Structure of three-quasiparticle isomers in ^{169}Ho and ^{171}Tm

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A three-quasiparticle isomer with $\tau = 170(8)$ μs and $K^\pi = (19/2^+)$ has been identified in the neutron-rich isotope ^{169}Ho. The isomer decays with K-forbidden transitions to members of a band associated with the $7/2^-[523]$ proton configuration, whose structure is characterized through analysis of the in-band γ-ray branching ratios. In the isotone ^{171}Tm, the rotational band based on the known $19/2^+$, three-quasiparticle isomer has also been observed. Alternative one-proton two-neutron configurations for the isomer in ^{169}Ho are discussed in terms of multiquasiparticle calculations and through a comparison with the structures observed in ^{171}Tm.

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I. INTRODUCTION

Information on γ decay in well-deformed nuclei a few neutrons beyond the stability line is generally limited. The nucleus ^{165}Ho, with $N = 98$, is the only stable holmium isotope; ^{166}Ho has been extensively studied through neutron capture, while there is progressively less information on the levels of ^{167}Ho and ^{168}Ho. The neutron-rich isotope ^{169}Ho was originally identified from the β decay of the ^{169}Dy parent produced in multinucleon transfer reactions induced by an ^{170}Er beam incident on a heavy target [1]. The ^{169}Ho ground state, populated by a fast β decay from the $\nu\, 5/2^-[512]$ ^{169}Dy ground state, was associated with the $7/2^-[523]$ proton orbital, as expected from theoretical considerations and systematics. The only γ ray observed in that study was a 1578-keV transition assigned as a decay to the ground state from a level of the same energy. The low $\log ft$ value (4.8) was the basis for a possible $7/2^-$ assignment to the 1578-keV state, presumably of three-quasiparticle character, but one without a firm configuration assignment [1]. The majority of information on excited states in ^{169}Ho comes from single-particle transfer studies including ^{170}Er(t,α) with polarized triton beams [2].

As summarized in Ref. [3], members of the $7/2^-[523]$ band up to the $11/2^-$ level had been identified earlier, with an accuracy of about 4 keV. Other intrinsic states, and a few band members in some cases, include a $3/2^+[411]$ level at 254 keV, the $3/2^+$ member of the $1/2^+[411]$ band at 359 keV, and a candidate for the $7/2^+[404]$ intrinsic state at 1079 keV. The situation in terms of known states is similar for the lighter isotope ^{167}Ho, but in that case the $3/2^+[411]$ state is an isomer with a half-life of 6 μs [4]. We present new results here on levels in ^{169}Ho observed in the decay of a three-quasiparticle isomer populated in transfer reactions using energetic ^{136}Xe beams, as well as additional results on the properties of the recently identified isomer in the isotone ^{171}Tm [5]. The relation between states in the isotones is discussed in the context of predictions from multiquasiparticle calculations.

II. EXPERIMENTAL PROCEDURES

The experimental techniques used in the present study are essentially identical to those reported in a series of measurements aimed at the spectroscopy of stable and neutron-rich, well-deformed nuclei near $Z \sim 70$ (see, for instance, [6–8]). The beam and target conditions in these experiments (with beam energies ~20% above the Coulomb barrier) result in inelastic processes with single and multiple transfer of nucleons as well as inelastic excitation of the target and projectile nuclei (e.g., [9]).

Pulsed and chopped beams of 830-MeV ^{136}Xe were provided by the ATLAS facility at Argonne National Laboratory. Gamma rays were detected with the Gammasphere array [10] and various timing conditions were used to identify isomers and to isolate specific structures using γ-γ-time correlations. The beams were incident on a 6 mg/cm^2 thick metallic foil, enriched in ^{170}Er, and placed on a 25 mg/cm^2 gold backing. Under these conditions, γ rays from very short lived states will exhibit attenuated Doppler shifts, thus limiting the identification of high-spin states, unless they are populated through isomers, in which case the final decays will come from nuclei at rest. Complementary results, particularly for ^{171}Tm, were also obtained from the earlier bombardments on ^{176}Yb [6].

