Deformation and orientation effects in the driving potential of the dinuclear model

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Abstract

A double-folding method is used to calculate the nuclear and Coulomb interaction between two deformed nuclei with arbitrary orientations. A simplified Skryme-type interaction is adopted. The contributions of nuclear interaction and Coulomb interaction due to the deformation and orientation of the nuclei are evaluated for the driving potential used in the description of heavy-ion fusion reaction. So far there is no satisfactory theory to describe the evolution of the dynamical nuclear deformation and orientations during the heavy-ion fusion process. Our results estimated the magnitude of above effects.

PACS numbers: 25.70. Jj; 25.70. -z; 24.10. -i

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I. INTRODUCTION

The activity of the study on the synthesis of super-heavy elements is still maintained in both experimentally and theoretically. On the experimental branch, S. Hofmann et. al in GSI, Darmstadt, performed experiments on the synthesis and identification of the nuclei $^{272}111$ and $^{277}112$ in order to confirm their previous results obtained in the middle of 90s of last century [2, 3]. Furthermore, several additional decay chains from the reactions $^{64}Ni + ^{208}Bi \rightarrow ^{273}111^*$ and $^{70}Zn + ^{208}Pb \rightarrow ^{278}112^*$ were also measured. The joint IUPAC-IUPAP Working Party (IWP) has confirmed the discovery of element with atomic number 110, which is named as darmstadtium (Ds), recently the new element with atomic number 111 has also been proposed by IWP to be named as roentgenium (Rg). Experiments on the synthesis of new elements with atomic numbers 115 as well as 113 in the reaction $^{243}Am + ^{48}Ca$ were carried out at the U400 cyclotron in Dubna [4], recently they also reported the results of excitation-function measurements for the $^{244}Pu + ^{48}Ca$ fusion-evaporation reactions for element 114 and the synthesis of new isotopes of element 116 with the $^{245}Cm + ^{48}Ca$ reaction [5].

On the theoretical branch, the physics on the more complicated dynamical process to super-heavy elements has been paid more attention [6] and investigated by several groups under different mechanisms, for example, the di-nuclear concept (see the recent works in [7, 8] and the references therein), the fluctuation-dissipation model [10, 11], the concept of nucleon collectivization [12, 13], as well as the macroscopic dynamical model [14, 15].

In the di-nuclear system (DNS) concept [7, 8, 9, 16, 17, 18], the fusion process is considered as the evolution of a di-nuclear system caused by the transfer of nucleons from the light nucleus to the heavy one. The nucleon transfer process is described in Ref. [8] by solving the master equation numerically. It is found that the fusion probability of the compound nucleus is very sensitive to the specific form of the driving potential. In Ref. [8], the Coulomb interaction potential of deformed nuclei with a tip-tip orientation is considered. However, spherical nuclei were adopted in calculating the nuclear interactions since it is thought that the nuclear interaction does not depend so strongly on the deformation of the nuclei as the Coulomb interaction due to the short range characteristics of the nuclear force. Although some reasonable results, such as the optimal excitation energies, the residual cross sections of super-heavy compound nuclei, were obtained for different heavy-ion fusion reactions, the
reliability has to be checked.

Presently a double-folding method is developed to calculate the nuclear and Coulomb interactions between the two deformed nuclei with arbitrary orientations. Here we consider the ground state deformations of the nuclei for all possible combinations of the DNS of a certain reaction. In principle, the deformed nuclei can have different relative orientations which supply quite different conditions for fusion. Some averaging over the orientations of the nuclei has to be carried out at least in the entrance channel. The deformation and the orientation evolutions are difficult to be described, which have not yet been investigated very well by any model so far. Nevertheless, it is important to bear in mind: what are the magnitudes that the deformation of nuclei contributes to the nuclear and Coulomb interactions, respectively, and to explore how and to which extent the orientations contribute. These investigations will give a direction for further improvement.

The paper is arranged as follows. In the next section, the treatment of the nuclear and Coulomb potentials is introduced. We present the calculated results and the corresponding discussions in Section III, where the interaction potentials between different deformed nuclei and their dependence on orientations as well as the driving potentials used in the DNS model for different fragmentations in reactions leading to $^{272}Ds$. Finally, Section IV gives a brief conclusion and outlook.

