20 μs isomeric state in doubly odd $^{134}_{61}$Pm

D. M. Cullen,[1,*] P. J. R Mason,[1] S. V. Rigby,[1,†] C. Scholey,[2] S. Eeckhaudt,[2] T. Grahn,[2,†] P. T. Greenlees,[2] U. Jakobsson,[2] P. M. Jones,[2] R. Julin,[2] S. Juutinen,[2] S. Ketelhut,[2] A. M. Kishada,[1] M. Leino,[2] A.-P. Leppänen,[2] K. Mäntyniemi,[2] P. Nieminen,[2] M. Nyman,[2] J. Pakarinen,[2,†] P. Peura,[2] P. Rahkila,[2] J. Sarén,[2] J. Sorri,[2] J. Uusitalo,[2] B. J. Varley,[1] and M. Venhart[2]

[1]*Schuster Laboratory, University of Manchester, Manchester M13 9PL, United Kingdom*

[2]*Department of Physics, University of Jyväskylä, Jyväskylä FIN-40014, Finland*

(Received 18 May 2009; published 7 August 2009)

Recoil-isomer tagging at the Accelerator Laboratory of the University of Jyväskylä has been used to establish the isomeric nature of a known (7^-) excited state in the doubly odd nucleus ^{134}Pm. The isomeric state was determined to have a half-life of 20(1) μs and was populated from the decay of a $\pi h_{11/2} \otimes \nu h_{11/2}$ band using the ^{92}Mo(^{54}Fe,2α3pn) reaction at 305 and 315 MeV. The isomer decays by a 71-keV transition that provides an intermediate step in linking the established ^{134}Pm high-spin level scheme to the lower-spin states observed from the β decay of ^{134}Sm. Electron-conversion analysis for the 71-keV γ-ray transition reveals that it is of $E1$ character and its small reduced-transition probability suggests that ^{134}Pm may have a nuclear shape more rigid than that of the neighboring nuclei.

DOI: 10.1103/PhysRevC.80.024303 PACS number(s): 23.35.+g, 21.10.Re, 23.20.Lv, 27.60.+j

I. INTRODUCTION

Isomeric nuclear states, with half-lives longer than one nanosecond, are known to exist throughout the nuclear chart [1]. To date, the long-lived nature of all of these states has been explained using three differing approaches: shape isomerism, spin traps, and K isomers [1]. In general, nuclear isomerism results from a difference between the properties (spin, shape, or K-quantum number) of the isomeric state and the state to which it decays. The mass 120–140 region of the nuclear chart provides a unique testing ground in that all three types of isomers have been identified in these nuclei. Spin-trap isomers tend to occur in the reduced-valence space normally found near closed shells, e.g., in the $^{124-130}$Sn nuclei around $Z = 50$ [2]. K isomers require an axially deformed nuclear shape and tend to occur when high-Ω orbits are being filled in the upper part of the shell, e.g., in the even-even $N = 74$ isotones a series of K isomers are known to exist in the deformed nuclei up to the proton drip line [3–6]. These isomers are built upon $K^\pi = 8^-$ two-quasineutron ([404]7/2 $\otimes$ [514]9/2) configurations and are directly analogous to the two-quasiproton $K^\pi = 8^-$ states established in the mass 170–180 region, with the two $N = 74$ neutrons exchanged for $Z = 74$ protons [1]. Nuclear shape isomers were first observed in the heavy-mass $\sim$250 region of the nuclear chart [7]. These so-called "fission isomers" were built upon highly deformed axially symmetric nuclear shapes. The long half-life of the highly deformed state was understood to be due to the large change in nuclear shape required for γ-ray decay back to the less deformed nuclear ground state.

The observation of an isomeric state in the doubly odd neutron-deficient nucleus ^{134}Pm is of particular interest for nuclear-shape isomers. The $Z = 61$ proton Fermi level lies among the lower-Ω orbits of the $h_{11/2}$ shell that would favor a prolate nuclear shape. In contrast, the $N = 73$ neutron Fermi level lies among the higher-Ω orbits of the $h_{11/2}$ shell that would favor an oblate nuclear shape. As a consequence, nuclei in this region often have soft-nuclear shapes that are particularly susceptible to nonaxial deformations and this has led to several predictions and searches for proposed nuclear chiral shapes [8–10]. Where isomers occur in these nuclei, ^{144}Ho [11,12] ^{142}Tb [11,13,14] ^{140}Eu [15], and ^{136}Pm [16], it has been reasoned that the isomerism is a consequence of the differences in nuclear shape between the initial and final states that are linked by an $E1$ transition. In these nuclei, however, it remains difficult to establish whether the isomerism results from the shape differences or whether it is due to the natural hindrance often associated with $E1$ transitions. Systematic studies of $E1$, $M1$, $E2$, and $M2$ transition probabilities have shown that $E1$ transitions between intrinsic states are often highly delayed compared with their single-particle Weisskopf or Nilsson estimates [17,18]. Lobner and Malmskog [18] showed that the observed range of hindrance factors could span up to five orders of magnitude (10^{-2}–10^{-7}) for $E1$ transitions. The specific delay for any particular $E1$ transition is not found to be a smooth function of nuclear mass and this behavior has compounded the difficulties involved in interpreting the effect in the various approaches that have been used [18,19].

