FUSHE 2012

Predictions of the FBD model for the synthesis cross sections of Z = 114-120 elements based on macroscopic-microscopic fission barriers

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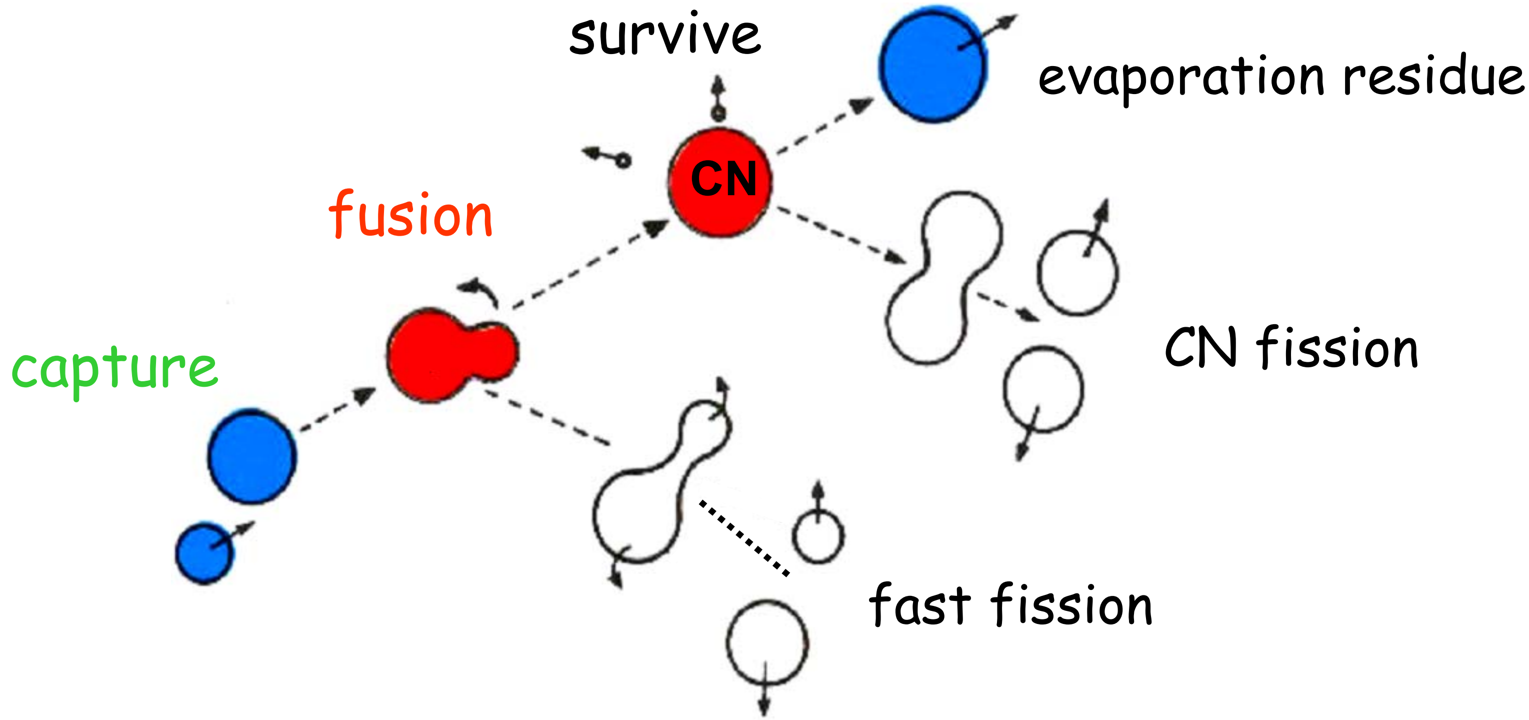
arXiv 1203.2252

Nucleus-nucleus collision which may lead to the formation of super-heavy nuclei



$$\sigma(\text{synthesis}) = \pi\lambda\!\!\!^{-2}\sum_{l=0}^{\infty}(2l+1)T_l P_l(\text{fusion})P_{xn}^{\ell}(\text{survive})$$

W. J. Świątecki, K. Siwek-Wilczyńska, and J. Wilczyński, *Acta Phys. Pol.* 34, 2049 (2003).
W. J. Świątecki, K. Siwek-Wilczyńska, and J. Wilczyński, *Phys. Rev.* C 71, 014602 (2005).
T. Cap, K. Siwek-Wilczyńska, J. Wilczyński, IJMP E20, 308 (2011)
T. Cap, K. Siwek-Wilczyńska, J. Wilczyński, PR C83, 054602 (2011)