The main measurements used nanosecond pulses, separated by 825 ns, and data were only recorded when at least three γ rays with a relative time difference within approximately

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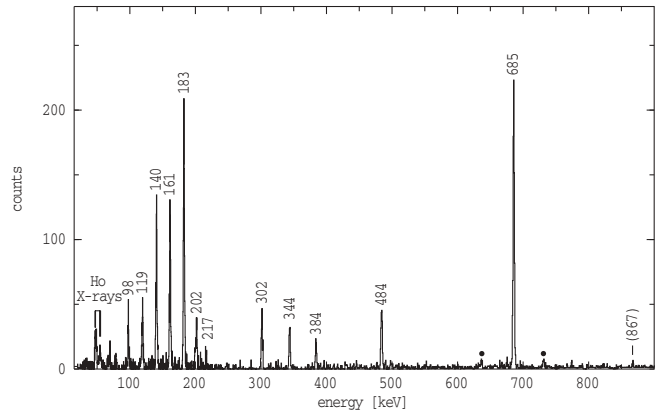

FIG. 1. Spectrum obtained from the sum of double γ-ray coincidence gates on the 98/{119,140,161,183}, 119/{161,183}, and 140/161 keV combinations. (Known contaminants are indicated by filled circles.)

$\pm$800 ns were detected. About 6×10^8 coincidence events of fold three and higher were collected in this configuration. A separate sequence of measurements was carried out with macroscopically chopped beams and beam-on–beam-off conditions that ranged from the regime of microseconds to seconds (as in Ref. [8]). In these measurements, out-of-beam events that satisfied a dual γ-γ-time condition were recorded.

III. RESULTS AND LEVEL SCHEMES

A. ^{169}Ho

A sample of the experimental results that forms part of the basis of the assignment in ^{169}Ho is given in Fig. 1. This spectrum was constructed by summing double-coincidence gates in the out-of-beam time region. A rotational band structure, including cascade and crossover transitions, is evident, with the main delayed feeding being through the prominent 685-keV transition. The observation of characteristic Ho x rays provides the Z identification, while the γ-ray energies of the first two cascade transitions in the band at 97.7 and 119.2 keV lead to level energies of 97.7 and 216.9 keV, in agreement with the energies of 98(4) and 215(4) keV reported for the $9/2^-$ and $11/2^-$ band members identified in the single-particle transfer studies [2,3]. The proposed level scheme can be found in Fig. 2.

The $g_K - g_R$ values deduced from the in-band branching ratios, as listed in Table I, are consistent with the expected values for the $7/2^-[523]$ proton configuration which would have $g_K = +1.3$ in the Nilsson model.

Although a weak 867.3-keV γ ray is marked in Fig. 1, it is only tentatively assigned as a branch from the isomeric state to the $15/2^-$ level. Its intensity is close to the limit of reliable observation, and there is a relatively strong 141-keV, 867-keV cascade in the decay of an isomer in ^{170}Er [11] which might lead to contamination in some coincidence gates.

A search was undertaken for additional decays from the isomer, as well as for structures associated with other intrinsic states and bands, but none were identified. This is not surprising since all low-lying intrinsic states except the ground

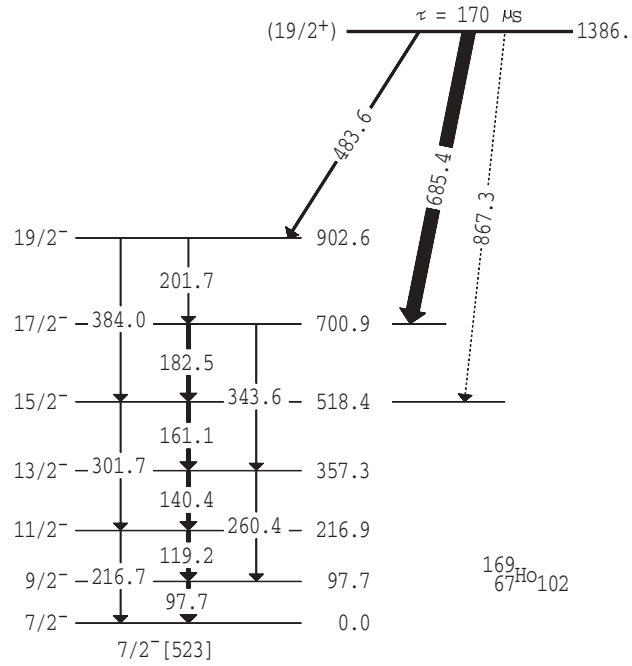

FIG. 2. Proposed decay scheme of an isomer in ^{169}Ho.

