Quasiparticle structure of superheavy nuclei in α-decay chains of ^{285}Fl and ^{291,293}Lv

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Abstract: Two mean-field potentials, Woods-Saxon and Skyrme based potentials, are used to calculate the energies of low-lying one-quasiparticle states. The spectra of the low-lying states and the α-decay spectra of nuclei belonging to the α-decay chains of ^{285}Fl and ^{291,293}Lv are calculated and compared with the available experimental data. Dependence of the splitting of the pseudospin doublets and of the energies of the unique parity neutron one-quasiparticle states on the mean field potential are discussed. As shown, the α-decay spectra could be different in the α-decay chain and at the direct production of the nucleus in a fusion reaction.

Keywords: structure of superheavy nuclei, α-decay chain, WS potential, SHF approach

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1 Introduction

The recent success in the synthesis of superheavy nuclei has opened the possibilities of studying their structure and of tracing shell evolution in the region of the heaviest nuclei [1–8]. The structure of superheavies is shown to be crucial for estimating the evaporation residue cross sections [9] and is of interest to be studied [10–25]. The identification of superheavy nuclei occurs by the α-decay chains. While some heaviest nuclei emit α-particles of one energy, others have several lines in the α-decay spectrum. The last indicates the existence of various open channels for α-decay related to the structure of the daughter nucleus and the presence of isomeric states in the mother nucleus. So, the prediction of α-decay spectra is important for the analysis of experimental data. The α-decay spectra of the nucleus could be different in the α-decay chain and at its direct production in fusion reaction. While some isomeric states cannot be populated in the α-decay chain, they show up in the evaporation residues.

The microscopic methods, which are used to study the structures of the heaviest nuclei, are the self-consistent approaches (non-relativistic and relativistic) [26–30] based on some parametrization of energy-density functional and the microscopic-macroscopic methods in which the parameters are introduced to write down the single-particle potential and to find the macroscopic part of potential energy.

In Refs. [31–34], the quasiparticle structure was studied with the microscopic-macroscopic approach based on the two-center shell model [35]. As shown in Ref. [36], the quasiparticle spectra obtained with this approach differ from those obtained with the self-consistent methods. However, the integral values as binding energies and Q_α-values for ground-state–to–ground-state α-decays could be close in different methods. Thus, a detailed study of the α-decay spectra and γ-transitions could help us to validate the microscopic method. For nuclei beyond Cn, α-decay studes are presently the only method to investigate nuclear structure because γ-spectroscopy requires larger yields of these nuclei.

In this work we compare the quasiparticle structures calculated with the self-consistent method and those calculated with the phenomenological Woods-Saxon (WS) single-particle potential at nuclear deformation found from the minimization of the sum of microscopic and macroscopic potential energies. The Skyrme-Hartree-Fock (SHF) approach results in a mean-field potential close to the Woods-Saxon form. The study of the α-decay chains with various well-established microscopic methods should elucidate the crucial observable to validate the given method.

2 Models

In the present paper the calculations are performed

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with the WS [37–39] and the microscopic SHF mean field potentials [40–42]. These potentials are used to investigate the excitation spectra of the odd-neutron nuclei belonging to the α-decay chains of ^{285}Fl and ^{291,293}Lv. The SHF potential is obtained with the Skyrme force SV-bas [43]. It is important for our aims that the fit of these forces involves the binding energies and Q_α values of heavy and superheavy nuclei. The calculations are performed with the code SKYAX [44]. The pairing is treated with the surface (density dependent) delta-force [45, 46] at the BCS approximation. The parameters of the WS potential have been fitted to achieve a better description of the properties of the known heavy nuclei [38, 39]. The equilibrium deformations are calculated by minimizing the sum of microscopic and macroscopic parts of potential energy [47, 48]. The monopole pairing is taken into consideration and treated in the BCS approximation with constant interaction strength.

