Properties of superheavy nuclei with $Z = 124$

M. S. Mehta$^1$, Harvinder Kaur$^{1,2}$, Bharat Kumar$^3$, and S. K. Patra$^3$

$^1$Department of Applied Sciences, Punjab Technical University, Kapurthala 144 601, India
$^2$Department of Physics, Rayat Bahra University, Mohali 140 104, India
$^3$Institute of Physics, Sachivalaya Marg, Bhubaneswar 751 005, India

We employ Relativistic Mean Field (RMF) model with NL3 parametrization to investigate the ground state properties of superheavy nucleus, $Z = 124$. The nuclei selected (from among complete isotopic series) for detailed investigation show that the nucleon density at the center is very low and therefore, these nuclei can be treated as semi-bubble nuclei. The considerable shell gap appears at neutron numbers $N = 172$, 184 and 198 showing the magicity corresponding to these numbers. The results are compared with the macro-microscopic Finite Range Droplet Model (FRDM) wherever possible.

PACS numbers: 21.10.Dr, 21.10.Ft, 21.10.Tg, 21.10.Gv

I. INTRODUCTION

The location of the center of 'island of stability' and hence the next magic number for proton beyond $^{208}\text{Pb}$ ($Z = 82, N = 126$) in superheavy mass region is debated since the prediction of the existence of long-lived superheavy nuclei in sixties by [1–6]. Since then a significant progress has been made in the discovery of superheavy nuclei [7–9]. Experimentally, the elements up to $Z = 118$ have been synthesized so far, with half-lives varying from a few minutes to milliseconds [8]. Recently, the nuclei with $Z = 104 - 118$ with mass number $A = 266 - 294$ have been detected at Dubna [10–17] using hot fusion reactions with the neutron-rich $^{48}\text{Ca}$ beam on actinides targets. These measurements show the increase in half-lives with in neutron number towards $N = 184$ give indication of stable center. In more detail, the cold fusion reactions involving a doubly magic spherical target and a deformed projectiles was used at GSI [7, 8, 18–21] to produce heavy elements upto $Z = 110 - 112$. At the production time of $Z = 112$ nucleus at GSI the fusion cross-section was extremely small (1 pb), which led to the conclusion that reaching still lighter nuclei by their $\alpha$-decay chains. The element $Z = 113$ was first reported by Oganessian et al. [22, 23].

But theoretically, the studies of the shell structure of superheavy nuclei in different approaches show that the magic shells beyond the spherical double-magic number $^{208}\text{Pb}$ ($N = 126$ and $Z = 82$), in superheavy mass region are isotope (combination of $Z$ and $N$) as well as parameter dependent. For example, recently, more microscopic calculations have predicted various other regions of stability, such as $Z = 114, N = 184$ [24]; $Z = 120, N = 172$ or 184 [25, 26] and $Z = 124$ or 126, $N = 184$ [27–29]. In the framework of relativistic Hartree-Bogoliubov theory, Zhang et al. [30] predicted $Z = 120, 132$ and 138 with neutron number $N = 172, 184, 198, 228, 238$ and 258 as the next nucleon shell gaps. However, in experiments, the heaviest nucleus that could be studied so far is $^{254}\text{No}$ ($Z = 102, N = 152$) [31]. In an effort along this direction, using inductively coupled plasma-sector field mass spectroscopy, Marinov et al. [32] have observed some neutron-deficient Th-isotopes in naturally occurring thorium substances. The long-lived isomeric states, with estimated half-lives $T_{1/2} \geq 10^8$ y, have been identified in the neutron-deficient $^{211,213,217,219}\text{Th}$ isotopes, which are associated with the super-deformed (SD) or hyper-deformed (HD) states (minima) in potential energy surfaces (PES). In our earlier investigation [33] of $Z = 122$ isotopes ($N = 160 - 198$), using relativistic mean field (RMF) and Skyrme Hartree Fock (SHF) models, we find the ground state solutions of some nuclei are super deformed and/or even hyper-deformed. Of course, the SD ground state structure of superheavy nuclei are reported earlier by Ren et al. [34], within the theoretical framework of RMF calculations. Recently, Marinov et al. [35] obtained a possible evidence for the existence of a long-lived superheavy nucleus with mass number $A = 292$ and atomic number $Z = 122$ or 124 in natural thorium. The half-life is again estimated to be the same as $T_{1/2} \geq 10^8$ y and the abundance is $(1 - 10) \times 10^{12}$ as compared to $^{232}\text{Th}$. This makes it interesting to make detailed investigation of the properties of nuclei in this mass region.

