INFLUENCE OF PROPERTIES OF SUPERHEAVY NUCLEI ON THEIR α DECAYS*

G.G. Adamian[a], N.V. Antonenko[a,b], A.N. Bezbakh[a], R.V. Jolos[a]
L.A. Malov[a], K. Wang[c], S.-G. Zhou[c], H. Lenske[d]

[a]Joint Institute for Nuclear Research, 141980 Dubna, Russia
[b]Tomsk Polytechnic University, 634050 Tomsk, Russia
[c]Institute of Theoretical Physics, CAS, 100190 Beijing, China
[d]Justus-Liebig-Universität, 35392 Giessen, Germany

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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 α-decay chains of ^{291,293}Ts and ^{288}Mc are considered.

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1. Introduction

The experiments on complete fusion reactions with ^{48}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 α, e^-, and γ spectroscopy [10]. In Ref. [7], the α-decay chains of ^{288}Mc nucleus were produced in the ^{48}Ca + ^{243}Am reaction. A structure information on the low-lying states of the odd–odd superheavy nuclei below ^{288}Mc was obtained in α–γ coincidences.

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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 α-decay chains

The structure of superheavies crucially influences the evaporation residue cross sections and α-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_α 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 α-decay chains of ^{291,293}Ts and ^{288}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_α values for the α decays from the ground state-to-ground state and T_α with the expression of Ref. [8].

In Fig. 1, the calculated one-quasiproton spectra of nuclei of α-decay chain of ^{291}Ts are shown. The α decays of ^{287}Mc, ^{283}Nh, ^{279}Rg, and ^{275}Mt were experimentally observed in one α-decay chain of ^{287}Mc [1]. The α particle from ^{271}Bh was missed. In Fig. 1, we marked the most probable α 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 α decay of ^{287}Mc populates the $9/2^-[505]$ state of ^{283}Nh from which the γ 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}Nh lives longer than 7 ms, the α decay from this state can occur.

As seen in Fig. 1, the α decay of ^{275}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}Hs and ^{276}Ds are estimated [15] as 5.8 and 2.1 s, respectively. Thus, the spontaneous fission of ^{275}Mt needs more than 3.5 s. The α decay occurs faster, $T_\alpha < 1$ s, even with $Q_\alpha = 9.61$ MeV. The α decay of ^{275}Mt can also occur into the first rotational state $11/2^+$ of ^{271}Bh. In this case,

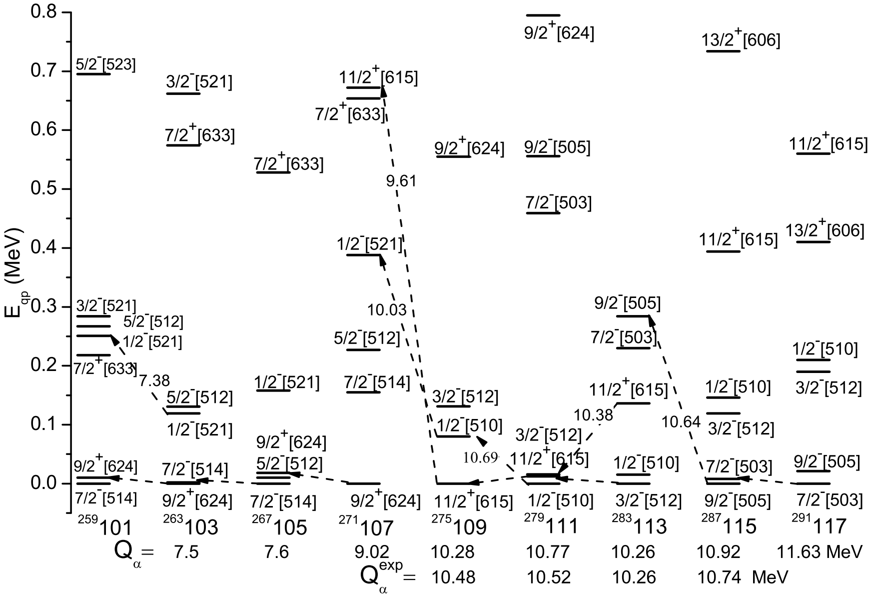

Fig. 1. Calculated energies of low-lying one-quasiproton states in the indicated nuclei of the α-decay chain of ^{291}Ts. The calculated values of Q_α are for the ground state-to-ground state α decay. The most probable α decays are traced by arrows. The experimental value of $Q_\alpha^{\rm exp}$ are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

