

## INFLUENCE OF PROPERTIES OF SUPERHEAVY NUCLEI ON THEIR $\alpha$ DECAYS\*

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(Received December 14, 2016)

The structure of superheavy nuclei is considered with the microscopic–macroscopic approach based on the two-center shell model. The shell effects are compared with those obtained in the self-consistent approaches. The  $\alpha$ -decay chains of  $^{291,293}\text{Ts}$  and  $^{288}\text{Mc}$  are considered.

DOI:10.5506/APhysPolB.48.441

### 1. Introduction

The experiments on complete fusion reactions with  $^{48}\text{Ca}$  beam and various actinide targets were successfully carried out [1–7] in order to synthesize superheavy nuclei with  $Z = 112$ –118. The investigation of transfermium elements expands our knowledge of the single-particle structure, location of the shell closures, and decay modes of heaviest nuclei [8]. The structure of superheavies crucially influences the evaporation residue cross sections in the actinide-based complete fusion reactions [9].

Although the low cross sections for production of superheavy nuclei offer rather restricted nuclear-structure information, in recent years a set of the experimental data on the structure of the heaviest nuclei has been considerably increased because the experimental setups began to combine  $\alpha$ ,  $e^-$ , and  $\gamma$  spectroscopy [10]. In Ref. [7], the  $\alpha$ -decay chains of  $^{288}\text{Mc}$  nucleus were produced in the  $^{48}\text{Ca} + ^{243}\text{Am}$  reaction. A structure information on the low-lying states of the odd–odd superheavy nuclei below  $^{288}\text{Mc}$  was obtained in  $\alpha$ – $\gamma$  coincidences.

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\* Presented by N.V. Antonenko at the Zakopane Conference on Nuclear Physics “Extremes of the Nuclear Landscape”, Zakopane, Poland, August 28–September 4, 2016.

In this paper, we exploit the potential of the two-center shell model (TCSM) [11] with the parameters determined in [12–14] to calculate the quasiparticle spectra. The shell closures obtained with the TCSM potential are compared with those calculated with the self-consistent single-particle potentials.

## 2. Structures of nuclei in $\alpha$ -decay chains

The structure of superheavies crucially influences the evaporation residue cross sections and  $\alpha$ -decay properties. Nuclear models contain a number of parameters which are fixed for the best description of known nuclei. In Ref. [12], we proposed the microscopic–macroscopic approach based on the TCSM. The parameters were set so to describe the spins and parities of the ground state of known heavy nuclei. This approach has been used in Ref. [14] to reveal the trends in the shell effects and  $Q_\alpha$  values with  $Z$ . These trends are close to those resulted from the self-consistent microscopic calculations [13]. Here, we will use the microscopic–macroscopic approach [14] to study the one-quasiparticle spectra of nuclei in the  $\alpha$ -decay chains of  $^{291,293}\text{Ts}$  and  $^{288}\text{Mc}$ .

Calculating the potential energy surface as a function of collective coordinates with the TCSM, we find the ground-state potential minimum in which the energies of the low-lying one-quasiparticle states are obtained. The details of the calculations of binding energies of nuclei in the ground states are presented in Ref. [14]. Using these energies, we calculate the  $Q_\alpha$  values for the  $\alpha$  decays from the ground state-to-ground state and  $T_\alpha$  with the expression of Ref. [8].

In Fig. 1, the calculated one-quasiproton spectra of nuclei of  $\alpha$ -decay chain of  $^{291}\text{Ts}$  are shown. The  $\alpha$  decays of  $^{287}\text{Mc}$ ,  $^{283}\text{Nh}$ ,  $^{279}\text{Rg}$ , and  $^{275}\text{Mt}$  were experimentally observed in one  $\alpha$ -decay chain of  $^{287}\text{Mc}$  [1]. The  $\alpha$  particle from  $^{271}\text{Bh}$  was missed. In Fig. 1, we marked the most probable  $\alpha$  decays from the ground and isomeric states. The calculated energies of the majority of these decays are in a good agreement with the experimental data. The  $\alpha$  decay of  $^{287}\text{Mc}$  populates the  $9/2^- [505]$  state of  $^{283}\text{Nh}$  from which the  $\gamma$  transitions occur into the  $11/2^+ [625]$  state or into the ground state (through the  $7/2^- [503]$  state). If the isomeric state  $11/2^+ [625]$  in  $^{283}\text{Nh}$  lives longer than 7 ms, the  $\alpha$  decay from this state can occur.

