PHYSICAL REVIEW C **83**, 064311 (2011)

Search for a 2-quasiparticle high-K isomer in ^{256}Rf

A. P. Robinson,[1,*] T. L. Khoo,[2] D. Seweryniak,[2] I. Ahmad,[2] M. Asai,[3] B. B. Back,[2] M. P. Carpenter,[2]
P. Chowdhury,[4] C. N. Davids,[2] J. Greene,[2] P. T. Greenlees,[5] K. Hauschild,[5,6] A. Heinz,[7,†] R.-D. Herzberg,[8]
R. V. F. Janssens,[2] D. G. Jenkins,[1] G. D. Jones,[8] S. Ketelhut,[5] F. G. Kondev,[2] T. Lauritsen,[2] C. J. Lister,[2]
A. Lopez-Martens,[5,6] P. Marley,[1] E. McCutchan,[2] P. Papadakis,[8] D. Peterson,[2] J. Qian,[7] D. Rostron,[8]
U. Shirwadkar,[4] I. Stefanescu,[2] S. K. Tandel,[4,‡] X. Wang,[2,9] and S. Zhu[2]
[1]*Department of Physics, University of York, Heslington, York, YO10 5DD, United Kingdom*
[2]*Argonne National Laboratory, Argonne, Illinois 60439, USA*
[3]*Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan*
[4]*Department of Physics, University of Massachusetts Lowell, Lowell, Massachusetts 01854, USA*
[5]*Department of Physics, University of Jyväskylä, FI-40014, Finland*
[6]*CSNSM, IN2P3-CRNS, F-91405 Orsay, France*
[7]*Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520, USA*
[8]*Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[9]*Physics Department, University of Notre Dame, Notre Dame, Indiana 46556, USA*
(Received 25 February 2011; revised manuscript received 19 May 2011; published 13 June 2011)

The energies of 2-quasiparticle (2-qp) states in heavy shell-stabilized nuclei provide information on the single-particle states that are responsible for the stability of superheavy nuclei. We have calculated the energies of 2-qp states in ^{256}Rf, which suggest that a long-lived, low-energy 8^- isomer should exist. A search was conducted for this isomer through a calorimetric conversion electron signal, sandwiched in time between implantation of a ^{256}Rf nucleus and its fission decay, all within the same pixel of a double-sided Si strip detector. A 17(5)-μs isomer was identified. However, its low population, ~5(2)% that of the ground state instead of the expected ~30%, suggests that it is more likely a 4-qp isomer. Possible reasons for the absence of an electromagnetic signature of a 2-qp isomer decay are discussed. These include the favored possibility that the isomer decays by fission, with a half-life indistinguishably close to that of the ground state. Another possibility, that there is no 2-qp isomer at all, would imply an abrupt termination of axially symmetric deformed shapes at $Z = 104$, which describes nuclei with $Z = 92$–103 very well.

DOI: 10.1103/PhysRevC.83.064311 PACS number(s): 23.20.Lv, 21.10.Pc, 21.10.Tg, 27.90.+b

I. INTRODUCTION

Superheavy nuclei represent an exciting frontier of nuclear physics. Recent reports [1] suggest that elements with atomic number Z up to 118 can be synthesized. The extended reach of the superheavy nuclei implies that the shell-induced fission barrier persists till $Z = 118$. The shell correction energy arises from gaps in the single-particle spectrum, direct information on which can be obtained from spectroscopic studies. A promising avenue for pushing the limits in Z for spectroscopy is through the identification of 2-quasiparticle (2-qp) states observed in the decay of isomers.

The occurrence of high-K isomers in ^{254}No [2,3], a series of $N = 150$ isotones [4–8] and several adjacent nuclei, establishes that K is a good quantum number in the heavy nuclei in an extended region of the periodic table; that is, the nuclei have axially symmetric prolate deformed shapes. This region extends from uranium ($Z = 92$) to lawrencium ($Z = 103$), with the β_2 deformation changing little ($\Delta\beta_2 \sim 0.02$) from U to No. It is not unreasonable to expect that Rf ($Z = 104$) nuclei would also be prolate, as predicted in all theoretical approaches [9–11]. The clustering of high-K orbitals near the Fermi level should give rise to isomers. To test whether this is indeed the case, our aim for this work is to search for high-K, 2-qp isomers in ^{256}Rf, with the prime motivation that measuring 2-qp energies provides direct information on single-particle energies.

In ^{254}No, 2-qp states with proton configurations and $K^\pi = 3^+$ and 8^- were found at 0.988 and 1.296 MeV [2,3], in agreement with values of 0.90 and 1.40 MeV calculated [2,12] using single-particle energies from a deformed "universal" Woods-Saxon potential [13]. Neutron configurations can be safely ruled out because a large $N = 152$ gap (1.4 MeV in nobelium [14]) results in significantly larger energies for neutron states, for example, the lowest neutron $K^\pi = 8^-$ state is calculated to lie at 1.74 MeV. Consequently, proton 2-qp configurations, which provide quantitative information on a spherical shell gap at $Z = 114$ predicted by the Woods-Saxon potential, are favored in $N = 152$ isotones.

Figure 1 illustrates the spectrum of states anticipated for ^{256}Rf ($N = 152$); the configurations leading to the 2-qp bands are given in Table I. The 8^- proton 2-qp state is predicted [12]

---

[*] Current address: School of Physics and Astronomy, Schuster Laboratory, University of Manchester, Manchester M13 9PL, United Kingdom.