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

The α decay of ^{271}Bh occurs in about 9.3 s to ^{267}Db. The α decay of ^{267}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 α-decay chain of ^{291}Ts or ^{287}Mc is terminated by the spontaneous fission of ^{267}Db.

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

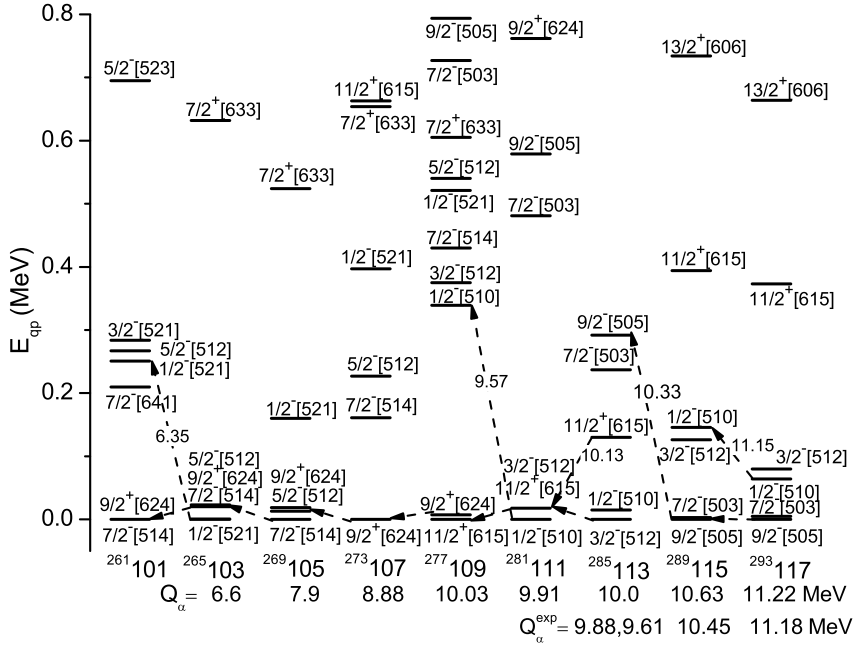

Fig. 2. The same as in Fig. 1, but for the α-decay chain of ^{293}Ts. The experimental value of $Q_\alpha^{\rm exp}$ are from Ref. [2].

The α decay of ^{281}Rg could populate the $1/2^-[510]$ isomeric state of ^{277}Mt. This state is at the energy of 0.34 MeV and has more than 10% admixture of $1/2^-[521]$ and $1/2^-[530]$ states. The calculated value of Q_α for the ground state-to-ground state α decay is 0.46 MeV smaller than in Ref. [16]. Taking into account the structures of $1/2^-[521]$ states, we estimate $T_\alpha = 8.1$ s for ^{281}Rg. If in ^{277}Mt the $1/2^-[521]$ state would be 0.25 MeV higher in energy, then $T_\alpha = 44$ s. The spontaneous fission half-life $T_{\rm sf}$ of ^{281}Rg can be estimated as the average of the values calculated [15] for two neighboring even–even nuclei ^{280}Ds and ^{282}Cn, and increased by the factor taking the effect of odd nucleon into account. For ^{281}Ds, this factor is found to be about 15. Thus, for ^{281}Rg $T_{\rm sf}$ is estimated as 0.6 s. This value is about 10 times smaller than T_α found and ^{281}Rg likely undergoes to spontaneous fission. However, the estimated $T_{\rm sf}$ is smaller than the experimental value 38 s [2] which is comparable with the calculated T_α. The half-lives with respect to the spontaneous fission are about 11 s for ^{283}Cn and ^{281}Ds with $N = 171$. In this nuclei, the spins of the ground states are 1/2 as in the case of ^{281}Rg ($N = 170$). As found, in Ds and Cn, the value of $T_{\rm sf}$ increases by about 2 orders of magnitude when the neutron number changes from 169 to 171 and from 170 to 172, respectively. The calculated $Q_\alpha = 9.906$ and 9.345 MeV [14] for ^{281}Rg and ^{282}Rg, respectively. The decrease of Q_α

