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# Search for $E(5)$ Symmetry in $^{102}\text{Pd}$

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## Abstract

Lifetimes of the excited states in the yrast band of  $^{102}\text{Pd}$  have been determined using the Recoil-Distance Doppler Shift experiment at INFN, Laboratori Nazionali di Legnaro. Excited states in  $^{102}\text{Pd}$  were populated by the  $^{92}\text{Zr}(^{13}\text{C},3\text{n})^{102}\text{Pd}$  fusion-evaporation reaction. Lifetimes were deduced using the Differential Decay Curve method and the corresponding  $B(E2)$  values were compared to the  $E(5)$  critical-point symmetry, and also the  $U(5)$  and  $O(6)$  limits of the Interacting Boson Model-1. It is evident that  $^{102}\text{Pd}$  agrees poorly with the predicted  $E(5)$  symmetry but has a very good (and somewhat surprising) agreement with the  $O(6)$  limit.

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## 1. Introduction

Within the classical limit of the Interacting Boson Model, two shape-phase transitions have been predicted. Firstly, between the spherical vibrator and  $\gamma$ -soft rotor limits (referred to as the  $E(5)$  symmetry [1]). Secondly, between the spherical vibrator and rigid rotor limits (referred to as  $X(5)$  symmetry [2]). These “dynamical” symmetries both occur when the spherical and deformed potentials coexist at the same depth, and both symmetries are modelled around infinite square-wells. In the case of  $X(5)$  symmetry,

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numerous nuclei show good agreement, both in terms of level energies and  $B(E2)$  values, to level scheme predicted in Ref. [2] (see for example [3–5]). A survey for potential  $E(5)$  candidates has been performed [6], and with the exception of  $^{134}\text{Ba}$  [7], information is lacking on the  $B(E2)$  values of the yrast-band transitions in the majority of the candidate nuclei. This paper focusses on the determination of lifetimes in  $^{102}\text{Pd}$ , a candidate for  $E(5)$  symmetry [6, 8], such that  $B(E2)$  values could be extracted and a more inclusive comparison to  $E(5)$  symmetry can be made.

## 2. Experimental Technique and Data Analysis

Intrinsic state lifetimes of various excited states in  $^{102}\text{Pd}$  were determined by a Recoil Distance Doppler-Shift experiment that was performed at INFN, Laboratori Nazionali di Legnaro (LNL). Excited states in  $^{102}\text{Pd}$  were populated using the  $^{92}\text{Zr}(^{13}\text{C}, 3n)^{102}\text{Pd}$  fusion-evaporation reaction, with  $E(^{13}\text{C}) = 48$  MeV. An enriched  $^{92}\text{Zr}$  target foil, of  $\approx 1$  mg/cm<sup>2</sup>, was mounted inside the Cologne plunger along with a separate 4 mg/cm<sup>2</sup> Au stopper foil. The average recoil velocity of the evaporation residues was  $\sim 0.8\%$  c. Measurements involving twenty-four different target-to-stopper distances were performed, with this distance being regulated by a piezoelectric feedback loop housed in the plunger. Reaction  $\gamma$  rays were detected using the GASP array [9] (in configuration “I”), which consisted of forty, large-volume, Compton-suppressed HPGe detectors coupled to a BGO inner ball. Valid events, which were recorded for offline analysis, consisted of coincident  $\gamma$  rays being detected in (at least) two different HPGe detectors. The HPGe detectors were grouped such that there were seven “rings” at angles of  $34.5^\circ$ ,  $59.4^\circ$ ,  $72.0^\circ$ ,  $90.0^\circ$ ,  $108.0^\circ$ ,  $120.6^\circ$  and  $145.4^\circ$ , with respect to the beam axis. These valid events were then sorted offline into  $\gamma$ -ray energy vs.  $\gamma$ -ray energy matrices for all ring permutations and for each individual distance.

Lifetimes were extracted using the Differential Decay Curve Method [10, 11]. In a nutshell, by placing a gate on the shifted component of a transition feeding the state of interest, the lifetime can be extracted by Equation 1:

$$\tau = \frac{I_U^{out}(x)}{v \cdot dI_S^{out}(x)/dx} \quad (1)$$

where  $I_U^{out}(x)$  is intensity of the unshifted component depopulating the state,  $v$  is the recoil velocity and  $dI_S^{out}(x)/dx$  is the rate of change of the shifted component as a function of target-stopper distance. In the case of indirect

Table 1: Lifetimes and corresponding  $B(E2)$  values of excited states populated in the  $^{92}\text{Zr}(^{13}\text{C}, 3n)^{102}\text{Pd}$  RDDS experiment.

