Search for stabilizing effects of $Z = 82$ shell closure against fission

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Background: Presence of closed proton and/or neutron shells causes deviation from macroscopic properties of nuclei which are understood in terms of the liquid drop model. Efforts to synthesize artificial elements are driven by prediction of existence of closed shells beyond the heaviest doubly magic nucleus found in nature. It is important to investigate experimentally the stabilizing effects of shell closure, if any, against fission.

Purpose: This work aims to investigate probable effects of proton shell ($Z = 82$) closure in the compound nucleus, in enhancing survival probability of the evaporation residues formed in heavy ion-induced fusion-fission reactions.

Method: Evaporation residue cross sections have been measured for the reactions $^{39}$F+$^{180}$Hf, $^{19}$F+$^{181}$Ta and $^{19}$F+$^{182}$W from $\simeq 9\%$ below to $\simeq 42\%$ above the Coulomb barrier; leading to formation of compound nuclei with same number of neutrons ($N = 118$) but different number of protons across $Z = 82$; employing the Heavy Ion Reaction Analyzer at IUAC. Measured excitation functions have been compared with statistical model calculation, in which reduced dissipation coefficient is the only adjustable parameter.

Results: Evaporation residue cross section, normalized by capture cross section, is found to decrease gradually with increasing fissility of the compound nucleus. Measured evaporation residue cross sections require inclusion of nuclear viscosity in the model calculations. Reduced dissipation coefficient in the range of $1 \times 10^{-2}$ s$^{-1}$ reproduces the data quite well.

Conclusions: Since entrance channel properties of the reactions and structural properties of the heavier reaction partners are very similar, degree of presence of non-compound nuclear fission, if any, is not expected to be significantly different in the three cases. No abrupt enhancement of evaporation residue cross sections has been observed in the reaction forming compound nucleus with $Z = 82$. Thus, this work does not find enhanced stabilizing effects of $Z = 82$ shell closure against fission in the compound nucleus. One may attempt to measure cross sections of individual exit channels for further confirmation of our observation.

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I. INTRODUCTION

Bohr and Wheeler [1] modelled the atomic nucleus as a homogeneously charged liquid drop. Many macroscopic properties of nuclei, most notably the phenomenon of fission [2], in which a heavy nucleus splits itself into lighter fragments, could be understood in terms of the liquid drop model. However, limitations of this model to explain microscopic features, e.g. enhanced stability of a few nuclei, led to development of the nuclear shell model by Mayers and others [3]. Since then, effects of shells on nuclear reaction dynamics has been a topic of great interest. Most significantly, superheavy nuclei, beyond the heaviest nucleus available in nature, have been hypothesised to exist solely because of shell stabilization effects. Sustained efforts in the field of heavy element research, since the first prediction [4] of a doubly shell-closed nucleus beyond $^{208}$Pb$_{126}$, culminated recently into completion of the seventh period of the periodic table of elements [5]. Though the trans-lead doubly shell-closed nucleus is yet to be synthesized in a laboratory, the cardinal role of shell stabilization in enhancing life time of superheavy nuclei has been firmly established [6].

Formation cross sections of superheavy evaporation residues (ERs) being vanishingly small, it is rather challenging to study the dynamics of such reactions. Several studies on effects of shell closure on reaction dynamics, therefore, have been reported in the mass region around $^{208}$Pb$_{126}$. One important difference between the nuclei in the vicinity of $Z = 82$, $N = 126$ and the superheavy nuclei, though, should be borne in mind. While the fission barrier in the latter arises solely because of shell effects, the liquid drop model accounts for a substantive part of...
TABLE I: Details of the nuclear reactions studied in this work. $\beta_2$, $V_B$, $Q_{CN}$, $\chi_{CN}$ and $\eta_{BG}$ are the quadrupole deformation, the Coulomb barrier, $Q$-value of the reaction, CN fissility and the Businaro-Gallon critical mass asymmetry, respectively.

| System | $\beta_2$ (target) | $V_B$ (MeV) | $Z_pZ_t$ | $\eta$ | $\chi_{CN}$ | $Q_{CN}$ (MeV) | $\eta_{BG}$ |
|--------|------------------|-------------|----------|--------|-------------|----------------|------------|
| $^{19}$F$_{10}^{+}+^{208}$Tl$_{108}$ | 0.274 | 76.8 | 648 | 0.809 | $^{126}$Tl$_{118}$ | -23.210 | 0.691 0.831 |
| $^{19}$F$_{10}^{+}+^{211}$Ta$_{108}$ | 0.269 | 77.9 | 657 | 0.810 | $^{209}$Pb$_{118}$ | -23.678 | 0.701 0.838 |
| $^{19}$F$_{10}^{+}+^{204}$W$_{108}$ | 0.250 | 79.0 | 666 | 0.811 | $^{201}$Bi$_{118}$ | -28.314 | 0.712 0.844 |

