INFLUENCE OF SHELL STRUCTURE ON LEVEL DENSITIES OF SUPERHEAVY NUCLEI*

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The intrinsic level densities of superheavy nuclei in the α-decay chains of $^{296;298;300}120$ nuclei are calculated using the single-particle spectra obtained with the modified two-center shell model. The level density parameters are extracted and compared with their phenomenological values used in the calculations of the survival of excited heavy nuclei. The dependences of the level density parameters on the mass and charge numbers as well as on the ground-state shell corrections are studied.

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The experimental trend of nuclear properties as well as the production cross sections of superheavy elements (SHE) reveal an increasing stability of nuclei approaching $N = 184$, and indicate quite large shell effects behind $Z = 114$ [1–4]. This means that the predictions of relativistic and non-relativistic mean-field models [5–8] seem to be valid. In accordance with these self-consistent models, a center of the stability island is expected at $Z = 120$–126 and $N = 172$ or 184. In the $(N;Z)$ plane, the line, along which all new SHE were discovered in the actinide-based reactions with ^{48}Ca beam, just approaches this region [1].

In this work, we investigate the nuclear level densities (NLD) of superheavy nuclei with $100 \leq Z \leq 130$ whose α-decay chains contain $^{296;298;300}120$. The nuclei $^{296;298}120$ can be perhaps synthesized in the reactions ^{54}Cr + ^{248}Cm and ^{50}Ti + ^{249,251,252}Cf. The level density, as a function of excitation energy, is required to calculate the survival probability and, correspondingly, the production cross section of heavy nucleus. The phenomenological values

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of level density parameter used in the calculations of evaporation residue cross sections have to be verified in the microscopical calculations. In addition, at low excitations the NLD are closely related to the shell structure and could indicate the position of the island of stability of heaviest nuclei.

In our work, we use the expression for the nuclear level density (NLD) adopted from the superfluid model [9, 10]. The pivotal ingredients of the calculations are the single-particle spectra of the nuclei obtained with the modified two-center shell model [11]. The internal (particle-hole) excibitions are treated in these spectra. The details of the calculations are described in Ref. [12] where we demonstrated a good description of experimental data in the region of known nuclei.

To establish a connection between our calculations of NLD and phenomenological models used in the calculations of survival probabilities, we fit the calculated intrinsic level densities with the Fermi-gas expression and extract the level density parameters. We found that the best fit is achieved if one uses the level density parameter expressed in terms of the excitation energy U and entropy S of the nucleus as

$$a = S^2/(4U) = S_N^2/4U_N + S_Z^2/4U_Z = a_N + a_Z \,. \tag{1}$$

Quantities $S_N(S_Z)$ and $E_N(E_Z)$ are the entropies and excitation energies of only neutron (proton) subsystems.

Figure 1 presents the dependences of shell corrections $\delta E_{\rm sh}$ and level density parameters a at $U = 10$ MeV and $U = 60$ MeV excitation energies on the atomic number A for three α-decay chains containing the SHE $^{296;298;300}120$. The data of Ref. [13] are used for $\delta E_{\rm sh}$. One can see the strong correlations between the shell corrections and level density parameter a at excitation energy $U = 10$ MeV. The larger negative shell corrections result in the decrease of the value of a with respect to the neighborhood nuclei. At higher excitation energy ($U = 60$ MeV), the correlation between $\delta E_{\rm sh}$ and a is destroyed and (as demonstrated in the upper part of Fig. 1) level density parameter becomes rather smooth function of A.

Based on the study of the dependencies of a on $\delta E_{\rm sh}$, U, and A, one can use the following parameterization [14] of the level density parameter:

$$a(A,U) = \tilde{a}(A)\left[1 + \frac{1-\exp\{-U/E'_{\rm D}\}}{U}\delta E_{\rm sh}\right] , \tag{2}$$

where $\tilde{a}(A)$ is the parameter smoothly depending on A. It defines a at large excitations when the shell effects are washed out. By analyzing the level density parameters with Eq. (2), the value of the damping parameter $E'_{\rm D} =$ 27 MeV is found. The corresponding asymptotic level density parameter $\tilde{a}(A)$ can be fitted with the following functions [14]

