261}Sg nuclei were produced in the ^{208}Pb(^{54}Cr,n) fusion-evaporation reaction at a beam energy of 261 MeV. The excitation function measured by Antalic *et al.* [10] indicated a peak excitation energy of 16 MeV ($\sigma \approx 1.9$ nb), corresponding to a center-of-target energy of ≈256 MeV. The center-of-target energy was calculated from the optimum excitation energy using experimental masses [11] for projectile and target, and the theoretical Thomas-Fermi mass [12] for the compound nucleus. The ^{257}Rf nuclei were produced in the ^{208}Pb(^{50}Ti,n) fusion-evaporation reaction at a beam energy of 238 MeV. The excitation function measured by Dragojević *et al.* [13] indicated a peak excitation energy of 19 MeV ($\sigma \approx 40$ nb), corresponding to a center-of-target energy of ≈233 MeV. In both experiments, the beam from the cyclotron passed through a ≈45 μg/cm^2 carbon window (separating the 0.5 torr He gas inside the BGS from the beamline vacuum) and was incident on ^{208}Pb targets. The targets comprised a stack of two ^{208}Pb foils; each foil had a thickness of ≈0.4 mg/cm^2 and was evaporated on ≈35 μg/cm^2 carbon backing. The energy loss through the target material and the carbon backing was calculated using

SRIM [14] to determine the optimum beam energy from the desired center-of-target energy. The targets were placed on a rotating target wheel, positioned such that the beam was incident on the target backing first, and the average beam intensity for both experiments was about 300 pnA. The ^{261}Sg experiment ran for about 5.5 days, and the ^{257}Rf experiment ran for about 7 days. Evaporation residues were separated from the beam and other reaction products by their differing magnetic rigidities, and then passed through a multiwire proportional counter (MWPC), before being implanted in a 1-mm thick 16×16 double-sided silicon strip detector (DSSD) with an active area of 5×5 cm. During the ^{257}Rf run, a 2.5 μm Mylar foil was placed in front of the DSSD to reduce the recoil energies. A standard high purity germanium (HPGe) clover detector [15] was mounted behind the 2 mm Al backplate of the BGS focal plane at approximately 5 mm from the DSSD. Standard γ-ray sources were used for energy and efficiency calibrations. The focal plane distribution of recoils was simulated, yielding an absolute photopeak efficiency of $\approx$17% at 122 keV and $\approx$3.5% at 1 MeV. All of the γ-ray spectra were created by treating the four clover crystals as individual detectors (no addback) in the analysis described in the following.

III. RESULTS

A. Decay of ^{261}Sg

Potential Sg implantation events were identified by a MWPC signal in coincidence with an implant in a DSSD pixel (3.0 MeV < E_{DSSD} < 40.0 MeV). Contamination from the 2n reaction channel producing ^{260}Sg is not likely, as the excitation function for ^{260}Sg differs from the peak of the excitation function for ^{261}Sg by 10 MeV [10]. ^{261}Sg recoils were identified by observing a characteristic ^{261}Sg α decay (9.2 MeV < E_α < 10.0 MeV) anticoincident with the MWPC [denoted as r-α(^{261}Sg) events] or observing an "escape" ^{261}Sg α decay followed by the α decay of the daughter nucleus ^{257}Rf (8.4 MeV < E_α < 9.2 MeV) [denoted as r-x(^{261}Sg)-α(^{257}Rf)] in the same pixel of the DSSD, following Sg implantation. An escape ^{261}Sg α decay is defined as a detected α that leaves the face of the DSSD, thus depositing only partial energy (0.5 MeV < E_{escape} < 7.5 MeV). During the experiment, a total of 199 r-α(^{261}Sg) events and 106 r-x(^{261}Sg)-α(^{257}Rf) events were identified. In addition, there were 88 r-α(^{261}Sg)-α(^{257}Rf) events. The half-life of r-α(^{261}Sg) events was measured to be 178 ± 14 ms, which agrees with the value of 184 ± 5 ms measured by Štreicher *et al.* [16]. Our analysis of the α decay energies agrees with prior measurements [10,16], and does not add any additional information to the previous α decay studies.

