Nuclear isomers: stepping stones to the unknown

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Abstract. The utility of isomers for exploring the nuclear landscape is discussed, including their role in superheavy-element research, and the possibility of observing neutron radioactivity. Emphasis is given to K isomers in deformed nuclei. Transition rates are examined in the N_pN_n scheme for 2- and 3-quasiparticle K-isomer decays, and in connection with level densities for higher quasiparticle numbers.

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INTRODUCTION

Nuclear isomers continue to make key contributions to the development and understanding of nuclear structure physics [1, 2]. Isomers are widely distributed in neutron number, proton number, excitation energy and angular momentum. With half-lives ranging from nanoseconds to years, they offer a variety of opportunities to explore unusual and extreme states of nuclei. The understanding of their occurrence and degree of stability promises additional nuclear structure insights, with the potential for novel applications.

Figure 1 shows a restricted set of isomers, with long half-lives and high excitation energies. It is clear that many such isomers are correlated with shell closures. These can be categorised as spin traps: they arise from special combinations of single-particle orbits in a spherical potential, with decay transitions that must carry high angular momentum (hence the long half-lives). Away from the closed shells are regions of deformed nuclei, where axial symmetry gives rise to the K quantum number. The associated K traps involve transitions with large changes in the orientation of the angular momentum (though not necessarily in the magnitude).

In Figure 1, only ^{242}Am represents shape isomers, where it is a nuclear shape change, rather than an angular-momentum change, that hinders the isomer deexcitation. A convenient listing of isomers, with their angular momenta and half-lives, can be found in ref. [3]. However, the tabulation is incomplete for isomers with half-lives < 1 ms.

The delay time for isomer decays provides an important experimental tool for separating them from the bulk of the radiation from nuclear reactions. This is all the more important when exploring the limits of nuclear stability, with non-selective reactions that lead to many final products. In the study of neutron-rich nuclei with deep-inelastic reactions, fragmentation reactions or fission, the additional selectivity provided by isomer decays can be especially valuable.

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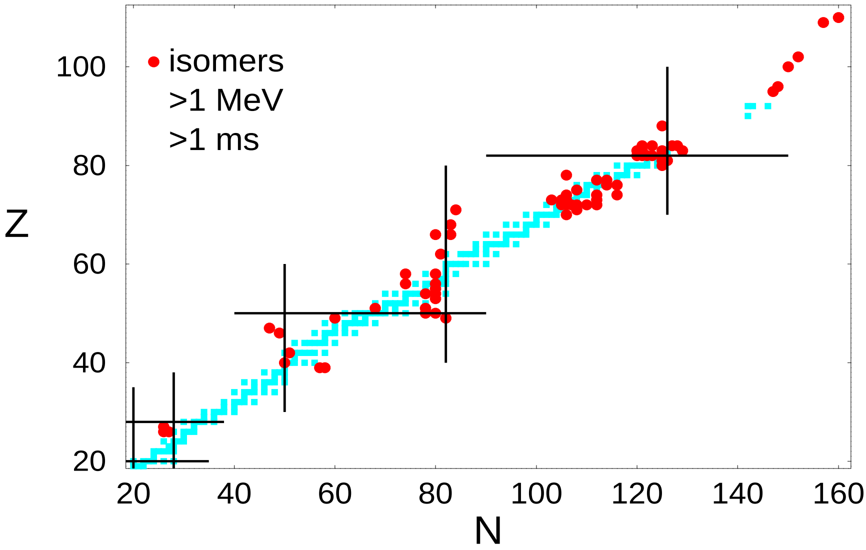

FIGURE 1. Nuclear chart: squares – naturally occurring nuclides; circles – isomers with half-lives > 1 ms and excitation energies > 1 MeV; and lines – closed shells (adapted from ref. [1]).

HIGH-K ISOMERS

The K value is the angular-momentum projection on the nuclear symmetry axis. This is not a directly measured quantity, but it is usually assumed to be equal to the total angular momentum (I) of the isomer (which is itself typically observed as the lowest-energy, lowest-spin member of a rotational band). To a first approximation, the K value is unaltered by collective rotation, which has it angular momentum perpendicular to the symmetry axis. However, inertial forces, principally the Coriolis force, cause K mixing and rotational alignment of individual nucleon orbits. It is these and other K-mixing effects that determine K-isomer decay rates.