II. TREATMENT OF DRIVING POTENTIALS FOR ORIENTATED DEFORMED NUCLEI OF DNS

For a dinuclear system, the local excitation energy is defined as follows,

$$\epsilon^* = E^* - U(A_1, A_2, R) - \frac{(J - M)^2}{2J_{rel}} - \frac{M^2}{2J_{int}}. \tag{1}$$

where $E^*$ is the intrinsic excitation energy of the dinuclear system converted from the relative kinetic energy loss, $M$ is the corresponding intrinsic spin due to the dissipation of relative angular momentum $J$. $J_{rel}$ and $J_{int}$ are the relative and intrinsic moments of inertia respectively. $U(A_1, A_2)$ is the driving potential energy responsible for the nucleon transfer in the DNS model, and is written down as,
\[ U(A_1, A_2, R) = U_{LD+SC}(A_1)+U_{LD+SC}(A_2)-U_{LD+SC}(A_{CN})+U_C(A_1, A_2, R)+U_N(A_1, A_2, R), \]

(2)

where \( A_1, A_2, \) and \( A_{CN} \) represent the mass numbers of the two nuclei and the corresponding compound nucleus, respectively, we have \( A_1 + A_2 = A_{CN}. \) In the DNS model, the driving potential is normally given as a function of \( \eta = (A_1 - A_2)/A_{CN}. \) The first three parts of the right hand side of the equation are calculated from the Liquid-Drop model plus the shell and pairing corrections \[19, 20\]. \( U_C(A_1, A_2, R) \) and \( U_N(A_1, A_2, R) \) are the corresponding Coulomb and nuclear potential energies between the nuclei and depend on the fragmentation of the dinuclear system, on the internuclear distance \( R \) and on the orientation and deformation of the nuclei. They could be calculated by different methods. In the present work, we calculate them by using the double-folding method

\[ U(r_1 - r_2) = \int \rho_1(r_1)\rho_2(r_2)v(r_1 - r_2)d\mathbf{r}_1d\mathbf{r}_2 \]

(3)

where \( \rho_1(r_1) \) and \( \rho_2(r_2) \) are the density distribution of 1 and 2 nucleons in a dinuclear system, \( v(r_1 - r_2) \) is the corresponding interaction between the two points. For the nuclear part \( U_N \) we use densities with a smooth falling off at the surface (see later) and constant densities for the Coulomb interaction. The long-range Coulomb interaction is not sensitive to the density at the surface which allows to simplify the calculations. Therefore, we write the Coulomb interaction as follows,

\[ U_C(R) = \rho_1^0\rho_2^0 \int \frac{d\mathbf{r}_1d\mathbf{r}_2}{|\mathbf{r}_1 - \mathbf{r}_2 - \mathbf{R}|}, \]

(4)

where \( \mathbf{R} \) is the vector between the two centers of the nuclei ("T" and "P") as illustrated in Fig.1. The charge densities are set as \( \rho_1^0 = \frac{Z_1}{\Omega_1} \) and \( \rho_2^0 = \frac{Z_2}{\Omega_2} \) where \( Z_{1,2} \) and \( \Omega_{1,2} \) are the proton numbers and the volumes of the two nuclei, respectively. The symmetry axes (\( \vec{a}_1 \) and \( \vec{a}_2 \)) of the two deformed nuclei and the \( \vec{z} \)-axis are assumed to be in the same plane. \( \gamma_1 \) and \( \gamma_2 \) are the corresponding angles between the symmetric axes and \( \vec{z} \)-axis, i.e., which represent the different orientations of the two nuclei, while \( \alpha_1 \) and \( \alpha_2 \) are the angles between arbitrary vectors \( \mathbf{r}_{1,2} \) and the symmetric axes \( \vec{a}_1 \) and \( \vec{a}_2 \), respectively. The distance between the two points is given by

\[ |\mathbf{r}_1 - \mathbf{r}_2 - \mathbf{R}| = \sqrt{(\mathbf{r}_1 - \mathbf{r}_2)^2 + R^2 - 2(\mathbf{r}_1 - \mathbf{r}_2) \cdot \mathbf{R}} \]

(5)
FIG. 1: Schematic presentation of the orientation of two axially quadrupolly deformed nuclei.

