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$K$-mixing in the doubly mid-shell nuclide $^{170}$Dy and the role of vibrational degeneracy

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1. Introduction

One of the most successful descriptions of the structure of atomic nuclei is the spherical shell model. However, despite being a powerful model for certain regions of the nuclear chart, it becomes impractical when moving away from closed-shell nuclei. Instead, it is the interplay between the macroscopic shape degrees of freedom and the microscopic nature of the underlying single-particle structure of shell-model orbitals in a deformed basis that offers an explanation for the observed nuclear structure. Lying precisely in the middle of the closed proton Z = 50, 82 and neutron N = 82, 126 shells, with Z = 66 and N = 104, 170Dy has become a central calibration point for tests of collective as well as single-particle models far from closed shells [1–4]. What speaks against this simplistic picture are possible deformed and spherical sub-shell closures and other deviations from the smooth systematics that are observed in, for example, 180W [5–7] and along the N = 100 isomeric chain [8–13]. Indeed, some theoretical studies predict that the quadrupole deformation maximum occurs below the N = 104 mid-shell neutron number within an isotope chain [4, 3,14], while some experimental data indicate that the deformation increases as Z decreases below mid-shell [11–13].

One predicted property of 170Dy is the long-lived Kt = 6+ two quasi-particle isomer [15,3,4], where K is the total angular momentum projection on the proton symmetry axis. The structural and decay properties of this predicted isomer also serve as a sensitive test of the structural evolution in the quadrupole deformed 150 ≤ A ≤ 180 region. In the present work, we focus on the interpretation of the reduced hindrance, fυ = Fυ / Fυ,W, which is defined as the reduced ratio of the experimental and Weisskopf estimated partial half-life of the Kt = 6+ decay pathway, Fυ,W = (1/2)ι1/2,W, where the forbiddenness of the decay, ν = |λ − ΔK|, is the difference between the multipolarity, λ, and the change in K between the initial and final state [16]. This quantity, in particular, is very sensitive to nuclear structure effects and depends strongly on the product, NpNn, of valence protons, Np, and neutrons, Nn. For a comprehensive discussion on this topic, see the recent reviews in Ref. [17,18].

The structure of 170Dy is challenging to study experimentally. Attempts have been made using projectile fragmentation of a lead beam [19]; multi-nucleon transfer reactions between 82Se and 170Er, where a 4+ → 2+ ground-state band transition candidate at 163 keV was reported [20], and more recently in-flight fission from where an isomeric state was observed [21]. In fact, even with the power of the current high-intensity fragmentation facilities, the frontier of observed dysprosium ground states does not reach beyond the N = 108–110 isotopes 174–176Dy [22,21,23], illustrating that this region is particularly difficult to access for experimental measurements. In this letter we present, for the first time, a detailed study of the low-lying excited-state structure of the doubly mid-shell nucleus 170Dy104. This is the highest-Z element that has so far yielded new structure information at the Japanese Radioactive Isotope Beam Factory (RIBF).

2. Experiment

Nuclei in the 170Dy region were produced by in-flight fission of a 345 MeV/u 238U beam with 10 pA intensity, incident on a Be target. The beam was delivered by the accelerator complex at the RIBF in RIKEN [24]. The fragments were separated and identified in the BigRIPS separator and the ZeroDegree spectrometer [25,26] event-by-event, based on their mass-to-charge ratio (A/q) and atomic number (Z). At the final focal plane of the beam line they were implanted in the WAS3ABI active stopper [27,28], which in this experiment consisted of two 40 × 60 mm2 double-sided silicon-strip detectors with strip widths of 1 mm in both horizontal and vertical directions.

The γ-rays emitted following isomer and β-decay of the implanted nuclei were detected using EURICA (Euroball–RIKEN Cluster Array) which consists of 84 HPGe crystals arranged in twelve clusters with a nominal distance of 22 cm from the center of the array [27,29]. However, during the experiment some detectors were moved closer to the center to increase the total full-energy peak detection efficiency to about 9% at a γ-ray energy of 1 MeV. Implanted ions were correlated to β-decay events when occurring within 2 mm of each other. Due to the high contamination of lighter fragments, a large plastic scintillator was placed behind WAS3ABI and used as a veto detector for fragments passing through the silicon detector. The experiment was carried out with two BigRIPS separator settings: 13.5 hours focusing on 170Dy (~10000 implantations); and 45 hours focusing on 172Dy, during which ~2500 170Dy nuclei were implanted.

