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Fast decay of a three-quasiparticle isomer in ^{171}Tm

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Incomplete-fusion reactions have been used to study high-spin states in ^{171}Tm. Gamma rays and conversion electrons were measured using pulsed-beam conditions for enhanced isomer sensitivity. A $K^\pi = 19/2^+$, three-quasiparticle isomer was identified, with a half-life of 1.7(2) μs. The faster than expected transition rates from the isomer can be understood as being due to a chance near-degeneracy, with mixing between the isomeric state and the $I^\pi = 19/2^+$ member of the one-quasiparticle rotational band to which it decays. The implied mixing matrix element is 12(2) eV.

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I. INTRODUCTION

High-K isomers are well known in the $A \sim 180$ region of the nuclear chart [1,2] but the identification of examples in the neutron-rich part of this mass region has proved challenging, because of the lack of production reactions with suitable selectivity. Considerable progress has nevertheless been made with deep-inelastic [3], fragmentation [4], and incomplete-fusion [5] reactions. With the possibility of low recoil energy, incomplete fusion can have a particular advantage for the measurement of conversion electrons, thus providing essential information for structural assignments. This is the approach taken in the present work.

The motivation is to extend in N and Z the accessible range of multi-quasiparticle isomers in the $A \sim 180$ region, with the intent of pinning down the relative importance of the different K-mixing mechanisms that have been put forward to explain K-isomer decay rates [2,6]. We report results from a study of odd-Z ^{171}Tm. A previous study [7] of this nuclide with the same reaction had revealed rotational bands up to $I = 19/2$ built on the $T_{1/2} = 1.9$y, $1/2^+$ ground state and a 2.6 μs, $7/2^-$ state at 425 keV, each of one-quasiparticle character. A 1.3 ns, $7/2^+$ one-quasiparticle state at 636 keV is also well known [8]. The present work reports delayed feeding through the $7/2^+$ state and establishes a three-quasiparticle, $19/2^+$ isomer with a half-life of 1.7 μs. We note that results from a parallel study of ^{172}Tm, measured with the same beam/target combination, have recently been published [9].

II. EXPERIMENTAL METHOD

Beams of 42 MeV ^{7}Li, from the ANU 14UD tandem accelerator, were incident on self-supporting ^{170}Er target foils. The main yield was from the ^{170}Er(^{7}Li,4n)^{173}Lu reaction, as reported by Venkova *et al.* [10], but here the focus is on the ^{170}Er(^{7}Li,α2n)^{171}Tm incomplete-fusion reaction.

The experiment was conducted in two parts. First, with a 4.1 mg/cm^2 target, γ rays were recorded with the CAESAR array, consisting of six Compton-suppressed coaxial Ge detectors and two unsuppressed planar Ge detectors. The latter gave improved performance at low γ-ray energies. The target was sufficiently thick to stop almost all the recoiling reaction products. A variety of beam-pulsing conditions, ranging from nanoseconds to microseconds, were employed, with γ-ray singles and coincidences timed relative to the beam bursts (see also the parallel study of ^{172}Tm [9]).

Following the observation of previously unreported γ-ray transitions with half-lives in the microsecond region, a conversion-electron measurement was performed with the ANU Super-e spectrometer [11], operated in lens mode. Gamma rays were measured simultaneously, using a single Compton-suppressed Ge detector. Both electron and γ-ray events were timed relative to the 1 μs beam bursts, which were separated by 9 μs. For this measurement, a 1.5mg/cm^2 target was employed, at 30° to the beam direction, which is thick enough to stop most of the reaction products.

III. EXPERIMENTAL RESULTS

The focus of the present measurements was on the detection of γ-ray and conversion-electron transitions between beam bursts, i.e., those associated with the decay of isomeric states. Table I lists these "delayed" transitions assigned to ^{171}Tm, and Fig. 1 shows the corresponding level structure, deduced on the basis of γ-γ-coincidence relationships. A γ-ray coincidence spectrum is shown in Fig. 2, illustrating transitions associated with isomeric decay from a level at 1674 keV.