The wide range of K-isomer half-lives is evident in Figure 2. It is also clear that the majority of K isomers are found in the A≈180 region. Indeed, it is only in that region that isomers involving > 3 quasiparticles are so far observed. Since the K values of isomers increase with quasiparticle number, it is through the properties of isomers in the A≈180 region that angular-momentum (and pairing) effects can best be studied.

Arguably the most famous K isomer is the 31-year, $K^{\pi} = 16^{+}$, 2.45-MeV excitation of ^{178}Hf, originally discovered over 35 years ago following reactor-neutron bombardment of natural hafnium [4]. The vast majority of the 31-year isomer decay strength is by (unobserved) conversion electrons associated with a 13-keV E3 transition to the I = 13

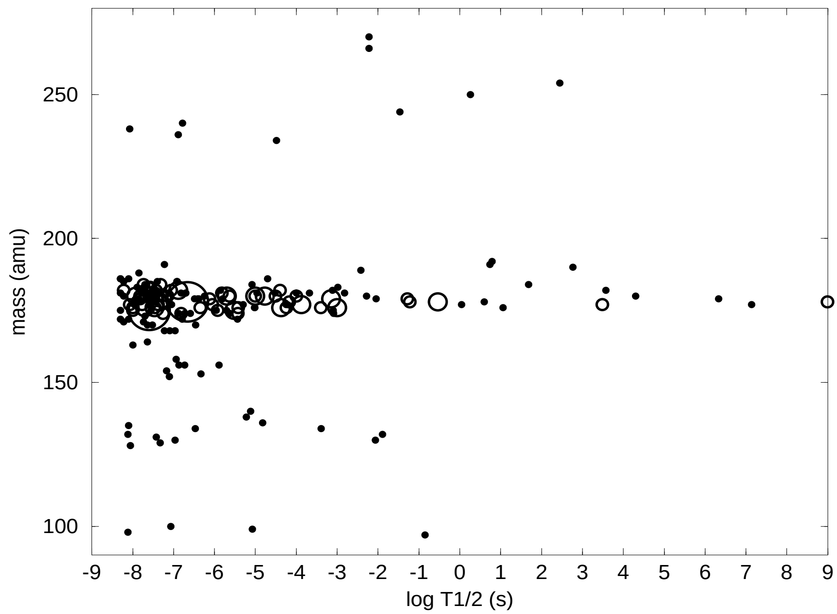

FIGURE 2. K-isomer mass number versus half-life (> 5 ns). The dots represent 2-quasiparticle isomers (excluding odd-odd nuclei) and 3-quasiparticle isomers, and the circles increase in size with quasiparticle number, up to 9 quasiparticles. Isomers in nuclides within four mass units of closed shells are omitted.

member of a K = 8 band. With decay by a $\lambda = 3$ transition, the isomer can be called a spin trap, and with a K change of 8 units the transition has a forbiddenness of $\nu = \Delta K - \lambda = 5$, classifying the isomer also as a K trap. This is an exceptional spin-trap/K-trap situation, which can explain the remarkable combination of high excitation energy and long half-life. Only recently have γ-ray emissions directly from the isomer been observed [5], in the form of low-intensity M4 and E5 branches, accounting for 0.015% and 0.006% of its decay, respectively. In comparison with Weisskopf single-particle estimates, these decays are hindered by factors, $F_W \sim 10^6 - 10^9$, while the reduced hindrances are much more uniform: $f_\nu = F_W^{1/\nu} \sim 100$.

