EPJ Web of Conferences **359**, 02003 (2026) https://doi.org/10.1051/epjconf/202635902003
*ICEMR-2025*

# Systematics of Survival Probability in Fusion Reactions with Radioactive Targets Forming Compound Nuclei in the Range $91 \leq Z \leq 104$

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**Abstract.** The synthesis of superheavy nuclei (SHN) through heavy-ion fusion–evaporation reactions critically depends on the probability that an excited compound nucleus survives fission during de-excitation. In this work, a simple semi-empirical relation for the survival probability ($W_{sur}$) has been formulated by systematically analyzing experimental data corresponding to compound nuclei in the atomic number range $91 \leq Z \leq 104$. The proposed expression incorporates the effects of excitation energy, Coulomb interaction parameter ($Z_{Coul}$) and compound nuclear charge, enabling a unified description of survival behavior across diverse reaction systems. The model reproduces the general trend of decreasing $W_{sur}$ with increasing excitation energy and nuclear charge, consistent with enhanced fission competition in heavier systems. The empirical formula successfully captures the energy and charge dependence of $W_{sur}$ though it tends to overestimate the magnitude by one to three orders for highly fissile nuclei. The framework provides a computationally efficient alternative for estimating survival probabilities in regions where microscopic approaches are limited or experimental data are unavailable, offering valuable guidance for optimizing reaction parameters in superheavy element synthesis.

**Keywords**:survival probability, fusion cross-sections, excitation energy, evaporation residue cross-sections

## 1 Introduction

The synthesis of superheavy elements (SHEs) with atomic numbers $Z > 103$ has been successfully achieved using heavy-ion fusion–evaporation techniques [1–4]. In such reactions,

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the evaporation residue cross-section, $\sigma_{ER}$, is governed by three key probabilities: capture, compound nucleus formation, and survival of the excited nucleus. It can be expressed as

$$\sigma_{ER}(E_{cm}) = \sum_{J=0} \sigma_c(E_{cm}, J) P_{CN}(E_{cm}, J) W_{sur}(E_{cm}, J) \tag{1}$$

where $\sigma_c$ is the capture cross-section, $P_{CN}$ is the compound nucleus formation probability, and $W_{sur}$ represents the probability that the excited nucleus survives against fission during its de-excitation process.

During the initial stage of a heavy-ion collision, the projectile is captured by the target, forming a dinuclear system that may evolve into a compound nucleus. Since the bombarding energy $E_{cm}$ typically exceeds the fusion $Q$-value, the compound nucleus is formed in an excited state and releases its excitation energy primarily through the evaporation of light particles and emission of $\gamma$ quanta. The probability that the system survives this de-excitation without undergoing fission—denoted by $W_{sur}$ plays a crucial role in determining the formation cross-sections of superheavy nuclei.

The accurate evaluation of $W_{sur}$ is therefore essential for understanding the limits of nuclear stability and optimizing reaction conditions for the synthesis of new elements. Several theoretical approaches have been developed to describe fusion–fission dynamics, including the macroscopic dynamics model [5], the fusion-by-diffusion model [6–8], multidimensional Langevin-type dynamical equations [9–11], the cluster dynamical decay model [12, 13], time-dependent Hartree-Fock theory (TDHF) [14, 15], and the extension time-dependent density-matrix theory (TDDM) [16], the two-step model [17], and the dinuclear system model [18–23, 23, 24]. These models have provided valuable insights into the reaction dynamics, but they often require extensive computational input and depend sensitively on fission barrier parameters and level densities. Sowmya et al., [25] used a modified back-shifted Fermi gas model incorporating shell and pairing energy corrections to explain high neutron decay widths in $^{25,26}$Mg+$^{248}$Cm reactions, predicting a neutron-to-total decay width ratio of 0.82–0.89, closely matching the experimental value 0.89 ± 0.13. The survival and compound nucleus formation probability were evaluated in heavy ion fusion reactions [26–29].

For heavy and superheavy nuclei, the $W_{sur}$ decreases sharply with increasing Coulomb repulsion and excitation energy due to enhanced fission competition. Recent studies by Qiao and Pei [30] and Liu and Bao [31] have demonstrated the importance of accurate $W_{sur}$ modeling to predict evaporation residue cross-sections at the picobarn level. However, most existing approaches are either fully microscopic or depend on multiple adjustable parameters, limiting their predictive simplicity.

