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$K^\pi = 0^+$ 2.29 s isomer in neutron-rich ^{174}Tm

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Gamma-ray and conversion-electron spectroscopy have established the existence of a 2.29(1) s, $K^\pi = 0^+$, isomeric state in neutron-rich ^{174}Tm. The isomer deexcites via 100- and 152-keV electromagnetic transitions. First results from a newly commissioned Si(Li) detector array have established their $M1$ and $E3$ multipolarities, respectively. The single-particle configurations of the excited states suggest that the $E3$ transition originates from a $\pi h_{11/2}^{-1} \rightarrow \pi d_{3/2}$ configuration change, whereas the $M1$ transition occurs between members of a Gallaghar-Moszkowski doublet. From the measured half-life, the deduced $B(E3)$ value of 0.024(2) W.u. is highly hindered. The reported measurements resolve ambiguities in the previously proposed β decay scheme of ^{174}Er to ^{174}Tm.

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I. INTRODUCTION

Models of exotic neutron-rich nuclei predict interesting, as yet unexplored, new physics [1]. However, these nuclei are largely difficult to access in experiments. Isomeric states are proving to be a convenient tool to access and explore excited states in neutron-rich nuclei [2]. In well-deformed nuclei, isomerism can usually be ascribed to K-forbidden and/or high-multipolarity transitions [3]. After accounting for these aspects, the reduced hindrance then depends primarily on "local" nuclear-structure K-mixing effects, such as density of states, deviations from axial symmetry, and Coriolis mixing [3]. Taken together, these many influences severely complicate the prediction of isomer decay rates. Nevertheless, the experimental identification of isomeric states has a pivotal role in studies of nuclei approaching the drip-lines [2,4] and even of some of the heaviest nuclei synthesized to date [5]. Although there is evidence for exotic proton and two-proton decay modes of isomers near the proton drip-line [6], analogous questions regarding the neutron decay mode of isomers in the neutron-rich region are still open [7]. Additionally, one of the goals of a future study of neutron-rich nuclei in the Dy-Hf region is to search for the possible existence of an "island" of β-decaying high-K isomers [3,8]. Furthermore, isomer production, especially with high-energy proton-induced reactions, is still poorly understood, and will be important for future radioactive-beam projects. There are open questions on the reaction mechanism and production cross sections of isomers in even-even, odd-even, and odd-odd nuclei [9]. Additional complications arise because of the unknown release times of isomers and exotic nuclei from, for example, surface-ionization ion sources. Thus, experiments form a crucial component to address these issues.

A new program of research in the deformed, isomer-rich, 170–190 mass region [3,8,10] has been launched at the Isotope Separator and Accelerator (ISAC) facility sited at TRIUMF, Vancouver, Canada. In the present work we report on the characterization of a new 2.29 s isomer in neutron-rich ^{174}Tm ($Z = 69$). The motivation to study such deformed odd-odd nuclei is based on their level structures, whose excitation spectra are among the most intricate and poorly characterized in nuclear structure physics [11]. This is associated with partially blocked pairing, high level density (resulting in a multitude of low-lying configurations), and complex decay patterns. The high probability of isomeric states is a key feature in the spectra of these nuclei, and their identification can lead to unambiguous temporal ordering of excited states. Such is the case with ^{174}Tm, as presented here.

II. EXPERIMENTAL PROCEDURE AND RESULTS

In the present series of experiments, nuclei far from the line of β stability are produced at the ISAC facility using 30-μA 500-MeV proton-induced reactions on a Ta target. The reaction products deexcite during transit, whereas long-lived

