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Properties of the low-lying $K^{\pi}=0^{+}$ excitations in ^{162}Er

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Excited states of ^{162}Er were populated in β decay and studied through γ-ray spectroscopy at TRIUMF ISAC to assess the nature of low-lying $K^{\pi}=0^{+}$ instrinsic excitations. Improved measurements of the decay properties of the lowest $K^{\pi}=0^{+}$ excitation suggest a β-vibrational nature for its structure. Data were also obtained ruling out the spin assignment of a previously assigned $K^{\pi}=(0_3^{+})$ excitation.

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The β-vibrational mode was proposed 50 years ago [1] and has since been widely accepted as a benchmark for the interpretation of the lowest $K^{\pi}=0^{+}$ excitation in rotational nuclei; however, the actual existence of a low-lying β-vibrational mode has not been well established as a property of axisymmetric deformed nuclei. A survey of the presently available data, as carried out in Ref. [2], reveals no unambiguous candidate for a first excited $K^{\pi}=0^{+}$ excitation with β-vibrational character in the rare earth nuclei. The situation may partly be a reflection of the lack of necessary data. Reliable values for key observables in the interpretation of the structure of low-lying 0^{+} excitations—level lifetimes and γ-ray or conversion electron branching ratios—are not available for many of the states of interest, in part since the 0^{+} bandhead states are not well populated by many production mechanisms. However, there are also general difficulties in the categorical interpretation of the lowest-lying $K^{\pi}=0^{+}$ excitation as a β vibration or as any form of collective excitation at all [2,3].

Recent developments in detector technology coupled with the effective use of low-spin population mechanisms have allowed the investigation of low-lying $K^{\pi}=0^{+}$ excitations to be approached with renewed vigor. Accurate measurement of low-intensity γ-ray transitions is of central importance in the interpretation of excitations. Measurements of intensities from singles data are notoriously prone to error due to the presence of unresolved contaminant transitions—β-decay experiments with Q_{β} values of a few MeV commonly produce several hundred identifiable γ-ray transitions, many of them yielding overlapping or unresolved peaks in the singles spectra. For instance, in ^{162}Er, five of the ten most strongly populated transitions in β decay are doublets [4,5]. The advent of compact, high-efficiency arrays of large-volume Ge detectors has permitted a new generation of γ-ray spectroscopy β-decay experiments which produce high-statistics coincidence data. These data provide much more reliable information on the placement of transitions in the decay scheme and allow γ-ray transition intensities to be determined from relatively clean gated spectra.

The availability of high-purity, high-intensity β-decay activities from ISOL-type radioactive beam production sources presently coming on line promises to provide the next major improvement in the quality of γ-ray spectroscopy data on $K^{\pi}=0^{+}$ excitations, allowing greatly improved measurements on nuclei near stability and making nuclei far from stability accessible to β-decay spectroscopy for the first time.

It is the purpose of this paper to present the results of an investigation of the low-lying collective structure of ^{162}Er, focusing specifically upon the properties of the low-lying $K^{\pi}=0^{+}$ excitations. This experiment was among the first to be performed at the recently commissioned TRIUMF Isotope Separator and Accelerator (ISAC) facility [6], a new generation radioactive beam facility. The present results significantly revise earlier data and resolve problems in interpretation of the $K^{\pi}=0_2^{+}$ excitation, suggesting a β-vibrational nature for its structure. Data were also obtained ruling out the spin assignment of the nominal $K^{\pi}=(0_3^{+})$ excitation, the only other low-lying excitation in ^{162}Er previously identified in the literature [5] as having $K^{\pi}=0^{+}$ character.

The nucleus ^{162}Er, with $N=94$, is the lowest neutron number member of the Er isotopic chain for which the ground state band observables indicate a well-deformed rotational structure, with a 2_g^{+} level energy of 102 keV, an $E(4_g^{+})/E(2_g^{+})$ energy ratio of 3.23, and a $B(E2;2_g^{+}\rightarrow 0_g^{+})$ strength of 191(1) W.u. [5]. The observed collective phenomena in the higher-mass isotopes—in particular ^{166,168}Er [7–11]—suggest that this is a fertile region for the investigation of collective intrinsic excitation modes.