In this study, we aim to establish a simple yet reliable empirical relation that captures the systematic behavior of the $W_{sur}$ across a broad range of compound nuclei and reaction conditions. To achieve this, we perform a comprehensive analysis of experimental data corresponding to compound nuclei in the atomic number range $91 \leq Z \leq 104$. The extracted survival probabilities are examined as functions of excitation energy, Coulomb interaction, and compound nuclear charge. This investigation not only enhances our understanding of how nuclear structure and Coulomb effects influence the survival of excited nuclei but also provides a practical framework for estimating $W_{sur}$ in systems where experimental measurements are limited or unavailable.

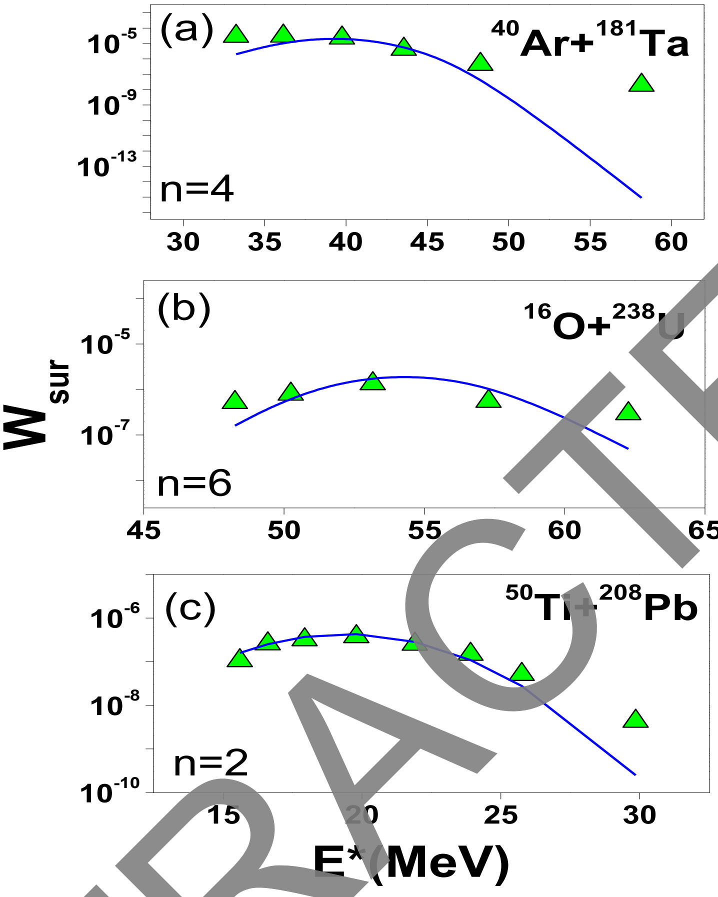

**Figure 1.** A plot of $W_{sur}$ extracted from experimental evaporation and fusion cross-sections as a function of excitation energy for the fusion reaction of (a) $^{40}$Ar+$^{181}$Ta [32, 33], (b) $^{16}$O+$^{238}$U [34, 35], and (c) $^{50}$Ti+$^{208}$Pb [36, 37] fusion reactions.

## 2 Construction of empirical formula for $W_{sur}$ in the compound nucleus atomic number range 91$\leq Z \leq$104

The $W_{sur}$ of a compound nucleus formed in heavy-ion fusion reactions is an important quantity, as it reflects the chance of the nucleus avoiding fission and decaying instead through particle evaporation. Experimentally, this probability can be extracted from measured evaporation residue and fusion cross-sections using the simple relation