It is easy to find the following relations,

\[(r_1 - r_2)^2 = r_1^2 + r_2^2 - 2r_1r_2(\sin \theta_1 \sin \theta_2 \cos(\phi_1 - \phi_2) + \cos \theta_1 \cos \theta_2)\],

\[(r_1 - r_2) \cdot R = (r_1 \cos \theta_1 - r_2 \cos \theta_2)R\].

where \(\theta_{1,2}\) and \(\phi_{1,2}\) are the angles of \(r_{1,2}\) with respect to the coordinates \((\vec{x}, \vec{y}, \vec{z})\) and \((\vec{x}', \vec{y}', \vec{z}')\), respectively.

The upper and lower limits of \(r_{1,2}, \theta_{1,2}, \) and \(\phi_{1,2}\) are

\[r_{1,2} : (0, R(\alpha_{1,2})); \quad \theta_{1,2} : (0, \pi) ; \quad \phi_{1,2} : (0, 2\pi)\].

where \(R(\alpha)\) describe the nuclear surface with quadrupole deformations.

\[R(\alpha_i) = R_0(1 + \beta_2^i Y_{20}(\alpha_i))\].

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Here $R_{0i}$ are the spherical radii of the two nuclei which preserve their fixed volumes. $Y_{20}(\alpha) = (5/4\pi)^{1/2}P_2(\cos \alpha) = (5/4\pi)^{1/2}(3 \cos^2 \alpha - 1)/2$ is spherical harmonics and the axial symmetry is preserved. The $\beta_i^2$ is the quadrupole deformation parameter of $i$-nucleus taken from Ref. [20]. It is easy to write down the expressions for $\alpha_1$ and $\alpha_2$ as

$$\cos \alpha_1 = \hat{a}_1 \cdot \hat{R}(\alpha_1) = \sin \theta_1 \cos \phi_1 \sin \gamma_1 + \cos \theta_1 \cos \gamma_1, \quad (10)$$

and

$$\cos \alpha_2 = \hat{a}_2 \cdot \hat{R}(\alpha_2) = \sin \theta_2 \cos \phi_2 \sin \gamma_2 + \cos \theta_2 \cos \gamma_2. \quad (11)$$

For the nuclear potential, following the work by Adamian et al. [18], we adopt the Skyrme-type interaction without considering the momentum and spin dependence, in which a zero-range treatment of the effective interaction $\delta(r_1-r_2)$ is assumed. The nuclear potential is obtained in the sudden approximation [18],

$$U_N(R) = C_0 \left\{ \frac{F_{in}-F_{ex}}{\rho_{00}} \left( \int \rho_1^2(r)\rho_2(r-R)dr \right) + \int \rho_1(r)\rho_2^2(r-R)dr + \int \rho_1(r)\rho_2(r-R)dr \right\} \quad (12)$$

with

$$F_{in,ex} = f_{in,ex} + f_{in,ex}' \frac{N_1 - Z_1}{A_1} \frac{N_2 - Z_2}{A_2}. \quad (13)$$

Here $N_{1,2}$ and $Z_{1,2}$ are the neutron and proton numbers of the two nuclei respectively. Obviously the isospin effect of the nucleon-nucleon interaction is considered here though the relative influence is small. The parameters $C_0 = 300 \text{ MeV} \cdot \text{fm}^3$, $f_{in} = 0.09$, $f_{ex} = -2.59$, $f_{in}' = 0.42$, $f_{ex}' = 0.54$, and $\rho_{00} = 0.17\text{fm}^{-3}$ are also used in this work. The functions $\rho_1$ and $\rho_2$ are two-parameter Woods-Saxon density distributions (now we set the center of the "P"-nucleus at the coordinate origin and $r_1 = r$)

$$\rho_1(r) = \frac{\rho_{00}}{1 + \exp((r - \tilde{R}_1(\alpha_1))/a_{\rho_1})} \quad (14)$$

and

$$\rho_2(r) = \frac{\rho_{00}}{1 + \exp((|r - \tilde{R}_2(\alpha_2)|)/a_{\rho_2})}, \quad (15)$$

