Enhanced Stability of Superheavy Nuclei Due to High-Spin Isomerism

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(Received 29 November 2003; published 25 June 2004)

Configuration-constrained calculations of potential-energy surfaces in even-even superheavy nuclei reveal systematically the existence at low excitation energies of multiquasiparticle states with deformed axially symmetric shapes and large angular momenta. These results indicate the prevalence of long-lived, multiquasiparticle isomers. In a quantal system, the ground state is usually more stable than the excited states. In contrast, in superheavy nuclei the multiquasiparticle excitations decrease the probability for both fission and α decay, implying enhanced stability. Hence, the systematic occurrence of multiquasiparticle isomers may become crucial for future production and study of even heavier nuclei. The energies of multiquasiparticle states and their α decays are calculated and compared to available data.

DOI: 10.1103/PhysRevLett.92.252501 PACS numbers: 21.10.–k, 21.60.–n, 23.20.Lv, 27.90.+b

It has long been a fundamental question as to what are the maximum charge and mass that a nucleus may attain. Recently, significant progress has been made experimentally in the synthesis of the heaviest elements [1,2]. According to classical physics, elements with $Z \geq 104$ should not exist due to the large Coulomb repulsive force. The occurrence of superheavy elements with $Z \geq 104$ is entirely due to quantal shell effects. Theoretically, predictions have been made that there should be an island of stability of superheavy nuclei around $N = 184$ and $Z = 114$, 120, or 126, depending on the model employed [3–7].

Information concerning the excited-state structure of superheavy nuclei is scarce, so the testing of structure calculations has been limited. A promising area of progress is represented by the observation of rotational γ-ray transitions in $^{252,254}_{102}$No [8,9] and $^{252,254}_{100}$Fm [10], showing the deformed character of these nuclei, which can be described theoretically [11]. The γ-ray transitions from noncollective one-quasiparticle states form another important probe into the structure of superheavy nuclei [12]. By measuring the properties and decays of quasiparticle states, essential information about the nucleonic orbits close to the Fermi surfaces can be gained. Indeed, detailed knowledge of single-particle states is required for the development of reliable nuclear structure models.

In the present work, we consider multiquasiparticle (multi-QP) states formed by breaking pairs of nucleons. Unpaired nucleons couple their angular momenta to states with total spin projection K onto the symmetry axis in deformed, axially symmetric nuclei. The K values can be large, and, due to the high degree of their K forbiddenness, γ-ray transitions from high-K into low-K states are strongly hindered, leading to the formation of long-lived high-K isomers. In addition, there are influences on fission and α-particle emission, which can be important in increasing the survival probability of superheavy nuclei. Indeed, high-K isomers might become crucial in the exploration of even heavier nuclei. In the present work, we focus on high-spin isomerism and the angular-momentum effect on the stability of even-even superheavy nuclei.

Configuration-constrained potential-energy-surface (PES) calculations [13] have been performed to determine the deformations and excitation energies of multi-QP states. Single-particle levels are obtained from the nonaxial deformed Woods-Saxon potential with the set of universal parameters [14]. In order to reduce the unphysical fluctuation of the weakened pairing field (due to the blocking effect of unpaired nucleons) an approximate particle-number projection has been used by means of the Lipkin-Nogami method [15], with pairing strengths determined by the average gap method [16]. In the configuration-constrained PES calculation, it is required to adiabatically block the unpaired nucleon orbits that specify a given configuration. This has been achieved by calculating and identifying the average Nilsson quantum numbers for every orbit involved in a configuration [13]. The total energy of a state consists of a macroscopic part that is obtained with the standard liquid-drop model [17] and a microscopic part that is calculated by the Strutinsky shell-correction approach, including blocking effects. The PES is calculated in the space of quadrupole (β_2, γ) and hexadecapole (β_4) deformations. The configuration-constrained PES calculation can properly treat the shape polarization due to unpaired nucleons.