In both WS and SHF approaches the excitation spectra are calculated in the independent quasiparticle approximation. Taking into account the present experimental and theoretical status of the spectroscopy of superheavy nuclei, this level of analysis looks quite satisfactory. In the WS and SHF approaches, the α-decay energies for the ground-state–to–ground-state transitions are obtained using the calculated ground state binding energies. This combination of the microscopic models makes the study more robust and allows us to reveal the variety of possible α- and γ- transitions.

The calculated equilibrium quadrupole deformations of nuclei belonging to the α-decay chains of ^{285}Fl and ^{291,293}Lv are listed in Table 1. As seen, the single-particle potentials used in the paper result in a smooth increase of the quadrupole deformation along the α-decay chains. The values of the quadrupole deformation in Lv and Fl isotopes are roughly equal to the amplitudes of the zero-point fluctuations in typical spherical nuclei. However, the calculations show sufficiently deep potential minima in these nuclei, 3–5 MeV. At the same time, the depth of the prolate and oblate minima are quite close in energy to each other. The WS single particle potential was used in our previous calculations to determine the one-quasiparticle spectra of odd-proton and odd-neutron nuclei with $Z \approx 100$ [49, 50]. The properties of the SHF potential are discussed in [43].

Using the calculated Q_α-value and the phenomenological expression from Ref. [51], one can estimate the half-life time T_α for α-decay.

Table 1. The calculated ground-state quadrupole deformations of nuclei in the α-decay chains of ^{285}Fl and ^{291,293}Lv. The results obtained with the WS and SHF methods are presented.

method	^{285}Fl	^{281}Cn	^{277}Ds	^{273}Hs	^{269}Sg	^{265}Rf	
WS	0.14	0.16	0.20	0.22	0.23	0.24	
SHF	0.15	0.18	0.22	0.24	0.25	0.26	
method	^{291}Lv	^{287}Fl	^{283}Cn	^{279}Ds	^{275}Hs	^{271}Sg	^{267}Rf
WS	0.09	0.13	0.16	0.19	0.21	0.23	0.20
SHF	0.11	0.13	0.16	0.19	0.23	0.24	0.25
method	^{293}Lv	^{289}Fl	^{285}Cn	^{281}Ds	^{277}Hs		
WS	0.09	0.10	0.14	0.18	0.20		
SHF	0.09	0.12	0.14	0.16	0.22		

3 One-quasiparticle spectra

The SHF one-quasineutron spectra for nuclei belonging to the α-decay chains of ^{285}Fl, ^{291,293}Lv are presented in Figs. 1–3. The WS spectra for the same nuclei are shown in Figs. 4–6. An interesting characteristic of these spectra is a splitting of the pseudospin doublets [52, 53]. There are four neutron pseudospin doublets located below 1 MeV excitation energy in the considered nuclei: 5/2[613]–3/2[611], 11/2[606]–9/2[604], 3/2[622]–1/2[620], 7/2[604]–5/2[602]. In the single-particle scheme of the WS potential the splitting of these doublets is equal to several hundreds of keV, although in some cases the splitting does not exceed 200 keV. In the single particle scheme of the SHF approach the splitting of the doublets 3/2[622]–1/2[620] and 7/2[604]–5/2[602] is smaller than 100 keV. The splitting of the doublet 11/2[606]–9/2[604] in many cases is around 100 keV, but can also reach 600 keV. The splitting of the doublet 5/2[613]–3/2[611] does not exceed 200 keV. Nuclear alpha-decay is known to be strongly influenced by pair correlations. For instance, the probability of the ground-state-to-ground-state alpha-decay is enhanced by about two orders of magnitude in comparison to the shell model results obtained without pairing. An appearance of the pseudospin doublets introduces some inhomogeneity to the single-particle spectra. Because the pair correlations are sensitive to the density of the single-particle states near the Fermi surface, this inhomogeneity can be the source of variation of the pairing. It could decrease the alpha-decay probability between the ground states and increase the decay probability from the ground state to the excited states.