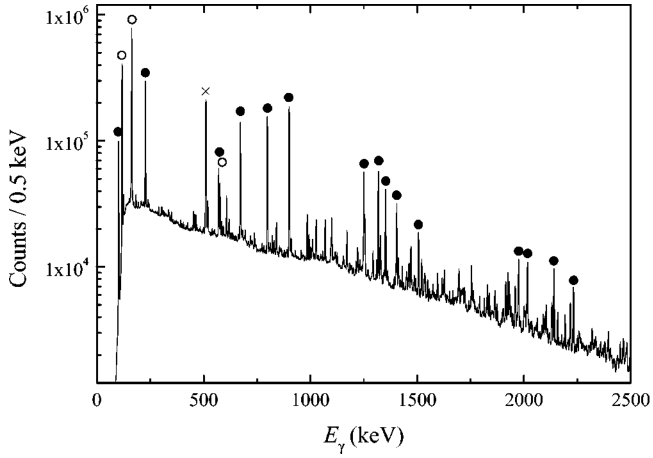

FIG. 1. Ge detector singles spectrum. Intense transitions from ^{162}Tm (open circles) and ^{162}Er (solid circles) and 511 keV annihilation radiation (cross) are marked.

The nucleus ^{162}Er is of special interest since the 2^+ state at 1171 keV, assigned [4] to the $K^\pi = 0_2^+$ band, is reported [12] to decay to the ground state band with a collective $B(E2)$ strength corresponding to a squared intrinsic matrix element $|\langle K^\pi = 0_2^+ | E2 | K^\pi = 0_g^+ \rangle|^2 = 8.0(13)$ W.u. This is comparable to the largest such values for any $K^\pi = 0^+$ excitation in the rare earth region [2] and fully half as large as for the γ-vibrational excitation in this nucleus $|\langle K^\pi = 2_\gamma^+ | E2 | K^\pi = 0_g^+ \rangle|^2 = 15.5(13)$ W.u. [12]. However, the reported relative $B(E2)$ strengths [4] of the transitions depopulating this level deviate from the Alaga rules by nearly an order of magnitude and can be reconciled with the Alaga rules through mixing of the ground and $K^\pi = 0_2^+$ bands only by invoking interaction strengths (~ 50 keV) for the 2^+ state an order of magnitude stronger than are typical for rotation-vibration interactions in the rare earth region. This casts some doubt on the $K^\pi = 0^+$ assignment for the 2^+ level and therefore the interpretation of the $K = 0_2^+$ excitation.

The nucleus ^{162}Er was populated in β^+/ϵ decay and studied through γ-ray coincidence spectroscopy. The present experiment was made possible by the availability of intense ($\sim 10^9$/s), high-purity beams of ^{162}Yb as β-decay parent nuclei at ISAC. The ^{162}Yb nuclei were produced in the ISAC ion source, through spallation of a Ta production target by a 500 MeV proton beam from the TRIUMF Cyclotron. The spallation products were extracted from a surface ion source, mass separated at 29 keV, and transported to the general purpose β-decay end station [13,14]. The beam nuclei were embedded into a 25-mm-wide aluminized Mylar tape inside a vacuum chamber. This tape was advanced at approximately 1-h intervals, carrying the collected activity through differential pumping to a shielded detector area.

The ^{162}Yb parent nucleus decays with an 18.9 m half-life through β^+/ϵ decay to ^{162g}Tm, which in turn decays with a 21.7 m half-life to ^{162}Er [5]. Transitions from both members of the decay chain—^{162}Tm and ^{162}Er—were present in the experiment (Fig. 1). No contaminants were present at observable levels.

Two large-volume coaxial Ge detectors (80% relative efficiency) were positioned 12 cm from the source position. The detectors were oriented obliquely with respect to each other and separated by lead shielding to suppress unwanted coincidence events due to β^+ annihilation photon pairs and Compton cross scattering. The combined photopeak efficiency was 0.8% at 1.3 MeV. The experiment was essentially detector limited in nature, due to the constraint of maintaining acceptable count rates in the individual detectors ($\lesssim 20$ kHz). The maximum beam deposition rate which could be accommodated was $\sim 10^5$ ^{162}Yb/s.

TABLE I. Relative intensities of transitions depopulating members of the $K^\pi = 0_2^+$ band and one-sigma intensity limits on unobserved transitions. $B(E2)$ values deduced from the intensities are shown, normalized to the literature $B(E2; 0_g^+ \rightarrow 2_{K=0_2}^+)$ value of 8.0(13) W.u. [12], along with the Alaga rule predictions.

