Characterization of long-lived isomers in the odd-odd heavy actinide ^{254}Md

P. C. Sood and R. Gowrishankar
Department of Physics, Sri Sathya Sai Institute of Higher Learning, Prasanthi Nilayam (AP) 515134, India
(Received 1 October 2016; revised manuscript received 11 January 2017; published 15 February 2017)

Bandhead energies of all the physically admissible low-lying two-quasiparticle configuration states in the doubly-odd heavy actinide $^{254}_{101}$Md$_{153}$ are evaluated using the well-tested two-quasiparticle rotor model with explicit inclusion of the residual proton-neutron interaction. A critical examination of these results, aimed at characterization of the long-lived ($t_{1/2} = 10$ min and 28 min; $\%\varepsilon \leqslant 100$) isomer pair, conclusively rules out a high-spin ($J \geqslant 5$) assignment for either of the isomers. Our analysis leads to $J^\pi K = 1^-0\{p: 1/2^-[521] \otimes n: 1/2^+)[620]\}$ and $3^-3\{p: 7/2^-[514] \otimes n: 1/2^+[620]\}$ assignments, respectively, to these isomers and designates the 10-min isomer as its ground state. Our study reveals a "landmark" position for ^{254}Md in the decay path of super heavy elements. The as-yet unobserved electron capture decay branches from each of the two ^{254}Md isomers to ^{254}Fm levels are specified.

DOI: 10.1103/PhysRevC.95.024317

I. INTRODUCTION

Spectroscopic data with respect to transfermium nuclei beyond the $N = 152$ deformed shell closure are very rare, and rarer still is a credible interpretation of such data [1]. Currently available experimental information [1,2] on the lightest such nucleus, $^{254}_{101}$Md$_{153}$, provides a typical instance illustrating this feature. This nucleus, first observed in 1970 [3,4] in the α irradiation of the Es ($Z = 99$) target, "was found to decay by EC with a $t_{1/2} = 10(3)$ min"; these experiments also "indicated another $t_{1/2} = 28(8)$ min isomer." Even 45 yr later no attempt to characterize these long-lived isomers (LLI) has been reported anywhere [1]. The latest Nuclear Data Sheets NDS2005 [2] evaluators took note of a pair of low-lying closely spaced n orbitals in the neighboring odd-A $N = 153$ isotones and also a similar pair of p orbitals in odd-A $Z = 101$ isotopes. Thence they enumerated eight different two-quasiparticle (2qp) configuration states as possible candidates of low-energy levels in $^{254}_{101}$Md$_{153}$; they did not indicate which one of them is its ground state (gs). NUBASE2012 [5] lists 10-min ^{254}Md ($J^\pi = 0^-$) and 28-min ^{254}Md^m ($J^\pi = 3^-$; $E_x = 50 \pm 100$ keV) as "values estimated from trends in neighboring nuclides with same Z and N parities" following their global nomenclature and without stating any nucleus-specific argument or basis for these assignments; they also make no mention of their possible 2qp configurations. It may be pointed out that NDS2005 lists four different 2qp structures for 0^- and 3^- pairs of ^{254}Md low-lying levels. NDS2005 also lists data from a 1971 ^{258}Lr α-decay study [6] populating four ($E_x \approx 80$–175 keV; $\Delta E = 30$ keV) "not to be considered well established" ^{254}Md levels. No other investigations of the ^{254}Md level scheme have been reported since then. Further NDS2005 lists only $t_{1/2}$ values for each of the two $\%\varepsilon \leqslant 100$ decaying LLIs with no mention whatsoever of spin-parity (J^π) or E_x assignment for either of them or to those of ε-decay populated levels in ^{254}Fm. Presently we seek to investigate the low-energy level structures in ^{254}Md and thereby deduce J^π and the 2qp configuration for each LLI, and also their EC decays to ^{254}Fm levels.

Before investigating the intrinsic level structures of ^{254}Md, we briefly examine its positional significance in the hierarchy of heavy elements. For this purpose we traced [7,8] the sequential radioactive connection between the $(4n + 2)$ naturally occurring radioactive series (NORS) elements and the heaviest related super heavy element (SHE). This exercise, as described in Sec. II, reveals a "landmark" position for ^{254}Md in the decay path of SHE based on very recent experiments [9,10] highlighting the role of the ^{258}Lr (α) ^{254}Md (ε) ^{254}Fm sequence in this process. Of particular interest in the present context are developments over the past decade enabling α-γ and α-conversion electron (CE) spectroscopy of transfermium nuclei. For instance, Hessberger *et al.* [11] studied decay properties of n-deficient isotopes of $Z = 101$–108 elements and provided "evidence of α decay or EC from isomeric states" of a few of these nuclides. On the other hand, α-γ decay studies by Streicher *et al.* [12] yielded improved spectroscopic data on J^π and Nilsson orbital assignments for low-lying levels and isomeric structures in odd-A $N = 153$ isotonic neighbors of $^{254}_{101}$Md$_{153}$, namely $^{251}_{98}$Cf$_{153}$, $^{253}_{100}$Fm$_{153}$, and $^{257}_{104}$Rf$_{153}$. Simultaneously detailed spectroscopic decay studies of K isomers in ^{254}No (an isobaric neighbor of ^{254}Md) were reported by Hessberger *et al.* [13]. Against this background any guidance (as sought for in the present study) on spectra of transfermium nuclei will be of great interest for further experiments in the coming years.