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TABLE I. Gamma-ray energy, relative intensity, and initial and final spin and parity, for transitions in ^{171}Tm associated with the $K^\pi = 19/2^+$ isomer and its decay. Energies and intensities are those obtained from the present study. Tentative assignments and uncertainties are given in parentheses.

E_γ (keV)	I_γ[a]	K, I_i^π	K, I_f^π
95.5(3)	14(5)	$7/2, 9/2^-$	$7/2, 7/2^-$
111.5(1)	2501(126)	$1/2, 5/2^+$	$1/2, 3/2^+$
115.0(5)	w[b]	$7/2, 7/2^+$	$7/2, 9/2^-$
116.7(2)	96(20)	$1/2, 5/2^+$	$1/2, 1/2^+$
116.8(2)	8(3)	$7/2, 11/2^-$	$7/2, 9/2^-$
117.0(2)	40(8)	$7/2, 9/2^+$	$7/2, 7/2^+$
124.0(3)	585(30)	$1/2, 7/2^+$	$1/2, 3/2^+$
138.6(2)	16(5)	$7/2, 13/2^-$	$7/2, 11/2^-$
141.4(1)	50(10)	$7/2, 11/2^+$	$7/2, 9/2^+$
159.6(2)	15(5)	$7/2, 15/2^-$	$7/2, 13/2^-$
164.3(5)[c]	–	$(19/2, 21/2^+)$	$19/2, 19/2^+$
164.9(2)	15(5)	$7/2, 13/2^+$	$7/2, 11/2^+$
181.3(2)	20(6)	$7/2, 17/2^-$	$7/2, 15/2^-$
184.2(5)[c]	–	$(19/2, 23/2^+)$	$(19/2, 21/2^+)$
187.4(1)	40(6)	$7/2, 15/2^+$	$7/2, 13/2^+$
209.0(5)	10(4)	$7/2, 17/2^+$	$7/2, 15/2^+$
210.7(1)	151(8)	$7/2, 7/2^+$	$7/2, 7/2^-$
219.2(1)	29(5)	$19/2, 19/2^+$	$7/2, 17/2^+$
230.0(5)[c]	–	$(7/2, 19/2^+)$	$7/2, 17/2^+$
232.3(2)	12(4)	$7/2, 9/2^+$	$7/2, 9/2^-$
256.0(5)	4(2)	$7/2, 13/2^-$	$7/2, 9/2^-$
258.5(1)	55(5)	$7/2, 11/2^+$	$7/2, 7/2^+$
296.0(1)	1083(22)	$7/2, 7/2^-$	$1/2, 7/2^+$
298.0(5)	5(2)	$7/2, 15/2^-$	$7/2, 11/2^-$
306.3(1)	35(8)	$7/2, 13/2^+$	$7/2, 9/2^+$
308.4(1)	2355(120)	$7/2, 7/2^-$	$1/2, 5/2^+$
327.8(2)	15(5)	$7/2, 9/2^+$	$7/2, 7/2^-$
341.0(2)	10(4)	$7/2, 17/2^-$	$7/2, 13/2^-$
352.3(1)	155(9)	$7/2, 15/2^+$	$7/2, 11/2^+$
373.7(2)	15(5)	$7/2, 11/2^+$	$7/2, 9/2^-$
396.1(2)	20(5)	$7/2, 17/2^+$	$7/2, 13/2^+$
428.0(1)	217(10)	$19/2, 19/2^+$	$7/2, 15/2^+$
439.0(5)[c]	–	$(7/2, 19/2^+)$	$7/2, 15/2^+$
470.5(2)	10(4)	$7/2, 15/2^+$	$7/2, 13/2^-$
506.5(2)	8(3)	$7/2, 7/2^+$	$1/2, 7/2^+$
518.8(2)	7(3)	$7/2, 7/2^+$	$1/2, 5/2^+$
558.1(3)	47(6)	$19/2, 19/2^+$	$7/2, 17/2^-$

[a]Delayed (out of beam) γ-ray intensity with arbitrary normalization.
[b]w indicates that the γ-ray intensity is low.
[c]Tentative prompt transition, with no delayed component identified.

