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Confirming Band Assignments in ^{167}Ytterbium with Gamma-Gamma-Electron Triple-Coincidence Spectroscopy

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Abstract. Multipolarity measurements are presented for transitions in the deformed odd-mass nucleus ^{167}Yb in support of tentative spin assignments and level interpretations based upon the cranked-Nilsson model. Internal-conversion coefficients were measured with the SAGE (Silicon And GErmanium) spectrometer confirming several $E2$ transition assignments. The array of high-purity germanium detectors enabled the recording of high-multiplicity events from which $\gamma\gamma\gamma$ and $\gamma\gamma e^-$ data sets were extracted and the technique of high-fold γ-ray gating was demonstrated to cleanly isolate transitions of interest.

PACS. 23.20.Nx Internal conversion and extranuclear effects (including Auger electrons and internal Bremsstrahlung) – 23.20.Lv transitions and level energies – 27.70.+q 150 A 189 – 21.10.Re Collective levels

1 Introduction

Determining the spins and parities of excited states in nuclei is amongst the most fundamental measurements in nuclear structure. However, direct measurement of the spin of a nuclear state is rarely possible [1]. Instead the spins and parities of states can be inferred by measuring the multipolarities of transitions between states and applying reasonable assumptions based on allowed angular momentum coupling and the L dependence of transition probabilities [2]. Assignments can also be made where certain sequences of states are predicted, such as rotational bands, and transition multipolarity measurements serve as confirmation.

Within a given nucleus, the most common way of performing spin measurements is to study electromagnetic de-excitations, usually in the form of a γ-ray angular distribution. Angular distribution may be measured either with respect to the beam-axis or to subsequent γ rays [4]. An alternative experimental approach is to perform an absolute measurement of the internal conversion coefficient (ICC) of a transition, that is the ratio of number of emitted internal conversion electrons (ICE) to γ rays. This value, denoted α_{exp}, can then be compared to values for pure multipolarity ICCs calculated using a theoretical code, such as BrICC [5]. This technique can be particularly useful at high Z and low E_γ, where the ICE process dominates, and when insufficient statistics are available for accurate γ-ray angular distribution measurements. Furthermore, an ICC is directly sensitive to the parity of the electromagnetic

