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HIGH-K STRUCTURES UNDER EXTREME CONDITIONS*

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High-K isomer decay rates are compared and interpreted, with an emphasis on the spin degree of freedom. It is argued that high-K values do not in themselves lead to K mixing. Rather, evidence is presented that the most important consideration is the isomer energy relative to a rotor whose moment of inertia is approximately 85 % of the rigid-body value. The high-spin limit to the occurrence of high-K isomers is then discussed in connection with predictions of competing oblate rotation-aligned structures. Finally, some observations are made regarding the use of K isomers as a tool to access exotic nuclei, including superheavy elements, and exotic nuclear structures.

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1. Introduction

Long-lived metastable states, or isomers, are found in a large range of atomic nuclei [1], though there is a concentration in those nuclei that are either spherical and close to closed shells (shell-model isomers) or well deformed and far from closed shells (K isomers). The latter form the subject of the present work. Their isomerism asises in axially symmetric (prolate) nuclei, where there is approximate conservation of the projection, K, of the angular momentum on the symmetry axis. Transitions (typically by γ-ray emission) that change the K value by more than the transition multipole order, λ, are called "K forbidden", with the degree of forbiddenness defined as $\nu = \Delta K - \lambda$. Large values of ν are associated with low transition rates and long half-lives, ranging from nanoseconds to years. The finite transition

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rates imply some degree of K mixing in the wavefunctions of the isomers, or in the states to which they decay, but a quantitative understanding remains to be developed.

It is observed empirically that there is a strong correlation of reducing isomer half-life with increasing isomer energy relative to a rotor of the same angular momentum. To a large extent this is simply a manifestation of the $E^{2\lambda+1}$ transition-rate dependence on the emitted γ-ray energy. However, as shown in Fig. 1, there is a more subtle effect of quasiparticle number (*i.e.* angular momentum) which suggests that the reference rotor moment of inertia should be taken as 85 % of the rigid-body value, if the best correlation is to be obtained. This reference rotor will be considered again later. It is notable that only in the mass 180 deformed region are K isomers observed with quasiparticle numbers greater than three. Hence, only in the mass 180 region can the influence of angular momentum be studied over a broad range of values.

A celebrated K-isomer example is the second metastable state of hafnium-178, ^{178m2}Hf, a 4-quasiparticle, $K^{\pi} = 16^{+}$ isomer with an excitation energy of 2.4 MeV and a half-life of 31 years. Recent measurements [2] have established direct photon emissions from the isomer, with multipolarities E5 and M4. The K-value change is $8\,\hbar$, so that $\nu = 3$ and 4, respectively. If the competing E3 transition is also considered, with $\nu = 5$, along with the M2

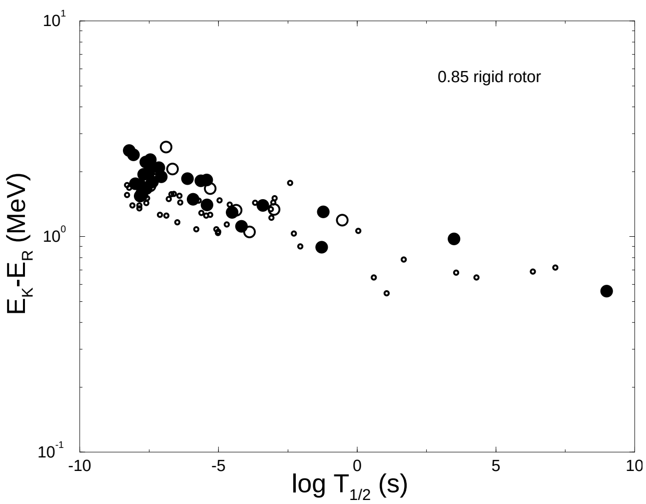

Fig. 1. Correlation of K-isomer half-life with energy relative to a rotor with 85 % of the rigid-body moment of inertia, for isomers in the mass 180 region. Small circles are for 2- and 3-quasiparticle isomers, large filled circles for 4- and 5-quasiparticle isomers, and large open circles for higher quasiparticle numbers (2-quasiparticle isomers in odd–odd nuclei are excluded from the graph). For odd-mass and odd–odd nuclei, pairing energies of 0.75 and 1.5 MeV have been added, respectively.

and E1 transitions from the lower-energy, $K^\pi = 8^-$, 4-s isomer (with $\nu = 6$ and 7, respectively) then the Weisskopf hindrance factors, F_W, are seen [2] to span about seven orders of magnitude. However, the reduced-hindrance values, $f_\nu = F_\mathrm{W}^{1/\nu}$, are all close to 100, *i.e.* for each unit of K forbiddenness the γ-ray transition rate decreases by two orders of magnitude. This is illustrated in Fig. 2.