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isomers ($T_{1/2} \geqslant$ a few milliseconds) allow a fraction of the isotopes to be delivered in an excited state. The reaction products are extracted using a surface ionization source and accelerated to an energy of 30 keV. A high-resolution mass analyzer separates species with different mass number, which are then transported to experimental stations such as the 8π spectrometer. This spectrometer has been reconfigured in a close-packed configuration [12] and is comprised of 20 Compton-suppressed high-purity germanium detectors. The low-energy beams from ISAC are focused at the center of the 8π array and stopped in a 12.7-mm-wide continuous-loop collector tape that is fed from a large aluminum storage chamber. The movable tape transport facility removes long-lived activity from the focus of the 8π array and minimizes the contaminating activity present in an isobaric beam. Within the 8π array, an aluminum hemispherical mounting houses five Si(Li) detectors in a pentagonal geometry, cooled to liquid-nitrogen temperatures. Typically, the off-line intrinsic resolution of the (cooled) Si(Li) detectors is 2.9-keV at 975-keV (*K*-shell converted electron of the 1063-keV transition in ^{207}Bi); whereas the in-beam resolution is 1.85-keV at 302-keV (*K*-shell converted electron of the 364-keV transition in ^{174}Tm β decay). Each of the five Si(Li) detectors, 5 mm thick, circular in shape, and with an area of 200 mm^2, was mounted at a distance of 2.2 cm from the beam focus. The Pentagonal Array for Conversion Electron Spectroscopy (PACES) covers 8% of the solid angle [13].

In two sets of experiments several of the known high-*K* isomers in the Dy-Hf region, with half-lives ranging from a few milliseconds to several minutes, have been accessed [14]. We report here the spectroscopy of a new 2.29(1) s isomer in the neutron-rich nucleus ^{174}Tm. An initial study measuring only the γ transitions was presented at ENAM04 [15]. The $A = 174$ isobaric beam was implanted into the movable tape transport facility, with beam-off/beam-on/beam-off cycling times of 2s/2s/2s, 2s/3s/3s, 5s/10s/10s, and 10s/100s/50s. Any remnant radioactive decay from the beam particles missing the tape were monitored in the initial beam-off period after moving the tape.

Singles and coincidence γ-γ, γ-electron, and electron-electron data were acquired and sorted off-line into several matrices; these include γ-time, electron-time, γ-γ, γ-electron, and electron-electron coincidence matrices. Standard radioactive sources of ^{152}Eu, ^{133}Ba, ^{207}Bi, as well as the known γ-ray and electron peaks from ^{174}Tm ground-state β decay, were utilized to calibrate the spectra. The accumulated γ-ray data were dominated by the ground-state β decay of ^{174}Tm ($T_{1/2} = 5.4$ min). The detection of new isomers is compounded by the presence of multiple decay sources of varying intensities in the form of (here, $A = 174$) isobaric contaminants as well as ionized fluoride/oxide molecular beams (leading to decays from the $A = 158$ and $A = 155$ mass chains). Despite contamination, a judicious choice of cycling times enabled rather clean separation of, especially, short-lived isomers. The yields of the $A = 174$ oxide beam, mainly emanating from the decay of ^{158}Er and ^{158}Tm, were measured to be 13 and 1% of the ^{174}Tm$_{\text{g.s.}}$ yield, respectively; whereas the decays from the $A = 174$ fluoride beam, primarily from ^{155}Tm, was measured to be at a 0.03% level. Figure 1 shows the singles γ-ray spectrum, after subtracting the dominant ^{174}Tm$_{\text{g.s.}}$ activity. The inset shows the growth and decay curve of the 2.29(1) s isomer in the 2s/3s/3s tape cycle [15]; the prominent peaks are the 100.3- and 152.1-keV γ-ray transitions and the Tm *K* x rays. The ground-state-to-isomer ratio (later corrected for electron conversion) is 200:1 and demonstrates the device sensitivity. The two coincident γ-ray transitions were, in addition, also known to be present in the ground-state β decay of ^{174}Er, which has a half-life of 3.3 min [16,17]. From the γ-γ coincidence data, *K*-conversion coefficients of 3.1(1) and 1.13(6) were extracted, respectively, for these two transitions and were the basis for *M*1 assignments in the previous works [15,17].

