Configuration dependence of K-forbidden transition rates from three-quasiparticle isomers

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Abstract

Reduced hindrance factors for K-forbidden $E2$ transitions from two- and three-quasiparticle isomers in the $A \approx 180$ deformed region are compared. Evidence is presented that when all three quasiparticles are of the same nucleon type (proton or neutron) there is a strong dependence of the $E2$ reduced hindrance factor on the isomer excitation energy.

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Long-lived excited states, or isomers [1], in axially symmetric, deformed atomic nuclei are understood to arise from the approximate conservation of the K quantum number, i.e. the projection of the angular momentum on the nuclear symmetry axis. Although there is already much experimental information about such isomers [2], there is only a poor understanding of the principal degrees of freedom that control K-isomer decay rates, beyond the basic considerations of transition energies, multipolarities and K-value changes. Nevertheless, the systematic variation of reduced transition rates can provide critical predictive power [2], which may be important for the study of exotic and superheavy nuclei. Indeed, such considerations are accentuated by the realisation that isomeric states in the most-exotic nuclei can be longer lived than their respective ground states [3–5], leading to a new perspective regarding the experimental techniques that are appropriate for their study. Furthermore, if the transition-rate behavior can be adequately systematized, then spin and parity assignments will be facilitated in exotic nuclei. Accordingly, it is worthwhile to understand better the properties of those isomers that are currently accessible.

The present study focuses on $E2$ decays from 2- and 3-quasiparticle isomers in the $A \approx 180$ well-deformed region. Earlier work [6] identified the product of the valence nucleon numbers, N_pN_n, as being a key variable for such decays, with extension also to the $A \approx 130$ and 250 deformed regions [7, 8]. Based on this approach, predictions have been made for the doubly mid-shell nuclide ^{170}Dy [9]. However, new results for ^{171}Tm [10] and ^{185}Ta [11] appear to contradict the earlier interpretation. The present work analyses this situation and suggests that the excitation energy of some 3-quasiparticle configurations may be an important degree of freedom that controls the decay rate, thus providing a link to decay rates associated with higher quasiparticle numbers [12, 13].

Data for $E2$, 2- and 3-quasiaprticle isomer decays are compiled in Table I, and f_ν values are shown as a function of N_pN_n in Figure 1. Here, the reduced hindrance is defined as $f_\nu = (T^\gamma_{1/2}/T^W_{1/2})^{1/\nu}$, where $T^\gamma_{1/2}$ is the partial γ-ray half-life, $T^W_{1/2}$ is the corresponding Weisskopf single-particle estimate, and $\nu = \Delta K - \lambda$ is the degree of forbiddenness of the transition with multipolarity λ. The reduced hindrance thus includes the effects of transition energy, multipolarity and degree of K forbiddenness, and variations of f_ν necessarily reflect the importance of other degrees of freedom. For consistency, only $E2$, $I \to I-2$ transitions are investigated here.

First, attention is given to the apparently simple behavior of the f_ν values associated with 2-quasiparticle isomer decays in even-even nuclei (filled circles in Figure 1). As pointed out earlier [6, 7], the relatively low reduced hindrances for small N_pN_n can be qualitatively understood as arising from increased K mixing in nuclei with smaller deformations. In the lower part of the $N = 82 - 126$ shell ($N < 104$) Coriolis K mixing associated with the low-Ω, $i_{13/2}$ neutrons is likely to be the most significant effect, while in the upper part of the shell ($N > 104$) the K mixing associated with loss of axial symmetry can be implicated. It is notable that, since 1990, there are no new data points for even-even nuclei, although the highest value, $f_\nu = 340$ for ^{174}Yb, has been confirmed [14], and the limit of $T_{1/2} < 5$ ns (hence $f_\nu < 8.4$) obtained [15] for the $K^\pi = 6^+$ isomer decay in ^{180}Hf ($N_pN_n = 180$) shows consistent behavior (not illustrated in Figure 1).

In contrast to the situation for 2-quasiparticle isomers, there are many new f_ν values for 3-quasiparticle isomers [10, 11, 16–27]. Remarkably, the 3-quasiparticle f_ν values (open symbols in Figure 1) now show almost no correlation with N_pN_n. Several different degrees of freedom have been investigated in an attempt to rationalise the 3-quasiparticle behavior, and what appears to be the simplest analysis is now presented.