In extreme superheavy mass region, it is difficult to identify the nuclei by their $\alpha$-decay chains unless a proper combination of neutron and proton close shell are located. Therefore, the identification of nuclei can be made through the comparison with theoretical calculations. In the present investigation we calculate the bulk properties of $Z = 124$ nucleus within the framework of RMF model. Here, we choose NL3 parameter set [36] for isotopic chain with neutron number $N = 158$ to $N = 220$, which encompasses the neutron numbers $N = 172$ and 184. Also, for the consistency of our results we calculate the similar quantities for isotopic chain of $Z = 120$ nucleus.
II. FORMALISM

It has now been well established that the RMF models involving sigma, omega, rho and photon along with the self-interactions among various mesons, i.e., the effective field theory is very successful in explaining the structure of nuclei throughout the nuclear landscape \([37-41]\). The RMF model has been proved to be a very powerful tool to explain the properties of finite nuclei and infinite nuclear matter \([42-44]\) for the last three decades. We start with the modified relativistic Lagrangian density of \(σ−ω\) model \([45]\) for a nucleon-meson many-body system, which describes the nucleons as Dirac spinors interacting through the exchange of scalar mesons \((σ)\), isoscalar vector mesons \((ω)\) and isovector mesons \((ρ)\). The scalar mesons cause attraction and the vector mesons produce repulsion, whereas the charge protons generate electromagnetic interaction.

\[
\mathcal{L} = \bar{\psi}i\gamma^\mu \partial_\mu - M)\psi_i + \frac{1}{2} g_σ^{2}\partial_\mu σ\partial^\mu σ - \frac{1}{2} m_σ^2 σ^2 - \frac{1}{3} g_3 σ^3
\]
\[- \frac{1}{4} g_4 σ^4 - g_5 ψ_i ψ_σ σ - \frac{1}{4} Ω^{\muν} Ω_{\muν} + \frac{1}{2} m_ω^2 ω^\mu ω^\nu - \frac{1}{4} e^2 \omega^\mu \omega^\nu - \frac{1}{4} \vec{B}^\mu \vec{B}^\nu
\]
\[+ \frac{1}{2} m_ρ^2 ρ^\mu \vec{R}^\mu - g_ρ \vec{ρ}^\mu \vec{Γ}_\mu \vec{ρ} - \frac{1}{4} F^{\muν} F_{\muν} - \frac{1}{2} \bar{\psi}_i σ^\mu \left(1 - τ_3\right) \psi_j A_\mu (1).
\]

The field for the \(σ\)-meson is denoted by \(σ\), that for the \(ω\)-meson by \(ω\) and for the isovector \(ρ\)-meson by \(R\). \(A_\mu\) denotes the electromagnetic field. The \(ψ_i\) are the Dirac spinors for the nucleons whose third component of isospin is denoted by \(τ_3\). Here \(g_σ\), \(g_ω\), \(g_ρ\) and \(\frac{e^2}{4\pi} = \frac{1}{137}\) are the coupling constants for \(σ\), \(ω\), \(ρ\) mesons and photon, respectively. \(g_σ, g_ω\) and \(c_3\) are the parameters for the nonlinear terms of \(σ\)- and \(ω\)-mesons. \(M\) is the mass of the nucleon and \(m_σ, m_ω\) and \(m_ρ\) are the masses of the \(σ\), \(ω\) and \(ρ\)-mesons, respectively. \(Ω^{\muν}\), \(\vec{B}^\mu\) and \(F^{\muν}\) are the field tensors for the \(V^\mu\), \(\vec{R}^\mu\) and the photon fields, respectively \([46]\).