state have low K values. In contrast, the $7/2^+[404]$ state, for example, lies above 1 MeV in excitation energy [3]. This situation differs from that in the isotone ^{171}Tm [5,13], as discussed later, where such states are lower (because of the higher proton Fermi surface) and the isomer has more decay paths available.

The long lifetime of the isomer (see the following) precluded the identification of transitions feeding it, including the identification of its rotational band, which would have been valuable in distinguishing among alternative assignments.

The lifetime of the 1386-keV state was determined from the chopped beam measurements. Figure 3 provides the intensity of the main decay lines extracted from selected coincidence spectra, gated to isolate the transitions of interest, in contiguous time intervals, with beam-on and beam-off conditions of 30 and 300 μs. A fit to this spectrum, indicated by the solid curve in the figure, leads to a mean life of $\tau = 170(8)$ μs.

A search was also made for higher states in the $7/2^-[523]$ band in the prompt beam time region, but it was not possible to extend the band beyond the $19/2^-$ level populated in the decay of the isomer.

TABLE I. Branching ratios and $g_K - g_R$ values for the $7/2^-[523]$ band in ^{169}Ho.

J^π	$E_\gamma(\Delta I = 1)$ (keV)	$E_\gamma(\Delta I = 2)$ (keV)	λ[a] exp.	$\mid g_K - g_R \mid$[b] exp.
$17/2^-$	183	344	0.613(36)	0.982^{+31}_{-28}
$15/2^-$	161	302	0.426(37)	0.975^{+47}_{-41}
$13/2^-$	140	260	0.310(29)	0.882^{+46}_{-40}
$11/2^-$	119	217	0.219(24)	0.676^{+42}_{-36}

[a]The ratio of $\Delta I = 2/\Delta I = 1$ γ-ray intensities.
[b]Calculated by assuming $Q_0 = 7.7$ e b.

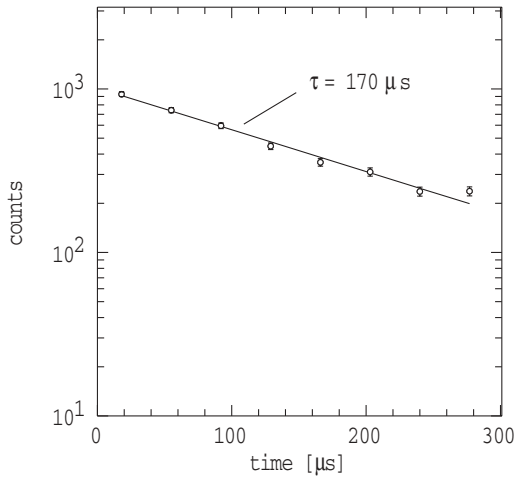

FIG. 3. Time dependence of the intensity of selected transitions that follow the decay of the isomer in ^{169}Ho. The solid line is a least-squares fit.

Transition strengths deduced from the measured γ-ray branching ratios, calculated conversion coefficients, and the measured lifetime are given in Table II. The tentative 867.3-keV branch to the $15/2^-$ state is given as a limit and thus its implied strength cannot be used as a primary argument for assignment. The reduced hindrance factors, f_ν, are also listed. The hindrance F is the inverse of the transition strength in Weisskopf units, the reduced hindrance being defined by $f_\nu = F^{1/\nu}$. The degree of forbiddenness for a multipolarity λ is given by the shortfall between the required K change and the transition multipolarity, that is, $\nu = |\Delta K| - \lambda$. Except for the case of $E1$ transitions, which are often already inhibited, typical values of f_ν range between about 50 and several hundred.

