Search of double shell closure in the superheavy nuclei using a simple effective interaction

S. K. Biswal, M. Bhuyan, S. K. Singh and S. K. Patra

Institute of Physics, Sachivalaya Marg, Bhubaneswar-751 005, India.

Received (received date)
Revised (revised date)

This paper refers to another attempt to search for spherical double shell closure nuclei beyond \( Z = 82, N = 126 \). All calculations and results are based on a newly developed approach entitled as simple effective interaction. Our results predict the combination of magic nucleus occurs at \( N = 182 (Z = 114, 120, 126) \). All possible evidences for the occurrence of magic nuclei are discussed systematically. And, the obtained results for all observables compared with the relativistic mean field theory for NL3 parameter.

1. Introduction

Starting from the discovery of nucleus, the formation of new element is an interesting topic in Nuclear Physics. So far the synthesis of heaviest element in laboratory is \( Z = 118 \) in the hot fusion reaction process at JINR Dubna\(^{12}\). The possibility of the existence (synthesis) of these superheavy elements is mainly due to the attractive shell corrections against the destructive Coulomb repulsion. Although atomic number \( Z = 114 \) was predicted to be the next magic number after \( Z = 82 \) and neutron number \( N = 184 \), recently attention has shifted to the nucleus \( Z = 120 \) with \( N = 182/184 \).\(^{345,6}\) The experimental discovery of the superheavy elements also support this prediction to some extent. Thus, the synthesis of \( Z = 120 \) is in full swing at the worlds’ most laboratories like, Dubna (Russia), RIKEN (Japan), GSI (Germany).

Using cold fusion reaction, elements from \( Z = 107 - 112 \) are synthesized at GSI\(^{7,8,9,10,11,21,13}\). At the production time of \( Z = 112 \) nucleus at GSI, the fusion cross section was extremely small \((1 \text{ pb})\)\(^{11} \), which led to the conclusion that reaching still heavier elements will be very difficult by this process. The element \( Z = 113 \) was also synthesized in cold-fusion reaction at RIKEN with a very low cross section \( \sim 0.03 \text{ pb} \)\(^{14} \) confirming the limitation of cold-fusion synthesis. To overcome this problem in hot fusion evaporation reaction with deformed actinide targets and neutron-rich doubly magic spherical projectile like \( ^{48}Ca \) are used in the production of superheavy nuclei \( Z = 112 - 118 \) at Dubna\(^{15,16,17,18,19,20}\).

It is thus a matter of challenge for every theoretical prediction in nuclear physics to find suitable combination of proton and neutron, which gives double closure shell
nuclei beyond $^{208}$Pb and will be the next element of epicenter for experimental synthesis. In the present work, our aim is to look for a suitable combination of proton and neutron in such a way that the resultant combination will be the next magic nucleus after $^{208}$Pb. This work is not a new, but a revisit of our earlier prediction with in a new simple effective interaction (SEI). The SEI interaction is recently developed by us \cite{21} and given a parameter set which is consistent with both nuclear matter and finite nuclei. Here, we have used this SEI interaction. A systematic investigation of the nuclear structure is done and confirmed the double closed nucleus as $Z=120$ with $N=182/184$.

The paper is organized as follows: In Sec. II, the theoretical formalism of the SEI is presented. The procedures for numerical calculations to estimate the binding energy and root mean square radii are outlined. The results and discussions are given in Sec. III. The characteristics of magic structure of nucleus using two neutron separation energy, pairing gap of proton and neutron are analyzed for superheavy region. In this section stability of such nuclei are also studied in terms of the chemical potentials. Finally a summary and a concluding remarks are given in Sec. IV.