An interesting feature of the single-particle spectra of nuclei under consideration is a behavior of the unique-parity neutron orbits 15/2[707] and 13/2[716] which originate from the $n1j_{15/2}$ state. The behavior of the unique-parity orbits is similar in both single-particle potentials.

If we compare the spectra of low-lying one-quasiparticle states of nuclei belonging to the α-decay chains of ^{285}Fl, ^{291,293}Lv, we find some similarities and also some differences. The low-lying spectra of Lv, Fl isotopes and of ^{281}Cn are rather different. However, the low-lying spectra of Ds and Hs are quite similar, although there are some differences in the order of levels.

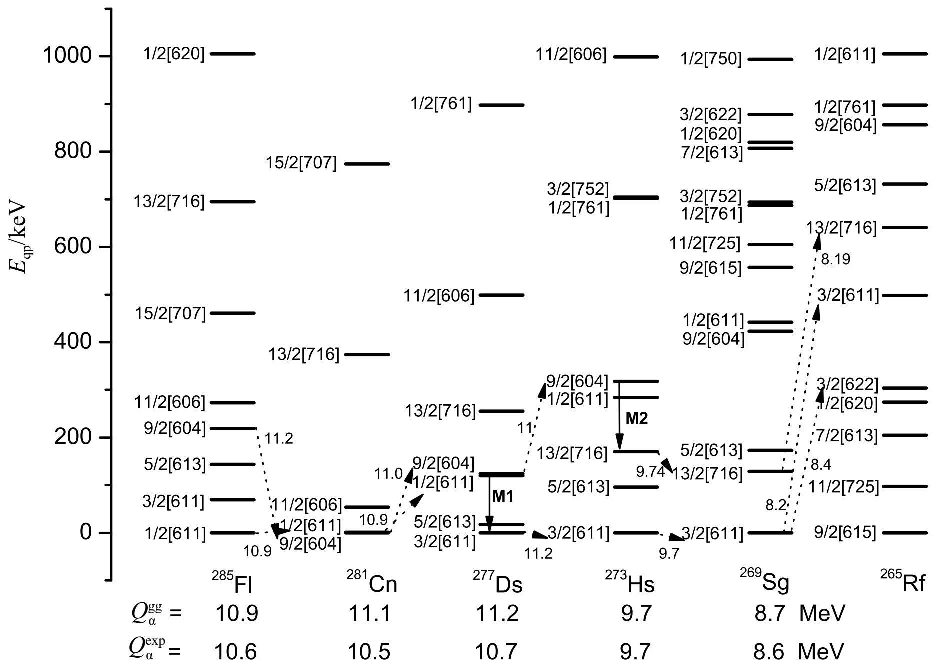

Fig. 1. The neutron one-quasiparticle spectra calculated within the SHF approach for the nuclei of the α-decay chain of ^{285}Fl. $Q_\alpha^{\rm gg}$ is the α-decay energy for the ground-state-to-ground-state transition. $Q_\alpha^{\rm exp}$ is the experimental α-decay energy [54, 55].