The parts of the level scheme involving the $K^\pi = 1/2^+[411]$ and $7/2^-[523]$ bands, and the $7/2^+[404]$ bandhead, were already known from previous studies [7,8] and the present work is in agreement. However, two excited members of the $7/2^+$ band, above the 636 keV level, had been tentatively identified by Drissi *et al.* [7], with γ-ray transitions at 108, 129, and 237 keV. No evidence is found for these transitions in the present data. The excited members of the $7/2^+$ band shown in Fig. 1, and the $19/2^+$ isomer at 1674 keV, are newly identified.

It is evident from Fig. 1 that there are many γ-ray branches, so that there are no ambiguities in the ordering of transitions within the level scheme. However, there is the potential for confusion with unresolved transitions in ^{173}Lu [10,12], which is much more strongly produced in the present study. In particular, the $7/2^+$ bands in each of these nuclides have essentially the same transition energies, at least over the spin range shown in Fig. 1. Nevertheless, there are two features that remove the ambiguity. First, in ^{173}Lu the $7/2^+$ bandhead forms the ground state, whereas in ^{171}Tm the $7/2^+$ bandhead is an excited state. This was already known [8] to decay primarily by a 211 keV transition, which, in the present work, gives rise to different γ-γ-coincidence relationships. Second, and crucially, there are significant differences between the K-electron binding energies (59.4 keV for Tm, and 63.3 keV for Lu). The comparison between the electron and γ-ray energies (see Fig. 3) demonstrates electron binding energies that are consistent only with Tm. It is therefore deduced that only states in ^{171}Tm are fed significantly by an isomer in the μs range. The half-life of the isomer is measured to be 1.7(2) μs, as illustrated in Fig. 4.

Two levels are tentatively placed above the $K^\pi = 19/2^+$ isomer, on the basis of "prompt-delayed" γ-γ-coincidence relationships, whereby gates are set on out-of-beam transitions and a time-difference condition selects in-beam transitions that feed the corresponding isomer. Firm placements are not possible for these transitions because of the low cross section for the incomplete-fusion reactions compared to the total cross section, leading to many unresolved in-beam transitions. The placement of the $19/2^+$ member of the $7/2^+[404]$ band is in a similar category, based on prompt γ-γ-coincidences. The situation is, however, considerably simpler for isomeric decays, leading to firm placements below the isomer. It is assumed that, where there is a well-defined sequence of levels for which the transition energies closely follow $I(I+1)$ proportionality, i.e., for the level sequences above the $7/2^-$ and $7/2^+$ isomers, the characteristic rotational-band spin assignments are justified.

For the analysis of the electron conversion coefficients, the known [8] $E1$ character of the 308 keV transition (seen in Figs. 1 and 3) from the 2.6 μs, $7/2^-$ isomer in ^{171}Tm provides a convenient internal calibration, with a theoretical conversion coefficient of $\alpha_K = 0.0151$ [13]. Based on this, together with off-line calibrations, other conversion coefficients are obtained, as listed in Table II.

TABLE II. K-conversion coefficients for selected transitions in ^{171}Tm.

E_γ (keV)	α_{exp}	α_{th} [13]
296.0	0.015(2)	$E1$: 0.017
		$E2$: 0.054
		$M1$: 0.126
352.3	0.025(5)[a]	$E1$: 0.011
		$E2$: 0.033
		$M1$: 0.079
428.0	0.017(3)	$E1$: 0.007
		$E2$: 0.020
		$M1$: 0.048

[a]The M-conversion component from the 296 keV transition has been subtracted.

