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

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Chopped-beam techniques and $\gamma$-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 $f_\gamma = 98$ 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 $\nu=7/2^- \otimes 9/2^+$ [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 $6\text{mg/cm}^2$ in thickness, with a $25 \text{mg/cm}^2$ Au foil directly behind. The target was thick enough to integrate over the main yield of inelastic processes from $\sim 20\%$ 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 $\gamma$-ray spectrum obtained by gating on the 163-keV $E1$ transition in a $\gamma \gamma$ 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 $E4/\ E2$ 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

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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 $M^2$ branch from the $8^-$ isomer to the $6^+$ state of $<2\%$ of the intensity of the 163-keV $\gamma$ 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 $K^\pi = 8^-$ two-quasiparticle state and the $K = 0$ ground-state-band members. The $E1$ transitions have forbiddenness $\nu = \Delta K - \lambda = 7$, where $\lambda$ is the multipolarity. The hindrance factor $F$ is given by the ratio of the partial mean lives to the Weisskopf estimates $\tau_W$, 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 $f_\nu$ 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. 1. Decay scheme of the $8^-$ isomer in $^{174}$Er [5] including the new lifetime result from the present work.

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.

FIG. 4. Time dependence of the decay of the $8^-$ isomer in $^{174}$Er together with a fit to an exponential curve.
configuration and a competing two-proton configuration \[9–12\]. The
has been corrected for the known mixing between the two-neutron
K bands, which was taken to imply the presence of higher
dynamic to the kinematic moment of inertia in the ground-state
isomers (as they were known then) and the ratio of the
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 \(f_0\) 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 configu-
ration 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.
(\textit{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 \[18,19\], \(^{176}\)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 to 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 \(\times\) 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 ad-
mixtures 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, \(\nu\). 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 \(A_K\) and \(B_K\) in the initial
and final states, with \(\nu_{K_f,K_i} = K_i - K_f - 1\) and therefore (for
\(\nu_{K_f,K_i} > 1\))

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

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,

\[
\frac{1}{F(8^-)} = \frac{(A_8)^2}{(f_0)^7} + \frac{(A_6)^2}{(f_0)^9} + \frac{(A_6)^2}{(f_0)^9} + \frac{(A_6)^2}{(f_0)^9} + \frac{(A_6)^2}{(f_0)^9} + \cdots
\]
The value of \( f_0 \) was then varied to reproduce the total \( 1E \) hindrance for each isotope. The values recovered in this way are given in Fig. 5. For \(^{182}\text{Os} \), for example, the observed total hindrance of \( 6.34 \times 10^{11} \) (corresponding to \( f_0 = 48.5 \)) 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 \(^{176}\text{Er} \) 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 \( 1E \) transitions. This quantitative approach avoids the need to resort to the inclusion of arbitrary reduction factors in evaluating (and comparing) \( 1E \) 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 \( \delta \) isomers in most cases and the other being the very small mixing matrix elements between states with large \( \Delta K \), 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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