High-spin isomers in some of the heaviest nuclei: Spectra, decays, and population

G. G. Adamian,[1,2] N. V. Antonenko,[1] and W. Scheid[3]

[1] *Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*

[2] *Institute of Nuclear Physics, 702132 Tashkent, Uzbekistan*

[3] *Institut für Theoretische Physik der Justus-Liebig-Universität, D-35392 Giessen, Germany*

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The isotopic dependence of two-quasiparticle isomeric states in Fm and No is treated for future experiments. The population of the isomeric states in evaporation residues is considered. In several even isotopes of Rf, Sg, Hs, and Ds, the K isomers and their decay modes are predicted. An α-decay chain through the isomeric states of superheavy nuclei is demonstrated for the first time and proposed for the experimental verification.

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I. INTRODUCTION

In recent years, the spectroscopic properties of heavy nuclei with $Z \geqslant 100$ have been intensively studied. High-spin K isomers, which are usually assumed as two-quasiparticle high-spin states, were observed in the heavy nuclei ^{250,256}Fm, ^{252,254}No, and ^{270}Ds [1]. The one-quasiparticle isomeric states were also revealed among odd heaviest nuclei [2]. The K isomers are important in the analysis of α-decay spectra and properties of spontaneous fission of superheavy nuclei [2,3] because of their unambiguous identification. For example, the α decay from the isomeric state can easily occur if the same state exists in a daughter nucleus at similar or smaller energy.

The shell structure of the nucleus near its ground state can be treated with, for example, the models presented in Refs. [4–8]. To simplify the microscopic treatment, the number of collective variables describing the nuclear shape is reduced by choosing the certain shape parametrization and single-particle Hamiltonian. Although this method is not self-consistent, it provides a powerful tool for extensive calculations and predictions. In the present paper, we suggest the shape parametrization adopted for the two-center shell model (TCSM) [8] and use it for finding the single-particle levels in the ground state of the nucleus. The mirror symmetric shape parametrization used in this paper effectively includes all even multipolarities. The dependence of the parameters of **ls** and l^2 terms on A and $N-Z$ are modified for the correct description of the ground-state spins of known odd actinides.

II. MICROSCOPIC-MACROSCOPIC APPROACH

In the two-center shell model [8], the nuclear shapes are defined by the following set of coordinates. The elongation $\lambda = l/(2R_0)$ measures the length l of the system in units of the diameter $2R_0$ of the spherical nucleus. For large elongations, this variable starts to describe the relative motion of fission fragments. The transition of the nucleons through the neck is described by the mass asymmetry η. The neck parameter $\varepsilon = E_0/E'$ is defined by the ratio of the actual barrier height E_0 to the barrier height E' of the two-center oscillator. The deformations $\beta_i = a_i/b_i$ of axial symmetric fragments are defined by the ratio of their semiaxes. In the compact shapes, β_i are related only to the left and right sides of the nucleus where the curvature radii are minimal.

For compact nuclear shapes near the ground state, one can set $\varepsilon = 0$ and $\eta = 0$. Therefore, we have only three parameters: λ, β_1, and β_2 to describe the deformations of various multipolarities. The octupole deformation occurs in the case of $\beta_1 \neq \beta_2$. The case of $\beta_1 = \beta_2 = \beta$, which is treated here, means the absence of the static deformations of odd multipolarities. As an example, in Fig. 1, the nuclear shapes are shown at indicated sets (λ, β). In the microscopic-macroscopic approach, the potential energy consists of the smoothly varying macroscopic energy calculated with the liquid-drop model and the microscopic correction which contains the shell and pairing corrections. Calculating the potential energy as a function of λ and β, we find the values of λ and β corresponding to the ground state. With given values of λ and β, one can calculate the quadrupole and hexadecapole nuclear moments. Then one can find the quadrupole and hexadecapole deformation parameters β_{02} and β_{04} corresponding to these moments. One can show that the value of β_{02} strongly depends on λ, while the value of β_{04} is mostly sensitive to the value of β.

The values of microscopic corrections and the quadrupole parameters of deformation calculated with the TCSM are close to those obtained with the microscopic-macroscopic approaches in Refs. [6,7]. The ground state of ^{248}Fm is found to be at $\beta_{02} = 0.25$ and $\beta_{04} = 0.027$. For comparison, in Ref. [7], $\beta_{02} = 0.235$ and $\beta_{04} = 0.049$ in this nucleus. While in ^{247,248,249}Fm the microscopic corrections in Ref. [7] are -3.52, -3.57, and -3.97 MeV, respectively, we get -3.85, -3.88, and -4.3 MeV. These values are also comparable with those in Ref. [6].

The contribution of an unpaired nucleon, occupying a single-particle state $|\mu\rangle$ with energy e_μ, to the energy of a nucleus is described by the one-quasiparticle energy $\sqrt{(e_\mu - e_F)^2 + \Delta^2}$. Here, the Fermi energy e_F and the pairing-energy gap parameter Δ are calculated with the BCS approximation. Pairing interaction of the monopole type with strength parameters $G_{n,p} = \left(19.2 \mp 7.4\frac{N-Z}{A}\right) A^{-1}$ MeV [5] for neutrons (upper sign) and protons (lower sign) is used. The values of Δ obtained in our calculations differ from those in Refs. [6,7] within 0.1 MeV.