High-angular momentum states in ^{134}Pm have been extensively studied by Wadsworth *et al.* [20]. Three rotational bands were established built upon $\pi h_{11/2} \otimes \nu h_{11/2}$ (band 2), $\pi(g_{7/2}/d_{5/2}) \otimes \nu h_{11/2}$ (band 1), and $\pi h_{11/2} \otimes \nu h_{9/2}$ (band 3) configurations [20]. Band 2 was the most intense band and the lowest transitions in bands 1 and 3 were populated with intensities of $\sim$90 and $\sim$26% of that of band 2, respectively [20]. The low-spin states in ^{134}Pm have also been extensively studied in fusion-evaporation and β-decay measurements by Vierinen *et al.* [21] and Kortelahti *et al.* [22]. Many γ-ray transitions have been established to be built upon a

*On sabbatical leave: Department of Physics, University of Jyväskylä, Jyväskylä FIN-40014, Finland.

†Present address: Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, UK.

low-spin isomeric (2^+) state in ^{134}Pm. The 23-s β decay of ^{134}Pm was also found to populate the 4^+ and 6^+ levels in the ground-state band of ^{134}Nd, implying that this allowed β decay must originate from a relatively high-spin state in ^{134}Pm with a probable spin of (5^+). However, neither of these studies were able to deduce which of these two levels, (5^+) or (2^+), was the ground-state in ^{134}Pm and the population of these states was found to be strongly dependent on the production method [21,22]. The (5^+) state was preferentially produced directly from fusion-evaporation measurements, ^{92}Mo(^{46}Ti,3pn), whereas the (2^+) level was preferentially produced from β-decay measurements. As a consequence, the high- and low-spin regions of the ^{134}Pm level scheme have not, to date, been connected to each other because of the different population and timing sensitivities of the experiments and production methods. The present article provides new information on the linking of the low- and high-spin level scheme by establishing the feeding and decay of a 20(1) μs isomeric state in ^{134}Pm.

II. EXPERIMENT AND DATA ANALYSIS

Moderate-spin states were populated in ^{134}Pm with an ^{54}Fe + ^{92}Mo reaction. The K130 cyclotron at the Accelerator Laboratory of the University of Jyväskylä, Finland, was used to accelerate the ^{54}Fe beam onto an ~500 μg/cm^2 ^{92}Mo target at energies of 305 and 315 MeV. An average beam current of ~6 pnA was applied for 19 h at 305 MeV and 66 h at 315 MeV. The main isomer channel observed at the focal plane in this reaction was ^{140}Eu [15] through the six particle exit $(5p1n)$ channel. ^{134}Pm was populated weakly through the six particle $(2\alpha 3pn)$ exit channel. The ability to select such exotic channels was only made possible by employing the high sensitivity and selectivity of recoil-isomer tagging [4], where prompt and delayed γ rays were correlated across isomeric states. Some preliminary results were discussed briefly in Refs. [16] and [23].

Prompt γ-ray decays were detected with 40 Compton-suppressed HPGe detectors of the JUROGAM array (~4% total photo-peak efficiency at 1.3 MeV [24]) at the target position. The nuclear recoils were transported to the focal plane of the gas-filled recoil ion transport unit (RITU) [25] where they were implanted into an ~500-μm-thick aluminum foil. In this work, the recoil-isomer tagging was performed with a two multiwire proportional counter (MWPC) setup. The full details of this setup can be found in Ref. [13]. The use of a dual-MWPC setup allows recoil implantation rates to be accommodated in recoil-isomer tagging larger than those with the standard setup where recoils are implanted into the GREAT double sided silicon strip detector (DSSSD) [26]. Delayed γ-ray transitions from nuclear isomeric states were measured in the GREAT planar- and clover-germanium detectors close to the aluminum foil. The triggerless total data readout (TDR) system [27] was used to time stamp and record each decay using a 100-MHz clock and the data were sorted into two-dimensional matrices with GRAIN [28] and analyzed with UPAK [29].