FBD $\rightarrow$ $$\sigma(\text{synthesis}) = \pi \lambda\!\!\!^{-}{}^2 \sum_{l=0}^{l_{max}} (2l+1) P_l(\text{fusion}) P_{xn}^{\ell}(\text{survive})$$

l_{max} – calculated from the capture cross section.

$$\sigma_{cap}(E) = \pi \lambda\!\!\!^{-}{}^2 \sum_{l=0}^{\infty} (2l+1) T_l \approx \pi \lambda\!\!\!^{-}{}^2 (l_{\max} + 1)^2$$

semiempirical formula

$$\sigma_{cap}(E) = \pi R_{\sigma}^2 \left[X \sqrt{\pi} \,(1 + erf\ X) + \exp(-X^2) \right] \frac{w}{E \sqrt{2\pi}}$$

$$where: \quad X = \frac{E - B_0}{\sqrt{2w}}, \qquad erf\ X -$$ Gaussian error function

This formula derived assuming:

- Gaussian shape of the fusion barrier distribution
- Classical expression for $\sigma_{fus}(E,B)=\pi R^2(1-B/E)$

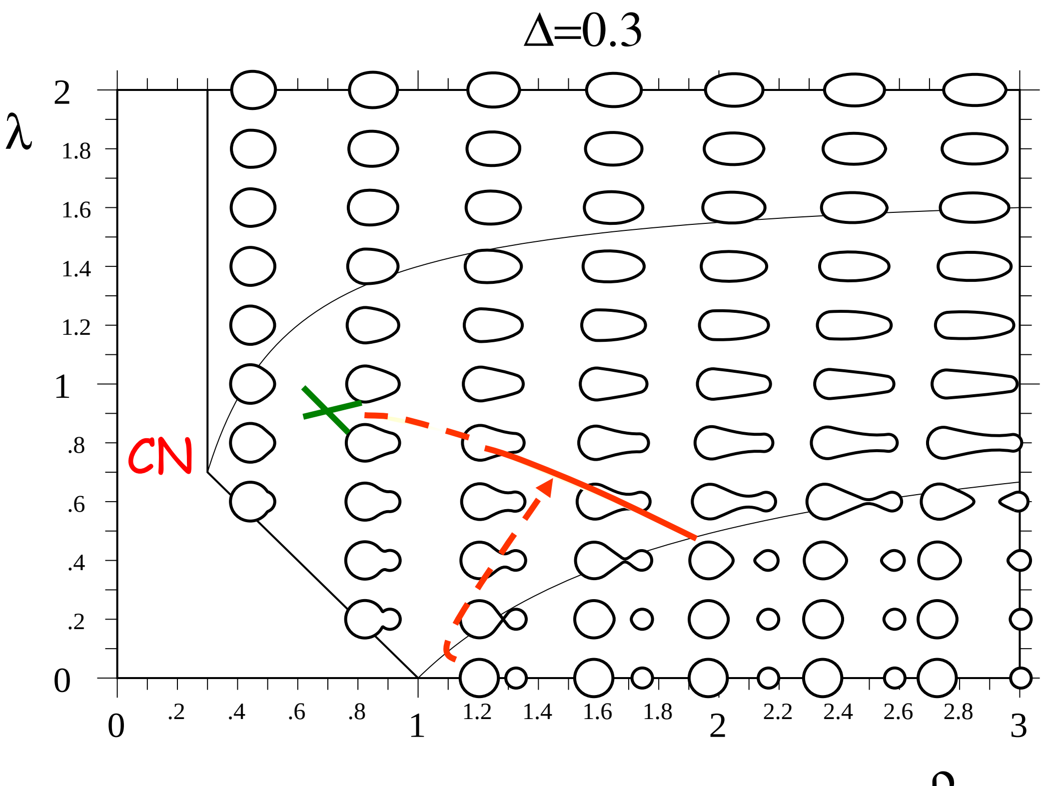
W. Świątecki, K. Siwek-Wilczyńska, J. Wilczyński Phys. Rev. C71 (2005) 014602,
Acta Phys. Pol. B34(2003) 2049

