Superdeformed shapes and stability in superheavy nuclei

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Introduction

The discovery of superdeformation in nuclei [1] constitutes an important landmark in nuclear physics. The presence of a second energy minimum in nuclei corresponding to an ellipsoidal shape with a major-to-minor axis ratio of 2:1 was particularly noteworthy given the short range of the strong interaction which binds the nuclear system. The appearance of relatively stable superdeformed shapes was attributed to the presence of considerable gaps in the single-particle energy spectrum at large values of the quadrupole deformation (ε_2) for specific values of nucleon numbers [2]. While the first instance of nuclear superdeformation at high spin was found in the A≈150 region, with later ones in other mass regions (A≈190, 130, 80, 40 *etc*.), the presence of a highly-deformed second energy minimum at low spin had already been established in several isotopes of the actinide elements. These states were labelled "fission isomers" arising from the predominant decay mode and their long half-lives. Many such fission isomers have been identified in isotopes of actinide elements ranging from U (Z = 92) to Cf (Z = 98), with the most notable example being the 13.9-ms isomer in ^{242}Am with spin-parity I^{π} = $(2^+, 3^-)$ and excitation energy E_x ≈ 2.2 MeV [3].

Selected examples of fission isomers are listed in Table 1. Among all the identified fission isomers, detailed measurements of their properties have been possible only in a few cases [3, 4, 5, 6]. The half-lives are found to range from nanoseconds to milliseconds with up to a few units of spin. In some instances, where quadrupole moments could be measured, the quadrupole deformation is inferred to range from ε_2 ≈ 0.5-0.7 [7, 8, 9], supporting the interpretation of superdeformed shapes for the fission isomers. Experimental studies of higher-Z elements are limited by the low production cross sections of these nuclei. It is expected that focused theoretical calculations would allow for determining the favored candidates in the actinide series and the superheavy elements beyond, for the observation of superdeformation and possible fission isomers.

Table 1: Some notable fission isomers in the actinide series [3-9, 10, 11]. In each case, the half-life, excitation energy, and spin-parity is listed, wherever it has been established. The inferred quadrupole deformations are also noted.

Nucleus	$T_{1/2}$	E_x (keV)	I^{π}	ε_2
$^{238}_{92}U_{146}$	280 ns	2558	(0^+)	0.47
$^{239}_{94}Pu_{145}$	7.5 µs	≈3100	$(5/2^+)$	0.54
$^{240}_{95}Am_{145}$	0.94 ms	≈3000	-	0.47
$^{242}_{95}Am_{147}$	13.9 ms	≈2200	$(2^+, 3^-)$	0.69
$^{242}_{96}Cm_{146}$	180 ns	≈2800	-	-
$^{244}_{97}Bk_{147}$	820 ns	$0+x$	-	-

Stability of superheavy nuclei

Isotopes of elements beyond Fm (Z = 100) owe their existence to the microscopic contributions from the shell-correction energy without which they would be unbound, *i.e.*, if only the macroscopic part of the energy were considered [12]. Evidently, (relative) stability is closely linked to the precise contribution from the shell-correction energy, particularly in the case of superheavy nuclei. In these nuclei, the ground states themselves are short-lived, and it is expected that in most cases, possible superdeformed states would have even lower half-lives, and would decay through fission.

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However, in certain nuclei, the conditions may be suitable for an excited superdeformed level to be longer-lived than the corresponding ground state. Such a situation is realized for a K isomer in *e.g.*, ^{270}Ds (Z = 110) where the I^{π} = (9^-, 10^-) state at $E_x \approx$ 1130 keV is found to have a half-life of 3.9 ms in contrast to the 0.2-ms half-life of its ground state [13]. In the past two decades, many K isomers have been established in nuclei around Z = 100, see, *e.g.*, [14, 15, 16, 17]. The presence of analogous shape (fission) isomers would be of particular interest both from the point of view of the understanding of nuclear structure and its implications for the stability of superheavy nuclei.

Theoretical calculations

Though the possibility of the realization of superdeformed shapes in superheavy nuclei has been explored through theoretical calculations, the extent of the work is quite limited. Calculations using the relativistic mean-field (RMF) theory have been reported for isotopes of elements with Z = 110-112, 114, 116 and 118 [18]. Macroscopic-microscopic model calculations using the Woods-Saxon potential have also been performed [19]. These results suggest the existence of superdeformed shapes which could have implications for the predicted island of stability for superheavy nuclei.

The present work utilizes macroscopic-microscopic calculations using the deformed oscillator potential in the framework of the Ultimate Cranker code [20]. The deformation space spanned in these calculations ranges from moderate deformation ($\varepsilon_2 \approx 0.1$) to quite large values ($\varepsilon_2 \approx 0.8$); axially symmetric prolate, oblate and triaxial shapes have all been allowed. There are two aspects which are being explored in this work. Firstly, the predictive power of the calculations is being inspected for the cases of actinides where fission isomers are well established. Once the validity of the results is reasonably established, calculations for the superheavy cases will be undertaken. Detailed results from the above calculations illustrating the normal deformed and possible superdeformed minima will be presented at the symposium.

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