Fusion probability and survivability in estimates of heaviest nuclei production

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1. Fusion probability and survivability as main values in estimates of the heaviest nuclei production

2. Production of heavy nuclei in the vicinity of a 126 neutron shell in fusion reactions having a different entrance-channel mass asymmetry

3. Macroscopic fission barriers and fusion probabilities in hot and cold fusion reactions leading to heavy actinides and transactinides

4. Survivability of nuclei close to the SHE region, which are produced in $^{48}$Ca induced reactions

5. Summary and conclusion
Inconsistency in the description of experimental ER cross sections for nearly symmetric combinations of fusioning nuclei in the framework of barrier passing and statistical models

R. N. Sagaidak et al., PRC 68, 014603 (2003)

G. Royer & B. Remaud, NP A444, 477 (1985)

V. I. Zagrebaev et al., http://nrv.jinr.ru/nrv/webnrv/driving/
Theoretical and experimental estimates of $P_{\text{fus}}$ ($\equiv P_{\text{CN}}$)

R. S. Naik et al., PRC 76, 054604 (2007)

$\sigma_{\text{EVR}} = \sum_{J=0}^{J_{\text{max}}} \sigma_{\text{capture}}(E_{\text{c.m.}}, J) P_{\text{CN}}(E_{\text{c.m.}}, J) \cdot W_{\text{sur}}$

$\sigma_{\text{cap}}(E_{\text{c.m.}}, J) = \pi \chi^2(2J+1)T(E_{\text{c.m.}}, J)$

Extraction of CN-fission events and $P_{\text{CN}}$ with the decomposition of FF angular distributions integrated over masses and energies (B.B. Back’s approach):
Theoretical and experimental estimates of $P_{\text{fus}}$ ($\equiv P_{\text{CN}}$)

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$P_{\text{fus}}$ experimentally obtained in reactions leading to less fissile Pb* CN

G. N. Knyazheva et al., PRC 76, 054604 (2007)

The comparison of ER cross sections with those obtained in a very asymmetric reaction implying no fusion suppression
$P_{\text{fus}}$ experimentally obtained in reactions leading to less fissile Pb* CN

G. N. Knyazheva et al., PRC 76, 054604 (2007)

The decomposition of fission fragment mass-angular and TKE distributions

The comparison of ER cross sections with those obtained in a very asymmetric reaction implying no fusion suppression
Comparison of the ER production in the $^{16}O+^{186}W$ and $^{48}Ca+^{154}Sm$ combinations leading to the $^{202}Pb^+$ CN
Why is the difference in $P_{\text{fus}}$ estimates obtained from comparison of the ER production in the $^{16}\text{O}+^{186}\text{W}$ and $^{48}\text{Ca}+^{154}\text{Sm}$ reactions and from fission measurements?

Fission and ER experiments were performed in the same runs following the same normalization procedure in the cross section estimates.

- The underestimate of QF events (obtained with the simple cutting and Gaussian fitting procedures) due to the interference of QF events with deep-inelastic ones.
- The overestimate of CN-fission events having a “right” variance of the mass distributions and symmetric angular distributions, which imply some equilibration and compactness of a system near the saddle point, but without passing over the fission barrier to form a true CN.

Estimates with ER cross sections measured in an asymmetric reaction

$$P_{\text{fus}}^{\text{emp}}(E_{\text{CN}}^*) = \frac{\sigma_{\text{ER}}^{\text{expt}}(E_{\text{CN}}^*)}{\sigma_{\text{ER}}^{\text{asym}}(E_{\text{CN}}^*)} \frac{k^2_{\text{asym}}}{k^2_{\text{asym}}}, \text{ at } E_{\text{CN}}^* > E_{\text{CN}}^*(B_{\text{Bass}}^{\text{asym}})$$

Estimates with calculated ER cross sections based on capture cross sections measured/calculated in the investigated reaction

$$P_{\text{fus}}^{\text{emp}}(E_{\text{CN}}^*) = \frac{\sigma_{\text{ER}}^{\text{expt}}(E_{\text{CN}}^*)}{\sigma_{\text{ER}}^{\text{calc}}(E_{\text{CN}}^*)} \left( \frac{\sigma_{\text{fus}}}{\sigma_{\text{cap}}} / (P_{\text{fus}} = 1) ; W_{\text{sur}}(B_{\text{fis}}^{\text{asym}}) \right)$$
Comparison of the ER production in different combinations leading to the $^{220}$Th$^*$ CN
ER production in different combinations leading to the neutron-deficient Th' CN (no ref. combinations, $k_f$ scaling)

$$k_f (A_{CN} = 214) = \frac{k_f (^{16}O + ^{204}Pb)}{k_f (^{40}Ar + ^{180}Hf, P_{fus} = 1)} \frac{k_f (^{32}S + ^{182}W, P_{fus} = 1)}{k_f (^{40}Ar + ^{180}Hf, P_{fus} = 1)}$$
Fusion probability in different reactions leading to Th* CN