$$W_{sur} = \sigma_{ER}^{exp}/\sigma_{fus}^{exp} \tag{2}$$

In this expression, $\sigma_{ER}^{exp}$ represents the cross-section of the experimentally determined evaporation residue, while $\sigma_{fus}^{exp}$ corresponds to the measured fusion cross-section. The ratio, therefore, gives a direct estimate of the fraction of fusion events in which the compound nucleus successfully survives the de-excitation cascade without splitting via fission. Where experimental fusion cross-sections were unavailable within the same energy range as the evaporation residue cross-sections, values were adopted from the Gemini++ code [38]. To formulate an empirical relation for the $W_{sur}$, we have considered a systematic analysis of experimental data for nuclei in the atomic number region $91 \leq Z \leq 104$. As illustrative cases, we examined the fusion reactions $^{40}$Ar+$^{181}$Ta [32, 33], $^{16}$O+$^{238}$U [34, 35], and $^{50}$Ti+$^{208}$Pb [36, 37]. The corresponding results are presented in Figure 1(a-c). In these figures, the neutron evaporation channels associated with each reaction are indicated at the lower left corner. The continuous solid lines represent the $W_{sur}$ values obtained using equation 2, while the triangular points correspond to the directly measured experimental data. At higher excitation energies, the calculated survival probabilities show noticeable deviation from experimental values. This behavior can be attributed to the increasing dominance of the fission decay channel, the damping of shell effects, and the strong energy dependence of the level density parameter. Since the survival probability depends exponentially on the ratio of neutron to fission widths, small uncertainties in fission barrier heights and shell damping prescriptions become amplified at large $E^*$. Nevertheless, an overall satisfactory agreement between the calculated and measured values is observed across the studied systems, thereby supporting the validity and robustness of the adopted approach. Such an analysis not only highlights the reliability of the method but also provides a framework for estimating $W_{sur}$ in the reactions where experimental data may be limited.

Since the survival probabilities follow a Gaussian distribution [39], we constructed a function such that the equation properly fits this Gaussian curve. The proposed expression effectively scales the peak value of the Gaussian distribution to reproduce the $W_{sur}$ . In doing so, we also accounted for evaporation residue cross-sections corresponding to different neutron evaporation channels. The central or mean value of the Gaussian distribution is determined by the parameter $E^*_{opt}$. The fitting parameter $b$ controls the position of this mean value, while the term $d^n$ modifies $E^*_{opt}$ for different evaporation channels. Thus, $d^n$ accounts for channel-specific effects, such as energy dissipation or redistribution, which influence the reference excitation energy for the $n^{th}$ evaporation channel. Furthermore, the effect of the Coulomb interaction was explicitly incorporated.

A larger Coulomb parameter, $Z_{Coul} = \frac{Z_1 Z_2}{A_1^{1/3}+A_2^{1/3}}$, directly influences the stability of the compound nucleus formed in heavy-ion fusion reactions. As $Z_{Coul}$ increases, the repulsive Coulomb interaction between the colliding nuclei becomes stronger, which enhances the probability of fission and thereby reduces the likelihood of compound nucleus survival. This effect is particularly important in the synthesis of superheavy elements, where high charge numbers significantly lower the $W_{sur}$. Figure 2 presents the variation of $W_{sur}$ as a function of $Z_{Coul}$. In this plot, the hollow spheres represent experimental values of $W_{sur}$, while the continuous line corresponds to the fitted curve obtained using the empirical formula. The decreasing trend of $W_{sur}$ with increasing $Z_{Coul}$ is clearly observed, confirming the dominant role of Coulomb repulsion in limiting the stability of superheavy nuclei. In addition, the survival probability has also been studied as a function of the compound nucleus atomic number, as shown in Figure 3. The plot demonstrates that $W_{sur}$ decreases systematically with increasing compound nucleus atomic number. This observation highlights the combined effect of nuclear charge and excitation energy on compound nucleus survival, providing further evidence of the strong dependence of $W_{sur}$ on both Coulomb and nuclear structure effects. By combining the above-mentioned considerations, we arrive at the empirical expression for the $W_{sur}$ as follows;

$$W_{sur} = \left[\frac{a}{Z_{Coul}^{(0.06Z_{comp}-5.3)}}\right] \frac{1}{exp\left[\frac{(E^*-E^*_{opt}bd^n)^2}{2c^2}\right]} \tag{3}$$