The ground-state spin and parity of ^{174}Tm are known to be $I^\pi = 4^-$, as deduced from the ground-state systematics of the odd-proton Tm isotopes and the $N = 105$ isotones, and the allowed-unhindered β decay proceeding to the lowest two excited 5^- states in ^{174}Yb [18]. However, the excited states in ^{174}Tm populated in the $I^\pi = 0^+$ ground-state β decay of ^{174}Er

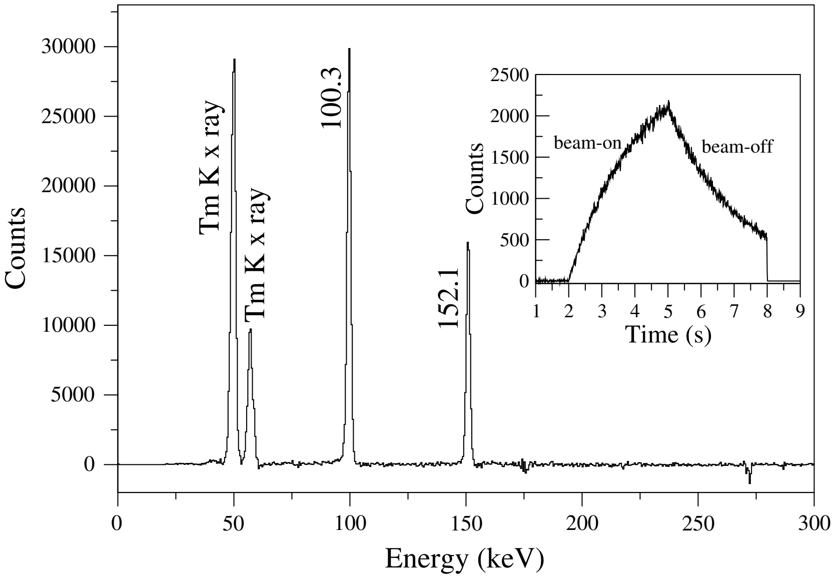

FIG. 1. The short-lived singles γ-ray spectrum showing prominently the Tm *K* x rays and the 100- and 152-keV γ-ray transitions. The 5.4-m ^{174}Tm ground-state β-decay component has been subtracted. The inset shows the growth and decay of the isomer gated by the 100-keV γ-ray transition.

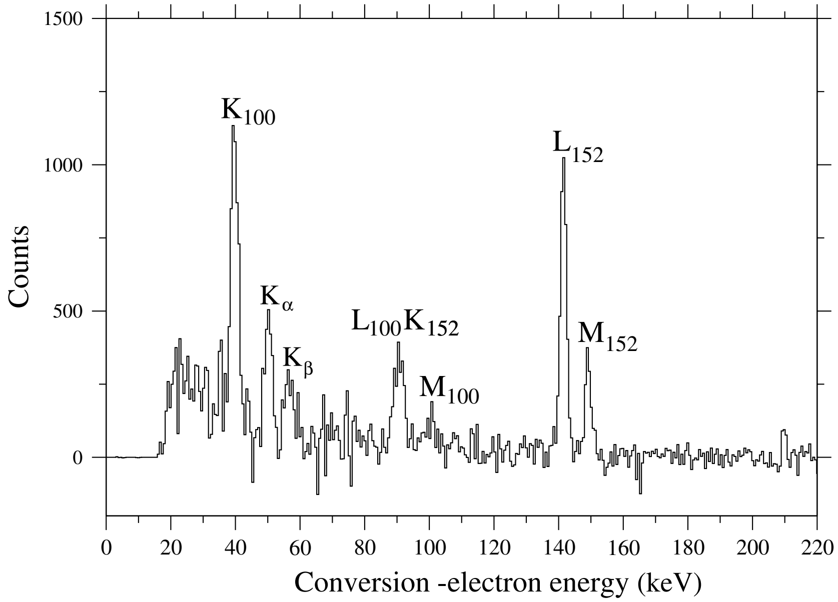

FIG. 2. The singles conversion-electron spectrum obtained by subtracting the 5.4-m ^{174}Tm ground-state β-decay component. K_γ denotes the conversion-electron corresponding to the γ-ray transition, whereas the Tm x rays are labeled K_α/K_β.

must be of low spin. Hence an unobserved low-energy, high-multipolarity transition was postulated between the low-spin states observed following β decay and the high-spin ground state [17]. However, several issues could not be resolved from γ-ray spectroscopy alone. These relate to the large intensity difference between the two, seemingly $M1$, γ-ray transitions at 100 and 152 keV; the absence of a 252-keV crossover $E2$ transition; and speculation that the isomeric state could be a new excited state, the decay of which could not itself be established, requiring population from a hypothesised high-K β-decaying isomer in ^{174}Er [15].