$I_i^\pi$	$E_x$ (keV)	$\tau$ (ps)	$I_i^\pi \rightarrow I_f^\pi$	$E_\gamma$ (keV)	$B(E2)$ (W.u.)
$2_1^+$	556.4	17.5 (6)	$2_1^+ \rightarrow 0_1^+$	556.4	30.8 (10)
$4_1^+$	1275.9	3.7 (3)	$4_1^+ \rightarrow 2_1^+$	719.4	40.7 (29)
$6_1^+$	2111.4	1.93 (8)	$6_1^+ \rightarrow 4_1^+$	835.5	36.8 (16)
$8_1^+$	3013.1	1.78 (15)	$8_1^+ \rightarrow 6_1^+$	901.7	27.3 (23)

feeding, one has to account for the feeding into the excited state of interest, as shown in Equation 2:

$$\tau = \frac{I_U^{out}(x) - I_U^{in}(x)}{v \cdot dI_S^{out}(x)/dx} \cdot \frac{[I_U^{out}(x) + I_S^{out}(x)]}{[I_U^{in}(x) + I_S^{in}(x)]} \quad (2)$$

where  $I_U^{in}(x)$  and  $I_S^{in}(x)$  are the unshifted and shifted components feeding the state. Gaussian peaks were fitted to the shifted and unshifted peaks to ascertain their intensities (using the program TV [12]) and a series of second-order polynomials were fitted to the intensities of both the unshifted and shifted peaks (using the program NAPATAU [13]). From these fits, the lifetime of the excited state was extracted. In this work, numerous direct and indirect gates were placed on yrast-band transitions, the weighted average of these results yielded the final lifetimes. The corresponding  $B(E2)$  values were compared to  $E(5)$  symmetry, and also the  $U(5)$  and  $O(6)$  limits of the IBM-1.

### 3. Results

Figure 1 shows the total projection spectrum seen in the detectors at  $34.5^\circ$  with respect to the beam-axis, where the target and stopper are in contact. The transitions labelled in Figure 1 are the yrast-band transitions of  $^{102}\text{Pd}$  populated in this experiment. An example of a complete set of gated-projection spectra is shown in Figure 2, which shows the 556-keV  $I^\pi = 2_1^+ \rightarrow 0_1^+$  transition (seen in the detectors at  $140.6^\circ$ ), from a gate placed on the forward-shifted component of the 719-keV,  $I^\pi = 4_1^+ \rightarrow 2_1^+$  transition (seen in the detectors at  $34.5^\circ$ ). The results for the yrast-band transitions are tabulated in Table 1.

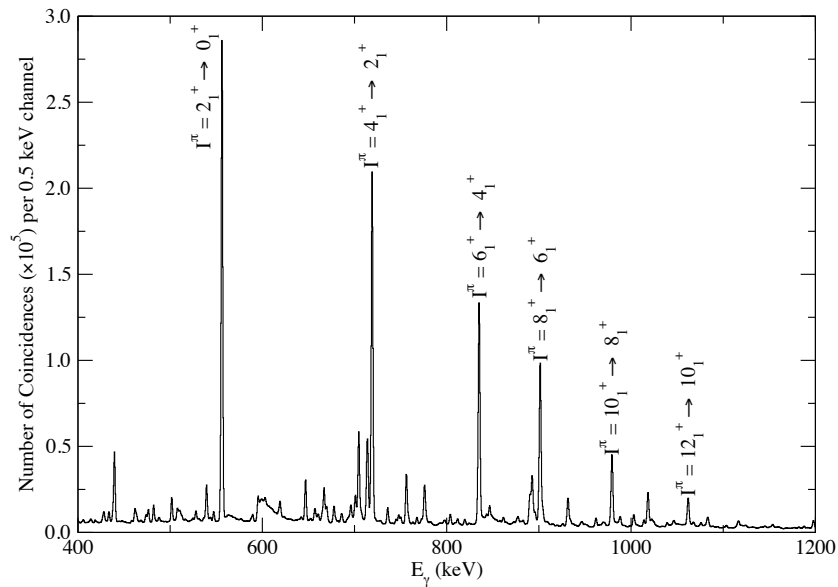


Figure 1: Total projection spectrum of the  $\gamma$  rays observed at  $34.5^\circ$  from the  $^{92}\text{Zr}(^{13}\text{C},3n)^{102}\text{Pd}$  reaction.