3. Results

The γ-ray spectrum obtained during a time window of 0.3–6 μs after 170Dy implantation is shown in Fig. 1. Peaks belonging to fully ionized 170Dy are labeled, while unblabeled peaks have been identified to originate from H-like charge states of 165Tb nuclei.

The level scheme obtained in the current work is shown in Fig. 2. The three lowest-lying excited states can be assigned as the 2+, 4+ and 6+ members of the ground-state rotational band with energies closely following the expected J(J + 1) rotational dependence. Note that the 4+ → 2+ transition confirms the observed
candidate in Ref. [20]. From γγ energy coincidences it was determined that the isomeric state mainly decays via the 497 and 386 keV transitions to two intermediate states, the lower of which feeds the 4þ and 2þ states of the yrast band via the 910 and 1076 keV transitions, respectively. The higher-lying state feeds the proposed 6þ and 4þ states of the yrast band through transitions with energies of 1021 and 764 keV. Based on the systematics of

the even-even \( N = 104 \) isomers the isomer was assigned to 6þ and from the decay pattern these two intermediate states were assigned to spin and parity 4þ and 5+, respectively. This would suggest that the 6þ \( \rightarrow \) 6þ transition has an energy of 1149 keV. There are three counts with that energy, one of which is coincident with the 257 keV \( \gamma \) ray assigned as the 6þ \( \rightarrow \) 4þ yrst transition. Besides these transitions, three other \( \gamma \)-rays are notable in the spectrum at energies of 527, 622 and 894 keV. As the latter is in coincidence with the 257 keV \( \gamma \)-ray it has been tentatively assigned to originate from a 6þ state. Such a state could be populated via a 255 keV transition from the isomer state. However, since this is very similar in energy to the 257 keV \( \gamma \)-ray and both are expected to be in coincidence with the 894 keV \( \gamma \)-ray, it is not possible to directly observe this transition in the current experiment. The other two transitions, 527 and 622 keV add up to 1149 keV which suggests that they are in cascade via an intermediate state. Since the relative intensity is significantly different between these states, we propose that the decay of the intermediate state is fragmented into more than one path. This proposition is strengthened by the observation of a 790 keV \( \gamma \)-ray that together with the 622 keV transition adds up to the 527 keV intensity within error bars. We tentatively assign the intermediate state as being a 5– state. The negative parity assignment of this state is discussed in more detail below. See Fig. 2 and Table 1 for details of these assignments.

From the \( \beta \)-delayed \( \gamma \)-ray spectrum we observe a strong transition at 790 keV that has been assigned to populate the 2+ state. This \( \gamma \)-ray is in coincidence with a 1169 keV \( \gamma \)-ray that would originate from a high-energy state that is well matched in energy with a 1105 keV decay to an intermediate state, in turn decaying into the 4+ and 2+ states of the yrast band. Based on the relative intensities of the 790, 854 and 688 keV \( \gamma \)-rays, these states have been assigned to spins 2 and 3, as shown in Fig. 2. We, furthermore, note that approximately 75% of the ground state band 2+ \( \rightarrow \) 0+ transition strength originates from the 861 keV \( J = 2 \) level and is, thus, only weakly populated directly from \( \beta \) decay. This means that these two \( J = 2 \) levels must be different in nature and, thus, we assign the 861 keV level to be the band head of a negative-parity band. We, furthermore, tentatively assign the other new states obtained from the \( \beta \)-decay data to share this negative-parity property. The \( f > l \) values obtained after these assignments are found to be consistent with our interpretation, see Table 1. For the \( f > l \) calculations an estimated value of \( Q_{\beta} = 6940(446) \) keV was used [30] and the \( \beta \)-decay half-life of \(^{170}\)Tb, used to calculate the \( f > l \) values, was measured to be 0.91(1) s. Furthermore, a weak 920 keV transition is observed, believed to be originating from a 2+ state decaying into the 2+ state of the yrast band. There is a small excess of events in the spectrum at 992 keV, which would correspond to the 2+ \( \rightarrow \) 0+ transition. However, due to the large background in this part of the spectrum, we have marked this transition as tentative.