2. The Theoretical Framework

2.1. Simple Effective Interaction

The present formalism is based on a simple way to make a consistent parametrization for both finite nucleus and infinite nuclear matter with a momentum dependence finite range term of conventional form, such as Yukawa, Gaussian or exponential to the standard Skyrme interaction \cite{22,23,21}. We have used the technique of Refs. \cite{22,23,21} considering a Gaussian term as the momentum dependence finite range interaction simulation the effect of Gogny type interaction \cite{24,25}. Then it is applied to nuclear equation of state as well as to finite nuclei through out the periodic table \cite{21}. The Hartree-Fock (HF) formalism is adopted to calculate the wave-function of the nuclear system which then used to evaluate the nuclear observables, such as binding energy, root mean square radii etc. The detail formalism and numerical procedure can be found in \cite{21}. The form of the simple effective interaction (SEI) is given by \cite{21},

$$v_{eff}(r) = t_0(1 + x_0P_\sigma)\delta(r) + t_3(1 + x_3P_\sigma)\left(\frac{\rho(R)}{1 + b\rho(R)}\right)\gamma\delta(r) + (W + BP_\sigma - HP_\tau - MP_\sigma P_\tau)f(r) + iW_0(\sigma_i + \sigma_j)(k' \times \delta(r_i + r_j))k.$$

(1)

Where, $f(r)$ is the functional form of the finite range interaction containing a single range parameter $\alpha$. The finite range Gaussian form is given as $f(r) = e^{-r^2}/\alpha^2$. The other terms having their usual meaning \cite{21}. To prevent the supra luminous
Table I. The value of interaction parameters for simple effective interaction (SEI) and RMF (NL3) [33] sets and their nuclear matter properties at saturation.

| SEI | RMF (NL3) |
|-----|-----------|
| $\gamma$ | $M$ (MeV) | 939 |
| $b$ (fm$^3$) | $m_\sigma$ (MeV) | 508.1941 |
| $t_0$ (MeV fm$^3$) | $m_\omega$ (MeV) | 782.6010 |
| $x_0$ | $m_\rho$(MeV) | 7630.0 |
| $t_3$ (MeV fm$^3$(γ+1)) | $g_\sigma$ | 10.2169 |
| $x_3$ | $g_\omega$ | 12.8675 |
| W (MeV) | $g_\rho$ | 8.9488 |
| B (MeV) | $g_2$ (fm$^{-1}$) | -10.4307 |
| H (MeV) | $g_3$ | 28.8851 |
| M (MeV) | $g_\sigma$ | -589.09 |
| $\alpha$ (fm) | $g_\omega$ | -192.16 |
| W$_0$ (MeV) | $g_\rho$ | 0.7596 |
| Nuclear matter | $g_2$ (fm$^{-1}$) | -16.0 |
| $\rho_o$ (fm$^{-3}$) | $g_3$ | -16.24 |
| $e(\rho_0)$ (MeV) | $E_s$ (MeV) | 35.0 |
| $K_0$ (MeV) | $E_s$ (MeV) | 37.4 |
| $K_0$ (MeV) | $\delta (\rho_0)$ (MeV) | 245 |
| $K_0$ (MeV) | $\delta (\rho_0)$ (MeV) | 271.5 |

2.2. Relativistic mean field (RMF) formalism

The starting point of the RMF theory is the basic Lagrangian containing nucleons interacting with $\sigma$, $\omega$- and $\rho$-meson fields. The photon field $A_\mu$ is included to take care of the Coulomb interaction of protons. The relativistic mean field Lagrangian density is expressed as [30,31]:

$$L = \bar{\psi}\left\{i\gamma^\mu \partial_\mu - M\right\}\psi + \frac{1}{2} \partial^\mu \sigma \partial_\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2$$

$$- g_\sigma \bar{\psi} \psi \sigma - \frac{1}{4} \Omega^{\mu\nu} \Omega_{\mu\nu} + \frac{1}{2} m_w^2 V^\mu V_\mu$$

$$- g_\omega \bar{\psi} \gamma^\mu \psi V_\mu - \frac{1}{4} \vec{B}^\mu\nu \cdot \vec{B}_{\mu\nu} + \frac{1}{2} m_\rho^2 \vec{R}^\mu \cdot \vec{R}_\mu$$