Following predictions from theory, many experiments [8–10] have demonstrated the systematic existence of deformed superheavy nuclei. In fact, almost all the superheavy nuclei found experimentally are believed to be deformed, and the stability of superheavy nuclei is enhanced due to deformed shell effects. Furthermore, deformed high-K orbits close to the Fermi surfaces can form various high-K multi-QP states at low excitation energies. In the present work, we are interested in possible isomeric states. The combination of high K, low energy, and axially deformed shape provides the necessary conditions for the formation of isomers. Additionally, a parity opposite to that of the ground state (g.s.) can further reduce the transition rate from an excited-state to the g.s. or to a member of the g.s. band (g.s.b.). Figures 1 and 2 display our calculations of low-energy high-K two-QP states with negative parity for even-even $Z \geq 100$ nuclei. These investigated states have deformed, axially symmetric equilibrium shapes.

In a recent experiment [18], α decays from isomeric states in $^{270}_{110}$Ds were observed with a half-life of $6.0^{+8.2}_{-2.2}$ ms that is significantly longer than the 100^{+140}_{-40} μs of the corresponding g.s. Possible configurations for these isomers were proposed to be $K^\pi = 9^-(\nu\frac{11}{2}^-[725] \otimes \frac{7}{2}^+[613])$ and/or $10^-(\nu\frac{11}{2}^-[725] \otimes \frac{9}{2}^+[615])$ [18]. Our calculations confirm these assignments and indeed show that the 9^- and 10^- two-quasineutron states exist systematically at low excitation energies (see Fig. 1) with axially symmetric deformations around $\beta_2 \sim 0.2$. In ^{270}Ds, the calculated energies of the 9^- and 10^- isomers are 1.39 and 1.26 MeV, respectively, agreeing with the experimental estimate of 1.13 MeV [18]. Furthermore, configuration-constrained PES calculations allow us to determine the Q_α value of the α decay from a given configuration of the parent nucleus to a given state of the daughter. Then, the α-particle kinetic energy is obtained from $E_\alpha = (1 - 4/A_p)Q_\alpha$, allowing for the recoil correction (where A_p is the mass number of the parent nucleus). Figure 3 shows schematically the α decays from the g.s. and isomers in ^{270}Ds. The calculated α decays of the two-quasineutron $\nu9^-$ and $\nu10^-$ isomers to the corresponding isomers of ^{266}Hs have very similar α-particle energies, giving an average value of 11.06 MeV. This is in good agreement with the observed energy of 10.95 MeV [18]. The $\nu9^-$ and $\nu10^-$ isomeric α decays to the g.s. of ^{266}Hs also have similar α energies with an average value of 11.93 MeV, in agreement with the measured energy of 12.15 MeV [18]. One also expects that the isomer can feed by α emission into other states with low angular momenta.

Also from ^{270}Ds, an observed α emission with $E_\alpha =$ 11.15 MeV was found in coincidence with a 218 keV γ-ray signal and was suggested to decay to the 8^+ member of the rotational g.s.b. of ^{266}Hs [18] (the γ-ray energy was found to be close to the calculated energy of the transition from the 8^+ to 6^+ states of the g.s.b. in ^{266}Hs). We calculate that the 8^+ to 6^+ transition has an energy of 234 keV. The calculated α energies of the $\nu9^-$ and $\nu10^-$ decays to the 8^+ state are 11.42 and 11.29 MeV, respectively. In ^{270}Ds, however, we found another low-lying 10^- state that has a two-quasiproton configuration $\pi\frac{11}{2}^+[615] \otimes \frac{9}{2}^-[505]$ with a calculated excitation energy of 1.07 MeV, giving $E_\alpha(\pi 10^- \rightarrow 8^+) = 11.10$ MeV, in good agreement with the observed value of 11.15 MeV. In ^{266}Hs, the $\pi10^-$ state has a relatively high excitation energy of 2.54 MeV.