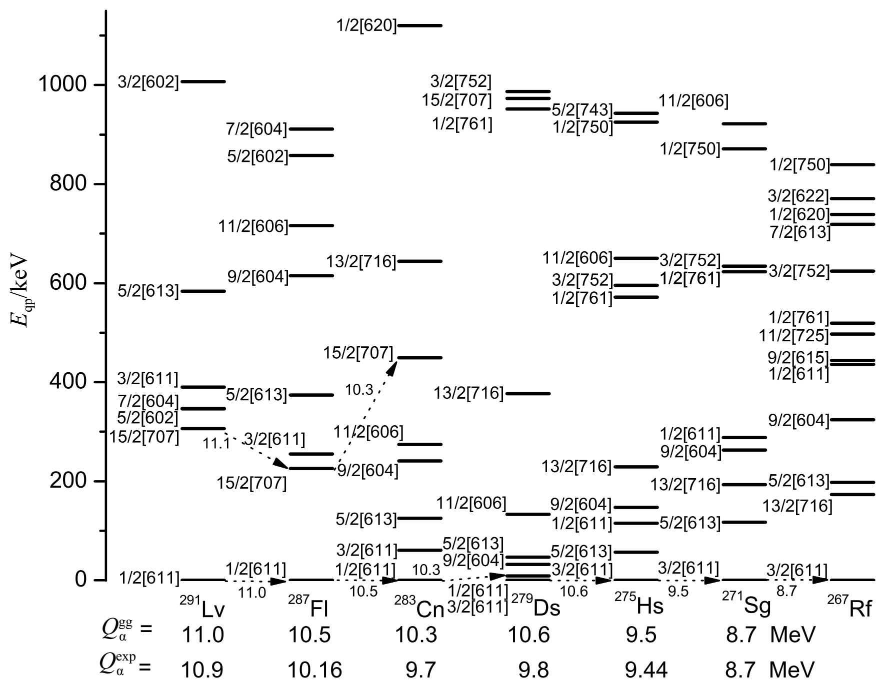

Fig. 2. The same as in Fig. 1, but for the nuclei of the α-decay chain of ^{291}Lv. $Q_\alpha^{\rm exp}$ is the experimental α-decay energy [56].

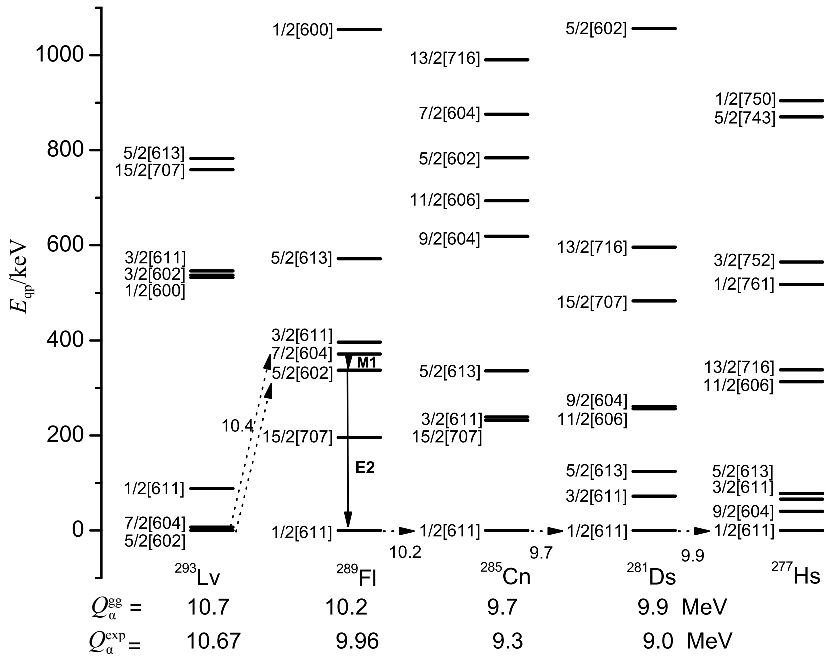

Fig. 3. The same as in Fig. 1, but for the nuclei of the α-decay chain of ^{293}Lv. $Q_\alpha^{\rm exp}$ is the experimental α-decay energy [57, 58].

4 α-decay chain of ^{285}Fl

Taking into account the possibility of the E1, E2, M1, and M2 γ-transitions between the excited states of the considered nuclei whose half-life times are shorter than the characteristic times T_α of the α-decays, and keeping only α-decays with the shortest lifetimes, we have analyzed α-decay spectra and possible γ-transitions in nuclei of the α-decay chain of ^{285}Fl. The most probable α-decays are marked in Figs. 1 and 4 for the SHF based and WS potentials together with the available experimental Q_α. The α-decays keeping the quantum numbers of the odd neutron are mainly taken into account. The probabilities of the allowed γ-transitions are estimated using the selection rules for the asymptotic quantum numbers. To verify these estimates we calculated the half-lives for γ-transitions in the framework of the Quasiparticle-Phonon Model [37] as well.

