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High-K isomers: some of the questions

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Abstract. High-K isomers exemplify the coexistence of individual-particle and collective motion in atomic nuclei. Here, the topic is briefly outlined, and some open questions are discussed. These include violations of the K quantum number; the high-spin limit to K isomerism; the fission stability of K isomers; possibilities for manipulation and control of K-isomer decay rates; and access to K isomers in neutron-rich nuclei.

1 Introduction

This conference celebrates the scientific life and work of George Dracoulis, who sadly passed away in 2014. I was privileged to be his first PhD student. During my PhD, we made an experimental study of high-spin states in ^{172}Hf [1, 2], and we thus embarked on a life-long journey exploring long-lived, excited states in deformed nuclei, the so-called K isomers. Amongst our many joint publications are a 1999 Nature review of isomers [3]; a 2001 review focussed on high-K isomers [4]; and finally an in-depth isomer review, soon to be published [5], that Dracoulis worked on until shortly before he died. He also published other related reviews, notably his recent Nobel symposium paper [6], and a new and comprehensive K-isomer tabulation [7].

The present paper introduces a selection of open questions relating to K isomers, where much research remains to be done. As we develop our understanding and push towards the outer reaches of the nuclear chart, one of the experimental issues that needs to be kept in mind was stated by Dracoulis [6]: "There is always a problem to be aware of with the study of isomers ... and that is that the popular techniques for their identification can be compromised if the lifetimes become very long, as might occur, paradoxically, in the more interesting cases."

First, though, some terminology needs a brief explanation. The K quantum number represents the projection of the nuclear angular momentum onto its deformation axis (symmetry axis) with the deformed shape being prolate in the vast majority of cases. High K values can be made by broken-pair, deformation-aligned excitations, with each broken pair increasing the number of quasiparticles (unpaired nucleons) by two units. Electromagnetic transitions from (multi-)quasiparticle states are called "K forbidden" if the change in K exceeds the multipole order of the transition, i.e. if $\Delta K > \lambda$. However, due to K-mixing mechanisms (rotational, vibrational or statistical [4]) such transition are hindered, rather than strictly forbidden. The degree of forbiddenness is defined as $\nu = \Delta K - \lambda$, and the reduced hindrance is expressed as $f_\nu = (F_W)^{1/\nu}$, where F_W is the Weisskopf hindrance factor [4, 7]. In this way, f_ν represents the hindrance per degree of K forbiddenness, giving some measure of the effect of K-mixing processes, with large f_ν values corresponding to little K mixing.

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2 Erosion of the K quantum number

There is no strict definition of the half-life needed for a nuclear excited state to be termed an "isomer". Nevertheless, it is clear that short half-lives generally correspond to low f_ν values. With germanium γ-ray detectors, it becomes difficult to determine half-lives of less than about 10 ns. One such case from the early work of Dracoulis and Walker [1, 2], alluded to above, is the half-life of the two-quasiproton, $K^\pi = 6^+$ isomer in ^{172}Hf. The curve fitting necessary to obtain the 5 ns value is illustrated in Fig. 1.

Perhaps surprisingly, after nearly four decades, this ^{172}Hf isomer is still at the edge of accessibility, with regard to having a measureable half-life: the corresponding state in the lighter adjacent even-even isotope, ^{170}Hf, only has a half-life limit, measured to be <5 ns [9]. The advent of fast-timing $LaBr_3$, γ-ray detectors (see, for example, Ref. [10]) may well remove this impasse, and open the door to a range of shorter-lived K isomers.

Nevertheless, as of now, there are five even-even hafnium isotopes with $K^\pi = 6^+$ isomers that have known half-lives, as given in Table 1. The most recently determined value is for ^{180}Hf, now listed in the 2015 review of Kondev *et al.* [7]. As seen in Table 1, the half-lives range over almost four orders of magnitude, and the f_ν values for the $E2$ decay branches vary by a factor of six. Clues to the observed behaviour come from inspection of the dependence of f_ν on the product of the valence nucleon numbers, N_pN_n, revealing a strong correlation [11, 12], as illustrated in Fig. 2. (Note that the new f_ν value for ^{180}Hf is in good