This much is reasonably well understood, and the structure of the isomer can be explained in terms of the single-particle orbitals close to the Fermi surface: a broken neutron pair and a broken proton pair each contribute half of the 4-quasiparticle isomer's 16 $\hbar$. A puzzle remains in the experimental data, however. Unplaced transitions, illustrated in Figure 3, are observed with similar intensity to the E5 decay of the isomer. Considering that the source was prepared from an irradiation performed in 1980, and the illustrated measurements date from 2003 [5], it would appear that the unplaced tran-

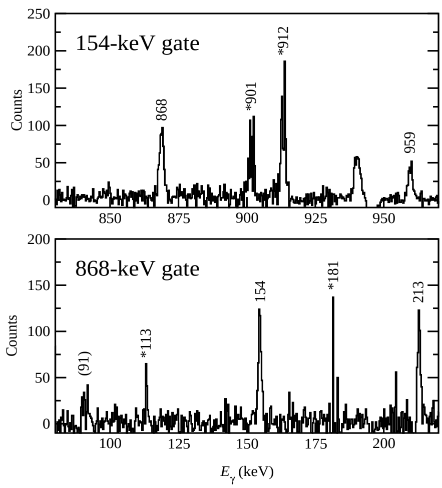

FIGURE 3. Gamma-ray coincidence spectra from a ^{178}Hf isomer source measurement [5] (see text). Known contaminant transitons are indicated by asterisks. Other labeled transitions are of unknown origin.

sitions, though of low intensity, are associated with a half-life of many years. Whether they might come from a higher-lying isomer in ^{178}Hf is speculation, but no trivial explanation has yet been found.

A more complete understanding of the γ-ray spectrum associated with the ^{178}Hf 31-year isomer decay is not only of academic interest. There has been much comment, see refs [1, 2], concerning the possibility of storing energy in nuclear isomers, potentially with controlled release of that energy. The ^{178}Hf isomer has been the most sought-after candidate, but the ability to trigger the release of the isomer's energy with < 100 keV photons has not yet been adequately demonstrated. Further knowledge of the nuclear structure of ^{178}Hf could prove valuable in this regard.

It may be noted that, while isomer triggering in ^{178}Hf remains unproven, the triggering of the only naturally occurring isomer, ^{180m}Ta, is well established [6], albeit with > 1 MeV photons; and the triggering pathway can be correlated in detail with the known level structure [7, 8]. This is an interesting example from an astrophysics perspective, as photo-activation could destroy the isomer in stellar *s*-process environments [6], if that is where the isomer is synthesised in the first place.

LIMITS OF NUCLEAR STABILITY

The drip lines, with associated proton and (potentially) neutron radioactivity, define the limits of nuclear stability in the N-Z plane, together with the fission and α decay of superheavy nuclei. Isomers can enhance our understanding of these limits, albeit complicated by their angular-momentum and excitation-energy dimensions.

In the superheavy domain, detailed measurements have now established high-K μs and ms isomers in $^{254}_{102}$No [9], highlighting the importance of conversion-electron detection. Going even heavier, a 6-ms isomer was recently found at ~ 1 MeV in $^{270}_{110}$Ds [10], with a half-life that is longer than that of its ground state. Xu et al. [11] have calculated that comparable isomers should exist in a range of even-even superheavy nuclei, and in a real sense isomers can provide extra stability, which may be important for future experimental discoveries.

Approaching the proton drip line for lighter masses, the isomer ^{53m}Co provided the first example of proton radioactivity [12]. Peker et al. [13] subsequently pointed out that the angular-momentum barrier could lead to neutron radioactivity from high-spin isomers close to the neutron drip line. In this context, it is interesting that some high-spin isomers, such as the $K^{\pi} = 57/2^{-}$, 22-ns isomer in ^{175}Hf [14, 15], are unbound to neutron decay. However, the high angular momentum makes the probability very small for neutron emission, and it would be necessary to find much longer-lived isomers on the neutron-rich side of stability, to have a realistic chance of detecting their neutron decay. Such a possibility could perhaps apply to ^{187}Hf, where favored multi-quasiparticle isomers are predicted, as shown in Figure 4. Nevertheless, 7-quasiparticle excitations are needed in order to exceed the neutron separation energy. Experimentally, the ground state of ^{187}Hf has already been observed [17] from projectile-fragmentation reactions, but whether the required high angular momenta are within reach is not yet proven. However, the population of a spin 43/2 isomer in ^{215}Ra following ^{238}U fragmentation [18], and the inference that there must be a large and unexpected collective contribution to the angular momentum generated in the final isomeric fragment, gives encouragement. While, therefore, the objective of finding neutron decay from isomers remains challenging, the issue is not one of too-rapid decay in the absence of the Coulomb barrier, it is one of too-hindered decay in the presence of the angular-momentum barrier.