[†] Current address: Fundamental Fysik, Chalmers Tekniska Högskola, S-412 96 Göteborg, Sweden.

[‡] Current address: Centre for Excellence in Basic Sciences, Mumbai 400098, India.

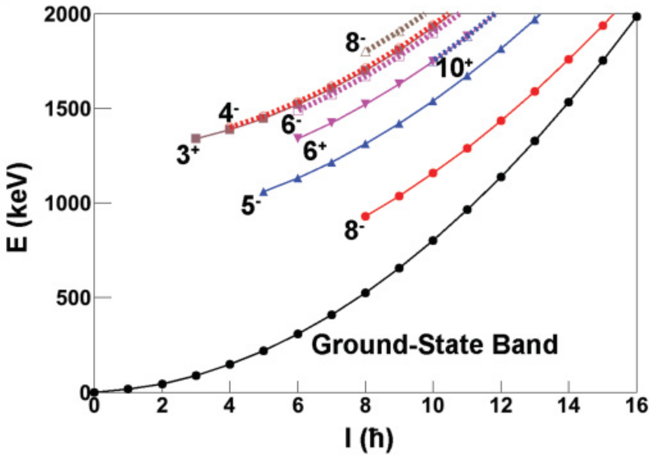

FIG. 1. (Color online) Estimated ground-state and 2-qp rotational bands in ^{256}Rf. The energies are given by $E(I) = A[I(I+1) - K(K+1)] + E_0$. Bandhead energies E_0, calculated as described in the text, are given in Table I. Rotational parameters A are taken as 7.3 and 6 keV for the ground-state and 2-qp bands, respectively. Solid and dotted lines denote proton and neutron configurations, respectively, K^π values are given for 2-qp bands. The origin and population of a high-K isomer depend on the relative energies of the high-K rotational bands.

at 0.93 MeV, a low energy because the Fermi level lies between the close-lying 7/2[514] and 9/2[624] levels. The partial γ-decay half-life is estimated to be between 0.14 and 18 s, based on retardation factors $f_\nu = 100$–200. (This estimate assumes a direct decay to the 8^+ level of the ground-state band and an interband transition energy of 0.5 MeV). Here f_ν is defined as $f_\nu = [T_{1/2}(\mathrm{exp})/T_{1/2}(WU)]^{1/\nu}$, where $T_{1/2}(\mathrm{exp})$ and $T_{1/2}(WU)$ are the experimental and Weisskopf half-lives, respectively, $\nu = \Delta K - \lambda$ and λ is the transition multipolarity. The case of ^{256}Rf is interesting, because the ground state decays by fission with a half-life of 6.4(2) ms. If one assumes the same half-life ratio for the isomer and ground state as for ^{250}No [15], where both states ostensibly fission, then the partial fission half-life for the ^{256}Rf isomer would be ~70 ms. In other words, there is a distinct possibility that the isomer could decay by fission instead of by γ emission.

TABLE I. 2-quasiparticle energies ($E_{2\text{-qp}}$) calculated for ^{256}Rf with the universal Woods-Saxon energies and the Lipkin-Nogami procedure for pairing (see text for details).

K^π	Configuration	$E_{2\text{-qp}}$ (MeV)[a]
8^-	π 7/2[514] π 9/2[624]	0.93
5^-	π 1/2[521] π 9/2[624]	1.06
6^+	π 7/2[514] π 5/2[512]	1.34
3^+	π 7/2[514] π 1/2[521]	1.34
4^-	ν 9/2[734] ν 1/2[620]	1.40
6^-	ν 9/2[734] ν 3/2[622]	1.49
10^+	ν 9/2[734] ν 11/2[725]	1.75
8^-	ν 9/2[734] ν 7/2[613]	1.80

[a] Residual nucleon-nucleon interactions are included: −0.1 and 0.1 MeV for singlet and triplet spin states, respectively.

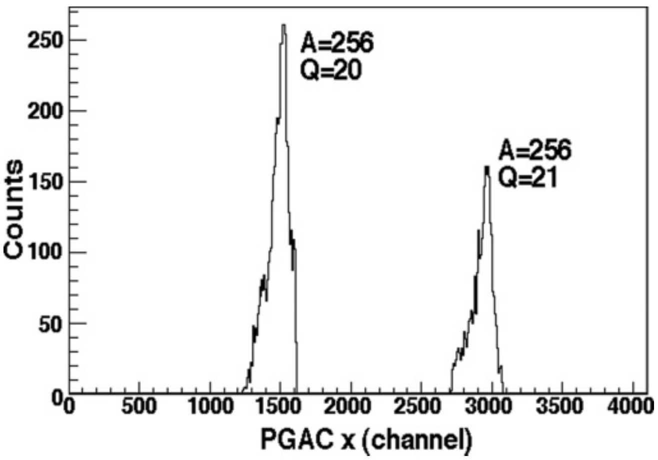

FIG. 2. A/Q spectrum for $A = 256$ recoils, measured at the focal plane of the FMA, with additional software gates placed on the time of flight between PGAC and DSSD and the recoil energy.

The decay of a 2-qp isomer in ^{256}Rf has recently been reported by Jeppesen *et al.* [16], who measured a half-life of 25(2) μs and proposed a neutron configuration, contrary to the expectations outlined above. Both our experimental results and interpretation disagree with those of Ref. [16].