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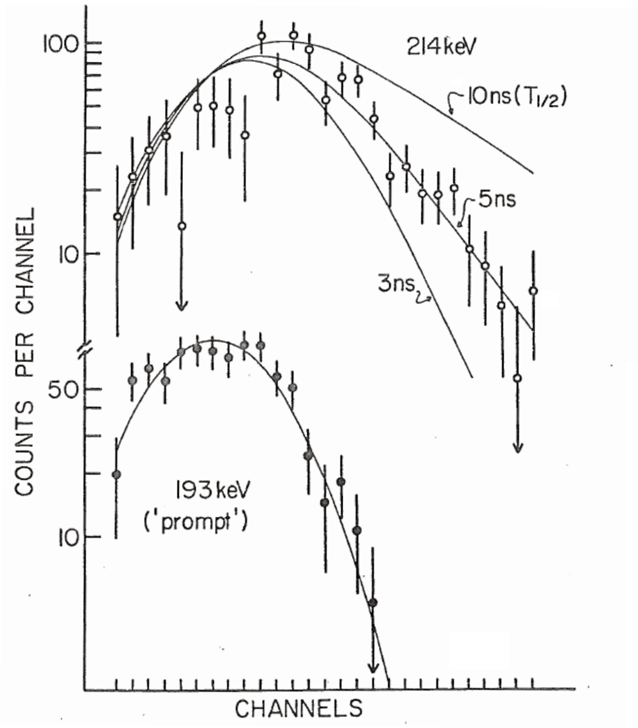

Figure 1. Illustration of the Gaussian-plus-exponential curve fitting needed to obtain the 5 ns half-life of the $K^\pi = 6^+$ isomer in ^{172}Hf, for 214 keV events (open circles) shown as a function of time, from Ref. [2]. The Gaussian curve for the 193 keV transition (filled circles) represents the "prompt" lineshape. Later measurements [8] obtained 4.8±0.4 ns for the half-life of the 6^+ state.

Table 1. Properties of $K^\pi = 6^+$ isomers in hafnium ($Z = 72$) isotopes, including reduced-hindrance (f_ν) values for $E2$, $\Delta K = 6$ decay branches. Data are from Ref. [7].

nuclide	E (keV)	$T_{1/2}$	f_ν ($E2$)	N_pN_n
^{170}Hf	1773	<5 ns	<4	160
^{172}Hf	1685	5 ns	10	180
^{174}Hf	1549	140 ns	17	200
^{176}Hf	1333	10 μs	42	220
^{178}Hf	1554	80 ns	16	200
^{180}Hf	1703	3 ns	7	180

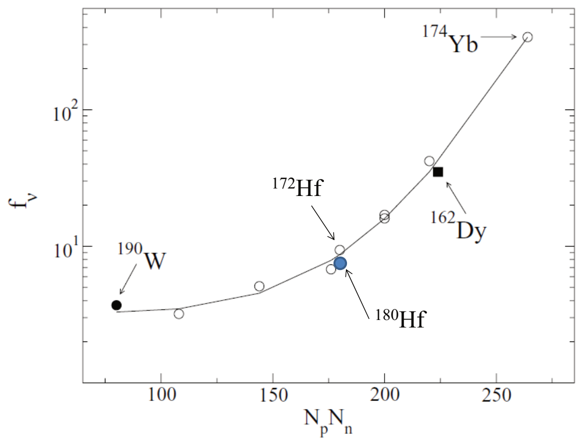

Figure 2. Reduced hindrance, f_ν, as a function of the product of the valence nucleon numbers, N_pN_n, for $\Delta K \geq 6$, $E2$ decays from two-quasiparticle isomers in even-even nuclei in the $A \approx 160-190$ deformed region. The figure is adapted from Ref. [12], with the inclusion of the ^{180}Hf data point [7]. The line through the data points is to guide the eye.

accord.) Qualitatively, the behaviour seems to be reasonably simple: small values of N_pN_n correspond to weak collectivity, which can reasonably be associated with poor K conservation, hence small f_ν values. However, a quantitative understanding of this relationship remains elusive. In contrast, a recent analysis by Chen *et al.* [13] of $K^\pi = 6^+$ isomers in the $N = 104$ isotones identifies mixing with the $I^\pi = 6^+$ member of the $K = 2$, γ-vibrational band as being a key determinant of the f_ν value. Whether this kind of analysis is also able to explain the hafnium f_ν values in Table 1 and, indeed, to predict as-yet unmeasured half-lives, remains to be evaluated.

Extension of the f_ν systematics from two-quasiparticle to multi-quasiparticle isomers is discussed elsewhere [4, 5, 7, 14]. For multi-quasiparticle states, it is evident that the level density is an important variable. Multi-quasiparticle states that are further above yrast (i.e. relative to the energy of the lowest-lying rotational state of the same spin) tend to have less-hindered decays and thus have shorter half-lives.