For the relativistic Lagrangian, we get the field equations for the nucleons and mesons. These equations are solved by expanding the upper and lower components of Dirac spinors and the Boson fields in a deformed harmonic oscillator basis with an initial deformation. The set of coupled equations is solved numerically by a self-consistent iteration method. The center of mass motion is estimated by the usual harmonic oscillator formula \(E_{c.m.} = \frac{3}{4}(41A^{1/3})\text{ MeV}\). The quadrupole deformation parameter \(β_2\) is evaluated from the resulting quadrupole moment \([46]\) using the formula,

\[
Q = Q_n + Q_p = \sqrt{\frac{9}{5\pi}} AR^2 β_2, (2)
\]

where \(R = 1.2A^{1/3}\text{ fm}\). The total binding energy of the system is,

\[
E_{\text{total}} = E_{\text{part}} + E_σ + E_ω + E_ρ + E_c + E_{\text{pair}} + E_{\text{c.m.}}, (3)
\]

where \(E_{\text{part}}\) is the sum of the single-particle energies of the nucleons and \(E_σ, E_ω, E_ρ, E_c\) and \(E_{\text{pair}}\) are the contributions of the mesons fields, the Coulomb field and the pairing energy, respectively.

For the open shell nuclei, the effect of pairing interactions is added in the BCS formalism. We consider only \(T=1\) channel of pairing correlation, i.e., pairing between proton-proton and neutron-neutron. In such case, a nucleon of quantum state \((|j, m_j\rangle\) pairs with another nucleons having same \(I_z\) value with quantum state \((|−j, −m_j\rangle\), which is the time reversal partner of other. The RMF Lagrangian density only accommodates term like \(ψ^\dagger ψ\) and \(ψ^\dagger ψ^\dagger\) or \(ψ^\dagger ψ\). The inclusion of pairing correlation of the form \(ψ^\dagger ψ^\dagger\) or \(ψ^\dagger ψ\) violates the particle number conservation \([47]\). Thus, a constant gap BCS-type simple prescription is adopted in our calculations to take care of the pairing correlation for open shell nuclei. The general expression for pairing interaction to the total energy in terms of occupation probabilities \(v_i^2\) and \(u_i^2\) is written as \([47, 48]\):

\[
E_{\text{pair}} = -G \left( \sum_{i>0} u_i v_i \right)^2, (4)
\]

with \(G = \text{pairing force constant}\). The variational approach with respect to the occupation number \(v_i^2\) gives the BCS equation \([48]\):

\[
2ε_i u_i v_i - Δ(v_i^2 - u_i^2) = 0, (5)
\]

with \(Δ = G \sum_{i>0} u_i v_i\).

The densities with occupation number is defined as:

\[
n_z = u_i^2 = \frac{1}{2} \left( 1 - \frac{ε_i - λ}{\sqrt{(ε_i - λ)^2 + Δ^2}} \right). (6)
\]

For the pairing gap (Δ) of proton and neutron is taken from the phenomenological formula of Madland and Nix \([49]\):

\[
Δ_n = r \exp(-sI + tI^2) \text{ (7)}
\]

\[
Δ_p = r \frac{3}{4} \exp(sI - tI^2) \text{ (8)}
\]

where, \(I = (N - Z)/A\), \(r = 5.73 \text{ MeV}, s = 0.117\), and \(t = 7.96\).

The chemical potentials \(λ_n\) and \(λ_p\) are determined by the particle numbers for neutrons and protons. The pairing energy of the nucleons using equation (7) and (8) can be written as:

\[
E_{\text{pair}} = -Δ \sum_{i>0} u_i v_i. (9)
\]

In constant pairing gap calculation, for a particular value of pairing gap \(Δ\) and force constant \(G\), the pairing energy \(E_{\text{pair}}\) diverges, if it is extended to an infinite configuration space. In fact, in all realistic calculations with finite range forces, the contribution of states of large momenta above the Fermi surface (for a particular nucleus) to \(Δ\) decreases with energy. Therefore, the pairing window in all the equations are extended up to the level \(|ε_i - λ| ≤ 2A^{1/3}\) as a function of the single particle energy. The factor 2 has been determined so as to reproduce the pairing correlation energy for neutrons in \(^{118}\text{Sn}\) using Gogny force \([46, 47, 50]\).
III. RESULTS AND DISCUSSIONS

The superheavy nucleus $Z = 124$ with neutron number $N = 158 - 220$ are studied for the investigation of ground state properties. The results are compared with other models of previous works including the Finite Range Droplet Model (FRDM), as the experimental observations could not be made at such a high Z region so far. In numerical calculations, the number of oscillator shell for Fermions and Bosons $N_F = N_B = 20$ are used to evaluate the physical observables with the pairing gaps of eqns. (7) and (8) in the BCS pairing scheme.