with increasing N indicates the approaching the neutron shell closure. In ^{282}Rg, we expect $T_\alpha \approx 25$ s and $T_{\rm sf} \approx 110$ s, *i.e.* about 10 times larger than for neighboring even–odd nuclei ^{283}Cn and ^{281}Ds. Thus, ^{282}Rg undergoes α decay as found in Ref. [2].

The one-quasiparticle spectra are shown in Figs. 3 and 4 for the nuclei of α-decay chain of ^{288}Mc. There are four pseudospin doublets located near the Fermi surface in the nuclei considered. Namely, two neutron doublets 5/2[613]–3/2[611], 11/2[606]–9/2[604] and two proton doublets 7/2[503]–9/2[505], 1/2[510]–3/2[512]. For some isotopes, the level 3/2[611] is out of the scale in Fig. 3. In our calculations, the splitting of the neutron doublet 5/2[613]–3/2[611] varies from 440 to 690 keV. In the single-particle scheme presented in Ref. [17], the splitting of this doublet is approximately equal to 650 keV. A splitting of the neutron doublet 11/2[606]–9/2[604] calculated with the TCSM is unexpectedly large. It exceeds 2 MeV, although this splitting is approximately equal to 1.3 MeV in Ref. [17]. The splitting is rather small for the proton pseudospin doublets calculated with the two-center potential. For the proton doublet 7/2[503]–9/2[505], it varies from 10 keV in ^{288}Mc to 150 keV in ^{268}Db. The single-particle spectrum in Ref. [17] shows the splitting of 835 keV. The splitting of the proton pseudospin doublet 1/2[510]–3/2[512] calculated with the TCSM is equal to 40–60 keV in all considered nuclei. The spectrum shown in Ref. [17] demonstrates a splitting of this doublet approximately equal to 220 keV.

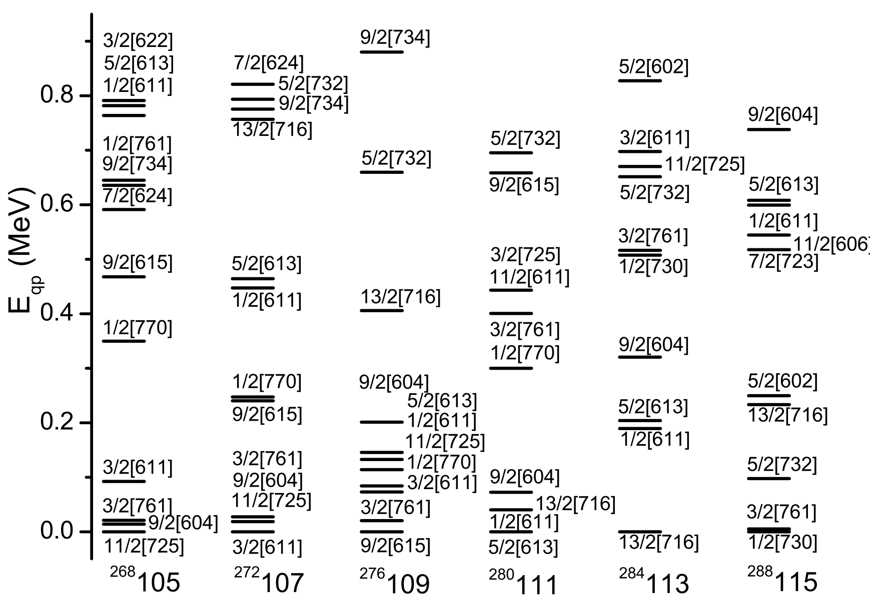

Fig. 3. The one-quasineutron spectra calculated with the TCSM for the nuclei of the α-decay chain of ^{288}Mc. The Nilsson asymptotic quantum numbers are indicated.