$$- g_\rho \bar{\psi} \gamma^\mu \bar{\tau}_i \vec{R}^\mu - \frac{1}{2} m_3^2 \delta^2 + g_8 \bar{\psi} \delta \bar{\tau}_i \psi. \quad (2)$$
Here $M$, $m_\sigma$, $m_\omega$ and $m_\rho$ are the masses for nucleon, $\sigma$-, $\omega$- and $\rho$-mesons and $\psi$ is the Dirac spinor. The field for the $\sigma$-meson is denoted by $\sigma$, $\omega$-meson by $V_\mu$, $\rho$-meson and photon respectively. $g_\sigma$, $g_\omega$, $g_\rho$ and $e^2/4\pi=1/137$ are the coupling constants for the $\sigma$, $\omega$, $\rho$-mesons and photon respectively.

$g_\sigma$ and $g_\rho$ are the self-interaction coupling constants for $\sigma$-mesons. By using the classical variational principle we obtain the field equations for the nucleons and mesons. A static solution is obtained from the equations of motion to describe the ground state properties of nuclei. The set of nonlinear coupled equations are solved self-consistently in one dimensional coordinate \[32\]. The total energy of the system is given by

\[ E_{\text{total}} = E_{\text{part}} + E_\sigma + E_\omega + E_\rho + E_c + E_{\text{pair}} + E_{\text{c.m.}}, \tag{3} \]

where $E_{\text{part}}$ is the sum of the single particle energies of the nucleons and $E_\sigma$, $E_\omega$, $E_\rho$, $E_c$, $E_{\text{pair}}$, $E_{\text{c.m.}}$ are the contributions of the meson fields, the Coulomb field, pairing energy and the center-of-mass motion correction energy, respectively. We have used the well known NL3 parameter set \[33\] in our calculations for RMF formalism.

### 2.3. Pairing Correlation

To take care of the pairing correlation for open shell nuclei the constant gap, BCS-approach is used in our calculations. The pairing energy expression is written as

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

with $G$ is pairing force constant. The quantities $v_i^2$ and $u_i^2 = 1 - v_i^2$ are the occupation probabilities \[34,35,36\]. The variational approach with respect to $v_i^2$ gives the BCS equation

\[ 2\epsilon_i u_i v_i - \Delta (u_i^2 - v_i^2) = 0, \tag{5} \]

using $\Delta = G \sum_{i>0} u_i v_i$. The occupation number is defined as

\[ n_i = v_i^2 = \frac{1}{2} \left[ 1 - \frac{\epsilon_i - \lambda}{\sqrt{(\epsilon_i - \lambda)^2 + \Delta^2}} \right]. \tag{6} \]

The chemical potentials $\lambda_n$ and $\lambda_p$ are determined by the particle number for protons and neutrons. The pairing energy is computed as $E_{\text{pair}} = -\Delta \sum_{i>0} u_i v_i$. For a particular value of $\Delta$ and $G$, 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, $\Delta$ decreases with state for large momenta near the Fermi surface. In the present case, we assume equal pairing gap for all states $| \alpha > | nljm >$ near the Fermi surface. We use a pairing window, where the equations are extended up to the level $\epsilon_i - \lambda \leq 2(41A^{1/3}) \tag{37}$. The factor 2 has been determined so as to reproduce the pairing correlation energy for neutrons in $^{118}\text{Sn}$ using Gogny force \[38,34,35\].
Table 2. The binding energy (BE) obtained from SEI calculation is compared with the RMF(NL3) [33], finite range droplet model (FRDM) [39] and with experimental data of some of the known superheavy nuclei. The BE is in MeV.