The momentum-dependent part of the single-particle Hamiltonian of the TCSM consists of the spin-orbit and

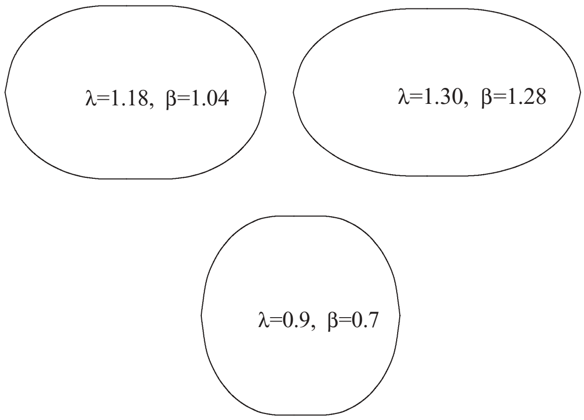

FIG. 1. Calculated nuclear shapes at indicated values of λ and β.

l^2-like terms (see Ref. [8]) with the parameters $\kappa_{n,p}$ and $\mu_{n,p}$, respectively. As known, these parameters depend on the nuclear mass number A and influence the quantum numbers of the last occupied single-particle level. To improve the description of the nuclear spins, we introduce the dependence on $(N-Z)$ in the parameters $\kappa_{n,p}$ and $\mu_{n,p}$. For the actinide and transactinide region, with $35 \leqslant N-Z \leqslant 56$, we suggest for neutrons

$$\begin{aligned}\kappa_n &= -0.076 + 0.0058(N-Z) - 6.53\times10^{-5}(N-Z)^2\\ &\quad + 0.002A^{1/3},\\ \mu_n &= 1.598 - 0.0295(N-Z) + 3.036\times10^{-4}(N-Z)^2\\ &\quad - 0.095A^{1/3},\end{aligned} \tag{1}$$

and for protons

$$\begin{aligned}\kappa_p &= 0.0383 + 0.00137(N-Z) - 1.22\times10^{-5}(N-Z)^2\\ &\quad - 0.003A^{1/3},\\ \mu_p &= 0.335 + 0.01(N-Z) - 9.367\times10^{-5}(N-Z)^2\\ &\quad + 0.003A^{1/3}.\end{aligned} \tag{2}$$

The parts in front of the terms with $A^{1/3}$ vary in the following intervals: (0.05–0.053) for κ_n, (0.88–0.92) for μ_n, (0.075–0.0768) for κ_p, and (0.58–0.61) for μ_p in the nuclei considered. Note that in the calculations with Woods-Saxon single-particle potential the dependence on $N-Z$ is included into the momentum-independent part of the potential. Here, with the Nilsson-type single-particle potential, the weak dependence on $N-Z$ is incorporated into the momentum-dependent part of the single-particle Hamiltonian. With Eqs. (1) and (2), we are able to describe correctly the ground-state spins of many heavy odd nuclei. The introduced dependence on $N-Z$ mainly supplies the better order of the single-particle levels near the Fermi surface in the ground state and has a minor influence on the potential energy surface as a function of deformation parameters.

III. CALCULATED RESULTS

To verify our approach, we calculated the energies of one- and two-quasiparticle states for the nuclei where they are well known. The discrepancy in energy between the calculated [9] and experimental one-quasiparticle states in actinides does not exceed 300 keV, which is quite satisfactory. The maximal disagreement between the calculated and experimental values of energies of two-quasiparticle states with $K^\pi = 8^-_\nu$ in the isotones from ^{176}Yb to ^{184}Pt ($N = 106$) does not exceed 200 keV (Fig. 2), which is quite satisfactory as well. Therefore, without the claim of high precision, one can describe the isotonic and isotopic trends in energy of quasiparticle states.

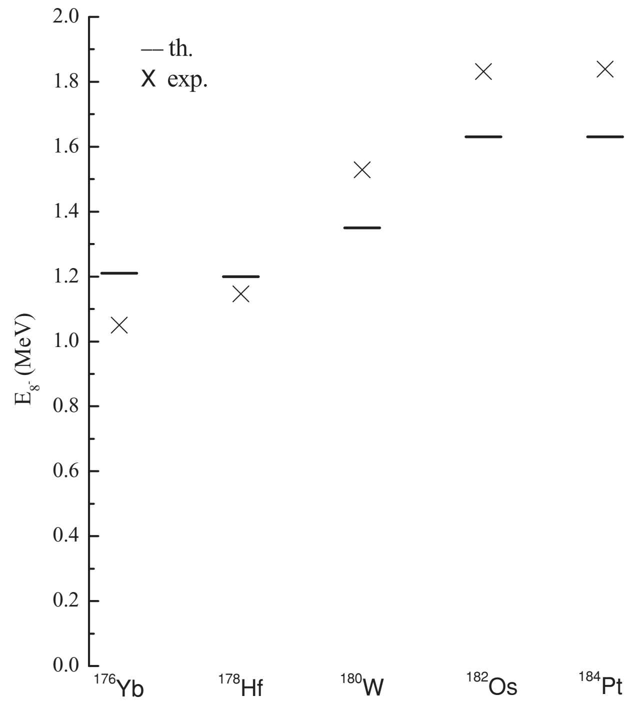

FIG. 2. Calculated (th) and experimental (exp) [18] energies E_{8^-} of two-quasiparticle states with $K^\pi = 8^-_\nu$ compared for the isotones from ^{176}Yb to ^{184}Pt.