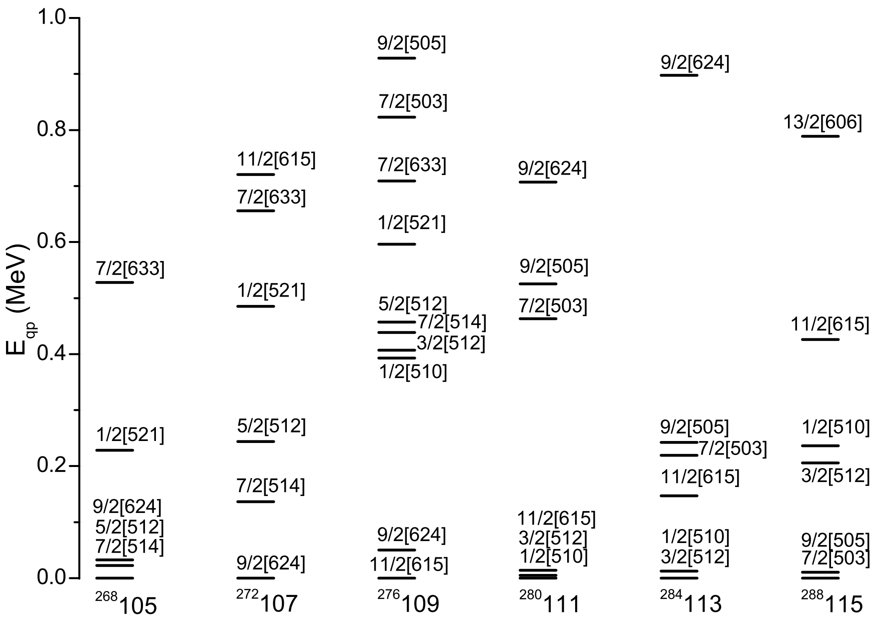

Fig. 4. The same as in Fig. 3, but for the one-quasiproton spectra.

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}Mc. The most favorable α decays from these states to the corresponding states (Fig. 5) of daughter nucleus ^{284}Nh have $Q_\alpha = 10.62$ and 10.47 MeV what is in a good agreement with the experimental data [3, 7].

In ^{284}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 α decay of ^{288}Mc with $Q_\alpha = 10.47$ MeV would lead to the population of isomeric state $n1/2[611] \otimes p11/2[615]$ in ^{284}Nh. The α decay of ^{288}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 sate in ^{284}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 α decay of ^{284}Nh from the $n1/2[611]\otimes p3/2[512]$ state with $Q_\alpha = 10.19$ MeV does not populate isomeric states in ^{280}Rg.

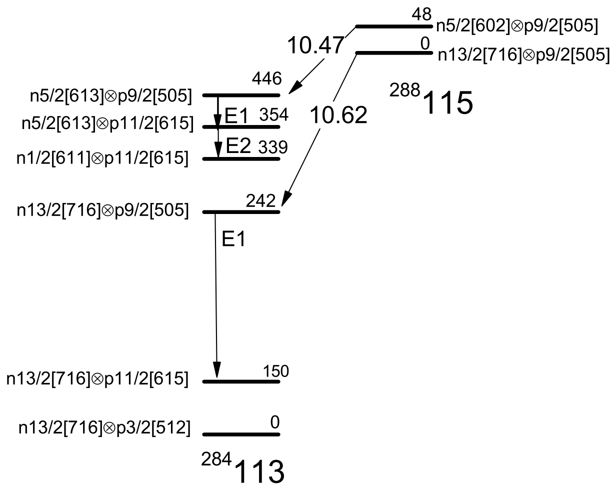

Fig. 5. Decay scheme of ^{288}Mc→^{284}Nh resulting from the calculations with the TCSM model. Energies of two-quasiparticle levels are in keV, Q_α values are in MeV. The most probable gamma transitions are marked.