| Element | SEI | RMF(NL3) | FRDM | Expt. |
|---------|-----|----------|------|-------|
| $^{258}Md$ | 1896.19 | 1897.70 | 1911.53 | 1911.69 |
| $^{258}Rf$ | 1884.95 | 1890.86 | 1905.25 | 1904.69 |
| $^{261}Rf$ | 1906.38 | 1911.04 | 1924.28 | 1923.93 |
| $^{259}Db$ | 1886.94 | 1894.58 | 1907.00 | 1906.33 |
| $^{260}Db$ | 1894.31 | 1901.4 | 1913.34 | 1912.82# |
| $^{260}Sg$ | 1888.62 | 1897.9 | 1909.90 | 1909.07 |
| $^{261}Sg$ | 1896.17 | 1905.02 | 1916.27 | 1915.68 |
| $^{264}Hs$ | 1906.86 | 1915.5 | 1927.62 | 1926.77 |
| $^{265}Hs$ | 1914.59 | 1922.9 | 1934.40 | 1933.50 |
| $^{269}Ds$ | 1932.81 | 1941.21 | 1952.06 | 1950.290 |
| $^{285}Fl$ | 2029.41 | 2039.19 | 2044.12 | 2040.03# |
| $^{286}Fl$ | 2036.74 | 2046.17 | 2051.59 | 2047.474# |
| $^{287}Fl$ | 2043.36 | 2052.50 | 2057.65 | 2053.19# |
| $^{288}Fl$ | 2050.14 | 2058.73 | 2065.01 | 2060.64# |
| $^{289}Fl$ | 2056.80 | 2064.87 | 2071.04 | 2066.06# |

3. Results and Discussions

The quasi local Density Functional Theory (DFT) is used in this work, which is similar to the one used by Hoffman and Lenske in Ref. [39]. The total energy is nothing but the sum of the energy density contribution from different components of the interaction along with spin-orbit and Coulomb term. The energy density $\mathcal{H}_0$ for SEI set can be expressed as

$$\mathcal{H}_0 = \frac{\hbar^2}{2m} (\tau_n + \tau_p) + \mathcal{H}_{d}^{Nuc}\!l + \mathcal{H}_{exch}^{Nuc}\!l + \mathcal{H}^{SO} + \mathcal{H}^{Coul}. \quad (7)$$

From this effective Hamiltonian $\tilde{\mathcal{H}}$ we obtain the quasi local energy functional as:

$$\varepsilon_0 \left[ \rho^{QL} \right] = \int \mathcal{H}_0 d^3 R. \quad (8)$$

The equations solved self-consistently to get the solution for nucleonic system. Here we have taken only spherical solution for both RMF and SEI.

3.1. Ground state binding energy

The main objective of the present study is to find the double shell closure in the superheavy valley. In this context, we have concentrated on few observables such as separation energy $S_{2n}$, chemical potential $\mu_n$, single-particle levels $E_{n,p}$ and pairing energy $E_{pair}$. Before going to this unknown region (superheavy valley), it is
important to test our model for known magic nuclei, which are experimentally and theoretically well established. We calculate the binding energy of few known superheavy nuclei using SEI. The obtained results are compared with RMF, finite-Range-Droplet-Model (FRDM) and experimental data in Table II. The # marks in the experimental column are for the extrapolated data from Ref. From the table, we find that the SEI and NL3 results are overestimated to the experimental values. A close observation of the table shows the superiority of FRDM over SEI or NL3 for lighter mass of the superheavy nuclei. In contrast to the lighter region, the SEI predicts better results for heavier isotopes. For example, binding energy of $^{289}$Fl is 2056.80 $MeV$ in SEI, whereas the values are 2064.87, 2071.04 and 2066.06 $MeV$ in RMF(NL3), FRDM and experiment (or systematics), respectively. Based on this trend, one can expect that the prediction of SEI gives us better insight about the magic structures of superheavy nuclei in heavier mass region, which is the main objective of the present investigation.

3.2. Density distribution of neutrons and protons

After convinced with the binding energy of the superheavy nuclei, we present the density distribution of protons and neutrons in Figure 1. The densities are compared with the RMF(NL3) calculations. In general, the RMF and SEI densities are almost
similar with each other. However, a proper inspection reveals that the SEI densities slightly over estimate the RMF(NL3) densities. This overestimation is mostly at the middle region of the nucleus. The humps at the central region for both the densities show shell effect for all nuclei shown in the figure.