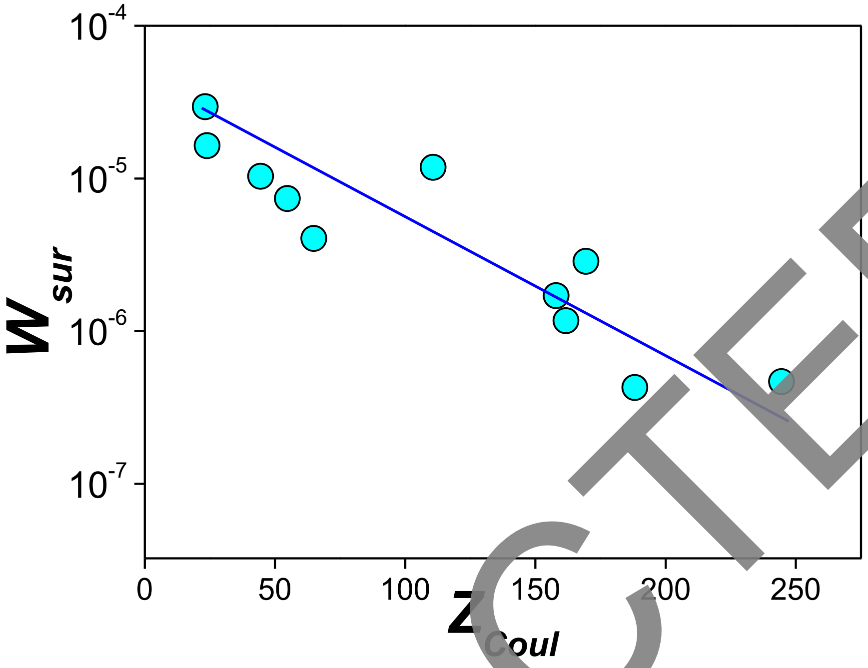

**Figure 2.** A plot of $W_{sur}$ as a function of $Z_{Coul}$ for the fusion reactions leading to form compound nuclei in the atomic number range $91 \leq Z \leq 104$.

where a = $5.93 \times 10^{-5}$, b = 0.62821, d = 1.09 and c=2.7. In Eq. 3, $E^*_{opt}$ and $E^*$ represent the excitation energies corresponding to the optimal and individual cross-sections, respectively. In the present work, we considered the optimal center of mass energy from the literature [40] is follows

$$E_{opt} = 0.79 + 1.025 \times [Z_{Coul} + (exp\beta_{2P} + exp\beta_{2T})] \tag{4}$$

where, $\beta_{2P}$ and $\beta_{2T}$ are quadrupole deformation parameters of projectile and target nuclei. In equation 3, the optimal excitation energy is evaluated using equation 4.

## 3 Results and Discussion

After proposing semi-empirical formula for energy dependent survival probabilities presented in the equation 2, we sought to reproduce the $W_{sur}$ values for the $^{40}$Ca+$^{196}$Hg. Figure 4 presents $W_{sur}$ as a function of $E_{cm}$. The $W_{sur}$ is plotted on a logarithmic scale, ranging from $10^{-10}$ to $10^{-5}$, which highlights the rapid decrease of $W_{sur}$ with increasing neutron evaporation channels. Three curves corresponding to 3n, 4n, and 5n evaporation channels are shown. The 3n channel dominates at lower excitation energies, exhibiting comparatively higher $W_{sur}$, while the 4n and 5n channels shift towards higher $E_{cm}$ values with reduced magnitude. This trend reflects the increasing competition from fission and decreasing probability of compound nucleus survival as more neutrons are emitted. The clear separation of the curves indicates the sensitivity of $W_{sur}$ to both excitation energy and neutron emission.

