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Lifetime of the $K^\pi = 8^-$ isomer in the neutron-rich nucleus ^{174}Er, and $N = 106$ $E1$ systematics

G. D. Dracoulis,[1,*] G. J. Lane,[1] F. G. Kondev,[2] H. Watanabe,[3] D. Seweryniak,[4] S. Zhu,[4] M. P. Carpenter,[4] C. J. Chiara,[2,†] R. V. F. Janssens,[4] T. Lauritsen,[4] C. J. Lister,[4] E. A. McCutchan,[4] and I. Stefanescu[4,5]

[1]*Department of Nuclear Physics, R. S. Phys. S. E, Australian National University, Canberra ACT 0200, Australia*
[2]*Nuclear Engineering Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[3]*RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[4]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[5]*Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA*

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Chopped-beam techniques and γ-ray spectroscopy with Gammasphere have been used to measure the lifetime of the 1112-keV 8^- isomeric state in ^{174}Er. The value obtained of $\tau = 5.8(4)$ s corresponds to a reduced hindrance of $f_\nu = 98$ for the 163-keV $E1$ transition to the 8^+ state of the ground-state band, in good agreement with the systematics of the corresponding $E1$ strengths in the $N = 106$ isotones. The K-mixing in the 8^- states is calculated in the context of the particle-rotor model and used to extract the underlying reduced hindrances.

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There is continuing interest in understanding the properties of metastable states in deformed nuclei. Such states arise for various reasons [1] including the fact that electromagnetic decays involving large charges in K, the quantum number that describes the projection of the total angular momentum on the nuclear symmetry axis, can be very inhibited. The ability to classify the decay strengths plays an important role in the assignment of intrinsic configurations, as seen in the recent studies of very heavy deformed nuclei (for example, Refs. [2–4]). These studies aim to define the Nilsson orbitals near the Fermi surface and hence the nuclear potential. In turn, systematic studies of the properties of states with well-defined configurations can contribute to a more quantitative description of "forbidden" transitions.

Partly in this context, but also motivated by our interest in probing the nuclear structure of neutron-rich nuclei, we report here new results for ^{174}Er and an analysis of $E1$ strengths for the $N = 106$ isotones. A long-lived 8^- isomer was recently identified [5] in ^{174}Er, establishing simultaneously its previously unknown yrast sequence and extending the sequence of isomers in the $N = 106$ isotones arising from the $\nu^2 7/2^-[514] \otimes 9/2^+[624]$ two-quasiparticle configuration, from $Z = 82$ down to $Z = 68$. However, only a limit of $\tau > 8$ ms on the lifetime was obtained previously, making this case the only one in an extensive chain for which the lifetime, and therefore the inhibited $E1$ strength, is not known. The decay sequence is shown in Fig. 1.

To define the lifetime, new measurements were made under conditions similar to those in which the isomer was first identified. These involved the use of chopped 840-MeV ^{136}Xe beams provided by the ATLAS facility at Argonne National Laboratory. The beams were incident on an enriched target of ^{176}Yb, approximately 6mg/cm^2 in thickness, with a 25 mg/cm^2 Au foil directly behind. The target was thick enough to integrate over the main yield of inelastic processes from ∼20% above the Coulomb barrier, down to the barrier. Gamma rays were detected with Gammasphere [6], with 99 Ge detectors in operation. The nucleus ^{174}Er is populated through two-proton removal from the target, at an intensity level of about 5% of the population of the related 8^- isomer in ^{176}Yb.

Distinguishing ^{174}Er from the much stronger product, ^{176}Yb, has the complication that their ground-state-band transitions are close in energy (differing by 1–2 keV), and the corresponding 8^- isomer in ^{176}Yb also has a long lifetime, in this case 17 s (see Ref. [7] and references therein). However, the primary $E1$ decays from the 8^- isomer to the 8^+ ground-state band are significantly different in energy. Figure 2 is a representative γ-ray spectrum obtained by gating on the 163-keV $E1$ transition in a γ-γ matrix in the out-of-beam time region, which shows the ground-state-band transitions in ^{174}Er without significant contamination.