The parameters $a_{\rho_1}$ and $a_{\rho_2}$ represent the diffuseness of the two nuclei, respectively. Whereas $\cos \alpha_1$ is given in Eq. (10), we use the following formula with $|r - \tilde{R}| = \sqrt{r^2 + \tilde{R}^2 - 2r\tilde{R}\cos \theta}$
\[
\cos \alpha_2 = \frac{(r - R) \cdot \hat{a}_2}{|r - R|}
\]
\[
= \frac{r (\sin \theta \cos \phi \sin \gamma_2 + \cos \theta \cos \gamma_2) - R \cos \gamma_2}{r^2 + R^2 - 2rR \cos \theta}.
\]

We directly calculate the six- and three-dimensional integrals in Eqs. (11) and (12) numerically. For Eq. (12), a truncation parameter \( r_{\text{cut}} \) for the upper limit of \( r \) is introduced due to the long tails of the nuclear densities expressed in Eqs. (14) and (15). For each mass asymmetry we calculated the sum of the Coulomb and nuclear potential energies as a function of the internuclear distance \( R \) and took the potential at the minimum in \( R \) which is shorter than \( R_{\text{CB}} \) (Coulomb-barrier saddle point) as the driving potential of the DNS model.

III. NUMERICAL RESULTS

In this paper, the nuclear and Coulomb interaction for the DNS of the reaction \(^{64}Ni + ^{208}Pb \rightarrow ^{272}Ds\) is studied by taking the nuclear deformations and the corresponding orientations into account. For simplicity, the diffuseness parameters \( a_{\rho_1} \) and \( a_{\rho_2} \) are chosen as \( a_{\rho_1} = a_{\rho_2} = 0.6\text{fm} \), which is a little bit larger than those in Ref. [18]. Furthermore, \( r_{01} = r_{02} = 1.2\text{fm} \) is used. The parameter \( r_{\text{cut}} = 25\text{fm} \) for the radial integration of the nuclear potential of the deformed nucleus in Eq. (12), is taken for an adequate precision.

Fig. 2(a) and (b) show the nuclear interaction potentials of two sets of projectile-target combinations, namely \(^{28}Na + ^{244}Es\) and \(^{74}Zn + ^{198}Hg\), to form the same compound nucleus \(^{272}Ds\) as a function of distance \( R \) between the centers of the two nuclei. The corresponding nucleus-nucleus potentials including both the nuclear and Coulomb interactions are given in Fig. 2(c) and (d). In Fig. 2(a) and (c), both nuclei are prolate deformed, \(^{28}Na\) with \( \beta_2 = 0.257 \) and \(^{244}Es\) with \( \beta_2 = 0.234 \), respectively, while in Fig. 2(b) and (d), \(^{74}Zn\) is prolate and \(^{198}Hg\) oblate with \( \beta_2 = 0.125 \) and \(-0.112\), respectively. The system \(^{74}Zn + ^{198}Hg\) is more mass-symmetric, i.e., it has a smaller \( |\eta| \) than the system \(^{28}Na + ^{244}Es\), and thus a higher Coulomb potential energy. In each panel, different orientations for the two systems, i.e., tip-tip, tip-belly and belly-belly orientations are investigated, an illustration is shown in (c) plot. When both \( \beta_2 \) values are positive in (a) and (c), the angles \( (\gamma_1, \gamma_2) = (0^0, 180^0), (0^0, 90^0), \) and \( (90^0, 90^0) \) are the corresponding ones for the tip-tip, tip-belly, and belly-belly cases,
respectively, while for the case of $\beta_2^1 > 0$ and $\beta_2^2 < 0$ in cases (b) and (d), $(\gamma_1, \gamma_2) = (0^0, 90^0), (0^0, 0^0)$, and $(90^0, 0^0)$, respectively. The two nuclei become more compact with a belly-belly orientation in contrast to the tip-tip one, and the minimum of the potential energy for a belly-belly orientation is at a smaller $R$ than that of the tip-tip case. When the orientation changes from the tip-tip type to the belly-belly one, the minima of the nuclear potentials in (a) and (b) behave differently as those of the total potentials shown in (c) and (d), i.e., the minima of the nuclear interaction go down while the minima of the total interaction increase. The reason for the decrease from tip-belly to belly-belly in (c) is that the increase of the Coulomb interaction energy is smaller than the decrease of the nuclear interaction energy.