As shown in Fig. 6, the α decays of ^{284}Nh populate the states in ^{280}Rg which are very close in energy to the ground state. The modified TCSM results in a very dense quasiparticle spectrum for ^{280}Rg because there is no reduction of the effective nucleon mass as in the self-consistent calculation. The α decay of ^{284}Nh from the $n13/2[716] \otimes p11/2[615]$ state with $Q_\alpha = 10.13$ MeV (Fig. 6) populates the same state in ^{280}Rg which

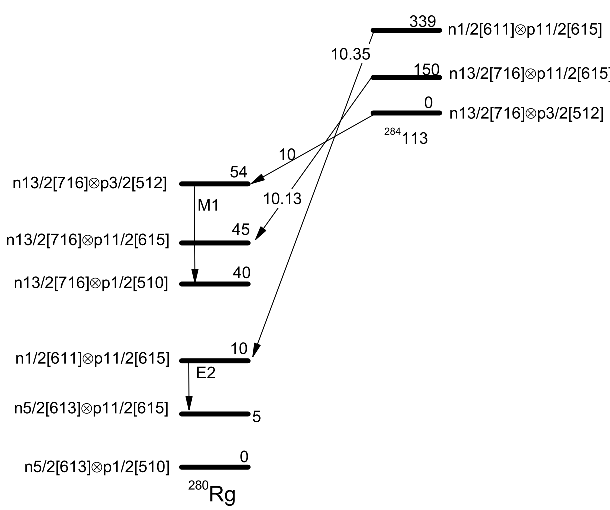

Fig. 6. The same as in Fig. 5, but for the decay ^{284}Nh→^{280}Rg.

seems to be isomeric. The α 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 α decay of ^{280}Rg as well. The detailed analysis of possible α decays of nuclei ^{288}Mc, ^{284}Nh, ^{280}Rg, ^{276}Mt, and ^{272}Bh is presented in Ref. [18].

3. Proton shell closure in heaviest nuclei

As seen in Fig. 7, the calculated Q_α 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_α on N. The strong role of the shell at $N = 184$ is reflected in the well-pronounced minimum of Q_α. The jump of Q_α 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 $E_{\rm sh}$ are shown in Fig. 8 for the nuclei of α-decay chain starting from ^{302}120. The shell effects predicted for these nuclei in Ref. [8] are weaker.

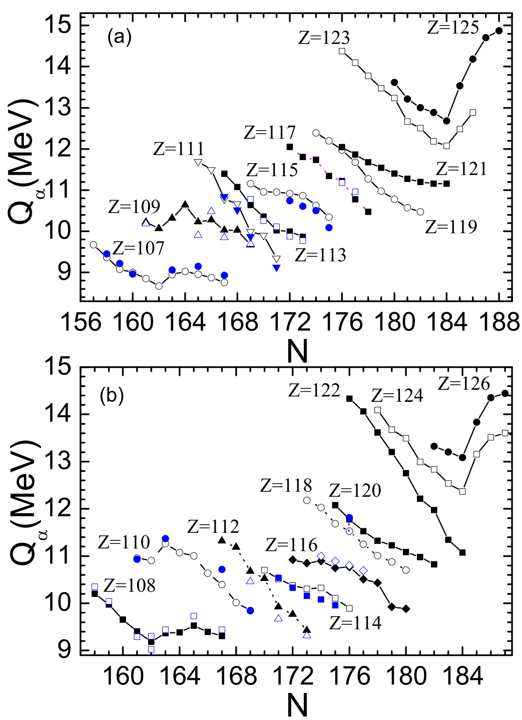

Fig. 7. Calculated α-decay energies (symbols connected by lines) are compared with available experimental data (symbols) [1, 2, 4, 6] for nuclei with $Z \geq 107$.

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-filed 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 $E_{\rm sh}$ at $Z = 116$–120 is similar to that in Ref. [8].