Our three-step two-quasiparticle rotor model (TQRM) formulation and evaluation therefrom of bandhead energies [14] of all the physically admissible 2qp configurations in ^{254}Md, within a specified energy range, are described in Sec. III. This model has been extensively and effectively used to describe the level schemes of various odd-odd deformed nuclei of both the actinide and the rare earth regions [14,15]. In particular, level structures of the isotonic ^{250}Bk [16] and ^{252}Es [17], isotopic ^{250}Md [18], and isobaric ^{254}Es [19] neighbors of ^{254}Md have been investigated earlier by us using this formalism. Analysis and discussion of our evaluated ^{254}Md level energies are presented in Sec. IV, leading to J^π and 2qp configuration assignments for each of the isomers. This section also includes a proposed decay scheme for each ^{254}Md LLI and identifies the corresponding ^{254}Fm levels populated therein. A summary and conclusions of our present investigations are given in the final section. A preliminary report on these investigations was recently presented at a national symposium [20].

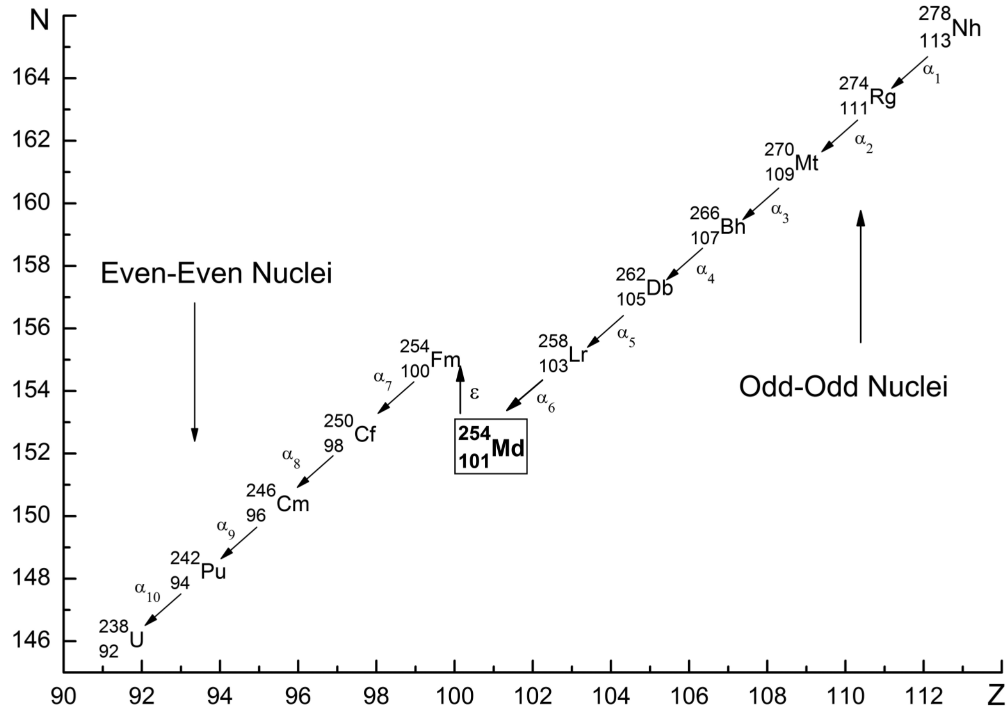

FIG. 1. Schematic plot of the radioactive connection between ^{238}U, the head of the $(4n+2)$ naturally occurring radioactive series, and the CF synthesized heaviest SHE, namely, the $Z = 113$ ^{278}Nh isotope. The plot clearly depicts the role of ^{254}Md as the transition point between the odd-odd nuclei for $Z \geqslant 101$ and the even-even nuclei for $Z < 101$.

II. ^{254}Md: A LANDMARK IN THE DECAY PATH OF SHE

The identification of a newly synthesized SHE in cold fusion (CF) reactions [21,22] is normally achieved by observation of a genetically correlated sequential α-chain terminating at an earlier known α- or spontaneous fission (SF)-decaying actinide or transactinide nuclide. For instance, first-time production of the heaviest SHE in a CF reaction of a $Z = 113$ element, since named nihonium (Nh) [23] was reported by Morita *et al.* [24,25] in the ^{209}Bi(^{70}Zn, $1n$)^{278}Nh reaction at RIKEN; its identity was established by observation of four consecutive α's followed by SF matching the known ^{266}Bh(α_4)^{262}Db (SF) data.