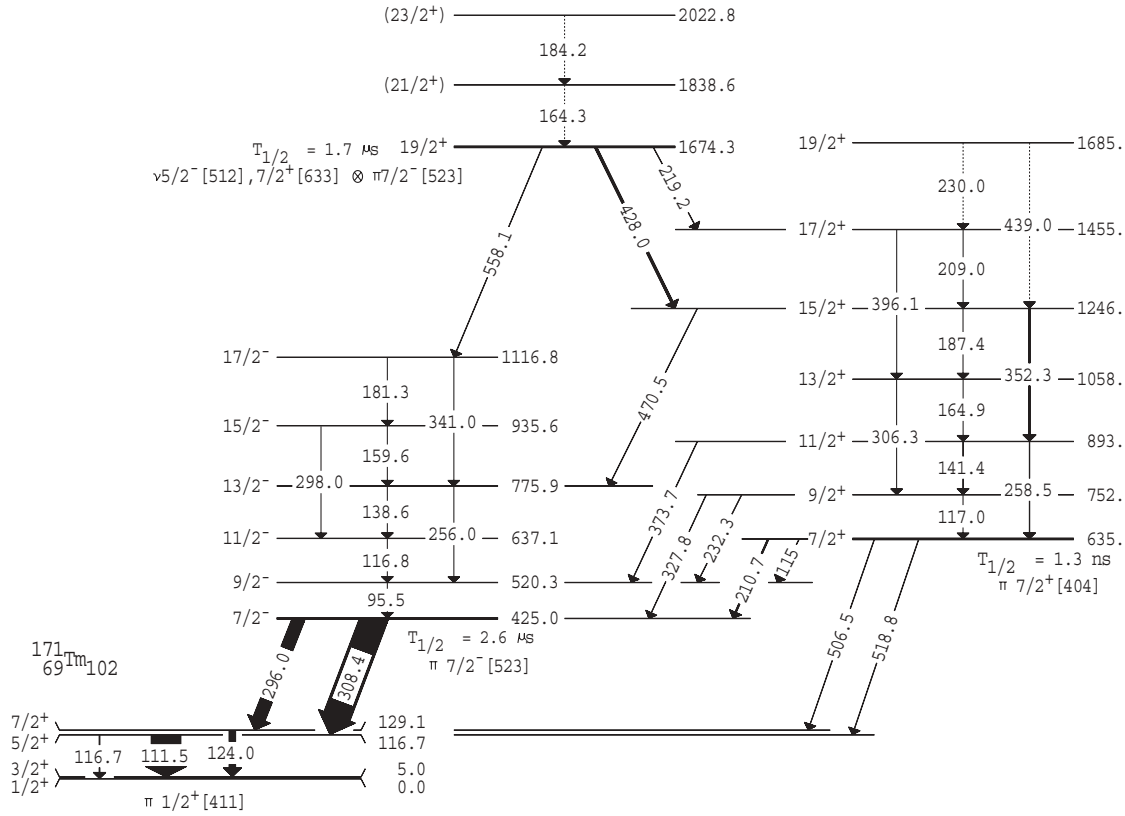

FIG. 1. Partial level scheme for ^{171}Tm, associated with the $K^{\pi} = 19/2^{+}$ isomer and its decay. The energies are those obtained in the present study. The $7/2^{+}$, 636 keV level and those fed from its decay, as well as the members of the $7/2^{-}$ band, were known from previous work [7,8].

The measured conversion coefficient of the 352 keV transition (Table II) establishes $E2$ character, which is consistent with its placement as a crossover transition in a strongly coupled rotational band. More significantly, the 428 keV transition is also established to have $E2$ multipolarity, which (in combination with the other observed decay branches) determines $I^{\pi} = 19/2^{+}$ for the spin and parity of the 1.7 μs isomer. In accordance with usual practice, the K value is taken to be equal to the bandhead spin, i.e., K =19/2.