3.3. Two neutron separation energy and location of closed shell

From the binding energy, we have calculated the two neutron separation energy using the relation $S_{2n}(N, Z) = BE(N, Z) - BE(N - 2, Z)$. The $S_{2n}$ for all the four isotopic chains are shown in Fig. 2 as a function of neutron number. In case of Pb isotopes, the sudden decrease of $S_{2n}$ at neutron number $N=126$, is the well known neutron magic number for the largest known $Z=82$ magic nucleus. The analysis is extended to the recently predicted proton magic numbers like $Z=114$, 120 and 126, which are currently under scrutiny for their confirmation.

It is important to mention that, the next proton magic number beyond $Z=82$ would be $Z=126$ considering the traditional proton and neutron and neutron magic numbers for known closed shell nuclei. However, several microscopic calculations suggest a shift of this number to 114. One of the cause of the shift is the Coulomb effect on the spherical single particle levels. The use of shell
correction by V. M. Strutinsky\cite{50} to the liquid-drop calculation of binding energy (BE) opens a more satisfactory exploration towards the search of double closed nucleus beyond $^{208}\text{Pb}$. Using this approach, $Z=114$ is supported to be the proton magic after $^{82}\text{Pb}$\cite{51,52,53,54}, which was regarded as the magic number in the super-heavy valley\cite{55} with $N=184$ as the corresponding neutron magic number. However, the recent relativistic mean field calculations using various force parameters\cite{5}, predict $Z=120$ as the next magic number with $N=172/182$ as the neutron closed shell. Contrary to all these predictions, some non relativistic calculations report $Z=126$ as the next magic proton in the superheavy valley. The microscopic calculations using Skyrme Hartree-Fock formalism predict $N=182$ as the next neutron closed shell after $N=126$, which differs by 2 unit from other predictions\cite{5}.

Analyzing the $S_{2n}$ energy for the isotopic chain of $Z=82$, 114, 120, 126, the sharp fall of $S_{2n}$ at $N=126$ is a clear evidence of magic combination of $Z=82$ and $N=126$. Our newly developed SEI model and previously existing NL3 follow the same trend as experiment. But whenever we analyzed the plots of $Z=114$, 120, 126 find a slight difference in two models (SEI and RMF). In RMF(NL3), when we go
from one magic neutron number to the next one, the $S_{2n}$ energy suddenly decreases to a lower value, which reflect in Fig. 2. In SEI, the $S_{2n}$ energy follows same pattern but the magnitude of decreseness some how less.

3.4. **Pairing gaps and pairing energy**

Another important quantity, which helps us to locate the closed shell is the pairing gaps of proton and neutron in a constant force BCS calculation. Here, we calculate the pairing gap for the isotopic chain of $Z=82$, 114, 120 and 126 and locate the minimum values of $\Delta_n$ and $\Delta_p$. The results are depicted in Figures 3 and 4 and also compared with the RMF(NL3) force. It is well known that NL3 force satisfies this criteria for the location of magicity. Although, SEI overestimates the paring gaps of $\Delta_n$, $\Delta_p$, the trend for both NL3 and SEI are found to be similar. Consistence with NL3 results as well as with earlier calculations with a variety of force parameters, our present SEI reproduces minima at $N=182/184$ and $Z=120$ and to some extent at $Z=114$.

To see the trend of pairing energy $E_{pair}$ at the discussed neutron number $N=184$, the
we plot $E_{\text{pair}}$ as a function of neutron number $N$ in Figure 5. Surprisingly, we get almost zero pairing energy at $N=126$ for $Z=82$ isotopic case. The formalism is extended to $Z=114$, 120 and 126 cases. We find minimum or zero $E_{\text{pair}}$ at $N=182/184$ confirming the earlier predictions of this neutron magic number at $N=182/184$. Qualitatively, the SEI interaction follows the trend of RMF(NL3) as shown in Fig 5, but fails when we have a quantitative estimation. For example, the $\Delta_n$ or $E_{\text{pair}}$ at $N=182/184$ is minimum but has a finite value unlike to the NL3 prediction. As a matter of fact, the validity of pairing scheme to this region of nuclei may not be 100% applicable. The importance of pairing is needed to keep the value of $\Delta_n$ and $\Delta_p$ zero at the appropriate magic number.