The calculated energies of low-lying two-quasiparticle states with $K \geqslant 4$ in several even isotopes of Fm and No are compared with available experimental data [1,10–12] in Figs. 3 and 4. In a recent experiment [11], the state $8^-_\nu(9/2^-[734] \otimes 7/2^+[624])$ was observed in ^{250}Fm at 1.199 MeV, which is close to our result. In ^{256}Fm, the isomeric state $7^-_\pi(7/2^+[633] \otimes 7/2^-[514])$ is not the lowest one, and it is populated only in the β decay of ^{256}Es [10]. The direct production of ^{256}Fm seems to be possible only in transfer-type reactions. In ^{248}Fm, the relatively low-lying isomeric states with $K^\pi = 6^+_\nu$ and 7^-_ν are expected. In ^{242,244}Fm, the isomeric states with $K \geqslant 6$ are above 1.38 MeV, which is larger than the energies of the revealed K isomers in ^{252,254}No [1,12]. To observe these isomers, one should produce the neutron-deficient Fm isotopes with the statistics larger than those for the nuclei ^{252,254}No, which is, of course, time consuming.

While in ^{250,252}No the states related to the break of a neutron pair are much lower in energy than the states related to the break of a proton pair, in ^{244,246,254}No the lowest two-quasiparticle states are related to the break of a proton pair (Fig. 4). Because of the subshell closure at $N = 152$, the

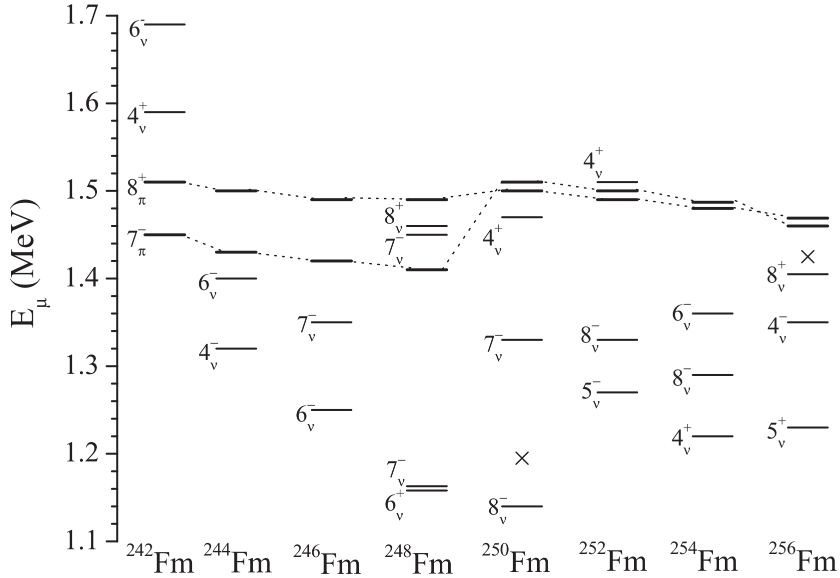

FIG. 3. Calculated energies of two-quasiparticle states in the indicated even isotopes of Fm. The states created by the break of proton and neutron pairs are shown by thick and thin lines, respectively. The available experimental data [10,11] are marked by X's.

energy of the lowest two-quasineutron isomer in ^{254}No is larger than that in ^{252}No. This is in a good agreement with available experimental data [1,12]. In ^{250}No, the two-quasineutron state 6^+ was attributed with the experimentally observed isomeric state [13]. The nucleus ^{256}No seems to be another good candidate for studying the low-lying isomeric states with $K^\pi = 8^-_\pi$.

To estimate the α-decay half-lives T_α, we use the expression

$$\log_{10} T_\alpha(Z, A) = 1.5372Z(Q_\alpha - E_\mu)^{-1/2} - 0.1607Z - 36.573,$$

recently suggested in Ref. [14], and the calculated value of Q_α for the treated α decay. Here, E_μ is the excitation energy of the quasiparticle state to which the α decay leads. If the α decay is accompanied by structure changes (transition from a two-quasiparticle to a rotational state), the obtained T_α is increased by two orders of magnitude [4]. If an α particle would carry out the angular momentum l, this α decay would be hindered by about a factor of $(3–4)^l$ [15]. Here, 4^l is used in our estimations. This hindrance is larger than the one resulting from the simple addition of the centrifugal part to the one-dimension potential barrier, because it takes into account the recoil effect and is consistent with the systematics in Ref. [16].