The fission barrier in the former. The first comprehensive investigation to verify reduction of fission competition in deexcitation of the compound nucleus (CN) due to stabilizing influence of the strong ground-state shell effect in the vicinity of $N = 126$ was reported by Vermeulen et al. However, the results showed ‘surprisingly’ low stabilizing influence of the spherical shell against fission. To explain absence of ‘expected’ stabilization effect, Andreyev et al. studied systematics of ER cross sections ($\sigma_{ER}$) for the neutron-deficient CN $^{184-192}$Bi$^*$ and $^{186-192}$Po$^*$ formed in complete fusion between two heavy ions. A satisfactory reproduction of the data by the statistical model demanded up to 35% reduction of the fission barrier. Based on the systematic analysis, the authors concluded ‘strongly’ increased fission probability above the shell closure at $Z = 82$. Nath et al. measured $\sigma_{ER}$ and ER-gated CN angular momentum ($\ell$) distribution for $^{19}$F$^{+}$-$^{184}$W. The results were further compared with those from neighbouring systems with nearly similar entrance channel charge product, $Z_pZ_t$ and mass asymmetry, $\eta = \frac{|A_p - A_t|}{A_p + A_t}$ (here $Z_p$ ($Z_t$) and $A_p$ ($A_t$) denote atomic number and mass number for the projectile (target), respectively). The fission barrier for the CN with $Z = 82$ was found to deviate from the systematic (N,Z) dependence. Similar measurements were carried out for the reactions $^{30}$Si$^{+}$-$^{170}$Er and $^{31}$P$^{+}$-$^{170}$Er forming the CN $^{208}$Pb$^{+}_{118}$ and $^{201}$Bi$^{+}_{118}$, respectively, by Mohanto et al. The results revealed no clear signature of extra stability due to $Z = 82$ shell closure, showing similar $\sigma_{ER}$ and moments of $\ell$-distribution for both the reactions at a given $E_{c.m.} - V_B$.

These works relied upon statistical model of decay of CN to interpret the data. This approach is questionable, in some cases, as reactions induced by heavier projectiles (e.g. $^{40}$Ar and $^{46}$Ti, $^{50,52}$Cr, $^{94,95,96}$Mo) have been known to go through non-equilibrium processes like quasi-fission, thereby inhibiting formation of CN, equilibrated in all degrees of freedom. There are many recent studies in support of this argument. The statistical models used by various groups of researchers also differ in details. To explain absence of ‘expected’ stabilization against fission for spherical nuclei near $N = 126$, Junghans et al. included collective enhancement of level density (CELD) in the calculation. Ad hoc reduction of fission barrier was also suggested to reproduce measured $\sigma_{ER}$.

In this article, we revisit the question whether $Z = 82$ shell closure enhances survival of ERs against fission. To improve upon earlier attempts, we have chosen three reactions to form CN with same number of neutrons ($N = 118$) and different numbers for protons across $Z = 82$ (see Table I). The facts – (a) the reactions are induced by $^{19}$F projectiles and (b) entrance channel parameters of the three reactions are nearly the same –lower the possibility of non-CN fission (NCNF) affecting ER formation significantly and with varying degree of severity in the three reactions. It is well known that shell effects tend to disappear at higher excitation energy ($E^*$). Recent measurements of fission fragment (FF) mass distribution from heavy CN $^{180,182}$Hf points to a threshold of $E^* \approx 40$ MeV, up to which shell effects persist. The three CN are formed with $E^*$ in the range of 42–92 MeV in the present experiment. The statistical model calculations performed in this work include all important physical phenomena known to affect fission dynamics and have a single adjustable parameter, viz. reduced dissipation coefficient, $\beta$. Thus, scrutiny of results of the three reactions is expected to bring forth stabilizing influences of $Z = 82$ shell closure against fission, if any.

The article is organized as follows. The experiment is described in Sec. II. Results from the experiment and model calculations are presented in Sec. III. Section IV contains a discussion followed by summary and conclusion in Sec. V.