The static moments of inertia deduced from the excited states in the yrast band are shown in Table 2. For the 2+ \( \rightarrow \) 0+ transition a value of 41.98(9) \( h^2 \) MeV\(^{-1} \) was obtained, compared to a value of 43.24 \( N^2 \) MeV\(^{-1} \) that was calculated for the ground state in Ref. [31]. For the proposed \( \gamma \) band the moments of inertia values agree well with the grounds state band, supporting the assignment of these states. Note that, although the 6+ member of the \( \gamma \) band is not firmly identified, rotational energy spacings imply the 6+ state would anyway be within a few keV of the tentatively assigned state. Finally, for the negative parity states the similar values suggest that these states also form a rotational band. For a more detailed discussion about the yrast states, see Ref. [32].
Table 1

Initial level energy, $E_i$, and spin-parity, $J_i^\pi$, of the levels in $^{170}$Dy. For each $\gamma$ ray the energy $E_{\gamma}$, $\gamma$-ray branching ratio $B_{\gamma}$, total intensity from isomer decay, $I_{\gamma}$/iso (relative to the total number of isomer implantations), and $\beta$ decay, $I_{\beta}/(\beta)$ (relative to the total number of transitions to the ground state), and final level spin-parity $J_f^\pi$, reduced isomer-hindrance, $f_i$, and $\beta$-decay hindrance, $\log f_t$, are listed. For the $0^+$ and $4^+$ states the $\log ft$ with uniqueness one are shown. The bold $f_i$ is the value used for the systematics in Fig. 3. The italic transitions are not observed directly in this experiment, but the deduced upper (lower) limit on the intensity (hindrance) is given.

| $E_i$ (keV) | $J_i^\pi$ | $E_{\gamma}$ (keV) | $B_{\gamma}$ | $I_{\gamma}$/iso (%) | $I_{\beta}/(\beta)$ (%) | $J_f^\pi$ | $f_i$ | $\log ft$ |
|------------|-----------|------------------|-------------|---------------------|----------------------|----------|------|-----------|
| 0          | 0         |                  |             |                     |                      |          |      | >7.2 (2U) |
| 71.46(15)  | (2)+      | 71.45(15)        | 100         | 9.2(24)             | 9.2(27)              | 0        |      | >5.85    |
| 237.32(18) | (4)+      | 165.84(11)       | 100         | 58(5)               | 15.1(33)             | (2)+     |      | 8.00(31) |
| 494.29(28) | (6)+      | 256.9(29)        | 100         | 9.0(28)             |                      |          |      |           |
| 861.35(21) | (2)+      | 789.93(15)       | 100         | 6.1(21)             | 74(9)                | (2)+     |      | 5.09(31) |
| 925.23(20) | (3)+      | 853.7(5)         | 100         | 4.2(20)             | 10.4(35)             | (2)+     |      | 5.9(4)   |
| 991.8(4)   | (2)+      | 920.2(4)         | 80(40)      | 9.7(35)             | (2)+                 | 5.72(22) |      |           |
| 1116.53(29)| (5)+      | 621.8(4)         | 100         | 4.4(19)             |                      | (6)+     |      |           |
| 1147.21(21)| (4)+      | 909.78(18)       | 66(14)      | 29(5)               |                      | (4)+     |      |           |
| 1205.58(30)|           | 1075.68(30)      | 83(14)      | 2.9(15)             |                      | (2)+     |      |           |
| 1257.77(20)| (5)+      | 764.4(4)         | 14(6)       | 3.3(21)             |                      | (6)+     |      |           |
| 1388.75(8) | (6)+      | 894.5(5)         | 100         | 3.3(17)             |                      | (6)+     |      |           |
| 1643.92(22)| (6)+      | 255              | −3.6        | −3.2                |                      |          |      |           |
| 1863.13(15)|           | 386.33(15)       | 33(5)       | 30(4)               |                      |          |      |           |
| 1936.41(14)|           | 496.64(14)       | 49(7)       | 44(5)               |                      |          |      |           |
| 2527.28(22)|           | 15.2(35)         | 13.7(30)    |                    |                      |          |      |           |
| 2030.43(21)|           | 1148.9(7)        | 2.3(16)     | 2.0(15)             |                      |          |      |           |
| 3146(2)    |           | 1406             | −2.4        | −2.4                |                      |          |      |           |
| 5204(2)    |           |                  | 6.0         |                    |                      |          |      |           |
| 2030.43(21)|           | 1104.5(6)        | 32(17)      | 8(4)                | (3)+                 |          |      | 5.08(22) |