In the course of performing isomer calculations in the region of ^{187}Hf, it has been found that collective oblate rotation becomes an increasingly important mode, as the neutron richness increases [19]. In ^{190}Hf, the ground state itself is predicted to be oblate, and that shape remains favored up to high spin [20]. At the same time, coexisting multi-quasiparticle prolate states are predicted. Consequently, with sufficient primary beam intensity, it may be possible to identify the oblate collective states through their population following prolate isomer decays.

K-ISOMER DECAY RATES

Even though the configurations and excitation energies of K isomers can be calculated with some confidence, it remains problematical to predict their half-lives. The wavefunction overlaps are small, and even the relative importance of the different mechanisms for generating the overlaps is not well defined. The principal K-mixing mechanisms, necessary for non-zero “K-forbidden” transition rates, can be categorised as: (i) Coriolis (orientation) mixing; (ii) γ-tunneling (shape) mixing; (iii) statistical (thermal) mixing; and (iv) mixing due to chance near-degeneracies.

These mechanisms have been discussed in many different contexts, see for example

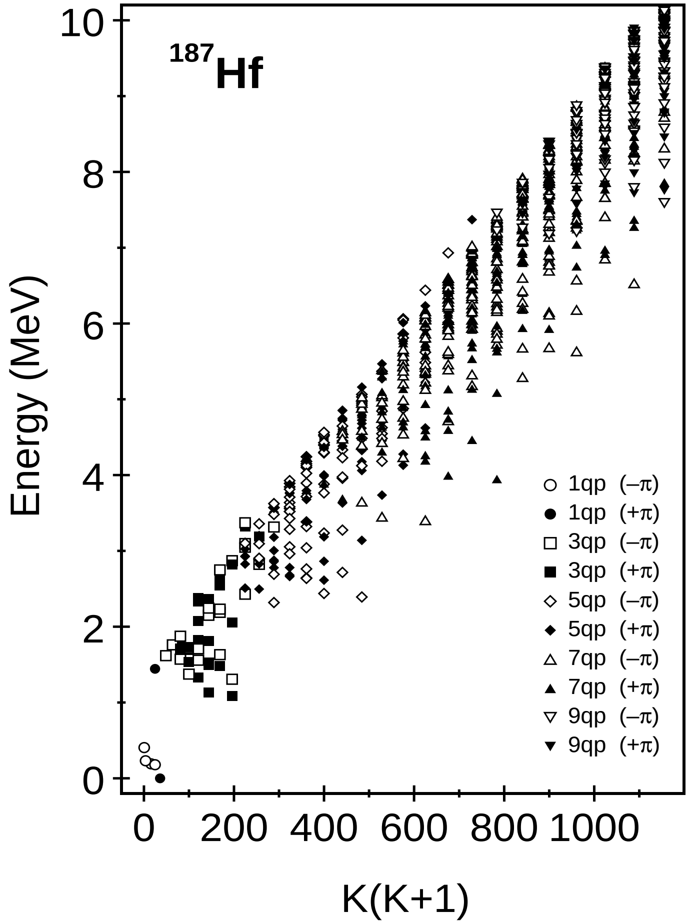

FIGURE 4. Multi-quasiparticle states in ^{187}Hf calculated with the Nilsson+BCS method of Jain et al. [16]. The neutron separation energy is approximately 4 MeV.

ref. [21], and here the presentation is restricted to extensions of the N_pN_n scheme for 2- and 3-quasiparticle isomers [22], and statistical mixing considerations for higher quasiparticle numbers [23], in both cases concentrating on K-forbidden E2 transitions in the A≈180 region.

