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Assessment of the Fission Stability of Nuclear Isomeric States

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Abstract. The fission stability of nuclear isomers is addressed. Empirical evidence indicates that broken-pair, high-spin isomers can be less susceptible to fission than their respective ground states. This effect is most important when the fully paired state has a short fission half-life.

1 Introduction

Fission is the process whereby an atomic nucleus splits into two or more pieces, under the influence of the Coulomb repulsion between the constituent protons. This can happen spontaneously, setting a fundamental limit to the existence of the most massive atomic nuclei. By way of example, ^{250}No, with 102 protons and 148 neutrons, fissions spontaneously with a half-life $\approx$6 μs [1]. However, angular momentum (spin) can inhibit the fission process. In particular cases, broken pairs of neutrons or protons can create isomers (i.e. long-lived excited states) with high spin values coming from the unpaired nucleons. Although the significant excitation energy of an isomer ($\sim$1 MeV for a broken-pair excitation) suggests the existence of a fission barrier that is $\sim$1 MeV lower than that of the fully paired ground state, and hence a shorter fission half-life, the high spin can nevertheless lead to fission inhibition. In the case of ^{250}No, there has been found to be an isomer [2] with a half-life that is about ten times longer than the ground-state value. The present work surveys the range of evidence for this spin-induced inhibition of the fission process.

2 Background

Nuclear isomers [3] can have half-lives ranging from nanoseconds to years. For example, ^{180}Ta has an isomer with half-life $> 10^{15}$ years, i.e. much longer than the age of the Universe. Isomers exist primarily due to angular momentum selection rules: a transition from an isomer may require a large change to the total spin (spin isomer) or a large re-orientation of the spin vector (K-isomer); and they can also exist due to nuclear shape changes which require tunnelling through a potential barrier (shape isomers). Although many isomer half-lives are found to be short (< 1 s) even short half-lives can correspond to extra stability when nuclear binding becomes weak. One such situation is found for the heaviest elements, with $Z > 100$, where the "liquid drop" stability vanishes and there is a vital dependence on stabilization from the quantum shell structure.

It was explained by Xu et al. [4] in 2004 how α-decay rates can be inhibited from high-spin isomers. In the same work, the isomeric effect on fission rates was briefly considered. Now, with new developments of configuration-constrained theoretical techniques, to include more complex nuclear shapes [5], the possible fission-rate inhibition of isomers may usefully be revisited.

The isomers that are considered here in more detail are of the "K-isomer" type, where it is changes in the angular momentum direction that lead to long half-lives [3, 6]. The approximately conserved K quantum number represents the projection of the angular momentum on the symmetry axis of the deformed nuclear shape. This is well known to give rise to γ-decay-rate inhibitions of many orders of magnitude. However, the situation for spontaneous fission decay is poorly known, and is reviewed in the present work.

3 The Fission Process

The way that a nucleus elongates and then separates into two parts, driven by Coulomb repulsion between the protons, has been the subject of theoretical modelling ever since the basic elements of the process were first understood by Meitner and Frisch [7]. The landscape of possible intermediate shapes is complex, and modern theories demonstrate the need for multi-dimensional barrier-tunnelling calculations [8] if realistic estimates of fission half-lives are to be obtained. Nevertheless, a rule-of-thumb emerges, in the sense that for each MeV reduction of barrier height, the fission half-life decreases by approximately six orders of magnitude.

Therefore, if we consider an isomer at an excitation energy of 1 MeV above the ground state, it might be expected that the fission half-life of the isomer would be a million times less than that of the ground state. It is also the case that 1 MeV is an appropriate isomer energy, since this is approximately the energy needed to uncouple a pair of orbiting nucleons (corresponding to twice the odd-even mass difference) and hence obtain a high-spin state.