II. EXPERIMENT

The ^{256}Rf nuclei of interest were produced using a ^{50}Ti beam from the Argonne ATLAS accelerator facility to bombard a ~0.5 mg cm^{-2} thick ^{208}Pb target, mounted on a rotating target wheel. A beam energy of 242.5 MeV was used, giving a center-of-target energy of ~240 MeV. The experiment ran for ~4 days with an average beam current of ~260 pnA. ^{256}Rf was produced via the $2n$-evaporation channel with a measured cross section of ~14 nb. The Argonne Fragment Mass Analyzer (FMA) [17] was set to transmit $A = 256$ recoils, with charge states $Q = 20^+$ and 21^+, to the focal plane detectors (see Fig. 2). In contrast to gas-filled spectrometers, as used in the work reported in Ref. [16], the FMA provides recoil mass identification in the form of A/Q dispersion, as shown in Fig. 2. A position-sensitive parallel grid avalanche counter (PGAC) located at the focal plane provided A/Q, time of arrival, and energy-loss signals for the recoiling nuclei, which were subsequently implanted into a 140-μm-thick double-sided Si strip detector (DSSD) with 40 × 40 strips, each 1 mm wide. Recoiling nuclei with $A = 256$ were identified by software cuts placed on A/Q, time of flight between PGAC and DSSD, and recoil energy. Further information on the experimental setup may be found in Refs. [18,19].

The DSSD was instrumented with semi-Gaussian shaping amplifiers and delay-line amplifiers in parallel to allow detection of half-lives down to 0.5 μs [20,21]. To facilitate setup, ^{170}Hf ions with an energy of ~57 MeV, produced from the reaction of a 222-MeV ^{50}Ti beam on a ~0.5 mg cm^{-2} thick ^{124}Sn target, were used to adjust the pole zeros on the delay-line amplifiers to ensure that they were fully recovered within 0.5 μs following the implantation of a heavy ion. This

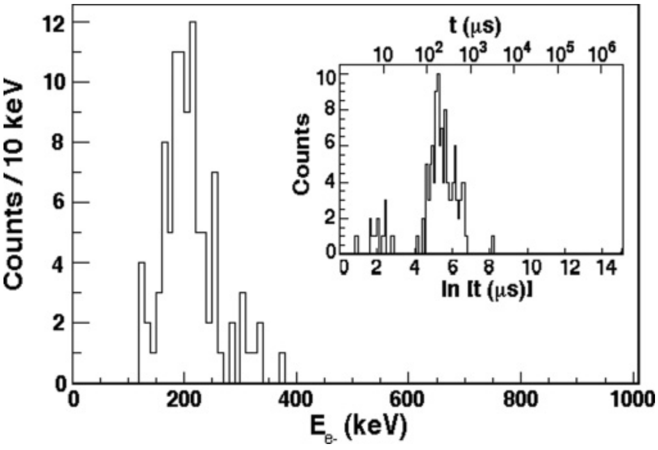

FIG. 3. Electron sum-energy spectrum from the decay of the 8^+ isomer in ^{216}Th. The inset gives the decay time distribution of the isomer [$t_{1/2} = 128(35)$ μs], where the x axis is given as ln(t), with t in μs.

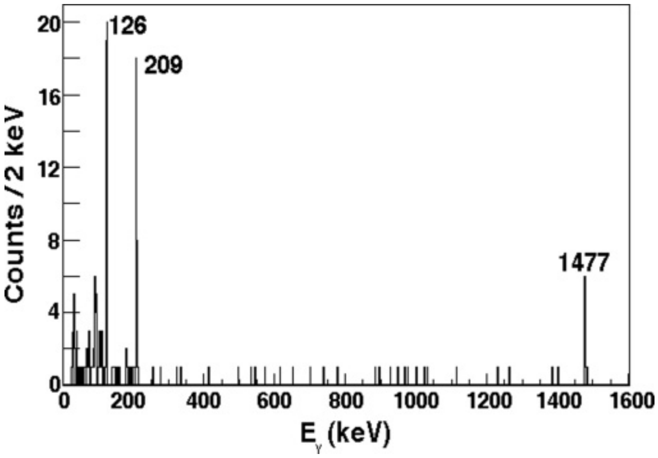

FIG. 4. γ spectrum in coincidence with the isomeric electrons from ^{216}Th shown in Fig. 3.

procedure ensured that the energy measured for any subsequent decays, which occurred after the recovery period (0.5 μs), would not include the tail of an overload pulse. This feature is especially important for low-energy (few hundred keV) signals from isomeric electrons.

To test the response of the system for short-lived (microsecond) isomers, we utilized the decay of a known 8^+ isomeric state in ^{216}Th ($t_{1/2} = 134(4)$ μs [22–24]), produced using the ^{170}Er(^{50}Ti,4n) reaction with a 222-MeV beam on a 0.55 mg cm^{-2} target. Conversion electron signals, from the decay of the isomeric state, were detected following the implantation of an $A = 216$ ion in the same pixel of the DSSD. The isomeric electrons were correlated—in the same pixel—with the subsequent ^{216}Th ground-state α decay ($E_\alpha =$ 7921 keV, $t_{1/2} = 26.0(2)$ ms [23,24]). Figure 3 presents the electron sum-energy spectrum [25] for these events. The electron time distribution (see inset) corresponds to a half-life of 128(35) μs, in agreement with previous measurements [22–24]. γ rays were detected, in prompt coincidence with isomeric electrons, in four large clover Ge detectors (each consisting of four crystals) with a total full-energy peak efficiency of ~9% at 900 keV. Figure 4 shows γ rays in prompt coincidence with the isomeric electrons; transitions from the ground-state band in ^{216}Th [23] are clearly visible.