Consider first the comparatively low f_ν for the ^{171}Tm isomer decay (lower-right data point in Figure 1, with $f_\nu = 7.6$ and $N_pN_n = 260$). This can be understood [10] as arising from the effect of a chance near-degeneracy. The $K^\pi = 19/2^+$ isomer has an energy that differs by only 11 keV from the $I^\pi = 19/2^+$ member of the rotational band to which the isomer decays. This is the closest near-degeneracy of all the cases shown in Figure 1, and it is therefore treated as a special case. A mixing matrix element of 11 eV is sufficient to explain the isomer half-life [10].

Next, the relatively high f_ν values (the four upper-left data points in Figure 1) are discussed. The uppermost data point ($f_\nu = 71$, $N_pN_n = 126$) is for ^{185}Ta [11]. Two of the others, illustrated by triangles in the figure, correspond to isomer decays where the 3-quasiparticle configurations are most likely of the 3π (3-quasiproton) and 3ν (3-quasineutron) type, in ^{181}Ta (21/2) and ^{181}Os respectively [16, 26]. Building on this observation, a different correlated behavior for decay rates from 3ν and 3π configurations has been found: f_ν depends on the isomer excitation energy relative to a rigid rotor of the same angular momentum, as illustrated in Figure 2. The other data are for ^{177}Ta (17/2) and ^{175}Ta, with 3π configurations, and for ^{183}W and ^{179}W, with 3ν configurations. Similar excitation-energy dependence was observed previously for higher quasiparticle numbers, $m > 3$ [12, 13]. In essence, it demonstrates that isomer decay rates are sensitive to the nuclear level density. It seems, provisionally, that there is a remarkable change in correlation at $m = 3$, from N_pN_n dependence to level-density dependence. If this can be further tested and substantiated, then we suggest that the physical origin is most likely to be related to the blocking of pairing correlations in multi-quasiparticle states, but a quantitative theoretical basis for such a supposition has not yet been found. It is notable that if the full set of 3-quasiparticle f_ν values is plotted against $E_K - E_R$, i.e. including all the $1\pi \otimes 2\nu$, $2\pi \otimes 1\nu$ and mixed configurations, then the correlation is lost.

It remains to address the nature of the ^{181}W and ^{185}Ta 3-quasiparticle configurations (corresponding to the circles in Figure 2). For ^{181}W, the data are tentative [25, 27]. For ^{185}Ta, there has been detailed discussion of the possible isomer configurations, with a $1\pi \otimes 2\nu$ configuration being favored over a 3π configurations, based on multi-quasiparticle energy-level calculations [11]. Nevertheless, there are no g-factor data to confirm the $1\pi \otimes 2\nu$ configuration assignment. With respect to Figure 2, it can be predicted that the ^{185}Ta and ^{181}W configurations are of 3π and 3ν character, respectively, in order to be consistent with the presented correlations.

Before concluding, a few comments are needed about the uncertainties in the f_ν values, which have not been quantified in Table I. Although the uncertainties in the partial half-lives can be $\approx 20\%$, when the fourth root is taken this reduces to $\approx 5\%$, which is comparable to the symbol size in Figures 1 and 2. Of greater importance is the integrity of the spin and parity assignments, since any errors in these will have more radical effects, e.g. removing data from the present considerations. It is notable, therefore, that for the highlighted cases, corresponding to isomer decays in ^{171}Tm and ^{185}Ta, the assignments are considered to be reliable, based on direct measurements of conversion coefficients in ^{171}Tm [10], and conversion-coefficient constraints deduced from isomer-decay intensity-balance considerations in ^{185}Ta [11]. Nevertheless, there is still a possibility that the ^{185}Ta isomer decays by weakly hindered $M2$ and $E3$ transitions, instead of the preferred interpretation [11] of strongly hindered $M1$ and $E2$ transitions.

In summary, an analysis of $E2$ reduced hindrance values from high-K, 3-quasiparticle isomers indicates a configuration dependence: a correlation with excitation energy exists for 3ν and 3π configurations, and there is an N_pN_n correlation for other configurations. Further experimental information, especially for the ^{185}Ta isomer structure, would test the proposed configuration dependence. Extension of these ideas to provide a better understanding of the decay rates from isomers in the $A \approx 250$ deformed region is a promising area for future study.