IV. DISCUSSION

The one-quasiparticle states (bandheads) shown in Fig. 1 have been assigned [7,8] the proton (π)$1/2^{+}$[411], $7/2^{-}$[523], and $7/2^{+}$[404] Nilsson configurations. The new γ-ray intensity data for the $7/2^{+}$ band (Table I) provide in-band branching ratios that can be used to give g-factor estimates, based on rotational-model formulas (given in Ref. [9]), and hence the $7/2^{+}$[404] assignment can be tested. Assuming an intrinsic quadrupole moment of $Q_o = 7.6$ eb, taken from a measurement for the same configuration in the isotone ^{173}Lu [14], the branching ratios yield $|g_K - g_R| = 0.33(3)$ (weighted average). This can be compared with the theoretical asymptotic-limit value, using the Nilsson quantum numbers with $g_s = 0.6 g_s^{\rm free}$ and $g_R = 0.35$, which gives $g_K - g_R = 0.31$, in agreement with the experimental value.

Multi-quasiparticle Nilsson-model calculations, of the type described by Jain *et al.* [15], have also been

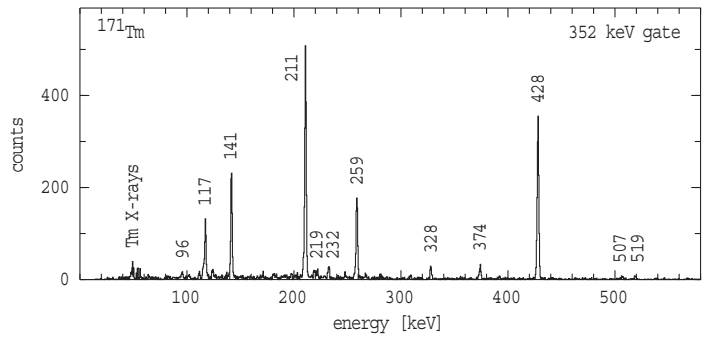

FIG. 2. Spectrum of γ rays in coincidence with the 352 keV transition in ^{171}Tm, with the additional requirement that the events occur between beam bursts. The labeled γ-ray transitions are included in the level scheme (Fig. 1).

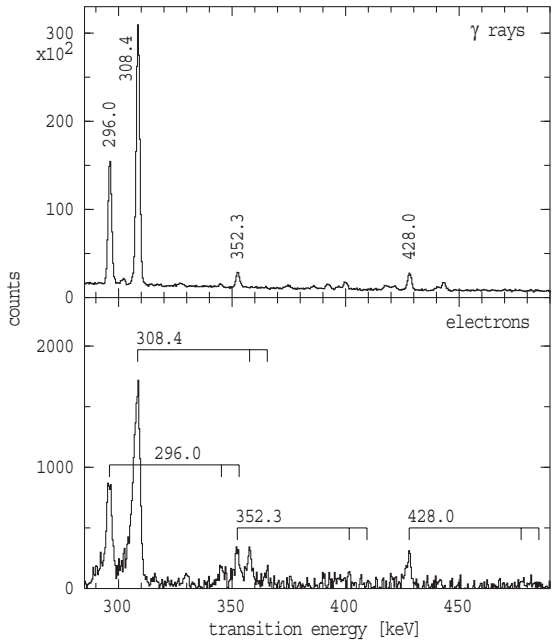

FIG. 3. The γ-ray (upper panel) and conversion-electron (lower panel) spectra in the 300–500 keV region, for the first 3 μs following 1 μs beam bursts. The subsequent 3 to 6 μs time region has been subtracted to remove long-lived activity. The electron energies have been shifted by the Tm K-binding energy of 59.4 keV so that the K-conversion peaks are aligned with the corresponding γ-ray peaks. The horizontal bars, with tick marks, show (left to right) the positions that correspond to K, L, and M conversion.