An initial evaluation of strengths leads to the conclusion that only the spin-parity combinations $J^\pi = 19/2^\pm$ and $21/2^\pm$ need to be considered. Of these, the $21/2^+$ possibility (not listed in the table) can be eliminated since the 484-keV transition would be of $M2$ character with $f_\nu = 12$, which is highly unlikely. (The tentative 867-keV γ ray would then be an $E3$ transition with $f_\nu \geqslant 17$.) From Table II, the $21/2^-$ possibility implies $f_\nu = 80$ for the 484-keV branch, which is acceptable, whereas the 685-keV branch has $f_\nu = 39$, a marginally low value. Thus, the $21/2^-$ alternative remains a possibility, but it is the least likely of the three. From Table II, both the $19/2^+$ and $19/2^-$ possibilities seem equally acceptable. These alternatives will be discussed in the following in the context of predictions of multiquasiparticle calculations, and in comparison with the properties of the three-quasiparticle $19/2^+$ isomer identified in the isotone ^{171}Tm [5].

B. ^{171}Tm

The properties of the $K^\pi = 19/2^+$ isomer at 1674 keV in ^{171}Tm were established in Ref. [5], including the tentative identification of two cascade transitions in the band based on the isomer. More extensive results were obtained in the present work by selecting transitions that feed the isomer, using double gates on pairs of delayed transitions that follow its decay. The main transitions are evident in Fig. 4. In the absence of any higher lying isomers, these events occur within the beam pulse, hence explaining the presence of a high continuous background and random coincidences. (The 207-keV transition indicated in parentheses is not placed in the rotational band, but it does feed the isomeric state.)

As can be seen from this spectrum, the crossover transitions are more intense than the cascade transitions. The in-band γ-ray branching ratios deduced from the measured intensities and the $g_K - g_R$ values are listed in Table III.

IV. MULTIQUASIPARTICLE CALCULATIONS AND CONFIGURATIONS

Calculations of the expected multiquasiparticle spectra were carried out using an approach similar to that of Jain *et al.* [14], but using a Lipkin-Nogami pairing treatment rather than BCS (see Refs. [15–17]). The procedure involves choosing a set of single-particle levels together with the neutron and

TABLE II. Transition strengths and hindrances for different spin assignments to the isomer in ^{169}Ho.

E_γ (keV)	I_γ relative	$\sigma\lambda$	α_T [a]	$B(\sigma\lambda)$ (e^2 fm$^{2\lambda}$ or μ_0^2 fm$^{(2\lambda-2)}$)	Strength (W.u.)	ν	f_ν
$K^\pi = 19/2^+$							
483.6	223(16)	$E1$	0.00577	$6.16(57)\times10^{-12}$	$3.13(29)\times10^{-12}$	5	200
685.4	940(40)	$E1$	0.00273	$9.13(67)\times10^{-12}$	$4.63(34)\times10^{-12}$	5	185
(867.3)	$\leqslant$16(4)	$M2$	0.0210	$\leqslant1.20(31)\times10^{-5}$	$\leqslant2.37(61)\times10^{-7}$	4	$\geqslant$45
$K^\pi = 19/2^-$							
483.6	223(16)	$M1$	0.0351	$5.49(51)\times10^{-10}$	$3.07(29)\times10^{-10}$	5	80
685.4	940(40)	$M1$	0.0145	$8.14(60)\times10^{-10}$	$4.55(33)\times10^{-10}$	5	74
(867.3)	$\leqslant$16(4)	$E2$	0.0043	$\leqslant1.30(34)\times10^{-7}$	$\leqslant2.35(60)\times10^{-9}$	4	$\geqslant$144
$K^\pi = 21/2^-$							
483.6	223(16)	$M1$	0.0351	$5.52(52)\times10^{-10}$	$3.09(29)\times10^{-10}$	5	80
685.4	940(40)	$E2$	0.0073	$2.50(18)\times10^{-5}$	$4.50(33)\times10^{-7}$	4	39
(867.3)	$\leqslant$16(4)	$M3$	0.0448	$\leqslant1.76(45)\times10^{2}$	$\leqslant1.14(29)\times10^{-1}$	3	$\geqslant$2.1

[a]BRICC, Ref. [12].

