On the possibility of enhanced fission stability for broken-pair excitations

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Abstract

The fission of high-K, two-quasiparticle isomers is considered, with specific reference to ^{250}No, ^{254}No, and ^{256}Fm. The published experimental evidence is discussed in relation to configuration-constrained potential-energy-surface calculations, which suggest that the high-K isomers should be less susceptible to fission than their corresponding ground states.

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It is a remarkable feature that some excited nuclear states, largely due to their high angular momentum, can confer extra stability, i.e. they can have longer half-lives than their respective ground states. For nuclei close to β stability this may appear to be a chance circumstance, producing some interesting curiosities, such as the quasi-stable isomer in ^{180}Ta with $T_{1/2} > 10^{15}$ y, compared to its 8 h ground state [1]. However, when considering the limits of nuclear binding, at the proton and neutron drip lines and for superheavy elements, extra stability becomes a vital issue of survival, and can be essential for experimental investigations. Breaking nucleon pairs costs energy, but can also generate angular momentum. We address the question: to what extent can this lead to extended fission half-lives?

Long-lived excited states, i.e. isomers, are widely found in deformed, axially symmetric nuclei [2], where the angular-momentum projection, K, on the symmetry axis of the deformed intrinsic shape is approximately conserved. The inhibition of so-called "K-forbidden" electromagnetic transitions is associated with isomers having extended γ-decay half-lives. Furthermore, it has been shown that such broken-pair, high-K isomers can be important in extending survival times with respect to the α-decay of superheavy nuclei [3, 4]. Although fission was also argued to be inhibited [4], there was then only one experimental observation of isomeric fission at normal deformation [5], which will be discussed later. In addition, high-K "fission isomers" have recently been discussed [6]. These are superdeformed states in the second well of the potential energy surface (PES). Despite limited data on such isomers [7, 8], the comparison with PES calculations gives added confidence that there is systematic inhibition of fission from high-K, second-well states, with half-lives sometimes exceeding those of the corresponding $K^\pi = 0^+$ minima, also in the second well, by three orders of magnitude. Nevertheless, it remains very challenging to obtain more robust experimental information about high-K isomers in the second well. Complementary to that aspect, we now explore further the fission susceptibility of high-K isomers in the normal-deformed well of the PES. It is notable that Adamian et al. [9] have calculated a range of high-K isomer energies in superheavy nuclei, and considered in detail their α decay.

Data on fissioning normal-deformed isomers involving broken-pair excitations are extremely limited. In the review of Herzberg and Greenlees [10], only two candidates are identified, ^{250}No [11] and ^{256}Fm [5]. More recently, Hessberger et al. [12] have reported evidence for the fission of an isomer in ^{254}No. Consider first the $K^\pi = 7^-$, two-quasiparticle isomer in ^{256}Fm, with an excitation energy of 1.43 MeV, and a half-life of 70 ns. It decays largely by γ-ray emission, but two delayed-fission events have been detected [5], indicating a partial fission half-life $\sim 10^{-3}$ s, albeit with large experimental uncertainty. Although argued [5] to be substantially inhibited compared to what might be expected at that excitation energy, the partial fission half-life is anyway much shorter than the ground-state partial fission half-life of 10^4 s [1], suggesting that the high-K isomer in ^{256}Fm fissions much more readily than the ground state. This is very different to the indications for high-K isomers in the second well of actinide nuclei [6].

The situation for normal-deformed ^{256}Fm is similar to that found in ^{254}No [12], where a $K^\pi = 8^-$, 275 ms isomer at 1.29 MeV has a fission probability of $(2.0 \pm 1.2) \times 10^{-4}$. While the authors estimate that fission from the isomer is inhibited by a factor of several hundred [12], the 20 minute partial fission half-life of the isomer is still much less than the 8 hours of the ground state [1].

These two cases, ^{256}Fm and ^{254}No, contrast with the other normal-deformed example, ^{250}No [11]. Here a probable $K^\pi = 6^+$, two-quasiparticle isomer is reported to fission with a half-life of 43 μs, compared to the ground-state fission half-life of 3.7 μs. In this case, fission inhibition compared to the ground state is evident, seemingly by a factor of about ten. In addition, the authors [11] point out that their experimental data are compatible with electromagnetic (γ ray and electron conversion) decay of the isomer to the ground state, followed by ground-state fission, and the partial fission half-life of the isomer is only really determined as a limit, i.e. ≥ 43 μs. This leaves open the possibility that there is more-substantial fission inhibition from the isomer.

In order to get an appreciation of the theoretical situation, PES calculations have been carried out. While many calculations of ground-state fission barriers have been performed by other groups, see for example Refs. [13–16], the present study emphasises the use of a configuration-constrained technique to obtain information about the PESs for broken-pair excitations. This builds on previous work [4, 6, 17].