A. Binding Energy

The binding energy of the isotopic chain of $Z = 124$ is calculated for mass number $A = 282 - 384$. Since there is no experimental observation for such a large $Z$ number so far, therefore, the only comparison can be made with theoretical models such as macroscopic-microscopic model. We compare our calculations with finite range droplet model (FRDM) [51]. Here in upper panel of Fig. 1, we compare the results (binding energy) with available FRDM results, which seem to be in good agreement. A small difference in binding energy at $N = 198$ region can be seen in the upper panel of Fig. 1. For example, the RMF results of binding energy and quadrupole deformation parameter for $^{334}124$ nucleus are 2284.71 MeV and $\beta_2 = 0.128$, whereas the FRDM calculations are 2286.75 MeV and $\beta_2 = 0.335$, respectively. Similarly for $^{312}124$, the RMF binding energy is 2166.19 MeV and FRDM value is 2163.84 MeV with a discrepancy of 2.35 MeV. In $Z = 124$ isotopes, we get a maximum difference in binding energy is 7.43 MeV for $N = 198$ isotopes of $Z = 124$. Except the values at these numbers, in general all other results compared with FRDM [51] agree for nuclei having $N = 172, 184$ and 198 can clearly be seen in both the cases confirming the magic character [24–26, 52] predicted in earlier studies. Although, $N = 172$ is not that much pronounced in our earlier investigation of odd nuclei [52], here the magicity at $N = 172$ increases as we move to extreme of superheavy mass region [53]. Contrary to some earlier literature, there is no signature of sudden change in separation energy at deformed magic number $N = 162$ [24] in the present calculations. The decrease in energy at $N = 172$ and 184 is $\sim 3.5$ MeV whereas $\sim 2$ MeV at $N = 198$, for $Z = 124$ nuclei. In case of $Z = 120$ isotopes the decrease in energy is $\sim 5.0$ MeV at $N = 172$ and $\sim 3.0$ MeV and 3.5 MeV at $N = 184$ and 198 respectively. Such decrease at $N = 198$ in our calculation is nearly same as in FRDM value. However, in FRDM the sudden decrease in separation energy appears at $N = 180$ and 200 for $Z = 124$. Except the values at these numbers, in general all other energies from our present calculations are in good agreement (within $\sim 2$ MeV accuracy) with macro-microscopic calculations (FRDM). We observed a couple of abnormal increase in $S_{2n}$ at ($N=194, Z=124$) and ($N=196, Z=120$), which are not seen in the present RMF calculations.

B. Separation Energy

The magic numbers in nuclei are characterized by the large shell gap in single particle energy levels. This means the nucleon in lower level has comparatively large value of energy than that in higher level giving rise to the more stability. The extra stability corresponding to certain numbers can be estimated from the sudden fall in the neutron separation energy. The separation energy is calculated by the difference in binding energies of two isotopes using relation:

$$S_{2n}(N, Z) = BE(N, Z) - BE(N - 2, Z)$$

\[344\]

C. Quadrupole Deformation Parameter

The quadrupole deformation parameter $\beta_2$ gives the shape of nuclei in ground state. The value of $\beta_2$ is positive, negative and zero for prolate, oblate and spherical respectively. In our calculation shown in Fig. 3, except for few nuclei all the isotopes of $Z = 124$ are either spherical or near spherical. The results compared with FRDM [51] agree for nuclei having $N = 176, 182 - 192$ as shown in the upper panel of Fig. 3. At $N = 176$ and $N = 184$ the nuclei are complete spherical. There is the least agreement beyond $N = 196$ for $Z = 124$. From the

\[345\]
The investigation of $\alpha$-decay of nuclei gives information about their degree of stability and possibility of existence in nature. Here we take the nucleus $^{296}\text{124} (Z = 124$ and $N = 172)$ for the calculation of $\alpha$-decay energy [54]. The $Q_\alpha$-energy and half life ($T_{\alpha}$) are compared with available experimental data as shown in Table 1. The $Q_\alpha$-energy is calculated using the following equation:

$$Q_\alpha(N, Z) = BE(N, Z) - BE(N - 2, Z - 2) - BE(2, 2).$$

In the equation, $BE(N, Z)$ is binding energy of the parent nucleus having $N$ neutrons and $Z$ protons, and $BE(N - 2, Z - 2)$ is the binding energy of daughter nucleus after emission of an $\alpha$-particle ($BE(2,2)$). The binding energy of $\alpha$-particle ($^4\text{He}$) is 28.296 MeV. The $Q_\alpha$ energy values are in good agreement with experimental data [55] as well as FRDM [51] as shown in Table. The decay chain is also plotted in Fig. 4 which shows good agreement with experiments as well as FRDM calculations. The half-life $\log_{10} T_{\alpha}(s)$ values are estimated using the phenomenological formula [56]:

$$\log_{10} T_{\alpha}(s) = \frac{aZ - b}{\sqrt{Q_\alpha}} - (cZ + d) - h_{\log},$$

where $Z$ is atomic number of parent nucleus, and the other parameters are; $a = 1.66175$, $b = 8.5166$, $c = 0.20228$, and $d = 33.9069$. The values of the parameters are used from Sobiczewski et al. [57]. The hindrance ($h_{\log}$) caused by odd number of protons and/or neutrons is zero here.

E. Density Distribution

The neutron and proton density distributions for $Z = 124$ and 120 nuclei are plotted in Fig. 5. The nuclei with $N = 172$, 184 and 198 are taken as representative cases for detailed...
TABLE I: The $Q_\alpha$ and $T_\alpha$ calculated using NL3 parameter set in RMF. The results are compared with finite range droplet model (FRDM)[51] as well as the available experimental data[55]. The binding energy is in MeV and half life is in seconds.

| $A$ | $Z$ | $BE$ | $Q_\alpha$ | $T_\alpha$ | $BE$ | $Q_\alpha$ | $T_\alpha$ | $BE$ | $Q_\alpha$ | $T_\alpha$ |
|-----|-----|------|------------|------------|------|------------|------------|------|------------|------------|
| 296 | 124 | 2056.01| 14.11      | $10^{-6.41}$| 292 | 122 | 2041.83| $10^{-4.68}$| 288 | 120 | 2026.51| $10^{-7.66}$| 2023.06| 13.92 | $10^{-7.02}$|
| 284 | 118 | 2012.49| 13.92      | $10^{-7.50}$| 2008.69| 13.10 | $10^{-5.95}$| 1998.12| 13.14 | $10^{-6.54}$| 1993.49| 12.42 | $10^{-5.10}$|
| 276 | 114 | 1982.96| 11.88      | $10^{-4.48}$| 1977.62| 12.33 | $10^{-5.44}$| 1966.55| 11.68 | $10^{-4.60}$| 1961.66| 11.61 | $10^{-4.45}$|
| 268 | 110 | 1949.93| 11.33      | $10^{-4.38}$| 1944.97| 10.94 | $10^{-3.47}$| 1943.53| 11.7 | $10^{-5.2}$|
| 264 | 108 | 1932.96| 10.56      | $10^{-3.14}$| 1927.62| 10.57 | $10^{-3.18}$| 1926.67| 10.59 | $10^{-3.2}$|
| 260 | 106 | 1915.22| 9.66       | $10^{-4.42}$| 1909.90| 9.93 | $10^{-2.15}$| 1909.06| 9.90 | $10^{-2.07}$|
| 256 | 104 | 1896.59| 8.12       | $10^{-2.73}$| 1891.53| 8.75 | $10^{0.59}$| 1890.56| 8.93 | $10^{0.05}$|
| 252 | 102 | 1876.41| 8.33       | $10^{-1.25}$| 1871.98| 8.35 | $10^{1.19}$| 1871.35| 8.54 | $10^{0.52}$|
| 248 | 100 | 1856.44| 7.07       | $10^{5.15}$| 1852.03| 7.64 | $10^{2.91}$| 1851.57| 8.0 | $10^{1.60}$|
| 244 | 98  | 1835.21| 7.25       | $10^{3.57}$| 1831.38| 6.90 | $10^{1.01}$| 1831.22| 7.32 | $10^{3.30}$|
| 240 | 96  | 1814.17| 5.93       | $10^{8.68}$| 1809.98| 6.52 | $10^{5.81}$| 1810.28| 6.40 | $10^{8.36}$|
| 236 | 94  | 1791.81| 4.30       | $10^{18.29}$| 1788.21| 5.77 | $10^{8.54}$| 1788.41| 5.87 | $10^{8.03}$|
| 232 | 92  | 1767.81| 3.41       | $10^{25.66}$| 1765.69| 5.14 | $10^{11.18}$| 1765.98| 5.41 | $10^{9.50}$|

FIG. 5: (Color online) The density of selected isotopes of $Z = 120$, 124 nuclei with NL3 parameter set.