III. RESULTS

The most intense delayed transitions observed in this experiment were from the known decay of an ~300 ns isomeric state in ^{140}Eu [15]. Despite the presence of these intense ^{140}Eu transitions, a new 71-keV delayed γ-ray transition was established in ^{134}Pm that was first observed, but not placed, in Refs. [23] and [30]. Recoil-isomer tagging in the present work revealed that this 71-keV transition was in delayed coincidence with a series of known prompt transitions from the $\pi h_{11/2} \otimes \nu h_{11/2}$ states in band 2 in ^{134}Pm [20]. Figure 1(a) shows the delayed 71-keV transition gated by the known prompt 272-keV transition in band 2 and Fig. 1(b) shows the correlated prompt transitions from band 2 in ^{134}Pm [20] gated by the delayed 71-keV transition. These spectra were taken from a prompt versus delayed matrix that was constructed with the condition that the delayed decays were detected 1–60 μs after a recoil passed through the first MWPC. The first 0–1 μs range was avoided to suppress the strong contamination from the known ~300 ns isomeric state in ^{140}Eu [15]. The matrix was background subtracted in time using the time interval 1–60 μs before a recoil was detected.

The isomer-tagged spectrum Fig. 1(a) does not show any coincidence with the lower-spin γ-ray transitions, established to be built upon the known (2^+) state in ^{134}Pm, within 60 μs after a recoil passed through the first MWPC. This is consistent with previous measurements where these transitions were only observed from β-decay measurements in contrast to the (5^+) state, which was only observed from the fusion-evaporation measurements [21,22]. Searches were also made for any other delayed γ rays that arrived up to 2 ms after the 71-keV

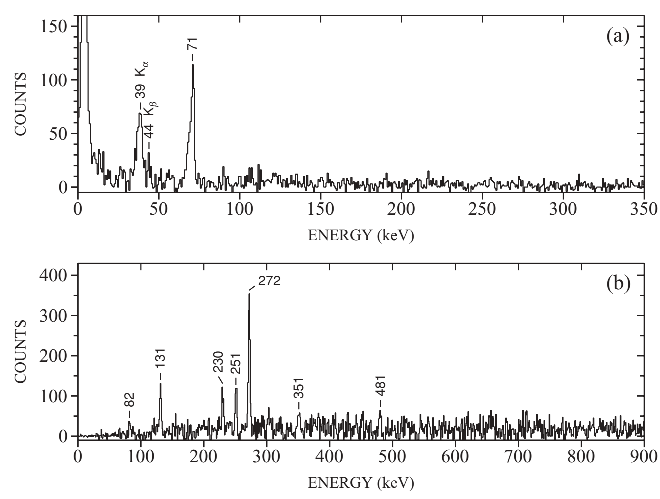

FIG. 1. Recoil-isomer-tagged spectra from a prompt-delayed matrix where the delayed γ rays were detected 1–60 μs after a recoil passed through the first MWPC. (a) Planar spectrum showing the new 71-keV delayed transition from a single gate on the known prompt 272-keV transition in ^{134}Pm. The 38.6- and 43.9-keV peaks are the K_α and K_β x rays of Pm, respectively. The low-energy tailing in this spectrum results from incomplete charge collection on the planar X strips. (b) JUROGAM spectrum showing prompt transitions from the $\pi h_{11/2} \otimes \nu h_{11/2}$ band in ^{134}Pm from a single gate on the delayed 71-keV γ ray in ^{134}Pm. All labeled peaks have been assigned to ^{134}Pm.

TABLE I. γ-ray energies, intensities, and initial and final spins for ^{134}Pm from the recoil-isomer tagged data in this work. The prompt and delayed intensities are normalized separately.

E_γ (keV)	I_γ	$J_i^\pi \to J_f^\pi$
	Delayed γ rays	
38.4(3)	72(4)	K_α
43.9(3)	13(10)	K_β
70.7(2)	100(5)	$(7^-) \to (6^+)$
	Prompt γ rays ($\pi h_{11/2} \otimes \nu h_{11/2}$ band 2)	
131.3(3)	33(5)	$(10^+) \to (9^+)$
230.2(3)	28(5)	$(12^+) \to (11^+)$
251.2(3)	33(5)	$(11^+) \to (10^+)$
272.0(2)	100(9)	$(8^+) \to (7^-)$
351.3(3)	18(4)	$(13^+) \to (12^+)$
481.0(3)	21(5)	$(12^+) \to (10^+)$

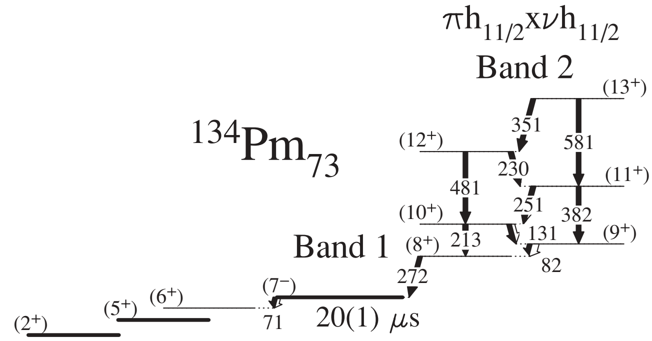

FIG. 2. Partial level scheme for ^{134}Pm showing the newly assigned 20(1) μs isomeric state and the new 71-keV $E1$ decay transition. The prompt transitions above the (7^-) state were established in Ref. [20]. The lower-spin (2^+) and (5^+) states are from β-decay and fusion-evaporation measurements, respectively; however, the ordering of these states is uncertain [21,22]. Several transitions are known to feed the (2^+) state populated from the β decay of ^{134}Sm; however, no transitions have been established to feed the (5^+) state [21,22].

transition at the focal plane. No other delayed γ-ray transitions were observed within this correlation time.