Table 2

Rotational frequencies, $\hbar \omega$, and static moments of inertia, $J^0$, for sequential combinations of spin and parity $J_2^\pi$ and $J_3^\pi$.

| $J_2^\pi$, $J_3^\pi$ | $\hbar \omega$ (MeV) | $J^0$ ($h^2$ MeV$^{-1}$) |
|----------------------|-----------------------|---------------------------|
| Ground state band    |                       |                           |
| $6^+$, $4^+$         | 0.128                 | 42.82(5)                  |
| $4^+$, $2^+$         | 0.0820                | 42.20(5)                  |
| $2^+$, $0^+$         | 0.0292                | 41.98(9)                  |
| $\gamma$ vibrational band |                       |                           |
| $6^+$, $5^+$         | 0.130                 | 45.82(10)                 |
| $5^+$, $4^+$         | 0.110                 | 45.22(12)                 |
| $4^+$, $2^+$         | 0.0768                | 45.05(13)                 |
| $2^+$, $2^+$         | 0.110                 | 45.22(12)                 |
| $2^+$, $0^+$         | 0.0258                | 44.98(9)                  |
| $\gamma$ band       | 0.130                 | 45.82(10)                 |

4. Discussion

In the following discussion, we will assume that the 1149 keV decay is of pure M1 character. An E2 mixing, even as large as $\delta_{M1/E2} = -1.80 \pm 0.7$ as observed in the corresponding $^{174}$Yb isomer [33], could influence the $K$-hinderance to the yrast band, but most likely not to the extent that it would change the conclusions. For the decay into the $\gamma$-vibrational band and the $K^\pi = 2^+$, however, such a mixing would strongly influence the hindrance and as it is not directly measured in the present work our discussion will focus on the ground-state band component. To obtain an estimate of the E2 strength to the yrast band, we have looked for the expected 1406 keV $\gamma$ ray, but it was not observed. From the current data, an upper limit of $4 \times 10^{-5}$ W.u. is obtained for this transition branch, which corresponds to a reduced hindrance of $f_i > 5.77$, compared to 6.8 (178W), 42 (176Hf), and 327 (174Yb) across the heavier $N = 104$ isotones. Recent calculations using the triaxial projected shell model show a strong correlation between the isomer hindrance and the properties of the $\gamma$ band [34].

In particular, we note the energy systematics of the $\gamma$ bands, see Fig. 3. While the $K^\pi = 2^+$ band head of $^{172}$Er was not observed in Ref. [35] it is expected to be at an energy close to 920 keV [35]. One interesting feature is the steady increase in the $K^\pi = 2^+$ band-head energies from W to Yb, with a sudden drop at Er. This also happens to be the point where the hindrance breaks out of the $N_pN_n$ extrapolation. The hindrance of the $K^\pi = 6^+$ isomers could be influenced by members of the $K^\pi = 2^+$ $\gamma$ band, both directly from the proximity of the two $J^\pi = 6^+$ states, as discussed in Ref. [34] and the general effect of low-lying $\gamma$ vibrations being a signal of increased $\gamma$ softness and, hence, more $K$ mixing.