3 High-spin limit to K

High-K isomers are known up to spin $57/2\hbar$, which is found for a nine-quasiparticle, $T_{1/2} = 22$ ns state in ^{175}Hf [7, 15]. It might be thought that high spin would destroy the K quantum number, on account of Coriolis K mixing. However, the K isomers themselves derive their angular momentum from individual nucleon orbits, rather than collective rotation, and it seems that the angular-momentum limit has not been reached. Indeed, the limit is most likely experimental, in the sense that the theoretically favoured nuclei (in the neutron-rich hafnium region [16]) cannot be synthesised at high spin, at least not yet in a way that enables their experimental study (though see also Section 6). According to calculations [16], $K > 40$ isomers will be yrast in neutron-rich hafnium isotopes, and the eventual limit would come from competition with coexisting rotation-aligned, oblate-deformed states.

4 Fissioning K isomers

One of the limits to nuclear binding is that of spontaneous fission. It can be argued that there is, as yet, no case where a K isomer has been conclusively established to fission [17, 18], and that, more generally, K isomers can provide extra stability for the heaviest elements [19]. The most recent example of resistance to fission is in ^{254}Rf [20], where a proposed four-quasiparticle isomer has a half-life of 250 μs, ten times longer than its spontaneously fissioning ground state, and no isomeric fission branch could be detected. The outstanding experimental challenge is therefore to measure the degree to which fission is inhibited from K isomers, i.e. to determine unambiguously a K-isomer fission probability. The corresponding theoretical description is also challenging.

5 Isomer manipulation

The high-energy-density storage capability of isomers is of long-standing interest [3, 21], and ways to release that energy have been sought. The photo-activation of ^{180m}Ta, the sole naturally occurring isomer, has been relatively well studied [22, 23], but the need for ≈1 MeV photons to release 75 keV of isomer energy mitigates against practical applications.

Initial studies of ^{178m2}Hf, the 31 year, $K^{\pi} = 16^{+}$ isomer of ^{178}Hf, at 2.4 MeV excitation energy, showed great promise for its energy release using <100 keV photons incident on radioactive targets of ^{178m2}Hf [24]. However, much lower cross-section limits were later set [25, 26]. Now there are again positive results reported [27], but this time at the lower cross-section values. This remains a controversial area of work.

Other avenues to induce isomer decay electromagnetically include Coulomb excitation with radioactive beams [28], nuclear superradiance [29], and nuclear excitation by electron capture [30, 31], though the latter remains unobserved. The field remains open for innovation and exploitation.

6 K isomers in neutron-rich nuclei

It is well known that a large number of nuclides remain to be discovered on the neutron-rich side of β stability, and an even larger number await having their structural properties measured. One of the problems is that they are typically produced in non-selective reactions and with tiny cross sections, in relativistic projectile fragmentation and fission reactions, so that the γ rays emitted at the target position cannot in general be related to specific nuclides. Microsecond isomers offer a selective route to structure information, since they can be transported through mass/charge separators, identified on an ion-by-ion basis, and have their γ-ray emissions time-correlated with the identified ions. Such isomers are now giving access to excited states in, for example, the doubly-mid-shell rare-earth deformed region [32], which is a region of both astrophysics and nuclear structure interest, relating to r-process nucleosynthesis, possible subshell gaps, and high-order (β_6) deformation. The growth in this knowledge is strongly related to the new generation of radioactive-beam facilities.

For long half-lives, the time correlation between identified ions and emitted γ rays is lost. An alternative approach is through the exploitation of heavy-ion storage rings, where single-ion sensitivity can be achieved. For example, a long-lived ($T_{1/2} \approx 12$ minutes) isomer has been discovered in ^{184}Hf, at an excitation energy of 2.5 MeV [33]. The challenge is now to measure its decay radiations, and establish its spectroscopic properties.

7 Outlook

Selected aspects of K isomerism have been discussed, with a focus on some of the open questions. These are interrelated. For example, an understanding of the breakdown of K isomerism through K mixing might lead to a breakthrough in isomer manipulation; and studying K isomers at very high spin is related to the problem of limited access to $A \approx 190$ neutron-rich nuclides. Perhaps one of the key future developments will be the production of high-quality isomeric beams [34], which could be used to initiate novel nuclear reactions. Also, the production of intense neutron-rich beams will open up that elusive side of the nuclear landscape at high spin. At the same time, there is the prospect that isomers will become increasingly important, through their extended half-lives, when approaching the limits of nuclear stability in heavy and superheavy nuclei.

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