$$\tilde{a}(A) = \alpha A + \beta A^2 \,, \tag{3}$$

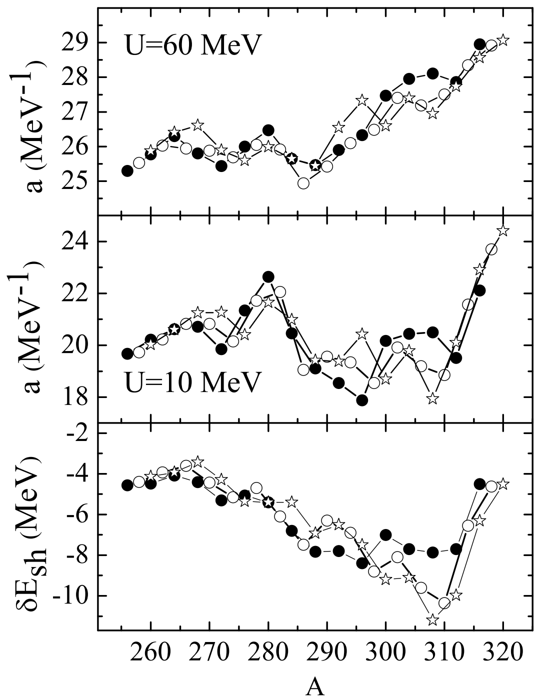

Fig. 1. Calculated ground-state shell corrections $\delta E_{\rm sh}$ (lower part), the level density parameter a at $U = 10$ (middle part) and 60 MeV (upper part), obtained with Eq. (1), as functions of mass number A. The nuclei from alpha-decay chains containing $^{296}120$, $^{298}120$, $^{300}120$ are marked by closed circles, open circles, and stars, respectively.

where the constants $\alpha = 0.118$ MeV^{-1} and $\beta = -0.53 \times 10^{-4}$ MeV^{-1} are found with the least square method. These values are close to those proposed in Ref. [14].

The level density parameters for the nuclei with $Z \geq 100$ are of especial interest to look for the position of the next proton and neutron shell closures beyond $Z = 82$. To separate the neutron and proton shell effects, one should investigate the proton (a_Z) and neutron (a_N) level density parameters defined in Eq. (1) (see Fig. 2). At $Z = 108$ and 120, there are minima of a_Z in all chains. This reflects quite strong proton shell effects at $Z = 108$ and 120. At $Z = 120$, the minima of a are the deepest and well pronounced. The similar behavior of a occurs near $Z = 82$. The sub-shell at $Z = 114$ exists but provides weaker shell effect than at $Z = 120$. For nuclei with $Z = 124$–128, the minima of a are due to the neutron shell at $N = 184$.

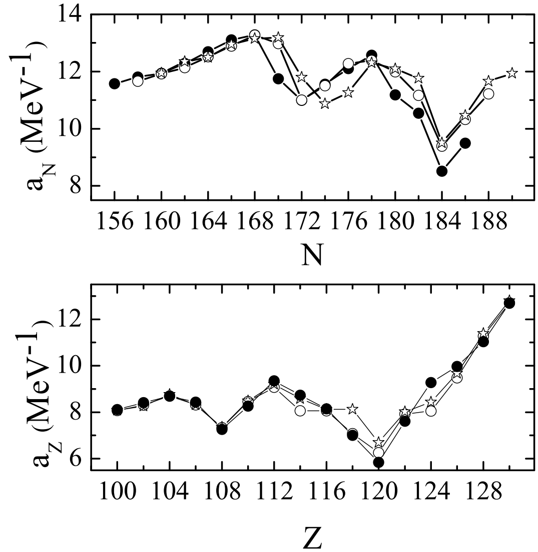

Fig. 2. Calculated proton (a_Z) and neutron (a_N) level density parameters ($U = 10$ MeV) as a function of neutron number N (upper part) and proton number Z (lower part) for the superheavy nuclei considered. The nuclei from alpha-decay chains containing $^{296}120$, $^{298}120$, $^{300}120$ are marked by closed circles, open circles, and stars, respectively.

In conclusion, the level density parameters were calculated for the nuclei of alpha-decay chains containing $^{296}120$, $^{298}120$, and $^{300}120$. The strong shell effects at $Z = 120$ and $N = 184$ were demonstrated that is in accordance with our previous calculations and shell-model predictions. The dependencies of the level density parameter on the shell correction and excitation energy were studied. The damping factor in the well-known expression (2) [13] was found to be $E'_{\rm D} = 27$ MeV. For superheavy nuclei considered, the level density parameter is approximately $A/(11–13)$ MeV at excitation energies corresponding to (3–5) neutron evaporation channels.

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