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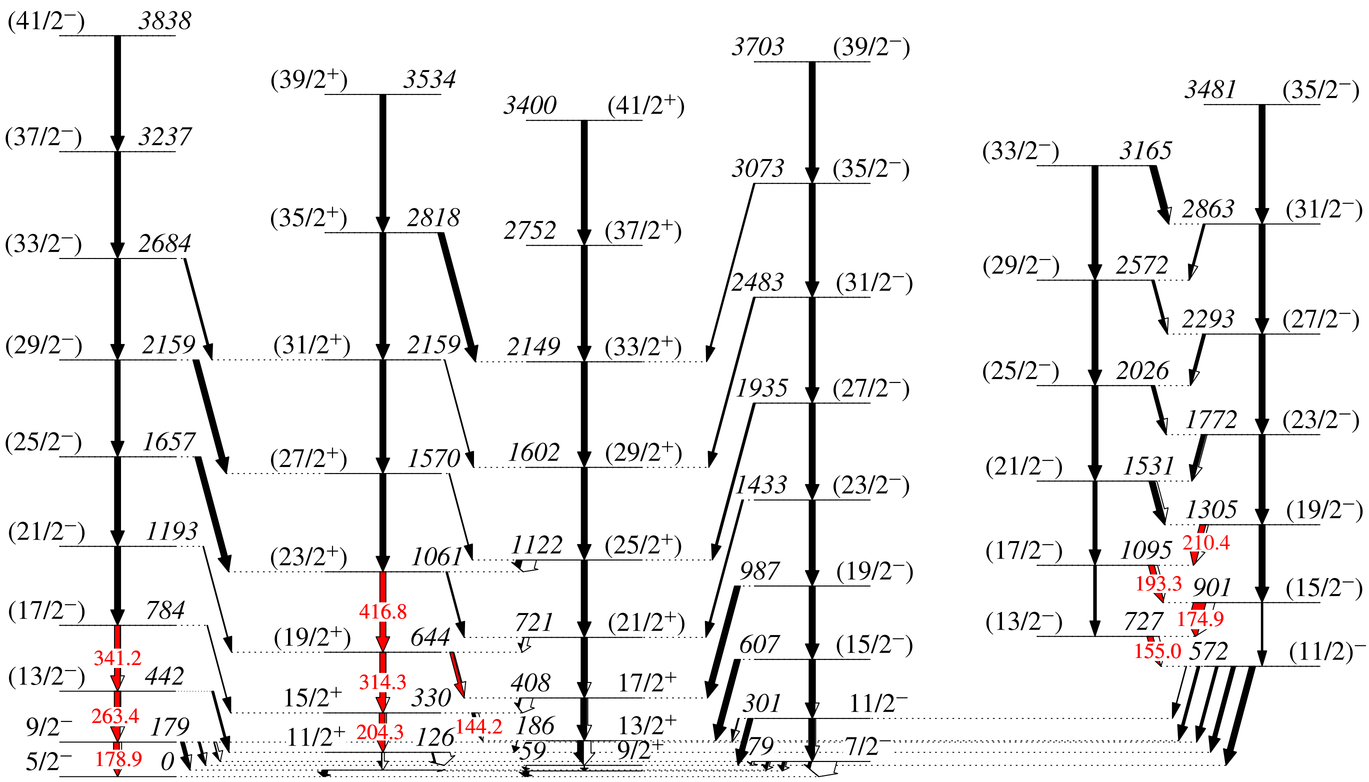

Fig. 1. Partial level scheme of the ^{167}Yb showing only states clearly identified in the experiment. Transitions discussed in the text are highlighted with their energy labels and red colour. Tentative assignments are shown as reported prior to this work. Where known, branching ratios are indicated by relative arrow thicknesses. The white portion of the arrows indicates internal-conversion contribution. Energy labels are in keV. Data are from Ref. [3].

transition operator, which requires more advanced techniques to extract from γ-ray measurements [6]. The ICC method of determining multipolarities has the advantage over angular distributions that it does not require a significant degree of initial-state spin alignment, as opposed to singles γ-ray measurements. Furthemore, multipolarity can be determined for a single transition independent of knowledge of the states' spins, unlike $\gamma\gamma$ angular correlations which depend on the multipolarities of both γ rays and on the spins of the three linked states.

Performing in-beam ICC measurements requires a high efficiency for the detection of both electrons and γ rays. To that end many modern ICE spectrometers have been developed with this capability in mind, by combining advanced electron detectors with high efficiency $\sim 4\pi$ germanium arrays, such as JUROGAM II [7,8,9]. Such spectrometers benefit from far higher γ-ray detection efficiency than has been available in previous γe^- experiments, in which smaller arrays or single germanium detectors were used [10,11]. Coincidence measurements also benefit from reduced systematic uncertainties compared to earlier asynchronous measurements of γ-ray and electrons in separate experiments [12]. The fundamental difference between experiments using a single germanium detector or a multi-detector array however, is the ability to measure multiple γ rays simultaneously in coincidence with an electron. This gives modern apparatus a significant advantage in resolving power, particularly useful when dealing with highly collective odd-mass nuclei, in which the dense level schemes make ungated ICE measurements impossible. The odd-mass nuclide ^{167}Yb (Z=70, N=97) is a highly deformed (Q=+2.70 eb from laser spectroscopy [13]) mid-shell nucleus with an unpaired valance neutron. Many of the excited states of ^{167}Yb can reasonably be grouped into bands described by the cranked-Nilsson model. This is an extremely successful model for providing a microscopic description of a deformed rotating nucleus [14]. In this model nucleons move in a deformed potential which is cranked, or rotated. Bands are formed by coupling the wavefunction of valence nucleons to a rotation of the intrinsic frame about the x axis. For ^{167}Yb, this corresponds to coupling the wavefunction of a neutron in the deformed potential formed by the ^{166}Yb core, to the rotation of this potential. Coriolis coupling breaks any symmetry about the z axis, lifting the degeneracy of Nilsson orbital time-reversed pairs. As a result two rotational bands are formed with spin $I = K, K+2, K+4$ for the $+1/2$ signature and $I = K+1, K+3, K+5$ for the $-1/2$ signature. Rotational bands are subsequently denoted by the original Nilsson orbital, followed by the band's parity and signature quantum numbers (π, α).