As described above, a simple measure of the goodness of the K quantum number is the hindrance per degree of K forbiddenness, often referred to as the reduced hindrance. For 2- and 3-quasiparticle E2 decays, there is found [22] to be a strong correlation of reduced hindrance with N_pN_n, the product of the valence nucleon numbers, which is itself a simple measure of collectivity. One may consider that for larger N_pN_n values

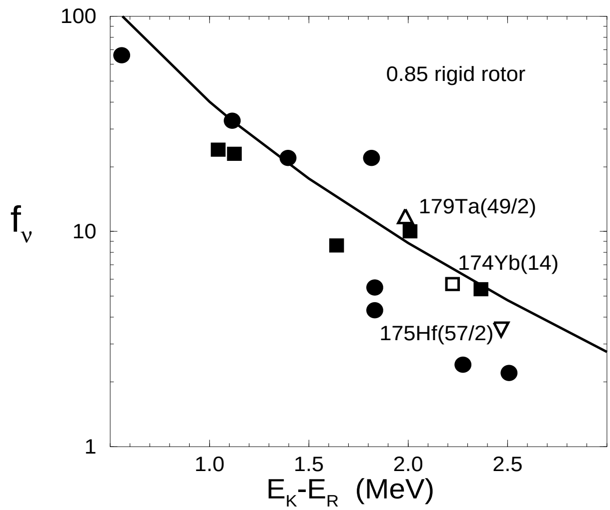

FIGURE 5. Variation of reduced hindrance with energy relative to a rotor with 85% of the rigid-body moment of inertia. Quasiparticle numbers are equal to 4 (circles − even-even nuclei), 5 (squares), 7 (triangle up), and 9 (triangle down). For the odd-mass nuclei, a pairing energy of 0.9 MeV has been added. The data are for E2 and E3 decays with $\Delta K > 5$. The full line represents the predicted level-density dependence [23]. The figure is adapted from ref. [28]. The labeled open symbols are discussed in the text.

the nuclei are more stably deformed and less susceptible to mixing effects, hence the correlation with reduced hindrance.

Recent data for a 6-ns $(31/2^+)$ isomer in ^{191}Os [24] indicate an extension of the systematic reduced-hindrance behavior to a low value of $N_pN_n = 66$, with $f_\nu = 1.9$. This is in marked contrast to the value for the 6^+ isomer in ^{174}Yb, having $N_pN_n = 264$, and $f_\nu = 322$, which represents the other extreme of our present knowledge in the A≈180 region (and disagrees with the γ-tunneling model [25]). The remarkably high ^{174}Yb reduced hindrance has been discussed and confirmed recently by Dracoulis et al. [25], though not in the context of N_pN_n systematics. Data at even larger N_pN_n values can be anticipated in the near future, as 6^+, 2-quasi*neutron* isomers are predicted in the isotones ^{172}Er and ^{170}Dy [26], with $N_pN_n = 308$ and 352, respectively.

For higher quasiparticle numbers (> 3) the systematic behavior is distinctly different, perhaps as a consequence of blocked pairing correlations. Statistical mixing seems to be an important factor. This can be related to the level density, which may itself be determined from the excitation energy relative to a rigid-rotor reference [23]. If only a small range of angular momentum is considered (previously 4- and 5-quasiparticle isomers) then there is little sensitivity to the reference moment of inertia. However, including recent data from 7- and 9-quasiparticle isomers in ^{179}Ta [27] and ^{175}Hf [15], respectively, reduction of the reference moment of inertia by a factor of 0.85 is seen to be appropriate [28]. The resulting dependence of the reduced hindrance on the relative excitation energy is illustrated in Figure 5, showing that the general behavior is indeed systematic, but there are considerable fluctuations that presumably result from other significant degrees of freedom (see also ref. [21]). The new data point for a 4-quasiparticle isomer in ^{174}Yb [25] is in good accord with expectations.

SUMMARY

Isomers provide many insights into the nature of nuclear excitations and the limits of stability. The present paper has reviewed some of these aspects and pointed out that neutron decay from high-spin isomers may be observable. Extensions of the systematic behavior of K-isomer reduced-hindrance values have been presented, covering the full range of observed multi-quasiparticle decays.

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