Transition	Experiment			Alaga
	E_γ (keV)	I_{rel}	$B(E2)$ (W.u.)	$B(E2)$ (W.u.)
$0_{K=0_2}^+ \rightarrow 2_g^+$	985.2(2)	100(5)		
2_γ^+	[186]	<3.4		
$2_{K=0_2}^+ \rightarrow 0_g^+$	1171.05(15)	100(5)	$\equiv 1.6(3)$	$\equiv 1.6$
2_g^+	1069.05(15)	100(5)	$2.5(5)^{a,b}$	2.3
4_g^+	841.37(18)	59(3)	$4.9(10)^{a}$	4.1
2_γ^+	[271]	<1.5	<37	
3_γ^+	[169]	<2.6	$<6.6\times 10^2$	

[a] The dominant contribution to the uncertainties in deduced $B(E2)$ values is from normalization to the $B(E2; 0_g^+ \rightarrow 2_{K=0_2}^+)$ value of Ref. [12]. Ratios of these $B(E2)$ values [e.g., for comparison with the Alaga rules or use in mixing analysis (see text)] may be obtained with much smaller uncertainties directly from the intensity values in column 3.

[b] $B(E2)$ value calculated assuming pure $E2$ multipolarity.

Data were acquired in event mode, with variously a Ge singles or doubles trigger. Energy and relative timing information for the Ge detectors were recorded using a CAMAC-based acquisition system read out by a PC/Linux front end computer running PSI/TRIUMF Midas [15]. Deposition rates and other diagnostic data were recorded by a scaler module. Data were taken with a Ge singles trigger for 16 h, yielding 1.5×10^8 events, and with a doubles trigger for 120 h, yielding 6×10^7 coincidence events.

Two members of the $K^\pi = 0_2^+$ band are populated in β decay: the 0^+ level at 1087 keV and the 2^+ level at 1171 keV. Intensities for the transitions depopulating these levels, obtained from the present coincidence data, are summarized in Table I. (The intensities obtained are consistent with those observed in singles.) Limits are shown for the intensities of transitions which were not observed. The level scheme for the low-spin members of the γ and $K^\pi = 0_2^+$ bands, including these levels, is presented in Fig. 2.

The present measurements of the decay properties of the $K^\pi = 0_2^+$ excitation substantially revise the γ-ray branching data. The intensity of the 1171 keV $2_{K=0_2}^+ \rightarrow 0_g^+$ transition, relative to the other branches depopulating the $2_{K=0_2}^+$ level,

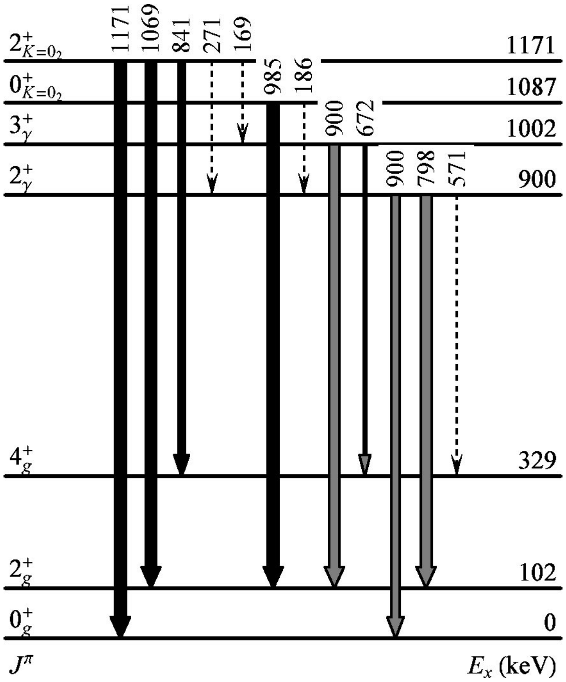

FIG. 2. Level scheme for the low-spin members of the ground, γ, and $K^\pi=0^+_2$ bands in ^{162}Er obtained from the present work. Transitions from the $K^\pi=0^+_2$ band members (black arrows) and from the γ band members (gray arrows) are shown. Arrow widths are proportional to the γ-ray intensity, normalized to the strongest transition from each level. Unobserved transitions for which intensity limits were obtained are indicated by dashed arrows.