Spin assignments have been made in ^{167}Yb by combining this interpretation with observed transition multipolarities, determined from in-beam γ-ray angular distributions [15], $\gamma\gamma$ angular correlations following β decay [16] and asynchronous ICC measurements [16,17]. Due to experimental limitations in these previous studies, several key low energy transition remain without firm assignments. In this paper we will present the confirmation of tentative spin assignments in rotational bands of ^{167}Yb by ICC measurements with the SAGE spectrometer [7]. High multiplicity γ-ray data are used to accurately select transitions of interest.

2 Experiment

The experiment was conducted at the Department of Physics of the University of Jyväskylä (JYFL). A beam of ^{16}O was delivered from the JYFL K130 cyclotron at an energy of 65 MeV and impinged on a 1.5 mg/cm^2 target foil of ^{154}Sm, isotopically enriched to 99%, mounted on the target wheel at the focal point of the SAGE array. SAGE utilised a total of 34 detectors (24 Clover and 10 EUROGAM PhaseI detectors) of JUROGAM II for γ-ray detection and the SAGE solenoid and upstream silicon detector were used for the transport and measurement of conversion electrons. Further details of the experimental setup and equipment can be found in [18, 19, 20].

Excited states in the nuclide ^{167}Yb were populated by the ^{154}Sm(^{16}O,3n)^{167}Yb* reaction channel. The ^{154}Sm(^{16}O,4n)^{166}Yb* channel and inelastic excitation of ^{154}Sm were also strongly populated. These data provided a suitable normalisation and yielded additional measurements that have been previously reported [18]. Three dimensional histograms were populated for coincident $\gamma\gamma\gamma$ and $\gamma\gamma e^-$ events; containing 6×10^8 and 8×10^7 events respectively. A pair of identical γ-ray gates were applied to both $\gamma\gamma\gamma$ and $\gamma\gamma e^-$ data sets to produce double-gated electron and double-gated γ-ray spectra. In this work, gates directly above and below the transition of interest are used; this preferentially selects the target transition over any other part of the cascade. While other transitions in the cascade of the two gating transitions appear in the resultant spectra, random background is strongly suppressed. Conversion coefficients were then determined using

$$\alpha_{exp} = \frac{N_{e^-} \cdot \varepsilon_\gamma}{N_\gamma \cdot \varepsilon_{e^-}} \cdot C_{\gamma\gamma e^-} \cdot W(\Theta)\,, \qquad (1)$$

