Discovery of a nonyrast $K^\pi = 8^+$ isomer in ^{162}Dy, and the influence of competing K-mixing mechanisms on its highly forbidden decay

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The ^{160}Gd(^{9}Be,α3n)^{162}Dy reaction has been used to study high-spin states in ^{162}Dy. Pulsed beam conditions were utilized for enhanced isomer sensitivity. An isomer at 2188.1(3) keV with a half-life of 8.3(3) μs has been discovered and assigned $K^\pi = 8^+$ with a two-quasineutron configuration. Among 11 γ-ray decay branches, an E2, $\Delta K = 8$ transition to the ground-state band was observed with a reduced hindrance of $f_\nu = 35$, agreeing well with systematics correlating f_ν with the product of the valence neutron and proton numbers ($N_p N_n$) over an extended N, Z range. Small deviations from $N_p N_n$ dependence are analyzed for a range of two-quasiparticle isomer decays and interpreted as arising from a weak dependence on the isomer excitation energy relative to the yrast line.

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I. INTRODUCTION

Understanding the decay rates from high-spin isomers in deformed nuclei remains a considerable challenge [1] and lacks an appropriate theoretical framework. Nevertheless, such isomers, apart from their own structural interest, may be important more generally, in astrophysical environments, at the limits of stability, and controversially, for novel energy-storage applications [2]. The present work attempts to clarify the relative importance of some of the degrees of freedom involved in isomer de-excitation.

The K quantum number is the projection of the angular momentum on the symmetry axis of the deformed nuclear shape. Half-life measurements for isomer decays that involve a change of K can establish the degree to which K is conserved. The reduced hindrance [1] for the isomeric state ($f_\nu = F_W^{1/\nu}$) relates the Weisskopf hindrance factor for the decay ($F_W = T_{1/2}^\gamma / T_{1/2}^W$) to the K forbiddenness ($\nu = \Delta K - \lambda$), where $T_{1/2}^\gamma$ is the partial γ half-life, $T_{1/2}^W$ is the Weisskopf estimate, and λ is the γ-ray multipolarity. This systematic approach to categorizing isomer decay rates can be extended by considering variables that reduce K conservation by generating mixing [3].

One form of K mixing arises due to the Coriolis effect, which intensifies with decreasing neutron and proton number in the lower half of the $N = 82 \rightarrow 126$ and $Z = 50 \rightarrow 82$ shells due to the population of high-j, low-Ω orbitals. In contrast, greater axial asymmetry occurs with increasing neutron and proton number in the upper half of the shells, leading to an increase in K mixing associated with γ tunnelling, where γ is the axial asymmetry parameter. The systematic effect of Coriolis and γ-induced K mixing may surprisingly be characterized through a single variable, the product of the valence neutron and proton numbers, $N_p N_n$, at least for two-quasiparticle (2QP) isomers decaying by E2 transitions [4]. The $N_p N_n$ product was introduced by Casten [5] and has proven to be useful in describing structural changes over extended regions [6]. For higher QP numbers there is a level-density effect that manifests as a dependence on the isomer's excitation energy relative to a rigid rotor ($E - E_R$), which is correlated with greater K mixing through increased level-density [7]. By studying a wider range of isomers we hope to clarify these behaviors.

The present work reports an investigation of ^{162}Dy and identifies a 2QP isomer well above the yrast line with multiple branches, including a highly forbidden E2 transition to the ground-state band. None of the three previous γ-spectroscopy studies of ^{162}Dy [8–10] identified any isomers.

II. EXPERIMENT

In the present study, ^{162}Dy was populated using the ^{160}Gd(^{9}Be,$\alpha 3n$)^{162}Dy incomplete fusion reaction. Pulsed and chopped beams were provided by the 14UD tandem accelerator at the Australian National University (ANU) Heavy Ion Accelerator Facility [11] at an energy of 57 MeV. This beam energy provided the greatest cross section for ^{164}Er production through the ^{160}Gd(^{9}Be,5n) reaction, in concordance with the objective of measuring isomer properties in that nucleus [12]. A highly enriched (>95%) ^{160}Gd target with an effective thickness of 4.36 mg/cm^2 was placed at the center of the Compton suppressed CAESAR array [13], consisting of six high-purity germanium (HPGe) detectors at $\pm 48^\circ$, $\pm 97^\circ$, and $\pm 147^\circ$ in the beam plane, and three larger HPGe detectors, out of plane at $\pm 45^\circ$ and $+135^\circ$. The array includes two out-of-plane low-energy photon spectrometer (LEPS) detectors at -90° and -135° for greater efficiency at low energies.