The configuration-constrained PES model [17] has been widely used to calculate the energies and shapes of high-K isomeric states in various mass regions, including the superheavy [4] and drip-line [18] regions. In the previous work, PESs were mainly calculated in the $(\beta_2, \gamma, \beta_4)$ deformation space. These three deformation degrees of freedom are usually sufficient for normally deformed nuclei. However, it has been found that other high-multipole deformations, especially those with reflection asymmetry, are important for understanding the large deformations of heavy nuclei. Therefore, the model was recently extended [6, 19] to take account of the deformation parameters $(\beta_2, \beta_3, \beta_4, \beta_5, \beta_6)$. Single-particle levels are obtained from the reflection-asymmetric Woods-Saxon potential with the set of universal parameters [20]. For the pairing correlations, particle-number projection is approximated by the Lipkin-Nogami technique [21], with the pairing strength determined by the average-gap method [22]. The total energy of a nucleus consists of a macroscopic part that is obtained with the standard liquid-drop model [23] and a microscopic part which is calculated by the Strutinsky approach [24].

In the configuration-constrained PES calculation, it is required to block adiabatically the unpaired nucleon orbits which specify a given configuration [17]. This has been achieved by calculating and identifying the average Nilsson quantum numbers for the orbits involved in the configuration. The process is the same as that in the $(\beta_2, \gamma, \beta_4)$ space [17] except that, for reflection-asymmetric deformation, parity is no longer conserved. (Note that Ω is still a good quantum number.) For the present purposes, the PES calculations are limited to $|\beta_3| \leq 0.3$ because higher β_3 deformation can cause strong mixing of orbits, leading to difficulty in tracing the given orbits. This is similar to the calculation for nonaxial deformations, where tracing orbits at large γ deformation needs special attention [17]. Such PESs can show the shape changes and barrier changes due to the polarization of unpaired nucleons.

It must be acknowledged that the procedure for connecting configurations through level crossings requires further study, taking into account sensitivity to the fission dynamics [25], especially for non-axial deformations. Nevertheless, the present work, by following particular configurations, provides valuable insights regarding the possibility of increased barrier heights for broken-pair excitations.

The resulting barriers to fission are presented for ^{250}No and ^{256}Fm in figures 1 and 2, respectively. The full lines consider only the axially symmetric β_2 degree of freedom. For normal deformations $(\beta_2 < 0.5)$ it is found that the γ deformation is important, and the effect of including this is shown by the dotted line. However, for large deformations $(\beta_2 > 0.5)$ it is the β_3 degree of freedom that must be accounted for [26], and the effect is shown by the dashed line. The final barrier heights are given in Table I, which includes the ground-state fission barriers from Möller et al. [15] for comparison. It should be pointed out that the ^{256}Fm configuration-constrained PESs were calculated earlier [4] but without consideration of the β_3 degree of freedom.

Before discussing the overall fission barriers, we note that there are second minima at superdeformed shapes ($\beta_2 \approx 0.7$) which could give rise to second-well fission isomers. This issue is considered in more detail by Zheng et al. [27].

For the normally deformed minima ($\beta_2 \approx 0.3$) of ^{250}No and ^{256}Fm, the calculated K-isomer fission barrier is about 1.4 MeV higher than the corresponding ground-state fission barrier. A similar result was found for ^{254}No [19], where the effect of β_6 deformation was also investigated. While acknowledging that the relationship between half-life and barrier height is complex, and the tunnelling probability depends also on the barrier width, Möller et al. [15] calculate half-life reductions of about 5 orders of magnitude per MeV of barrier height (comparing, for example, ^{252}Fm and ^{258}Fm ground states). For quasiparticle excitations there is, in addition, fission inhibition due to reduced pairing [7], which affects the fission dynamics. Despite its limitations, the present configuration-constrained approach provides an important step towards quantifying the fission probabilities from high-K isomers, although further work is needed to follow the constrained configurations when there are large γ and octupole deformations, so that the full barrier widths can be determined.

With the qualitative result that the calculated high-K fission barriers are significantly higher than the respective ground-state fission barriers, it is appropriate to comment further on the experimental observations. For both ^{256}Fm [5] and ^{254}No [12] the limited data indicate the converse: partial fission half-lives are shorter for the isomer than the ground state. However, for the ^{256}Fm isomer only two fission events were observed, and for the ^{254}No isomer the fission probability is within two standard deviations of zero. It would be highly desirable to improve the experimental data, to see if these fission branches can be substantiated.

For ^{250}No the existing data [11] are in better accord with our calculations, and the fissioning high-K isomer is longer lived than its ground state. In this case, the internal (electromagnetic) decay remains to be measured, and the partial fission half-life could be substantially longer than the measured value. Again, improved data are certainly needed.