The electromagnetic decay of isomers was identified by searching for a delayed electron signal (50 keV < $E_{electron}$ < 2000 keV) within the same pixel of the DSSD, following Sg implantation but prior to the α decay [17]. A total of 24 r-e-α(^{261}Sg) events and 15 r-e-x(^{261}Sg)-α(^{257}Rf) events were identified. The energy distribution of the electron bursts for r-e-α(^{261}Sg) or r-e-x(^{261}Sg)-α(^{257}Rf) events is shown in Fig. 1, indicating a maximum energy of $\approx$200 keV. The time difference between recoil implants and the subsequent electron burst is shown in the inset of Fig. 1. The fit was constructed using a maximum likelihood method with an

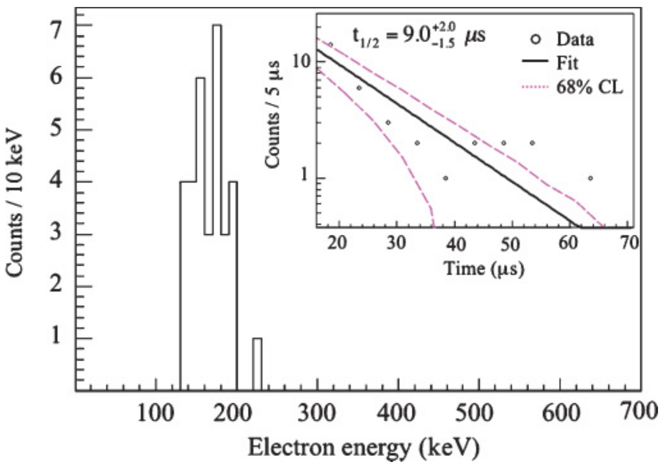

FIG. 1. (Color online) Electron energy spectrum from r-e-α(^{261}Sg) or r-e-x(^{261}Sg)-α(^{257}Rf) events with an inset showing the electron decay curve. The solid line represents the fit to the decay curve, performed with a maximum likelihood method with an exponential decay. The upper and lower dashed lines are the limits which encompass 68% of the probability in a Poisson distribution, centered on the number of counts expected during the interval from the most probable fit.

exponential decay, yielding a half-life of $9.0^{+2.0}_{-1.5}$ μs for the isomeric state. Upper and lower limits were calculated which encompass 68% of the probability in a Poisson distribution centered on the number of counts expected during the interval from the most probable fit, following the method by Gregorich [18]. It should be noted that there is the possibility of the isomer decaying during the $\approx$15 μs deadtime of the data acquisition, and thus only those events occurring 15 μs after implantation were included in Fig. 1.

B. Decay of ^{257}Rf

Potential Rf implantation events were identified by a MWPC signal in coincidence with an implant in a DSSD pixel (5.0 MeV < E_{DSSD} < 14.0 MeV). Possible contamination comes from the 2n reaction producing ^{256}Rf, as the peak of the excitation function for ^{256}Rf is only 4 MeV from the excitation energy of ^{257}Rf used in the present work. However, ^{257}Rf can easily be distinguished from ^{256}Rf by comparing the ground-state decay properties. ^{256}Rf has a dominant ($\approx$100%) fission branch [19] while ^{257}Rf has a dominant α branch (>98.6%) [20]. Therefore, the ^{257}Rf recoils were identified by observing an α decay (8.0 MeV < E_α < 10.0 MeV) in the same pixel of the DSSD and anticoincident with the MWPC, following Rf implantation [denoted as r-α(^{257}Rf) events]. During the experiment, a total of 1904 r-α(^{257}Rf) events were recorded. The r-α(^{257}Rf) energy spectrum is shown in Fig. 2(a). The time difference between recoil implants and the subsequent α decay is shown in the inset of Fig. 2(a). The fit to the decay curve was performed using a maximum likelihood method with an exponential decay. The half-life for all r-α(^{257}Rf) events was deduced to be 4.8 ± 0.2 s, which agrees with the value of 4.7 ± 0.3 s given in a recent article by Qian *et al.* [21].