Chopped and bunched 1-ns beam pulses, with a 1.7-μs separation, provided ideal conditions for the measurement of γ-ray events timed relative to the driving rf signal. Detected between beam pulses, γ rays that were coincident within 150 ns were used to create an "out-of-beam γ-γ" matrix. Furthermore, in order to detect correlated events across

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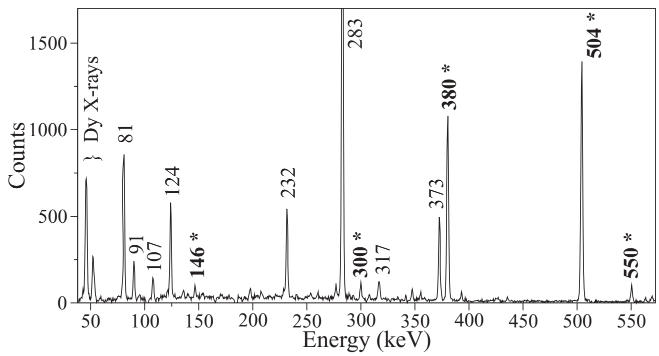

FIG. 1. Coincidence spectrum for the 185-keV transition in the out-of-beam $\gamma-\gamma$ matrix. The strongest direct decays from the isomer are denoted by an asterisk.

TABLE I. Relative intensity, final angular momentum, multipolarity, total conversion coefficient, hindrance factor, forbiddenness, and reduced hindrance for the direct branches from the ^{162}Dy isomer, based on a $K^\pi = 8^+$ assignment. Uncertainty in the γ-ray energies is typically 0.1 keV for $E_\gamma < 1$ MeV and 0.2 keV above.

E_γ(keV)	I_γ	$I_f^\pi(\sigma\lambda)$	α^T [14]	F_W	ν	f_ν
146.4	1.6(2)	8^+(M1)	0.810	1.4×10^8	3	516(23)
228.6	1.5(3)	9^-(E1)	0.034	5.4×10^{10}	5	140(6)
248.0	0.4(1)	9^-(E1)	0.028	2.6×10^{11}	2	$5.1(7)\times10^5$
300.3	4.0(3)	7^+(M1)	0.113	4.7×10^8	3	780(22)
341.8	0.9(2)	8^-(E1)	0.013	3.0×10^{11}	5	197(9)
380.2	65(2)	8^-(E1)	0.010	5.7×10^9	2	$7.6(2)\times10^4$
435.4	1.3(2)	6^+(E2)	0.022	1.7×10^6	2	1312(116)
504.3	100(1)	7^-(E1)	0.005	8.7×10^9	2	$9.3(2)\times10^4$
550.3	6.2(4)	7^-(E1)	0.004	1.8×10^{11}	5	179(3)
1266.5	0.6(2)	8^+(M1)	0.003	2.4×10^{11}	7	42.2(28)
1639.2	1.0(2)	6^+(E2)	0.001	1.7×10^9	6	34.5(14)

isomeric states, an "early-delayed γ-γ" matrix was produced from events with a time difference of between 150 and 832 ns. To measure lifetimes that were long compared to the 1.7-μs pulsing, another measurement was performed where the beam was chopped (30 μs on, 150 μs off) and γ-ray times were measured using a clock register, relative to the driving rf, to create a "γ-time" matrix.

III. RESULTS

In the out-of-beam γ-γ matrix, a gate on the $4^+ \rightarrow 2^+$ (185-keV) ground-state band transition yielded clear evidence for an isomer decaying by 504- and 380-keV γ transitions within ^{162}Dy (see Fig. 1). Other less intense decay routes were subsequently determined. For example, Fig. 2 shows two direct transitions to the ground-state band. In the early-delayed γ-γ matrix, an in-beam requirement was used to identify transitions within the isomer band (see Fig. 3). This measurement had low efficiency, as the delayed component had a width of 682 ns, compared with the 8.3(3)-μs half-life of the isomer. The half-life was measured in the γ-time matrix with a background-subtracted gate on 504-keV γ rays, as shown in Fig. 4. Other time spectra gave consistent values.