For ^{270}Ds, ^{266}Hs, ^{262}Sg, ^{258}Rf, and ^{254}No, the calculated values of Q_α for the ground-state to ground-state α decays are compared with the available experimental assignments [17–19] in Fig. 5, where the lowest two-quasiparticle states are shown. We underestimate the Q_α value for ^{266}Hs as in Refs. [7,20], resulting in $Q_\alpha = 9.69$ and 10.04 MeV, respectively. While we overestimate the value of Q_α for ^{254}No, Refs. [7,20] underestimate it. Therefore, our description

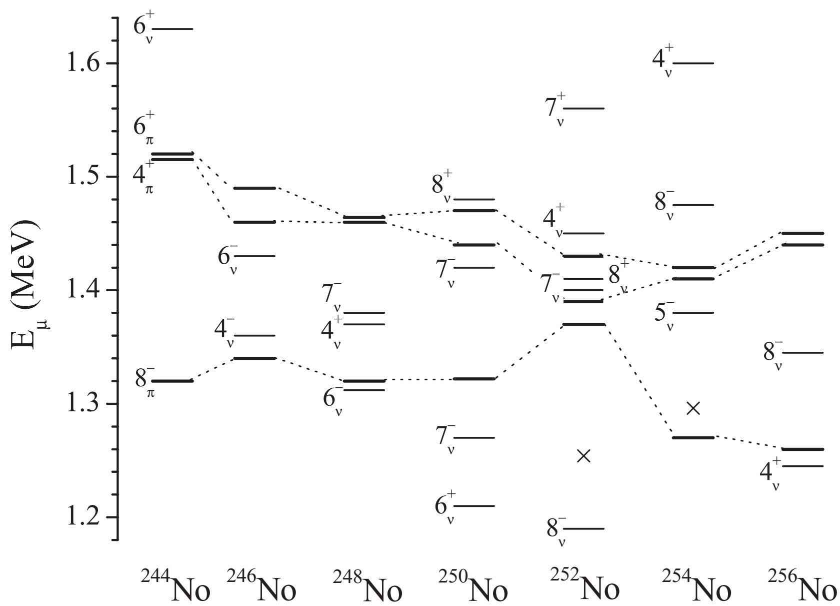

FIG. 4. Same as in Fig. 3, but for even isotopes of No. The available experiments are from Refs. [1,12].

TABLE I. Possible decay modes of indicated states of heavy nuclei. The calculated values of Q_α and half-lives T_α are listed along with the available experimental half-lives $T_{1/2}^{\rm exp.}$ and decay branches for α decay and spontaneous fission (SF) [18,19].

Nucleus	Decay mode	Q_α (MeV)	T_α	$T_{1/2}^{\rm exp.}$
^{270}Ds	$0^+_{\rm g.s.} \xrightarrow{\alpha} 0^+_{\rm g.s.}$	11.22	0.17 ms	0.1 ms, %$\alpha \approx 100$
	$0^+_{\rm g.s.} \xrightarrow{\alpha} 2^+_{\rm g.s.}$	11.17	3.3 ms	
	$10^-_\nu, 6^+_\nu \xrightarrow{\gamma's} 0^+_{\rm g.s.} \xrightarrow{\alpha} 0^+_{\rm g.s.}$	11.22		
	$10^-_\nu \xrightarrow{\alpha} 10^-_{K=1^-} \xrightarrow{\gamma's} 0^+_{\rm g.s.}$	11.3	10 ms	
	$6^+_\nu \xrightarrow{\alpha} 6^+_{\rm g.s.} \xrightarrow{\gamma's} 0^+_{\rm g.s.}$	12.05	0.3 ms	
	$6^+_\nu \xrightarrow{\alpha} 4^+_{\rm g.s.} \xrightarrow{\gamma's} 0^+_{\rm g.s.}$	12.25	2 ms	
	$6^+_\nu \xrightarrow{\alpha} 2^+_{\rm g.s.} \xrightarrow{\gamma} 0^+_{\rm g.s.}$	12.35	16.5 ms	
	$6^+_\nu \xrightarrow{\alpha} 6^+_\nu$	10.98	0.6 ms	
^{266}Hs	$0^+_{\rm g.s.} \xrightarrow{\alpha} 0^+_{\rm g.s.}$	10.1	37 ms	2.3 ms, %$\alpha \approx 100$
	$9^-_\nu, 4^-_\nu \xrightarrow{\gamma's} 0^+_{\rm g.s.} \xrightarrow{\alpha} 0^+_{\rm g.s.}$	10.1		
	$9^-_\nu \xrightarrow{\alpha} 9^-_{K=1^-} \xrightarrow{\gamma's} 0^+_{\rm g.s.}$	10.33	530 ms	
	$4^-_\nu \xrightarrow{\alpha} 4^-_{K=1^-} \xrightarrow{\gamma's} 0^+_{\rm g.s.}$	10.7	67 ms	
^{262}Sg	$0^+_{\rm g.s.} \xrightarrow{\alpha} 0^+_{\rm g.s.}$	9.45	250 ms	6.9 ms, %SF $\geqslant 78$
	$5^-_\pi, 5^+_\nu \xrightarrow{\gamma's} 0^+_{\rm g.s.} \xrightarrow{\rm SF}$			
	$5^-_\pi, 5^+_\nu \xrightarrow{\rm SF}$			
^{258}Rf	$0^+_{\rm g.s.} \xrightarrow{\alpha} 0^+_{\rm g.s.}$	9.4	72 ms	14.7 ms, %$\alpha \approx 31 \pm 11$,
	$4^+_\nu, 8^-_\nu \xrightarrow{\gamma's} 0^+_{\rm g.s.} \xrightarrow{\rm SF,\alpha}$			$T_\alpha^{\rm exp.} = 47^{+24}_{-12}$ ms
	$4^+_\nu, 8^-_\nu \xrightarrow{\rm SF}$			
	$4^+_\nu \xrightarrow{\alpha} 4^+_{\rm g.s.} \xrightarrow{\gamma's} 0^+_{\rm g.s.}$	10.51	11 ms	
^{254}No	$0^+_{\rm g.s.} \xrightarrow{\alpha} 0^+_{\rm g.s.}$	8.45	9.4 s	51 s, %$\alpha \approx 90$
	$8^-_\pi \xrightarrow{\gamma's} 0^+_{\rm g.s.} \xrightarrow{\alpha} 0^+_{\rm g.s.}$			