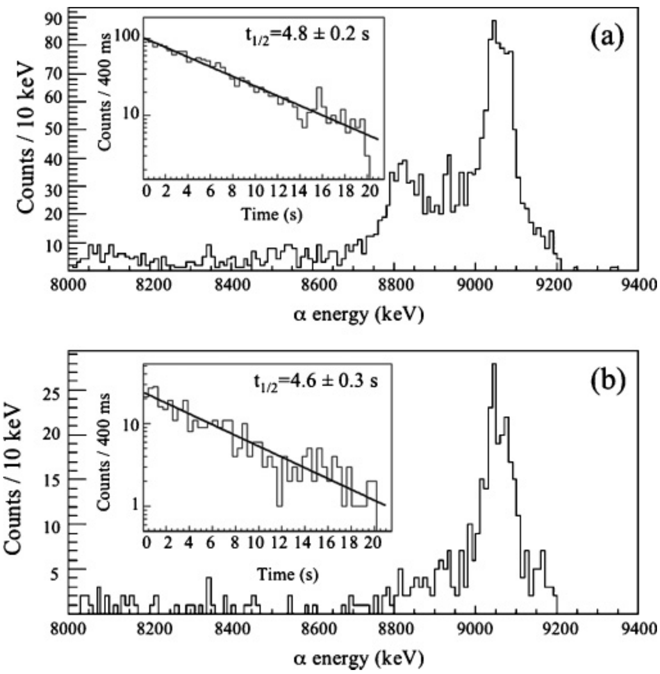

FIG. 2. (a) α energy spectrum from r-α(^{257}Rf) events with an inset showing the decay curve for all r-α(^{257}Rf) events. The α energy spectrum for alphas preceded by a conversion electron decay is shown in (b) with an inset showing the decay curve for the r-e-α(^{257}Rf) events.

The electromagnetic decay of isomers was identified by searching for a delayed electron signal (50 keV < $E_{electron}$ < 2000 keV), within the same pixel of the DSSD as an implanted recoil. There were a total of 1083 such r-e events, indicating the presence of an isomer. Conversion electrons coming from the decay of ^{257}Rf were distinguished from those coming from the decay of ^{256}Rf by observing an α decay following the conversion electron in the same pixel of the DSSD. There were 371 such events, labeled r-e-α(^{257}Rf). Further, the electron events from the decay of ^{256}Rf had a spontaneous fission event following in the same pixel of the DSSD. There were 191 of such events, labeled r-e-f(^{256}Rf). The α energy spectrum of r-e-α(^{257}Rf) events is shown in Fig. 2(b). The time difference between recoil implants and the α decay is shown in the inset of Fig. 2(b). A comparison of Figs. 2(a) and 2(b) reveals that only the higher-energy α events are observed when the nuclear decay proceeded through the isomeric state. The half-life for α from r-e-α(^{257}Rf) events was deduced to be 4.6 ± 0.3 s, which agrees with the value of 4.1 ± 0.4 s observed for the higher-energy α events reported by Qian *et al.* [21].

The electron energy spectra for r-e, r-e-f(^{256}Rf), and r-e-α(^{257}Rf) events are shown in Fig. 3. The narrow energy distribution for r-e-f(^{256}Rf) centered at ≈175 keV agrees with that observed by Jeppesen *et al.* [22]. There were 21 r-e-e-f(^{256}Rf) events identified in the present study, indicating the presence of multiple isomers in ^{256}Rf, as observed in Ref. [22]. The energy distribution of the first electron burst for r-e-e-f(^{256}Rf) events is broader than that of the second electron burst, and both are centered at ≈175 keV. The lifetime of the first electron burst is 13.2 ± 3.3 μs, while the lifetime of the second electron burst is 36.5 ± 8.6 μs. Within error, both

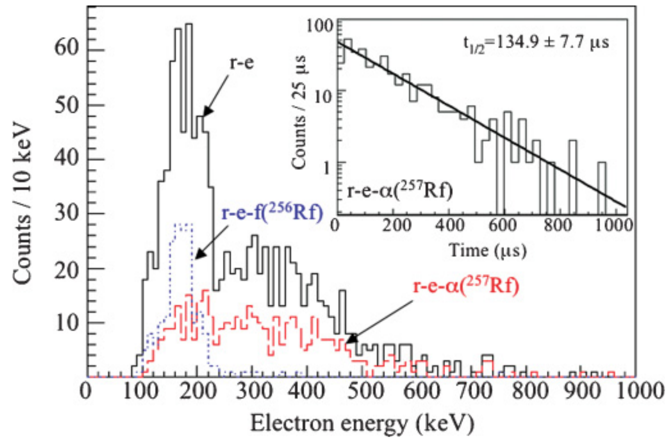

FIG. 3. (Color online) Energy spectrum from r-e, r-e-f(^{256}Rf), and r-e-α(^{257}Rf) events with an inset showing the electron decay curve for all r-e-α(^{257}Rf) events.

lifetimes are in agreement with the observations of Jeppesen *et al.* [22]. The time difference between recoil implants and the subsequent electron burst for all r-e-α(^{257}Rf) events is shown in the inset of Fig. 3. The fit was constructed using a maximum likelihood method with an exponential decay, yielding a half-life of 134.9 ± 7.7 μs for the isomeric state. Qian *et al.* [21] collected 22 r-e-α(^{257}Rf) events, and they measured a half-life of 160^{+42}_{-31} μs, which is in agreement with our value. In addition, Jeppesen *et al.* [22] mentioned an isomeric state in ^{257}Rf with a half-life of 109 ± 13 μs that is presumed to be the same isomer as observed by both Qian *et al.* [21] and in the present work.