where N_{e^-} and N_γ are the experimentally measured ICE and γ-ray counts respectively, ε_{e^-} and ε_γ are ICE and γ-ray detection efficiency at the given energy, $C_{\gamma\gamma e^-}$ is a timing constant and $W(\Theta)$ is an angular correlation factor. While the detection efficiency for the gating γ rays can be taken as the same for both data sets and thus cancelled, ε_γ for the target transition is scaled to account for two detectors effectively removed from the array by the coincidence requirement, decreasing the value and increasing the uncertainty. The ICE detection efficiency of SAGE, ε_{e^-}, has been characterized with GEANT4 simulations [7] and fit to absolute source measurements taken immediately prior to the experiment using ^{133}Ba and ^{207}Bi sources, which provide ICE calibration points in the ranges 40-380 keV and 500-1700 keV respectively. At 100 keV, ε_{e^-} has a value of 5%. This efficiency increases to a maximum of 6% at 200 keV, then falls to 4% at 300 keV and continues to decrease to 1% at 650 keV. An additional ^{152}Er^{133}Ba γ-ray source was used in the calibration of ε_γ, which has a maximum value of 11% at 120 keV. The triple-timing constant $C_{\gamma\gamma e^-}$ accounts for coincidence timing gate width and detector live time, this was determined from experimental in-beam normalisation and timing spectra. In-beam normalisation was performed by comparing ICC values calculated with BrICC to ICC measurements of 20 $E2$ yrast transitions in ^{152,154}Sm and ^{166}Yb, spanning 60-500 keV. The factor $W(\Theta)$ accounts for differences in $\gamma\gamma\gamma$ and $\gamma\gamma e^-$ angular correlations between sequential transitions, which results in differences of measured ICC following γ-gating dependant on detector placement. However, the angular coverage of SAGE is sufficiently large, that when data from all detectors are taken together, the sensitivity to this effect is reduced to a 2% systematic error. Hence, we may take a value $W(\Theta) = 1.00(2)$. In this work, as neighbouring L- and M-shell electron peaks were not sufficiently resolvable to measure individual peak areas, the areas were summed to calculate a combined α_{L+M}, resulting in improved precision.

3 Results

States that were populated in ^{167}Yb are shown in Fig. 1 in which the transitions to be studied and relevant gating transitions are highlighted.

The 263-keV transition connects the 179-keV $9/2^-$ and the 442-keV $(13/2^-)$ states. These states are suggested to be members of a $(\pi, \alpha) = (-, +\frac{1}{2})$ rotational band in the cranked-Nilsson model built on the unpaired valance neutron in the $[523]\frac{5}{2}^-$ orbital [21, 22]. The spin of the 442-keV state remains tentative as the multipolarity of the 263-keV transition, determined from γ-ray angular distributions in Reference [23], is also tentative.

In order to isolate the 263-keV transition, coincidence gates were placed directly above and below on the in-band 341-keV and 179-keV transitions. Double-gated electron and γ-ray spectra for the 263 keV transition are shown in Fig. 2. The K-, L- and M-shell ICE peaks of the 263-keV transition are clearly observed, as is the corresponding γ ray. There is notable contamination from the 227-keV $4^+_1 \rightarrow 2^+_1$ transition of ^{166}Yb, which has a genuine coincidence with a 341-keV γ-ray gate and is of sufficient intensity that Compton continuum in the lower gate results in the false triple coincidence observed. The L and M electrons peaks of the contaminant were included in the fit of the gated electron spectrum to improve accuracy. Values of $\alpha_{K,exp} = 0.057(11)$ and $\alpha_{L+M,exp} = 0.032(16)$ were measured for the 263-keV transition of ^{167}Yb. The lower panel of Fig. 2 shows the advantage of measuring ICC for multiple atomic shells. The additional multipolarity dependence of the ICC shell-ratio provides an assignment with a higher degree of certainty than the precision of either measurement in isolation would allow. Furthermore, the shell-ratio alone is sufficient to distinguish between certain multipolarities such as $M1$ and $E2$ transitions.