In summary, configuration-constrained PES calculations for ^{250}No, ^{254}No, and ^{256}Fm have been discussed in relation to existing experimental data, with an emphasis on the relative fission probabilities of high-K isomers and their respective ground states. It is necessary to better understand these comparisons. The calculations indicate higher fission barriers for the isomers, but the experimental data are not yet of sufficient quality to reach a conclusion. Improvements are also needed with the PES calculations, so that a wider deformation space can be studied, and dynamic effects will need to be included. Only then will it be possible to properly understand the fission stability of normally deformed high-K isomers, and thus provide guidance in the search for the heaviest elements, where broken-pair, high-K isomers may confer extra stability.

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TABLE I: Experimental partial fission half-lives and calculated fission barriers.

	K^π	$T_{1/2}^{fission}$ (s)	E_B (MeV)
^{250}No	0^+	3.7×10^{-6}	5.45 [5.83]^a
	6^+	$\geq 4.3 \times 10^{-5}$	6.89
^{256}Fm	0^+	1×10^4	5.20 [5.11]^a
	7^-	$\sim 10^{-3}$	6.56

Note: ^{a} From Möller et al. [15]

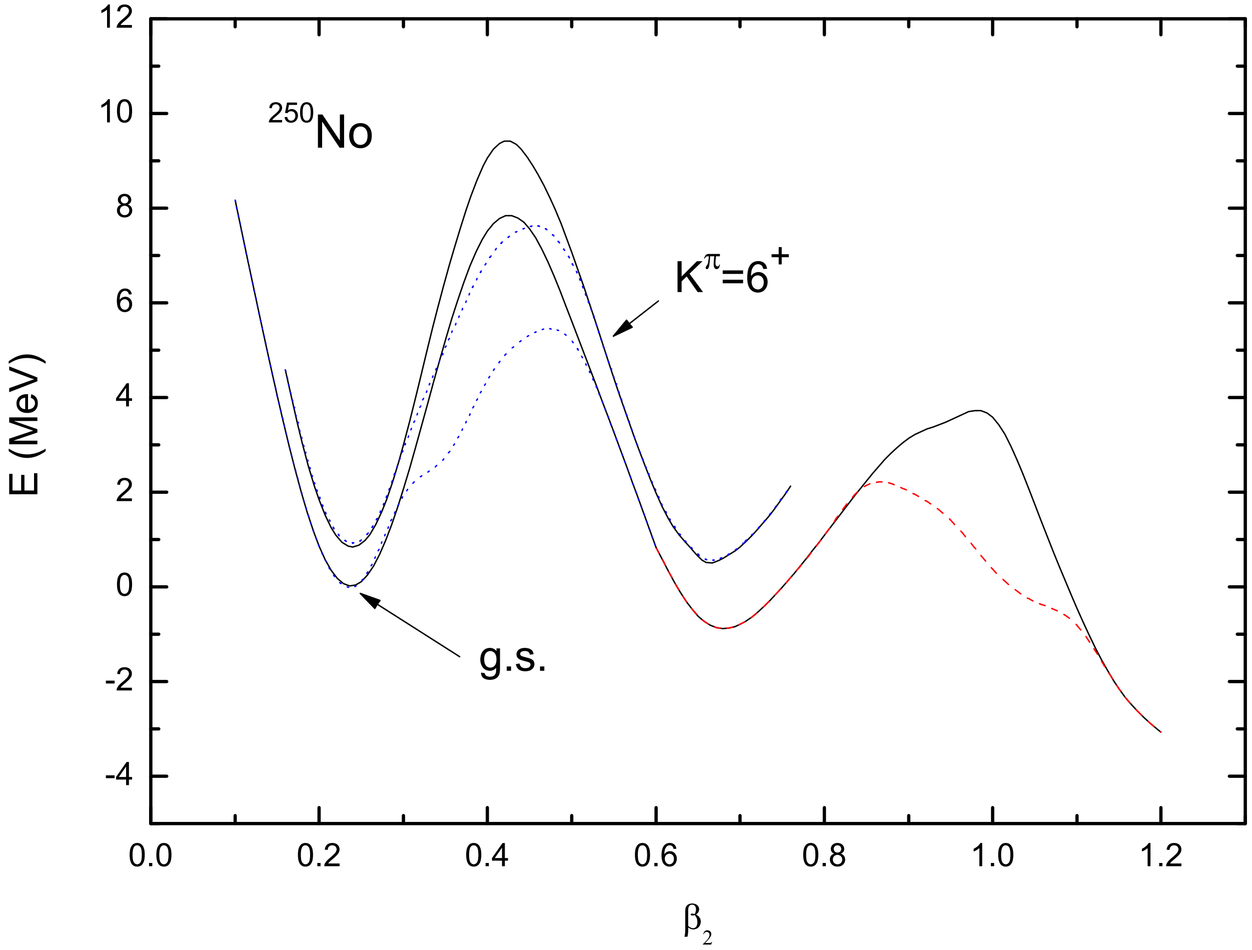

FIG. 1: (Color online) Calculated energy as a function of β_2 deformation for the ground state and the $K^\pi = 6^+$ isomer in ^{250}No. The dotted (blue) line shows the effect of γ deformation, while the dashed (red) line includes the effect of β_3.