of Q_α seems to be satisfactory. The most probable decay modes are presented in Table I. There are the lowest two-quasineutron isomeric states $10^-_\nu(11/2^-[725] \otimes 9/2^+[604])$ and $6^+_\nu(11/2^-[725] \otimes 1/2^-[761])$ in ^{270}Ds. One can expect the γ transitions from these isomeric states to the ground state with subsequent α decays. The event number 2 in Ref. [17] can be attributed to this possibility and also to the α decay from the $0^+_{\rm g.s.}$ state of ^{270}Ds to the $2^+_{\rm g.s.}$ state of ^{266}Hs.

Analyzing the possible α decays from the isomers 10^-_ν and 6^+_ν in ^{270}Ds, we propose that the most probable α decays occur either to the 10^- states of the $K^\pi = 1^-$ band or to the states 2^+, 4^+, and 6^+ of the ground-state rotational band of ^{266}Hs. The energies of rotational states are estimated as in Ref. [21]. These α decays can be related to the event numbers 7 and 8 in Ref. [17] since they correspond to similar Q_α and T_α. For the reliable check of the calculated results, an experiment with better statistics is desirable. One can see in Fig. 5 and Table I that the α decay of ^{270}Ds from the 6^+_ν state to the same state in ^{266}Hs is possible. However, in ^{266}Hs, the isomer 6^+_ν rapidly decays into the low-lying states, and the continuation of the α-decay chain via the isomeric states is impossible.

Another example of a possible α-decay chain starting from a K isomer is given in Fig. 6 for the case of ^{268}Ds as a head of the α-decay chain. In ^{268}Ds, the estimated half-lives of the $E4$ transition from $4^+_\nu(7/2^+[613] \otimes 1/2^+[620])$ to $0^+_{\rm g.s.}$ and the $E1$ transition from $8^+_\nu(7/2^+[613] \otimes 9/2^+[604])$ to $9^-_\nu(7/2^+[613] \otimes 11/2^-[725])$ are larger than 60 μs. The α decays from 9^-_ν and 8^+_ν states populate the rotational states $9^-_{\rm g.s.}$ and $8^+_{\rm g.s.}$, respectively, in ^{264}Hs. The α decays from the K isomers 4^+_ν and 8^+_ν of ^{268}Ds (Table II) can occur because the corresponding values of T_α are shorter than the estimated half-lives with respect to the fission and γ transitions.

As seen in Table II, the α decay from the K isomer $8^-_\nu(9/2^-[734] \otimes 7/2^+[613])$ of ^{264}Hs (^{260}Sg) to the same state in ^{260}Sg (^{256}Rf) has properties similar to those of the ground-state to ground-state α decay. The α decays from the isomer 8^-_ν of ^{264}Hs (^{260}Sg) to the rotational levels of ^{260}Sg (^{256}Rf) are unfavorable. In ^{264}Hs, ^{260}Sg, and ^{256}Rf, the γ emission from 8^-_ν to the lower states $5^+_\nu(3/2^+[622] \otimes 7/2^+[613])$, 4^+_ν, and $5^-_\nu(9/2^-[734] \otimes 1/2^+[620])$, respectively, needs more than 1 s. Note that in Figs. 5 and 6 the energies of two-quasiproton states in ^{260,262}Sg differ because of the small difference in the ground-state deformations obtained. In ^{256}Rf, the time

TABLE II. Possible decay modes of indicated states of heavy nuclei. The calculated values of Q_α and half-lives T_α are listed along with the available experimental half-lives $T_{1/2}^{\mathrm{exp.}}$ and decay branches for α decay and spontaneous fission (SF) [18].

