Fusion Hindrance using a Markov Chain Method

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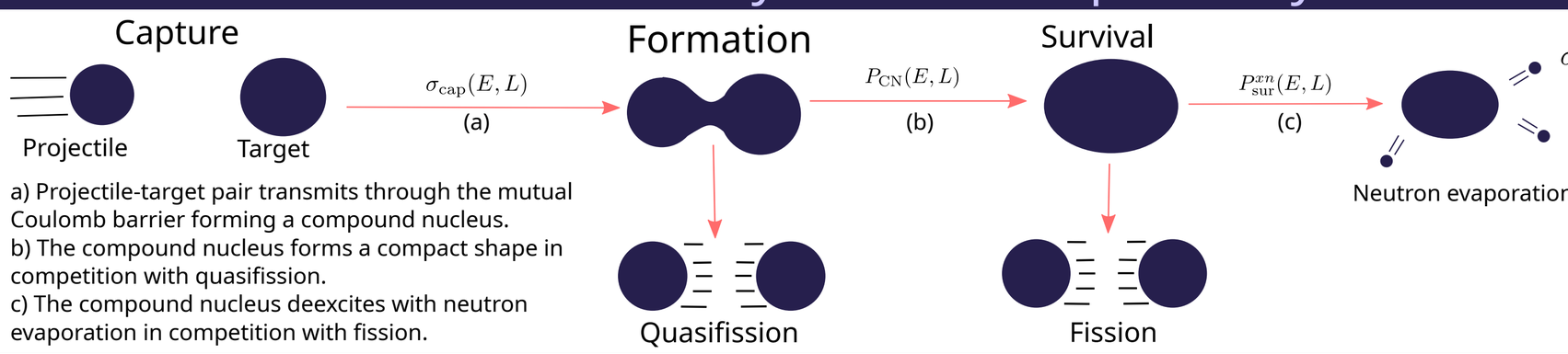
Synthesis of superheavy elements

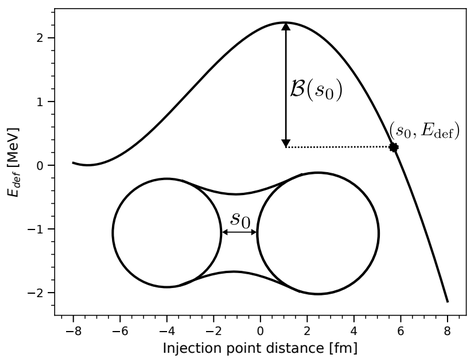


a) Projectile-target pair transmits through the mutual Coulomb barrier forming a compound nucleus.
b) The compound nucleus forms a compact shape in competition with quasifission.
c) The compound nucleus deexcites with neutron evaporation in competition with fission.

$$\sigma^{xn}_{er}(E) = \sum_{L=0}^{\infty}(2L+1)\sigma_{\rm cap}(E,L)P_{\rm CN}(E,L)P^{xn}_{\rm sur}(E,L)$$

$P_{\rm CN}(E,L)$ formation probability determined using the Langevin equation of motion on two different potentials seen below.

One-dimensional solution



Analytical solution to the Langevin equation of motion on a one-dimensional potential.

$$P_{\rm CN} = \tfrac{1}{2}\mathrm{erfc}\left(\sqrt{\frac{\mathcal{B}(s_0)}{\mathcal{T}'}} - \frac{1}{x+\sqrt{1+x^2}}\sqrt{\frac{K_{\rm rem}(E,L)}{\mathcal{T}'}}\right)$$