II. THE EXPERIMENT

The experiment has been carried out at the 15UD Pelletron accelerator facility of IUAC, New Delhi. A pulsed $^{19}$F beam, with pulse separation of 4 $\mu$s, has been incident upon $^{180}$Hf (150 $\mu$g/cm$^2$), $^{181}$Ta (175 $\mu$g/cm$^2$) and $^{182}$W (70 $\mu$g/cm$^2$) targets, all with thin (~20 $\mu$g/cm$^2$) $^{nat}$C backing. Important parameters of the three reactions are listed in Table I. ER cross sections ($\sigma_{ER}$) have been measured, employing the recoil mass spectrometer Heavy Ion Reaction Analyzer (HIRA) at projectile energies ($E_{lab}$) in the range of 80–124 MeV. Two silicon detectors, placed inside the target chamber at $\theta_{lab} = 15.5^\circ$ with respect to the beam direction and in the horizontal plane, have been used for monitoring position of the beam on targets and absolute normalization of $\sigma_{ER}$. ERs have been separated from the overwhelmingly-dominant background events by the HIRA and transported to its focal plane. To ensure that charge states of ERs follow the
equilibrium distribution, a thin (~ 30 \( \mu g/cm^2 \)) natC foil has been placed at \( \theta_{lab} = 0^\circ \), 10.0 cm downstream from the target. The ERs have been detected by a multi-wire proportional counter (MWPC), placed at the focal plane of the spectrometer. The MWPC, with an active area of 15.0 x 5.0 cm\(^2\) and a mylar window of thickness 0.5 \( \mu m \), has been operated with isobutane at 3 mbar pressure. Measurements have been performed keeping the HIRA at \( \theta_{lab} = 0^\circ \) and with full acceptance of 10 msr. Time of flight (TOF) of the ERs, over the distance from the target to the MWPC, have also been recorded. List mode data have been collected with the logical OR of the timing signals from the MWPC and the two monitor detectors as the master trigger.

\[ \Delta E \text{ (arb. units)} \]

\[ \text{TOF (arb. units)} \]

\[ \Delta E \text{ (arb. units)} \]

**FIG. 1:** Scatter plots between \( \Delta E \) and TOF of the events recorded at the focal plane of the HIRA for (a) \( ^{19}\text{F} + ^{180}\text{Hf} \) at \( E_{lab} = 119.7 \text{ MeV} \left( \frac{E_{\text{cm}}}{v_{\text{th}}} \approx 1.41 \right) \), (b) \( ^{19}\text{F} + ^{181}\text{Ta} \) at \( E_{lab} = 99.6 \text{ MeV} \left( \frac{E_{\text{cm}}}{v_{\text{th}}} \approx 1.16 \right) \) and (c) \( ^{19}\text{F} + ^{182}\text{W} \) at \( E_{lab} = 79.6 \text{ MeV} \left( \frac{E_{\text{cm}}}{v_{\text{th}}} \approx 0.91 \right) \). \( E_{\text{c.m.}} \) stands for energy available in the centre of mass (c.m.) frame of reference. ER events are enclosed within an elliptical gate in each plot.

### III. DATA ANALYSIS AND RESULTS

#### A. ER cross sections

The first step towards experimental determination of \( \sigma_{\text{ER}} \) is to identify the ERs unambiguously at the focal plane of the spectrometer. This is achieved by generating scatter plots between energy loss of ERs (\( \Delta E \)) at the focal plane and the TOF signals. Three such plots for the three reactions are shown in Fig. 1. Inherently background rejection capability of the HIRA, for very asymmetric reactions like the present ones, ensures that the ERs can be clearly separated from the few projectile-like particles reaching the focal plane. It is generally observed that the intensity of background events at the focal plane of the HIRA, though insignificant in most cases, increases gradually with decrease in projectile energy. However, quite satisfactory separation between ERs and background events has been obtained over the entire range of \( E_{lab} \) in the present experiment, as is evidenced by the \( \Delta E – \text{TOF} \) plot for \( ^{19}\text{F} + ^{182}\text{W} \) at the lowest \( E_{lab} \), shown in panel (c) of Fig. 1.

The second most important aspect in the analysis is to estimate efficiency of HIRA \( \epsilon_{\text{HIRA}} \). Only a fraction of ERs, produced in a fusion reaction, reaches the focal plane and is recorded by the detector. \( \epsilon_{\text{HIRA}} \) for the ERs varies depending upon several reaction parameters. The same has been calculated employing the semi-microscopic Monte Carlo code TERS [20] following the formalism outlined in Ref. [2].