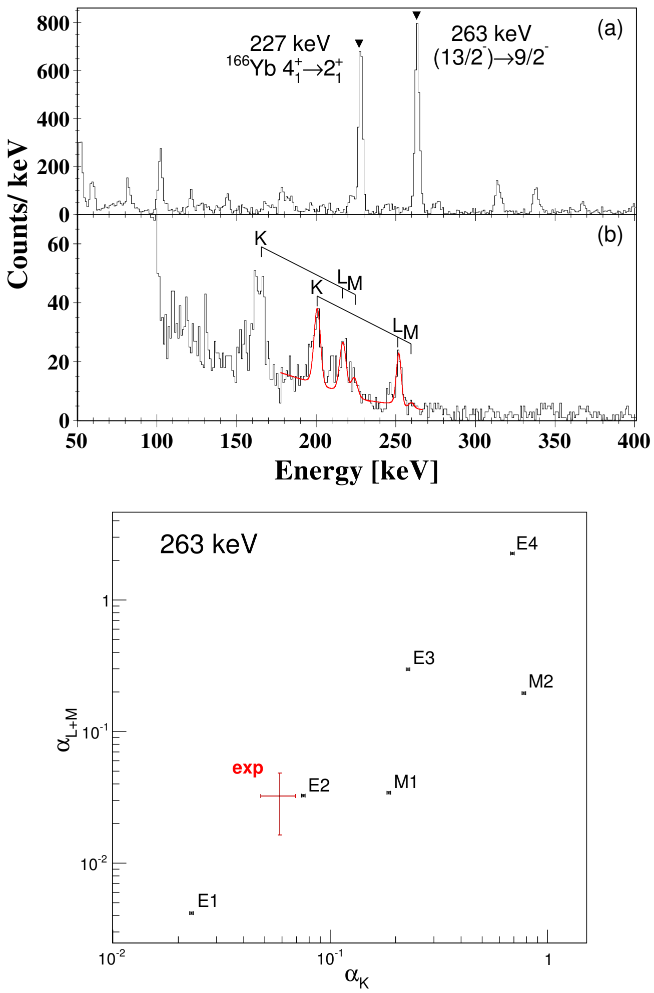

Fig. 2. (Upper) Double γ-gated γ-ray (a) and electron (b) spectra coincident with 179 keV and 341 keV gates, highlighting the ^{167}Yb 263-keV transition. The 227-keV $4^+_1 \to 2^+_1$ transition of ^{166}Yb is also prominent. (Lower) Measured ICC compared to ICC for pure multipolarity transitions at the given transition energy, calculated with BrICC.

The measured values are consistent with a pure $E2$ transition which supports a $13/2^-$ assignment for the 442-keV state and, by extension, confirms the tentative spin assignments of the following three states in the band at 784 keV, 1193 keV and 1657 keV, which are linked by E2 transitions confirmed in earlier measurements [15].

The 314-keV transition links the 330-keV $15/2^+$ and the 644-keV $(19/2^+)$ states. These states are proposed members of the $(\pi,\alpha) = (+,-\frac{1}{2})$ rotational band built on the $[642]\frac{5}{2}^+$ orbital [21,22]. In the measurement of the 314-keV transition a sum of data from two sets of γ-ray coincidence gates was used. Firstly a coincidence with the 417-keV in-band transition directly above was required. Then a following second coincidence was required with either the 204-keV in-band transition directly below, or the 144-keV inter-band transition, also directly below. The resultant double-gated electron and γ-ray spectra are shown in Fig. 3. The spectra are particularly clean and yield values of $\alpha_{K,exp} = 0.048(6)$ and $\alpha_{L+M,exp} = 0.020(3)$. These measured values are consistent with a pure $E2$ transition which supports a $19/2^+$ assignment for the 644-keV state. This also supports the $23/2^+$ assignment of the 1061-keV state that is linked to the $19/2^+$ state by a confirmed $E2$ in-band transition [15].