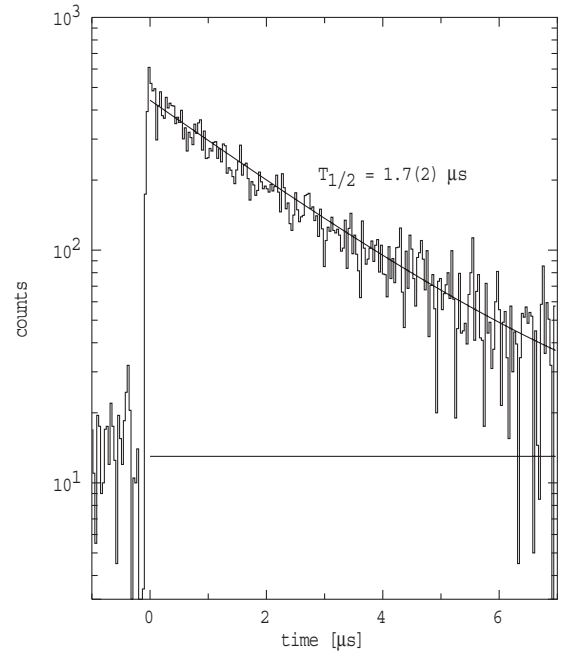

FIG. 4. Half-life fit (including a constant background, as indicated) for ^{171}Tm out-of-beam 352 and 428 keV γ-ray events.

performed. These indicate a three-quasiparticle $K^\pi = 19/2^+\{\pi 7/2^-[523], \nu 7/2^+[633], \nu 5/2^-[512]\}$ configuration for the 1.7 μs isomer. Indeed, using standard parameters [15] with pairing strengths of $G_\nu = 20.25/A$ MeV and $G_\pi = 21.25/A$ MeV, deformations of $\epsilon_2 = 0.263$, $\epsilon_4 = 0.035$ [16], and no specific allowance for configuration-dependent residual interactions, the $K^\pi = 19/2^+$ isomer is calculated to have an excitation energy of 1694 keV. This is in good agreement with the experimental energy of 1674 keV. However, it should be noted that this kind of calculation [15] has uncertainties ~100 keV, so that the small (20 keV) difference between the experimental and calculated energies is fortuitous.

The remainder of the discussion focuses on the implications of the isomer half-life in terms of K-mixing mechanisms. For decay γ rays that are highly K forbidden, it is common practice to consider the hindrance per degree of K forbiddenness, also called the *reduced hindrance*, $f_\nu = (T^\gamma_{1/2}/T^W_{1/2})^{1/\nu}$, where $T^\gamma_{1/2}$ is the experimentally deduced partial γ-ray half-life for the transition, $T^W_{1/2}$ is the corresponding Weisskopf single-particle estimate, and ν is the degree of forbiddenness (with $\nu = \Delta K - \lambda$, for multipolarity λ). In the present case, three K-forbidden transitions are observed from the $K^\pi = 19/2^+$ isomer. Their properties are given in Table III. For the interpretation given below, the reduced hindrance of the 438 keV, $E2(\nu = 4)$ transition, $f_\nu = 7.6$, is the most important.

It is reasonable to say that reduced hindrance values are typically in the range $20 < f_\nu < 300$ [17]. In addition, for $E2$ transitions from two- and three-quasiparticle isomers, reduced hindrance values have been shown [6] to be strongly correlated with the product of the valence nucleon numbers, N_pN_n. This is perhaps not surprising because, in essence, the more deformed nuclides, with higher N_pN_n values, would have less Coriolis K mixing, though other factors also need to be taken into account [6]. In the present case, ^{171}Tm has $N_pN_n = 260$, which is close to the ^{174}Yb value of $N_pN_n = 264$. However, the $E2\,(\nu = 4)$ decay component from the $K^\pi = 6^+$ isomer of ^{174}Yb is highly hindered, with $f_\nu = 341$ [18]. Therefore, the ^{171}Tm value of $f_\nu = 7.6$ is seen, by comparison, to be remarkably small, and more detailed consideration is appropriate.

One factor is that the three-quasiparticle configuration includes the $7/2^+[633]$, $i_{13/2}$ neutron, which, because of its high-j value, is susceptible to Coriolis-induced rotation alignment and associated K mixing. However, comparison with other isomers suggests that this does not have a dramatic

TABLE III. K-forbidden transitions from the $K^\pi = 19/2^+$, 1.7 μs isomer in ^{171}Tm.