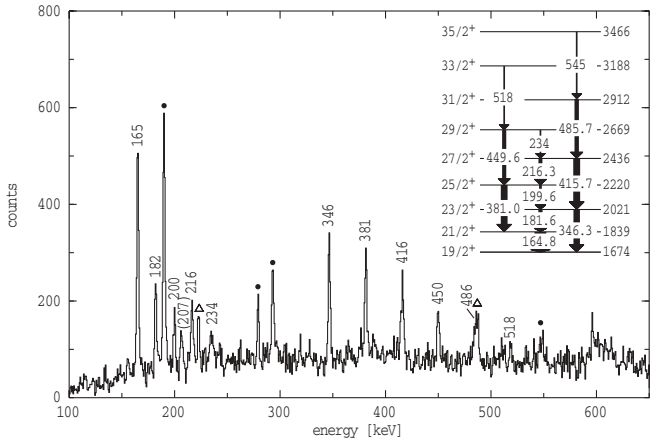

FIG. 4. Spectrum of transitions within the beam pulse and feeding the 1674-keV isomer in ^{171}Tm. The main contaminants (indicated by filled circles) are due to random coincidences with strong (prompt) transitions from the ^{176}Yb target and the ^{197}Au backing. Other known contaminants are indicated by open triangles. The inset shows the proposed level scheme based on the $19/2^+$ isomer.

proton pairing strengths G_ν and G_π and incorporates a self-consistent treatment of the Fermi level and pairing gaps. Particle-number conservation and blocking of occupied states for multiquasiparticle configurations are included. For the present calculations, three oscillator shells were used for each of the neutron and proton spaces, resulting in 64 levels (128 states) with 29 active protons and 62 active neutrons. The Nilsson orbitals were calculated by assuming the predicted deformations [18] of $\epsilon_2 = 0.275$ and $\epsilon_4 = 0.040$ for ^{169}Ho and $\epsilon_2 = 0.267$ and $\epsilon_4 = 0.053$ for ^{171}Tm, to give a set of single-particle states. For simplicity, there were no adjustments to the nominal energies, although this has been a common procedure in more extensive comparisons. The $1/2^+[411]$ configuration generally forms the ground state in Tm nuclei whereas the $7/2^-[523]$ proton in the Ho isotopes is lowest, owing to the lower Fermi level.

The pairing strengths were taken as $G_\nu = 18.0/A$ and $G_\pi = 20.8/A$, the same values selected in evaluations of a range of Yb, Ta, and Lu isotopes (see, for example, Refs. [7,15]) and recently for the nearby even-even Er isotopes $^{168-172}$Er [11]. Empirical residual interactions [14,17] are included in the calculation of final-state energies so that the final energies are given by $E_{\rm calc} = E_{\rm qp} + E_{\rm res}$. The lowest calculated three-quasiparticle states of relevance in ^{169}Ho and ^{171}Tm are listed in Table IV. Since all are from two-neutron, one-proton configurations and both isotopes are expected to have similar deformations, the essential difference between the isotones is that the predicted states are about 400 keV lower in ^{169}Ho, since the $7/2^-[523]$ configuration forms the ground state in ^{169}Ho but is, in contrast, 425 keV above the $1/2^+[411]$ ground state in ^{171}Tm.

TABLE III. Transitions, branching ratios, and $g_K - g_R$ values for the $19/2^+$ isomer band in ^{171}Tm.