3.5. Chemical energy and stability

It is to be noted that one can find similar information about the stability of a nucleus either from the chemical potential or the nucleon separation energy. However, the neutron or proton separation energies are obtained from the binding energy, whereas the chemical potential (both for proton and neutron) calculated self-
consistently while solving the field equations. To see the consistency between these two observables ($S_{2q}$ or $\mu_q; q=n, p$), we have analyzed these quantities separately in the present paper. For a bound nucleus, both the chemical potentials of protons $\mu_p$ and neutrons $\mu_n$ must be negative. To realize the relative stability from chemical point of view, we have plotted $\mu_p$ and $\mu_n$ with neutron number in Fig. 6. The results are also compared with the $\mu-$value of NL3 set. In both the cases, we find similar chemical potential. In some previous papers it was suggested that we can take $N=172$ as magic number for neutron. But our SEI model show that the combination $Z=120$ and $N=172$ is strictly not allowed. Because in this case $\mu_p = 0.69$ MeV, which gives proton instability. However NL3 result shows this combination is a loosely bound system having $\mu_p = -1.240$ MeV and $\mu_n = -7.007$ MeV. Although the BE/A curve show a local maximum at $Z=114$ and $N=172$ in SEI model, we can not take this as a stable system because of $\Delta_n$ and $\Delta_p$ value, which does not shows any signature of stability. The SEI model gives a clear picture that the isotope $^{302}_{120}$ be, a suitable combination for the next double closed nucleus. One
can justify it by analysis of BE/A data of $^{302}120$. For example $BE/A = 7.007$ MeV which create a local maxima in its neighborhood for $^{302}120$. In the same time, the optimum negative value of chemical potential energies of $\mu_n$ and $\mu_p$ gives a sign of maximum stability. A similar analysis of numerical data for $\mu_p$ of isotopes of $Z=126$ shows that there is no reason of taking $Z=126$ and $N=182/184$ as a stable combination. This is because of the positive value of $\mu_p$ (1.36) MeV.

3.6. Single particle energy

The single particle energies for $^{304}120$ with NL3 and SEI for proton and neutron are shown in Fig 7. The single particle solutions are obtained without including the pairing correlation into account to intact the degeneracy of the levels. The calculation of single particle energies of SEI with pairing shows that the degeneracy of the energy levels are not invariant. The basic cause of this discrepancy is the over estimation of our pairing strength in SEI model which may be an interesting analysis for pairing in future. The filling up single particle energy levels for neutrons in SEI with pairing is different from that of without pairing. The energy levels without pairing are given by [178] $(3d_{3/2})^4, (4s_{1/2})^2$ while the same with pairing are [178] $(3d_{3/2})^3, (4s_{1/2})^1, (1j_{11/2})^2$. That means an empty orbital is created at $4s_{1/2}$ and
occupied in $1j_{11/2}$. We have also analyzed the single particle levels for $^{302}120$, which is not given in the figure. From the anatomy of $\epsilon_n$ and $\epsilon_p$, we find large gaps at neutron number $N=184$ and proton number $Z=120$. The value of neutron gap at $N=184$ is $1.949 \text{ MeV}$ and that of proton is $1.275 \text{ MeV}$ for the last occupied and first unoccupied nucleon. On the other hand the neutron and proton gap for $^{302}120$ are respectively $\sim 0.6$ and $\sim 1.663 \text{MeV}$. The above data say the energy gaps for the neutron and proton in $^{304}120$ are greater than the gap in $^{302}120$. This give us an indication to take the combination $N=184$ and $Z=120$ as the next magic nucleus. From the analysis of single particle energy level of $^{304}120$ with NL3 parameter set one can see the neutron and proton gaps are $1.4503 \text{ MeV}$ and $2.1781 \text{ MeV}$ respectively for the last occupied and first unoccupied nucleon. The RMF(NL3) and SEI data are comparable with each other.