4 Examples of Isomeric Fission

A recent review of the structure of heavy nuclei [9] identified just two cases of K isomers where there is evidence for fission. The first case is ^{256}Fm [10], which has a 70 ns isomer at an excitation energy of 1.43 MeV. In the experiment, only two fission events were attributed to the isomer decay, indicating an isomer fission probability of 2×10^{-5}, and hence a partial fission half-life of approximately 1 ms. The authors [10] estimated an inhibition factor of about 10^3, on account of the broken-pair configuration of the isomer. Compared with the ground-state partial fission half-life of almost 3 hours [1], the isomer value of 1 ms seems very short, but at 1.43 MeV excitation energy, a significantly faster isomer decay could have been expected.

The second example is ^{250}No [2], which has already been mentioned in the introduction. This is a particularly interesting case because the isomer has about a ten times longer fission half-life than the ≈6 μs ground state. It is therefore reasonable to say that the isomer confers extra stability against fission. Furthermore, due in part to the shorter ground-state half-life, it has not been determined experimentally to what degree the isomer might γ decay to the ground state. Hence, the isomer's $partial$ fission half-life could be even longer. But does this case represent a general phenomenon that occurs as the limits to nuclear binding are approached, or is it just an experimental oddity?

A third example, ^{254}No, has recently been reported [11], where a 275 ms isomer at 1.29 MeV has a fission probability of 2×10^{-4}. While the authors estimate that the fission from the isomer is inhibited by a factor of several hundred [11], the 20 minute partial fission half-life of the isomer is still much less than the 8 hours of the ground state [1].

It seems that, to test the isomer effect at the limits of nuclear binding, it is desirable to study shorter-lived (more fissile) nuclei. From this point of view, the classic "fission isomers" provide key information.

5 Fission Isomer Half-Lives

Fission isomers have highly elongated "superdeformed" shapes, and are found for proton numbers $Z = 92$ to 97. They were studied intensively in the 1960s and 1970s [12]. Their occurrence depends on an energy gap in the shell-structure that gives rise to a local region of extra binding for a major-to-minor axis ratio of 2:1, resulting in a "second well" in the potential energy as a function of elongation. A few cases have γ-decay branches leading back to the ground state, but all undergo spontaneous fission, with half-lives that range from a few picoseconds to a several milliseconds.

While the basic understanding of fission isomers is centred on the nuclear shape effect, with angular momentum playing no more than a minor role, several cases were observed [12] that correspond to excited states (∼1 MeV) within the second well. These may be interpreted as second-well K isomers, analogous to the normal (first well) K isomers discussed in the previous section. A remarkable feature is the systematically longer half-lives of the second-well K isomers, compared to the lowest-energy states in the second well. This aspect is illustrated in Figure 1 (for nuclides with even N and even Z).

In the context of the earlier discussion, it is immediately evident that the second-well K isomers confer extra stability. Their fission half-lives are from one to four orders of magnitude longer, despite their higher excitation energy. Unfortunately, little is known experimentally about the character of these states, beyond their approximate excitation energies and half-lives. Therefore, to aid in their understanding, additional theoretical calculations are being performed [5] with constrained configurations. These calculations show for the first time that

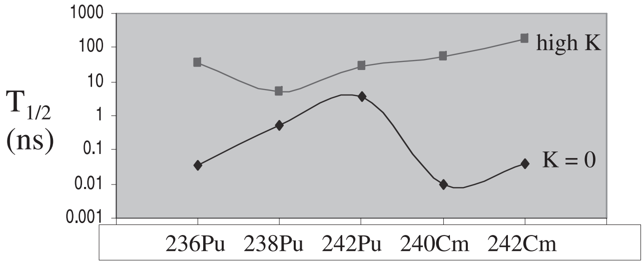

Figure 1. Half-lives of fission isomers in even-even nuclei. The label “K = 0” refers to the lowest-energy state in the second well, and “high K” refers to the excited isomer in the second well. The data are from Bjørnholm and Lynn [12].

the second-well high-K states do indeed have higher fission barriers than their K = 0 counterparts, leading to a better understanding of the fission process.

6 Conclusion

The combination of sparse experimental information and new potential-energy calculations demonstrates that, when nuclear binding is weak, high-spin isomers can confer extra stability in the form of extended fission half-lives, despite higher excitation energies. The half-life effect can be several orders of magnitude. It will be important to take this effect into account when studying the high-mass limit to nuclear binding.

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