Measured \( \sigma_{\text{ER}} \) for the three reactions are shown in Fig. 2. ER excitation function for \( ^{19}\text{F} + ^{181}\text{Ta} \) had been reported earlier [21]. Nevertheless we have measured \( \sigma_{\text{ER}} \) for this reaction, along with the same for the other two reactions, to ensure similar systematic errors, if any, in measured data. Our results for \( ^{19}\text{F} + ^{181}\text{Ta} \) are in agreement with the same reported in Ref. [21] within experimental uncertainties.

#### B. Statistical model calculation

The fate of a CN is decided in the present statistical model (SM) by following its time evolution through Monte Carlo sampling of the decay widths of various channels. Emission of neutrons, protons, \( \alpha \)-particles and \( \gamma \)-rays along with fission are considered as the probable channels of decay. A CN can undergo either fission with or without preceding evaporated particles and photons or reduce to an ER. The final values of various observables are obtained as averages over a large ensemble of events. The fission width is obtained from the transition-state model of fission due to Bohr and Wheeler [1] with certain modifications as outlined below. The particle and \( \gamma \)-decay widths are obtained from the Weisskopf formula as given in Ref. [22].

We obtain the fission barrier in the present calculation by including shell correction in the liquid-drop nuclear
mass. Since the shell correction term $\delta$ is defined as the difference between the experimental and the liquid-drop model (LDM) masses ($\delta = M_{\text{exp}} - M_{\text{LDM}}$), the full fission barrier $B_f(\ell)$ of a nucleus carrying angular momentum $\ell$ is given as

$$B_f(\ell) = B_{f,\text{LDM}}(\ell) - (\delta_g - \delta_s)$$  \hspace{1cm} (1)$$

where $B_{f,\text{LDM}}(\ell)$ is the finite-range liquid drop model (FRLDM) fission barrier and $\delta_g$ and $\delta_s$ are the shell correction energies at the ground state and the saddle configurations, respectively. The shell corrections at ground state and saddle are obtained following the recipe given in Ref. [24] for including deformation dependence in shell correction energy.

It is usually assumed that the orientation of the CN angular momentum remains perpendicular to both the reaction plane and the symmetry axis throughout the course of the reaction and the LDM fission barrier thus is obtained for $K = 0$, where $K$ is the angular momentum component along the symmetry axis. However, the initial CN angular momentum direction can change its orientation due to perturbation by intrinsic nuclear motion [23]. Therefore, fission barriers for $K \neq 0$, which are larger than the $K = 0$ barrier, are also to be considered. This results in a reduction of the fission width which we have taken into account following Ref. [26].

The influence of shell structure in nuclear single-particle levels in the nuclear level density which is used to calculate various decay widths of the CN is obtained from the works of Ignatyuk et al. [27] where the following form of the level density parameter $a$ is given

$$a(E^*) = a \left(1 + \frac{g(E^*)}{E^*} \delta\right)$$  \hspace{1cm} (2)$$

where

$$g(E^*) = 1 - \exp\left(-\frac{E^*}{E_D}\right)$$  \hspace{1cm} (3)$$

and $E_D$ is a parameter which determines the rate at which the shell effect decreases with increase of $E^*$. The level density parameter is shape dependent and its asymptotic form $a$ at high $E^*$ is taken from Ref. [28].

We next consider the collective enhancement of level density (CELD) which arises due to the residual interaction giving rise to correlation among particle-hole states resulting in collective excitations. The total level density $\rho(E^*)$ then can be written as [29]

$$\rho(E^*) = K_{\text{coll}}(E^*)\rho_{\text{intr}}(E^*)$$  \hspace{1cm} (4)$$

where $\rho_{\text{intr}}(E^*)$ is the intrinsic level density and $K_{\text{coll}}$ is the collective enhancement factor.

The rotational ($K_{\text{rot}}$) and vibrational ($K_{\text{vib}}$) enhancement factors are taken from the work of Ignatyuk et al. [30]. A smooth transition from $K_{\text{vib}}$ to $K_{\text{rot}}$ with increasing quadrupole deformation $|\beta_2|$ of the CN is obtained using a function $\varphi(|\beta_2|)$ given as follows [31]

$$K_{\text{coll}}(E^*) = [K_{\text{rot}}\varphi(|\beta_2|) + K_{\text{vib}}(1 - \varphi(|\beta_2|))] f(E^*),$$  \hspace{1cm} (5a)$$

where

$$\varphi(|\beta_2|) = \left[1 + \frac{\beta_0^2}{\Delta \beta_2^2}\right]^{-1}.$$  \hspace{1cm} (5b)**
IV. DISCUSSION