The nature of the 71-keV decay transition from the isomer was deduced by consideration of its electron-conversion coefficient. Because the only delayed transition is the 71-keV γ ray [see Fig. 1(b)] then all of the K_α x-ray yield must be associated with its electron conversion. The experimental intensities given in Table I reveal that the experimental K-shell electron-conversion coefficient for this transition is $\alpha_K^{\rm expt}(71) = 0.72(5)$. In comparison, the calculated K-shell conversion coefficients [31] for a 71-keV transition in ^{134}Pm are $\alpha_K(E1) = 0.572(8)$, $\alpha_K(M1) = 3.56(5)$, and $\alpha_K(E2) = 2.87(4)$. The experimental K-shell electron-conversion coefficient associated with the 71-keV γ-ray transition is only consistent with an $E1$ assignment. This reveals that the spin of the new state to which the 71-keV transition decays to must have $I^\pi = (6^+)$, (7^+), or (8^+), with the most likely value being $I^\pi = (6^+)$.

Figure 2 shows a partial level scheme of ^{134}Pm deduced from this recoil-isomer tagging study. The γ-ray energies and intensities from the recoil-isomer-tagged spectrum shown in Figs. 1(a) and 1(b) are given in Table I. In Ref. [20] it was suggested that the $I^\pi = (7^-)$ state, to which band 2 decays via a 272-keV transition, could also be the bandhead state of band 1. In the present work, the fact that the delayed gate on the new 71-keV delayed transition in Fig. 1(b) does not show a correlation with transitions from the known prompt band 1 in ^{134}Pm [20] suggests that the known prompt bands 1 and 2 may not feed into the same (7^-) state, at least within the limited statistical accuracy of this experiment. (Band 1 is expected to be populated with an intensity ~90% of that of band 2 from Ref. [20].) Similarly, in Ref. [20], states with $I^\pi > (9^+)$ in band 3 were observed to be in coincidence with the 272-keV transition from the (8^+) bandhead state of band 2; however, discrete linking transitions were not established. Figure 1(b) from the present study can neither confirm nor reject this scenario because band 3 is only expected to be populated with an intensity ~26% of that of band 2 [20].

A. Measurement of the ^{134}Pm half-life

The half-life of the new isomeric state in ^{134}Pm was determined from a focal-plane time spectrum gated on the delayed 71-keV γ-ray transition (see Fig. 3). The time parameter in this spectrum was defined as the time difference between a recoil passing through the first MWPC and a γ ray detected in the planar Ge detector using the 100 MHz TDR clock. As discussed more fully in Ref. [13], to maximize the counting statistics in this isomer-tagging experiment, high-beam currents were used with this dual-MWPC setup. As γ rays are associated with the last recorded recoil, with increasing recoil-implantation rate, misidentification of γ rays with recoils can occur yielding an inaccurate half-life. To account for this, half-lives were measured by fitting a sum

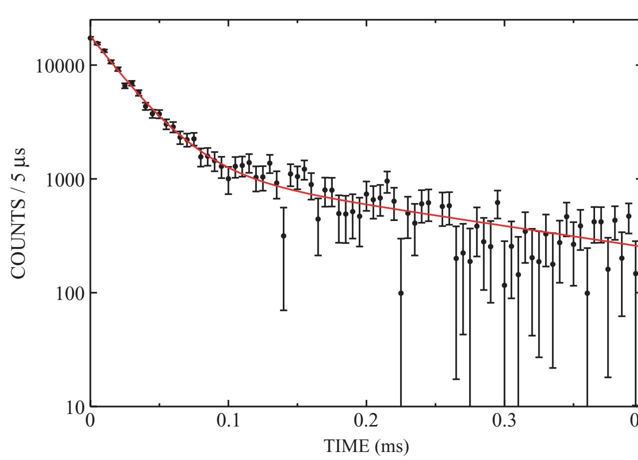

FIG. 3. (Color online) Time spectrum for the new 71-keV delayed γ-ray transition in ^{134}Pm. The solid line represents the sum of two fitted exponentials, with the longer-lived component representing the effect of random correlations (see text for details). The "TIME" axis label refers to the time difference between a recoil passing through the first MWPC and the detection of the delayed γ ray.

of two exponentials to the data, with the second, longer-lived exponential representing the effect of random correlations. The decay constant for the shorter-lived exponential was corrected for these random correlations as described in Ref. [32]. This approach was recently validated in the measurement of the half-life of the established 26(1) μs isomeric state in ^{142}Tb with this dual-MWPC setup [13,14]. In this work, the half-life of the (7^-) isomeric state in ^{134}Pm was deduced to be 20(1) μs and the half-lives of the two exponential components of the fit, corresponding to the background and uncorrected decay of the isomer, were 164 and 18 μs, respectively.