A total of 128 isomeric electrons were identified in correlation with ~5500 ground-state α decays from ^{216}Th. The data acquisition system has a 40-μs dead-time period, starting 25 μs after the implantation of a heavy ion and an overall system dead time of ~5%. With a decay time less than 25 μs, 17(4) isomeric electrons were observed (see Fig. 3), in good agreement with the 18 decays expected in this time period. These results demonstrate the sensitivity of the experimental setup to short-lived microsecond isomeric decays.

The isomer ratio for the 8^+ state in ^{216}Th was previously found to be 0.34(11) [26]. A 5% α decay branch from the 8^+ isomeric state has been observed [23]. The threshold for the detection of correlated isomeric electrons from ^{216}Th in the DSSD was ~130 keV (see Fig. 3). The efficiency for detecting isomeric electrons from the implantation and subsequent decay of ^{216}Th in the DSSD was simulated (as described in Ref. [27]) using the Monte Carlo simulation package GEANT4 [28]. Using this simulation, it was found that a threshold of 130 keV corresponds to an efficiency of 18% for detecting isomeric electrons (mostly from a single 200-keV transition). After correcting for the dead time of the data-acquisition system, the known α decay branch of the 8^+ state [23], and the simulated electron detection efficiency (18%), the isomer ratio for the 8^+ state in ^{216}Th was found to be 0.18(6), in reasonable agreement with the previous value of 0.34(11) [26].

III. RESULTS

Seven hundred eighty-three ^{256}Rf nuclei were identified by observing the spontaneous fission of ^{256}Rf, with a characteristic half-life of 6.9(4) ms (in agreement with the accepted value, 6.4(2) ms [29,30]), in the DSSD, following an $A = 256$ implantation in the same pixel. Figure 5 shows the time distribution of 1322 fission events from ^{256}Rf, which includes the data from this experiment and from an earlier measurement, performed using the same experimental setup, but where the system was not sensitive to events with short (<100 μs) decay times.

Isomeric decays were identified in the DSSD by their characteristic decay chain consisting of an electron signal, which was sandwiched in time between an $A = 256$ implant and fission of ^{256}Rf. The electron sum-energy spectrum (with 19 events) for isomeric decays is given in Fig. 6. The electron time distribution corresponds to a half-life of 17(5) μs (see inset), determined using the method of maximum likelihood. γ rays detected in prompt coincidence with the isomeric electrons are shown in Fig. 7 and do not reveal any candidates for isomeric transitions. The electron-fission correlations were detected over the duration of the experiment, indicating that the setup functioned properly for the whole run.

The threshold for the detection of correlated isomeric electrons from ^{256}Rf in the DSSD was ~130 keV, as can be

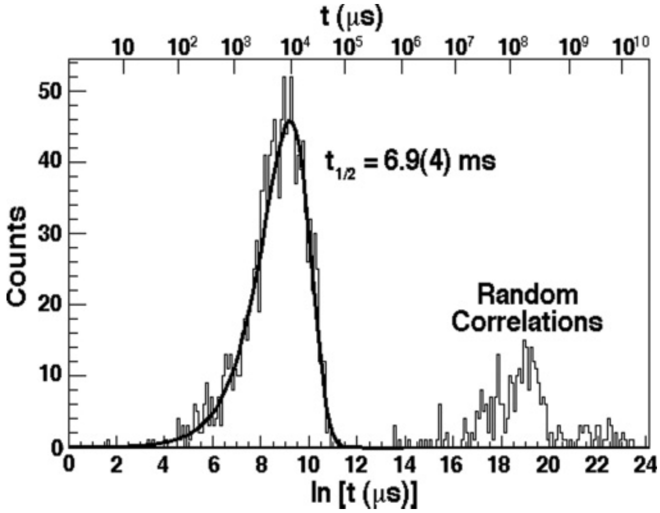

FIG. 5. Time distribution for fission events from ^{256}Rf [$t_{1/2} =$ 6.9(4) ms] for a combined data set, which includes the data from this experiment and from an earlier measurement using the same experimental setup, but where the system was not sensitive to decay times of $<$100 μs. The long-lived component is the result of random correlations. The x axis is given as ln(t), with t in μs.

seen in Fig. 6. The efficiency for detecting isomeric electrons from the implantation and subsequent decay of ^{256}Rf in the DSSD was estimated using the same simulation program as for ^{216}Th (see Sec. II). It was found that for the decay of ^{256}Rf a threshold of 130 keV corresponds to an efficiency of 79% for detecting the calorimetric sum of isomeric electrons (taken as a cascade starting from the 8^+ level of the ground band, which is assumed to have the same energies [18,19] as in ^{254}No). After correcting for the data acquisition dead-time gap (25–45 μs), the overall system dead time (∼5%) and the simulated electron detection efficiency (79%), the electron signals yielded an isomer ratio of 0.05(2).