A closer examination of the K-electron conversion coefficient for the 152-keV transition, extracted from x-ray and γ-ray intensities [15,17], reveals that it agrees, within error, with the values expected [19] for a $M1$ multipolarity ($\alpha_K = 0.81$) and an $E3$ multipolarity ($\alpha_K = 1.18$). Furthermore, a $E3$ multipolarity for the 152-keV transition would explain the large intensity imbalance with the 100-keV transition that arises from the earlier deduction of $M1$ multipolarity for both transitions. However, the L-conversion coefficients would differ greatly ($\alpha_L = 0.12$ and 4.1 for $M1$ and $E3$ multipolarity, respectively), motivating a measurement involving a conversion-electron spectrometer. Therefore, in a follow-up experiment, a new conversion-electron spectrometer, PACES, was brought on-line at the 8π-spectrometer station. The singles conversion-electron spectrum obtained by subtracting (with appropriate time restrictions) the transitions from the 5.4 m ^{174}Tm ground-state β decay is depicted in Fig. 2. This clearly illustrates electrons from K-, L-, and M-converted transitions that are involved in the isomer decay, in addition to the Tm K_α and K_β x rays. The conversion-electron spectrum, gated by the 100-keV γ-ray transition, is shown in Fig. 3. The key feature is

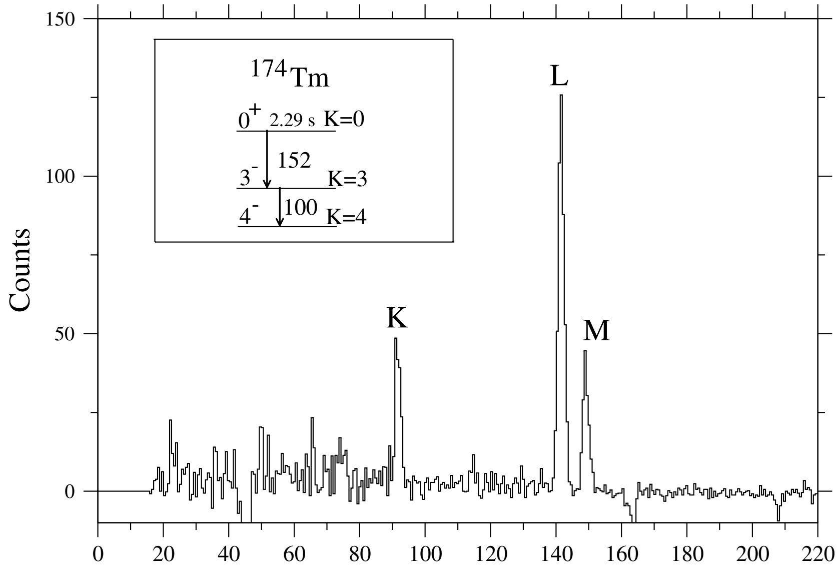

FIG. 3. The conversion-electron spectrum gated by the 100-keV γ-ray transition. The earlier [15,17], incorrect, $M1$-multipole assignment for the 152-keV transition would have given rise to strong K conversion and very little L and M conversion. The inset depicts the isomer decay scheme as a result of the present work.

TABLE I. Relative γ-ray intensities, experimental and theoretical internal conversion coefficients (ICC).

E_γ keV	I_γ	ICC (present expt.)	ICC (Ref. [17])	ICC(theo., Ref. [19])	Multipolarity
152.1	66.5(6)	α_K 1.13 ± 0.06	α_K 0.54 ± 0.06	$\alpha_K(E3)$ 1.18	$E3$
		α_L 3.31 ± 0.48	—	$\alpha_L(E3)$ 4.10	
		α_M 1.10 ± 0.12	—	$\alpha_M(E3)$ 0.99	
100.3	100.0(6)	α_K 3.1 ± 0.01	α_K 1.7 ± 0.3	$\alpha_K(M1)$ 2.66	$M1$
		α_L 0.45 ± 0.10	—	$\alpha_L(M1)$ 0.40	
		α_M 0.14 ± 0.03	—	$\alpha_M(M1)$ 0.09	

