Properties of neutron-rich lutetium and hafnium high-spin isomers

Letter of intent to INTC – January 2010

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Abstract: It is proposed to study high-K isomers in neutron-rich lutetium (Z = 71) and hafnium (Z = 72) isotopes, using collinear laser spectroscopy and low-temperature nuclear orientation. An exceptional combination of low energy and high spin is predicted for the isomers, with consequently long half-lives. This makes them accessible to ISOL experiments. Beam development is needed with actinide and iridium targets.

Introduction

Long-lived isomers in exotic nuclides give key structure information, which could be important for understanding heavy-element nucleosynthesis [1,2], and, more generally, the limits to particle stability [3]. Although experimental investigation is extremely challenging, great progress has already been made using projectile fragmentation reactions, combined with the observation of γ-ray decays from microsecond isomers, see e.g. [1]. However, the γ-ray detection gives no experimental sensitivity to isomers with half-lives greater than 1 s, due to the need to time-correlate the arrival of each fragment with its subsequent γ-ray decay. The present work seeks to exploit spallation reactions combined with the ISOL method to study long-lived ($T_{1/2} > 1$ s) isomers. Collinear laser spectroscopy and low-temperature nuclear orientation will be used to obtain nuclear-structure and decay-mode information.

Motivation

The hafnium isotopes are well known [4] to contain long-lived isomers, such as the 31-y, 2.4-MeV yrast trap in ^{178}Hf, with $K^{\pi} = 16^{+}$. This remarkable case has attracted considerable attention and controversy with regard to its potential as an energy-storage medium [5]. Nevertheless, the exceptional combination of high spin and low excitation energy is probably not unique. Nilsson model calculations [4,6] indicate an even more favoured $K^{\pi} = 18^{+}$ isomer in ^{188}Hf. The present work addresses the experimental challenge to identify and characterise isomers in this region. To illustrate the energy favouring, calculated four-quasiparticle hafnium isomer energies, relative to a rigid rotor, are shown in Fig.1.

Notwithstanding the basic experimental challenge, there are additional physics issues involved. A leading consideration is that the ^{188}Hf neutron number of N = 116 is close to a region of predicted prolate-oblate instability [7,8]. This is not expected to alter the basic isomer structure itself, but the states to which the isomer decays could be of oblate rotation-aligned character [9], which may significantly influence the isomer

CERN-INTC-2010-005 / INTC-I-085
07/01/2010

half-life. Furthermore, high-K isomers and their decays could provide an exceptional opportunity to study the high-spin structure in this unique region, where both the protons and the neutrons are in the upper regions of their respective shells (Z = 50 – 82, N = 82 – 126) leading to reinforcing stabilisation of well-deformed collective oblate rotation. Initial experimental evidence has recently been found in ^{180}Hf for this phenomenon [10], which is predicted to become an increasingly dramatic feature in the more neutron-rich isotopes [9].

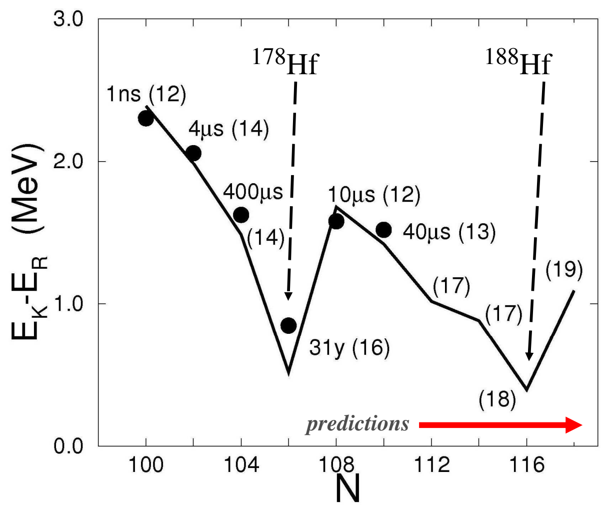

Fig. 1: Experimental (dots) and calculated (line) excitation energies relative to a rigid rotor of the same mass and spin, shown as a function of neutron number for four-quasiparticle isomers in even-even hafnium (Z = 72) isotopes. Spin values are given in parentheses, and experimental half-lives are shown. The figure is from ref. [6]. Note the strong empirical inverse correlation of excitation energy with half-life.

A more general consideration is the need to understand isomer decay rates, since isomers can be longer lived than their respective ground states in exotic nuclei [3]. Indeed, due to the nature of experiments, it could be that various exotic nuclei are known only in isomeric states, rather than ground states. Further to these features, long-lived isomers can influence, or reveal significant information about, nucleosynthesis pathways [1,2]. We therefore consider that this n-rich, A ~ 190 region of long-lived isomers is a key testing ground for models of nuclear structure.

New data from the GSI Experimental Storage Ring (ESR) provide compelling evidence [11] for the existence of a long-lived (> 10 m) four-quasiparticle isomer in ^{184}Hf, confirming the prediction [4,6] (but without spectroscopic information). This gives a specific objective for the initial phase of the present work: to obtain the electromagnetic moments and charge radius of this new isomer in ^{184}Hf. It is expected that ^{186,188}Hf isomers are also within experimental reach, together with other long-lived isomers in the region. Neutron-rich lutetium (Z = 71), hafnium (Z = 72) and tantalum (Z = 73) isomers are all strongly favoured theoretically.