The SHF-based calculations provide us the nuclear binding energies and Q_α values for the ground-state–to–ground-state α-decays. In the case of the WS-based calculations, the Q_α values for the ground-state–to–ground-state α-decays are found as in Ref. [34], where the microscopic-macroscopic approach has been used. The Q_α values for the ground-state–to–ground-state transitions found in both approaches are presented in Figs. 1–6.

As seen in Fig. 1, the state 9/2[604] could be the isomeric state in ^{285}Fl from which the α-decay can occur with $T_\alpha \approx 3$ ms, because the E2 transition to the state 5/2[613] is strongly suppressed. Within the WS approach the state 15/2[707] goes down to become the isomeric state in Fig. 4. While in the SHF approach the isomeric state 1/2[611] is predicted in ^{281}Cn, in the WS approach the state 11/2[606] is expected to be the isomeric one (Fig. 4). The ground and isomeric states of ^{281}Cn are expected to be populated in the α-decay chain of ^{285}Fl. In Fig. 1, the α-decays of ^{281}Cn from the states 9/2[604] and 1/2[611] go to the states with the same quantum numbers in ^{277}Ds. The M1 transition from the 1/2[611] state brings ^{277}Ds to the ground state. The E2 transition from the 9/2[604] state requires a longer time than the indicated α-decay with $Q_\alpha \approx 11$ MeV and $T_\alpha \approx 0.5$ ms. Within the WS approach (Fig. 4) the α-decay of ^{281}Cn from the isomeric 11/2[606] state is forbidden because the 11/2[606] state in ^{277}Ds lies at quite high energy. So, the α-decay from this state likely populates either the ground or isomeric 3/2[611] state in ^{277}Ds after some γ-transitions. The α-decay of ^{277}Ds can occur from the isomeric and ground state (Figs. 1 and 4). In the SHF and WS approaches the ground 3/2[611] and isomeric 13/2[716] states of ^{273}Hs are populated in the α-decay chain of ^{285}Fl (Figs. 1 and 4). The α-decays from these states populate the corresponding states in ^{269}Sg from which the α-decays with $T_\alpha > 410$ s occur and compete with the spontaneous fission. The α-decay of ^{265}Rf would need a few hours while the spontaneous fission requires about 1 minute and interrupts the α-decay chain. The calculated values of Q_α seem to be close to the experimental data [54, 55]. As seen in Figs. 1 and 4, all expected isomeric states can be populated in the nuclei of the α-decay chain of ^{285}Fl.

5 α-decay chain of ^{291}Lv

Let us consider the α-decay of ^{291}Lv. In the case of the SHF calculations we assume that the ground state 1/2[611] and the isomeric state 15/2[707] with E_{qp}=306 keV are populated in ^{291}Lv (Fig. 2). The allowed α-decays populate the ground state 3/2[611] of ^{287}Fl with Q_α=11.0 MeV and the isomeric state 15/2[707] with Q_α=11.8 MeV. The experimental Q_α is 10.9 MeV [56]. In the WS-based calculations (Fig. 5), there are also two α-decay lines from the very close 5/2[602] (ground state) and 1/2[620] one-quasiparticle states to the states with the same quantum numbers in ^{287}Fl where they are very close in energy as well. The values of Q_α for these transitions are about 10.5 MeV, which is consistent with the experimental data [56]. However, there is no isomeric state in ^{287}Fl (Fig. 5). This nucleus decays from the ground state into the 3/2[611] state of ^{283}Cn. Because of the strong M1 transition, ^{283}Cn jumps from this 3/2[611] state to the ground state.