IV. DISCUSSION

Previously, the configurations for the three prompt rotational bands in ^{134}Pm were established based on the properties of their aligned-angular momenta, signature splittings, and branching ratios in comparison with the cranked-shell and total Routhan surface (TRS) models [20]. The TRS calculations show evidence that particular configurations in the deformed nucleus ^{134}Pm are expected to be triaxial with $\gamma = -5$ to -10° [20]. These suggestions are supported by the more recent calculations of Möller *et al.* [33], which include axial asymmetry. Although ^{134}Pm is not tabulated, ^{135}Pm and ^{136}Pm have $(\beta_2, \beta_4, \gamma) = (0.225, 0.04, 17.5^\circ)$ and $(0.200, 0.04, 20^\circ)$, respectively, showing an increasing axial asymmetry with decreasing quadrupole deformation for the heavier Pm isotopes. Lifetime measurements for band 3 were performed in Ref. [20] that confirmed its deformed nature with a quadrupole deformation of $5.3 \pm 0.9\, eb$ corresponding to $\beta_2 = 0.29$. The three bands in ^{134}Pm were assigned configurations built upon $\pi h_{11/2} \otimes \nu h_{11/2}$ states (band 2), $\pi(g_{7/2}, d_{5/2}) \otimes \nu h_{11/2}$ states (band 1), and $\pi h_{11/2} \otimes \nu h_{9/2}$ states (band 3) [20]. These assignments are consistent with the single-particle bands established in the neighboring odd-proton and odd-neutron nuclei. The odd-proton isotopes, ^{133}Pm [34] and ^{135}Pm [35], both have proton $h_{11/2}$ ground states and first excited $(5/2^+)$ and $(3/2^+)$ states. The nearest-neighbor odd-neutron isotones, ^{133}Nd [36] and ^{135}Sm [37], have a neutron $(7/2^+)$ and $(3/2^+, 5/2^+)$ ground states, respectively.

A. Linking the high- and low-spin states in the mass 130–140 nuclei

Linking the high- and low-spin level schemes for the mass 130-140 extremely neutron-deficient nuclei has proved difficult in the past because of the differing spin and excitation-energy regions populated by the two main production methods: fusion-evaporation (yrast) and β decay (largely non-yrast). Connecting these yrast and non-yrast parts of the level schemes has not been possible, to date, in both the neighboring odd-odd isotopes and isotones, ^{136}Pm [16] and ^{132}Pr [38], respectively. In the odd-odd isotope, ^{136}Pm, a 1.5(1) $\mu s\, \pi h_{11/2} \otimes \nu h_{11/2}$ isomer was established to decay by a delayed 43-keV transition [16]. However, no subsequent γ-ray transitions were established within a search time of up to 2 ms after the arrival of the 43-keV transition at the focal plane [16]. (Note that the ^{136}Pm isomeric level is the $I^\pi = (8^+)$ bandhead state and not the $I^\pi = (7^-)$ isomeric state established here in ^{134}Pm.) In the odd-odd isotone ^{132}Pr, which has a level-scheme structure more similar to that of ^{134}Pm, an (8^+) bandhead state has been established [38] to decay to a (7^-) state. This (7^-) state was not connected to the lower-spin β-decaying states [39], perhaps because it too may be isomeric.

In the present work on ^{134}Pm, no subsequent γ-ray transitions were established within a search time of up to 2 ms after the arrival of the 71-keV isomer-decay transition at the focal plane. The nonobservation of any additional transitions that would link the new (6^+) state, fed by the isomer, to the (5^+) β-decaying state observed in Ref. [21] may be because the 71-keV transition feeds an unobserved low-energy $M1$ transition. Such a scenario is only likely if the energy of the unobserved transition is below the K-shell binding energy as all of the K x-ray intensity in Fig. 1(a) is already associated with the electron conversion of the 71-keV $E1$ transition. Such a low-energy $M1$ transition would, however, have a large L-shell electron-conversion component and would be expected to produce L x rays. Some of this L x-ray yield may contribute to the large low-energy peak in Fig. 1(a). Unfortunately, with the present data, the L x-ray yield contribution cannot be distinguished from low-energy noise in the planar detector because they are both convolved in this nonlinear low-energy region of the analogue to digital converter (ADC). A new high-statistics prompt and delayed study focused on ^{134}Pm as the main exit channel using a different calibration and timing conditions would be required to fully search for the existence of this low-energy transition.