To understand the above observations, we note that the probability for α decay is determined by two factors: (i) an exponential dependence on the height of the barrier that the α particle needs to penetrate and (ii) the preformation factor, characterizing the ease with which an α particle is formed at the surface. The latter is proportional to the pair density at the Fermi surface [19], implying a considerable reduction for two-QP states, as is the case for high-K isomers. An α decay between two different isomeric configurations is in principle forbidden. Furthermore, if the α particle carries a certain angular momentum, the barrier is increased due to the centrifugal potential. The increase of the barrier height and width reduces the α-emission probability and hence increases the lifetime. However, due to the exceptionally high energy of the α particle for the case of superheavy nuclei, the centrifugal barrier is of less importance, and the

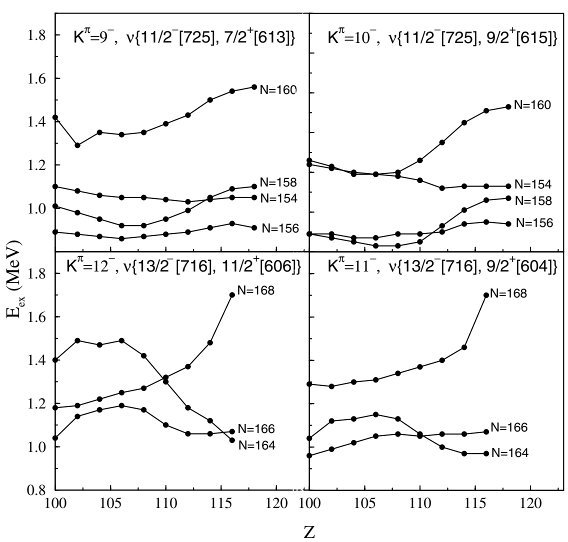

FIG. 1. Calculated excitation energies for two-quasineutron states.

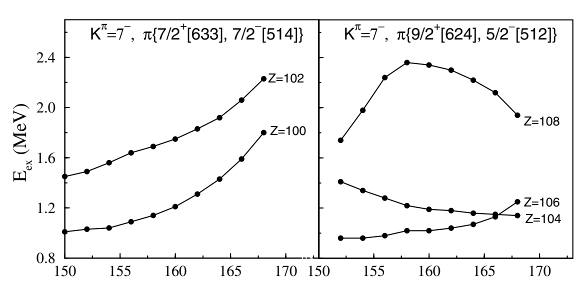

FIG. 2. Calculated excitation energies for two-quasiproton states.

decay from an isomer to the g.s. can in fact compete with the decay to the corresponding isomer. This is consistent with the observation of the relatively long lifetimes for the α decays of the isomers in ^{270}Ds and ^{266}Hs [18]. Therefore, the high-K isomerism can enhance the stability of such nuclei against α emission.

High-K isomers have also been found in ^{250,256}Fm and ^{254}No. In ^{250}Fm, a 1.8-s isomer [20] was observed at an excitation energy of 1.0 MeV [10]. The ^{254}No nucleus has a 0.28-s isomer [20] with an energy >0.5 MeV [10], and there is recent evidence for associated collective structure [21]. However, experiments have not determined spins and parities for these two isomers. A likely configuration in ^{250}Fm is $\pi\frac{7}{2}^+[633]\otimes\frac{7}{2}^-[514]$, resulting in a 7^- state. As shown in Fig. 2, the calculated excitation energy of the 7^- configuration is 1.01 MeV, which agrees well with the experimental value of 1.0 MeV [10]. A two-quasineutron 8^- configuration, $\nu\frac{7}{2}^+[624]\otimes\frac{9}{2}^-[734]$, is also possible with a calculated energy of 0.97 MeV in ^{250}Fm. Our calculations show that 8^- states exist systematically in the $N=150$ isotones with excitation energies around 1.0 MeV. In ^{254}No, alternative configurations for the observed isomer are $\nu\frac{7}{2}^+[613]\otimes\frac{9}{2}^-[734]$ and $\pi\frac{7}{2}^-[514]\otimes\frac{9}{2}^+[624]$, with $E_{\mathrm{ex}}^{\mathrm{cal}}=1.12$ and 1.48 MeV, respectively. The low-lying $\nu\frac{7}{2}^+[613]\otimes\frac{9}{2}^-[734]$ states exist systematically in the $N=152$ isotones with calculated energies around 1.1 MeV.