Eleven branches directly from the isomer were identified. The relative intensities, determined in the out-of-beam γ-γ matrix, are shown in Table I. The γ-ray energies of these branches place the isomeric state at 2188.1(3) keV. A partial level scheme with measured γ-ray transitions that are related to the isomer is shown in Fig. 5. The 504- and 380-keV transitions have been previously reported by Fields *et al.* [8] and Aprahamian *et al.* [10], although both works tentatively assigned the parent level as the (9^-) member of a $K^\pi = (6^-)$ band not detected in the present work. As the level is now shown to be isomeric, the earlier assignments need to be re-evaluated. In the present work, all of the other direct isomeric branches, as well as the transitions above the isomer, are newly observed. The other parts of the level scheme are well established [8–10].

The experimental intensities for the assigned decays of the isomer, shown in Table I, limit its spin and parity. Transitions to the 6^+ levels are too strong to result from a spin 9 state, and the absence of transitions to either of the 6^- levels rules out the possibility of a spin 7 state. Finally, an 8^+ assignment is favored over 8^-, as the latter would require M2 transitions to the 6^+ levels, which are not likely to compete with E1 and M1 decays. Therefore, with the usual assumption that the K value is equal to the band-head spin, we propose a $K^\pi = 8^+$ assignment for the ^{162}Dy isomer.

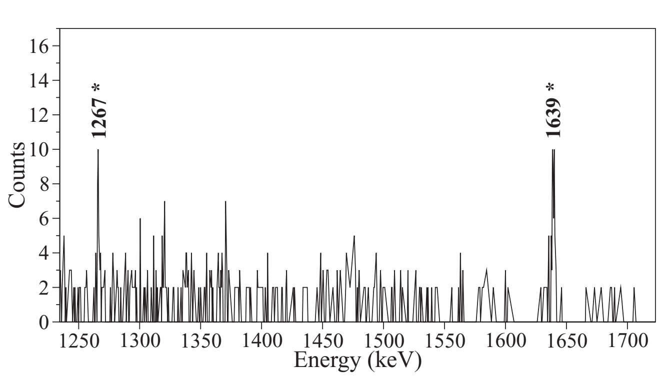

FIG. 2. Summed coincidence spectra for the 185- and 283-keV transitions in the out-of-beam $\gamma-\gamma$ matrix, showing isomeric transitions to the ground-state band.

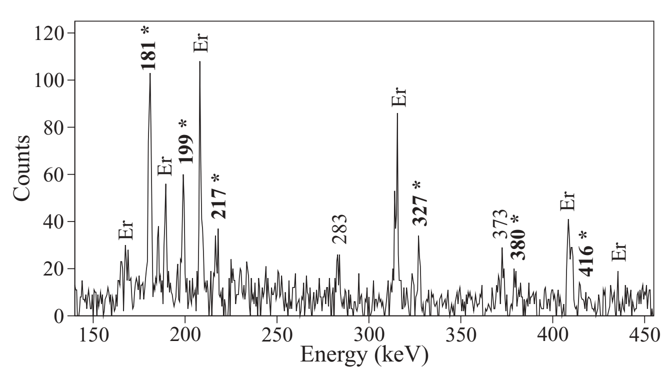

FIG. 3. Summed coincidence spectra for the delayed 504- and 1135-keV transitions, showing transitions which precede the isomer (denoted by an asterisk). Contaminant transitions from random coincidences in ^{162}Dy are labeled with their energy, and those from ^{164}Er are labeled Er.

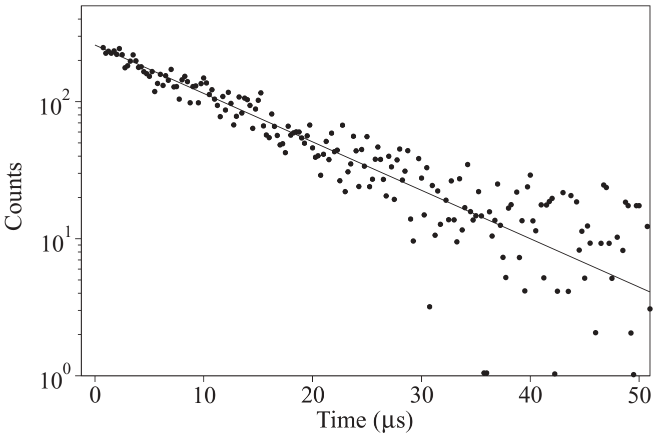

FIG. 4. Time spectrum for 504-keV γ rays. The fitted half-life is 8.3(3) μs.

