K-Isomers as a Probe of Nuclear Structure and Advanced Applications

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Abstract. Nuclear K-isomers play a pivotal role in understanding the structure of deformed, axially symmetric nuclei. Examples are presented of recent studies of exotic multi-quasiparticle isomers in the A~180 rare-earth region at the extreme of angular momentum and neutron number. A specific band-mixing scenario is invoked to explain the unusual decay path of the $K^π=57/2^-$ isomer ($T_{1/2}=22$ ns) in $^{175}$Hf, the highest spin K-isomer known in nature. The discovery of a suite of high-K isomers, above the previously known $K^π=23/2^-$ ($T_{1/2}=160$ d) state in $^{177}$Lu, using deep-inelastic and multi-nucleon transfer reactions is discussed.

INTRODUCTION

Nuclear isomers are excited, long-lived states in atomic nuclei that may de-populate by one or more of the conventional radioactive decay modes, such as $α$, $β$, $γ$, fission, etc. The first isomer was discovered in $^{234}$Pa ($T_{1/2}=70$ s) by O. Hahn in 1921 and, since then, many more were observed all over the nuclear chart. In general, when an isomer decays by gamma radiation, the long lifetime is a consequence of de-excitation properties. In a schematic way, the decay rate can be written as

$$\frac{1}{\tau} \propto E_γ^{2λ+1} |\langle ψ χ |T_λ |ψ\rangle|^2$$

and, therefore, a low transition energy, $E_γ$ and/or a large transition multipole order, $λ$, may lead to a significant lifetime. However, nuclear structure may also play an important role through the third term of Eq. (1). One example is fission isomers in the actinide region, where there is a notable difference between the shape of the isomer and that of the final state that leads to profound dissimilarity in the single-particle basis, and, as a consequence, a larger hindrance. Another example is K-isomers in deformed, axially symmetric nuclei, where $K$ is the projection of the intrinsic angular momentum on the symmetry axis. In this case, the isomerism arises due to the approximate conservation of the K-quantum number, so that $γ$-ray transitions between states with large K-value differences are strongly retarded. The degree of K-forbiddenness, $ν=\Delta K·λ$, is correlated with the Weisskopf hindrance factor $F_w=\tau/\tau_W$ and, in general, the so-called reduced hindrance per degree of K-forbiddenness, $f_ν=(F_w)^{1/ν}$, is typically larger than 20. There are cases, however, where $f_ν$ is very small ($f_ν<10$). Such anomalous decays have been commonly associated with K-mixing introduced by shape changes involving the $γ$ degree of freedom [1], or with random mixing because of the high density of states above the yrast line [2], although the exact mechanism remains uncertain and controversial.

One of the regions that is known to be a “haven” for the study of nuclear K-isomers is the rare-earth region near $A\sim 180$, where there is dominance of high-K orbitals in the vicinity of both the neutron and proton Fermi surfaces. This gives rise to the presence of high-K, multi-quasiparticle structures that are often isomeric with half-lives ranging from a few nanoseconds to hundreds of years [3]. The attraction of studying K-isomers in this mass region is multitudinous. For example, they offer the opportunity to probe particular aspects of nuclear structure in well-defined configurations, including the interplay between collective and intrinsic motion, the limits of conservation of the K-quantum number under extreme conditions and the seniority dependence of the major residual interactions in deformed nuclei. On the other hand, the interest is also motivated by their relevance to many applications, including (but not necessarily limited to) nuclear astrophysics and nuclear energy.
ISOMERS AT THE EXTREMES OF ANGULAR MOMENTUM

The hafnium nuclei near and below the mid-neutron shell (N=104) provide some of the textbook examples of multi-quasiparticle isomers in the A~180 region. The availability of heavy-ion induced fusion evaporation reactions in producing states at high-spin in these nuclei has made them a focus of many studies at the extremes of angular momentum. Using the recoil-shadow technique in conjunction with the 130Te(48Ca,3n) reaction, Gjorup et al. [4] reported on the discovery of a particularly exotic high-K isomer in 175Hf at 7.5 MeV. Although the spin, parity, and lifetime of this state were not precisely determined, it was suggested that K=57/2-. In order to account for such a large intrinsic spin value, at least nine quasiparticles have to be involved (a seniority nine state), thus making it the highest seniority K-isomer known in nature. With so many levels in the vicinity of both the proton and neutron Fermi surfaces occupied by the valence nucleons, one may expect pairing correlations to be completely quenched in this state, due to the “blocking effect.” This would affect not only the decay rates, but also the properties of collective structures associated with the isomer. In addition, it has been suggested [4] that the main decay of the isomer proceeds via the 661-keV transition directly to the l'=55/2 member of the K'=35/2 band. Such a transition is 10-fold K-forbidden and it violates significantly the K-selection rule of minimizing the change in the K-quantum number at each step of the decay. Strictly speaking, the decay path should have never occurred, but surprisingly, it is reported [4] to be the main decay branch of the isomer. A seven-quasiparticle state with tentative spin, parity, and half-life was also reported to be long-lived, but no connection to the nine-quasiparticle isomer was established.