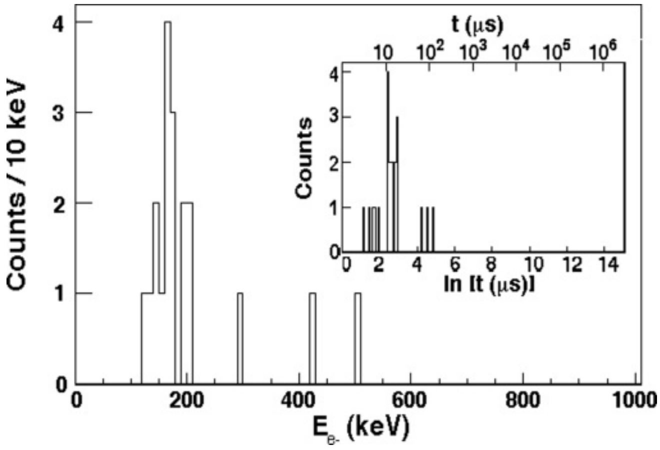

FIG. 6. Electron sum-energy spectrum from the decay of the isomer in ^{256}Rf. The inset gives the decay time distribution of the isomer; $t_{1/2} = 17(5)\,\mu$s was determined with the maximum likelihood method. The x axis is given as ln(t), with t in μs.

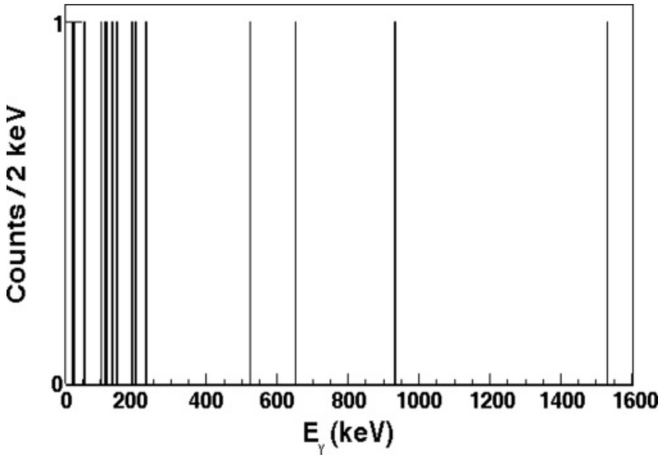

FIG. 7. γ spectrum in coincidence with the isomeric electrons shown in Fig. 6. No candidates for isomeric transitions are detected.

IV. DISCUSSION

A. General approach

In interpreting the results, we adopt an approach wherein all heavy, shell-stabilized, deformed nuclei should be described within one framework, which accurately describes the whole body of spectroscopic data for the heaviest nuclei. We adopt the "universal" Woods-Saxon potential [13], with deformation parameters β_λ that minimize the ground-state energy [9,10]. Inclusion of high-order deformation terms up to at least β_6 is essential [31]. With this potential, single-particle energies are obtained, which are close to those deduced [32–34] from the 1-qp states of Bk, Es, Cm, and Cf nuclei. In addition, 1- and 2-qp energies in a broad region of nuclei from Pu to Lr are well described within 0.25 MeV [12,34–36]. Energies of 1- and 2-qp configurations are calculated [12] based on the Woods-Saxon single-particle energies, with deformation parameters taken from Ref. [10]. Pairing is treated with the Lipkin-Nogami procedure, with pairing force strengths $G_p = 17.8/A$ and $G_n = 24/A$. Arbitrary shifts of 2-qp energies $>$0.3 MeV are deemed not justifiable, unless one concomitantly invokes a breakdown of the model, for example, a departure from axial symmetry or a dramatic change of deformation. One explicit aim of this approach is to test the limits of the model with increasing Z. In this procedure, one attempts to interpret results within one overarching framework, a definite asset when data are limited.

Given the excellent description of the Woods-Saxon model for all deformed nuclei in this region [34,37], we are also guided by the fact that a common description applies for phenomena in all nuclei, such as the population intensity of a particular class of isomers. For heavy shell-stabilized nuclei, 2-qp isomers have large population: 28(2)%, ≈50%, and 37(2)% of the ground-state strength for 2-qp 8^- isomers in ^{254}No, ^{252}No, and ^{250}Fm, respectively [5,38,39]. The 2-qp isomer in ^{250}No, which decays by fission, also has a similar isomer ratio of ≈30% [15]. The reason for the strong 2-qp isomer population is that the isomer, usually the lowest of the high-K configurations, collects the full population from high-K states. The population strength is governed by the density of high-K states, which is similar in neighboring nuclei with low-lying high-K states. As a consequence, the large isomer ratio is quite robust, as observed in the No region, as well as in the Hf region, which is well-known for high-K isomers.

In contrast, the isomer ratio of the known 4-qp isomer in ^{254}No is much smaller, 4(1)% [38], owing to its higher energy. *The weak population of the isomer in ^{256}Rf suggests that it is more likely to be associated with a 4-qp rather than a 2-qp configuration.* In particular, if an 8^- isomer were to exist at a low energy of ≈1 MeV, as predicted, it should be even more strongly fed than the above cases.