Taking note of the fact that each CF produced SHE, in principle, connects to an actinide heading the NORS, we undertook a study [7,8] to take the reverse track by tracing the upwardly extended radioactive series (UERS) right up to the heaviest identifiable SHE. An N-Z plot of the $(4n+2)$ UERS from our 2011 data [8] is shown in Fig. 1. It is interesting to note that the 6α-decay path of $^{278}_{113}$ based on the August 12, 2012 experiment, as shown in Fig. 3 of Morita *et al.* [9], directly verifies the ^{278}Nh(6α)^{254}Md segment of our Fig. 1. Taken together with the well-established ^{254}Fm(4α)^{238}U segment of Fig. 1, and the sequential ^{238}U $\rightarrow$ ^{206}Pb $(4n+2)$ NORS, the heaviest CF produced SHE, namely, ^{278}Nh, is thus connected all the way down to the stable ^{206}Pb species.

^{254}Md may be termed as a landmark in the decay path of SHE primarily on two counts. First, it is the final identity-confirming end product in a sequential correlated α chain of every $(4n+2)$ SHE. Specifically in the present context, ^{258}Lr(α)^{254}Md (EC) characteristics have been explicitly used as identifying indicators for ^{262}Db [10,26,27], ^{266}Bh [28], ^{278}Nh [9], etc. The same role is played by ^{252}Md in the $4n$ series [8]. Second, and more significantly, ^{254}Md serves as a "transition point" in the SHE decay path in the sense that all the $Z \geqslant 101$ members are odd-odd nuclei, whereas all the $Z < 101$ α-decaying members therein through $Z = 92$, and up to $Z = 82$, are even-even nuclei. This feature, evident in our Fig. 1, may partly arise from the fact that e-e nuclei of the SHE region are more liable to undergo fission in competition with other decay modes.

Studies related to SHE have been extensively pursued [11,12,21,22] over the past 2 decades, yielding significant spectroscopic information on several transfermium (and also transactinide) nuclei primarily for even-even and odd-A nuclei so far. In the Introduction, we have explicitly referred to certain recent α-γ and α-CE studies that have yielded specific spectroscopic data on odd-A $N = 153$ isotonic neighbors of ^{254}Md [12], on decays of transfermium ($Z = 101$–108) nuclei [11], and on spectroscopy of K isomers in its isobaric neighbor, namely, ^{254}No [13]. A recent study [10] of $^{262}_{105}$Db(α)$^{258}_{103}$Lr(α)$^{254}_{101}$Md is of particular interest in our present context, because a better resolution investigation of ^{258}Lr α decay can yield definitive information on ^{254}Md level structures suggested herein.

III. MODEL FORMULATION AND CALCULATION

Bandhead energies of 2qp structures in odd-odd deformed nuclei are, in principle, given by the expression [14,15]

$$E(K:\Omega_p,\Omega_n) = E_0 + E_p(\Omega_p) + E_n(\Omega_n) + E_{\text{rot}} + \langle V_{pn}\rangle, \quad (1)$$

TABLE I. Physically admissible 2qp GM doublet bands in $^{254}_{101}$Md$_{153}$ arising from coupling of the 1qp p orbitals (top rows) and the n orbitals (first column); numbers beside p_i/n_j are E_x (keV) and those within parentheses are the summed $[E(p_i)+E(n_j)]$ energies in keV.

p_i → n_j ↓	p_0:0 $7/2^-[514\downarrow]$ K_T K_S	p_1:44 $1/2^-[521\downarrow]$ K_T K_S	p_2:450 $7/2^+[633\uparrow]$ K_T K_S
n_0:0 $1/2^+[620\uparrow]$	3^- 4^- (0)	0^- 1^- (44)	4^+ 3^+ (450)
n_1:124 $3/2^+[622\downarrow]$	5^- 2^- (124)	2^- 1^- (168)	2^+ 5^+ (574)
n_2:140 $7/2^+[613\uparrow]$	0^- 7^- (140)	3^- 4^- (184)	7^+ 0^+ (590)
n_3:350 $11/2^-[725\uparrow]$	2^+ 9^+ (350)	5^+ 6^+ (394)	9^- 2^- (800)

wherein E_p/E_n are the observed [1,29] excitation energies of the respective orbitals in the neighboring odd-mass isotope or isotone, $E_{\rm rot}$ is the correction for the zero-point rotational energy, and $\langle V_{pn}\rangle$ is the contribution from the residual proton-neutron interaction. Because our present interest is only in the low-lying ^{254}Md spectrum, we take into consideration $E_p/E_n \leqslant 500$ keV levels in the spectra of respective odd-A neighbors. These data on $N=153$ orbitals, as identified in ^{253}Fm [29], are listed in the first column of Table I. With respect to the $Z=101$ p orbitals, only $7/2^-[514]$ is observed as the gs in all odd-A Md isotopes. For other p orbitals we look at the spectra of odd-A $(Z\pm 2)$ isotonic neighbors, namely, ^{251}Es and ^{255}Lr. Based on the available data for these nuclei [29], we place the p_1:$1/2^-[521]$ orbital at 44 keV and the p_2:$7/2^+[633]$ orbital at 450 keV, as entered in first row of Table I.