J^π	$E_\gamma(\Delta I = 1)$ (keV)	$E_\gamma(\Delta I = 2)$ (keV)	λ[a] exp.	$\lvert g_K - g_R\rvert$[b] exp.
$29/2^+$	234	450	2.41(74)	0.165^{+48}_{-32}
$27/2^+$	216	416	1.73(15)	0.165^{+11}_{-10}
$25/2^+$	200	381	2.45(32)	0.068^{+18}_{-17}
$23/2^+$	182	346	1.53(12)	$0.023^{+18}_{-(\rm nd)}$ [c]

[a]The ratio of $\Delta I = 2/\Delta I = 1$ γ-ray intensities.
[b]Calculated by assuming $Q_0 = 7.7\ e$ b.
[c]nd: not defined; for $K = 19/2$, $\lambda < 1.65$.

TABLE IV. Calculated three-quasiparticle states in ^{169}Ho and ^{171}Tm.

K^π	Configuration		$E_{\rm qp}$	$E_{\rm res}$	$E_{\rm calc}$
	ν	π		(keV)	
^{169}Ho					
$19/2^+$	$5/2^-[512]\ 7/2^+[633]$	$7/2^-[523]$	1172	−11	1161
$19/2^-$	$5/2^-[512]\ 7/2^-[514]$	$7/2^-[523]$	1522	−245	1277
$21/2^+$	$7/2^-[514]\ 7/2^+[633]$	$7/2^-[523]$	1486	−95	1391
^{171}Tm					
$19/2^+$	$5/2^-[512]\ 7/2^+[633]$	$7/2^-[523]$	1641	−11	1630
$19/2^-$	$5/2^-[512]\ 7/2^-[514]$	$7/2^-[523]$	1852	−245	1607
$21/2^+$	$7/2^-[514]\ 7/2^+[633]$	$7/2^-[523]$	1900	−95	1805

V. CONFIGURATION ASSIGNMENTS FOR ^{169}Ho AND COMPARISON WITH ^{171}Tm

The isomer in ^{171}Tm has a firm spin-parity assignment of $K^\pi = 19/2^+$ and is associated, therefore, with the $\nu 5/2^-[512]7/2^+[633] \otimes \pi 7/2^-[523]$ configuration [5]. This is supported by new results on the properties of the rotational band identified above it, particularly the alignment, as discussed in the following.

As can be seen from Fig. 5, the alignment is essentially equal to the sum of the alignments for the 6^- two-neutron core in ^{172}Yb (containing the $7/2^+[633]$ $i_{13/2}$ neutron) [19] and the $7/2^-[523]$ proton in ^{171}Tm [13]. The agreement in this case is consistent with the expectation that additivity of alignments would apply in cases where the two components are of different character, that is, a proton and a neutron configuration, whereas in instances where orbitals of common character occur, there is additional blocking and saturation of the alignment sum [20].

The observed $g_K - g_R$ values extracted from the in-band branching ratios are small in magnitude (see Table III), but only roughly consistent with an expected value of -0.04. (The low magnitude arises because the proton and neutron components cancel approximately.) However, although they are not precisely determined, there is an indication of a spin dependence in the experimental values. Although that might also be expected, given the significant spin alignment in the band, the values obtained when the alignment is taken into account using the formalism given by Bark *et al.* [21] are predicted to be approximately constant, at ∼0.075, for all observed states. The magnitude agrees with the *average* of the observed values but the spin dependence differs.