Finally, the 175-keV inter-band transition connects the 901-keV $(15/2^-)$ and 727-keV $(13/2^-)$ states identified as members of the $(\pi,\alpha) = (-,-\frac{1}{2})$ and $(-,+\frac{1}{2})$ bands respectively, built on a valance neutron in the $[505]\frac{11}{2}^-$ orbital [24]. The transition was isolated by requiring coincidences with the 193-keV and 155-keV inter-band transitions directly above and below, shown in Fig. 1. Resultant electron and γ-ray spectra are shown in Fig. 4. Resultant values of $\alpha_{K,exp} = 0.19(5)$ and $\alpha_{L+M,exp} = 0.14(5)$ were measured. These values are consistent with a pure $E2$ transition ($\delta^2 \geq 2.5$), with negligible $M1$ contribution

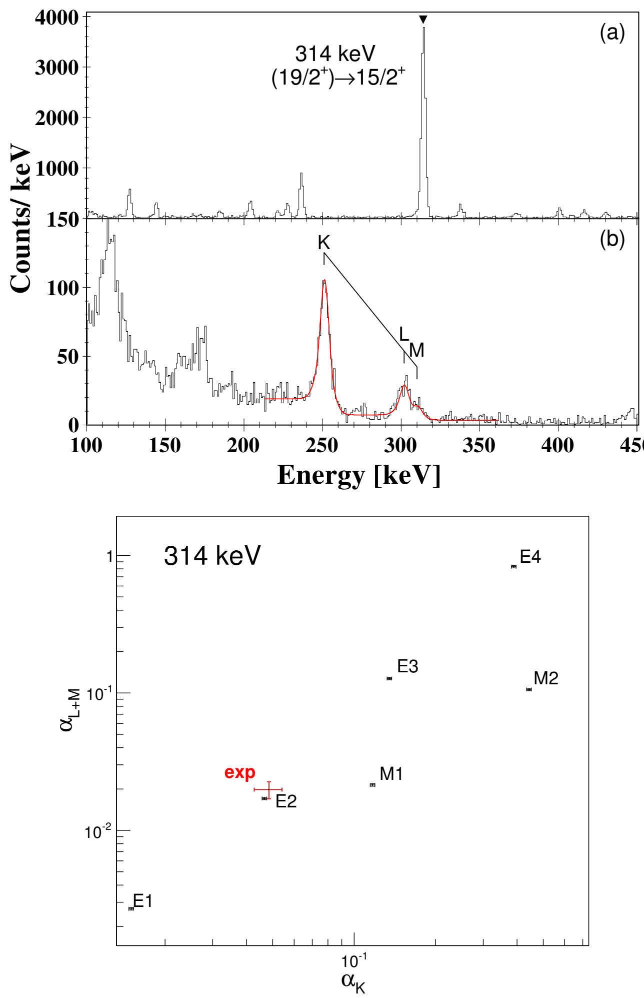

Fig. 3. (Upper) Double γ-gated γ-ray (a) and electron (b) spectra coincident with 155/204 keV and 417 keV gates, highlighting the ^{167}Yb 314-keV transition. (Lower) Measured ICC compared to ICC for pure multipolarity transitions at the given transition energy, calculated with BrICC.

Table 1. ICC measured for transitions in ^{167}Yb in this work. Energies are give in keV.

E_i	E_f	E_γ		α_{exp}	$\alpha_{BrICC}(E2)$	$\alpha_{BrICC}(M1)$
442.5	178.9	263.4	K	0.057(11)	0.076(1)	0.186(3)
			L+M	0.032(16)	0.033(1)	0.034(1)
644.4	330.2	314.3	K	0.048(6)	0.047(1)	0.117(2)
			L+M	0.020(3)	0.017(1)	0.021(1)
901.45	726.6	174.9	K	0.19(5)	0.244(5)	0.586(11)
			L+M	0.14(5)	0.178(4)	0.109(2)
1304.98	1094.70	210.4	K	0.20(5)	0.143(2)	0.346(5)