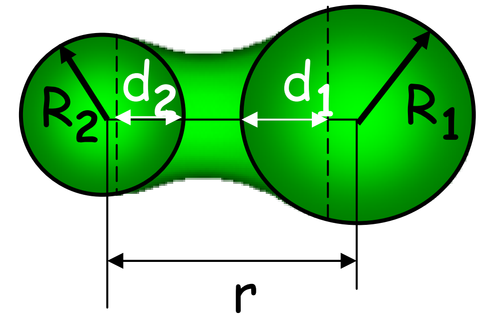
3 parameters: B_0, w, R_{σ} obtained from χ^2 fit to 48 experimental near-barrier fusion excitation functions for $40 < Z_{CN} < 98$

(K. Siwek-Wilczyńska, J. Wilczyński Phys. Rev. C 69 (2004) 024611)

P_l(fusion)

J. Błocki, W. J. Świątecki, Nuclear Deformation Energies, Report LBL 12811 (1982)





$\lambda = (d_1 + d_2)/(R_1 + R_2)$ - neck parameter

$\rho = r/(R_1 + R_2)$ – relative distance

$\Delta = (R_1 - R_2)/(R_1 + R_2)$ – asymmetry parameter

Smoluchowski Diffusion equation for the parabolic potential

$$P_l(\text{fusion}) = ½(1-\text{erf}\sqrt{H(l)/T})$$

H - the barrier opposing fusion
T - the temperature of the fusing system

P_{xn}^{l}(survive) for xn reaction

- Partial widths for neutron emission - Weisskopf formula

$$\Gamma_{in} = \frac{m_n}{\pi^2\hbar^2}(2s_n+1)\int_0^{E_{in}^{\max}} \varepsilon_{in}\sigma_{in}\frac{\rho_{in}\left(E_{in}^{\max}-\varepsilon_{in}\right)}{\rho\left(E^*\right)}d\varepsilon_{in}$$

$$E_{in}^{\max} = E_{(i-1)}^{*} - E_{rot}^{in} - B_{in} - P$$

Upper limit of the final-state excitation energy after emission of a particle *i*

σ_i – cross section for the production of the compound nucleus in the inverse process
m_i, s_i, ε_i - mass, spin and kinetic energy of the emitted particle
ρ, ρ_i – level densities of the parent and daughter nuclei

- The fission width (transition state method)

$$\Gamma_{ifiss} = \frac{1}{2\pi}\int_0^{E_{if}^{\max}} \frac{\rho_{fiss}\left(E_{if}^{\max}-K\right)}{\rho\left(E^*\right)}dK$$

$$E_{if}^{\max} = E_{i-1}^{*} - B_{if} - E_{rot}(saddle) - P$$

Upper limit of the thermal excitation energy at the saddle

- The level density is calculated using the Fermi-gas-model formula including shell efects

included as proposed by Ignatyuk
(A.V. Ignatyuk et al., Sov. J. Nucl. Phys. 29 (1975) 255)

$$a = a_{macro}\left[1+\frac{\delta_{shell}}{U}\left(1-e^{-U/E_d}\right)\right]$$

To calculate the survival probability we need to know (for all nuclei in the xn deexcitation cascade):

- ground state masses,
- fission barriers,
- shell correction energies and deformations (in the ground state and saddle).

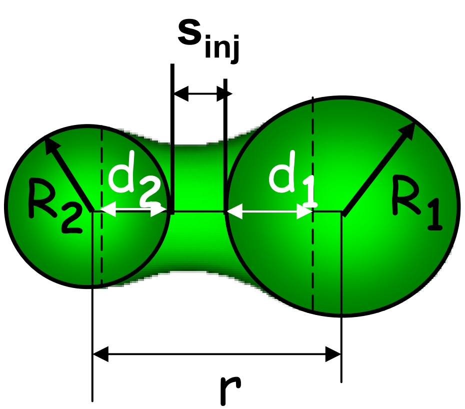
Lack of systematic theoretical studies !