![Graph showing fusion probability as a function of energy difference](image)
Fusion probability and fission barriers in reactions leading to Po^* CN

Macroscopic fission barriers for Rn, Ra, Fr and Th nuclei
Production of Fm nuclei in hot and cold fusion reactions
Production of Fm nuclei in hot and cold fusion reactions
Production of No nuclei in very asymmetric hot fusion reactions
Production of No nuclei in the $^{48}$Ca+$^{208}$Pb reaction
Production of No nuclei in the $^{48}$Ca+$^{208}$Pb reaction
Production of Rf and $P_{\text{fus}}$ derived from fission data obtained in hot fusion reactions
Energy dependence of $P_{\text{fus}}$ derived from fission (ER) data and $P_{\text{fus}}$ systematics

I.M. Itkis et al., PRC 83, 064613 (2011)
Hs production in the S+^{238}U fusion reactions

\[ \sigma_{\text{fus}} \]

\[ \sigma_{\text{bp}} \]

\[ E_{\text{CN}}^* \text{ (MeV)} \]

\[ \Sigma(3n-5n) \]

Capture, Shen et al.
Fusion, Shen et al.
Capture, Frielfelder et al.
Fission, Nishio et al.
\( V_0 = 65, \sigma(r_0)/r_0 = 6\% \)
\( \langle P'_{\text{fus}} \rangle = 0.268 \)
\( \Sigma(3n-5n), \) Graeger et al.
\( V_0 = 60, \sigma(r_0)/r_0 = 6\% \)
\( \sigma(r_0)/r_0 = 3.5\%, B_i^m = 0 \)
\( \langle P'_{\text{fus}} \rangle = 0.273, B_i^m = B_f^{LD} \)
Hs production in the $^{26}\text{Mg}+^{248}\text{Cm}$ and $^{48}\text{Ca}+^{226}\text{Ra}$ fusion reactions
Fission barriers for the heaviest nuclei

Scaling parameter:

LD fission barrier

Ground-state shell correction

Macroscopic fission barrier

$Z=110$

$Z=111$

$Z=112$

$Z=113$

$Z=114$

$Z=115$

$Z=116$

$Z=117$

$Z=118$

$M - A$ (MeV) vs. Neutron number
Fission barriers for the heaviest nuclei

Scaling parameter
LD fission barrier
Ground-state shell correction
Macroscopic fission barrier
Production cross sections for Z=112, 114 nuclei in $^{48}$Ca induced reactions

$B_f = -\Delta W_{gs}$, FRLDM-masses, P. Möller et al., ADNDT 59, 185 (1995)
Production cross sections for $Z=116, 118$ nuclei in $^{48}\text{Ca}$ induced reactions
Summary and conclusion

- Being critical and correlating values in the estimates of ER cross sections, fusion probability and survivability in CN-reactions leading to heavy and heaviest nuclei were considered using the potential barrier passing model for capture and statistical model (SM) for the CN de-excitation.

- The survivability of heavy nuclei produced in the vicinity of a 126 neutron shell in very asymmetric projectile-target combinations can be reproduced with reduced values of the liquid-drop (LD) component of fission barriers in the framework of SM. These barriers can be used for the empirical estimates of the fusion probability for more symmetric reactions.

- Production of heavy nuclei from Fm to Rf in very asymmetric “hot” fusion reactions can be reproduced with the 20% increase in the LD component of fission barriers using a similar approach with SM. The corresponding estimates of the fusion probability for more symmetric “cold” fusion reactions are differed from those predicted by theories and obtained in fission experiments.

- Production of the heaviest nuclei with Z>104 in “hot” fusion reactions induced by massive projectiles can be reproduced with the fusion probabilities obtained from fission data and with some reduction in the LD component of fission barriers (for Hs nuclei). Data analysis implies a disappearance of the macroscopic (LD) component for nuclei with Z>108.

- Estimates of atomic masses and shell corrections are mainly responsible for the description of the heaviest nuclei production in reactions induced by $^{48}$Ca and heavier projectiles, bearing in mind an absence of the macroscopic component in the fission barriers for these nuclei.
Thank you for your attention