As well as the transition energies in the yrast bands of ^{174}Er and ^{176}Yb being similar, so are the corresponding sequences in the $N = 104$ isotonic pair, ^{172}Er and ^{174}Yb, consistent with saturation of the deformation near midshell as noted previously [5]. Furthermore, the experimental E_{4^+}/E_{2^+} ratios are essentially identical for the $N = 104$ and $N = 106$ isotones with $Z = 68$, 70, and 72, as seen in Fig. 3. This results in an experimental issue in identifying other structures in ^{174}Er since it is not possible to correlate through the isomers because of the long lifetimes, and, at least for the simplest two-quasiparticle configurations, such as the expected 8^- rotational band itself, they may be very similar to, and possibly unresolvable from, corresponding structures in more strongly populated nuclei such as ^{176}Yb.

The lifetime limit reported previously [5] was obtained from measurements using a macroscopically chopped beam with (beam on)/(beam off) conditions of 1 ms/3 ms for the ^{176}Yb target, and with out-of-beam dual coincidence events recorded in reference to a precision clock. Gamma-gamma matrices as a function of the time were constructed, allowing long lifetimes

*Corresponding author: george.dracoulis@anu.edu.au
†Present address: Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA, and Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA.

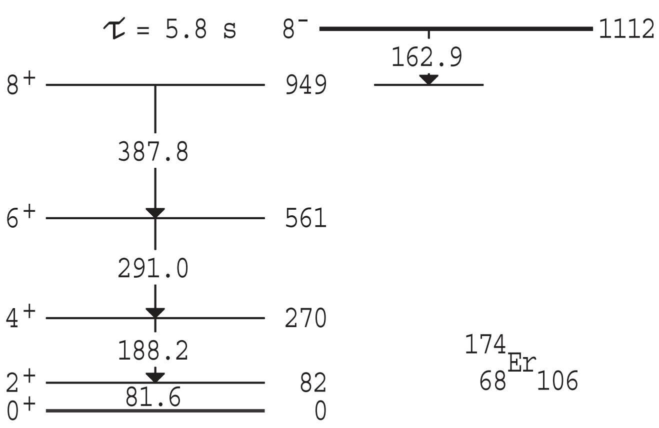

FIG. 1. Decay scheme of the 8^- isomer in ^{174}Er [5] including the new lifetime result from the present work.

to be isolated by gating on specific cascades within the nucleus of interest. Similar conditions and analysis techniques were used in the present experiment, but with longer time ranges, progressing in steps of factors of 10 from an initial value of 10 ms/33 ms up to 1 s/3.3 s, the longest time range that could be accessed conveniently.

Figure 4 provides the intensity of the ^{174}Er ground-state-band transitions obtained with gates on the 163-keV transition as outlined earlier, together with a fit, which gives $\tau = 5.8(5)$ s. The 163-keV transition is the only branch observed from the isomer: A limit on the possible 551-keV $M2$ branch from the 8^- isomer to the 6^+ state of $<2\%$ of the intensity of the 163-keV γ ray corresponds to a limit on the reduced hindrance (defined in the following) of $f_\nu > 46$, consistent with its nonobservation. Such branches are therefore not competitive in this case and in others such as ^{176}Yb, ^{178}Hf, ^{180}W, and ^{182}Os (see Ref. [5]).

As is well known, the isomerism in these nuclei arises from the forbidden nature of the decays between the $K^\pi = 8^-$

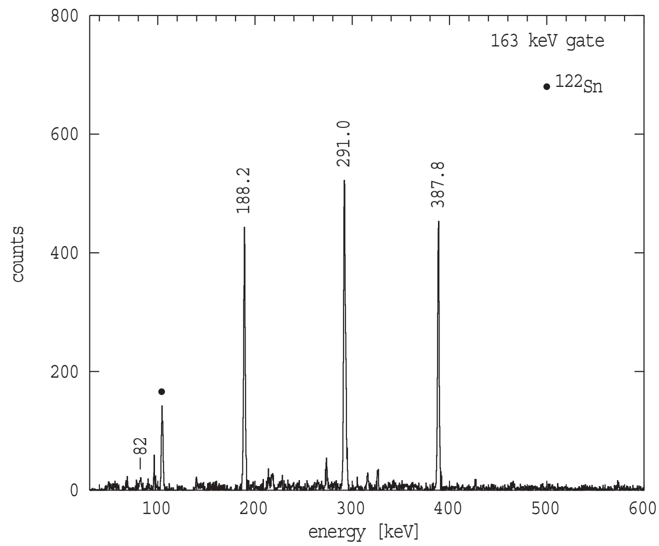

FIG. 2. Coincidence spectrum with a single 163-keV gate in the out-of-beam time region.