Another interesting example is the ^{256}Fm nucleus, in which a 70-ns, 7^- isomer was observed to undergo spontaneous fission [22]. The 7^- isomer was populated from the β decay of an 8^+ isomer of odd-odd ^{256}Es.

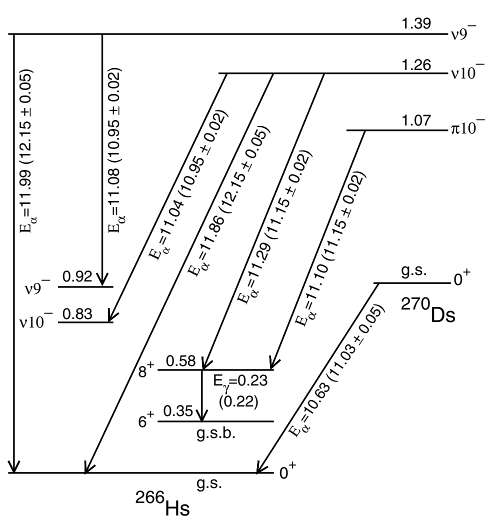

FIG. 3. Schematic figure for the α decays corresponding to the reported decay events [18] from ^{270}Ds to ^{266}Hs. Different options for the initial isomer are indicated. The energies (in MeV) are not drawn to scale. The configurations are $\nu9^-=\nu\frac{11}{2}^-[725]\otimes\frac{7}{2}^+[613]$; $\nu10^-=\nu\frac{11}{2}^-[725]\otimes\frac{9}{2}^+[615]$; $\pi10^-=\pi\frac{11}{2}^+[615]\otimes\frac{9}{2}^-[505]$. The values in parentheses are the experimental energies [18].

The ^{256}Es 8^+ isomer has a half-life of 7.6 h, which is much longer than the 25 min of the corresponding 1^+ g.s. We calculate that the excitation energy of the 7^- ($\pi\frac{7}{2}^+[633]\otimes\frac{7}{2}^-[514]$) isomer in ^{256}Fm is 1.1 MeV (see Fig. 2), about 0.3 MeV less than the experimental value of 1.42 MeV [22].

In ^{256}Fm, the observed partial fission half-life of the 7^- isomer is 0.8 ms, which is remarkably longer than the expected value of 2.5 μs, assuming no hindrance from unpaired nucleons [22]. In Ref. [23], it has been shown that the spontaneous-fission half-life increases considerably due to the effect of the unpaired nucleon in odd-mass nuclei. This can be understood in terms of reduced superfluidity. The configuration-constrained PES calculations allow us to determine the fission barrier for a given configuration. Figure 4 shows the configuration-constrained fission barrier for the 7^- isomer in ^{256}Fm. (It needs to be mentioned that an isomer might undergo a more complex dynamical process during fission, without keeping a fixed configuration.) The increase of the fission barrier in both height and width implies an increase in the fission lifetime. In the calculations of fission barriers, the inclusion of the nonaxial γ deformation is important because the γ degree of freedom can significantly affect the shape of the fission barrier. In ^{256}Fm, for example, the nonaxial PES calculations result in the barrier heights being lowered by 2.4 and 2.6 MeV for the g.s. and 7^- isomer, respectively, compared with axial calculations. Figure 5 displays the calculated PES of the g.s. in ^{256}Fm, with the fission trajectory marked. The 7^- isomer has a similar fission trajectory.