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TABLE I: Reduced hindrance values for $E2$ decays from 2- and 3-quasiparticle isomers, with $\nu \geq 4$.

nuclide	N_pN_n	K^π	E (keV)	E_γ (keV)	$T_{1/2}$	$T^{\gamma}_{1/2}(E2)$	ν	f_ν	ref.
^{174}Yb	264	6^+	1518	1265	830 μs	42 ms	4	340	[14]
^{172}Hf	180	6^+	1685	1376	5 ns	16 ns	4	9.4	[27]
^{174}Hf	200	6^+	1549	1252	133 ns	290 ns	4	17	[27]
^{176}Hf	220	6^+	1333	1043	9.5 μs	24 μs	4	42	[27]
^{178}Hf	200	6^+	1554	1247	78 ns	220 ns	4	16	[27]
^{178}W	176	6^+	1665	1322	3 ns	5 ns	4	6.8	[27]
^{182}W	144	10^+	2231	1086	1.4 μs	2.6 μs	8	5.1	[27]
^{184}Os	108	10^+	2366	1092	20 ns	60 ns	8	3.2	[27]
^{171}Tm	260	$19/2^+$	1674	428	1.7 μs	2.4 μs	4	7.6	[10]
^{175}Lu	242	$19/2^+$	1391	797	930 μs	1.3 ms	4	82	[16]
^{171}Hf	170	$19/2^+$	1645	1263	6 ns	100 ns	4	14	[17]
^{175}Hf	210	$19/2^+$	1433	867	1.1 μs	4.7 μs	4	22	[27]
^{177}Hf	210	$23/2^+$	1316	229	1.1 s	1.2 s	5	38	[27]
^{175}Ta	180	$21/2^-$	1568	710	2 μs	10 μs	4	21	[18]
^{177}Ta	198	$17/2^+$	1523	890	6 ns	125 ns	4	10	[19]
^{177}Ta	198	$21/2^-$	1355	550	6 μs	46 μs	4	24	[19]
^{179}Ta	180	$21/2^-$	1252	475	320 ns	870 ns	4	6.9	[20]
^{181}Ta	162	$21/2^-$	1485	711	25 μs	150 μs	4	41	[16]
^{181}Ta	162	$29/2^-$	2230	295	210 μs	800 μs	8	4.6	[16]
^{185}Ta	126	$21/2^-$	1274	280	12 ms	120 ms	4	71	[11]
^{179}W	168	$21/2^+$	1632	884	390 ns	920 ns	4	15	[21]
^{181}W	152	$21/2^+$	1653	1054	200 ns	2.2 μs	4	24	[27]
^{183}W	136	$19/2^-$	1746	556	13 ns	60 ns	4	4.3	[22]
^{181}Re	140	$21/2^-$	1656	584	250 ns	750 ns	4	8.6	[23]
^{183}Re	126	$25/2^+$	1907	194	1.0 ms	1.4 ms	8	3.8	[27]
^{181}Os	126	$21/2^+$	1745	1213	13 ns	62 ns	4	12	[26]
^{191}Os	66	$31/2^+$	2640	453	61 ns	63 ns	8	1.9	[24]