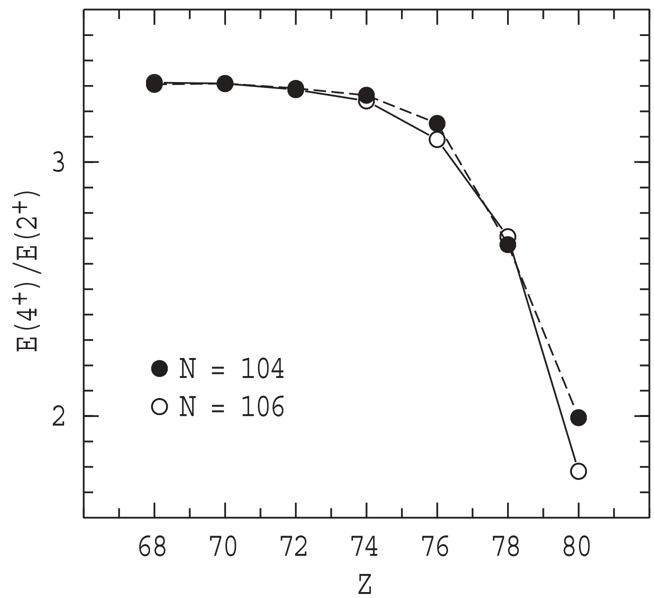

FIG. 3. Ratio of 4^+ and 2^+ state energies for the $N = 104$ and $N = 106$ isotones.

two-quasiparticle state and the $K = 0$ ground-state-band members. The $E1$ transitions have forbiddenness $\nu = \Delta K - \lambda = 7$, where λ is the multipolarity. The hindrance factor F is given by the ratio of the partial mean lives to the Weisskopf estimates τ_W, so that $F = \frac{\tau}{\tau_W}$. The corresponding reduced hindrances $f_\nu = F^{1/\nu}$ for the $N = 106$ isotones, including the new result for ^{174}Er, are given in Fig. 5.

The f_ν values vary relatively smoothly from a value of 98 in ^{174}Er to $\sim$30 in ^{188}Pb, a nucleus where the presence of this isomer has been used as an argument for the prolate nature of the secondary well in a situation where three shapes

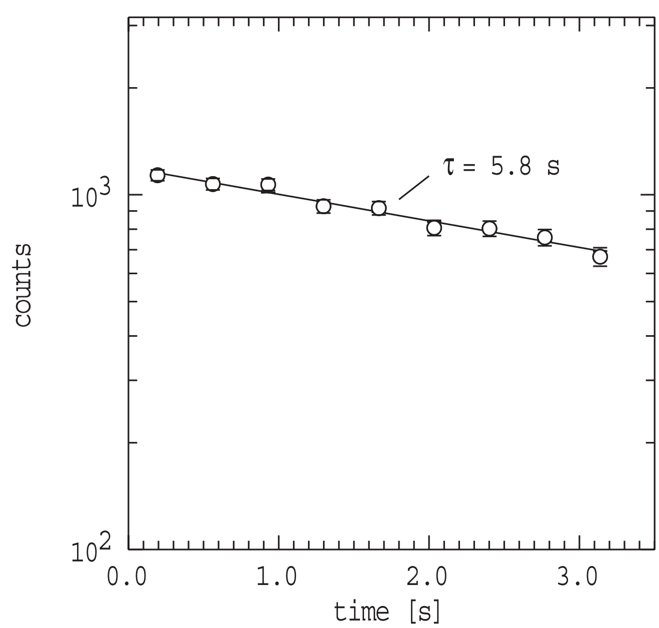

FIG. 4. Time dependence of the decay of the 8^- isomer in ^{174}Er together with a fit to an exponential curve.