Effects of shell closure on nuclear reaction dynamics have been investigated through various observables. Enhanced FF anisotropy with respect to those predicted by the standard statistical saddle point model, observed in $^{12}$C+$^{198}$Pt \cite{41}, was attributed to the effects of the $N = 126$ shell in the potential energy surface (PES) of the CN. On the other hand, no signature of the modification of the PES due to the effect of $N = 126$ shell closure was manifest in FF mass distribution \cite{42}, as normalized width of mass distributions from $^{12}$C+$^{194,198}$Pt (leading to CN with $N = 120$ and 126, respectively) was found to be almost identical. Influence of shell closure in the reaction partners on the mass and angle distribution of FFs \cite{43} and signatures of the $Z = 82$ shell closure in $\alpha$-decay process in heavy nuclei \cite{44} have been reported in recent years.

Unlike FFs and neutrons, which may originate from both equilibrated CN or non-equilibrium processes, ERs are the most unambiguous signatures of CN formation. However, theoretical reproduction of $\sigma_{ER}$ is not always free from uncertainties. For heavy fissionable systems, $\sigma_{ER}$ can be expressed as

$$\sigma_{ER}(E_{c.m.}) = \sum_{\ell=0}^{\infty} \sigma_{cap}(E_{c.m., \ell})P_{CN}(E_{c.m., \ell})P_{sur}(E^*, \ell)$$

where the three terms on the right hand side of Eq. (8) denote (a) probability of the collision partners to overcome the potential barrier in the entrance channel, (b) probability that the composite system will evolve into an equilibrated mononucleus starting from the touching configuration inside the fission saddle point and (c) probability that the CN will survive as a cold ER, respectively.

The second term on the right hand side of Eq. (8) is the least precisely known. Considerable variance is also known to exist among the different statistical models, which are frequently used to calculate the third term on the right hand side of Eq. (8). Given these difficulties, comparing the ER excitation functions of three similar reactions and looking for signatures of $Z = 82$ shell closure are quite challenging.

While trying to reproduce $\sigma_{ER}$ with the statistical model for decay of CN, it is implicitly assumed that $P_{CN} = 1$. In other words, the target-projectile composite system is assumed to yield an equilibrated CN and not to proceed towards non-equilibrium fission-like processes. This assumption is questionable. Several studies on presence of non-equilibrium processes in 200 amu mass region have been reported. Shidling et al. interpreted reduction of $\sigma_{ER}$ in $^{19}$F+$^{181}$Ta, compared to the same in $^{16}$O+$^{184}$W, as a consequence of pre-equilibrium fission \cite{45}. Nasirov et al. \cite{38} performed detailed analysis of these two reactions within the framework of the di-nuclear system (DNS) model. According to the results from the DNS model, quasi-fission and fast fission cause hindrance to complete fusion in both reactions, albeit
with varying degree of severity. On the other hand, study of FF mass distribution did not find any signature of quasi-fission for the reactions $^{19}$F+$^{181}$Ta and $^{16}$O+$^{184}$W [46].

In the light of these conflicting reports, we argue that (a) presence of NCNF in the three $^{19}$F-induced reactions under consideration is not significant and (b) influence of NCNF, if any, on $\sigma_{\text{ER}}$ in these reactions are comparable as the entrance channel parameters $Z$, $t$, $\eta$, and structural features of the targets are rather similar.

In reproducing observables from fusion-fission reactions, the input parameters in the SM such as level density, fission barrier and fission delay time are often varied in an ad hoc manner. In the present work, no parameter of the SM except for $\beta$ is varied to interpret the data. Fig. 2 shows that while $\beta = 1-2 \times 10^{21} \text{ s}^{-1}$ reproduces the ER excitation functions of $^{19}$F+$^{180}$Hf and $^{19}$F+$^{181}$Ta systems over the entire range of excitation energy, higher values of $\beta = 2-3 \times 10^{21} \text{ s}^{-1}$ are required for the $^{19}$F+$^{182}$W system. Similar observations are also made in Fig. 3 where measured and calculated $\sigma_{\text{ER}}$, normalized by $\sigma_{\text{cap}}$ (obtained from coupled-channels calculations), are plotted. The necessity of a higher value for $\beta$ for the $^{19}$F+$^{182}$W reaction possibly arises from the facts that (a) the excitation energy of the CN for this system is about 5 MeV less than those of the other two systems and (b) the parameters deciding the energy dependence of CELD (Eq. 5) are not optimized for the present systems but are taken from an earlier work [17]. The latter aspect requires further investigation in future studies. However, the above values of $\beta$ are in agreement with the theoretical estimate of pre-saddle dissipation strength based on the chaos-weighted wall formula [47]. It can also be noted from Fig. 3 that $\frac{\sigma_{\text{ER}}}{\sigma_{\text{cap}}}$ decreases gradually with increasing $\chi_{\text{CN}}$. This is as expected since fission becomes a more dominant decay mode in CN with larger fissility.