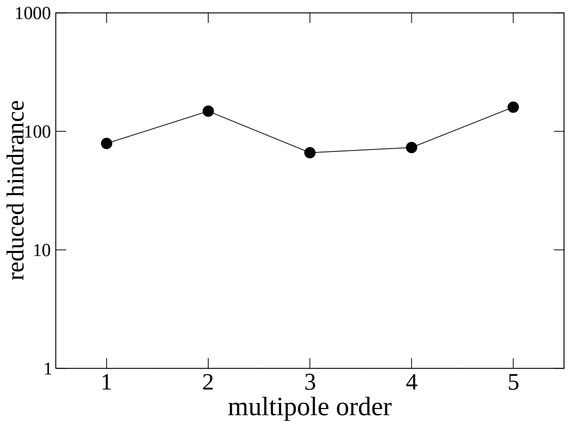

Fig. 2. Reduced-hindrance values for K-forbidden decays from $K^\pi = 8^-$ and 16^+ isomers in ^{178}Hf. The $\lambda = 2$ value is a lower limit.

2. Reduced hindrance values

The near-constant value of $f_\nu \approx 100$ for the ^{178}Hf isomeric transitions is in accord with the general behaviour noted by Löbner [3], but recent studies demonstrate a wide variation of reduced-hindrance values, with a systematic decline as the energy relative to a rigid rotor increases, at least for 4- and 5-quasiparticle isomers [1,4–6]. The full rigid-body moment of inertia was assumed. (The dependence of 2- and 3-quasiparticle isomer reduced-hindrance values [7] on the valence nucleon product, N_pN_n, is clearly different, perhaps due to the stronger pairing correlations.) This analysis and interpretation of what are essentially *thermal* nuclear structure effects complements the quasi-continuum studies of high-K rotational bands [8]. However, the analysis of discrete isomer reduced-hindrance values is so far only for a limited range of angular momenta, and consequently there is little sensitivity to the moment of inertia of the reference rotor. Now, new data for K-forbidden E2 decays from 7- and 9-quasiparticle isomers in ^{179}Ta, $K^\pi = 49/2^+$, $f_\nu = 12$ [9] and ^{175}Hf, $K^\pi = 57/2^-$, $f_\nu = 3.5$ [10], respectively, significantly extend the angular momentum range. It then appears that a better systematic description is obtained with 85 % of the rigid-body moment of inertia for the reference rotor, as illustrated in Fig. 3.

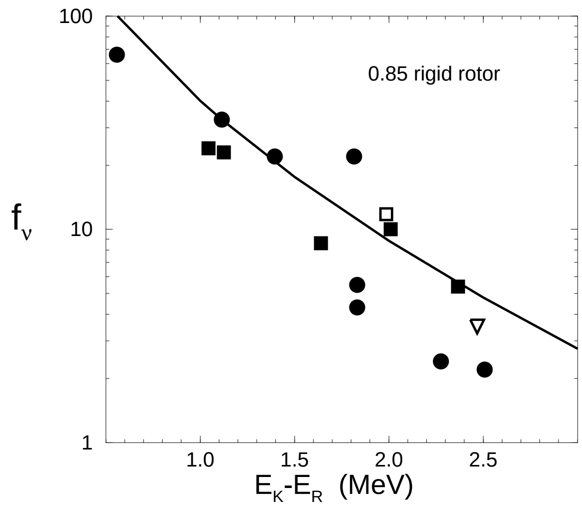

Fig. 3. Variation of reduced hindrance with energy relative to a rotor with 85 % of the rigid-body moment of inertia, for even-even nuclei (filled circles: 4-quasiparticle isomers) and odd-mass nuclei (filled squares: 5-quasiparticle isomers) *cf.* Ref. [5]. The open square corresponds to a 7-quasiparticle isomer in ^{179}Ta [9], and the open triangle to a 9-quasiparticle isomer in ^{175}Hf [10]. 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 [4].