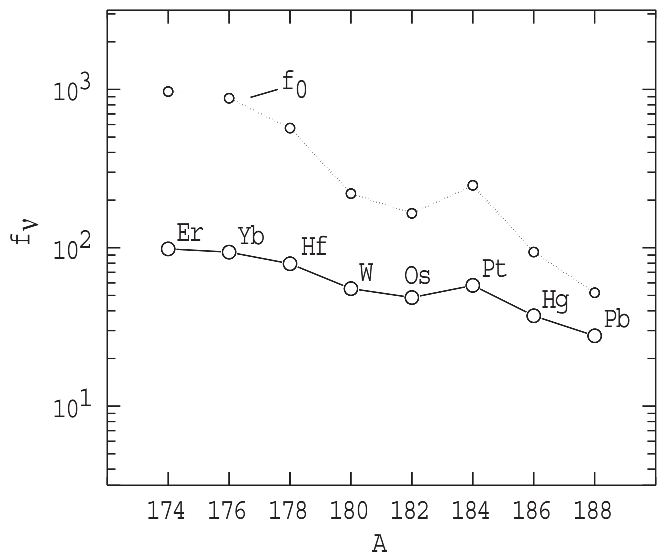

FIG. 5. Reduced hindrances for the $E1$ decays from the 8^- isomers in the $N = 106$ isotones. The value for the ^{178}Hf case has been corrected for the known mixing between the two-neutron configuration and a competing two-proton configuration [9–12]. The smaller symbols, connected by the dashed line, are the values obtained after correction for Coriolis mixing in the initial state (see text).

coexist [8]. The only point that might deviate significantly in the systematic behavior is that obtained for ^{184}Pt. There are two issues with this value. The first one is experimental in that a significant branch occurs through an unobserved low-energy transition. The second is that this is a case where the deformation of the final states may be less well defined than in nuclei where either the ground state is well deformed or where shape coexistence is sufficiently well established that the potential minima are well separated in deformation. Triaxiality may therefore be a factor in ^{184}Pt, although in general one would expect this to lead to the lowering of apparent hindrances because of a broader K-distribution in the final states.

Note that the $E1$ strengths extracted here do not include the additional factor of 10^3–10^4 often arbitrarily used in the evaluation of reduced hindrances, but the hindrances could be seen already, as being relatively low for $E1$ transitions. In actuality, K-forbidden $E1$ strengths show large variations between specific mass regions, probably indicative of the underlying configuration, configuration-change, or coupling dependencies (see, for example, Refs. [12–15]). Such nuclear structure effects could be disguised by using additional arbitrary reduction factors.

Walker *et al.* [12] pointed out a correlation between the fall in the f_ν values for the $E1$ transitions from the 8^- isomers (as they were known then) and the ratio of the dynamic to the kinematic moment of inertia in the ground-state bands, which was taken to imply the presence of higher K-components in the (nominally) $K = 0$ ground-state band. This particular contribution is difficult to treat quantitatively; however, another factor that will affect the absolute rates is K-mixing in the initial state, as was also noted in Ref. [12].

Mixing is expected since the two-neutron 8^- configuration contains the $9/2^+[624]$ orbital from the $i_{13/2}$ neutron configuration and, thus, will be Coriolis-mixed, even though the Fermi surface is relatively high in the shell.