In the rotor-particle model of odd-odd deformed nuclei, each 2qp $(\Omega_p,\ \Omega_n)$ structure couples to give rise to two bands with quantum numbers $K^{\pm}=|\Omega_p\pm\Omega_n|$. The relative energy ordering of these two bands is governed by the Gallagher-Moszkowski (GM) rule [30], which places the spins-parallel triplet $(\Sigma=1)$ K_T band lower in energy than its GM doublet partner spins-antiparallel singlet $(\Sigma=0)$ K_S band. The physically admissible 2qp GM doublets in $^{254}_{101}$Md$_{153}$ for each (p_in_j) coupling are listed in Table I. Entries therein are the band quantum numbers K_T and K_S according to the GM rule; numbers within parentheses are the summed (E_p+E_n) energies in keV, which provide a zeroth-order estimate of $E_x(K_T)$, with $E_x(K_S)$ estimated ~100 keV above it.

Finally the 2qp bandhead energies are evaluated using the following expressions [14,15] in Eq. (1):

$$E_{\rm rot}=\frac{\hbar^2}{2I}[K-(\Omega_p+\Omega_n)]=-\frac{\hbar^2}{2I}(2\Omega_<)\delta_{K,K^-}, \quad (2)$$

$$\langle V_{pn}\rangle=-\left(\frac{1}{2}-\delta_{\Sigma,0}\right)E_{\rm GM}+(-)^I E_N\delta_{K,0}. \quad (3)$$

The term $\hbar^2/2I$ in Eq. (2) is the usual rotational band inertial parameter. The terms $E_{\rm GM}$ and E_N in Eq. (3) denote, respectively, the GM doublet splitting energy and the Newby [31] odd-even shift for only the $K=0$ bands arising from the residual n-p interaction V_{pn} for the specified configuration.

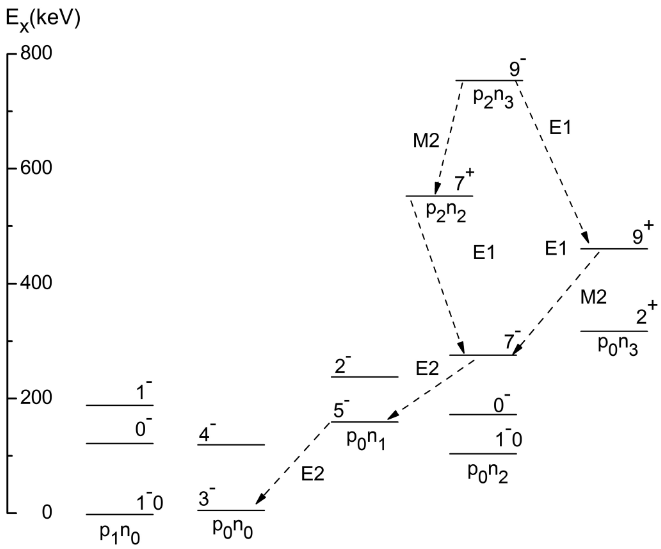

FIG. 2. Partial level scheme of ^{254}Md including all the low-lying (<250 keV) levels and only the high-spin (⩾7) bands for higher energy. The bandheads are labeled by K^π, which equals I^π for all $K^\pi\neq 0$ bands; for the two $K^\pi=0^-$ bands, the lower-lying $J^\pi=1^-$ rotational levels are labeled by $J^\pi K=1^-0$. Arrows therein denote the lowest multipole decay path for each high-spin state.

In principle the model parameters $E_{\rm GM}$ and E_N can be evaluated theoretically, as described in our earlier papers [32–34]. However, more recently we have been using a semiempirical approach [14,15] on the assumption that these parameters are only configuration specific and not nucleus dependent. Thus the experimentally observed $E_{\rm GM}$ and E_N values in any neighboring odd-odd nucleus can be used in Eqs. (1)–(3) to evaluate the bandhead energies. This formulation has been effectively employed to describe, and to predict, the location and character of 2qp bands and to interpret the frequently occurring LLI pairs of several odd-odd actinides ranging from $_{93}$Np through $_{101}$Md [14,17–19,35]. In the present case, many of the 2qp configurations of Table I have been experimentally identified in ^{250}Bk [1] and/or in ^{252}Es [17]. As noted in our analysis of the ^{252}Es spectrum, wherein all three $K=0$ bands in Table I also appear, the corresponding E_N values thereof place the $J=1$ rotational level below the $J=0$ bandhead in each case [33]. As witnessed hereafter, this fact is of vital importance in characterizing the ^{254}Md gs. In the case of the GM pairs of Table I, where $\Delta E_{\rm GM}$ is not experimentally available from the ^{250}Bk and ^{252}Es spectra, we adopt a default value of $\Delta E_{\rm GM}=100$ keV.