B. Absence of experimental evidence for electromagnetic decay of a long-lived 8^- isomer

We did not find evidence for a 2-qp isomer which decays by electromagnetic radiation, especially one with the expected half-life in the seconds range. The possibility must then be considered that if a low-lying 2-qp isomer does exist, it decays by fission. Only one component in the fission decay curve (see Fig. 5) could be identified, with a half-life of 6.9(4) ms, close to the accepted value of 6.4(2) ms for ^{256}Rf fission decay. A search for two components in the fission decay curve (Fig. 5), with relative intensities of the components fixed at 70:30, as expected for ground and isomeric populations, yielded negative results. Of course, it would not be possible to discern two components if the half-lives were close (within 1–2 ms). Thus, if the 2-qp isomer decays by fission, its half-life must be close to that of the ground state. The observed correlations between isomeric electrons and fission fragments supports this hypothesis, that is, a 4-qp decay followed by fission of a 2-qp isomer. If the half-lives were indeed close, there is another indication that they would be indistinguishable. The fission half-life measured for the ^{256}Rf ground state, when it is populated by α decay from ^{260}Sg, is $6.3^{+2.7}_{-1.4}$ ms [40] (within errors the same as the 6.4(2) ms measured [29,30]), when ^{256}Rf is directly populated in a fusion reaction, which should include feeding of both the ground and 2-qp states. The similarity of the lifetimes makes it difficult to provide experimental proof for the hypothesis that both the ground and 2-qp states fission with close decay rates. Confirmation could come from a future in-beam experiment, which identifies γ rays—directly preceding fission—from both the 2-qp and ground bands.

C. Possibility of fission decay of a 2-qp isomer

What is the probability that a 2-qp isomer decays by fission? The probability is high in ^{256}Rf because the ground state fissions. A good example for comparison is ^{250}No, where both the ground and isomeric states fission, with partial half-lives of 3.7 and 43 μs, respectively [15]. Although the latter half-life is given as a lower bound in Ref. [15] to allow for the possibility of a competition with γ decay, that possibility is very low. If one considers the much longer 34-ms [41] γ half-life of the 2-qp isomer in the isotone ^{244}Cm, a reasonable lower bound for the partial γ half-life in ^{250}No is 1 ms. This observation is based on four 8^- isomers [4–8] in $N = 150$ isotones with $Z = 94$, 96, 100 and 102, which have remarkably similar (within a factor of 6) partial half-lives for decay to the 8^+ ground-band levels.

If the ratio of lifetimes were the same as in ^{250}No, the partial fission half-life for the isomer in ^{256}Rf would be ≈70 ms. If, instead, one adopts the ratio from ^{254}No [38], the partial fission half-life for the isomer in ^{256}Rf would be ≈0.4 ms. In other words, based on the little information available, the partial fission half-life for the 2-qp isomer in ^{256}Rf ranges from 0.4 to 70 ms. With a γ partial half-life estimated in the seconds domain (e.g., 6 s with $f_\nu = 170$, typical of the $N = 150$ isomers) the isomer decay is indeed expected to be dominated by fission. The above spread in estimated fission half-life for the isomer encompasses the value of ≈7 ms, which could make the isomer and ground-state half lives indistinguishable. While this scenario is plausible and is also supported by the measured electron-fission correlations, the present data cannot provide unambiguous proof.

D. Possibility that the 8^- 2-qp state is not isomeric

An alternative interpretation is that the predicted low-lying 8^- 2-qp state is not isomeric, either because its energy is substantially higher or that K is not a good quantum number. For nuclei from uranium ($Z = 92$) to lawrencium ($Z = 103$), the description works extremely well in terms of nuclei with axially symmetric prolate deformation [4], where the deformation parameters change slowly with Z and by only a small amount. The known 1- and 2-qp energies are described rather well [12,34] with single-particle energies given by the deformed Woods-Saxon potential. Hence, a considerable body of data suggests that the prediction of a 2-qp $K^\pi = 8^-$ state at ≈1.0 MeV is rather robust. If such an isomer were indeed absent, or had a half-life 6 orders of magnitude shorter than predicted, it would imply an abrupt shape change and, hence, termination at $Z = 104$ of a description which works remarkably well from $Z = 92$–103. Such an abrupt termination would contradict theoretical predictions [9–11] and does not seem likely.

E. Possibility of a $K^\pi = 5^-$ isomer

A third alternative, with less drastic implications, would be a bypass decay of the 8^- {7/2[514] 9/2[624]} state via the 6^- member of a 5^-{1/2[521] 9/2[624]} band, leading to a shorter half-life. This would require raising the 8^- energy by >0.22 or 0.1 MeV, based on either the calculated energies or estimates from the nearly degenrate $K^\pi = 1/2^-$ and $7/2^-$ 1-qp energies in the neighboring $N = 152$ isotones, ^{255}Lr and ^{251}Md [42]. The half-life for the 8^- decay via the 5^- band could then be in the range of tens of μs if $f_\nu = 200$–600. The 5^- decay to the ground band would be relatively fast, <4 μs for f_ν up to 600. The isomer would still collect all the high-K strength, leaving the conundrum of a weak isomer population unexplained. Overall, the bypass scenario does not provide a consistent picture.

F. Possibility of large half-life for the $K^{\pi} = 8^{-}$ isomer

When correlations within the same pixel are required, detection of a long-lived isomer is limited by random coincidences. An isomer, which γ decays to the ground state, followed by fission, would be detected in the time spectra for fission (see Fig. 5) or electron-fission (Fig. 6). In this manner, one can exclude a strongly populated (>30%) 2-qp isomer with a half-life between 0.01 and 50 s. We can further exclude half lives between 5 and 120 h from a negative search for fission events in a counting period of ≈24 h after the beam was turned off. Longer half-lives cannot be ruled out, but are unlikely because they would be extraordinarily hindered ($f_{\nu} > 900$).