The less-than-rigid moment of inertia is consistent with that needed to describe the half-life data, as presented above. In this context, it is notable that the unpaired moments of inertia for rotational bands in the mass 180 region are also lower than the rigid-body value [11,12]. This is related to the prevalence around the neutron and proton Fermi surfaces of high-K single-particle orbitals, which give only low contributions to angular momentum generation perpendicular to the symmetry axis.

The evidence, therefore, indicates that K-forbidden decay rates can be understood, at least approximately, by comparing isomer excitation energies with a reference rotor whose moment of inertia is substantially below the rigid-body value. The K value itself is apparently not a major determining factor, leaving open the question as to what might be the highest K value that can be associated with isomerism. However, additional data are needed to test this viewpoint. Furthermore, the low reduced-hindrance values for some decays, evident in Fig. 3, need to be better explained, incorporating both t-band effects [5] and the influence of axially asymmetric shapes [13] in a consistent framework, and chance near degeneracies may also play an important role [9].

3. High-*K* limits and oblate shapes

The highest-K isomer (with an electronically measured half-life) observed to date is in ^{175}Hf, with $K^{\pi} = 57/2^{-}$ [10,14] and $t_{1/2} = 22 \pm 2$ ns [10]. Although it is expected that the hafnium ($Z = 72$) high-K isomers become systematically more favoured (lower excitation energies and longer half-lives) as the neutron number increases [5, 15] up to as far as ^{188}Hf, experimental access through fusion-evaporation reactions is optimum for ^{175}Hf. High-spin studies become more and more difficult with increasing neutron number, since only deep-inelastic and fragmentation reactions can then be used. Potential-energy-surface calculations [15] indicate that, as the neutron number increases, there is increasing competition from another degree of freedom: well deformed oblate shapes with large contributions of angular momentum from the rotation alignment of individual nucleons. In essence, the optimum nucleon-number conditions for prolate, high-K states correspond at the same time to the optimum conditions for oblate, low-K states. It is, therefore, interesting to consider whether there is any evidence for oblate rotation in existing high-spin data, and again it is ^{175}Hf that may offer the best combination of neutron richness and accessibility at high-spin. Indeed, recent Gammasphere data for ^{175}Hf [16] reveal remarkable high-spin, low-K structure, up to $\sim 60\,\hbar$, that may involve the oblate rotational mode, but further work is needed to clarify this aspect.

4. Isomers as stepping stones

High-K isomers provide a valuable tool to access nuclei far from stability, and to study their excited states. For this purpose, microsecond isomers are ideal, as they survive sufficiently long to mass separate, or otherwise to identify, the ions that recoil from nuclear reactions; and a microsecond lifetime is short enough to enable ion–γ-ray delayed coincidences to be correlated unambiguously. For example, a $K^{\pi} = 8^{-}$ isomer was recently discovered in proton-rich ^{140}Dy [17, 18] following fusion-evaporation reactions, and a $K^{\pi} = 10^{-}$ isomer has been found in neutron-rich ^{190}W [19] following projectile-fragmentation reactions. Furthermore, K-isomers are proving important in the identification and study of superheavy elements [20, 21] where the survival time can be substantially longer in an excited isomeric state than in the ground state.

Another aspect of the selectivity and sensitivity obtained from isomer studies is that they can reveal unusual aspects of nuclear structure. It was, for example, by studying the decay of a $K^{\pi} = 35/2^{-}$ isomer in ^{179}W that the influence of t-bands was first exposed [22], and, more recently, levels above the $K^{\pi} = 25^{+}$ isomer in ^{182}Os have been identified and interpreted [23] as the first evidence for multi-phonon excitations in a well deformed nucleus.

5. Summary

The utility of high-K isomers for studying nuclear structure phenomena has been presented, with reference to their occurrence at large values of angular momentum, temperature, proton number, neutron number and mass number, with emphasis given to the angular momentum properties. It is suggested that it is the isomer excitation energy, relative to a rotor at the same angular momentum, that is the key factor in determining reduced-hindrance values. New results favour a reference rotor moment of inertia that is about 85 % of the rigid-body value.

K isomers can also be useful for illuminating other degrees of freedom, such as t-bands, oblate bands, and multi-phonon bands at high angular momentum.

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