4. Summary and Conclusions

In summery, we have calculated binding energy $S_{2n}$ energy, single particle levels, pairing gaps and chemical potential, in the isotopic chain of $Z=82, 114, 120$ and 126. All our calculations are done in the frame work of SEI interaction. We have compared our results with standard RMF(NL3) interaction. Over all discussion and analysis of all possible evidences of shell closure property show that, one can take $Z=120$ and $N=182$ as the next magic combination beyond $Z = 82$ and $N = 126$, which is different from Skyrme, Gogny, RMF(NL3) by two unit. However on the basis of single particle energy levels, the preferred gap is at $N=184$ which is consistent with these (Skyrme, Gogny and RMF) force parameters. This happens due to the overestimation of pairing strength. As we only use SEI interaction to predict the magic nuclei, so it is out of scope of our status to change its original pairing strength. We can just make a comments to this observation and left for further study.

5. Acknowledgments

We thanks Ms. Shikha for careful reading of the manuscript.

References

1. Yu. Ts. Oganessian et al., Phys. Rev. C, 74, (2006) 044602.
2. Yu. Ts. Oganessian et al., Phys. Rev. Lett, 109, (2012) 162501.
3. S.K. Patra, R.K Gupta and W. Greiner, Mod. Phys. Lett. A12 (1997) 1727.
4. K. Rutz ,M. Bender , T. Bürvenich, T. Schilling ,P.-G. Reinhard , J. A. Maruhn and W. Greiner, Phys. Rev. C 56, (1997) 238.
5. M. Bhuyan and S.K. Patra, Mod. Phys. Lett.A 27, (2012) 1250173.
6. Tapas Sil,S. K. Patra, B. K. Sharma , M. Centelles and X. Viñas, Phys. Rev. C 69, (2004) 044315.
7. S. Hofmann and G. Münzenberg, Rev. Mod. Phys. 72, (2000) 733.
8. G. Münzenberg et al., Z. Phys. A 300, (1981) 107.
9. S. Hofmann et al., Z. Phys. A 350, (1995) 277.
10. S. Hofmann et al., Z. Phys. A 350, (1995) 281.
11. S. Hofmann et al., Z. Phys. A 354, (1996) 229.
12. S. Hofmann et al., Rep. Prog. Phys. 61, (1998) 639; Acta Phys. Pol. B 30, (1999) 621.
13. S. Hofmann, Russ. Chem. Rev. 78, (2009) 1123.
14. K. Morita et al., J. Phys. Soc. Jpn. 76, (2007) 043201; 2007 ibid 76 045001.
15. Yu.Ts. Oganessian, Phys. Rev. Lett. 83, (1999) 3154.
16. Yu.Ts. Oganessian et al., Nucl. Phys. A 685, (2001) 17c.
17. Yu.Ts. Oganessian et al., Phys. Rev. C 69, (2004) 021601(R).
18. Yu.Ts. Oganessian, J. Phys. G: Nucl. Part. Phys. 34, (2007) R165.
19. Yu. Ts. Oganessian et al., Phys. Rev. Lett. 104, (2010) 142502.
20. Yu. Ts. Oganessian et al. Phys. Rev. C 83, (2011) 754315.
21. B. Behera , X. Viñas, M. Bhuyan, T. R. Routray, B. K. Sharma and S. K. Patra, J. Phys. G: Nucl. Part. Phys. 40, (2013) 095105; T. R. Routray, X. Vinas, S. K. Tripathy, M. Bhuyan, S. K. Patra and B. Behera, J. Phys.: Conf. Ser., 420 (2013) 012114.
22. B. Behera, T. R Routray and R. K. Satpathy, J. Phys. G: Nucl. Part. Phys. 24 (1998) 2073.