Using the specific model parameters mentioned above as input in Eqs. (1)–(3), we have evaluated the bandhead energies of all 2qp states listed in Table I. A plot of the thus-determined ^{254}Md energy levels up to $E_x\sim 800$ keV is shown in Fig. 2. Analysis and discussion of these results is taken up in the following section.

IV. ANALYSIS AND DISCUSSION

Now we proceed to critically examine and analyze the TQRM-evaluated level energies of the preceding section in the context of available experimental data to deduce appropriate $J^\pi K$ and 2qp configurations of the two observed ^{254}Md isomers.

A. Characterization of ^{254}Md LLI pair

An examination of the data in Table I and Fig. 2 reveals that two closely spaced low-spin levels, namely, $J^\pi K = 1^-0$ and 3^-3, are placed around the ^{254}Md gs. Hence the occurrence of two isomers with $\%\varepsilon \leqslant 100$ and comparable $t_{1/2}$ normally would include the low-spin gs as one LLI, and the other higher-lying LLI would have high spin ($J > 7$). Accordingly we plot, in Fig. 2, a partial ^{254}Md level scheme including all the 2qp levels up to $E_x \leqslant 250$ keV and only the high-spin ($J \geqslant 7$) higher-lying bandheads. This plot also includes the lower-lying $J^\pi K = 1^-0$ rotational levels of both the $K^\pi = 0^-$ bands. In this figure, we have also shown the admissible lowest multipole γ decay path for each of the $J \geqslant 5$ levels. It needs to be pointed out that, because $J^\pi = K^\pi$ for all $K \neq 0$ bandheads, $\Delta J = \Delta K$ for all the multipole transitions shown in Fig. 2; all such transitions are subject to the usual spin-parity selection rule, with the K selection rule being not applicable in cases wherein $K^\pi \leqslant J^\pi$. These considerations lead us to the conclusion that each of the high-spin levels in Fig. 2 can decay by an observable $\Delta I \leqslant 2$ γ transition and hence cannot be identified as $\%\varepsilon \leqslant 100$ decaying LLI. Having ruled out a high-spin excited level as a ^{254}Md LLI, we now examine other alternatives.

Next we examine whether the pair of low-lying low-spin with $J^\pi K = 1^-0$ and 3^-3 (Fig. 2) can be designated as the $\%\varepsilon \leqslant 100$ decaying ^{254}Md LLI pair. Prima facie, with $\Delta J = 2$ and no parity change, they admit, in principle, of an $E2$ interconnection with 1 order of K forbiddenness. However, NUBASE2012 [5] suggests their widely overlapping energy placement. Our evaluation places these two levels just a few keV apart around ^{254}Md(gs). This consideration renders the theoretically admissible multipole ($E2$) interconnection experimentally nonobservable. This conclusion is in accord with the fact that the presently listed $t_{1/2}$ value for each of the LLI pair levels is determined solely from the measured activities in ^{254}Md(EC)^{254}Fm decay, with no contribution thereto from any other decay mode (α, SF, γ, etc.) observed to date.

In view of these considerations, we arrive at the following assignments for the ^{254}Md LLI pair:

$$\text{10 min} \quad \text{gs} \qquad 1^-0\{p_1 : 1/2^-[521] \otimes n_0 : 1/2^+[620]\}, \quad (4)$$

$$\text{28 min} \quad 0+x \qquad 3^-3\{p_0 : 7/2^-[514] \otimes n_0 : 1/2^+[620]\}. \quad (5)$$

The above assignments are further supported by the following considerations. First, we take note of the fact that all the rotational levels in a band have the same intrinsic structure and/or 2qp configuration as that of the bandhead. Next, we note that the low-lying intrinsic states in even-mass deformed nuclei are mainly 2qp structures, whereas γ decay involves a change in just one particle orbital with the other constituent particle acting as a spectator involving no change in its orbital configuration. Within this framework, we find that the 1^-0 and the 3^-3 levels of Fig. 2 have the same n_0 constituent, while the proton orbitals, namely, $p_0 : 7/2^-$ and $p_1 : 1/2^-$, differ by $\Delta\Omega = 3$. As seen in Table II, these orbitals are experimentally identified in $_{101}$Md ($A = 247$ and 249) and $_{103}$Lr ($A = 253$) nuclides as close-lying LLI pairs with comparable $t_{1/2}$ and no isomeric transition (IT) in each case. In the case of the odd-odd ^{254}Md LLI pair, the $p_0 : 7/2^- \Leftrightarrow p_1 : 1/2^-$ orbital change, underlying the connecting γ thereof, corresponds to $\Delta\Omega = \Delta K = 3$, even though due to the composite structure of the $J^\pi K = 1^-0$ it shows up as $\Delta I = 2$. The experimentally deduced $\%\varepsilon \leqslant 100$ (no IT) characteristic of each of the ^{254}Md isomers is thus consistent with the observed "no IT" decay of odd-A isotopes as seen in Table II.