#### 4. Discussion

The ratios of measured  $B(E2)$  values to those predicted for a harmonic vibrator,  $\gamma$ -soft rotor,  $E(5)$  limit [14], the  $U(5)$  limit (see Eqn. 4 in Ref. [15]) and  $O(6)$  limit (see Eqn. 5.14 in Ref. [16]) both with  $N = 5$  bosons are shown in Figure 3. It is evident that a very good agreement is observed between the experimentally deduced  $B(E2)$  values and the  $O(6)$  limit. Furthermore, in the  $O(6)$  limit, the  $B(E2; 0_2^+ \rightarrow 2_1^+) = 0$ , this compares to an upper limit of 0.004 [17]. IBA calculations to show the nature of the excited level scheme and for all inter- and intraband transitions are currently being performed.

#### 5. Conclusion

Lifetimes of the yrast-band states in  $^{102}\text{Pd}$  have been determined using the Recoil-Distance Doppler Shift technique. Significant deviations from the  $E(5)$  symmetry are noted and it is apparent that from the yrast-band transitions,  $^{102}\text{Pd}$  is a good candidate for  $O(6)$  symmetry. A fuller account of this work is being prepared for publication [18] and will also be found in the Ph.D. thesis of T. Konstantinopoulos [19].

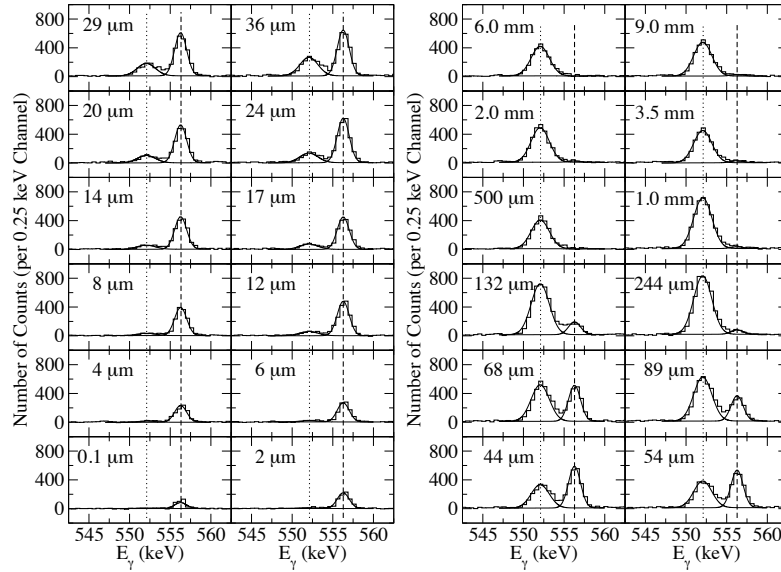


Figure 2: Deconvoluted spectra for all separate target-stopper distances of the stopped and backward-shifted component of the 556-keV,  $I^\pi = 2_1^+ \rightarrow 0_1^+$  transition, from a gate placed on the forward-shifted component of the 719-keV,  $I^\pi = 4_1^+ \rightarrow 2_1^+$  transition. The centroids of the stopped and backward-shifted peaks are shown by the dashed and dotted lines respectively.

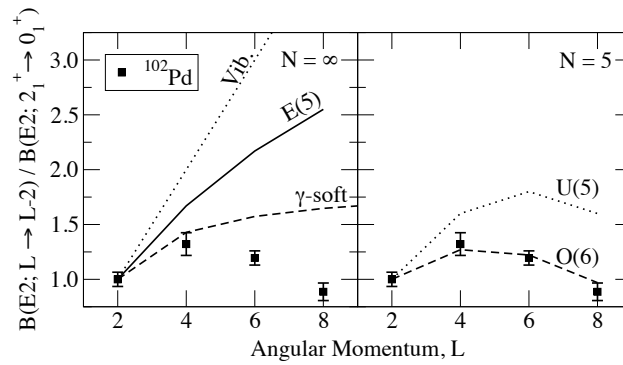


Figure 3: Left: Comparison of the experimentally deduced  $B(E2; L \rightarrow L-2)/B(E2; 2_1^+ \rightarrow 0_1^+)$  ratios of the yrast-band transitions in  $^{102}\text{Pd}$  to the classical harmonic vibrator,  $\gamma$ -soft rotor and  $E(5)$  limit. Right: Comparison of the experimentally deduced  $B(E2; L \rightarrow L-2)/B(E2; 2_1^+ \rightarrow 0_1^+)$  ratios of the yrast-band transitions in  $^{102}\text{Pd}$  to the  $U(5)$  and  $O(6)$  limits with  $N = 5$  bosons.

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