We have estimated the K-mixing in the initial state in the context of a simplified model [16] that treats the non-high-j particles, in this case a single $7/2^-[514]$ neutron, as spectators, since Coriolis-mixing among its partner orbitals is small. In this model there are $(2j+1)$ possible projections of the $i_{13/2}$ set of orbitals, $\Omega = -13/2, -11/2, \ldots, +11/2, +13/2$. (Note that the sign relative to the nonparticipating orbitals needs to be retained in enumerating the set of basis states [17].) There are various parameters in this model, particularly the pairing strengths, whose choice can be guided by the mass differences (see also the discussion in Ref. [5]) and the unperturbed band moments of inertia. The approach taken has been to approximately constrain these by reproducing the energies of states in the 8^- rotational bands. These are now known for ^{176}Yb [18,19], ^{178}Hf [9–11], ^{180}W [20], ^{182}Os [21], ^{184}Pt, [22], ^{186}Hg [23,24], and ^{188}Pb [8]. This structure has not been identified in ^{174}Er but, as noted earlier, in all likelihood, it is expected be very similar to that of ^{176}Yb. The energies of the intrinsic states were taken from the Nilsson model by assuming predicted deformations [25,26]. A 14×14 matrix can be constructed for the highest spins in each case, with off-diagonal matrix elements within the $i_{13/2}$ set of orbitals connecting states of the same spin and with $\Delta K = \pm 1$ (as shown schematically in Fig. 17 of Ref. [17]). The Coriolis matrix can then be diagonalized to give the perturbed energies and the wave function admixtures in terms of the normalized amplitudes, A_K.

The results of these calculations give very similar admixtures for all cases. Those for ^{182}Os, for example, are $A(K=8) = 0.9625$; $A(K=7) = 0.2644$; $A(K=6) = 0.0590$; $A(K=5) = 0.0120$; $A(K=4) = 0.0025$; lower K-components are negligible.

By including such components explicitly, it is possible to extract the underlying reduced hindrance f_0 with the implicit assumption that the reduced hindrance is independent of the rank of the forbiddenness, ν. This was the approach taken recently in analyzing hindrances in another case where admixtures can be calculated [27]. The formulation follows from the fact that the inverse of the total hindrance F is related to the total decay width and, therefore, can be constructed from the sum of partial widths for each K-component. In the general situation there are K-admixtures A_{K_i} and B_{K_f} in the initial and final states, with $\nu_{K_iK_f} = K_i - K_f - 1$ and therefore (for $\nu_{K_iK_f} > 1$)

$$\frac{1}{F} = \sum_{K_i,K_f} \frac{\left(A_{K_i} B_{K_f}\right)^2}{(f_0)^{\nu_{K_iK_f}}}.$$

In the present case, we assume that the final state (8^+ in the ground-state band) is pure $K_f = 0$ (i.e., $B_0 = 1.0$), and thus have, for the 8^- states,

$$\frac{1}{F(8^-)} = \frac{(A_8)^2}{(f_0)^7} + \frac{(A_7)^2}{(f_0)^6} + \frac{(A_6)^2}{(f_0)^5} + \frac{(A_5)^2}{(f_0)^4} + \frac{(A_4)^2}{(f_0)^3} + \cdots.$$

The value of f_0 was then varied to reproduce the total $E1$ hindrance for each isotone. The values recovered in this way are given in Fig. 5. For ^{182}Os, for example, the observed total hindrance of 6.34×10^{11} (corresponding to $f_\nu = 48.5$) can be reproduced with the calculated mixed-K amplitudes and $f_0 = 165$. A similar rescaling is seen in all cases, with the extracted value for ^{174}Er rising by an order of magnitude from 98 to 970. It should be noted, however, that the dominant term is that from the lowest K value of $K = 4$, despite its very low amplitude. The presence of very small amplitudes of even lower K that might fall below the numerical accuracy of the present calculations would result in an underestimate of f_0. For example, components of $K = 0, 1$ become significant at amplitude levels of $\sim 10^{-5}$. This (obvious) sensitivity means that the extracted values will only be approximate, given the uncertainties in the model calculation. Nevertheless, the high values for the underlying hindrances exposed when the admixtures are taken into account are more in line with those expected for K-forbidden $E1$ transitions. This quantitative approach avoids the need to resort to the inclusion of arbitrary reduction factors in evaluating (and comparing) $E1$ transition strengths.

From another perspective, the high sensitivity to the admixture of low-K components in highly forbidden transitions implies that random fluctuations could be expected, yet a relatively smooth behavior is observed. This apparent contradiction can be attributed to two factors, one being the near-yrast nature of the 8^- isomers in most cases and the other being the very small mixing matrix elements between states with large ΔK, as revealed through specific instances of random mixing [5] that introduce collective components into the wave functions. These are distinct from situations where sequential K-mixing occurs from known Coriolis effects as treated here.

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