TABLE II. Experimental [36] data on LLI pairs with no interconnecting IT (γ) in neighboring odd-A. Odd-Z nuclei are listed in the upper block, while the corresponding data for the odd-odd ^{254}Md, as suggested herein, are in the lower block. Configurations are in the notation of Table I.

Z	X	A	$t_{1/2}$	E_x (keV)	J^π	Decay mode
101	Md	247	1.2 s	0	$p_0(7/2^-)$	α 99.9%
		247m	0.25 s	$0+x$	$p_1(1/2^-)$	α 79%, SF 21%
		249	21.7 s	0	$p_0(7/2^-)$	α 60%, $\varepsilon \leqslant 40\%$
		249m	1.9 s	$0+x$	$p_1(1/2^-)$	α
103	Lr	253	0.57 s	0	$p_0(7/2^-)$	α 98.7%, SF 1.3%
		253m	1.49 s	$0+y$	$p_1(1/2^-)$	α 92%, SF 8%
101	Md	254	10 min	0	$1^-0(p_1 1/2^- \otimes n_0 1/2^+)$	$\varepsilon \leqslant 100\%$
		254m	28 min	$0+x$	$3^-3(p_0 7/2^- \otimes n_0 1/2^+)$	$\varepsilon \leqslant 100\%$

B. EC decays of ^{254}Md isomers

Observation of ^{254}Md as a new $Z = 101$ isotope was concluded as the "parent of ^{254}Fm" [2,3]. However, until now no details whatsoever of EC decay of either of the ^{254}Md LLIs have been reported [1]. Having assigned $J^\pi K$ and 2qp configurations to these $\%\varepsilon \leqslant 100$ decaying isomers, we now proceed to identify their EC decay branches to ^{254}Fm levels. In EC decays, the n orbital in the parent remains a spectator, while the p orbital transforms to an n orbital constrained by the $\Delta J \leqslant 1$ and $\Delta K \leqslant 1$ selection rule for substantially populated ^{254}Fm levels.

With the $J^\pi K = 1^-0\{p_1 : 1/2^-[521] \otimes n_0 : 1/2^+)[620]\}$ 2qp assignment to the 10-min ^{254}Md parent, its EC decay under the abovementioned constraints populates only the 0^+ and 2^+ levels of the ^{254}Fm $K^\pi = 0^+_{\rm gs}$ band through the transformation

$$p : 1/2^-[521] \quad -(\text{EC}) \rightarrow \quad n : 1/2^+[620]$$

as shown in our Fig. 3. An additional feature of the 10-min isomer decay is that, even though the parity-changing β transition is first forbidden (1f), its log ft value is very similar to the value for an allowed transition. This feature for β transitions of the actinide region was firmly established in a detailed study by Sood *et al.* [37]. More specifically,

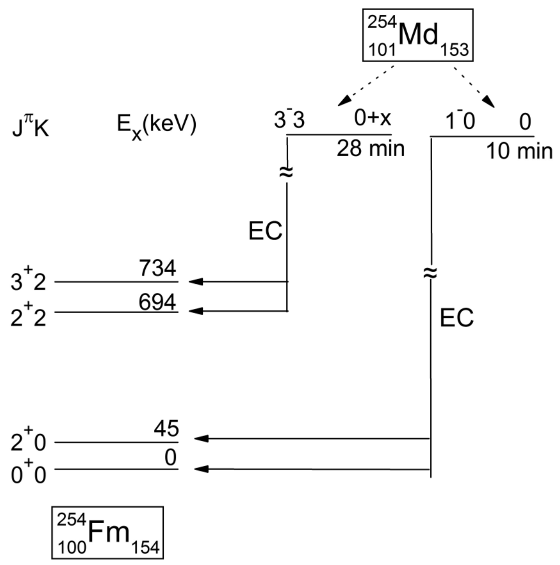

FIG. 3. EC decay scheme of the ^{254}Md LLI pair deduced from the present investigations of the ^{254}Fm levels.

the corresponding data for ^{255}Md(EC)^{255}Fm transitions are as given below [29]:

$$7/2^-[514] - (\mathrm{EC}) \rightarrow \text{gs band } 7/2^+[613], \quad \log ft = 5.47,$$
$$- (\mathrm{EC}) \rightarrow 231 \text{ keV } 9/2^+[624], \quad \log ft = 5.56.$$

In view of these facts, we expect $\log ft = 6.0(5)$ for the 10-min ^{254}Md(EC)^{254}Fm gs band levels.

With the $J^\pi K = 3^-3\{p_0 : 7/2^-[514] \otimes n_0 : 1/2^+[620]\}$ assignment to the 28-min ^{254}Md parent, its EC decay populates the known 2^+ and 3^+ levels of the ^{254}Fm $K^\pi = 2^+_\gamma$ band [2] through the transformation

$$p : 7/2^-[514] \quad - (\mathrm{EC}) \rightarrow \quad n : 3/2^+[622].$$

This EC branch populates the ^{254}Fm $K^\pi = 2^+_\gamma$ band levels through their $2^+\{n : 3/2^+[622] \otimes n : 1/2^+[620]\}$ component [38].