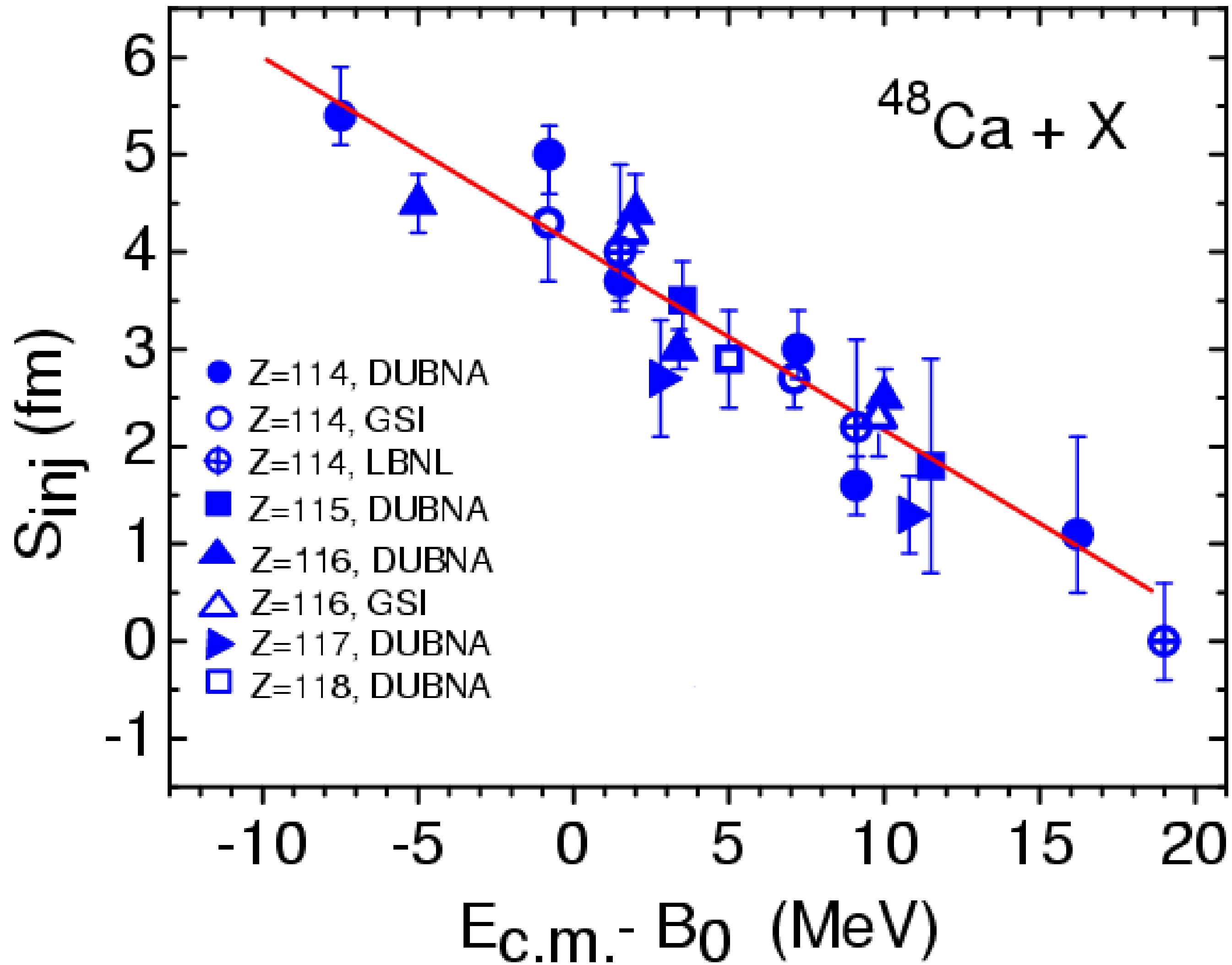
Those values were calculated using the Warsaw macroscopic-microscopic model including the nonaxial shapes.