Nucleus	Decay mode	Q_α (MeV)	T_α	$T_{1/2}^{\mathrm{exp.}}$
^{268}Ds	$0^+_{\mathrm{g.s.}} \xrightarrow{\alpha} 0^+_{\mathrm{g.s.}}$	11.8	9.4 μs	
	$4^+_\nu \xrightarrow{\alpha} 4^+_{\mathrm{g.s.}}$	12.86	8 μs	
	$9^-_\nu \xrightarrow{\alpha} 9^-_{\mathrm{g.s.}} \xrightarrow{\gamma's} 0^+_{\mathrm{g.s.}}$	12.07	0.26 ms	
	$8^+_\nu \xrightarrow{\alpha} 8^+_{\mathrm{g.s.}} \xrightarrow{\gamma's} 0^+_{\mathrm{g.s.}}$	12.71	15 μs	
^{264}Hs	$0^+_{\mathrm{g.s.}} \xrightarrow{\alpha} 0^+_{\mathrm{g.s.}}$	10.53	1.7 ms	$\approx$ 0.8 ms, %$\alpha \approx$ 50, %SF $\approx$ 50
	$8^-_\nu \xrightarrow{\alpha} 8^-_\nu$	10.508	1.9 ms	
	$5^+_\nu \xrightarrow{\alpha} 4^-_{K=1^-} \xrightarrow{\gamma's} 0^+_{\mathrm{g.s.}}$	11.04	55 ms	
	$8^-_\nu \xrightarrow{\alpha} 8^-_{K=1^-} \xrightarrow{\gamma's} 0^+_{\mathrm{g.s.}}$	10.87	27 ms	
^{260}Sg	$0^+_{\mathrm{g.s.}} \xrightarrow{\alpha} 0^+_{\mathrm{g.s.}}$	9.81	26 ms	3.6 ms, %$\alpha \approx$ 50, %SF $\approx$ 50
	$8^-_\nu \xrightarrow{\alpha} 8^-_\nu$	9.92	13.4 ms	
	$4^+_\nu \xrightarrow{\alpha} 4^+_{\mathrm{g.s.}} \xrightarrow{\gamma's} 0^+_{\mathrm{g.s.}}$	11.04	2.7 ms	
^{256}Rf	$0^+_{\mathrm{g.s.}} \xrightarrow{\alpha} 0^+_{\mathrm{g.s.}}$	9	1 s	6.4 ms, %$\alpha \approx$ 0.32, %SF $\approx$ 99.68
	$8^-_\nu \xrightarrow{\alpha} 8^-_\nu$	9.12	0.45 s	
^{252}No	$0^+_{\mathrm{g.s.}} \xrightarrow{\alpha} 0^+_{\mathrm{g.s.}}$	8.4	13.6	2.4 s, %α > 66.7, %SF = 32.2
	$8^-_\pi \xrightarrow{\gamma's} 0^+_{\mathrm{g.s.}} \xrightarrow{\alpha}$	8.4		

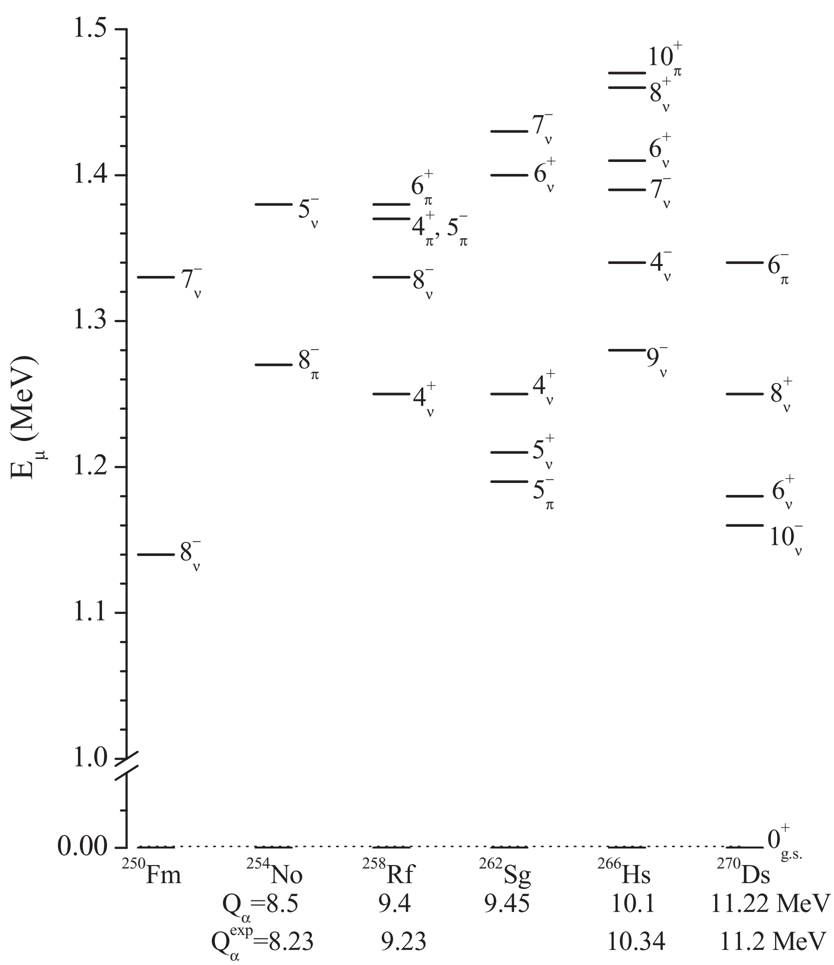

FIG. 5. Calculated energies of low-lying two-quasiparticle states in the indicated nuclei of the α-decay chain of ^{270}Ds. The calculated values of Q_α are compared with available experimental data [17–19].