IV. DISCUSSION

Considering now the quasiparticle structure, the Fermi surface for ^{162}Dy lies between the $5/2^{-}[523]$ and $5/2^{+}[642]$ neutron orbitals. The Nilsson model [15] and experimental single-particle energies for neighboring odd nuclei [16] indicate the close proximity of the $11/2^{-}[505]$ neutron orbital, suggesting either an 8^{+} $(\nu 11/2^{-}[505]\nu 5/2^{-}[523])$ or 8^{-} $(\nu 11/2^{-}[505]\nu 5/2^{+}[642])$ two-quasineutron structure.

The alignment of the band above the isomer, shown in Fig. 6, favors a structure involving the $5/2^{-}[523]$ rather than the $5/2^{+}[642]$ neutron, as the alignment of the isomer band is significantly lower than the alignment of the $5/2^{+}[642]$ neutron in ^{161}Dy.

Intrinsic g factors were extracted from γ-ray intensity measurements for the isomer band. Using the theoretical method outlined in Regan *et al.* [18], we predict $g_K - g_R = -0.30$ for the 8^{+} configuration and $g_K - g_R = -0.59$ for the 8^{-} configuration. The experimental values summarized in Table II again favor the 8^{+} configuration.

TABLE II. Intrinsic g factors for the isomer band, assuming $K = 8$, $g_R = 0.3$, and a quadrupole moment of $Q_0 = 7.3$ b [19]. The intrinsic spin g factors used were $+5.4$ and -3.8 for protons and neutrons, respectively, with a quenching factor of 0.6.

I_i, K	$E_{\gamma}^{\Delta I=1}$	$E_{\gamma}^{\Delta I=2}$	$I_{\gamma}^{\Delta I=1}$	$I_{\gamma}^{\Delta I=2}$	$\lvert g_K - g_R \rvert$
10,8	199.0	379.8	1.0(1)	0.51(8)	0.24^{+4}_{-4}
11,8	216.7	415.7	0.36(6)	0.30(7)	0.27^{+8}_{-6}

In addition, multi-quasiparticle (MQP) calculations were performed with a BCS (Bardeen, Cooper and Schrieffer) blocking code to produce theoretical level energies for the two candidate configurations. The code was first used to determine the Nilsson level energies required to reproduce a selection of low-lying experimental one-quasiparticle energies in neighboring odd nuclei ($Z \pm 1, N$ and $Z, N \pm 1$). These Nilsson energies were then averaged for ^{162}Dy, allowing MQP energies to be calculated. The pairing energy for neutrons was adjusted to fit the 5^{-} $(\nu 5/2^{-}[523]\nu 5/2^{+}[642])$ band-head at 1486 keV. The MQP calculations predict the 8^{+} configuration only 12 keV away from the experimental energy. The 8^{-} configuration is predicted 226 keV above the experimental energy. The estimated uncertainty is 150 keV, based on the difference between experimental and predicted energies for the $K = 4^{+}(\nu 5/2^{-}[523]\nu 3/2^{-}[521])$ band-head. Residual interactions were not included, but the pairing energy was chosen to better reproduce configurations that are favored by residual interactions. If included, the 8^{-} configuration would be about 200 keV further from the experimental energy.

All of these considerations support a $K^{\pi} = 8^{+}$ assignment for the isomer. We next address the transition rates associated with its decay.

Table I shows that the E1 transition rate to the 9^{-} level in the $K^{\pi} = 2^{-}$ band is greater than to the 9^{-} level in the $K^{\pi} = 5^{-}$ band. The levels are 20 keV apart, at 1940 and 1960 keV (see Fig. 5). As the transition rates are, as expected, higher to