can be obtained in a straightforward fashion from spectra gated on transitions feeding the $2^+_{K=0_2}$ level [Fig. 3(a)]. The present data provide an intensity about 7 times greater than previously reported. (Most of the singles intensity of the 1171 keV line was previously assigned [4] to a placement elsewhere in the level scheme. The present high-statistics coincidence data eliminate this other placement and show that essentially all of the intensity corresponds to the $2^+_{K=0_2}\rightarrow 0^+_g$ transition.) With this newly measured transition intensity, the relative $B(E2)$ values for the branches from the $2^+_{K=0_2}$ level change accordingly and are now in reasonably good agreement with the Alaga rules (Table I). The measured $B(E2;2^+_{K=0_2}\rightarrow 4^+_g)/B(E2;2^+_{K=0_2}\rightarrow 0^+_g)$ ratio is 3.1(2). The deviation of this from the Alaga value of 2.6 can be attributed to relatively minor mixing effects, discussed below. [In contrast, the literature data [4] corresponded to a $B(E2)$ ratio of 20(15), which would have suggested an order of magnitude larger mixing.]

The $B(E2;0^+_g\rightarrow 2^+_{K=0_2})$ transition strength is reported from a Coulomb excitation cross section measurement [12] to be 8.0(13) W.u. The procedure used in Ref. [12] for extracting the $B(E2;0^+_g\rightarrow 2^+_{K=0_2})$ value from the Coulomb excitation cross section was noted, in Ref. [16], to be suspect since it ignores multistep processes. However, since the present branching ratio data show the relative $2^+_{K=0_2}\rightarrow 0^+_g$ γ-ray branch to be much stronger than previously thought, direct excitation is greatly enhanced over any possible two-step excitation. Coulomb excitation yield calculations using the present intensities and the semiclassical formalism of Alder and Winther [17] show that excitation via the 2^+_g state and reorientation effects can produce at most a 10% change in the $B(E2)$ value obtained.

With the new branching ratio data, which now allow a firm association of the 2^+ level at 1171 keV with the $K=0^+_2$ band, and with the validation of the $B(E2;0^+_g\rightarrow 2^+_{K=0_2})$ value of 8.0(13) W.u., the 0^+_2 excitation is established as an excellent candidate for a β vibrational excitation. However, it should be noted that the enhancement observed for the $0^+_g\rightarrow 2^+_{K=0_2}$ transition falls substantially short of that expected from a geometric picture [18] for a β vibra-