the prominent peak at 142-keV because of L conversion, with the K- and M-conversion peaks being of relatively low intensity in this spectrum. The deduced conversion coefficients, as well as the K/L- and L/M intensity ratios, compare very well with an $E3$ multipolarity assignment for the 152-keV transition and rule out the $M1$ alternative. Similarly, the conversion electron data unambiguously assign $M1$ multipolarity to the 100-keV transition. The K-, L-, and M-conversion coefficients from the present and the previous data are shown in Table I. The deduced isomer decay scheme is depicted in the inset of Fig. 3. Analysis of the electron-electron coincidence matrix shows the expected coincidence relationships between the K and L conversions emanating from the two coincident transitions.

III. DISCUSSION

As discussed, the ground-state spin-parity of ^{174}Tm was deduced to be 4^-. In view of the lack of a crossover γ-ray transition (I_γ 252-keV $\leqslant$ 0.34% I_γ 100-keV) or a highly converted $M4$ transition, in the "singles" conversion-electron spectrum (Fig. 1), it is reasonable to infer that the 100- and 152-keV transitions are of stretched $M1$ and $E3$ character, respectively. A 100-keV $M1$ transition would not give rise to such a long half-life, so the 152–100 keV transition ordering is well defined. Accordingly, the spin-parity sequence is (in increasing energy order) either $4^- - 5^- - 8^+$ or $4^- - 3^- - 0^+$. Only the 0^+ assignment for the 252-keV isomer is consistent with the known indirect feeding from the β decay of ^{174}Er [16,17].

Because this is one of the most deformed regions of the nuclear chart, the levels can be classified by the K quantum number, equal to the value of the spin of each intrinsic state. Thus, the isomer acquires a $K^\pi = 0^+$ assignment. The identification of the isomer contradicts the previous claim of observing the 100- and 152-keV γ-ray transitions in coincidence with β particles from the ^{174}Er ground-state decay [16,17]. Transitions with energies of 637, 643, 708, 714, 766, and 773 keV were observed in both the LBNL and GSI ^{174}Er β decay data [16,17], though not in the present work, as an erbium beam is not produced efficiently by the ion source. These γ-ray transitions likely feed the $K^\pi = 0^+$ isomer and originate from low-spin levels, consistent with a scenario of allowed Gamow-Teller β decay. Indeed, the summed singles intensities of all these transitions [17] is 94(4)% of the total $(\gamma + e^-)$ intensity of each of the 100- and 152-keV transitions (from the deduced $M1$ and $E3$ assignments, respectively). Furthermore, a direct $^{174}\mathrm{Er}\,(I^\pi = 0^+_{\mathrm{g.s}}) \rightarrow {}^{174}\mathrm{Tm}(I^\pi = 0^+_{\mathrm{isomer}})$ Fermi transition will be strongly suppressed because of the nonanalog nature of the orbitals involved, consistent with the observed intensity flow.

The same selection rule also forbids β decay of the ^{174}Tm isomer to ^{174}Yb $K^\pi = 0^+$ levels. An upper limit of 1.0(5)% β-decay branch could be deduced for such a forbidden decay. This limit was determined from the peak-free region of the electron spectrum from the 2s/3s/3s tape cycle after background subtraction from the e^- time data. (A significant branch would indicate the importance of the so-called correction terms [20].)

A simple structural description of the observed states can be obtained purely by considering the available single-particle orbitals near the Fermi surface. For ^{174}Tm, the relevant proton single-particle Nilsson orbitals have quantum numbers $1/2^+[411]$ and $7/2^-[523]$, at a calculated quadrupole deformation of $\beta_2 \sim 0.28$ [21]. These orbitals couple with the neutron Nilsson orbitals, namely $7/2^-[514]$, $5/2^-[512]$, and $1/2^-[521]$, to produce a set of low-lying intrinsic states in ^{174}Tm. By comparison to the odd-A neighbors, the odd proton of ^{174}Tm is likely to be in the $1/2^+[411]$ Nilsson orbital (^{173,175}Tm $I^\pi_{\mathrm{g.s.}} = 1/2^+$), and the odd neutron in the $7/2^-[514]$ Nilsson orbital (^{173}Er,^{175}Yb $I^\pi_{\mathrm{g.s.}} = 7/2^-$). Following the empirical Gallagher-Moszkowski (GM) rules [22], a coupling of the orbitals $\pi 1/2^+[411] \otimes \nu 7/2^-[514]$, a spin-parallel triplet state, is especially energetically favored and gives rise to the ground-state spin-parity of $K^\pi = 4^-$. The observation of allowed-unhindered β decay to the $K^\pi = 5^-$ states in ^{174}Yb lends further support to this assignment [18].