B. Reduced-transition probabilities and the lifetime of the (7^-) isomeric state

The single-particle Weisskopf estimate, $t_{1/2}$(Weisskopf), for a 71-keV $E1$ transition in ^{134}Pm gives a half-life of 1.07 ps, which is much shorter than the 20(1) μs experimental value, $t_{1/2}$(experiment). The large additional hindrance for the 71-keV γ-ray decay corresponds to a reduced-transition probability [40] of

$$S = \frac{t_{1/2}(\text{Weisskopf})}{t_{1/2}(\text{experiment})} = 9 \times 10^{-8}$$

using the Weisskopf single-particle estimate corrected for internal conversion. This reduced-transition probability in ^{134}Pm lies just below minimum expected transition probability (10^{-7}) for $E1$ transitions from the systematic studies of Lobner and Malmskog [18]. The source of this small additional hindrance may possibly be attributed to shape differences between the states above and below the isomer.

Table II shows the reduced-transition probability for a series of $E1$ decays, grouped by the spin of the initial state, in the neighboring even-mass nuclei in this region and in the more neutron-rich Te isotopes near to the $Z = 50$ and $N = 82$ closed shells [40].

The top panel of Table II shows that the new reduced-transition probability for the 71-keV, $(7^-) \rightarrow (6^+)$, $E1$ transition in ^{134}Pm is also smaller than all of the established values for isomer decays in the neighboring odd-odd nuclei (^{142}Tb [13,14], ^{140}Eu [15], ^{144}Ho [11,12], and ^{136}Pm [16]).

TABLE II. Experimental reduced-transition probabilities for a series of $E1$ transitions for the even-mass nuclei in the vicinity of ^{134}Pm and the more neutron-rich Te isotopes near to the $Z = 50$ and $N = 82$ closed shells from Ref. [40]. The reduced-transition probabilities for ^{142}Tb are from Refs. [13,14], for ^{140}Eu from Ref. [15], for ^{144}Ho from Refs. [11,12], and for ^{136}Pm from Ref. [16].

Nucleus	E_γ (keV)	Assigned multipolarity	$J_f^\pi \rightarrow J_i^\pi$	$t_{1/2}$ (ns)	Reduced-transition probability, S
^{136}Pm	43	$E1$	$(8^+) \rightarrow (7^-)$	$1.5(1) \times 10^3$	$1.6(1) \times 10^{-6}$
^{138}Pm	174	$E1$	$8^+ \rightarrow 7^-$	21(5)	$2.2(5) \times 10^{-6}$
^{140}Eu	37	$E1$	$8^+ \rightarrow 7^-$	299(3)	$7.6(8) \times 10^{-6}$
^{140}Eu	98	$E1$	$8^+ \rightarrow 7^-$	299(3)	$1.4(1) \times 10^{-7}$
^{142}Tb	37	$E1$	$8^+ \rightarrow 7^-$	$26(1) \times 10^3$	$1.4(1) \times 10^{-7}$
^{144}Ho	57	$E1$	$8^+ \rightarrow 7^-$	519(5)	$1.1(1) \times 10^{-6}$
^{148}Dy	95	$E1$	$8^+ \rightarrow 7^-$	95(30)	$1.7(6) \times 10^{-6}$
^{126}Te	720	$E1$	$7^- \rightarrow 6^+$	0.219(7)	$4.5(2) \times 10^{-6}$
^{128}Te	527	$E1$	$7^- \rightarrow 6^+$	3.47(4)	$9.7(1) \times 10^{-7}$
^{130}Te	331	$E1$	$7^- \rightarrow 6^+$	166(12)	$6.3(5) \times 10^{-8}$
^{132}Te	151	$E1$	$7^- \rightarrow 6^+$	$13(3) \times 10^3$	$7.8(18) \times 10^{-9}$
^{134}Pm	71	$E1$	$(7^-) \rightarrow (6^+)$	$20(1) \times 10^3$	$9.0(4) \times 10^{-8}$

These neighboring isomers have been discussed in terms of shape isomers and the comparison with ^{134}Pm may be slightly complicated by the fact that the $\pi h_{11/2} \otimes \nu h_{11/2}$ isomer decay takes place from (7^-) to (6^+) in ^{134}Pm and 8^+ to 7^- in the neighbors. However, the fact that the reduced-transition probability for ^{134}Pm is smaller than all others in the neighboring nuclei may be related to differences in the nuclear deformation and the shape polarizability of particular single-particle orbits. Lifetime measurements for one of the rotational bands in ^{134}Pm [20], and the calculations of Möller *et al.* [33], which include axial asymmetry show that ^{134}Pm has a larger deformation and a smaller axial asymmetry than its heavier isotopes (^{136}Pm, ^{138}Pm) and neighbors (^{140}Eu, ^{142}Tb, ^{144}Ho). This more deformed and more-rigid shape of ^{134}Pm may be responsible for the smaller established reduced-transition probability. In comparison, the shapes of the states above and below the isomers in the less-deformed and more γ-soft neighbors may be more mixed, resulting in larger reduced-transition probabilities.