It is of interest to note that the ^{256}Md(EC)^{256}Fm transition had been earlier investigated in detail by Ahmad *et al.* [39]. Their decay scheme is remarkably similar to the 10-min ^{254}Md EC decay shown in Fig. 3. In particular they had observed maximum intensity to the ^{256}Fm $K^\pi = 0^+$ gs band with $\log ft = 6.6$ and "no detectable EC intensity to the 652 keV $K^\pi = 2^+$ band."

V. SUMMARY AND CONCLUSIONS

Upward extension of the $(4n + 2)$ naturally occurring radioactive series was traced from $^{238}_{92}$U all the way up to the heaviest CF-synthesized SHE, namely, $^{278}_{113}$Nh, which has been identified through its time-correlated 6α decay to ^{254}Md. This exercise highlights the role of ^{254}Md as the final identity-confirming end product in sequential α decays of SHE and also its landmark position as a transition point with only odd-odd nuclei appearing in the $Z \geqslant 101$ segment and only even-even nuclei in the $Z < 101$ domain. Our investigations, primarily aimed at characterizing the 10-min and the 28-min ^{254}Md isomer pair, involved evaluation of low-lying bandhead energies of all the physically admissible 2qp configurations within a specified energy range using the well-tested TQRM formalism. A critical examination of these data concluded that all the high-spin $(J \geqslant 5)$ levels in the ^{254}Md spectrum admit of observable $\Delta J \leqslant 2$ γ decay, thus ruling out identification of any of them as a long-lived isomer. Detailed analysis of the results leads us to assign the 10-min isomer as ^{254}Md gs with the $J^\pi K$ and 2qp configuration as $1^-0\{p_1 : 1/2^-[521] \otimes n_0 : 1/2^+[620]\}$ and to assign $J^\pi K = 3^-3\{p_0 : 7/2^-[514] \otimes n_0 : 1/2^+[620]\}$ to the close-lying 28-min isomer. It is noted therein that the theoretically admissible $E2$ transition interconnecting these two isomers, with energy separated by just a few keV, remains nonobservable—a fact inherent in the experimental data that their listed $t_{1/2}$ values are solely determined from observed activities in ^{254}Md(EC)^{254}Fm decay, with no contribution admitted from any other (including IT) decay channel. These assignments further led us to work out ^{254}Md (EC) decay branches from the 10-min isomer to the ^{254}Fm gs band levels, and from the 28-min isomer to the ^{254}Fm 2^+_γ band levels. With the recent advances enabling α-γ- and α-β-decay studies in the heavy actinides and the lighter SHE nuclei, experimental verification of the suggested ^{254}Md level scheme and EC decays of its long-lived isomer pair may be expected in the next few years.

ACKNOWLEDGMENTS

The authors' association with K. Vijay Sai in the early stages of these investigations is gratefully acknowledged.

[1] *Evaluated Nuclear Structure Data File (ENSDF) and XUNDL* (September 2016 Version) continuously updated data files (NNDC, Brookhaven NY).
[2] A. Bhagwat, N. J. Thompson, and J. K. Tuli, Nucl. Data Sheets **105**, 959 (2005).
[3] P. R. Fields, I. Ahmad, R. F. Barnes, R. K. Sjoblom, and E. P. Horwitz, Nucl. Phys. **A154**, 407 (1970).
[4] M. Thoennessen, At. Data Nucl. Data Tables **99**, 312 (2013).
[5] G. Audi, F. G. Kondev, M. Wang, B. Pfeiffer, X. Sun, J. Blachot, and M. MacCormick, Chin. Phys. C **36**, 1157 (2012).
[6] K. Eskola, P. Eskola, M. Nurmia, and A. Ghiorso, Phys. Rev. C **4**, 632 (1971).
[7] R. Gowrishankar, K. Vijay Sai, K. Venkataramaniah, and P. C. Sood, Proceedings of the DAE (India) Symposium on Nuclear Physics **53**, 321 (2008).
[8] K. Vijay Sai, B. Shankaranand, R. Gowrishankar, and P. C. Sood, Proceedings of the DAE (India) Symposium on Nuclear Physics **56**, 186 (2011).
[9] K. Morita *et al.*, J. Phys. Soc. Jpn. **81**, 103201 (2012).
[10] H. Haba *et al.*, Phys. Rev. C **89**, 024618 (2014).

[11] F. P. Hessberger, S. Hofmann, B. Streicher, B. Sulignano, S. Antalic, D. Ackermann, S. Heinz, B. Kindler, I. Kojouharov, P. Kuusiniemi, M. Leino, B. Lommel, R. Mann, A. G. Popeko, S. Saro, J. Uusitalo, and A. V. Yeremin, Eur. Phys. J. A **41**, 145 (2009).