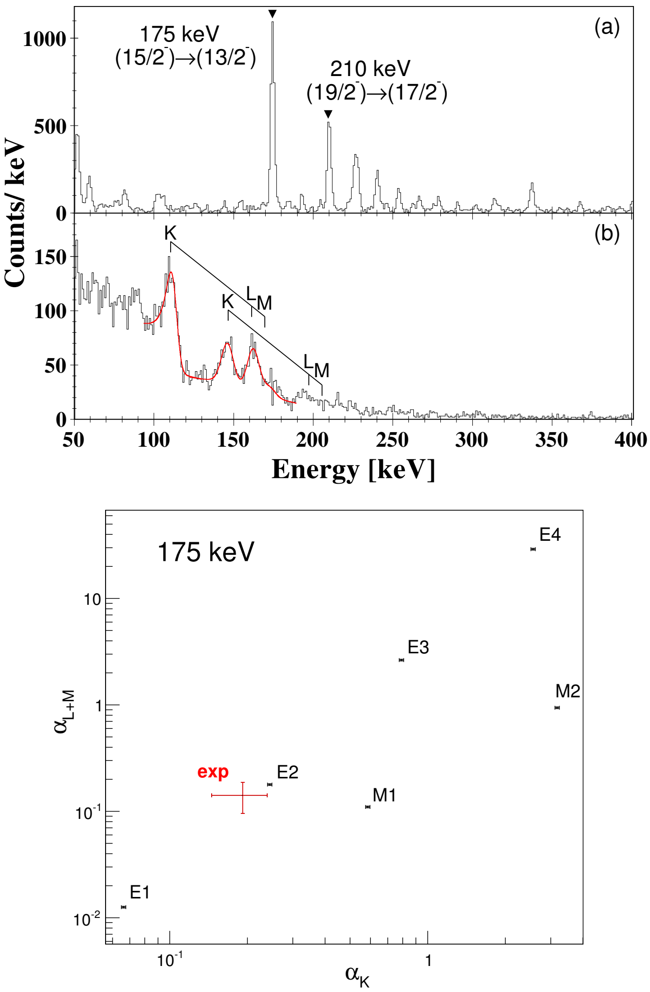

Fig. 4. (Upper) Double γ-gated γ-ray (a) and electron (b) spectra coincident with 155 keV and 193 keV gates, highlighting the ^{167}Yb 175-keV transition. The 210-keV transition is also prominent. (Lower) Measured ICC compared to ICC for pure multipolarity transitions at the given transition energy, calculated with BrICC.

that would be allowed by the tentative spin assignments. The 210-keV inter-band transition, which is genuinely coincident with both gates, has a significant contribution to the spectra. Subsequently, the K-shell electron peak from the 210-keV transition is included in the fit yielding $\alpha_{K,exp} = 0.20(6)$, which is also consistent with a smaller $M1$ contribution ($\delta^2 \geq 0.9$). In the current interpretation of these bands the transition is of a collective nature, which involves both a change in the core rotation and transition of the unpaired neutron between signature orbitals, and suppression of $M1$ strength is a reasonable expectation.

4 Summary

States populated in ^{167}Yb by fusion evaporation were studied with the SAGE spectrometer to study ICE and γ-ray transitions respectively. By combining data from these devices $\gamma\gamma\gamma$ and $\gamma\gamma e^-$ events were constructed. High-fold γ-ray gating was used to cleanly isolate transitions on interest and ICC measurements were made to confirm multipolarities. The experimental results are summarised in Table 1 and show good agreement with the $E2$ ICC values calculated by BrICC. Tentative assignments were confirmed for multiple members of the $[523]\frac{5}{2}^-$ $(\pi, \alpha) = (-, +\frac{1}{2})$ and $[642]\frac{5}{2}^+$ $(\pi, \alpha) = (+, -\frac{1}{2})$ rotational bands. This is in agreement with Ref. [25] which measured lifetimes of these states and calculated $B(E2)$ values that were found to be consistent with the model assignments. The clarity of these results, and of spectra shown, demonstrate the power of high-fold gated electron spectroscopy possible with SAGE and the strength of the ICC multipolarity measurement technique.

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