As seen in Fig. 1, the  $\alpha$  decay of  $^{275}\text{Mt}$  is hindered because the corresponding one-quasiparticle states in the daughter nucleus have high energies. The lifetimes with respect to the spontaneous fission for neighboring even–even nuclei  $^{274}\text{Hs}$  and  $^{276}\text{Ds}$  are estimated [15] as 5.8 and 2.1 s, respectively. Thus, the spontaneous fission of  $^{275}\text{Mt}$  needs more than 3.5 s. The  $\alpha$  decay occurs faster,  $T_\alpha < 1$  s, even with  $Q_\alpha = 9.61$  MeV. The  $\alpha$  decay of  $^{275}\text{Mt}$  can also occur into the first rotational state  $11/2^+$  of  $^{271}\text{Bh}$ . In this case,

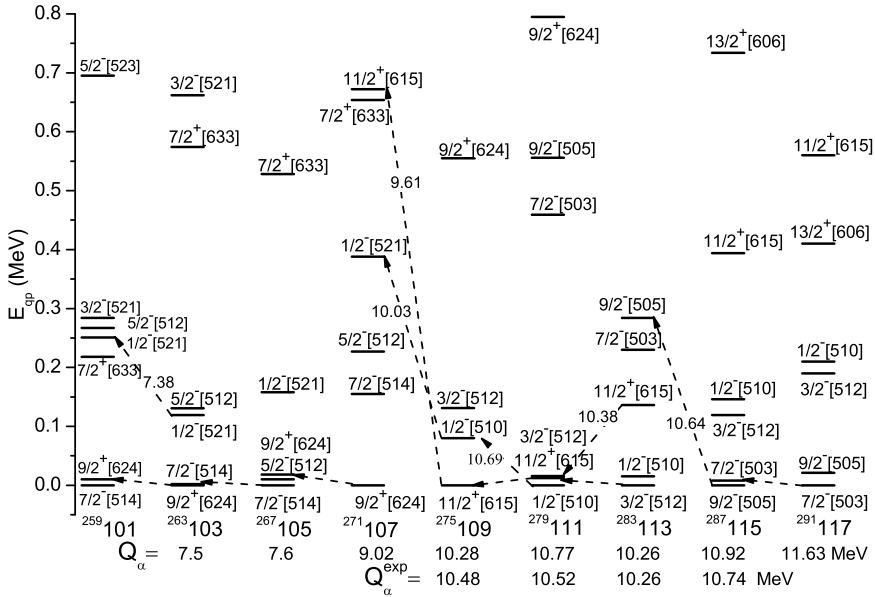


Fig. 1. Calculated energies of low-lying one-quasiproton states in the indicated nuclei of the  $\alpha$ -decay chain of  $^{291}\text{Ts}$ . The calculated values of  $Q_\alpha$  are for the ground state-to-ground state  $\alpha$  decay. The most probable  $\alpha$  decays are traced by arrows. The experimental value of  $Q_\alpha^{\text{exp}}$  are from Ref. [1].

the calculated  $Q_\alpha$  value would be about 10.28 MeV and  $T_\alpha > 15$  ms. Note that we underestimate  $Q_\alpha$  within 0.2 MeV for  $^{275}\text{Mt}$  in comparison with the experimental data [1].

The  $\alpha$  decay of  $^{271}\text{Bh}$  occurs in about 9.3 s to  $^{267}\text{Db}$ . The  $\alpha$  decay of  $^{267}\text{Db}$  would need about 35 h that is too long in comparison with the time of spontaneous fission which occurs in about 1 h [1]. Therefore, the  $\alpha$ -decay chain of  $^{291}\text{Ts}$  or  $^{287}\text{Mc}$  is terminated by the spontaneous fission of  $^{267}\text{Db}$ .

The calculated one-quasiproton spectra of the nuclei of the  $\alpha$ -decay chain of  $^{293}\text{Ts}$  are presented in Fig. 2. The possible  $\alpha$  decays from the ground and isomeric states are marked. The  $1/2^- [510]$  state can be the isomeric state in  $^{293}\text{Ts}$ . If it lives longer than 30 ms with respect to  $\gamma$  transitions, the  $\alpha$  decay occurs from this state. The nucleus  $^{289}\text{Mc}$  seems to have no one-quasiparticle isomeric states (long living states with respect to  $\gamma$  decay) and emits  $\alpha$  from the ground state to populate the  $9/2^- [505]$  state of  $^{285}\text{Nh}$ . The  $\gamma$  transitions from this state feed the ground state and the  $11/2^+ [615]$  isomeric state. The lifetime of  $^{285}\text{Nh}$  in this isomeric state seems to be shorter than the time  $T_\alpha > 0.7$  s for  $\alpha$  decay. Thus, the  $\alpha$  decay of  $^{285}\text{Nh}$  likely occurs from the ground state into the  $3/2^- [512]$  state of  $^{281}\text{Rg}$  from which M1 transition occurs into the ground state.