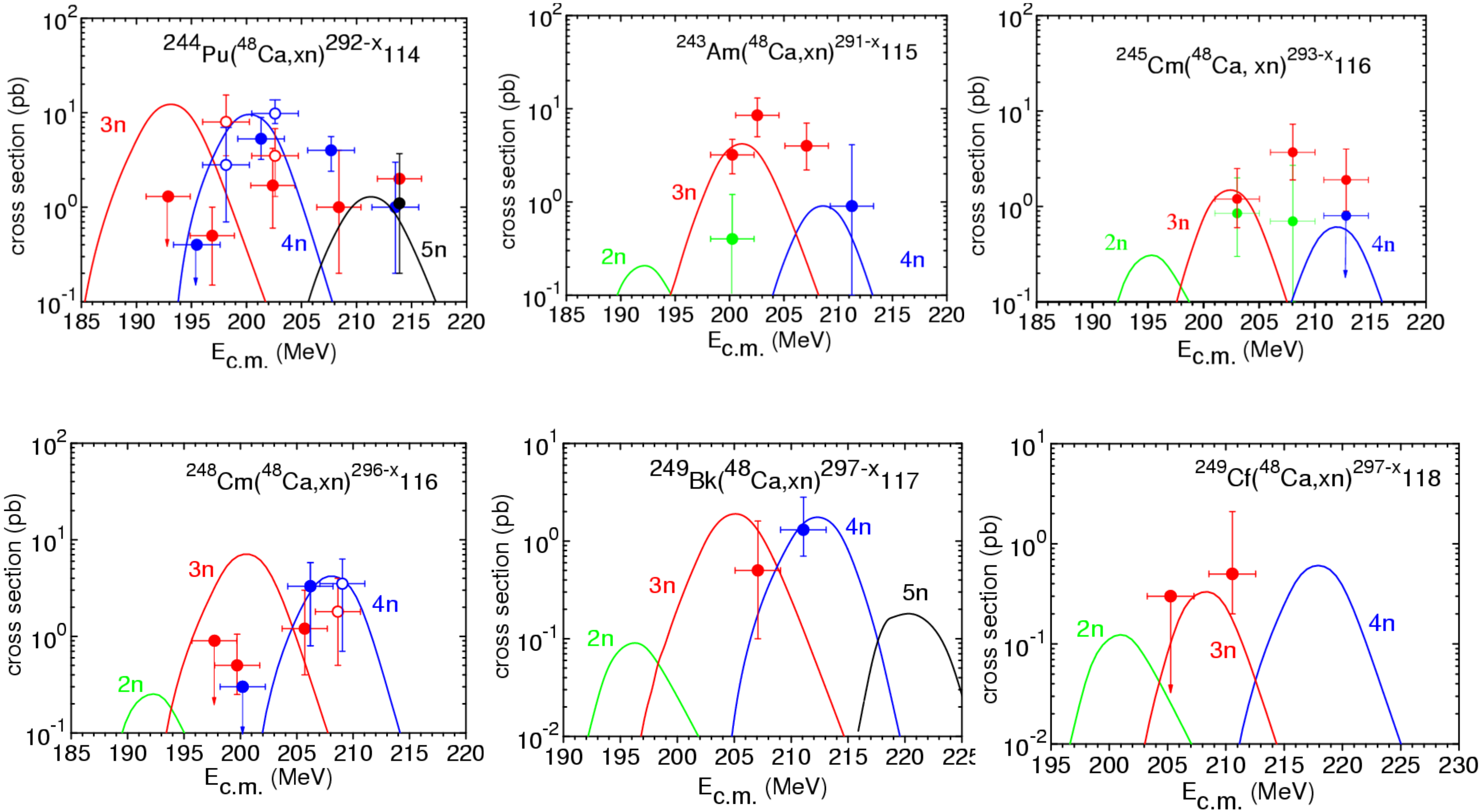
M. Kowal, Jachimowicz, A. Sobiczewski, Phys. Rev. C82 (2010) 014303
M. Kowal (unpublished) , A. Sobiczewski (unpublished) .

$$\sigma(\text{synthesis}) = \pi \lambda\!\!\!^{-}{}^2 \sum_{l=0}^{lmax} (2l+1) P_l(\text{fusion}) P_{xn}^{\ell}(\text{survive})$$

Systematics of the s_{inj} parameter from the fit to the maximum values of the experimental cross sections for 2n, 3n, 4n and 5n channels in ^{48}Ca + X reactions (complete set of existing data)







● experiment Dubna

○ experiment GSI

Uncertainties of calculated cross sections

$$\sigma(\text{synthesis}) = \pi\lambda\!\!\!^{-2} \sum_{l=0}^{l\max} (2l+1) P_l(\text{fusion}) P^{\ell}_{xn}(\text{survive})$$