The $K^\pi = 3^-$ state at 100-keV is suggested to be the singlet coupling of the GM-doublet arising out of the same orbitals, $\pi 1/2^+[411] \otimes \nu 7/2^-[514]$. The 100-keV $M1$ transition is then a K-allowed transition between the GM-doublet members. Indeed, calculations based on the quasiparticle phonon model (QPM) predict the two lowest lying intrinsic states in ^{174}Tm as a result of such a coupling, and the calculated splitting of 94-keV is very close to the observed splitting of 100-keV (neglecting zero-point rotational motion) [11]. The contribution of this quasiparticle configuration is about 66 and 63% in the triplet and singlet states, respectively; a small contribution of 12% is calculated to arise from a Q_{22} collective vibration.

The $K^\pi = 0^+$ state at 252 keV is seen to result from a favored coupling of the $\pi 7/2^-[523] \otimes \nu 7/2^-[514]$ Nilsson orbitals. The 152-keV $E3$ transition is then a K-allowed proton-hole transition from the intruder $h_{11/2}(\otimes h_{9/2})$ orbital to the normal-parity $d_{3/2}$ orbital. Incidentally, for this configuration the protons and neutrons occupy the spin-orbit partners of the $1h$ orbital; such states are, supposedly, highly favored because of an attractive proton-neutron interaction. The 152-keV transition occurs between two intrinsic states differing only in the proton orbital, whereas the neutron orbital is a spectator. Likewise, the 100-keV transition involves a proton spin-flip. Thus, the two observed transitions in the decay scheme of the 2.29 s isomer can be explained as being K-allowed transitions that occur between three deformed intrinsic states involving only proton excitations. In well-deformed odd-odd nuclei, in addition to the usual K-selection rule, there is a two-particle transition selection rule involving the so-called nonoverlap forbidenness such that a simultaneous change of proton and neutron intrinsic configurations is severely hindered [23]. The proposed excitation scheme is consistent with the requirements of these two selection rules. From the measured half-life of 2.29 s, a $B(E3)$ value of 0.021(1) W.u. [using theoretical value of $\alpha(\text{theo})_{(\text{total})} = 6.61$] or, using the measured conversion electron coefficient $\alpha(\text{expt.})_{(K+L+M)} = 5.5(5)$, a $B(E3)$ value of 0.024(2) W.u. could be deduced for the 152 keV, $K^{\pi} = 0^{+} \rightarrow K^{\pi} = 3^{-}$, transition. In terms of the hindrance factor, defined as [24]

$$F_W = \frac{T_{1/2\gamma}\,(\text{experiment})}{T_{1/2\gamma}\,(\text{Weisskopf})}, \qquad (1)$$

the $E3$ transition is calculated to have $F_W = 42(4)$ [$\alpha(\text{expt.})_{(K+L+M)} = 5.5(4)$] or 48.7(2) [$\alpha(\text{theo})_{(\text{total})} = 6.61$], which is well within the prescribed range for a K-allowed $\Delta K = 3$, $E3$ decay [24].

IV. CONCLUSION

In summary, through γ-ray and conversion electron spectroscopy the excitation energy and decay properties of the 2.29 s isomeric level in ^{174}Tm have been firmly established. The results of three different experiments [15–17] can be combined to explain all the data consistently with a minimum number of states. The isomeric level is characterized by a $K^{\pi} = 0^{+}$ assignment and the two coincident γ-ray transitions involve mainly proton excitations. The deduced transition rate is hindered but well within the prescribed limits of K-allowed $E3$ decays. It is important for future experiments on heavy neutron-rich nuclei that there should be simultaneous measurements of both γ rays and conversion electrons, to derive unambiguous level schemes.

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