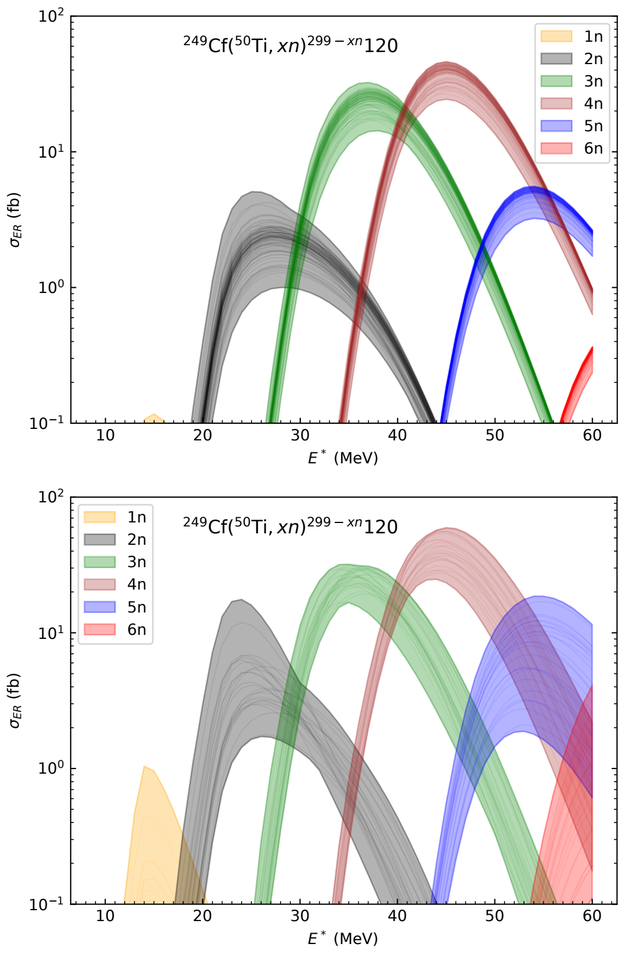
with $x = \frac{\beta}{2\omega}$, where the parameters
s_0 – injection point distance,
β – friction coefficient,
are the model's free parameters

KEWPIE

KEWPIE2 [1] is a code for calculating the survival probability in fusion evaporation reactions, and was recently extended [2] to include the formation probability seen above. Presented below is preliminary predictions and uncertainty estimation of the code.

(a) Variation of prediction due to variation in choice of data included in fit.
The 28 point dataset is resampled by excluding 15% of the data in each run, refitting the model on the reduced dataset. This shows the sensitivity of the model to the choice of fitting data. Shaded area shows total variation of the 100 runs.

(b) Variation of prediction due to variation of some settings available to user. Model parameters are refit to data when varying the available settings.
Plot shows the 25 best settings combinations with best fit to data of the 144 chosen combinations.



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[2] H. Dungo, Study of Reaction Mechanisms for the Synthesis of Super-Heavy Elements, PhD Thesis, Normandie Université, 2024.
[3] P. Möller, A. J. Sierk, T. Ichikawa, and H. Sagawa, Nuclear ground-state masses and deformations: FRDM(2012), At. Data Nucl. Data Tables 109–110, 1 (2016).
[4] M. Albertsson, B. G. Carlsson, T. Døssing, J. Randrup, D. Rudolph, and S. Åberg, Formation of transfermium elements in reactions with Pb 208, Phys. Rev. C 110, 014624 (2024).
[5] F. Agert, Fusion Cross Section of Superheavy Elements Using a Markov Chain Method, Master thesis, Division of Mathematical Physics, Lund University, 2025.
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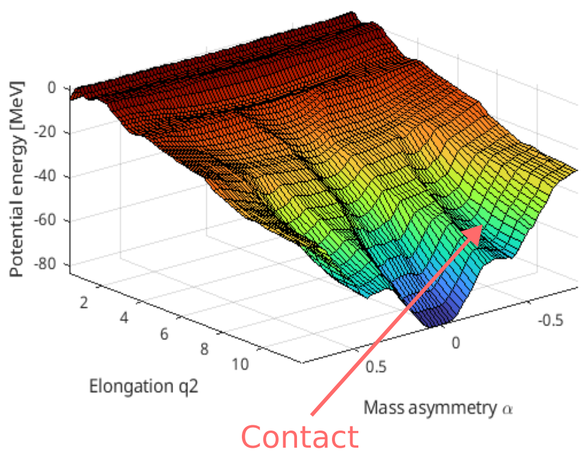
Microscopic-macroscopic potential