The γ-ray spectrum obtained in prompt coincidence with the electron bursts for all r-e events that did not have a spontaneous fission event following the electron is shown in Fig. 4. K-shell x rays at energies expected for Rf [23] are seen (marked with an asterisk), along with a few prominent γ

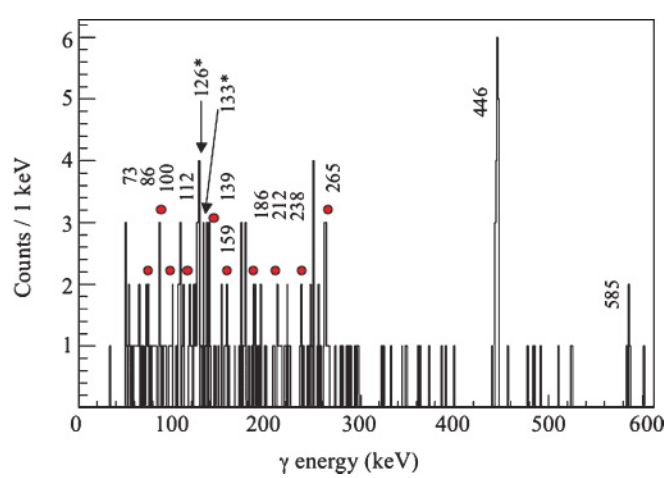

FIG. 4. (Color online) Energy spectrum of γ in coincidence with the electron bursts from ^{257}Rf for all r-e events that did not have a spontaneous fission event following the electron. Asterisks indicate known Rf x rays. The red circles represent γ-ray lines that match the transition energies calculated with the rotational model (see Sec. IV B).

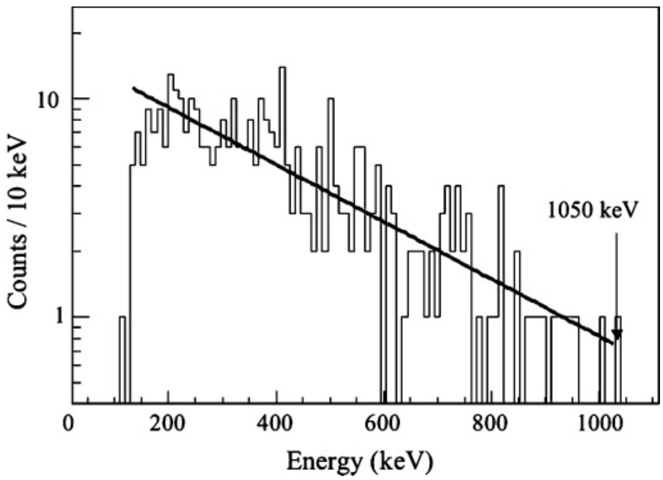

FIG. 5. Energy spectrum of conversion electrons added to the energy of coincident γ rays on an event-by-event basis for ^{257}Rf. The maximum energy extracted from the curve is ≈1050 keV.

lines which are attributed to ^{257}Rf. While the γ-ray statistics are low, the presence of two high-energy γ lines at 446 and 585 keV may be attributed to the decay of the isomer. This work represents the first observation of any significant γ rays originating from the isomeric decay of ^{257}Rf. Qian *et al.* [21] observed seven γ-ray events in coincidence with a delayed electron event, but could only identify two counts associated with K-shell x rays.

A total excitation energy curve is obtained by adding the γ-ray energy to the conversion electron energy on an event-by-event basis. The maximum energy of ≈1050 keV was extracted from the curve, as shown in Fig. 5, which corresponds to the approximate deexcitation energy of the isomeric state.

IV. DISCUSSION

A. Interpretation of ^{261}Sg results

Previous α-decay data have shown ^{261}Sg to have a ground-state spin and parity of $3/2^+$, which was assigned to the [622]$3/2^+$ Nilsson orbital [10,16]. Macroscopic-microscopic calculations [1,24], shown in Fig. 6, place the neutron [622]$3/2^+$ orbital close in energy to the [620]$1/2^+$ orbital (within 20 keV or less), with the [620]$1/2^+$ orbital being the ground state. In addition, there are [725]$11/2^-$ and [613]$7/2^+$ orbitals in the vicinity of the ground state, and a [734]$9/2^+$ orbital, higher in excitation energy at ≈300 keV. In this work, a 9.0 μs isomeric state, which is likely a one-qp state, was observed with an excitation energy of ≈200 keV. Although no γ rays were observed directly, any γ ray emitted from the isomeric state must have an energy of less than the total excitation energy of 200 keV. The hindrance factor F_w for a given state is calculated as

$$F_w = \frac{T^{\gamma}_{1/2}(\text{experiment})}{T^{\gamma}_{1/2}(\text{Weisskopf estimate})}. \quad (1)$$