G. Comparison of our results and interpretation with those in Ref. [16]

The 17(5)-μs isomer detected in our experiment may be the same as the 25(2)-μs isomer reported in Ref. [16]. However, our isomer ratio is much smaller: 5(2)% vs 27%. (The latter number is our estimate from the data given in Ref. [16]). This is the main discrepancy, which affects the assignment of the isomer as a 2- or 4-qp state. Reference [16] also reported a sequence of three isomers with ≈20 μs, which our experiment could not verify owing to our lower statistics and our instrumental dead time of ≈40 μs for second- and third-generation isomers. Given the problems anticipated with short-lived isomers (small signal within the recovery time of a large implant signal), we took pains to ensure proper pole-zero correction in our delay line amplifiers, which have a short recovery time of 0.5 μs (see discussion in Sec. II). In addition, we specifically tested and calibrated our detection system by using a 134-μs isomer in ^{216}Th, observed in our test reaction, as described above. Reference [16] reported 35 counts of a 900-keV γ ray coincident with first-generation electrons, whereas we do not detect any (see Fig. 7), which is consistent with our smaller number of isomeric electrons. These experimental differences are difficult to reconcile.

The assignment of Ref. [16] for the configuration and their decay scheme of the first-generation isomer in ^{256}Rf are at variance with what is known about the structure of nuclei in this mass region. Reference [16] assigned the isomer as a *neutron* 2-qp configuration. However, as shown in Fig. 1 and Table I, this assignment is unlikely because the lowest predicted energy for such a configuration is 1.4 MeV owing to the $N = 152$ gap. Their suggestions for 2-qp configurations were based on calculations of 2-qp energies, which omitted higher-order deformation terms and resulted in the absence of the well-established $N = 152$ gap. Indeed, recent calculations by some of the same authors [43] confirm that the gap develops with inclusion of the β_6 term, resulting in increases in neutron 2-qp energies. It has long been known that high-order deformation terms affect single particle energies and are necessary to reproduce known gaps at $Z = 100$ and $N = 152$ (see Fig. 11 in Ref. [31]).

Reference [16] proposes that the isomer decays via a $K^{\pi} = 2^{-}$ octupole band. However, this vibrational band has low energy only when $N = 150$ or $Z = 98$ [4], because the main constituent 2^{-}, 2-qp excitations have low energies at only these specific neutron or proton numbers. Furthermore, the known 2^{-} octupole bands exhibit [4–6] many interband transitions to the ground-state band, contrary to the proposed decay scheme of Ref. [16].

V. CONCLUSIONS

The available spectroscopic data for a wide range of the heaviest nuclei strongly support a mean-field description in terms of quasiparticles moving in axially symmetric prolate potential, with K being a good quantum number. We advocate that new data in shell-stabilized nuclei should be tested against a mode that has been demonstrated to successfully describe the whole body of available data, with the purpose of testing its limits of applicability. The “universal” Woods-Saxon potential yield 1- and 2-qp energies that generally agree with experiment within 0.25 MeV [12,34–36], provided deformation parameters, including high-order ones, are properly specified from a minimization of the total energy. The advocated approach contrasts with some found in the literature, where configurations are assigned with the guidance of an assortment of models or new results are compared with model calculations, in some cases without verifying that the model single-particle energies reproduce known data.

We have performed calculations of 2-qp states in ^{256}Rf, which suggests that an 8^{-} isomer built on protons should occur around 1 MeV. The best estimate of its radiative half-life is around 6 s, compared with an estimate of 0.4–70 ms for its fission half-life. Experiments to search for this isomer found one with a half-life of 17(5) μs, which was weakly populated with an isomer ratio of only ∼5(2)%, considerably lower than the typical value of ∼30% observed for 2-qp isomers in heavy shell-stabilized nuclei. Owing to the weak population, we favor an assignment as a 4-qp isomer.

The lack of evidence for radiative decay of a 2-qp isomer leads us to speculate that it decays by fission. Because the decay curve exhibits only one decay component, its half-life has to be indistinguishably close to that of the fissioning ground state ($t_{1/2} = 6.3^{+2.7}_{-1.4}$ ms [40]). Our observed electron-fission correlations, which can be interpreted as a 4-qp decay followed by a 2-qp isomer decay with a fission half-life of $5.5(+1.7/-1)$ ms, support this hypothesis. Because the purported fission decay times for the isomer and ground state are equal within errors, it is not possible to provide unambiguous proof for this scenario. An alternative interpretation is that the prediction of a low-energy, isomeric 8^{-} state is not valid: Either its energy is significantly higher or K is no longer a good quantum number in ^{256}Rf. The inevitable consequence is that there is an abrupt termination in Rf at $Z = 104$ of a description of a nucleus with axially symmetric prolate deformation, which works remarkably well for nuclei from U to Lr ($Z = 92$–103). This interpretation is disfavored as it would contradict all predictions [9–11] based on different theoretical approaches and would involve a sudden breakdown of a highly successful model.

In view of the open questions and of the noted discrepancies with the results of Ref. [16], additional experimental investigations of the structure of Rf nuclei are highly desirable. In experiments where cross sections are small, an independent confirmation of results, for example, as for ^{254}No [2,3] and ^{252}No [4,5], is almost a necessity.

ACKNOWLEDGMENTS

This research is supported by the US Department of Energy, Office of Nuclear Physics, under Contracts No. DE-AC02-06CH11357, No. DE-FG02-94ER40848, and No. DE-FG02-91ER-40409. We would like to thank the ATLAS staff for providing the intense Ti beam.