V. SUMMARY AND CONCLUSION

ER excitation functions have been measured for three reactions in similar range of excitation energies in order to look for stabilizing effects of $Z = 82$ shell closure against fission. The systems have been chosen in such a way that the three CN, formed in these reactions, have same number of neutrons ($N = 118$) but different numbers of protons ($Z = 81, 82, 83$). A not-so-heavy projectile ($A_p < 20$) has been chosen to ensure that the effect of NCNF on ER formation is not severe. The three targets also have quite similar structural features. Entrance channel parameters for the three reactions being comparable, presence of NCNF, if any, is thus expected to affect ER formation in the three reactions quite similarly. Measured cross sections have been compared with statistical model predictions. The model includes shell effect in level density, shell correction in fission barrier, $K$-orientation and CELD. Reduced dissipation coefficient is the only adjustable parameter. It is found that the ER excitation functions can be reasonably reproduced with values of $\beta$ in the range of $1-3 \times 10^{21} \text{ s}^{-1}$. The ratio $\frac{\sigma_{\text{ER}}}{\sigma_{\text{cap}}}$ decreases with increasing fissility of the CN in the similar range of excitation energies. No significant and abrupt deviations have been found in the results obtained from $^{19}$F+$^{181}$Ta as an evidence in favour of stabilizing effects of $Z = 82$ shell closure against fission. For further validation of this conclusion, a more exclusive measurement of individual exit channel cross sections in such reactions can be carried out in future.