F_w was determined for the 9.0 μs isomeric state for the three most probable multipole transitions at a few different energies

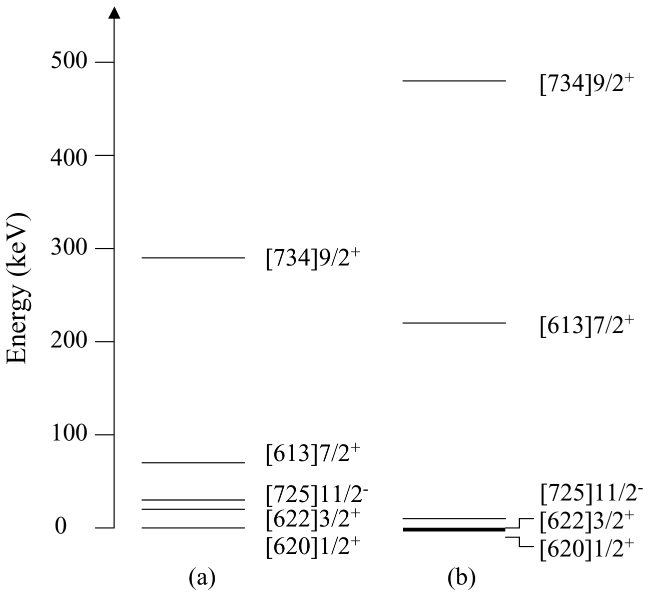

FIG. 6. Calculated neutron level scheme for ^{261}Sg with energies in keV from (a) Ref. [1] with deformation parameter $\beta_2 = 0.240$ and (b) Ref. [24] with $\beta_2 = 0.249$.

to estimate the ΔK, as shown in Table I. The likely transition can then be determined based on these calculated hindrance factors and estimates by Löbner [25]. The isomeric state cannot be one of the positive parity states because it will rapidly decay to the next-lowest positive parity state and will not be observed (for example, the lifetime of the [734]$9/2^+ \rightarrow$ [613]$7/2^+$ or [613]$7/2^+ \rightarrow$ [622]$3/2^+$ decays will be picoseconds for an $E1$ transition based on Weisskopf estimates). Therefore, the isomer must originate from the [725]$11/2^-$ state. It is unlikely that the decay from the [725]$11/2^-$ state populates the rotational band built on the [622]$3/2^+$ ($\Delta K = 4$) or [620]$1/2^+$ ($\Delta K = 5$) states since such transitions, probably with $E1$ character, are highly forbidden (as inferred from Table I) and typical F_w values would yield a much longer half-life than that observed experimentally. However, if the

TABLE I. Estimated ΔK values from Löbner [25] for possible transitions from the isomeric state in ^{261}Sg based on the calculated hindrance factors F_w for various γ-ray energies.

Transition	γ-ray Energy (keV)	F_w	Löbner estimate
$E1$	50	1.4×10^7	$\Delta K = 1$ or 2
	100	6.4×10^7	$\Delta K = 1$ or 2
	150	2.0×10^8	$\Delta K = 2$ or 3
	200	4.9×10^8	$\Delta K = 2$ or 3
$M1$	50	7.8×10^6	$\Delta K = 3$
	100	8.6×10^6	$\Delta K = 3$
	150	1.0×10^7	$\Delta K = 3$
	200	4.0×10^7	$\Delta K = 3$ or 4
$E2$	50	5.8×10^2	$\Delta K = 2$ or 3
	100	7.3×10^2	$\Delta K = 2$ or 3
	150	9.9×10^2	$\Delta K = 2$ or 3
	200	1.6×10^3	$\Delta K = 2$ or 3

[613]7/2$^+$ state was lower in energy than the [725]11/2$^-$ state, the isomer will decay from the [725]11/2$^-$ Nilsson state to the rotational band built on the [613]7/2$^+$ Nilsson state via a $\Delta K = 2$, $E1$ transition, which is possible based on Table I. We conclude that this is the most likely scenario. The energy levels built on the [613]7/2$^+$ state were calculated using the simple rotational model $E = E_K + \frac{\hbar^2}{2J}[I(I+1) - K^2]$, where E_K is the band-head energy, J is the moment of inertia, and I is the spin of the rotational state. The moment of inertia used in the calculation was $\frac{\hbar^2}{2J} = 6.6$, which is consistent with the value extracted for the [613]7/2$^+$ state in ^{251}Cf. Based on the calculation, the 13/2$^+$ rotational state will be higher in energy than the [725]11/2$^-$ isomer state, and therefore the isomeric state will decay to either the 11/2$^+$ rotational state or the 9/2$^+$ rotational state via an $E1$ transition. This work represents the first observation of the electromagnetic decay of an excited state in any nucleus with $Z > 104$.