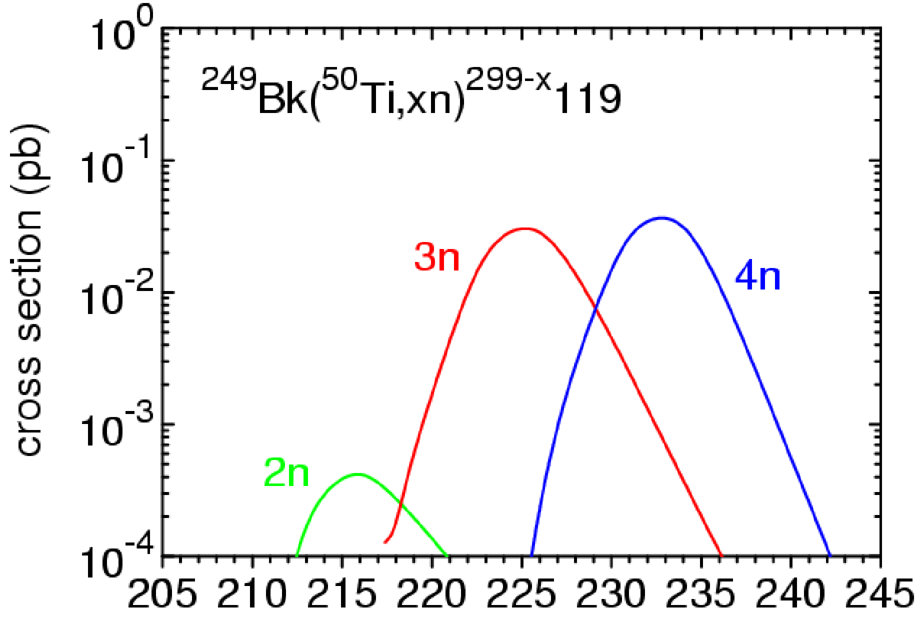
σ(capture) does not change significantly from one system to another. Resulting uncertainties are not large unless the deeply sub-barrier reactions are studied (e.q. cold fusion)

P(fusion) depends on the asymmetry of the colliding system and the entrance channel energy. Theoretical (or phenomenological) predictions may result in large uncertainties of several orders of magnitude only for unexplored heavy and symmetric systems.

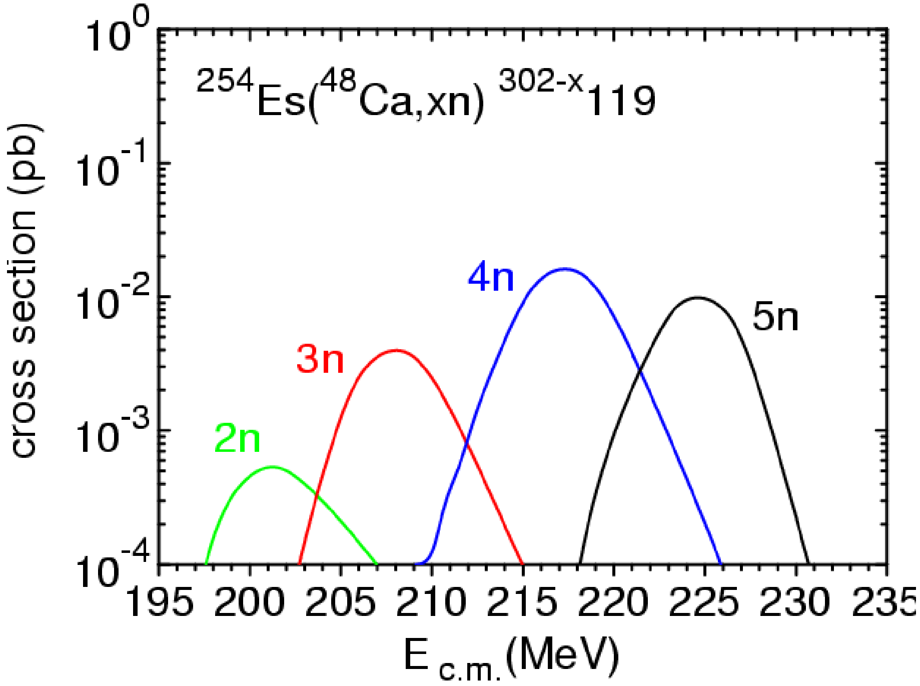
P(survival) Very strong dependence on B_f-B_n easily resulting in orders of magnitude differences of the cross section (1 MeV difference - about 1 order of magnitude on each step of the deexcitation cascade).