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[1] N. Bohr and J. A. Wheeler, Phys. Rev. 56, 426 (1939).
[2] O. Hahn and F. Strassmann, Naturwissenschaften 27, 11 (1939); L. Meitner and O. R. Frisch, Nature (London) 143, 239 (1939); O. R. Frisch, Nature (London) 143, 276 (1939).
[3] M. G. Mayer, Phys. Rev. 74, 235 (1948); O. Hazel, J. H. D. Jensen, and H. E. Suess, Phys. Rev. 75, 1766 (1949); M. G. Mayer, Phys. Rev. 75, 1969 (1949); M. G. Mayer, Phys. Rev. 78, 16 (1950); M. G. Mayer, Phys. Rev. 78, 22 (1950).
[4] A. Sobiczewski, F. A. Gareev, and B. N. Kalinkin, Phys. Lett. 22, 500 (1966).
[5] https://iupac.org/what-we-do/periodic-table-of-elements/
[6] J. H. Hamilton, S. Hofmann, and Yu. Ts. Oganessian, Ann. Rev. Nucl. Part. Phys. 63, 383 (2013).
[7] D. Vermeulen, H.-G. Clerc, C.-C. Sahm, K.-H. Schmidt, J. G. Keller, G. Münzenberg, and W. Reisdorf, Z. Phys. A 318, 157 (1984).
[8] A. N. Andreyev, D. Ackermann, S. Antalic, I. G. Darby, S. Franchoo, F. P. Heßberger, S. Hofmann, M. Huyse, P. Kunusienie, B. Lommel, B. Kindler, R. Mann, G. Münzenberg, R. D. Page, S. Sáro, B. Sulignano, B. Streicher, K. Van de Vel, P. Van Dappen, and D. R. Wise, Phys. Rev. C 72, 014612 (2005).
[9] S. Nath, P. V. Madhusudhana Rao, Santanu Pal, J. Gehlot, E. Prasad, Gayatri Mohanto, Sunil Kalkal, Jhilam Sadhukhan, P. D. Shidling, K. S. Golda, A. Jhingan, N. Madhavan, S. Muralithar, and A. K. Sinha, Phys. Rev. C 81, 064610 (2010).
[10] S. Nath, J. Gehlot, E. Prasad, Jhilam Sadhukhan, P. D. Shidling, N. Madhavan, S. Muralithar, K. S. Golda, A. Jhingan, T. Varughese, P. V. Madhusudhana Rao, A. K. Sinha, and Santanu Pal, Nucl. Phys. A 850, 22 (2011).
[11] Gayatri Mohanto, N. Madhavan, S. Nath, Jhilam Sadhukhan, J. Gehlot, I. Mazumdar, M. B. Naik, E. Prasad, Ish Mukul, T. Varughese, A. Jhingan, R. K. Bhowmik, A. K. Sinha, D. A. Gothe, P. B. Chavan, Santanu Pal, V. S. Ramamurthy, and A. Roy, Nucl. Phys. A 890–891, 62 (2012).
[12] G. Mohanto, N. Madhavan, S. Nath, J. Gehlot, Ish Mukul, A. Jhingan, T. Varughese, A. Roy, R. K. Bhowmik, I. Mazumdar, D. A. Gothe, P. B. Chavan, J. Sadhukhan, S. Pal, Maninder Kaur, Varinderjit Singh, A. K. Sinha, and V. S. Ramamurthy, Phys. Rev. C 88, 034606 (2013).
[13] R. du Rietz, E. Williams, D. J. Hinde, M. Dasgupta, M. Evers, J. C. Lin, D. H. Luong, C. Simenel, and A. Wakle, Phys. Rev. C 88, 054618 (2013).
[14] A. Shamlath, E. Prasad, N. Madhavan, P. V. Laveen, J. Gehlot, A. K. Nasirov, G. Giardina, G. Mandaglio, S. Nath, Tathagata Banerjee, A. M. Vinodkumar, M. Manganaro, A. I. Mušnikov, F. P. Heßberger, A. Kindler, J. H. D. Jensen, and H. E. Suess, Phys. Rev. C 95, 044610 (2017).
[15] A. R. Junghans, M. Evers, C. J. Lin, D. H. Luong, C. Simenel, and A. Wakle, Phys. Rev. C 88, 054618 (2013).
[16] A. Chaudhuri, T. K. Ghosh, K. Banerjee, S. Bhattacharya, Jhilam Sadhukhan, C. Bhattacharya, S. Kundu, J. K. Meena, G. Mukherjee, R. Pandey, T. K. Rana, P. Roy, T. Roy, V. Srivastava, and P. Bhattacharya, Phys. Rev. C 91, 044620 (2015).
[17] K. Nishio, A. N. Andreyev, R. Chapman, X. Derkx, Ch. E. Düllmann, L. Ghis, F. P. Heßberger, K. Hirose, H. Ikezoe, J. Khuyagbaatar, B. Kindler, J. B. Lommel, H. Makii, I. Nishinaka, T. Ohtsuki, S. D. Pain, R. Sagaidak, I. Tsekhmanovich, M. Venhart, Y. Wakabayashi, and S. Yan, Phys. Rev. C 748, 89 (2015).
[18] T. Banerjee, S. R. Abhilash, D. Kabiraj, S. Ojha, G. R. Umapathy, M. Shareef, P. V. Laveen, H. Duggal, R. U. Amarnad, J. Gehlot, S. Nath, and D. Mehta, Vacuum 119, 140 (2017).
[19] A. K. Sinha, N. Madhavan, J. J. Das, P. Sugathan, D. O. Kataria, A. P. Patro, and G. K. Mehta, Nucl. Instrum. Methods A 339, 543 (1994).
[20] S. Nath, Comput. Phys. Commun. 179, 492 (2008); ibid. 180, 2392 (2009).
