# Exploring the possibility to synthesize Lawrencium (Lr) nucleus via $^{45}$Sc+$^{208}$Pb, $^{48}$Ca+$^{209}$Bi, $^{23}$Na+$^{238}$U reactions

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## Introduction

One of the challenges faced by the physicists is to produce the stable heavy elements with Z≥100. Therefore, the scrutiny of finding suitable target and projectile pairs (and corresponding beam energy) leading to the fusion cross section data within measurable range is very important. Despite the remarkable progress in the nuclear structure and relative dynamics, the accuracy in the predicted cross-sections is still desirable, particulary for the odd-Z (very heavy and superheavy nuclei)

Numerous experimental studies have been performed in the past to explore the dynamics of No (Z=102) [1, 2] and Rf (Z=104) systems [3] but Lr (Z=103) nucleus is not much investigated so far. In view of this, the present work is carried out to explore the capture and fission dynamics of Lr nucleus formed in $^{45}$Sc+$^{208}$Pb→$^{253}$Lr$^*$, $^{48}$Ca+$^{209}$Bi→$^{257}$Lr$^*$, and $^{23}$Na+$^{238}$U→$^{261}$Lr$^*$ reactions. The $\ell$-summed Wong model [4] is used to obtain the compound nucleus fission cross-sections ($\sigma_{fission}$) of above mentioned channels. Along with this, the percentage contribution of fission and quasi-fission events in the capture cross-sections is calculated .

TABLE I: $\ell$-summed Wong model predicted capture ($\sigma_{Cap.}$), fusion-fission ($\sigma_{FF}$), and quasi-fission ($\sigma_{QF}$) cross-sections for the reactions $^{45}$Sc+$^{208}$Pb, $^{48}$Ca+$^{209}$Bi, and $^{23}$Na+$^{238}$U. % contribution of $\sigma_{FF}$ and $\sigma_{QF}$ to the $\sigma_{Cap.}$ is also mentioned in the table.

| $\frac{E_{c.m.}}{E_{Bass}}$ | $\ell_{max}$ | $\sigma_{Cap.}$ | $\sigma_{fission}$ | $\sigma_{QF}$ | $\frac{\sigma_{fission}}{\sigma_{Cap.}}$ | $\frac{\sigma_{QF}}{\sigma_{Cap.}}$ |
|---|---|---|---|---|---|---|
| | ($\hbar$) | (mb) | (mb) | (mb) | (%) | (%) |
| $^{45}$Sc+$^{208}$Pb→$^{253}$Lr$^*$ (V$_C$=187.68 MeV) | | | | | | |
| 1.00 | 15 | 23.4 | 11.1 | 12.27 | 48 | 52 |
| 1.04 | 44 | 182.6 | 138.9 | 43.6 | 76 | 24 |
| 1.08 | 63 | 355.2 | 303.2 | 52 | 85 | 15 |
| $^{48}$Ca+$^{209}$Bi→$^{257}$Lr$^*$(V$_C$=178.49 MeV) | | | | | | |
| 1.00 | 12 | 15.11 | 8.09 | 7.02 | 53 | 46 |
| 1.03 | 43 | 173.88 | 145.5 | 28.35 | 83 | 16 |
| 1.08 | 60 | 322.02 | 309.8 | 12.22 | 95 | 5 |
| $^{23}$Na+$^{238}$U→$^{261}$Lr$^*$(V$_C$=113.29 MeV) | | | | | | |
| 1.00 | 10 | 27.79 | 14.56 | 13.23 | 52 | 48 |
| 1.03 | 20 | 110.15 | 76.66 | 33.5 | 69 | 31 |
| 1.09 | 36 | 337.04 | 309.74 | 27.3 | 92 | 8 |