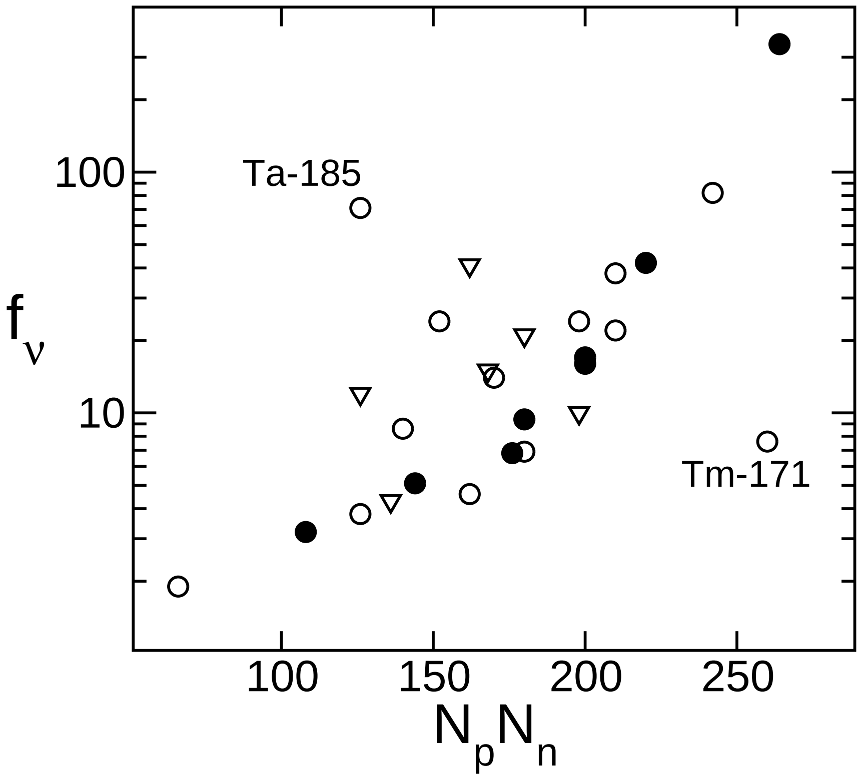

FIG. 1: Reduced hindrance values for 2- and 3-quasiparticle isomer decays, shown as a function of the product of the valence nucleon numbers, for $E2$ transitions with $\nu \geq 4$ in the deformed $A \approx 180$ region. Filled circles: 2-quasiparticle isomers (even-even nuclei); triangles: 3-quasiparticle isomers, where the configurations consist of three nucleons of the same type (3ν or 3π); and open circles: other 3-quasiparticle isomers. Numerical values are given in Table I.

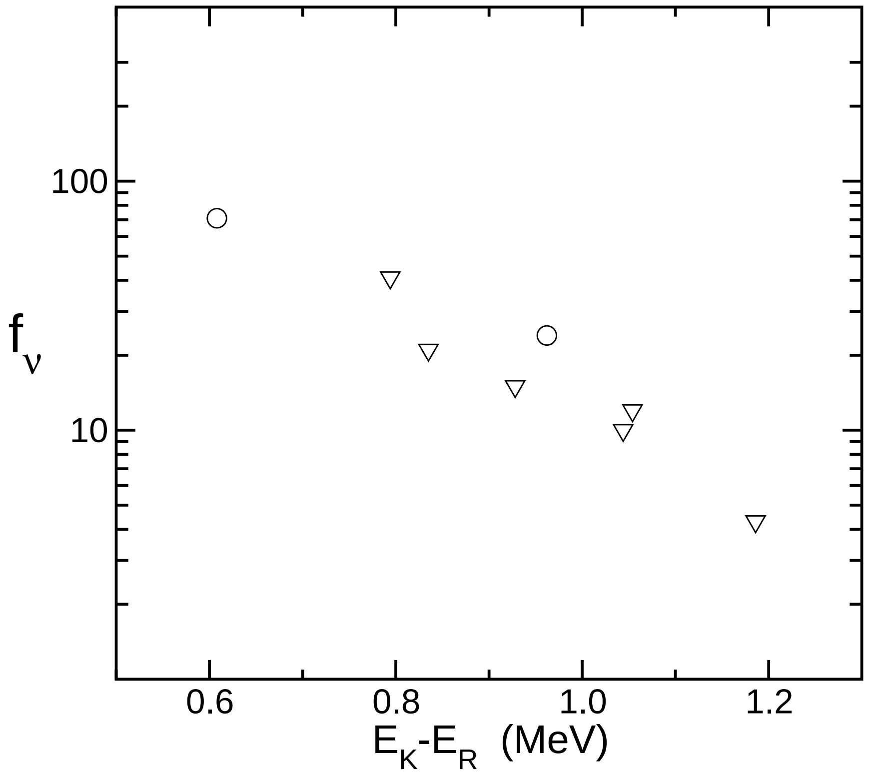

FIG. 2: Reduced hindrance values shown as a function of excitation energy relative to a rigid rotor, for $E2$ decays with $\nu \geq 4$, from 3-quasiparticle isomers in the deformed $A \approx 180$ region. The triangles are for isomer configurations with three nucleons of the same type (3π or 3ν) and the circles correspond to isomers in ^{181}W and ^{185}Ta (see text and Table I). The rotor moment-of-inertia reference is chosen as 85 $\hbar^2 MeV^{-1}$ for $A = 178$, scaling as $A^{5/3}$.