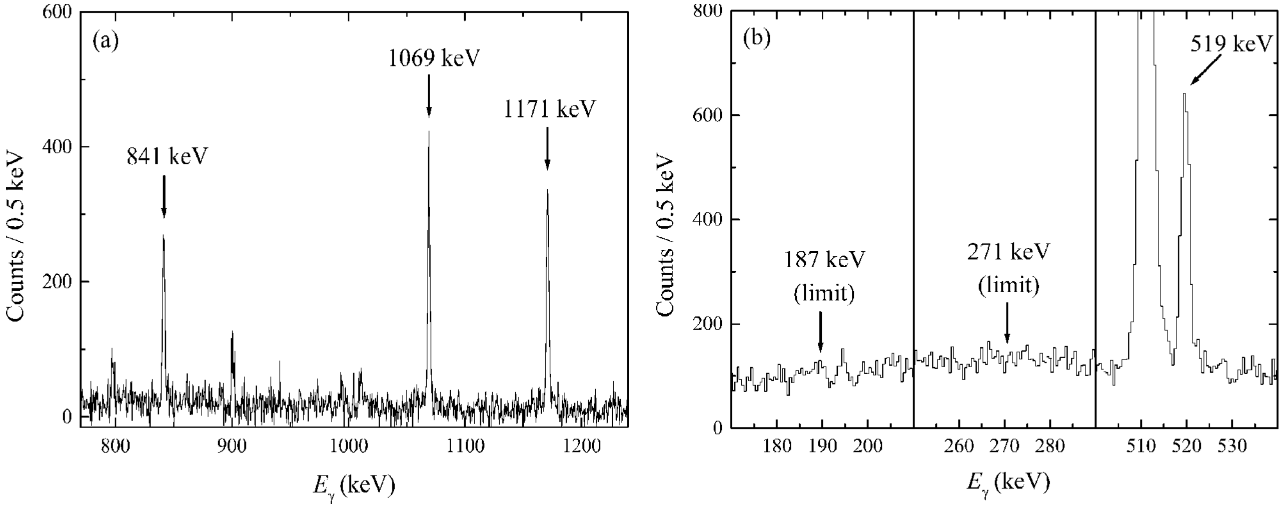

FIG. 3. Transitions from $K^\pi=0^+_2$ band members. (a) Composite spectrum gated on 551, 639, 1224, 1236, and 2096 keV transitions feeding the $2^+_{K=0_2}$ level at 1171 keV, showing the 841, 1069, and 1171 keV branches from this level. (b) Spectrum gated on the 798 keV $2^+_\gamma\rightarrow 2^+_g$ transition. Nonobservation of 186 or 271 keV transitions from $0^+_{K=0_2}$ or $2^+_{K=0_2}$ to 2^+_γ in this spectrum allows limits to be placed upon their intensities. The observed 519 keV transition from the misassigned (0^+) level at 1420 keV (see Table II) is shown for comparison.

tion at the same excitation energy, suggesting that inclusion of other degrees of freedom may be necessary for the interpretation of this excitation.

A new $\rho^2(E0;2^+_{K=0_2}\rightarrow 2^+_g)$ value can be deduced by combining existing conversion electron data with the present γ-ray data. The K-conversion intensity for the $2^+_{K=0_2}\rightarrow 2^+_g$ transition in ^{162g}Tm β decay was obtained from singles conversion electron data in Ref. [4]. The value in that reference is given indirectly, as a γ-ray intensity together with a K-conversion coefficient, but it is straightforward to extract the result $I_K(2^+_{K=0_2}\rightarrow 2^+_g)=0.43(5)$, normalized to $I_\gamma(4^+_g\rightarrow 2^+_g)\equiv 100$. In these same units, the present γ-ray intensity for the $2^+_{K=0_2}\rightarrow 0^+_g$ transition is 17.3(15). The $\rho^2(E0)$ value may be calculated directly from these intensities. The transition probability per unit time for K-shell $E0$ electron emission is

$$T_K(E0)=\rho^2(E0)\Omega_K, \qquad (1)$$

where Ω_K is the K-shell electronic factor for the $E0$ transition [19]. Thus, the $\rho^2(E0)$ value may be expressed in terms of the intensities as

$$\rho^2(E0;2^+_{K=0_2}\rightarrow 2^+_g) = \frac{T_\gamma(E2;2^+_{K=0_2}\rightarrow 0^+_g)}{\Omega_K(2^+_{K=0_2}\rightarrow 2^+_g)}\,\frac{I_K(E0;2^+_{K=0_2}\rightarrow 2^+_g)}{I_\gamma(E2;2^+_{K=0_2}\rightarrow 0^+_g)}, \qquad (2)$$

where $T_\gamma(E2)$ is the transition probability per unit time for the $E2$ γ-ray transition and can be directly expressed in terms of the $B(E2)$ value for that transition. The experimental $2^+_{K=0_2}\rightarrow 2^+_g$ K-shell electron intensity includes $E0$, $M1$, and $E2$ contributions, and so the $M1$ and $E2$ contributions must be subtracted on the basis of the known $2^+_{K=0_2}\rightarrow 2^+_g$ γ-ray intensity in order to recover the $E0$ contribution. The $M1/E2$ mixing ratio for this transition is not known, but the value of the mixing ratio affects the calculated $\rho^2(E0)$ by at most 10%. Assuming no $M1$ contribution, the extracted $\rho^2(E0)$ is 0.061(14).

If the $K^\pi=0^+_2$ excitation is assumed to be a β vibration, the rotation vibration model (RVM) [18] relates the $E0$ strength to $E2$ strengths as [16]

$$\rho^2(E0;\beta\rightarrow g)=\frac{4B(E2;0^+_g\rightarrow 2^+_\beta)\beta_0^2}{e^2 r_0^4 A^{4/3}}, \qquad (3)$$

where the equilibrium quadrupole deformation β_0 can be extracted from the ground state intraband $B(E2;2^+_g\rightarrow 0^+_g)$ strength [20]. The present experimental value 0.061(14) is in excellent agreement with the RVM value of 0.077(12). In comparison, the previously existing branching data would have led to a $\rho^2(E0)$ value of 0.5(4), far larger than any other reported $\rho^2(E0)$ value in the deformed rare earth nuclei [16].