E_γ (keV)	λ	I_γ	$\alpha_{\rm tot}$	$T^\gamma_{1/2}$ (μs)	ν	f_ν	$f^{\rm a}_\nu$
219.2	$M1$	29(5)	0.34	18	5	24.3(11)	
428.0	$E2$	217(10)	0.026	2.4	4	7.6(3)	
558.1	$E1$	47(6)	0.005	11	5	97(4)	16

[a]After taking out a factor of 10^4 from the hindrance, to account approximately for $E1$ systematics.

effect on the decay rate. For example, the configuration of the $19/2^+$ isomer in ^{175}Hf [19] includes the $7/2^+[633]$ neutron, and the $E2$ reduced hindrance still follows the N_pN_n correlation [6].

Inspection of the ^{171}Tm level scheme reveals that the $K^\pi = 19/2^+$ isomer is very close in energy to the $I^\pi = 19/2^+$ member of the $K^\pi = 7/2^+$ rotational band. The two $19/2^+$ states are only $\Delta E = 11$ keV apart. (The fact that the $K^\pi = 7/2^+$ band extension beyond spin 17/2 is tentative leads to only a small energy uncertainty, estimated to be ± 2 keV, because the energy spacing of the levels is seen to be regular, and is almost identical to that of the corresponding $7/2^+$ band in ^{173}Lu [12]. In the latter case, the $E2$ transition from the $19/2^+$ band member has an energy of 440 keV, compared to the tentative 439 keV in ^{171}Tm.) It is therefore appropriate to evaluate the effect of mixing between the two $19/2^+$ levels and to see whether this can account for the unexpectedly fast $E2$ decay of the isomer.

The suggestion is that a small $K = 7/2$ admixture in the predominantly $K = 19/2$ bandhead can explain the experimental 428 keV, $E2$ transition rate. It is assumed that there is a collective $K = 7/2$ component with reduced transition probability, $B(E2) = \frac{5}{16\pi} e^2 Q_o^2| < I_1 K 20 | I_2 K > |^2$. Because the final state is taken to be pure $K = 7/2$, it is only the $K = 7/2$ component in the isomeric state that needs to be evaluated. Assuming, as before, that $Q_o = 7.6$ eb, then the required admixture (amplitude squared) is $\beta^2 = 1.2 \times 10^{-6}$. In the two-level-mixing interpretation, the mixing matrix element for small β is $|V| = \Delta E \times \beta$ [20], and here $\Delta E = 11(2)$ keV. Thus $|V| = 12(2)$ eV is obtained. This fits well with the analysis of chance near-degeneracies given by Dracoulis *et al.* [20]. Therefore, the fast decay from the $K^\pi = 19/2^+$ isomer in ^{171}Tm can be explained as being due to a chance near-degeneracy with a lower-K state of the same spin and parity.

If this analysis of the $E2$ transition rate from the isomer is correct, then the $M1$ strength from the isomer should follow the rotational-model formulas, as used earlier for the branching ratios within the $7/2^+$ band. Based on this approach, the branching ratio for the isomeric 428 and 219 keV transitions, with $K = 7/2$ imposed, yields $|g_K - g_R| = 0.35(3)$, which agrees with the value of $|g_K - g_R| = 0.33(3)$ obtained for the $K^\pi = 7/2^+$ band itself. This agreement supports the two-level-mixing interpretation.

Although a simple explanation has thus been found for the $E2$ decay rate from the three-quasiparticle isomer, the present work highlights the difficulty in predicting K-isomer half-lives. This is because near-degeneracies are inevitably difficult to predict accurately, and the half-life of an isomer is very sensitive to any small admixture that provides an allowed component for a transition that is otherwise forbidden.

V. CONCLUSION

A γ-ray and conversion-electron study of ^{171}Tm, using pulsed-beam techniques, has revealed an isomer at 1674 keV, with a half-life of 1.7(2) μs, assigned as a $K^\pi = 19/2^+$, three-quasiparticle state. The $E2$ decay rate from the isomer is much faster than expected from N_pN_n systematics and is interpreted as being due to a chance near-degeneracy.

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