The middle panel of Table II shows the reduced-transition probabilities established for a series of $E1$, $7^- \rightarrow 6^+$, isomer decays in the even-mass Te isotopes with proton and neutron numbers close to the respective $Z = 50$ and $N = 82$ closed shells. As a consequence, these vibrational nuclei are expected to have fairly rigid nuclear shapes and small reduced-transition probabilities. The new reduced-transition probability for the 71-keV, $(7^-) \rightarrow (6^+)$, $E1$ transition in ^{134}Pm, $9.0(4) \times 10^{-8}$, appears to fit well with the values of the more-rigid Te isotopes, especially the heavier ones ($6.3(5) \times 10^{-8}$ in ^{130}Te and $7.8(18) \times 10^{-9}$ in ^{132}Te). However, a full theoretical study (including nonaxial shapes) of the polarizability of the single-particle orbits around the Fermi surface for the Pm isotopes in conjunction with more extensive and precise experimental spin and parity assignments would be extremely useful to quantify the extent of shape isomerism in this extremely neutron-deficient region of the nuclear chart.

V. CONCLUSIONS

A known (7^-) state in doubly odd ^{134}Pm has been established to be isomeric from a recoil-isomer tagging experiment at the University of Jyväskylä. The isomer decays via a 71-keV transition with a 20(1) μs half-life whose internal-conversion coefficient is only consistent with that of an electric-dipole transition. The 71-keV delayed transition provides new information on the linking of the established high-spin level scheme to the lower-spin states observed from the β decay of ^{134}Sm. However, the nonestablishment of any subsequent γ-ray transitions after the 71-keV transition may suggest the presence of an unobserved low-energy $M1$ transition that feeds into the known (5^+) β-decaying state. The small reduced-transition probability for the 71-keV $E1$ decay in ^{134}Pm nuclei suggests that ^{134}Pm may have a nuclear shape more rigid than that of its neighboring nuclei. A full theoretical study of the polarizability of the single-particle orbits, including nonaxial shapes, in conjunction with more extensive and precise experimental spin and parity assignments is ideally required to fully quantify the extent of shape isomerism in these γ-soft mass ~130–140 nuclei.

ACKNOWLEDGMENTS

Useful discussions with P.M. Walker are gratefully acknowledged. This work has been supported by the EU 6th Framework program, "Integrating Infrastructure Initiative-Transnational Access," Contract 506065 (EURONS), and by the Academy of Finland under the Finnish Centre of Excellence Programme 2006-2011 (Nuclear and Accelerator

Based Physics Programme at JYFL). The authors acknowledge the EPSRC/IN2P3 loan pool and GAMMAPOOL for the use of the JUROGAM detectors. PJRM and SVR acknowledge support by EPSRC. DMC acknowledges the support of the STFC through Contract PP/F000855/1. CS (Contract 209430), PTG (Contract 119290), and PN (Contract 121110) acknowledge the support of the Academy of Finland.