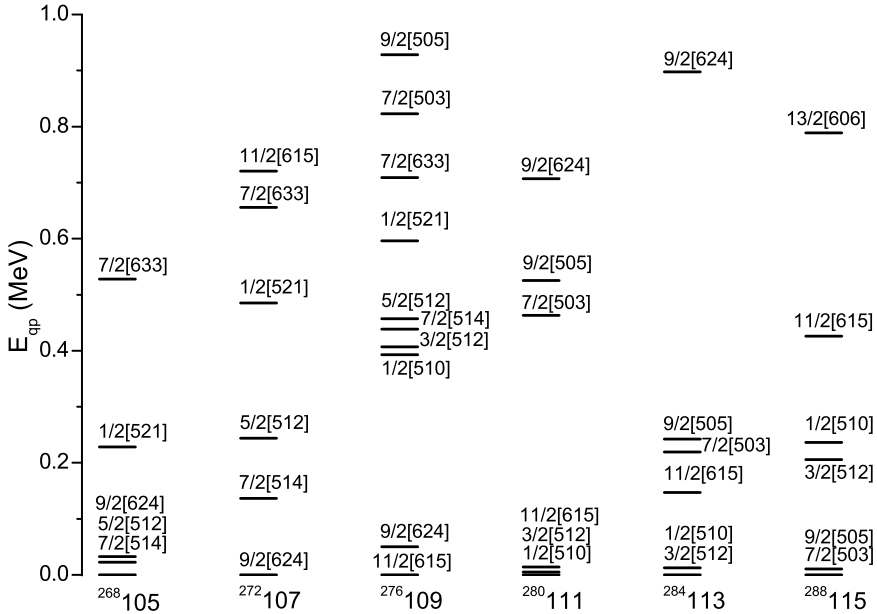


Fig. 4. The same as in Fig. 3, but for the one-quasiproton spectra.

Besides the ground state, the possible isomeric state  $n5/2[602] \otimes p9/2[505]$  is populated with almost the same probability in the evaporation residue  $^{288}\text{Mc}$ . The most favorable  $\alpha$  decays from these states to the corresponding states (Fig. 5) of daughter nucleus  $^{284}\text{Nh}$  have  $Q_\alpha = 10.62$  and  $10.47$  MeV what is in a good agreement with the experimental data [3, 7].

In  $^{284}\text{Nh}$ , the M1 transition  $p9/2[505] \rightarrow p7/2[503]$  is estimated to be four orders of magnitude slower than the E1 transition  $p9/2[505] \rightarrow p11/2[615]$ . This E1 transition follows by E2 transition in about 5 ms (Fig. 5). So, the  $\alpha$  decay of  $^{288}\text{Mc}$  with  $Q_\alpha = 10.47$  MeV would lead to the population of isomeric state  $n1/2[611] \otimes p11/2[615]$  in  $^{284}\text{Nh}$ . The  $\alpha$  decay of  $^{288}\text{Mc}$  with  $Q_\alpha = 10.62$  MeV follows by the E1 transition ( $T_\gamma \approx 30$  ps) to the possible isomeric state  $n13/2[716] \otimes p11/2[615]$ . The population of the ground state in  $^{284}\text{Nh}$  because of the consequence of slower M1 and E2 transitions is unlikely but cannot be excluded. The population of the  $n1/2[611] \otimes p3/2[512]$  state from the  $n5/2[613] \otimes p9/2[505]$  state via M1, and two E2 transitions over the states  $n5/2[613] \otimes p7/2[503]$  and  $n5/2[613] \otimes p3/2[512]$  is unlikely because it requires a longer time. As found, the  $\alpha$  decay of  $^{284}\text{Nh}$  from the  $n1/2[611] \otimes p3/2[512]$  state with  $Q_\alpha = 10.19$  MeV does not populate isomeric states in  $^{280}\text{Rg}$ .



seems to be isomeric. The  $\alpha$  decays with  $Q_\alpha = 10.35$  and 10 MeV follow by the low-energy E2 and M1 transitions, respectively, to the corresponding isomeric states. Because this E2 transition requires about 2 s, the  $n1/2[611] \otimes p11/2[615]$  state is considered in the  $\alpha$  decay of  $^{280}\text{Rg}$  as well. The detailed analysis of possible  $\alpha$  decays of nuclei  $^{288}\text{Mc}$ ,  $^{284}\text{Nh}$ ,  $^{280}\text{Rg}$ ,  $^{276}\text{Mt}$ , and  $^{272}\text{Bh}$  is presented in Ref. [18].