It is useful to assess the extent to which $\Delta K=0$ mixing between the $K^\pi=0^+_2$ and ground state bands affects the value deduced for the intrinsic interband matrix element. The observed $B(E2;2^+_{K=0_2}\rightarrow 4^+_g)/B(E2;2^+_{K=0_2}\rightarrow 0^+_g)$ ratio corresponds to a mixing parameter value [20] of $a_0=-0.0044(19)$, which would be induced by an intrinsic interaction strength $|\langle K^\pi=0^+_2|h_0|K^\pi=0^+_g\rangle|=0.44(19)$ keV (or a mixing matrix element of $\sim$2.6 keV for the 2^+ state). With this mixing, the squared intrinsic matrix element $|\langle K^\pi=0^+_2|E2|K^\pi=0^+_g\rangle|^2$ is 8.4(16) W.u.

While it would be interesting to have the results of a full three-band mixing calculation [21,22] involving the ground, γ, and $K^\pi=0^+_2$ excitations, there is currently insufficient information on higher-lying band members and on $M1/E2$ mixing ratios [5] for such an analysis to be feasible. Mixing between the γ and $K^\pi=0^+_2$ bands is only expected to have a significant effect upon the $K^\pi=0^+_2$ to ground state band transition strengths in nuclei for which the $K^\pi=0^+_2$ and γ bands are nearly degenerate. For mixing between the γ and $K^\pi=0^+_2$ bands to account for the observed $B(E2;2^+_{K=0_2}\rightarrow 0^+_g)$ strength in ^{162}Er would require nearly complete mixing of the $2^+_{K=0_2}$ and 2^+_γ states, corresponding to an interaction matrix element of $\sim$100 keV. Such mixing would also result in a strong $2^+_{K=0_2}\rightarrow 2^+_\gamma$ transition [$B(E2;2^+_{K=0_2}\rightarrow 2^+_\gamma)\approx 176$ W.u.]. Experimentally, no γ-ray transition was observed between the $2^+_{K=0_2}$ and 2^+_γ states [Fig. 3(b)], and the $B(E2)$ limit obtained (Table I) is inconsistent with such a mixing picture.

Transitions between the $K^\pi=0^+_2$ and γ bands are also important for interpretation within the framework of the interacting boson model (IBM), since the IBM can predict substantial transition strengths between these two bands [23,24]. For IBM parameter values relevant to ^{162}Er [25], the predicted interband to in-band transition strength ratio is $B(E2;2^+_{K=0_2}\rightarrow 2^+_\gamma)/B(E2;2^+_{K=0_2}\rightarrow 2^+_g)\approx 6$, which is not inconsistent with the present experimental limit of <15 (Table I).

The other low-lying $K^\pi=0^+$ excitation in ^{162}Er identified in the literature is based upon a tentative spin assignment of 0^+ for the level at 1420 keV. This excitation, from its reported decay properties, would have been of interest as a possible two-γ-phonon excitation candidate.

There are several reasons given in Ref. [4] for a 0^+ assignment for the level at 1420 keV. The only observed γ rays were to 2^+ states: 2^+_g and 2^+_γ. Conversion electron data suggested a possible $E2$ character for the $(0^+)_{1420}\rightarrow 2^+_g$ transition [$\alpha_K=1.6(7)\times 10^{-3}$], although the stated uncertainty does not exclude $E1$ character at two standard deviations. There was also a possible $E0$ transition from this level to the ground state, though this transition was at the limit of observation. Because of the uncertainties in these arguments, Ref. [4] also suggests 2^- as a possible spin for this level.

The present coincidence data show the existence of a weak 418.1(2) keV transition from the level at 1420 keV to the 3^+ member of the γ band (Fig. 4). The existence of such a transition is inconsistent with a 0^+ assignment for the level