[1] P. Walker and G. Dracoulis, Nature (London) **399**, 35 (1999).
[2] R. L. Lozeva, G. S. Simpson, H. Grawe, G. Neyens, L. A. Atanasova, D. L. Balabanski, D. Bazzacco, F. Becker, P. Bednarczyk, G. Benzoni *et al.*, Phys. Rev. C **77**, 064313 (2008).
[3] A. M. Bruce, P. M. Walker, P. H. Regan, G. D. Dracoulis, A. P. Byrne, T. Kibèdi, G. J. Lane, and K. C. Yeung, Phys. Rev. C **50**, 480 (1994).
[4] D. M. Cullen *et al.*, Phys. Rev. C **58**, 846 (1998).
[5] D. Cullen *et al.* Phys. Lett. **B529**, 42 (2002).
[6] W. Królas, R. Grzywacz, K. P. Rykaczewski, J. C. Batchelder, C. R. Bingham, C. J. Gross, D. Fong, J. H. Hamilton, D. J. Hartley, J. K. Hwang *et al.*, Phys. Rev. C **65**, 031303(R) (2002).
[7] H. Britt, At. Data Nucl. Data Tables **12**, 407 (1973).
[8] K. Starosta, T. Koike, C. J. Chiara, D. B. Fossan, D. R. LaFosse, A. A. Hecht, C. W. Beausang, M. A. Caprio, J. R. Cooper, R. Krücken *et al.*, Phys. Rev. Lett. **86**, 971 (2001).
[9] D. Tonev *et al.*, Phys. Rev. C **76**, 044313 (2007).
[10] S. Mukhopadhyay *et al.*, Phys. Rev. Lett. **99**, 172501 (2007).
[11] C. Scholey *et al.*, Phys. Rev. C **63**, 034321 (2001).
[12] P. J. R. Mason *et al.* (submitted to Phys. Lett. B, July 2009).
[13] P. J. R. Mason, D. M. Cullen, C. Scholey, S. Eeckhaudt, T. Grahn, P. T. Greenlees, U. Jakobsson, P. M. Jones, R. Julin, S. Juutinen *et al.*, Phys. Rev. C **79**, 024318 (2009).
[14] M. N. Tantawy *et al.*, Phys. Rev. C **73**, 024316 (2006).
[15] D. M. Cullen *et al.*, Phys. Rev. C **66**, 034308 (2002).
[16] S. V. Rigby *et al.*, Phys. Rev. C **78**, 034304 (2008).
[17] K. E. G. Lobner, Phys. Lett. **B26**, 369 (1968).
[18] K. E. G. Lobner and S. G. Malmskog, Nucl. Phys. **80**, 505 (1966).
[19] G. D. Dracoulis and P. M. Walker, Nucl. Phys. **A330**, 186 (1979).
[20] R. Wadsworth, S. Mullins, P. Bishop, A. Kirwan, M. Godfrey, P. Nolan, and P. Regan, Nucl. Phys. **A526**, 188 (1991).
[21] K. S. Vierinen, J. M. Nitschke, P. A. Wilmarth, R. B. Firestone, and J. Gilat, Nucl. Phys. **A499**, 1 (1989).
[22] M. O. Kortelahti, B. D. Kern, R. A. Braga, R. W. Fink, I. C. Girit, and R. L. Mlekodaj, Phys. Rev. C **42**, 1267 (1990).
[23] D. M. Cullen *et al.*, AIP Conf. Proc. **1012**, 220 (2008).
[24] P. T. Greenlees *et al.*, Eur. Phys. J. A **25** s01, 599 (2005).
[25] M. Leino *et al.*, Nucl. Instrum. Methods Phys. Res. B **99**, 653 (1995).
[26] R. D. Page *et al.*, Nucl. Instrum. Methods Phys. Res. B **204**, 634 (2003).
[27] I. Lazarus *et al.*, IEEE Trans. Nucl. Sci. **48**, 567 (2001).
[28] P. Rahkila, Nucl. Instrum. Methods Phys. Res. A **595**, 637 (2008).
[29] W. T. Milner, *UPAK, The Oak Ridge Analysis Package*, Oak Ridge National Laboratory, Tennessee, 37831 (private communication).
[30] S. V. Rigby, Ph.D. thesis, University of Manchester, 2006.
[31] T. Kibédi, T. Burrows, M. Trzhaskovskaya, C. Davidson, and P. M. Nestor, Jr., Nucl. Instrum. Methods Phys. Res. A **589**, 202 (2008).
[32] M. E. Leino, S. Yashita, and A. Ghiorso, Phys. Rev. C **24**, 2370 (1981).
[33] P. Moller, R. Bengtsson, B. Carlsson, P. Olivius, T. Ichikawa, H. Sagawa, and A. Iwamoto, At. Data Nucl. Data Tables **94**, 758 (2008).
[34] P. H. Regan, R. Wadsworth, J. R. Hughes, G. J. Gyapong, W. Gelletly, M. J. Godfrey, I. Jenkins, Y. J. He, S. M. Mullins, P. J. Nolan *et al.*, Nucl. Phys. **A533**, 476 (1991).
[35] R. Wadsworth, J. M. O'Donnell, D. L. Watson, P. J. Nolan, A. Kirwan, P. J. Bishop, M. J. Godfrey, D. J. Thornley, and D. J. G. Love, J. Phys. G **14**, 239 (1988).
[36] J. B. Breitenbach, J. L. Wood, M. Jarrio, R. A. Braga, J. Kormicki, and P. B. Semmes, Nucl. Phys. **A592**, 194 (1995).
[37] S. M. Mullins, R. Wadsworth, J. M. O'Donnell, P. J. Nolan, A. J. Kirwan, P. J. Bishop, M. J. Godfrey, and D. J. G. Love, J. Phys. G **13**, L201 (1987).
[38] S. Shi, C. W. Beausang, D. B. Fossan, R. Ma, E. S. Paul, N. Xu, and A. J. Kreiner, Phys. Rev. C **37**, 1478 (1988).
[39] D. Bucurescub *et al.*, Nucl. Phys. **A587**, 475 (1995).
[40] P. M. Endt, At. Data Nucl. Data Tables **26**, 47 (1981).