[12] B. Streicher, F. P. Hessberger, S. Antalic, S. Hofmann, D. Ackermann, S. Heinz, B. Kindler, J. Khuyagbaatar, I. Kojouharov, P. Kuusiniemi, M. Leino, B. Lommel, R. Mann, S. Saro, B. Sulignano, J. Uusitalo, and M. Venhart, Eur. Phys. J **A45**, 275 (2010).

[13] F. P. Hessberger, S. Antalic, B. Sulignano, D. Ackermann, S. Heinz, S. Hofmann, B. Kindler, J. Khuyagbaatar, I. Kojouharov, P. Kuusiniemi, M. Leino, B. Lommel, R. Mann, K. Nishio, A. G. Popeko, S. Saro, B. Streicher, J. Uusitalo, M. Venhart, and A. V. Yeremin, Eur. Phys. J. A **43**, 55 (2010).

[14] P. C. Sood, D. M. Headly, R. K. Sheline, and R. W. Hoff, At. Data Nucl. Data Tables **58**, 167 (1994).

[15] A. K. Jain, R. K. Sheline, D. M. Headly, P. C. Sood, D. G. Burke, I. Hrivnacova, J. Kvasil, D. Nosek, and R. W. Hoff, Rev. Mod. Phys. **70**, 843 (1998).

[16] P. C. Sood and R. N. Singh, Nucl. Phys. A **419**, 547 (1984).

[17] M. Sainath, K. Venkataramaniah, and P. C. Sood, J. Phys. G: Nucl. Part. Phys. **35**, 095105 (2008).

[18] P. C. Sood, M. Sainath, and K. Venkataramaniah, Int. J. Mod. Phys. E **09**, 309 (2000).

[19] M. Sainath, K. Venkataramaniah, and P. C. Sood, Eur. Phys. J. A **31**, 135 (2007).

[20] P. C. Sood, R. Gowrishankar, and K. Vijay Sai, Proceedings of the DAE (India) Symposium on Nuclear Physics **61**, 274 (2016).

[21] R. D. Herzberg and D. M. Cox, Radiochimica Acta **99**, 441 (2011).

[22] S. Hofmann, Radiochim. Acta **99**, 405 (2011).

[23] L. Ohrstrom and J. Reedijk, Pure Appl. Chem. **88**, 1225 (2016).

[24] K. Morita, K. Morimoto, D. Kaji, T. Akiyama, S. Goto, H. Haba, E. Ideguchi, R. Kanungo, K. Katori, H. Koura, H. Kudo, T. Ohnishi, A. Ozawa, T. Suda, K. Sueki, H. Xu, T. Yamaguchi, A. Yoneda, A. Yoshida, and Y. Zhao, J. Phys. Soc. Jpn. **73**, 2593 (2004).

[25] K. Morita, K. Morimoto, D. Kaji, T. Akiyama, S. i. Goto, H. Haba, E. Ideguchi, K. Katori, H. Koura, H. Kikunaga, H. Kudo, T. Ohnishi, A. Ozawa, N. Sato, T. Suda, K. Sueki, F. Tokanai, T. Yamaguchi, A. Yoneda, and A. Yoshida, J. Phys. Soc. Jpn. **76**, 045001 (2007).

[26] R. Dressler, B. Eichler, D. T. Jost, D. Piguet, A. Turler, C. Dullmann, R. Eichler, H. W. Gaggeler, M. Gartner, M. Schadel, S. Taut, and A. B. Yakushev, Phys. Rev. C **59**, 3433 (1999).

[27] D. Trubert, C. Le Naour, F. M. Guzman, M. Hussonnois, L. Brillard, J. F. Le Du, O. Constantinescu, J. Gasparro, V. Barci, B. Weiss, and G. Ardisson, Radiochim. Acta **90**, 127 (2002).

[28] K. Morita *et al.*, J. Phys. Soc. Jpn. **78**, 064201 (2009).

[29] E. Browne and J. K. Tuli, Nucl. Data Sheets **114**, 1041 (2013).

[30] C. J. Gallagher and S. A. Moszkowski, Phys. Rev. **111**, 1282 (1958).

[31] N. D. Newby, Phys. Rev. **125**, 2063 (1962).

[32] P. C. Sood and R. N. Singh, Nucl. Phys. A **373**, 519 (1982).

[33] P. C. Sood and R. S. Ray, Pramana **27**, 537 (1986).

[34] D. Nosek, J. Kvasil, R. K. Sheline, P. C. Sood, and J. Noskova, Int. J. Mod. Phys. E **3**, 967 (1994).

[35] P. C. Sood, R. Gowrishankar, and A. K. Dora, Phys. Rev. C **89**, 034308 (2014).

[36] P. C. Sood and R. K. Sheline, Phys. Scr. **42**, 25 (1990).

[37] P. C. Sood, R. K. Jain, and O. S. K. S. Sastri, Phys. Rev. C **69**, 057303 (2004).

[38] P. C. Sood, D. M. Headly, and R. K. Sheline, At. Data Nucl. Data Tables **51**, 273 (1992).

[39] I. Ahmad, R. R. Chasman, and P. R. Fields, Phys. Rev. C **61**, 044301 (2000).