B. Interpretation of ^{257}Rf results

Qian *et al.* [21] compiled α-decay data for ^{257}Rf from experiments by Bemis *et al.* [26,27], Heßberger *et al.* [16,28,29], and their own data. Based on α-decay hindrance factors, a partial level scheme and α-decay scheme was constructed for ^{257}Rf. The authors in Ref. [21] assigned a Nilsson configuration of [620]1/2$^+$ for the ground state of ^{257}Rf, which is the same ground-state configuration as other known even Z, $N = 153$ isotones. A single quasiparticle isomeric state was assigned a Nilsson configuration of [725]11/2$^-$ located at $\approx$75 keV. The lower energy α lines from ^{257}Rf (from $\approx$8.2 MeV to $\approx$8.8 MeV) were shown to decay from the ground state of ^{257}Rf to single quasineutron states in ^{253}No, while the higher energy α lines (from $\approx$8.9 MeV to $\approx$9.2 MeV) were shown to decay from the 75 keV isomeric state in ^{257}Rf. It was also suggested in Ref. [21] that the longer-lived high-K isomeric state might decay to a rotational band built on the 75 keV isomeric state.

Our data support the findings of Qian *et al.* [21] and adds further information to the level scheme of ^{257}Rf. In Fig. 2(b), only the higher-energy α lines are observed in coincidence with the electron burst, and therefore the suggestion of Qian *et al.* [21] that the high-K state decays to a rotational band built on the [725]11/2$^-$ state in ^{257}Rf is supported. The differences in rotational energy levels built on the [725]11/2$^-$ state were calculated using the simple rotational model. Possible γ lines matching these rotational energy differences were found within the γ-ray energy spectrum in Fig. 4 and labeled with a red circle. On this basis, we present a postulated decay scenario, which is shown in Fig. 7. Additional support for the decay scenario comes from looking at the total excitation energy for r-e-α(^{257}Rf) events, which is the sum of the electron and γ-ray energies for each event. As shown in Fig. 5, we observe an energy spectrum that ends at a maximum energy of $\approx$1050 keV. The energy difference between the [725]11/2$^-$ state and the 134 μs isomeric state is 1080 keV based on our proposed decay scenario, which is comparable to the observed excitation energy (see Fig. 5).

Further support for the proposed decay scenario is obtained from examining the hindrance factors of transitions

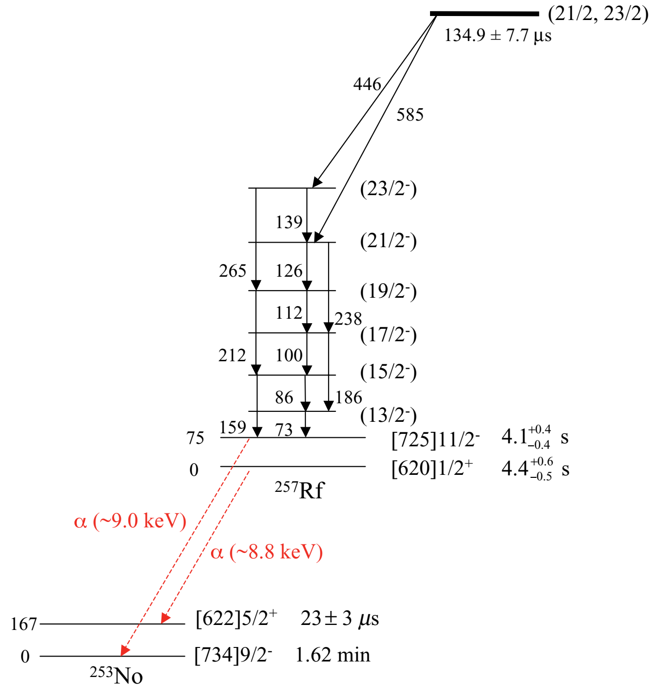

FIG. 7. (Color online) Proposed decay scenario for ^{257}Rf. The energies of states and transitions are not to scale. Alpha transitions (dashed red arrows) and gamma decay (solid black arrows) are indicated schematically. Energies are in keV and suggested spins and parities are indicated in parentheses. The isomeric state in ^{257}Rf is indicated by a thicker black line. The figure is based on data from the present work and from Qian *et al.* [21]. The lifetime and energy of the excited state in ^{253}No was taken from Ref. [30]