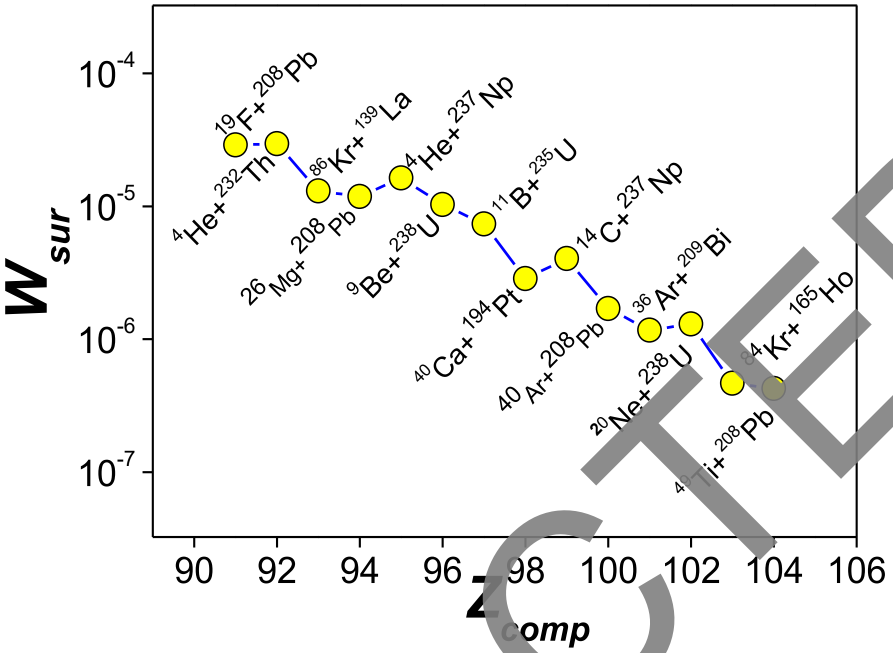

**Figure 3.** A plot of $W_{sur}$ as a function of $Z_{comp}$ nuclei in the atomic number range $91 \leq Z \leq 104$.

Figure 5 presents the $W_{sur}$ as a function of center-of-mass energy ($E_{cm}$) for several fusion reactions classified into hot-fusion 3n channels (panels a and b) and cold-fusion 2n channels (panel c). The vertical axis spans many orders of magnitude ($10^{-18}$ to $10^{-3}$), highlighting the extreme sensitivity of $W_{sur}$ to excitation energy and nuclear fissility. In general, each curve follows a characteristic trend: $W_{sur}$ is negligible at lower $E_{cm}$, increases sharply as the compound nucleus gains sufficient excitation to emit the required neutrons, attains a broad maximum where neutron evaporation successfully competes with fission, and then decreases at higher energies where fission dominates due to excessive excitation. For hot-fusion systems with light projectiles such as $^{4}$He, $^{9}$Be, and $^{11}$B on actinide targets, the $W_{sur}$ are relatively higher compared to heavier projectiles like $^{84,86}$Kr. This is attributed to reduced fissility and more favorable excitation energy balance in asymmetric entrance channels. Similarly, reactions in panel (b) show variations depending on the choice of projectile, with lighter ions offering better survival trends. By contrast, cold-fusion 2n channels involving projectiles like $^{19}$F, $^{26}$Mg, $^{36}$Ar and $^{49}$Ti with $^{208}$Pb and $^{209}$Bi targets exhibit higher $W_{sur}$ at relatively lower center of mass energy ($E_{cm}$). This reflects the lower excitation energy required for 2n evaporation and the stabilizing influence of doubly magic targets, favoring compound nucleus survival. Overall, the graph emphasizes how projectile–target asymmetry, excitation energy, and the choice of fusion channel strongly govern survival probabilities, thus determining the feasibility of forming evaporation residues in superheavy element synthesis.

Table 1 compares survival probabilities of calculated $W_{sur}^{PW}$ and $W_{sur}$ using equation 2 for heavy-ion fusion reactions forming compound nuclei in the atomic number range $91 \leq Z \leq 104$. The selected reactions include both light and heavy projectile–target combinations, covering excitation energies ($E^*$) between 22 and 50 MeV and Coulomb parameters ($Z_{Coul}$) from 23.9 to 187.7. A systematic decrease in $W_{sur}$ with increasing $Z_{Coul}$ is observed,

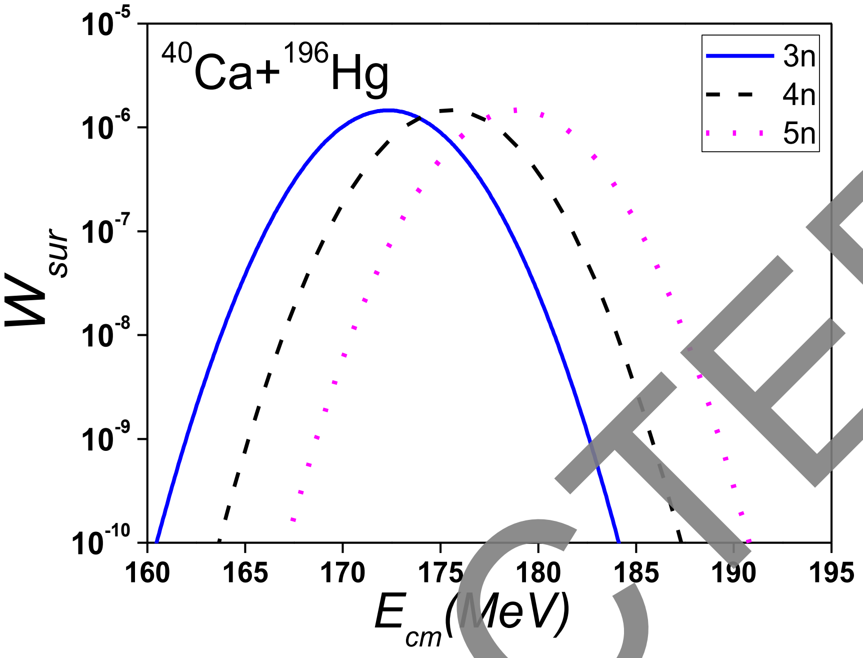

**Figure 4.** A plot of predicted $W_{sur}$ as a function of center of mass energy for the fusion reaction of $^{40}$Ca+$^{196}$Hg for neutron evaporation of 3n, 4n, and 5n.