## Methodology

For very heavy and superheavy nuclei fusion cross-section is generally lesser than the capture cross-section. Also, as the evaporation residue cross-sections ($\sigma_{ER}$) are in nb or pb order so $\sigma_{fusion}$=$\sigma_{ER}$+$\sigma_{fission}$ ≈ $\sigma_{fission}$. In terms of angular-momentum ($\ell$) partial waves, the fusion cross-sections (for two deformed and oriented nuclei in the same plane with center-of-mass (c.m.) energy $E_{c.m.}$, reads as [4]

$$\sigma_{fusion}(E_{c.m.},\theta_i)=\frac{\pi}{k^2}\sum_{\ell=0}^{\ell_{max}}(2\ell+1)P_\ell P_{CN} \tag{1}$$

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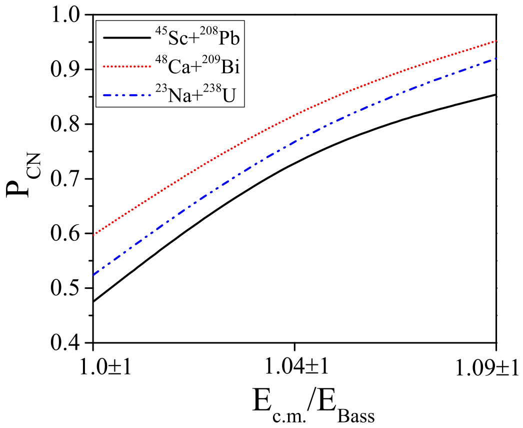

FIG. 1: $\ell$-summed Wong model predicted capture and fusion/fission cross-sections of Z=103 formed in different entrance channels.

where k=$\sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}}$, $\mu$ is reduced mass, $P_\ell$ is barrier penetrability, and $P_{CN}$ is compound nucleus formation probability calculated as [5]

$$P_{CN}(E^*_{CN},\ell) = \frac{P^0_{CN}}{1+exp[(E^*_B - E^*_{CN})/4]} \tag{2}$$

## Calculations and Results

Table I shows the theoretically predicted cross-sections of Lr nucleus formed via $^{45}$Sc+$^{208}$Pb→$^{253}$Lr$^*$, $^{48}$Ca+$^{209}$Bi→$^{257}$Lr$^*$, and $^{23}$Na+$^{238}$U→$^{261}$Lr$^*$ reactions. In the table capture and fission cross-sections are shown and fission cross-sections are obtained using relation: $\sigma_{FF}$=$\sigma_{Cap}$×$P_{CN}$. The predictions are made at near- and above- barrier energies as $\ell$-summed Wong model is more suitable at this energy domain. For the better comparison, the predictions are obtained at same $\frac{E_{c.m.}}{E_{Bass}}$ ratio. It is observed from Table I that regardless of the reaction channel, the capture and fission cross-sections increases with the increase in incident energy. The percentage contribution of fission events into capture also increases. Highest contribution of $\sigma_{fission}$ is noted for $^{48}$Ca+$^{209}$Bi channel which shows increment in cross-section from 53% to 95% followed by $^{23}$Na+$^{238}$U (52% to 92%) and $^{45}$Sc+$^{208}$Pb (48% to 85%) respectively. One can also calculate the quasi-fission contribution as difference between capture and fission cross-sections *i.e.* $\sigma_{QF}$=$\sigma_{Cap}$-$\sigma_{fission}$ (or $\sigma_{Cap}$×(1-$P_{CN}$)).

To support the above analysis, the compound nucleus formation probability ($P_{CN}$) of considered systems is calculated using Eq.(2) and plotted in Fig.1. It is observed that lowest $P_{CN}$ is noted for Pb-based reaction and highest for $^{48}$Ca+$^{209}$Bi channel. Higher $P_{CN}$ values indicate higher chances of fusion and vice-versa. The result is in line with the results of Table I.

Concluding this, we can say that higher fission contribution into capture cross-sections and higher $P_{CN}$ values of $^{48}$Ca+$^{209}$Bi indicating it as a better option to synthesize Z=103 nucleus. In future study, it will be of further interest to explore the formation and decay dynamics of aforementioned reactions in details.

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