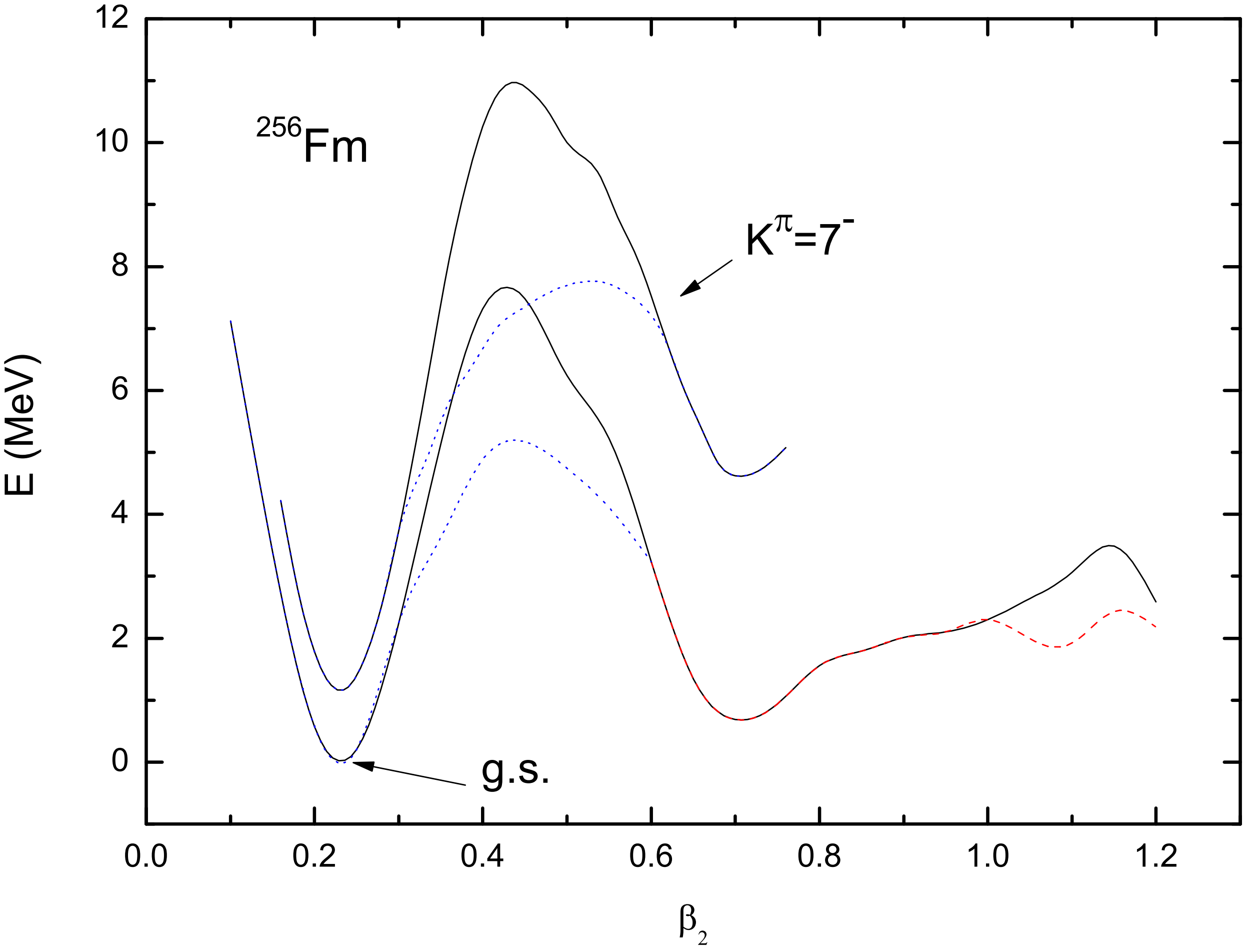

FIG. 2: (Color online) As Fig. 1, but for the ground state and the $K^{\pi} = 7^{-}$ isomer in ^{256}Fm. This figure is similar to that shown in Ref. [4], but now includes β_3 variation.