FIG. 6: Two-dimensional density contours for nuclei 284,290,292,304,318 120 shown using NL3 parameter set.

In general, it is clear from the figures that the central region in all nuclei except $^{308}$124 nucleus have considerably low density. In case of isotopes of $Z = 120$, as shown in Fig. 6, N = 170 nucleus is slightly deformed ($\beta_2 = 0.021$) and all other(N = 164, 170, 184 and 198) are spherical in their ground state. The nuclei with $Z \geq 120$ have large number of protons and hence considerable Coulomb repulsion among protons. The strong repulsion changes the entire distribution of nucleons. The doubly magic nucleus $^{292}$120 is largely studied previously [58–60] and is predicted to be semi-bubble. In the present calculations using RMF(NL3), semi-bubble structure
of these nuclei can be clearly seen in Fig. 6. The hollow region at the center is spread over the radius of 1 - 2 fm. This may suggest that these nuclei might be a fullerene type structure consisting of 60 $\alpha$-particles and a binding neutron per alpha and/ or few neutron clusters. The clusters of some heavier nuclei might be possible. The density distribution of $^{288,294,296,308,322}_{124}$ nuclei is shown in Fig. 7. In this case the density of nucleus $N = 184$ is more at the central region while all other nuclei studied here are showing bubble type structure. The low density region extends up to $\sim 2$ fm. The nuclei with $N = 164$, 170, 172 and 198 are near spherical ($\beta_2 = 0.041$, 0.056, 0.034 and 0.023 respectively) whereas $N = 184$ is spherical in shape. In order to give further insight into the arrangement of nucleons, we plot the density distribution of neutron and proton separately (Fig. 8). It is clear from the figure that both neutrons as well as protons are shifted from the central region except for $N = 184$ nucleus.

IV. CONCLUSION

In the present work we use RMF(NL3) model to explore the structure of superheavy nucleus $Z = 124$. The results of our calculations are compared with macro-microscopic FRDM prediction. We calculate binding energy, quadrupole deformation parameter ($\beta_2$), two neutron separation energy ($S_{2n}$), and decay half-life ($T_{1/2}$) for the isotopic series of $Z = 124$ and for the consistence of our results we calculate the same quantities for $Z = 120$ nucleus. The quadrupole deformation parameter at heavier side of series show more deviation from FRDM values. The two neutron separation energy shows the sudden fall in energy at neutron numbers $N = 172, 184$, and 198 indicating the magic structure. The $\alpha$-decay energy and half-life are also calculated and compared with the experiments and FRDM results which seem to be in good agreement. The density profile of the selected nuclei show that the depression in the density at the central region of the nuclei with the exception of $^{308}_{124}$. This nucleus is the only candidate which does not show the depression at the center. Finally, this theoretical investigation of ground state properties of $Z = 124$ nuclei may be helpful for an experimental exploration to locate the “island of stability” which is expected to be existed in the large Z superheavy region.

FIG. 8: The neutrons and protons density distribution for nuclei $^{296,308,322}_{124}$.