**Table 1.** Tabulation of fusion cross-sections, formed compound nuclei, excitation energy, evaporation channel, Coulomb interaction parameter, $W_{sur}$(PW) obtained using equation 3, and $W_{sur}$(eq-2).

| Reactions | CN | $E_{CM}$ (MeV) | $E^*$ (MeV) | Ch | $Z_{Coul}$ | $W_{sur}$ (PW) | $W_{sur}$ (eq-2) |
|---|---|---|---|---|---|---|---|
| $^{40}$Ar+$^{181}$Ta [33] | $^{221}$Pa | 147.95 | 43 | 4n | 144.77 | $5.26\times10^{-6}$ | $2.23\times10^{-8}$ |
| $^{22}$Ne+$^{208}$Pb [41] | $^{230}$U | 98.84 | 37.45 | 4n | 93.96 | $6.36\times10^{-6}$ | $2.13\times10^{-8}$ |
| $^{48}$Ca++$^{184}$W [42] | $^{232}$Pu | 159.89 | 31.62 | 3n | 158.76 | $9.76\times10^{-7}$ | $6.02\times10^{-9}$ |
| $^{4}$He+$^{237}$Np [43] | $^{241}$Am | 38.55 | 32.91 | 3n | 23.92 | $1.26\times10^{-6}$ | $3.87\times10^{-6}$ |
| $^{36}$S+$^{207}$Pb [44] | $^{243}$Cf | 147.03 | 32.87 | 3n | 142.34 | $2.53\times10^{-7}$ | $1.82\times10^{-9}$ |
| $^{48}$Ca+$^{197}$Au [42] | $^{245}$Es | 172.91 | 31.40 | 2n | 167.14 | $2.88\times10^{-8}$ | $6.32\times10^{-10}$ |
| $^{16}$O+$^{238}$U [35] | $^{254}$Fm | 88.02 | 49.69 | 5n | 84.43 | $2.19\times10^{-6}$ | $1.27\times10^{-8}$ |
| $^{13}$C+$^{246}$Cm [45] | $^{259}$No | 70.63 | 42.35 | 4n | 66.84 | $3.91\times10^{-7}$ | $2.07\times10^{-9}$ |
| $^{48}$Ca+$^{209}$Bi [42] | $^{257}$Lr | 176.83 | 22.14 | 2n | 173.48 | $7.30\times10^{-8}$ | $7.45\times10^{-7}$ |
| $^{50}$Ti+$^{208}$Pb [46] | $^{258}$Rf | 191.15 | 22.15 | 2n | 187.74 | $4.96\times10^{-8}$ | $2.34\times10^{-8}$ |

indicating the enhanced likelihood of fission in highly fissile and strongly Coulomb-repulsive systems. Lighter systems such as $^{4}$He+$^{237}$Np, and so on exhibit higher survival probabilities from $10^{-6}$ to $10^{-7}$ due to lower fissility and favorable neutron evaporation competition, whereas heavier systems like $^{50}$Ti+$^{208}$Pb and $^{48}$Ca+$^{209}$Bi show significantly reduced survival of $10^{-8}$, reflecting strong fission suppression. The empirical formula successfully reproduces the qualitative behavior and order of magnitude of $W_{sur}$, particularly capturing its dependence on excitation energy and Coulomb interaction. However, it generally overestimates the