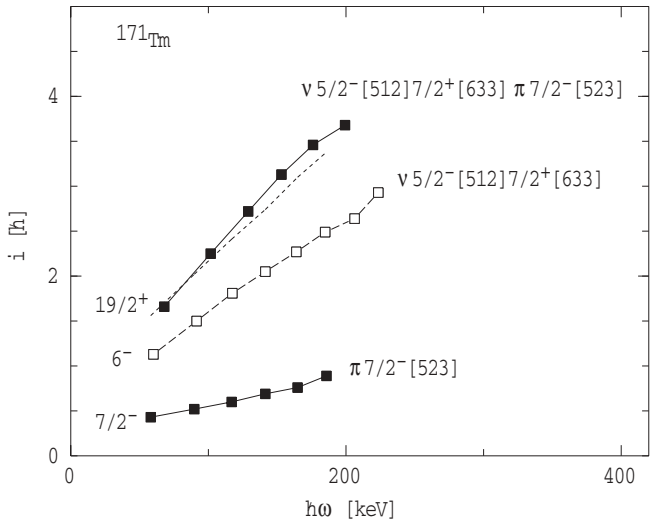

FIG. 5. Net alignments as a function of rotational frequency for the $19/2^+$ band in ^{171}Tm, compared to the alignments for the one-proton (^{171}Tm) and two-neutron (^{172}Yb) components in the configuration. The dashed line (no points) indicates the sum of the two components. Reference parameters of $\Im_0 = 41.1$ MeV$^{-1}\,\hbar^2$ and $\Im_1 = 47$ MeV$^{-3}\,\hbar^4$ were used.

Unfortunately, the much longer lifetime in ^{169}Ho precludes the direct identification of the equivalent band above the isomer, and, as discussed earlier, the spectroscopic information on its decay is insufficient to distinguish between the $19/2^-$ and $19/2^+$ possibilities. (The expected $g_k - g_R$ values are in fact of opposite sign, but of similar magnitude, being $\sim +0.17$ for the $19/2^-$ configuration and -0.04 for the $19/2^+$ alternative already discussed.) Since the $19/2^-$ configuration does not contain an $i_{13/2}$ neutron, its band would exhibit a much lower alignment than that expected (and observed in ^{171}Tm) for the $19/2^+$ case.

When comparing the decay properties in the two isotopes, it should be noted that the 1674-keV ^{171}Tm isomer has a relatively short mean life of 1.7 μs, partly because of mixing with a collective state in the proton $7/2^+[404]$ band resulting in a relatively fast decay path, in addition to the branches to the $7/2^-[523]$ band [5]. As discussed earlier, the $7/2^+[404]$ configuration (and its band members) is located at a much higher energy in ^{169}Ho. The only equivalent decay in ^{171}Tm, (if both have $K^\pi = 19/2^+$) is a 558-keV $E1$ branch to the $17/2^-$ member of the $7/2^-[523]$ band with $f_\nu = 97(4)$, significantly less hindered than the strengths for the implied $E1$ transitions in ^{169}Ho, which have $f_\nu \sim 200$ (Table II). Although the description proposing a dependence of the reduced hindrances on the energy above the yrast line was not developed for $E1$ transitions [22], the lower hindrance in ^{171}Tm could be consistent with the higher excitation energy and therefore increased mixing, being about 500 keV more nonyrast than in the ^{169}Ho case.

While the multiquasiparticle calculations marginally favor the $19/2^+$ assignment in ^{169}Ho, this conclusion should be tempered with the consideration that the excitation energy is somewhat underestimated and that the same calculations predict that the $19/2^-$ state would be slightly lower in ^{171}Tm, although in that case the $19/2^+$ rather than the $19/2^-$ level is observed. This should simply be viewed as an indication that the calculations cannot be expected to be more accurate than about 100 keV. It also implies that the $19/2^-$ intrinsic state would be close by and could be expected to have preferential decays (because of the high K) to the $19/2^+$ isomer and its band, as would a $21/2^+$ intrinsic state predicted to lie about 200 keV higher (see Table IV).

VI. SUMMARY

A long-lived isomer with $\tau = 170(8)$ μs has been identified in the neutron-rich isotope ^{169}Ho. The isomer decays to the rotational band based on the $7/2^-[523]$ ground state, allowing characterization of that band. The isomer probably has $K^\pi = 19/2^+$, from the same two-neutron, one-proton configuration that produces the $19/2^+$ isomer in ^{171}Tm. The rotational band associated with the ^{171}Tm isomer has also been identified and the observed spin alignment provides additional support for the original configuration assignment. The lower energy in ^{169}Ho (1386 keV compared to 1674 keV in ^{171}Tm) arises from the lower proton Fermi level. The K-forbidden transition strengths are consistent with this interpretation, although in the absence of identification of the band above it, the alternative $19/2^-$ assignment for the isomer, from a competing two-neutron, one-proton configuration, cannot be completely discounted.

ACKNOWLEDGMENTS

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