depopulating the isomer. F_W was determined for the 134 μs state assuming the 446 keV γ line has a 100% branching ratio B_γ and calculated for $E1$, $M1$, and $E2$ transitions. When compared to the estimates by Löbner [25], the possible transitions yield a ΔK value of 4, 5, or 6, as shown in Table II. Note that changing B_γ does not alter the calculated F_w significantly, and not enough to change the estimated ΔK value. The calculations in Ref. [21], using a Woods-Saxon potential [31] and the Lipkin-Nogami [32] prescription for pairing, yield a number of possible three-qp states. These include $[\pi^2\{[624]9/2^+ \otimes [521]1/2^-\}_{K=5^-} \otimes \nu[725]11/2^-]_{K=21/2}$ or $[\pi^2\{[514]7/2^- \otimes [512]5/2^-\}_{K=6^+} \otimes \nu[725]11/2^-]_{K=23/2}$, at excitation energies of $\approx$1125 and $\approx$1400 keV, respectively. A transition from the $K = 21/2$ state or the $K = 23/2$ state to states built on the [725]11/2$^-$ rotational band would yield a ΔK value of 5 or 6, respectively. It appears that the

TABLE II. Estimated ΔK values from Löbner [25] for possible transitions from the isomeric state in ^{257}Rf based on the calculated hindrance factors, F_w.

Transition	F_w	Löbner estimate
$E1$	6.5×10^{10}	$\Delta K = 4$ or 5
$M1$	9.6×10^8	$\Delta K = 4$ or 5
$E2$	4.1×10^5	$\Delta K = 4$, 5 or 6

134 μs isomeric state can be based on one of these three-qp configurations.

V. SUMMARY

Delayed spectroscopy was performed on the isotopes ^{261}Sg and, in a separate experiment, on the α daughter nucleus ^{257}Rf. The obtained α-decay energies and decay half lives agree with previous studies. A [725]11/2$^-$ isomeric state was identified in ^{261}Sg with a half-life of $9.0^{+2.0}_{-1.5}$ μs, representing the first observation of the electromagnetic decay of an excited state in any nucleus with $Z > 104$. New information was obtained in ^{257}Rf, including the first identification of significant γ decay branches from a high-K isomer. The half-life of 134.9 $\pm$ 7.7 μs observed for the isomeric state agrees with previous studies, but for the first time a decay scenario was proposed. The decay of the isomer populates a rotational band built on an [725]11/2$^-$ one-qp isomeric state in ^{257}Rf. Based on the energy of the observed dominant γ ray and the lifetime of the isomeric state, the decay of the isomer proceeds through a $\Delta K = 5$ or 6 transition. Calculations with a Woods-Saxon potential and Lipkin-Nogami prescription for pairing predict either $[\pi^2\{[624]9/2^+ \otimes [521]1/2^-\} \otimes \nu[725]11/2^-]_{K=21/2}$ or $[\pi^2\{[514]7/2^- \otimes [512]5/2^-\} \otimes \nu[725]11/2^-]_{K=23/2}$ as possible configurations.

ACKNOWLEDGMENTS

The authors thank the 88-Inch Cyclotron operations staff for providing the beams for this experiment. The work was supported in part by the US DOE under Contract No. DE-AC02-05CH11231 (LBNL) and under Grant Nos. DE-FG52-06NA26206 and DE-FG02-05ER41379. Part of this work was performed under the auspices of the US Department of Energy Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344. P.A.E. was supported by the US DOE National Nuclear Security Administration, Stewardship Science Graduate program.