Defining a distance between the surface of the two nuclei, for example, for the tip-tip case, $\Delta R = R_{\text{min}} - (R_1^{\text{long}} + R_2^{\text{long}})$, while for the belly-belly case, $\Delta R = R_{\text{min}} - (R_1^{\text{short}} + R_2^{\text{short}})$ ($R_i^{\text{long,short}}$ represent the long and short axes of the deformed nucleus $i$, respectively), we find that $\Delta R$ changes a little for different orientations. When $|\eta|$ decreases from 1 to 0, the value of $\Delta R$ increases due to a larger repulsive Coulomb force, which can be seen more clearly in Fig.5. Therefore, the effect of the mass asymmetry and the orientation of the DNS on the driving potential can be analyzed from these results.

Fig.3 shows the potentials at the minimum of $U_N + U_C$ illustrated in Fig.2 for the above two combinations as a function of the orientation, the orientation is chosen in a way that keeps $\gamma_1 + \gamma_2 = 180^0$ for the system $^{28}Na + ^{244}Es$ and $\gamma_2 + \gamma_1 = 90^0$ for $^{74}Zn + ^{198}Hg$. On the left hand side, $\gamma_1$ goes from $180^0$ to $0^0$ and $\gamma_2$ from $0^0$ to $180^0$, on the right hand side, $\gamma_1$ is chosen from $0^0$ to $-180^0$ and $\gamma_2$ from $90^0$ to $270^0$ in order to obtain similar trends of the variation of potentials as a function of the orientation of the two nuclei as on the left hand side, in the two cases, both of the orientation changes from the tip-tip orientation to the belly-belly one and finally back to the tip-tip orientation (the orientation of the nuclei is shown in the lower-left plot of Fig.3). With the changing of the orientations of the two nuclei, the nuclear potentials (upper panels) form a valley while the Coulomb potentials (middle panels) attain a peak value for the tip-tip orientation. The summation of the two contributions shown in the bottom panels is similar in shape to the Coulomb potential but the change with angle is gentler.

Fig.4 displays the driving potentials in Eq. (2) for different orientations. In the upper panel of the figure we fixed $\gamma_1$ and $\gamma_2$ to $0^0$ or $90^0$, while in the lower panel, the results for the tip-tip and belly-belly orientations are shown. The curves in Fig.4 were calculated by
FIG. 2: The nuclear (in (a) and (b)) and the nuclear+Coulomb potentials (in (c) and (d)) for two sets of projectile-target combinations for the same compound nucleus $^{272}Ds$ are shown as a function of $R$ for different orientations of the two nuclei.

starting with the initial fragmentation $^{64}Ni + ^{208}Pb (\eta_i)$ transferring nucleons in steps of one proton or one neutron by searching for the minimum of potential energy. Therefore, the potentials are only approximately symmetric with respect to $\eta = 0$ for the tip-tip and belly-belly cases while for the cases with orientations of $(0^0, 0^0)$ and $(0^0, 90^0)$ in the upper panel, this symmetry is lost obviously. From Fig.4 we find that the driving potential is quite sensitive to the choice of orientations of the two nuclei. The driving potential for the tip-tip configuration is smaller than that for the belly-belly configuration in the whole range of $\eta$. This result is in disagreement with that obtained in Ref. [21], this discrepancy might be associated to the different consideration of the fusion process of heavy-ions.