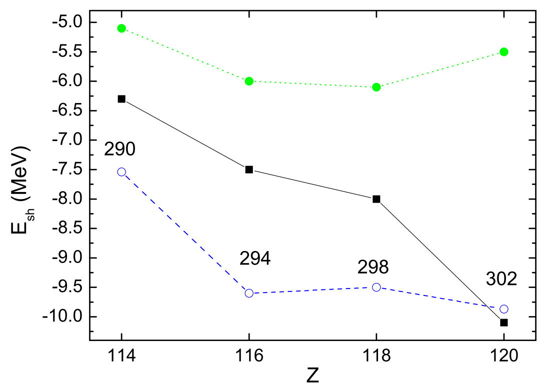

Fig. 8. Shell corrections to the biding energies of the nuclei of α-decay chain of $^{302}120$. The results of the TCSM [14] are shown by solid squares connected by solid line. The results of Ref. [8] are presented by solid circles. The values of $E_{\rm sh}$ obtained for the Woods–Saxon potential extracted 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 α-decay chain by spontaneous fission.

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REFERENCES

[1] Yu.Ts. Oganessian, *J. Phys. G* **34**, R165 (2007).

[2] Yu.Ts. Oganessian *et al.*, *Phys. Rev. Lett.* **104**, 142502 (2010).

[3] Yu.Ts. Oganessian *et al.*, *Phys. Rev. C* **87**, 014302 (2013).

[4] S. Hofmann *et al.*, *Eur. Phys. J. A* **32**, 251 (2007).

[5] W. Loveland *et al.*, *Phys. Rev. C* **66**, 044617 (2002); K.E. Gregorich *et al.*, *Phys. Rev. C* **72**, 014605 (2005).

[6] L. Stavsetra *et al.*, *Phys. Rev. Lett.* **103**, 132502 (2009).

[7] D. Rudolph *et al.*, *Phys. Rev. Lett.* **111**, 112502 (2013).

[8] I. Muntian, Z. Patyk, A. Sobiczewski, *Acta Phys. Pol. B* **32**, 691 (2001); **34**, 2141 (2003); I. Muntian, S. Hofmann, Z. Patyk, A. Sobiczewski, *Acta Phys. Pol. B* **34**, 2073 (2003); *Phys. At. Nucl.* **66**, 1015 (2003); A. Parkhomenko, I. Muntian, Z. Patyk, A. Sobiczewski, *Acta Phys. Pol. B* **34**, 2153 (2003); A. Parkhomenko, A. Sobiczewski, *Acta Phys. Pol. B* **36**, 3095 (2005).

[9] G.G. Adamian, N.V. Antonenko, W. Scheid, *Eur. Phys. J. A* **41**, 235 (2009).

[10] R.-D. Herzberg, P.T. Greenlees, *Prog. Part. Nucl. Phys.* **61**, 674 (2008).

[11] J. Maruhn, W. Greiner, *Z. Phys.* **251**, 431 (1972).

[12] G.G. Adamian, N.V. Antonenko, W. Scheid, *Phys. Rev. C* **81**, 024320 (2010); G.G. Adamian, N.V. Antonenko, S.N. Kuklin, W. Scheid, *Phys. Rev. C* **82**, 054304 (2010).

[13] G.G. Adamian *et al.*, *Phys. Rev. C* **84**, 024324 (2011).

[14] A.N. Kuzmina, G.G. Adamian, N.V. Antonenko, W. Scheid, *Phys. Rev. C* **85**, 014319 (2012).

[15] R. Smolańczuk, J. Skalski, A. Sobiczewski, *Phys. Rev. C* **52**, 1871 (1995).

[16] A. Sobiczewski, *Acta Phys. Pol. B* **41**, 157 (2010).

[17] A. Bohr, B. Mottelson, *Nuclear Structure*, Benjamin, NY 1975, vol. II.

[18] A.N. Bezbakh *et al.*, *Phys. Rev. C* **92**, 014329 (2015).

[19] G.G. Adamian *et al.*, to be published.

[20] F. Hofmann, H. Lenske, *Phys. Rev. C* **57**, 2281 (1998).

[21] J. Meng *et al.*, *Prog. Part. Nucl. Phys.* **57**, 470 (2006).