In the SHF calculations, the ground state 1/2[611] of ^{287}Fl decays to the ground state of ^{283}Cn with Q_α=10.5 MeV (Fig. 2). The α-decay from the isomeric state 15/2[707] with Q_α=10.25 MeV and $T_\alpha\approx$0.5 s cannot be excluded. However, in ^{283}Cn the state 15/2[707] decays by M2, M1, and E2 transitions through several intermediate states to the ground state (Fig. 2). The experimental value of Q_α for ^{287}Fl is 10.16 MeV [56].

As seen in Figs. 2 and 5, the α-decay of ^{283}Cn occurs only from the ground state. The isomeric state 11/2[606] predicted in Fig. 5 could play a role in the direct production of ^{283}Cn. In the SHF- and WS-based calculations (Figs. 2 and 5), the α-decay of ^{279}Ds occurs only from the ground state. The α-decay of ^{279}Ds from the isomeric 9/2[604] state predicted in Fig. 2 could be only at the direct production of this nucleus.

In the SHF calculations (Fig. 2) there is only one line in the α-decay spectrum of ^{275}Hs to the ground state of ^{271}Sg, Q_α=9.5 MeV. Therefore, the α-decay spectrum of ^{271}Sg would have only one line as well. In the WS calculations (Fig. 5), the α-decay of ^{275}Hs from the isomeric state 3/2[611] with Q_α=9.5 MeV and $T_\alpha\approx$0.9 s cannot be excluded. The α-decay of ^{275}Hs from the ground state and following the M2 transition results in the population of the isomeric state 13/2[716] in the daughter nucleus ^{271}Sg. So, the existence of two lines in the α-decay spectrum of ^{275}Hs (Fig. 5) results in the two lines in the α-decay spectrum of ^{271}Sg. At Q_α=8.7 MeV in ^{271}Sg the T_α is estimated as 43 s, which is consistent with the experimental value of 2.4 minutes. The α-decay chain of ^{291}Lv is interrupted by the spontaneous fission of ^{267}Rf.

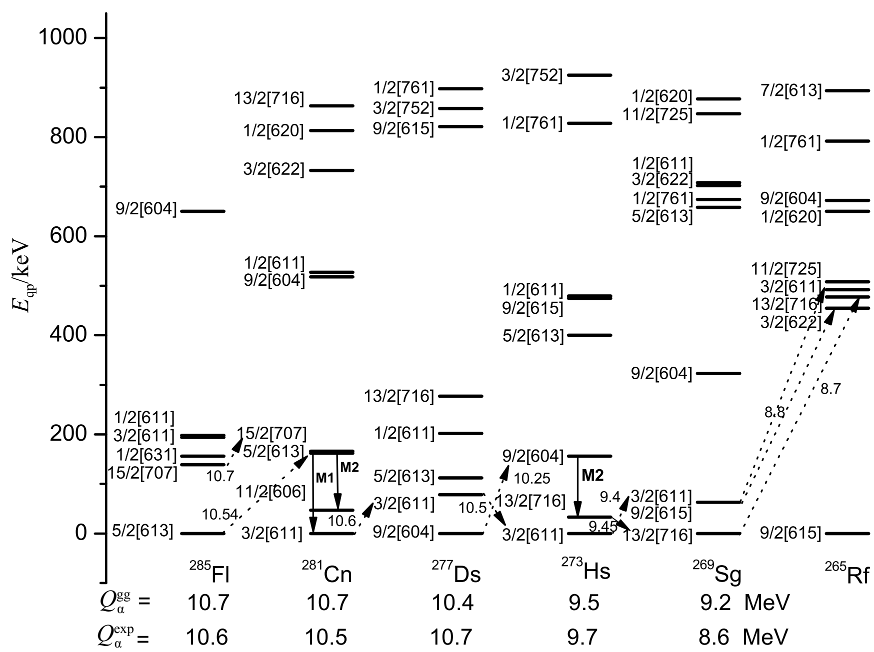

Fig. 4. The neutron one-quasiparticle spectra calculated within the WS approach for the nuclei of the α-decay chain of ^{285}Fl. Q_α^{gg} is the α-decay energy for the ground-state–to–the ground-state transition. Q_α^{exp} is the experimental α-decay energy [54, 55].