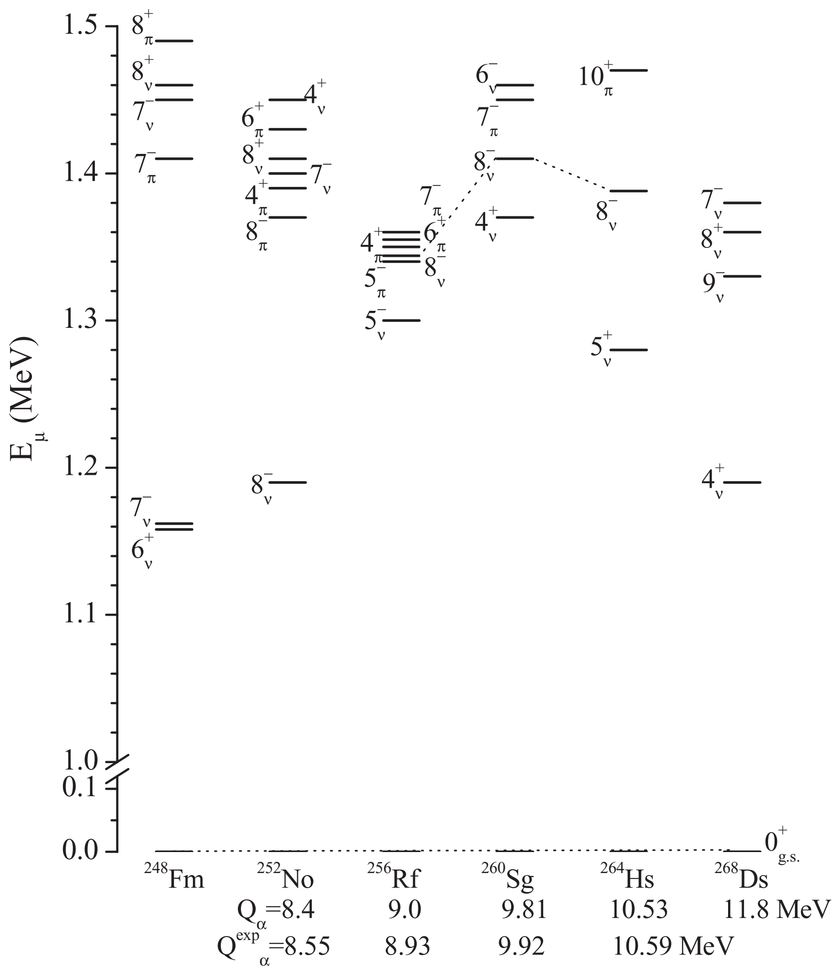

FIG. 6. Same as in Fig. 5, but for the nuclei of the α-decay chain of ^{268}Ds. The possible isomer-isomer α decays are traced by dashed lines. The experimental values of Q_α are from Ref. [18].

of γ emission to the ground-state band from the isomer 8^-_ν seems to be shorter than the time of α decay. Therefore, the α-decay chain starting from the 8^-_ν states in ^{264}Hs can be ended by γ emission from the 8^-_ν state of ^{256}Rf with sequential fission or α decay from the ground state. This interesting finding demonstrates the possibility of an α-decay chain via the isomeric states. One can suggest the experimental verification of this phenomenon by using the complete fusion reaction ^{58}Fe + ^{207}Pb to produce ^{264}Hs in the isomer $K^\pi = 8^-_\nu$ state. The γ transition from the isomeric state to the ground state of ^{256}Rf is a good indication of the α-decay chain through K isomers. The γ emissions from the isomeric states $5^+_\nu(3/2^+[622] \otimes 7/2^+[613])$ of ^{264}Hs and $4^+_\nu(1/2^+[620] \otimes 7/2^+[613])$ of ^{260}Sg are more probable than the α decays. In ^{252}No and ^{248}Fm, the decays of K isomers through the cascade of γ quanta seem to be dominant.

In the isotones ^{252}Fm, ^{254}No, and ^{256}Rf with $N = 152$, the low-lying two-quasineutron states are similar (Figs. 3, 4, and 6). If the isomers 5^-_ν and 8^-_ν would be revealed in one of these nuclei, they should also be in others. In ^{252}Fm ($4n$ channel of the ^{18}O + ^{238}U reaction), the γ transitions from these isomeric states are expected. The recent experiment [22] revealed that the two lowest isomeric states in ^{256}Rf at $E_\mu \approx$ 1.12 and 1.395 MeV have $K \approx 6$ or 7 and 10, respectively, which is in conformity with our results in Fig. 6.