[1] S. Ćwiok, S. Hofmann, and W. Nazarewicz, Nucl. Phys. A **611**, 211 (1996).
[2] A. V. Afanasjev, T. L. Khoo, S. Frauendorf, G. A. Lalazissis, and I. Ahmad, Phys. Rev. C **67**, 024309 (2003).
[3] M. Bender, P. Bonche, T. Duguet, and P.-H. Heenen, Nucl. Phys. A **723**, 354 (2003).
[4] Yu. Ts. Oganessian *et al.*, Phys. Rev. Lett. **83**, 3154 (1999).
[5] L. Stavsetra, K. E. Gregorich, J. Dvorak, P. A. Ellison, I. Dragojević, M. A. Garcia, and H. Nitsche, Phys. Rev. Lett. **103**, 132502 (2009).
[6] Yu. Ts. Oganessian *et al.*, Phys. Rev. C **74**, 044602 (2006).
[7] Yu. Ts. Oganessian *et al.*, Phys. Rev. C **69**, 054607 (2004).
[8] M. Leino and F. P. Hessberger, Annu. Rev. Nucl. Part. Sci. **54**, 175 (2004).
[9] C. M. Folden III, Ph.D. thesis, University of California, Berkeley, Report No. LBNL-56749 (2004).
[10] S. Antalic, B. Štreicher, F. P. Hessberger, S. Hofmann, D. Ackerman, Š. Šáro, and B. Sulignano, Acta Physica Slovaca **56**, 87 (2006).
[11] G. Audi, A. H. Wapstra, and C. Thibault, Nucl. Phys. A **729**, 337 (2003).
[12] W. D. Myers and W. J. Światecki, Lawrence Berkeley National Laboratory Report: LBNL-36803 (1994).
[13] I. Dragojević, K. E. Gregorich, Ch. E. Düllmann, M. A. Garcia, J. M. Gates, S. L. Nelson, L. Stavsetra, R. Sudowe, and H. Nitsche, Phys. Rev. C **78**, 024605 (2008).
[14] J. F. Ziegler, computer software SRIM-2006, available from [http://www.srim.org/SRIM/SRIM2006.htm].
[15] G. Duchêne, F. A. Beck, P. J. Twin, G. de France, D. Curien, L. Han, C. W. Beausang, M. A. Bentley, P. J. Nolan, and J. Simpson, Nucl. Instrum. Methods A **432**, 90 (1999).
[16] B. Štreicher, S. Antalic, S. Saro, M. Venhart, F. P. Hessberger, S. Hofmann, D. Ackermann, B. Kindler, I. Kojouharov, B. Lommel, R. Mann, B. Sulignano, and P. Kuusiniemi, Acta Phys. Pol. **38**, 1561 (2007).
[17] G. D. Jones, Nucl. Instrum. Methods A **488**, 471 (2002).
[18] K. E. Gregorich, Nucl. Instrum. Methods A **302**, 135 (1991).
[19] Y. A. Akovali, Nucl. Data Sheets **87**, 249 (1999).
[20] A. Artna-Cohen, Nucl. Data Sheets **88**, 155 (1999).
[21] J. Qian *et al.*, Phys. Rev. C **79**, 064319 (2009).
[22] H. B. Jeppesen *et al.*, Phys. Rev. C **79**, 031303(R) (2009).
[23] *Table of Isotopes*, 8th ed., edited by R. Firestone and V. Shirley (Wiley, New York, 1996).
[24] A. Parkhomenko and A. Sobiczewski, Acta Phys. Pol. B **36**, 3115 (2005).
[25] K. E. G. Löbner, Phys. Lett. B **26**, 369 (1968).
[26] C. E. Bemis Jr., R. J. Silva, D. C. Hensley, O. L. Keller Jr., J. R. Tarrant, L. D. Hunt, P. F. Dittner, R. L. Hahn, and C. D. Goodman, Phys. Rev. Lett. **31**, 647 (1973).
[27] C. E. Bemis, J. R. Tarrant, R. J. Silva, L. D. Hunt, D. C. Hensley, P. F. Dittner, O. L. Killer, and R. L. Hahn, Oak Ridge National Laboratory Annual Report, ORNL-4976, 1973, p. 37 (unpublished).
[28] F. P. Heßberger, S. Hofmann, V. Ninov, P. Armbruster, H. Folger, G. Münzenberg, H. J. Schött, A. G. Popeko, A. V. Yeremin, A. N. Andreyev, and S. Saro, Z. Phys. A **359**, 415 (1997).
[29] F. P. Heßberger, S. Hofmann, D. Ackermann, P. Armbruster, G. Münzenberg, Ch. Stodei, A. Yu. Lavrentev, A. G. Popeko, A. V. Yeremin, S. Saro, and M. Leino, AIP Conf. Proc. **495**, 145 (1999).
[30] F. P. Heßberger, Phys. At. Nucl. **70**, 1445 (2007).
[31] S. Ćwiok, J. Dudek, W. Nazarewicz, J. Skalski, and T. Werner, Comput. Phys. Commun. **46**, 379 (1987).
[32] Y. Nogami, Phys. Rev. **134**, B313 (1964).