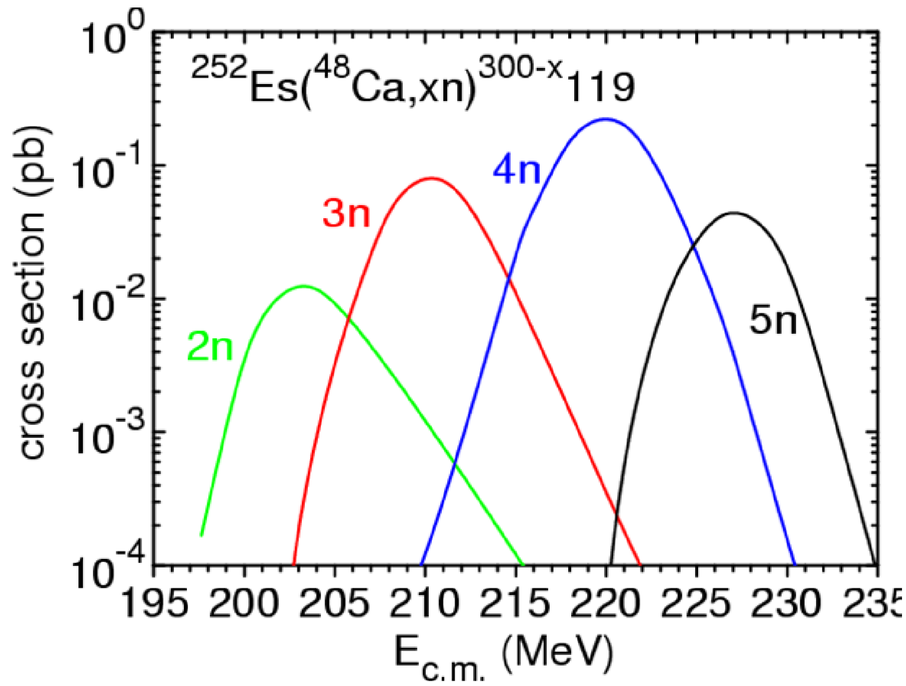
It is very important to do systematic studies and use well tested theoretical predictions for both, ground state and saddle properties.

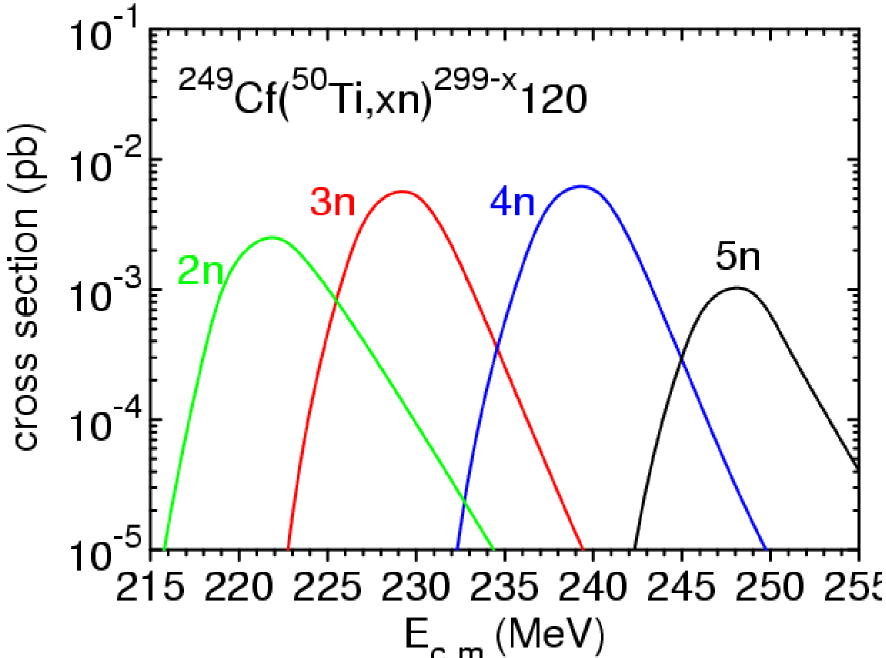
The systematics of the s_{inj} used to predict cross sections for elements of Z = 119 and 120