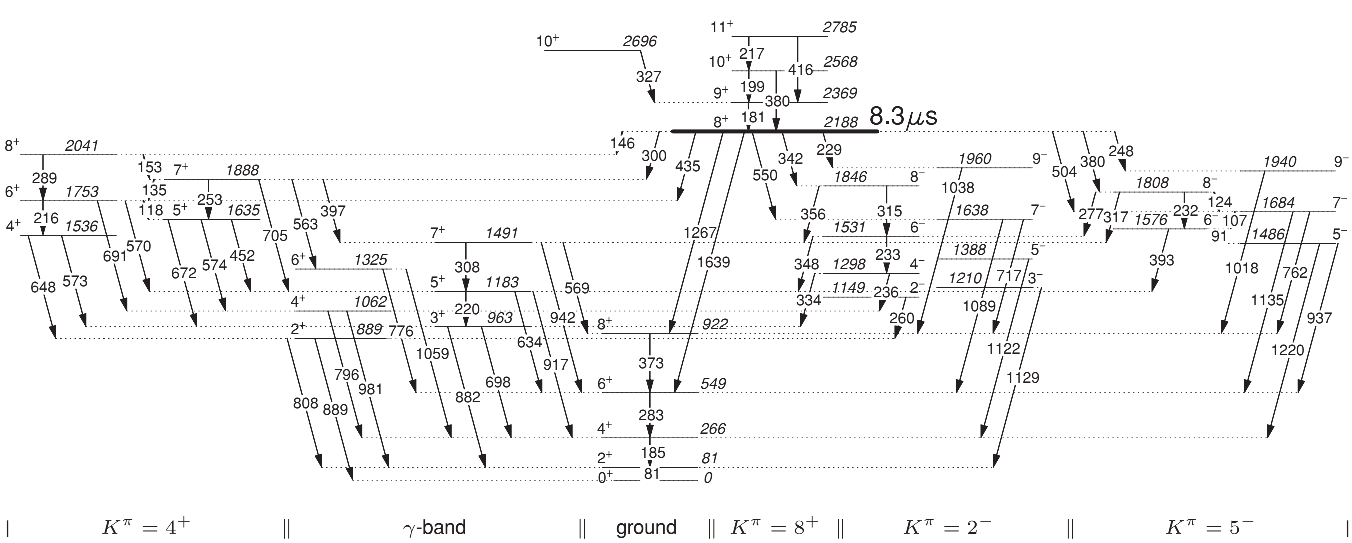

FIG. 5. Partial level scheme for ^{162}Dy showing transitions related to the isomer and its band ($K^{\pi} = 8^{+}$). Energies are in keV.

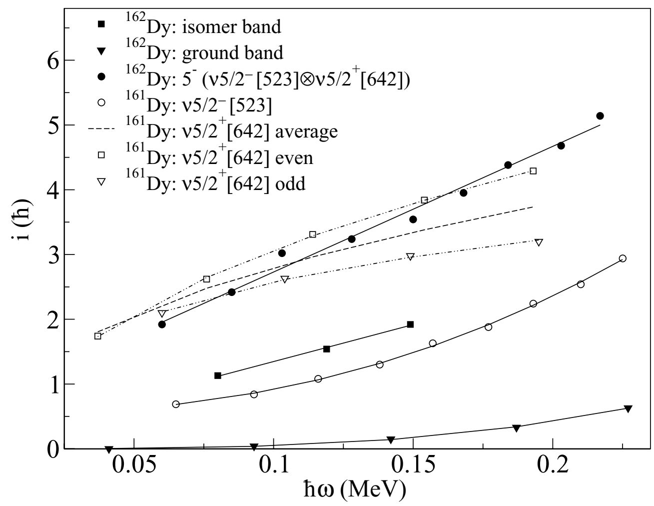

FIG. 6. Angular momentum alignment with the rotation axis for the isomer band, the 5^- band involving the two candidate 5/2 orbitals, and single-particle values for those orbitals in ^{161}Dy. All measurements are from this experiment. For the isomer band, $\Delta I = 1$ transitions were chosen to provide more data. Elsewhere, $\Delta I = 2$ transitions were chosen to minimize fluctuations. The Harris parameters are $\mathcal{J}_0 = 37\hbar^2$ MeV^{-1}; $\mathcal{J}_1 = 42\hbar^4$ MeV^{-3} [17].