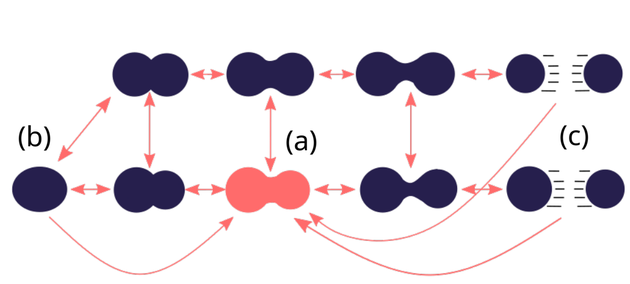
$$P_{\rm CN} = \frac{\#\text{ events leading to formation}}{\#\text{ total events}}$$

5D potential map of a compound system from FRLDM [3] spanning 7 million shapes, with shape coordinates:

α - Mass asymmetry
Q_2 - Elongation of system
r_c - Neck radius
ε_l - Left fragment quadrupole deformation
ε_r - Right fragment quadrupole deformation

Langevin Eq. of motion not analytically solvable. By assuming an overdamped Langevin Eq. of motion, formation probability obtained by repeating a random-walk on the potential [4].

Markov Chain



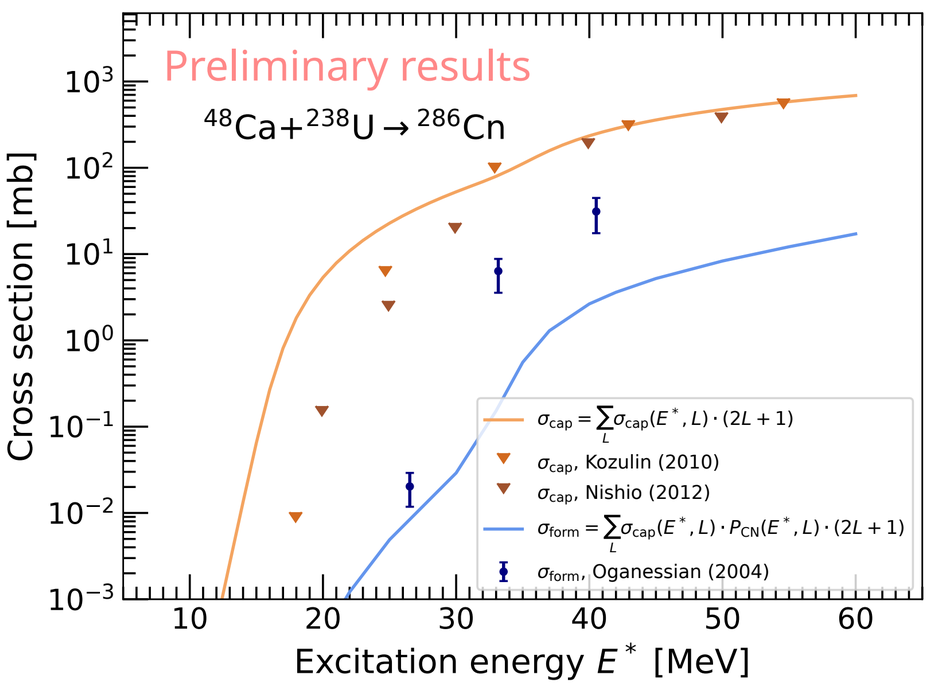
(a) Starting shape determined from capture stage. Repeat random walk from here

(b) Fusion of CN into compact shape.

(c) Quasifission

Repeat a random walk from the contact point (in orange) to obtain formation probability.

At low formation probability, runtime is long due to bad statistics, but can be turned into a sparse eigenvalue problem using a Markov chain, reducing computational time significantly [5]. Computation time for one partial wave is reduced from 5 hours to 3 minutes using this method.



Results above is currently being extended to yield systematic cross section predictions for different combinations of projectile and targets in [6].

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