[1] A. Sobie´cze´ski, F. A. Gareev and B. N. Kalinkin, Phys. Lett. B 22, 500 (1966).
[2] H. Meldner and Arkiv Fysik 36, 593 (1967).
[3] W. D. Myers and W. J. Swiatecki, Arkiv Fysik 36, 343 (1967).
[4] S. G. Nilsson et al., Nucl. Phys. A 131, 1 (1966).
[5] U. Mosel and W. Greiner, Z. Phys. 222, 261 (1969).
[6] G. T. Seaborg, J. Chem. Educ. 46, 626 (1969).
[7] S. Hofmann et al., Z. Phys. A 354, 229 (1996).
[8] S. Hofmann and G. Münzenberg, Rev. Mod. Phys. 72, 733 (2000); S. Hofmann et al., Eur. Phys. J. A 14, 147 (2002).
[9] K. Kumar, Superheavy Elements (Adam Higler, Bristol, 1989).
[10] Yu. Ts. Oganessian et al., Phys. Rev. Lett. 83, 3154 (1999).
[11] Yu. Ts. Oganessian et al., Phys. Rev. C 62, 041604(R) (2000); Yu. Ts. Oganessian et al., Phys. Rev. C 63, 011301 (2000).
[12] Yu. Ts. Oganessian et al., Nucl. Phys. A 685, 17c (2001).
[13] Yu. Ts. Oganessian et al., Phys. Rev. C 69, 054607 (2004); Yu. Ts. Oganessian et al., Phys. Rev. C 69, 021601(R) (2004).
[14] Yu. Oganessian, J. Phys. G: Nucl. Part. Phys. 34, R165 (2007).
[15] R. Eichler et al., Nucl. Phys. A 787, 373c (2007).
[16] Y. T. Oganessian et al., Phys. Rev. Lett. 104, 142502 (2010);
[17] Yu. Ts. Oganessian et al., Phys. Rev. C 83, 054315 (2011).
[18] S. Hofmann et al., Z. Phys. A 350, 277 (1995).
[19] S. Hofmann et al., Z. Phys. A 350, 281 (1995).
[20] S. Hofmann et al., Rep. Prog. Phys. 61, 639 (1998).
[21] S. Hofmann et al., Acta Phys. Pol. B 30, 621 (1999).
[22] K. Morita et al., J. Phys. Soc. J pn. 73, 2593 (2004).
[23] K. Morita et al., J. Phys. Soc. Jpn 81, 103201 (2012).
[24] K. Rutz, M. Bender, T. Bürvenich, T. Schilling, P.-G. Reinhard, J. A. Maruhn, and W. Greiner, Phys. Rev. C 56, 238 (1997); M. Bhuyan and S. K. Patra, Mod. Phys. Lett. A 27, 1250173 (2012).
[25] R. K. Gupta, S. K. Patra, and W. Greiner, Mod. Phys. Lett. A 12, 1727 (1997).
[26] S. K. Patra, C.-L. Wu, C. R. Praharaj, and R. K. Gupta, Nucl. Phys. A 651, 117 (1999).
[27] A. T. Kruppa, M. Bender, W. Nazarewicz, P.-G. Reinhard, T. Vertse, and S. Ćwiok, Phys. Rev. C 61, 034313 (2000).
[28] S. Ćwiok, J. Dobaczewski, P.-H. Heenen, P. Magierski, and W. Nazarewicz, Nucl. Phys. A 611, 211 (1996); S. Ćwiok, W. Nazarewicz, and P. H. Heenen, Phys. Rev. Lett. 83, 1108 (1999).
[29] S. Ćwiok, P.-H. Heenen, W. Nazarewicz, Nature 433, 709 (2005).
[30] W. Zhang, J. Meng, S. Q. Zhang, L. S. Geng and H. Toki, Nucl. Phys. A 753, 106 (2005).
[31] R. D. Herzberg et al., Nature (London) 442, 896 (2006).
[32] A. Marinov, I. Rodushkin, Y. Kashiv, L. Halicz, I. Segal, A. Pape, R. V. Gentry, H. W. Miller, D. Kolb, and R. Brandt, Phys. Rev. C 76, 021303(R) (2007).
[33] S. K. Patra, M. Bhuyan, M. S. Mehta, and Raj K. Gupta, Phys. Rev. C 80, 034312 (2009).
[34] Zhongzhou Ren and Hiroshi Toki, Nucl Phys. A 689, 691 (2001).
[35] A. Marinov, I. Rodushkin, D. Kolb, A. Pape, Y. Kashiv, R. Brandt, R. V. Gentry, and H. W. Miller, arXiv:0804.3869v1 [nucl-ex]; A. Marinov, I. Rodushkin, A. Pape, Y. Kashiv, D. Kolb, R. Brandt, R. V. Gentry, H. W. Miller, L. Halicz, and I. Segal, Int. J. Mod. Phys. E 18, 621 (2009).
[36] G. A. Lalazissis, J. König and P. Ring, Phys. Rev. C 55, 540 (1997).