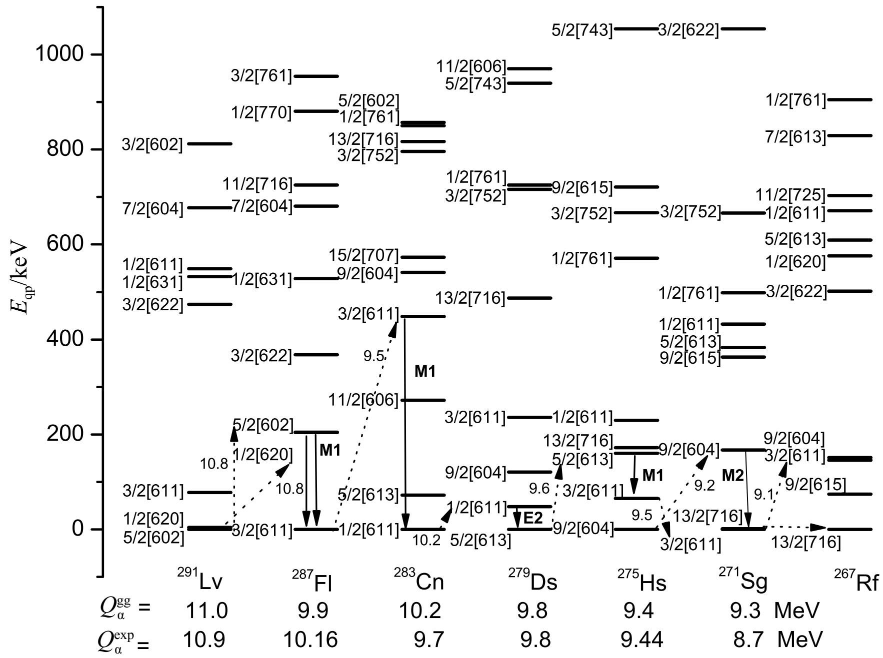

Fig. 5. The same as in Fig. 4, but for the nuclei of the α-decay chain of ^{291}Lv. Q_α^{exp} is the experimental α-decay energy [56].

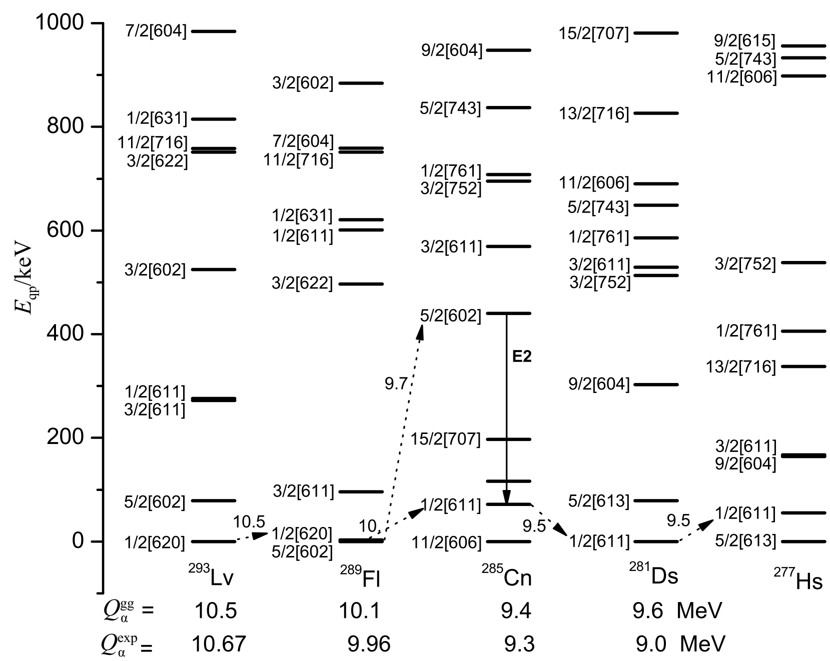

Fig. 6. The same as in Fig. 1, but for the nuclei of the α-decay chain of ^{293}Lv. Q_α^{exp} is the experimental α-decay energy [57, 58]