[21] R. J. Charity, J. R. Leigh, J. J. M. Bokhorst, A. Chattarjee, G. S. Foote, D. J. Hinde, J. O. Newton, S. Ogaza, and D. Ward, Nucl. Phys. A 457, 441 (1986).
[22] P. Fröbrich and I. I. Gontchar, Phys. Rep. 292, 131 (1998).
[23] A. J. Sierk, Phys. Rev. C 33, 2039 (1986).
[24] W. D. Myers and W. J. Swiatecki, Nucl. Phys. 81, 1 (1966).
[25] J. P. Lestone and S. G. McCalla, Phys. Rev. C 79, 044611 (2009).
[26] J. P. Lestone, Phys. Rev. C 59, 1540 (1999).
[27] A. V. Ignatyuk, M. G. Itkis, V. N. Okolovich, G. M. Smirenkin, and A. Tishin, Yad. Fiz. 21, 485 (1975) [Sov. J. Nucl. Phys. 21, 255 (1975)].
[28] W. Reisdorf, Z. Phys. A 300, 227 (1981).
[29] S. Bjørnholm, A. Bohr and B.R. Mottelson, in Proceedings of the International Conference on the Physics and Chemistry of Fission, Rochester, 1973 (IAEA, Vienna, 1974) Vol. 1, p. 367.
[30] A.V. Ignatyuk, G.N. Smirenkin, M.G. Itkis, S.I. Mull’gin and V.N. Okolovich, Fiz. Elem. Chastits At. Yadra 16, 709 (1985) [Sov. J. Part. Nucl. 16 (1985) 307].
[31] V. I. Zagrebaev, Y. Aritomo, M. G. Itkis, Y. T. Oganessian, and M. Ohta, Phys. Rev. C 65, 014607 (2001).
[32] M. Ohta, in Proceedings on Fusion Dynamics at the Extremes, Dubna, 2000, edited by Yu. Ts. Oganessian and V. I. Zagrebaev (World Scientific, Singapore, 2001), p. 110.
[33] H. A. Kramers, Phys. (Amsterdam, Neth.) 7, 284 (1940).
[34] P. Grangé, Li Jun-Qing, and H. A. Weidenmüller, Phys. Rev. C 27, 2063 (1983).
[35] K.H. Bhatt, P. Grangé, and B. Hiller, Phys. Rev. C 33, 954 (1986).
[36] Tathagata Banerjee, S. Nath, and Santanu Pal, Phys. Lett. B 776, 163 (2018).
[37] Tathagata Banerjee, S. Nath, and Santanu Pal, Phys. Rev C 99, 024610, (2019).
[38] A. K. Nasirov, G. Mandaglio, M. Manganaro, A. I. Mušnikov, F. P. Heßberger, A. Kindler, J. H. D. Jensen, and H. E. Suess, Phys. Rev. C 95, 044610 (2017).
[39] R. C. Hagino, N.Rowley, and A. T. Kruppa, Comput. Phys. Commun. 123, 143 (1999).
[40] Tathagata Banerjee, S. Nath, A. Jhingan, N. Saneesh,
Mohit Kumar, Abhishek Yadav, Gurpreet Kaur, R. Dubey, M. Shareef, P. V. Laveen, A. Shamlath, Md. Moin Shaikh, S. Biswas, J. Gehlot, K. S. Golda, P. Sugathan, and Santanu Pal, Phys. Rev. C 96, 014618 (2017).
[41] A. Shrivastava, S. Kailas, A. Chatterjee, A. M. Samant, A. Navin, P. Singh, and B. S. Tomar, Phys. Rev. Lett. 82, 699 (1999).
[42] A. Chaudhuri, T. K. Ghosh, K. Banerjee, S. Bhattacharya, Jhilam Sadhukhan, S. Kundu, C. Bhattacharya, J. K. Meena, G. Mukherjee, A. K. Saha, Md. A. Asgar, A. Dey, S. Manna, R. Pandey, T. K. Rana, P. Roy, T. Roy, V. Srivastava, P. Bhattacharya, D. C. Biswas, B. N. Joshi, K. Mahata, A. Shrivastava, R. P. Vind, S. Pal, B. R. Behera, and Varinderjit Singh, Phys. Rev. C 92, 041601(R) (2015).
[43] C. Simenel, D. J. Hinde, R. du Rietz, M. Dasgupta, M. Evers, C. J. Lin, D. H. Luong, and A. Wakhle, Phys. Lett. B 710, 607 (2012).
[44] A. N. Andreyev, M. Huyse, P. Van Duppen, C. Qi, R. J. Liotta, S. Antalic, D. Ackermann, S. Franchoo, F. P. Heßberger, S. Hofmann, I. Kojouharov, B. Kindler, P. Kuusiniemi, S. R. Lesher, B. Lommel, R. Mann, K. Nishio, R. D. Page, B. Streicher, Š. Šáro, B. Sulignano, D. Wiseman, and R. A. Wyss, Phys. Rev. Lett 110, 242502 (2013).
[45] P. D. Shidling, N. Madhavan, V. S. Ramamurthy, S. Nath, N. M. Badiger, Santanu Pal, A. K. Sinha, A. Jhingan, S. Muralithar, P. Sugathan, S. Kailas, B. R. Behera, R. Singh, K. M. Varier, and M. C. Radhakrishna, Phys. Lett. B 670, 99 (2008).
[46] A. Chaudhuri, A. Sen, T. K. Ghosh, K. Banerjee, Jhilam Sadhukhan, S. Bhattacharya, P. Roy, T. Roy, C. Bhattacharya, Md. A. Asgar, A. Dey, S. Kundu, S. Manna, J. K. Meena, G. Mukherjee, R. Pandey, T. K. Rana, V. Srivastava, R. Dubey, Gurpreet Kaur, N. Saneesh, P. Sugathan, and P. Bhattacharya, Phys. Rev. C 94, 024617 (2016).
[47] G. Chaudhuri and S. Pal, Phys. Rev. C 65, 054612 (2002).