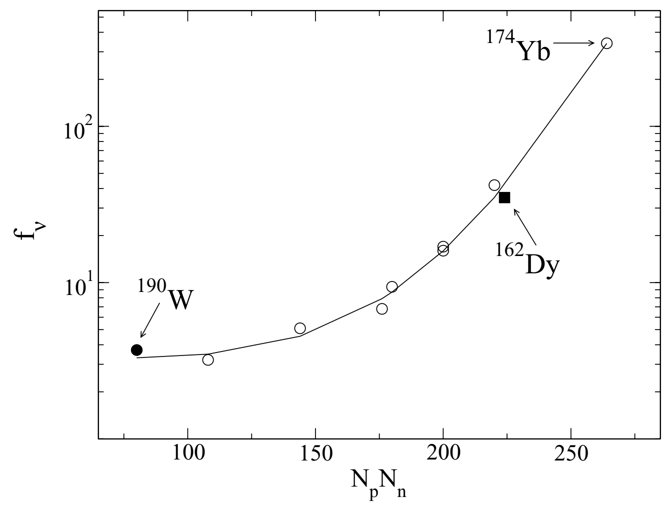

FIG. 7. Modified plot from Walker *et al.* [4]. The open circles represent the reduced hindrance of all E2, $\nu > 4$ transitions for 2QP isomers in the $N = 82 \rightarrow 126$ shell as a function of N_pN_n. New data are shown for ^{162}Dy with the filled square, and for ^{190}W [21] with the filled circle. The fit-line is of the form $g_\nu = A + \exp[(N_pN_n - 80)^B/C]$, where $A = 2.3$, $B = 1.873$, and $C = 3 \times 10^3$.

the 8^- and 7^- states in the $K^\pi = 5^-$ band, the rates to the 9^- levels are surprising. A simple two-band-mixing analysis [8] at the band crossing ($7\hbar \rightarrow 9\hbar$), aiming to replicate the experimental transition rates from the isomer to the 7^- and 9^- levels, produced a mixing strength of $V \sim 9$ keV. The analysis required a higher K for the daughter level of the more intense transition, necessitating an interchange of the 9^- levels. On the basis of our analysis, the 1960-keV level is predominantly $K = 5$, and the 1940-keV level is predominantly $K = 2$. We therefore recommend rearranging the levels between the two bands to coincide with their dominant configuration.

After applying this change and replotting the alignment from Fig. 6, the deviations from the $K^\pi = 5^-$ fit at low angular frequency are reduced. Similarly, the hindrance factors (F_W) in Table I favor interchanging the 9^- levels, as the 248.0-keV transition is more hindered while being less forbidden than the 228.6-keV transition.

Another feature seen in Table I and Fig. 5 is that the hindrances of the transitions to the $K^\pi = 4^+$ band are unusually large. This perhaps necessitates a re-examination of the structure of that band, especially since the band-head, and hence the K value, is not well defined. However, in general the detailed understanding of f_ν values is poor when ν is small, and the contributions of competing K-mixing mechanisms are more apparent when considering large-ν decays to ground-state bands.

For the $K^\pi = 8^+$ isomer in ^{162}Dy, the E2, $\nu = 6$ transition (1639.2 keV) to the ground-state band has a reduced hindrance of $f_\nu = 35$. The relation between N_pN_n and reduced hindrance is shown in Fig. 7. The graph shows 2QP, E2 data from Walker *et al.* [4], with the addition of the ^{162}Dy transition from this work, and a 694-keV transition from a recently discovered isomer in ^{190}W [21]. The new data agree remarkably well with the existing trend. The previously known isomers are in $Z = 70 \rightarrow 76$ and $N = 100 \rightarrow 108$ nuclei. The ^{162}Dy data point extends this to $Z = 66$ and $N = 96$, while ^{190}W has $N = 116$.

The small yet significant deviations from the fit in Fig. 7 can be attributed to excitation energy effects. For example, the ^{162}Dy isomer, which has an f_ν that is marginally below the fit, has an energy considerably above the yrast line, suggesting a reduction in f_ν through level-density induced K mixing. Figure 8 shows f_ν as a function of $E - E_R$ for the isomers being discussed.

In Fig. 8 the correlation with $E - E_R$ is poorest for ^{162}Dy and ^{174}Yb, which have the two largest N_pN_n values, and ^{190}W, which has the smallest N_pN_n value. It is apparent that N_pN_n dependent K mixing is responsible for the poor correlation in Fig. 8, while the quality of the correlation in Fig. 7 establishes f_ν as being highly dependent on N_pN_n.