We have performed new studies on 175Hf using the same 130Te(48Ca,3n) reaction, but now utilizing the pulsed beam technique. The beam, with energy of 194 MeV, was supplied by the ATLAS superconducting linear accelerator at the Argone National Laboratory and it was swept to give ~1-ns-wide pulses separated by 825 ns. The target was enriched up to 98% with 130Te and was about 1 mg/cm² thick on a 16-mg/cm² Au backing, sufficiently thick to stop the recoiling nuclei. In order to accommodate beam intensities as high as 2 pnA, without a degradation of the target due to heating, the beam was wobbled 2.5 mm across the target with a magnetic steerer. Gamma rays were detected using the Gammasphere spectrometer [5] consisting, for this experiment, of 100 large-volume escape-suppressed Ge detectors. Coincidence measurements were carried out with a condition that at least three Ge detectors fired within a 800-ns time window. The sweeping of the beam and the recorded time information allowed highly sensitive measurements of γ rays across long-lived states to be performed. This proved to be vital in constructing the 175Hf level scheme. In addition, measurements using a 0.5-mg/cm²-thick 130Te target on a 0.2-mg/cm² Au foil were also performed. The beam sweeping conditions were ~1-ns-wide pulses, 82.5 ns apart. The thickness of the target and the backing was such that the nuclei could recoil into vacuum and decay in flight, thus enabling a significant enhancement in the observation of high spin states to be made. The third experiment [6], aimed at measuring lifetimes in the μs region, was performed at the 14UD Pelletron accelerator facility of the Australian National University. The 176Er(9Be,4n) reaction was employed at a beam energy of 50 MeV and a self-supported target of 170Er, enriched up to 95% and having a thickness of approximately 4.0 mg/cm², was used. Pulsed beams with 4 μs on and 64 μs off were used, and only singles γ rays and their time relative to the beam pulse in the out-of-beam region were collected using the CAESAR array, equipped with seven escape-suppressed Ge detectors.

The present data significantly extend the previously known level scheme of 175Hf [4]. Firm K=45/2+ and 57/2 assignments were made to the previously reported high-spin isomers and half-lives of 1.9(1) μs and 22(2) ns were measured, respectively. A time-correlated spectrum showing γ rays above the K=45/2+ isomer is presented in Fig. 1. These γ rays were assigned to a rotational band associated with the isomer, as well as to two new high-K seven-quasiparticle bands. Similarly, a rotational band associated with the K=57/2 isomer, as well as another nine-quasiparticle state with K=61/2,

![FIGURE 1. A time-correlated spectrum of γ rays that were placed above the K=45/2+ isomer (T1/2=1.9 μs) in 175Hf.](image-url)
including its associated collective band, were also discovered. The properties of collective structures, such as the $|g_{K}g_{K}/Q_{0}|$ values, aided in assigning the configurations to the multi-quasiparticle states. For example:

$K=45/2^+$ isomer at 4635 keV:

$\pi^2 (7/2[404],9/2[514])$

$\nu^5 (1/2[521],5/2[512],7/2[514],7/2[633],9/2[624])$

$K=57/2^-$ isomer at 7453 keV:

$\pi^4 (5/2[402],7/2[523],7/2[404],9/2[514])$

$\nu^5 (1/2[521],5/2[512],7/2[514],7/2[633],9/2[624])$

$K=61/2^+$ state at 8371 keV:

$\pi^4 (5/2[402],7/2[523],7/2[404],9/2[514])$

$\nu^5 (5/2[512],7/2[514],5/2[642],7/2[633],9/2[624])$

The analysis of the current data showed that the decay of the $K^\pi=57/2^-$ isomer ($T_{1/2}=22$ ns) is much more complex than anticipated earlier [4]. The observed new decay branches via the 94.4-keV and 157.0-keV transitions to the high- K structures identified above the $K^\pi=45/2^+$ isomer ($T_{1/2}=1.9$ $\mu$s), obey the K-selection rule. Sample $\gamma$-ray spectra in the out-of-beam region are given in Fig. 2. We confirm the main isomer decay path via the anomalous 661.0-keV ($f_\gamma=4.0$) transitions, but we also report on another anomalous, 1083.2-keV ($f_\gamma=3.5$) E2 transition to the $53/2^-$ level. An additional branch via the 561.6-keV ($f_\gamma=82.9$) transition to the $53/2^-$ member of the newly observed $K^\pi=49/2^-$ band was also discovered. This latter structure, whose configuration is that of the $K^\pi=35/2^-$ band with the addition of a pair of $i_{13/2}$ neutrons, plays a key role in explaining the anomalous reduced hindrance values for the 661.0- and 1083.2-keV transitions. In a simplified manner, the $K^\pi=35/2^-$ and $49/2^-$ bands interact in the $I^\pi=49/2^-$ - $57/2^-$ spin region (note, that this is the region where the $K^\pi=35/2^-$ band undergoes a sharp upbend), and this leads to the introduction of high-K admixtures into the structure of the lower-K ($K^\pi=35/2^-$) band. Figure 3 shows a plot of the excitation energies as a function of spin for these bands, as well as for the $K=57/2^-$ structure. It is worth mentioning that the observation of many intra-band transitions between the $K=35/2^-$ and $49/2^-$ bands also supports such a scenario.

FIGURE 2. Sample gamma-ray spectra in the out-of-beam region showing transitions above the $K^\pi=45/2^+$ ($T_{1/2}=1.9$ $\mu$s) isomer in $^{175}$Hf.

FIGURE 3. A plot of the excitation energy, with subtracted rigid rotor reference, as a function of the angular momentum for the $K^\pi=35/2^-$, 49/2-, and 57/2- bands in $^{175}$Hf.
K-ISOMERS IN NEUTRON RICH NUCLEI NEAR $^{176}$LU

Most of the studies in the A=180 region so far have been focused on neutron-deficient nuclei that are readily accessible by heavy-ion fusion evaporation reactions. The information for nuclei near or on the neutron-rich side of the valley of stability is very scarce, despite the fact that this is the region where the longest-lived isomers are known to reside, and hence, there is interest for various applications. Two of the longest-lived cases known, the $\pi = 16^+$, 31 $\gamma$ isomer in $^{178}$Hf and the $\pi = 23/2^-$, 160 $\delta$ isomer in $^{177}$Lu, have been recently examined by Carroll et al. [7] as possible candidates for an x-ray-driven energy emission. In [7] the reported overall figure of merit for the latter case is significantly better when compared to that for the much debated $\pi = 16^+$ isomer in $^{176}$Hf [8,9]. There is no doubt that nuclear isomers can store a significant amount of energy. What is not so clear, however, is how this energy can be released. In other words, how the stored energy can be gained back. This is why knowledge of the levels and their structure above long-lived isomers is important, at least from this application point of view. The discovery of states above very long-lived isomers is a challenge to the experimentalists, since practical coincidences across them are impossible owing to the long lifetime. In addition, the above-mentioned high-spin isomers in $^{175}$Lu and $^{179}$Hf cannot be populated by heavy-ion-induced fusion evaporation reactions, due to the lack of such reactions with the currently available stable beam/target combinations. However, studies of $^{178}$Hf using incomplete fusion reactions in conjunction with the $\alpha-\gamma-\gamma$ correlation technique [10] proved to be valuable in revealing the high-spin levels above the $\pi = 16^+$ isomer. In the case of $^{177}$Lu, a 25/2$^-$ rotational state was tentatively assigned in early (d, p) studies [11] and band members up to a 29/2$^-$ state have recently been identified using $\gamma$-ray spectroscopy and Li-induced, incomplete fusion reactions [12]. Multi-quasiparticle-state calculations carried out with the approach described by Jain et al. [13], but with the inclusion of a Lipkin–Nogami treatment of pairing correlations (see, for example, [14,15]), reproduce the excitation energy of the $\pi = 23/2^-$ isomer, and also predict the presence of a $\pi = 39/2^-$ five-quasiparticle state at about 3400 keV. This level is particularly favored in energy and is, thus, likely to lead to a higher-lying isomer. It may be expected that its decay would proceed through levels above the long-lived $\pi = 23/2^-$ isomer. Recently, Al-Garny et al. [16] have reported the observation of $\gamma$ rays from the well-known $\pi = 37/2^+$, 51.4-min isomer at 2740 keV in $^{171}$Hf [17], which they attributed to indirect population through $\beta$-decay from a previously unknown high-K isomer in $^{177}$Lu. A 7(2)-min half-life was deduced from the growth curve for the decay of the 51-min $^{177}$Hf isomer, but no $\gamma$ rays within $^{177}$Lu were identified. Hence, both the identification and association with the predicted state in $^{177}$Lu are uncertain, and, importantly, the excitation energy is unknown.