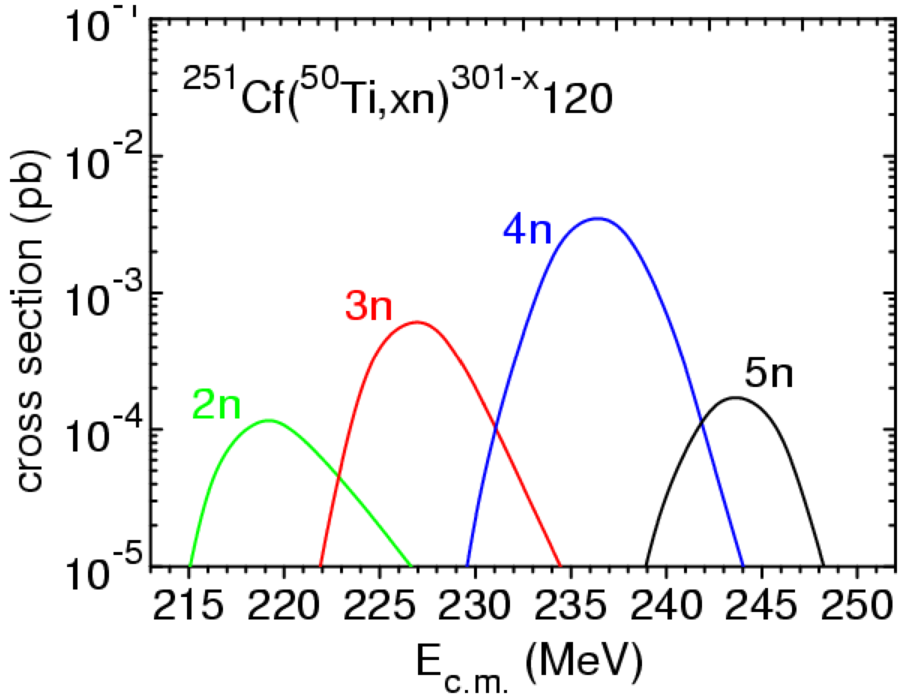


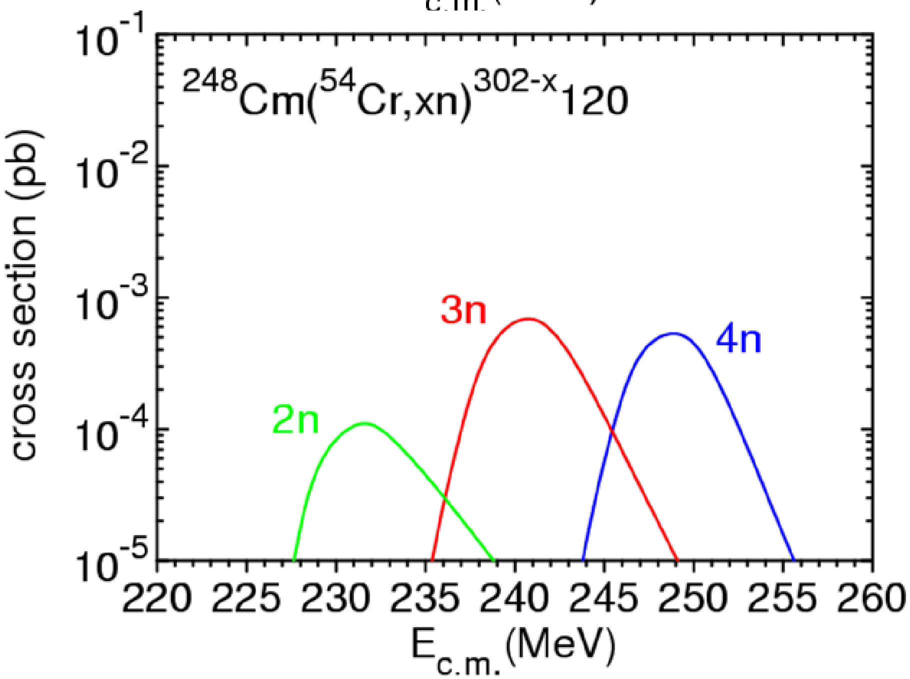
The reaction $^{48}Ca + ^{252}Es$ predicted to have measurable cross section











The largest cross section for producing the element 120 is expected for the reaction $^{50}Ti + ^{249}Cf$. Maximum value, of several femtobarns, is however below possibilities of present experiments.

V.Zagrebaev and W. Greiner, Phys. Rev. C78 (2008) 034610
Z. H. Liu, Jing-Dong Bao, Phys. Rev C80 (2009) 054608
K. Siwek-Wilczynska, T. Cap, J. Wilczynski, IJMP E19 (2010) 500
A. Nasirov et al. IJMP E20 (2011) 406

SUMMARY

The Fusion by Diffusion model was applied to calculate synthesis cross sections of superheavy nuclei of Z =114 – 120 in hot fusion reactions.

Fission barriers and ground state masses calculated with the Warsaw macroscopic-microscopic model (including nonaxial shapes) were applied. Good agreement with experimental cross sections was obtained.

This allowed us to use the same theoretical input to predict cross sections for synthesis of elements Z = 119 and 120.