6 α-decay chain of ^{293}Lv

Let us consider the third α-decay chain: ^{293}Lv→^{289}Fl→^{285}Cn→^{281}Ds→^{277}Hs. Because the 7/2[604] state is close in energy to the ground state in ^{293}Lv (Fig. 3), the SHF calculations indicate the possibility of two close lines in the α-decay spectrum of ^{293}Lv: 5/2[602] (ground state)→ 5/2[602] (E_{qp}=337 keV) and 7/2[604] → 7/2[604] (E_{qp}=371 keV). The values of Q_α for these decays are close to 10.4 MeV. The experimental value of Q_α is 10.67 MeV [57, 58]. However, after the γ-transitions the α-decay of ^{289}Fl likely occurs from the ground state. So, in the α-decay chain in Fig. 3 there are single lines in the α-decay spectra of ^{289}Fl, ^{285}Cn, ^{281}Ds, and ^{277}Hs. The isomeric states 15/2[707] (^{289}Fl, ^{285}Cn), 11/2[606] (^{281}Ds), and 9/2[604] (^{277}Hs) do not affect the α-decay chain in Fig. 3 and can be explored in the direct production of these nuclei.

In the WS calculations, the α-decay of ^{293}Lv occurs only from the ground state with Q_α=10.5 MeV populating the one-quasiparticle state 1/2[620] with very low calculated excitation energy 3 keV. So, this state could be the isomeric one in ^{289}Fl, whose α-decay could be from the 1/2[620] and 5/2[602] states (Fig. 6). Because the 1/2[620] state in ^{285}Cn lies at quite high energy, the α-decay of ^{289}Fl from 1/2[620] likely goes to the state 1/2[611] of ^{285}Cn which contain a small admixture of 1/2[620]. As seen in Fig. 6, the population of the ground state of ^{285}Cn in the α-decay chain is unlikely in the WS approach. So, the α-decay spectra of ^{285}Cn and ^{281}Ds could be with one line and the possible isomeric state 9/2[604] in ^{281}Ds does not affect the α-decay chain, which is interrupted by the spontaneous fission of ^{277}Hs.

7 Summary

The excitation spectra and the characteristic α-decays of nuclei in the α-decay chains of ^{285}Fl, and ^{291,293}Lv are investigated within two models. The self-consistent Skyrme and the phenomenological WS mean field were used. The pairing was treated at the BCS level. The α-decay spectra were obtained and compared with available experimental data.

The calculations performed in the framework of the SHF and WS potentials demonstrate, as a rule, different orders of low-lying one-quasiparticle states. However, the presence of isomeric states in the heaviest nuclei as well as the values of Q_α are reliably predicted. Our predictions could be verified by comparing the α-decay spectra in the α-decay chain and at the direct production of the nucleus. The α-decay mainly occurs between the one-quasiparticle states with the same quantum numbers in the mother and daughter nuclei. So, some isomeric states are not populated in the α-decay chain. As found, there is a visible difference between the α-decay chains of ^{291}Lv predicted within the SHF and WS approaches. In the direct production of ^{283}Cn, ^{279}Ds, ^{275}Hs, and ^{271}Sg one can probably observe more lines in the α-decay spectra. So, further experimental efforts in studying the structure of the heaviest nuclei would help to adjust the parameters of the microscopic model in the region of the superheavies. It is interesting to mention that the calculated α-decay spectra are usually characterized by one or two lines.

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