Following new spectroscopic information on isomers and band structures in the nuclei $^{175}$Lu, $^{176}$Lu, and $^{179}$Lu that has become available through studies of Li-induced reactions [12], we have pursued studies of lutetium nuclei around $^{176}$Lu, and the neighboring ytterbium, hafnium, and tantalum isotopes, that are located near and beyond the line of stability using the Gammasphere spectrometer in conjunction with time-correlated $\gamma$-ray coincidence techniques. In a recent experiment, a 820-MeV pulsed beam (1 ns on/820 ns off) of $^{136}$Xe from the ATLAS accelerator at Argonne National Laboratory was used to bombard several targets, including $^{174}$Yb, $^{175}$Lu, and enriched $^{176}$Lu. Many nuclei in the region near $^{176}$Lu and $^{136}$Xe were populated using so-called deep-inelastic and multi-nucleon transfer reactions. The results on $^{176}$Lu and $^{179}$Ta have been published recently [18,19]. Figure 4 shows a gamma-ray spectrum, obtained with the $^{176}$Lu target, of a sequence of transitions following the decay of a long-lived isomer, with branches of 619 and 227 keV feeding the upper states of a rotational band, apparently isolated from other structures. The lowest transitions in the band match those assigned by McGoram et al. [12], Lu $\gamma$-rays are observed in coincidence, and the cross comparison of isotope yields support placement of the band as feeding the $\pi = 23/2^-$ state in $^{177}$Lu. The new isomer is placed at 3530 keV and firm $\pi = 39/2^-$ was assigned, based on the established M1 character of the 227-keV depopulating transition [18]. The lifetime of the isomer was not determined accurately, since it was outside the range of the present measurements and we

![Figure 4](image-url)
It is important to address the possibility that the established and two new branches in parallel to the main decay path were also associated with the claimed $\beta^-$ decaying state in [16]. The transition strengths for the K-forbidden 227-keV and 619-keV transitions, as well as the log $ft$ value assuming a $\beta^-$ decay branch to the $K^\pi=37/2^+$ isomer in $^{177}$Hf, seem to be in agreement with the $\beta^-$ decay scenario proposed in [16]. However, there are some discrepancies. It has been suggested by Al-Garny et al. [16] that the excitation energy of the $K^\pi=39/2^-$ isomer in $^{177}$Lu is ~3.9 MeV, where we placed it unambiguously at 3530 keV, following the observed isomer $\gamma$-ray decay paths towards the $K^\pi=23/2^-$ state at 970 keV [18]. In addition, the $\gamma$-ray transitions associated with the decay of the $K^\pi=39/2^-$ isomer (see for example figure 4) act as a fingerprint of this state, but none of them were reported in the earlier work [16]. Finally, assuming the reported half-life of 7 (2) min [16], the transition strength for the non-K forbidden 755.8 keV E3 transition to the $K^\pi=33/2^-$ state [18] is more than 10$^9$ times retarded when compared to the Weisskopf estimate. This is an unprecedented hindrance value that needs detailed explanation. Direct measurements of the lifetime of the $K^\pi=39/2^-$ isomer through its $\gamma$-ray decay path are planned. These will address some of the discrepancies mentioned above.

**SUMMARY AND CONCLUSIONS**

Nuclear K-isomers play a seminal role in studying properties of deformed axially symmetric nuclei. Selective examples were presented on investigation of multi-quasiparticle isomers at the extremes of angular momentum and neutron number. The decay of the $K^\pi=57/2^+$ isomer in $^{175}$Hf, that is the highest spin K-isomer known in nature, has been elucidated. The unusually fast branches to members of the $K^\pi=35/2^-$ band are suggested to be not a consequence of some erosion of the K-quantum number, but rather due to a specific mixing between two configuration-related collective structures. The use of deep-inelastic and multi-nucleon transfer reactions made it possible to extend the knowledge towards more neutron rich nuclei. The discovery of a particularly favored five-quasiparticle $K^\pi=39/2^-$ isomer in $^{177}$Lu is presented. The association of this state with a previously reported $[16]$ $\beta^-$ decaying isomer is discussed.

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