---

[1] Yu. Ts. Oganessian *et al.*, Phys. Rev. C **74**, 044602 (2006).
[2] S. K. Tandel *et al.*, Phys. Rev. Lett. **97**, 082502 (2006).
[3] R.-D. Herzberg *et al.*, Nature (London) **442**, 896 (2006).
[4] A. P. Robinson *et al.*, Phys. Rev. C **78**, 034308 (2008).
[5] B. Sulignano *et al.*, Eur. Phys. J. A **33**, 327 (2007).
[6] P. T. Greenlees *et al.*, Phys. Rev. C **78**, 021303(R) (2008).
[7] S. K. Tandel *et al.* (unpublished).
[8] U. Shirwadka, Ph.D. thesis, University of Massachussetts Lowell, 2009.
[9] A. Sobiczewski, I. Muntian, and Z. Patyk, Phys. Rev. C **63**, 034306 (2001).
[10] P. Möller [http://t2.lanl.gov/data/astro/molnix96/molnix.html].
[11] M. Bender, P. Bonche, T. Duguet, and P. H. Heenen, Nucl. Phys. A **723**, 354 (2003).
[12] F. G. Kondev *et al.*, in *Proceedings of the International Conference on Nuclear Data for Science and Technology (ND2007), April 22–27, 2007, Nice, France* (EDP Science, Les Ulis Cedex, France, 2008), pp. 61–64.
[13] S. Ćwiok, J. Dudek, W. Nazarewicz, J. Skalski, and T. Werner, Comput. Phys. Commun. **46**, 379 (1987).
[14] J. Qian *et al.*, Phys. Rev. C **79**, 064319 (2009).
[15] D. Peterson *et al.*, Phys. Rev. C **74**, 014316 (2006).
[16] H. B. Jeppesen *et al.*, Phys. Rev. C **79**, 031303(R) (2009).
[17] C. N. Davids, B. B. Back, K. Bindra, D. J. Henderson, W. Kutschera, T. Lauritsen, Y. Nagame, P. Sugathen, A. V. Ramayya, and W. B. Walters, Nucl. Instrum. Methods B **70**, 358 (1992).
[18] P. Reiter *et al.*, Phys. Rev. Lett. **82**, 509 (1999).
[19] P. Reiter *et al.*, Phys. Rev. Lett. **84**, 3542 (2000).
[20] A. P. Robinson, C. N. Davids, G. Mukherjee, D. Seweryniak, S. Sinha, P. Wilt, and P. J. Woods, Phys. Rev. C **68**, 054301 (2003).
[21] D. Seweryniak *et al.*, Phys. Rev. C **73**, 061301(R) (2006).
[22] R. Hingmann, H. G. Clerc, C. C. Sahm, D. Vermeulen, K. H. Schmidt, and J. G. Keller, Nucl. Phys. A **404**, 51 (1983).
[23] K. Hauschild *et al.*, Phys. Rev. Lett. **87**, 072501 (2001).
[24] P. Kuusiniemi, F. P. Hessberger, D. Ackermann, S. Hofmann, B. Sulignano, I. Kojouharov, and R. Mann, Eur. Phys. J. A **25**, 397 (2005).
[25] G. Jones, Nucl. Instrum. Methods Phys. Res., Sect. A **488**, 471 (2002).
[26] K. Hauschild (private communication).
[27] Ch Theisen, A. Lopez-Martens, and Ch. Bonnelle, Nucl. Instrum. Methods Phys. Res., Sect. A **589**, 230 (2008).
[28] S. Agostinelli *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).
[29] Yu Ts. Oganessian, A. G. Deminand, M. Hussonnois, S. P. Tretyakova, Y. P. Kharitonov, V. K. Utyonkov, I. V. Shirokovsky, O. Constantinescu, H. Bruchertseifer, and Y. S. Korotkin, Z. Phys. A **319**, 215 (1984).
[30] F. P. Hessberger *et al.*, Z. Phys. A **359**, 415 (1997).
[31] Z. Patyk and A. Sobiczewski, Nucl. Phys. A **533**, 132 (1991).
[32] I. Ahmad, A. M. Friedman, R. R. Chasman, and S. W. Yates, Phys. Rev. Lett. **39**, 12 (1977).
[33] I. Ahmad, R. R. Chasman, J. P. Greene, F. G. Kondev, E. F. Moore, E. Browne, C. E. Porter, and L. K. Felker, Phys. Rev. C **68**, 044306 (2003).
[34] T. L. Khoo *et al.* (unpublished).
[35] A. Parkhomenko and A. Sobiczewski, Acta Phys. Pol. B **35**, 2447 (2004).
[36] A. Parkhomenko and A. Sobiczewski, Acta Phys. Pol. B **36**, 3115 (2005).
[37] R. R. Chasman, I. Ahmed, A. M. Friedman, and J. R. Erskine, Rev. Mod. Phys. **49**, 833 (1977).
[38] F. P. Heßberger *et al.*, Eur. Phys. J. A **43**, 55 (2010).
[39] S. Ketelhut, Ph.D. thesis, University of Jyväskylä, 2010, Research Report No. 11/2010.
[40] G. Münzenberg *et al.*, Z. Phys. A **322**, 227 (1985).
[41] P. G. Hansen, K. Wilsky, C. V. K. Baba, and S. E. Vandenbosch, Nucl. Phys. **45**, 410 (1963).
[42] A. Chatillon *et al.*, Eur. Phys. J. A **30**, 397 (2006).
[43] H. L. Liu, F. R. Xu, P. M. Walker, and C. A. Bertulani, Phys. Rev. C **83**, 011303(R) (2011).