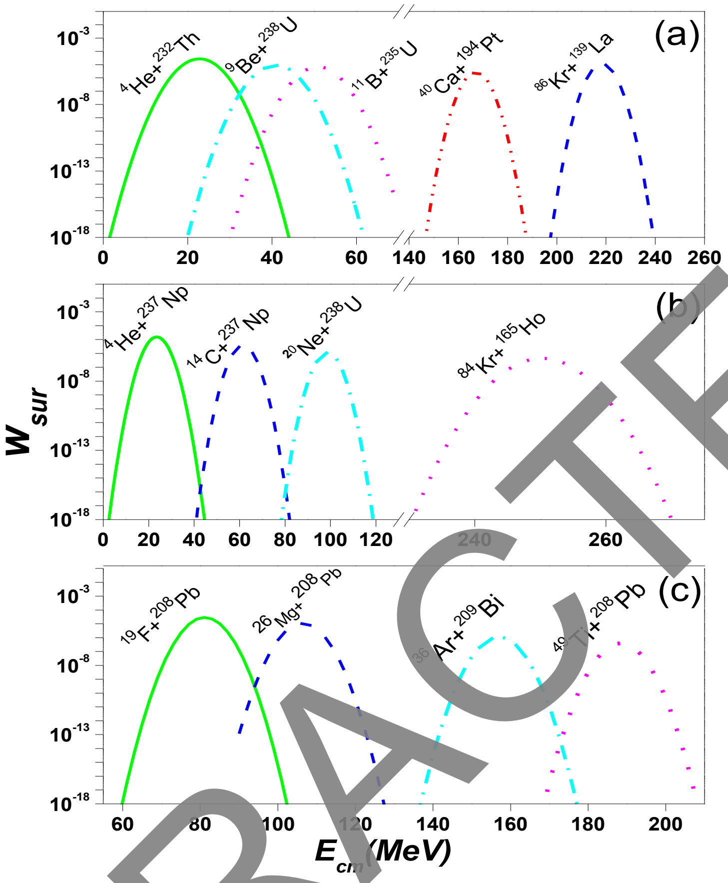

**Figure 5.** A plot of $W_{sur}$ as a function of center of mass energy ($E_{cm}$) for the fusion reactions such as

(a) $^{4}$He+$^{232}$Th, $^{9}$Be+$^{238}$U, $^{11}$B+$^{238}$U, $^{40}$Ca+$^{194}$Pt, and $^{86}$Kr+$^{139}$La for 3n evaporation channel of hot fusion reactions (b) $^{4}$He+$^{237}$Np, $^{14}$C+$^{237}$Np, $^{20}$Ne+$^{238}$U, and $^{84}$Kr+$^{165}$Ho for 3n evaporation channel of hot fusion reactions and (c) $^{19}$F+$^{208}$Pb, $^{26}$Mg+$^{208}$Pb, $^{36}$Ar+$^{209}$Bi and $^{49}$Ti+$^{208}$Pb for 2n evaporation channel of cold fusion reactions.

$W_{sur}$ using equation 2 values by one to two orders of magnitude, especially for systems with high $Z_{Coul}$, such as $^{48}$Ca+$^{197}$Au, and $^{50}$Ti+$^{208}$Pb, suggesting that angular momentum effects, shell damping, and temperature-dependent fission barrier are not fully accounted for. In general, the table demonstrates that the proposed empirical relation provides a consistent and computationally efficient description of survival probabilities in a wide range of compound nuclei, establishing a practical framework for estimating $W_{sur}$ in heavy ion fusion reactions. These predicted survival probabilities are helpful in the prediction of new isotopes of known elements in the atomic number range $91 \leq Z \leq 104$.

## 4 Conclusions

A systematic evaluation of survival probabilities for compound nuclei formed in heavy-ion fusion reactions within the atomic number range $91 \leq Z \leq 104$ has been performed using the proposed empirical relation. The calculated survival probabilities ($W_{sur}^{PW}$) show a consistent decreasing trend with increasing excitation energy and Coulomb interaction parameter, reflecting the enhanced probability of fission in heavier systems. Lighter and more asymmetric combinations, such as $^{4}$He+$^{237}$Np and $^{22}$Ne+$^{208}$Pb, exhibit higher survival probabilities due to lower fissility and efficient neutron evaporation competition. In contrast, heavier systems like $^{48}$Ca+$^{209}$Bi and $^{50}$Ti+$^{208}$Pb show significantly reduced $W_{sur}$ values, emphasizing the dominance of fission in highly charged compound nuclei. Although the empirical model slightly overestimates values obtained using equation 2, it effectively reproduces the overall energy and charge dependence of $W_{sur}$. These predicted survival probabilities provide a practical and computationally efficient approach for estimating the likelihood of compound nucleus survival, thereby aiding in the prediction and design of new isotopes of known elements in the atomic number range $91 \leq Z \leq 104$.

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