To evaluate the difference between the different orientations, we show the differences between the potential energies of the various cases with respect to the tip-tip case in the upper half of Fig.5, where $U_{\text{belly}} - U_{\text{tip}}$ is shown with a line, while the other two cases
FIG. 3: The potentials with $\gamma_1 + \gamma_2 = 180^0$ for $^{28}\text{Na} + ^{244}\text{Es}$ (left panel) and $\gamma_1 + \gamma_2 = 90^0$ for $^{74}\text{Zn} + ^{198}\text{Hg}$ (right panel). See text for details.

are shown with different scattered symbols. The differences are peaked in two regions, one in $|\eta| < 0.5$ and the other in $|\eta| > 0.5$. In each region there exists a large deformation of the nuclei, especially when $|\eta|$ is $0.1 \sim 0.4$. However, the detailed deformation of the two nuclei in each part is different, that is, when $|\eta| > 0.5$, the smaller nucleus is almost spherical while the larger counterpart is prolately deformed. When $|\eta| < 0.5$, prolate and oblate deformations of the two nuclei occur, for example, for $\eta = -0.243$, the corresponding configuration is $^{103}\text{Mo} + ^{169}\text{Er}$ with a couple of large prolate deformation $\left(\beta_1, \beta_2\right) = \left(0.358, 0.304\right)$. When $\eta = -0.169$, the corresponding $^{113}\text{Pd} + ^{159}\text{Gd}$ consists of a negatively $(-0.25)$ deformed $^{113}\text{Pd}$ and a positively $(0.28)$ deformed $^{159}\text{Gd}$. The separation distance $\Delta R$ between the surface of the two nuclei of the DNS is shown in the lower graph of Fig.5. Because of the relatively large Coulomb potential, $\Delta R$ is stretched when the masses of the two participating nuclei become more equal, which has also been shown in Fig.2.
For the di-nuclear system $^{64}Ni + ^{208}Pb \rightarrow ^{272}Ds$, Fig. 4 shows the comparison between the present driving potential shown by dots and that calculated in Ref. [8] shown by a fine line for the tip-tip orientation. In the present calculations, the ground state deformation has been taken into account for both the nuclear and Coulomb interactions, and in Ref. [8] a parameterized Morse formula without considering the deformation of the nuclei has been adopted for the nuclear potential. We find that the two potentials are basically very close each other, however, some obvious deviations appear in the relatively large deformed regions, for example, around $|\eta| \sim 0.2$ and $|\eta| \sim 0.8$. It should be pointed out that a deviation also occurs at $|\eta| \sim 0$. After checking the detailed path of evolution, we find that the configurations of the DNS in the two cases are different at this point. For the case with a nuclear interaction of spherical nuclei, the combination ($^{136}La + ^{136}I$) is preferred, while for the one with that of deformed nuclei, a more charge-symmetric combination ($^{136}Ba + ^{136}Xe$) is taken into account. Obviously, the effect of a large deformation in the deformed region
FIG. 6: The comparison of the driving potential by using the ground state deformation and the tip-tip orientation for both the nuclear and Coulomb interactions with previous calculations which did not take into account the deformation in the nuclear part of interaction.

$|\eta| \sim 0.2$ changes the final path of the evolution near $\eta = 0$.

IV. CONCLUSION AND OUTLOOK

A double-folding method used to calculate the nucleus-nucleus potential between deformed nuclei is further developed to improve the driving potential of nuclear fusion in the DNS model. By taken into account the nuclear deformation in the nuclear interaction together with the Coulomb interaction, the formalism for calculating the driving potential of heavy-ion fusion becomes more reasonable. The deformations and orientations of the interacting nuclei contributing to the nuclear and Coulomb interactions are investigated for every fragmentation of the DNS considered. It is natural that the tip-tip orientation has the
lowest interaction energy, and may be preferred during the nucleon exchange process. The minimum energies of the nucleus-nucleus interaction along the distance between the centers of the two nuclei appear at larger distances when mass-asymmetry $|\eta|$ changes from unit to zero, which is due to the larger Coulomb force, and is in favor for the quasi-fission process. So far a dynamical evolution of the deformation and orientation during the heavy-ion fusion process is not reasonably treated by the present models to our knowledge, our results have estimated the effects of the deformation and orientation of the nuclei, on the driving potential. Hopefully it will give a direction for the further investigation and improvement.