### 3. Proton shell closure in heaviest nuclei

As seen in Fig. 7, the calculated  $Q_\alpha$  are in a good, within 0.3 MeV, agreement with the available experimental data. The shell effects at  $Z = 114$  and  $N = 172$ – $176$  provide rather weak dependence of  $Q_\alpha$  on  $N$ . The strong role of the shell at  $N = 184$  is reflected in the well-pronounced minimum of  $Q_\alpha$ . The jump of  $Q_\alpha$  values at transition from  $Z = 120$  to  $Z = 122$  indicates a rather strong shell effect at  $Z = 120$ . So, the TCSM results in the proton shell closure at  $Z = 120$ . The values of the shell correction  $E_{\text{sh}}$  are shown in Fig. 8 for the nuclei of  $\alpha$ -decay chain starting from  $^{302}120$ . The shell effects predicted for these nuclei in Ref. [8] are weaker.

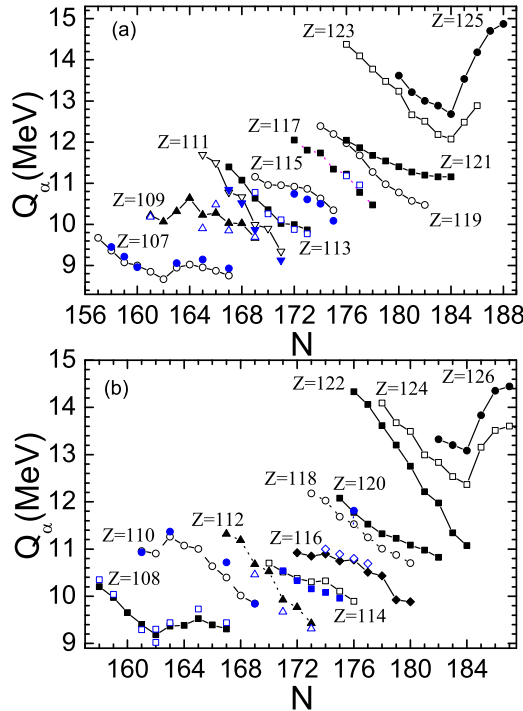


Fig. 7. Calculated  $\alpha$ -decay energies (symbols connected by lines) are compared with available experimental data (symbols) [1, 2, 4, 6] for nuclei with  $Z \geq 107$ .



The Schrödinger equivalent single-particle potential can be obtained [19] from the self-consistent calculations based on the non-relativistic [20] and relativistic [21] mean-field approaches. As found, these different approaches result in almost the same single-particle potential in the Woods–Saxon form with the depths  $V_0 = -59 \pm 30 \frac{N-Z}{N+Z}$  for neutrons and protons. The shell corrections calculated with the microscopic–macroscopic approach using this potential are also presented in Fig. 8. As seen, the self-consistent approaches produce stronger shell effects than the TCSM. However, the weak variation of  $E_{sh}$  at  $Z = 116$ – $120$  is similar to that in Ref. [8].

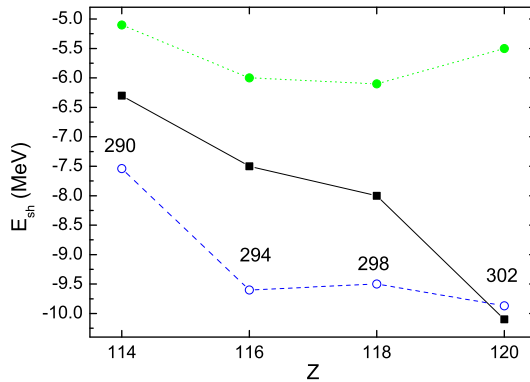


Fig. 8. Shell corrections to the binding energies of the nuclei of  $\alpha$ -decay chain of  $^{302}120$ . The results of the TCSM [14] are shown by solid squares connected by solid line. The results of Ref. [8] are presented by solid circles. The values of  $E_{sh}$  obtained for the Woods–Saxon potential extracted from the self-consistent microscopical calculations are shown by open circles.

### 4. Summary

The calculations with the modified TCSM result in realistic quasiparticle spectra and reveal quite strong shell effects at  $Z = 120$ . So, our macroscopic–microscopic treatment qualitatively leads to the results close to those in the mean-field treatments. Two self-consistent approaches provide similar Schrödinger equivalent single-particle potentials in which the shell effects at  $Z = 120$  are stronger than at  $Z = 114$ . Peculiarities of quasiparticle spectra could be responsible for the termination of  $\alpha$ -decay chain by spontaneous fission.

This work was supported in part by RFBR, DFG, and NSFC. The Polish–JINR (Dubna) Cooperation Programmes are gratefully acknowledged.

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