In the isotones ^{250}Fm, ^{252}No, ^{254}Rf, and ^{256}Sg with $N =$ 150, the low-lying 8^-_ν states exist. In ^{252}No, the lifetime 110 ± 10 ms of 8^-_ν state is about 20 times smaller than the corresponding lifetime in ^{250}Fm [11,12]. If the same trend is assumed toward larger Z, the half-life of the 8^-_ν state in ^{254}Rf would be about 1 ms. For ^{254}Rf, a spontaneous fission activity with $T_{1/2} = 0.5$ ms was reported in Ref. [23]. However, this result was not confirmed in Ref. [24], where $T_{1/2} = 23$ μs was revealed. The population of the 8^-_ν isomer in the ^{50}Ti + ^{206}Pb reaction can be shielded by the population of nearby short-lived states, for example, the 5^-_π state.

The ground-state spontaneous fission half-life of ^{252}Rf is expected to be 0.65 μs [25], which is too short to be detected. Nevertheless, if some fission activity would be observed in the reaction ^{50}Ti + ^{204}Pb→^{252}Rf + $2n$, it can be only related to the K isomer 6^+_ν [26] existing also in the neighboring isotones ^{250}No [13]. This experiment would help to reveal the change of half-lives of K isomers in the isotones of heavy nuclei.

Typically the isomers of interest exist at $E_{\rm is} = 1.2$–1.3 MeV with respect to the ground state. In the cold fusion reactions, the maxima of quite narrow excitation functions of the $1n$ evaporation channel correspond to the excitation energies $E^*_{\rm CN} = 11$–15 MeV. The Coulomb barrier shields the fusion at lower energies. In this case, the ratio $w = W_{\rm sur}(E^*_{\rm CN} -$

$E_{\rm is})/W_{\rm sur}(E^*_{\rm CN})$ of the survival probabilities in the isomer and ground states is about 2 as follows from our calculations [27]. The states $8^+_{\rm g.s.}$ and $10^+_{\rm g.s.}$ of the ground-state rotational band have energies $E_{\rm rot} = 0.5$ and 0.8 MeV, respectively, [21]. The probability of the population of an isomeric state in the excited nucleus is found to be

$$p_{\rm is} = \frac{\exp[-(E_{\rm is} - E_{\rm rot})/T]}{1 + \exp[-(E_{\rm is} - E_{\rm rot})/T]} \approx 0.32,$$

where T is the thermodynamics temperature. The ratio of the cross sections for producing the evaporation residue in the isomeric state and in the ground state is $\sigma_{\rm ER}(\text{is})/\sigma_{\rm ER}(\text{g.s.}) = wp_{\rm is}/(1 - p_{\rm is})$, i.e. about 0.64/0.68 at $E_{\rm is} = 1.2$ MeV. Indeed, the experiment [17] reveals that the cross section is approximately shared equally between the ground state and the isomeric state in the $1n$ channel. If the nucleus is produced in xn ($x > 1$) evaporation channel, $w \approx 1$ because the excitation function is quite broad. In the case of $x = 2$ and $E^*_{\rm CN} = 20$–24 MeV, we get $p_{\rm is} \approx 0.35$ (0.31) and $\sigma_{\rm ER}(\text{is})/\sigma_{\rm ER}(\text{g.s.}) \approx 0.35/0.65$ (0.31/0.69) at $E_{\rm is} = 1.2$ (1.3) MeV; i.e., the population of the isomeric state in the evaporation residue is about 50% of the ground-state population. This agrees well with the experimental data [12]. If several K isomers are close in energy to each other, the fraction of the isomeric state is shared between them.

IV. SUMMARY

In conclusion, the modified TCSM is suitable for describing some properties of heaviest nuclei and predicting the isotopic trends of isomeric states. The nuclei ^{248,252}Fm, ^{256}No, and ^{262}Sg produced in the reactions ^{20}Ne + ^{232}Th, ^{12}C + ^{248}Cm, ^{22}Ne + ^{238}U, and ^{18}O + ^{249}Cf seem to be next good candidates for studying the low-lying K isomers. The experimental search of a K isomer in the neighboring isotones is desirable. The experiment on the search of spontaneous fission from the K isomeric state 6^+_ν in ^{252}Rf is suggested. Some calculated α decays from the isomeric states of ^{270}Ds can be related to the measured ones [17]. The knowledge of α- and γ-decay modes of the$K$ isomer is important for the correct identification of superheavy nuclei. An interesting finding is that the α-decay chain ^{264}Hs$\to$^{260}Sg$\to$^{256}Rf over the isomeric states 8^-_ν seems to be observable. In the ^{58}Fe + ^{207}Pb reaction, the 8^-_ν isomeric state in ^{264}Hs seems to be populated with the cross section $0.25\sigma_{\rm ER}(\text{g.s.})$.

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