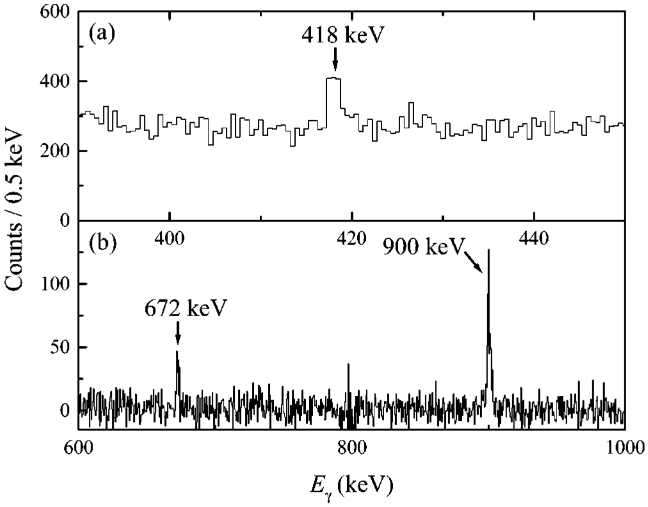

FIG. 4. Specta gated on the (a) 900 keV and (b) 418 keV transitions, supporting the placement of the 418 keV transition as directly feeding the 3_{γ}^{+} level (see Fig. 2).

TABLE II. Relative intensities of transitions depopulating the level at 1420 keV with revised tentative spin assignment 2^{-} and one-sigma intensity limits on unobserved transitions.

Transition	E_{γ}(keV)	I_{rel}
$(2^{-})\rightarrow 0_{g}^{+}$	[1420]	<1.1
2_{g}^{+}	1318.42(11)	100(4)
4_{g}^{+}	[1090]	<0.6
6_{g}^{+}	[753]	<0.15
2_{γ}^{+}	519.54(13)	11.9(4)
3_{γ}^{+}	418.1(2)	0.95(13)
$0_{K=0_2}^{+}$	[333]	<0.18
4_{γ}^{+}	[292]	<0.8
$2_{K=0_2}^{+}$	[249]	<0.9

at 1420 keV. A summary of intensities for transitions depopulating the level at 1420 keV is given in Table II. This evidence that the level does not have spin 0^{+} is corroborated by recent angular correlation experiments [26,27], which show that the $(0_{3}^{+})\rightarrow 2_{g}^{+}\rightarrow 0_{g}^{+}$ and $(0_{3}^{+})\rightarrow 2_{\gamma}^{+}\rightarrow 0_{g}^{+}$ γ-ray cascades do not exhibit the characteristic $0^{+}\rightarrow 2^{+}\rightarrow 0^{+}$ angular correlation pattern.

A spin assignment of 2^{-} for the level at 1420 keV is reasonable in the context of the systematics of octupole excitations in the deformed rare earth region, where a $K^{\pi}=2^{-}$ band at comparable excitation energy is known in several of the neighboring nuclei [28]. The $B(E1;2_{K=2}^{-}\rightarrow 3_{\gamma}^{+})/B(E1;2_{K=2}^{-}\rightarrow 2_{\gamma}^{+})$ ratios for the neighboring nuclei cluster in the range 0.4–0.6, close to the Alaga value of 0.5. In ^{162}Er, this ratio has a somewhat lower value of 0.15(2), as extracted from the intensities in Table II.

In summary, one of the first experiments at the new TRIUMF ISAC exotic beam facility has led to revised γ-ray branching data showing that the decays from the 2^{+} state at 1171 keV in ^{162}Er are in good agreement with the Alaga rules for a $K^{\pi}=0^{+}$ excitation. Moreover, the previously measured $B(E2;0_{g}^{+}\rightarrow 2_{K=0_2}^{+})$ value [8.0(15) W.u.] from Coulomb excitation [12] is validated by the present results. These results provide evidence for a collective intrinsic matrix element between the ground and $K^{\pi}=0_{2}^{+}$ excitations, as expected for a β vibration. This case is therefore one of only a few in which evidence for such β-vibrational structure exists, especially for the lowest 0^{+} excitation. Also, the resulting $\rho^{2}(E0)$ value is in agreement with the RVM prediction for a β vibration, and moderately restrictive limits are placed upon transitions to the γ band. The spin assignment of the previously reported $K^{\pi}=(0_{3}^{+})$ excitation was also altered, leaving the $K^{\pi}=0_{2}^{+}$ excitation as the only identified low-lying $K^{\pi}=0^{+}$ excitation in ^{162}Er. The neighboring higher-mass Er isotopes (^{164,166,168}Er) are all known [7–9,29] to have several excited 0^{+} states below 2 MeV, and so it is likely that ^{162}Er does as well. The present results highlight the need to obtain a more complete set of information on the low lying excitations of ^{162}Er, which will require further experiments using other low-spin population mechanisms, such as (p,t) transfer reactions or $(n,n'\gamma)$ scattering.

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