In the next step, we will calculate the fusion probability of various projectile-target combinations with deformed nuclei. Furthermore, when the distance between the surface of the two nuclei is elongated the effect of quasi-fission is expected more pronounced. We will further consider a two-dimensional potential as functions of the mass asymmetry $\eta$ and the internuclear distance $R$ in order to investigate the effect of quasi-fission in the subsequent work.

V. ACKNOWLEDGMENT

The authors (Q. Li, W. Zuo, E. Zhao, J. Li, and W. Li) acknowledge the warm hospitality of the Institut für Theoretische Physik, Universität Giessen, Germany. We are also grateful to Dr. A. D. Torres for valuable discussions. The work is supported by the National Natural Science Foundation of China under Grant No.10175082, 10235020, 10375001, 10311130175; the Major Basic Research Development Program under Grant No. G2000-0774-07; the Knowledge Innovation Project of the Chinese Academy of Sciences under Grant No. KJCX2-SW-N02; One Hundred Person Project of CSA; CASK.C. Wong Post-doctors Research Award Fund; the National key program for Basic Research of the Ministry of Science and Technology (2001CCB01200, 2002CCB00200) and the financial support from DFG of Germany.

[1] S. Hofmann, et al., Eur. Phys. J. A 14, 147(2002).
[2] S. Hofmann, et al., Z. Phys. A 350, 277(1995).

[3] S. Hofmann, et al., Z. Phys. A 354, 229(1996).

[4] Yu. Ts. Oganessian, et al., Phys. Rev. C 69, 021601R(2004); Erratum ibid. C 69 029902E(2004).

[5] Yu. Ts. Oganessian, et al., Phys. Rev. C 69, 054607(2004).

[6] A.C. Berriman, D.J. Hinde, M. Dasgupta, C.R. Morton, R.D. Butt, and J.O. Newton, Nature, 413, 144(2001).

[7] G.G. Adamian, N.V. Antonenko, and W. Scheid, Phys. Rev. C 69 011601R(2004); ibidem 014607(2004).

[8] W.F. Li, N. Wang, J.F. Li, H.S. Xu, W. Zuo, E.G. Zhao, J.Q. Li, and W. Scheid, Europhys. Lett. 64 750(2003).

[9] G.G. Adamian, N.V. Antonenko, and W. Scheid, Nucl. Phys. A 618, 176(1997).

[10] C.W. Shen, G. Kosenko, and Y. Abe, Phys. Rev. C 66, 061602(2002).

[11] Y. Abe and B. Bouriquet, Nucl. Phys. A 722, 241(2003); Erratum ibid. A 733 321(2004).

[12] V.I. Zagrebaev, Phys. Rev. C 64, 034606(2001).

[13] V.I. Zagrebaev, Nucl. Phys. A 734, 164(2004).

[14] W.J. Swiatecki, Phys. Scr. 24, 113(1981).

[15] J.P. Blocki, H. Feldmeier, and W.J. Swiatecki, Nucl. Phys. A 459, 145(1986).
[16] V.V. Volkov, Izv. Akad. Nauk SSSR, Ser. Fiz. 50, 1879(1986).

[17] N.V. Antonenko, E.A. Cherepanov, A.K. Nasirov, V.B. Permjakov, and V.V. Volkov, Phys. Lett. B 319, 425(1993).

[18] G.G. Adamian, N.V. Antonenko, R.V. Jolos, S.P. Ivanova, and O.I.Melnikova, Int. Jour. of Mod. Phys. E 5, 191(1996).

[19] W.D. Myers, W.J. Swiatecki, LBL Report, UCRL-11980, (1965).

[20] P. Möller, J.R. Nix, W.D. Myers, and W.J. Swiatecki, At. Data Nucl. Data Tables, 59, 185(1995).

[21] Ş. Mişicu, W. Greiner, Phys. Rev. C 66, 044606(2002).