Although the production of high-spin states in superheavy nuclei is generally inhibited by their increased fission probability, this does not apply when the angular-momentum is noncollective and aligned with the symmetry axis, as for high-K states. Therefore, there should be a significant production of high-K isomers in fusion

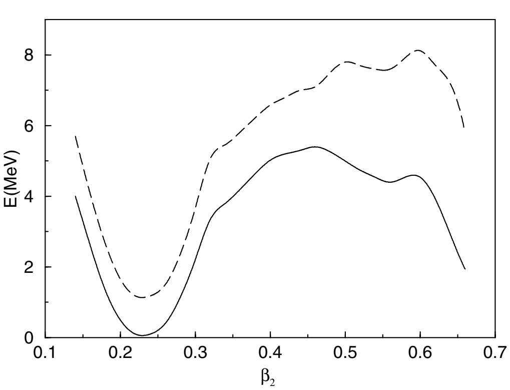

FIG. 4. Calculated potential energies versus β_2 deformation in ^{256}Fm. The solid and dashed lines represent the ground state and the $\pi\frac{7}{2}^+[633]\otimes\frac{7}{2}^-[514]$ isomer, respectively. At each β_2 point, the energy has been minimized with respect to the γ and β_4 deformations.

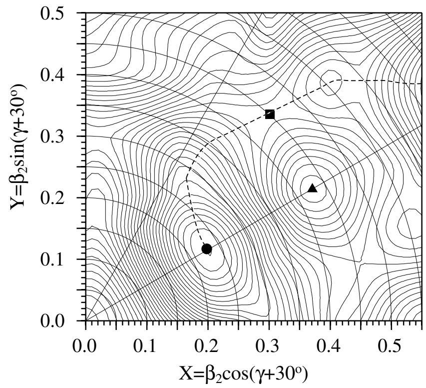

FIG. 5. Calculated PES for the ground state of ^{256}Fm. The dashed line indicates the fission trajectory. The solid circle, triangle, and square are at the minimum, maximum, and saddle points, respectively. At each (β_2, γ) point, the energy has been minimized with respect to the β_4 deformation.

reactions. Two-QP excitations can also appear in odd-mass and odd-odd superheavy nuclei, resulting in three- and four-QP states, respectively. These have not yet been considered in detail. Furthermore, the present investigation is limited to deformed superheavy nuclei. However, the angular-momentum effects should also apply to spherical superheavy nuclei.

In summary, we have investigated multi-QP states in even-even superheavy nuclei using configuration-constrained PES calculations. Low-energy high-K deformed configurations are predicted to be present in the vicinity of the Fermi surface, resulting in the formation of high-spin isomeric states. The high-spin isomerism increases the barrier to fission and decreases the probability of α-particle emission. For a given class of superheavy nuclei with sufficiently short lifetimes, we have discussed an inversion of stability, in that the excited states can be longer lived than the corresponding ground states. These effects result in increased survival probabilities of superheavy nuclei. Therefore, it can be stated that via the population of high-K states in experiments, one may be able to extend the nuclear chart further into the island of superheavy nuclei. The energy calculations of multi-QP states and their α decays indicate that the single-particle orbits of the deformed Woods-Saxon potential apply also to the superheavy mass region. Further studies of high-K states will provide essential tests, not only of our specific isomer predictions, but also of mean-field models in general.

This work was supported by the Chinese Major State Basic Research Development Program No. G2000077400, the Chinese National Natural Science Foundations (Grants No. 10175002 and No. 10047001), the Doctoral Foundation of Chinese Ministry of Education (20030001088), the Knowledge Innovation Project of Chinese Academy of Sciences (KJCX2-SW-N02), the Swedish Science Research Council(VR), the U.K. Royal Society, and the U.K. Science and Engineering Research Council.

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