The small differences between the reduced hindrances and the fit line in Fig. 7, given by $f_\nu - g_\nu$, indicate the

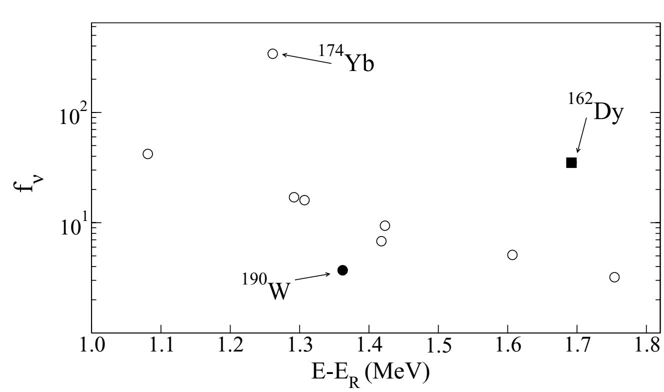

FIG. 8. f_ν as a function of $E - E_R$ for the data in Fig. 7. The rotor moment of inertia is chosen at $85\hbar^2$ MeV^{-1} for $A = 178$, scaling as $A^{5/3}$. Uncertainties are smaller than the data points.

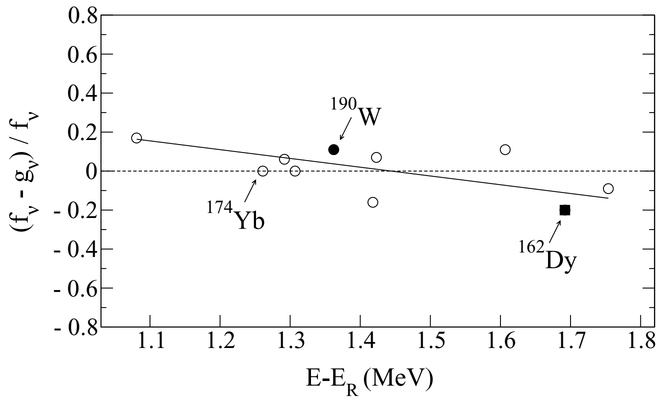

FIG. 9. The relative scatter from the fit in figure 7 as a function of $E - E_R$. The solid line is to guide the eye. Uncertainties are smaller than the data points.

magnitude of the reduced hindrance that can be attributed to degrees of freedom other than N_pN_n. The ratio $(f_\nu - g_\nu)/f_\nu$ is the fraction of the reduced hindrance that this magnitude represents, a quantity that can be compared for all of the isomers being discussed. As the correlation of f_ν with N_pN_n is very good, it is reasonable to assume that the ratio removes all dependence on N_pN_n. Figure 9 shows this ratio as a function of $E - E_R$, identifying a small yet significant dependence on $E - E_R$, and confirming that it is partially responsible for the deviations from the N_pN_n correlation. However, it is clear that this dependence is small in comparison to the N_pN_n dependence. This suggests that the contribution of level-density K mixing to f_ν is small for E2 decays from 2QP isomers, in contrast to the situation for higher quasiparticle numbers [1,2,4,7].

The N_pN_n dependence, which incorporates γ asymmetry and Coriolis effects, must be predominantly responsible for the K mixing. As $E - E_R$ largely accounts for the residual deviations from the N_pN_n fit, it appears that other considerations such as the isomer configurations are relatively unimportant. This is perhaps not surprising if the dominant K mixing occurs within the daughter state of isomeric transitions. Nevertheless, the remaining scatter of data points in Fig. 9 implies that other degrees of freedom do indeed play a small role.

V. SUMMARY

A $T_{1/2} = 8.3(3)$ μs, two-quasineutron isomer has been discovered in ^{162}Dy. The intrinsic g factor and alignment of its rotational band, MQP calculations, and transition rates all support a $K^{\pi} = 8^{+}$ assignment. The isomer band was measured up to $11\hbar$, and 11 branches directly from the isomer were identified.

An E2, $\Delta K = 8$ transition from the isomer to the ground-state band has a reduced hindrance of $f_\nu = 35$, which agrees well with systematics correlating f_ν with the product of valence neutron and proton numbers (N_pN_n). The reduced hindrance of the ^{162}Dy isomer is marginally lower than the trend, which could be explained by the isomer being considerably above the yrast line.

The correlation quality of f_ν with N_pN_n and $E - E_R$ indicated its dependence on the two variables. The dependence on $E - E_R$ was shown to be weak, indicating that level-density K mixing has a small effect on E2, $\nu > 4$ transitions from 2QP isomers. The N_pN_n variable, which incorporates γ-induced and Coriolis K mixing, is seen to be more important in understanding transition rates from these isomers.

ACKNOWLEDGMENTS

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