23. B. Behera , T. R Routray, B. Sahoo and R. K. Satpathy, Nucl. Phys. A 699 (2002) 770.
24. J. Decharge and D. Gogny, Phys. Rev. C 21 (1980) 1568.
25. J. F. Berger , M. D. Girod, D. Gogny, Nucl. Phys. A 428 (1984) 23c.
26. B. Behera, T. R. Routray, A. Pradhan, S. K. Patra and P. K. Sahu, Nucl. Phys. A 753 (2005) 367.
27. B. Behera, T. R. Routray, A. Pradhan , S. K. Patra and P. K. Sahu, Nucl. Phys. A 794 (2007) 132.
28. B. Behera, T. R. Routray and S. K. Tripathy, J. Phys. G: Nucl. Part. Phys. 36 (2009) 125105.
29. B. Behera , T. R. Routray and S.K. Tripathy, J. Phys. G: Nucl. Part. Phys. 38 (2011) 115104.
30. J. Boguta and A. R Bodmer, Nucl. Phys. A 292 (1977) 413.
31. B. D Serot and J. D Walecka, Adv. Nucl. Phys. 16 (1986) 1.
32. M. Del Estal, M. Centelles, X. Viñas and S. K. Patra, Phys. Rev C 63 (2001) 024314; M. Del Estal, M. Centelles , X.Vinéas and S. K. Patra, Phys. Rev. C 63 (2001) 044321.
33. G. A. Lalazissis, J. König and P. Ring Phys. Rev. C 55 (1997) 540.
34. S.K Patra, Phys. Rev. C 48 (1993) 1449.
35. P.Pannert, P. Ring, and J. Boguta, Phys. Rev. Lett. 59 (1987) 2420.
36. M. A. Preston and R.K. Bhaduri, Structure of Nucleus, Addison-Wesley Publishing Company, Ch. 8 (1982) page 309.
37. S. K. Patra, M. Bhuyan, M. S. Mehta and Raj K. Gupta, Phys. Rev. C 80 (2009) 034312.
38. J. Decharge and D. Gogny, Phys. Rev. C 21 (1980) 1568.
39. F. Hoffmann and H. Lenske, Phys. Rev. C 57 (1998) 2281.
40. P. Möller, J. R. Nix, W. D. Wyers and W. J. Swiatecki, At. Data Nucl. Data Tables 59 (1995) 185; P.Möller J. R. Nix and K. L. Kratz ibid., 66 (1997) 131.
41. M. Wang, G. Audi, A. H. Wapstra, F.G. Kondev, M. MacCormick, X. Xu and B. Pfeiffer, Chin. Phys. C (HEP&NP) 36 (2012) 12.
42. Schiffl-Goldhaber, Nucleonics 15 (1957) 122.
43. W.D. Myers and W.J. Swiatecki, Nucl. Phys. 81 (1966) 1.
44. S.G. Nilsson , Mat. Fys. Medd. Dan. Vid. Selsk, 29 (1995) 16.
45. B.R. Mottelson and S.G. Nilsson, *Phys. Rep.* **99** (1995) 1615; *Mat. Fys. Skr. Dan. Vid. Selsk* **8** (1959) 1.
46. G. Andersson, S.E Larsson, G. Leander, S.G Nilsson, I. Ragnarsson and S. Aberg, *Phys. Lett. B* **65** (1976) 209.
47. H. W. Meldner, *Ark. Fys.* **36** (1978) 593.
48. H. W. Meldner, in *Superheavy Elements* ed. M. A. K. Lodhi, (Oxford: Pergamon) p. 495.
49. H.S K"ohler, *Nucl. Phys. A* **162** (1971) 385.
50. V. M. Strutinsky, *Nucl. Phys. A* **95** (1967) 420; **122** (1968) 1.
51. P. Möller and J.R Nix, *J. Phys. G* **20** (1994) 1681.
52. A. Sobiczewski, *Phys. Part. Nucl.* **25** (1194) 295.
53. A. Sobiczewski and K. Pomorski, *Prog. Part. Nucl. Phys.* **58** (2007) 292.
54. R. Smolanczuk, j. Skalski and A. Sobiczewski, *Phys. Rev. C* **52** (1995) 1871.
55. K. Kumar, *Superheavy Elements* (IOP Publishing Ltd. 1989); *Physica Scripta*, **T32** (1990) 31.