Under the assumption that the $(6\nu_1^+)^{6\nu_2^+}$ mixing matrix elements are similar and small, the ratio between the hindrances, $F_W$, and of the excitation energy differences, $\Delta E^2$, should stay constant. For the closest neighbor, $^{172}$Er, the 6$\nu_1^+$ is, unfortunately, not known, but can be determined by extrapolation of the known energies to be close to 1390 keV [35]. Together with the tentative 6$\nu_1^+$ state in $^{170}$Dy, this gives a $\Delta E(170\text{Dy})^2/\Delta E(172\text{Er})^2 = 255^2/110^2 \approx$
5.4. Comparing this to the value of $F_W(170\text{Dy})/F_W(172\text{Er}) = 3.1 \cdot 10^6/0.55 \cdot 10^6 \approx 5.6$, we find that there is indeed a remarkable similarity in the band-mixing effects of these nuclei. On the other hand, comparing these values for $^{178}$W, that has a similar level structure to $^{170}$Dy and is known to be a γ soft, we get the numbers $\Delta E(170\text{Dy})/\Delta E(178\text{W}) = 255^2/128^2 \approx 4.0$ and $F_W(170\text{Dy})/F_W(178\text{W}) = 3.1 \cdot 10^6/0.35 \cdot 10^6 \approx 9200$. From this we can conclude that although the large $N_pN_n$ value should predict a very hindered decay in $^{170}$Dy [15], the near degeneracy between the $K^\pi = 6^+$ state and the $6^+$ state of the γ-vibrational band plays the key role in reducing the actual hindrance.

Potential energy surface calculations, similar to those reported in Ref. [15,11], were performed for the ground state and $K^\pi = 6^+$, $5/2^-\{512\} \otimes 7/2^-\{514\}$ two-neutron configurations, including $\beta_2$ deformation [11]. While the deformation parameters were chosen to minimize the potential energy, the neutron-neutron pairing strength was adjusted according to systematics of similar nuclei in this region. It is already known that a factor of 1.115 adjustment is needed for calculating the multi quasi-particle states in $^{178}$W [36]. Using the same method as in Ref. [36], a factor of 1.05 and 1.06 was obtained for $^{172}$Er and $^{166}$Dy, respectively. However, due to the absence of experimental odd-even mass differences, this method cannot be used for more neutron-rich nuclei. Furthermore, it has been pointed out [37] that the pairing strength to reproduce the measured excitation energies of the $K^\pi = 6^+$ states in the $N = 104$ chain is larger than that needed to reproduce the mass difference. Thus, in this work, we have adopted an adjustment factor of 1.1 for the entire chain, increasing the energies of the states with approximately 300 keV and giving a satisfactory reproduction of the experimental data, as shown in Fig. 3.

The interpretation of the low-K states is less straightforward than the high-K ones as they are created through an interplay of several different configurations and have a tendency to be collective. The log ft values in Table 1 suggest a $J^\pi = 2^-$ ground state in $^{170}$Tb. In this case $\pi 7/2^-\{523\} \otimes \pi 3/2^-\{411\}$ is populated as a pure two-proton configuration, where the $2^-$ coupling is energetically favored. The excitation energy of 861 keV for the first $J^\pi = 2^-$ state is the lowest in all $N = 104$ isotones, which may be indicative of an octupole character. This is also consistent with the assignment of the $J^\pi = 2^-$ band head at 1148 keV in $^{162}$Dy expected to be the dominant component of the $J^\pi = 2^-$ octupole vibration, [38,39].

5. Summary

In summary, a detailed study of the structure of the doubly mid-shell valence maximum nucleus $^{170}$Dy has been carried out. From the γ-ray spectra following isomeric and β decay several states of this nucleus were observed. We have identified the yrast band up to the $J^\pi = 6^+$ state, the γ-vibration band up to the $5^+$ state with a tentative $6^+$ state, a low-lying negative-parity state that could be a candidate for the lowest energy octupole deformed state, and the $K^\pi = 6^+$ two quasi-particle isomer. The $6^+$ isomer was observed with a reduced hindrance an order of magnitude smaller than originally predicted, which has been attributed to γ-vibrational mixing.

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