The use of laser spectroscopy to study exotic isotopes and isomers is well established [12]. In essence, it is a highly sensitive technique that yields nuclear electromagnetic moments and charge radii. With respect to K isomers, it is a remarkable feature, found by laser spectroscopy, that multi-quasiparticle states display systematically decreasing mean-square charge radii with increasing numbers of quasiparticles [13], whilst their associated quadrupole moments (i.e. deformations) appear to increase. This phenomenon directly contradicts droplet model predictions, whilst reflecting aspects of normal odd-even staggering. Further clarification of this effect would be highly valuable, and is a key objective of the current work.

Physics motivation also comes from the possibility, associated with their long half-lives, to study the high-spin isomer decays in the NICOLE on-line dilution refrigerator at ISOLDE, by the technique of low-temperature nuclear orientation. In addition to complementing the laser measurements of electromagnetic moments, orientation measurements give access to electromagnetic multipolarity information in the isomer decays, including the issue of parity mixing in nuclear states. Excellent new data on transition mixing ratios in the decay of isomers of ^{177,179}Hf have been obtained in recent NICOLE experiments and notable evidence for parity admixture in the decay of the 8^- isomer of ^{180}Hf has been published [14]. Extension of these measurements to the ^{182}Hf and ^{184}Hf isomers is a high priority. Although insufficient yields are currently available at ISOLDE, the proposed target/ion-source developments (discussed below) would radically improve the situation.

Experimental method

In order to produce the neutron-rich lutetium and hafnium beams, new target development will be required, complementing the existing (lighter) hafnium beams uniquely developed at ISOLDE in recent years. This would naturally build on the success and expertise gained with the already existing Ta foil targets. Previous work at the SC with powder Th:Nb targets suggested that a Th foil target (although getting easily oxidised) could present one possible solution to access the neutron-rich rare-earth isotopes. Equally, an iridium foil target may prove even more suitable for at least some of the cases highlighted in this proposal, and potentially the release efficiency from iridium may be better than from Ta/W targets. Ion beams of lutetium would be in principle extracted from these alternative foil targets without the need of a CF_4 leak. Hafnium would require fluorination and therefore a method is required for breaking up the molecule after mass separation. The new RF-quadrupole cooler and trap (ISCOOL) [15] allows an ensemble of molecular ions to be trapped and manipulated. Utilization of an intense RF field in the trapping region may allow the molecules to be broken up and would need to be tested.

Subsequent laser spectroscopy would be carried out on the ions in a collinear geometry. In the case of lutetium, the technique of pumping in the cooler [16] would be used to pump the ion into a suitable electronic state that would allow the spin, magnetic dipole moment, electric quadrupole moment and isotope shift to be studied. The testing of the pumping scheme will be undertaken using the off-line ion source and RFQ cooler-trap on the CRIS beam line.

The development of new beams of neutron-rich rare-earth elements in this LoI is primarily for the purpose of laser spectroscopy. However, this work would also benefit the ISOLDE community in general since such beams are currently only available at fragment separators. Specific reference has been given above to the benefits for low-temperature nuclear orientation. The development of new targets, as well as methods to manipulate molecular ions after mass separation, is a crucial part of maintaining ISOLDE's status at the cutting edge of RIB research.

Yield estimates

Köster et al. [17] have compared experimentally obtained ISOLDE yields with different cross-section model calculations for hafnium ground-state yields, though the situation for high-spin isomers is more complex. Two-proton removal from ^{186}W appears to be a good way to populate ^{184}Hf, but the four-quasiparticle isomer is probably not produced with comparable yield. (A ^{197}Au beam was used for its discovery [11].) What is anyway clear is that targets heavier than ^{186}W are needed, if heavier hafnium isotopes are to be produced. Of particular interest is ^{193}Ir (63% abundance) which can in principle (at its n-rich limit) yield ^{188}Hf following five-proton removal. The ground-state in-target yield predicted by the Silberberg and Tsao code is about 10^4 per μC [17]. However, at this level of neutron richness, it becomes more favourable to use actinide targets. For example, EPAX2 calculations indicate an order of magnitude greater yield of ^{188}Hf from a thorium target, and the high-spin isomer yield may be additionally favoured. (Since more nucleons must be removed from ^{232}Th, there is greater opportunity for angular momentum generation).

From the point of view of the present LoI, it is evident that great progress can be made with either iridium or thorium targets, and both need to be tested.

Summary of key tests

• Neutron-rich Lu and Hf yields out to ^{187}Lu and ^{188}Hf (>100/s, with isobaric contamination $<10^6$ particles per bunch) from Ir and Th targets.
• Off-line development of in-trap methods for breaking up HfF_4 molecules.
• Access and procedures for launching a laser into the ISCOOL cooler for pumping the ionic states of Lu.

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