Reaction dynamics in the synthesis of superheavy nuclei

T. Cap

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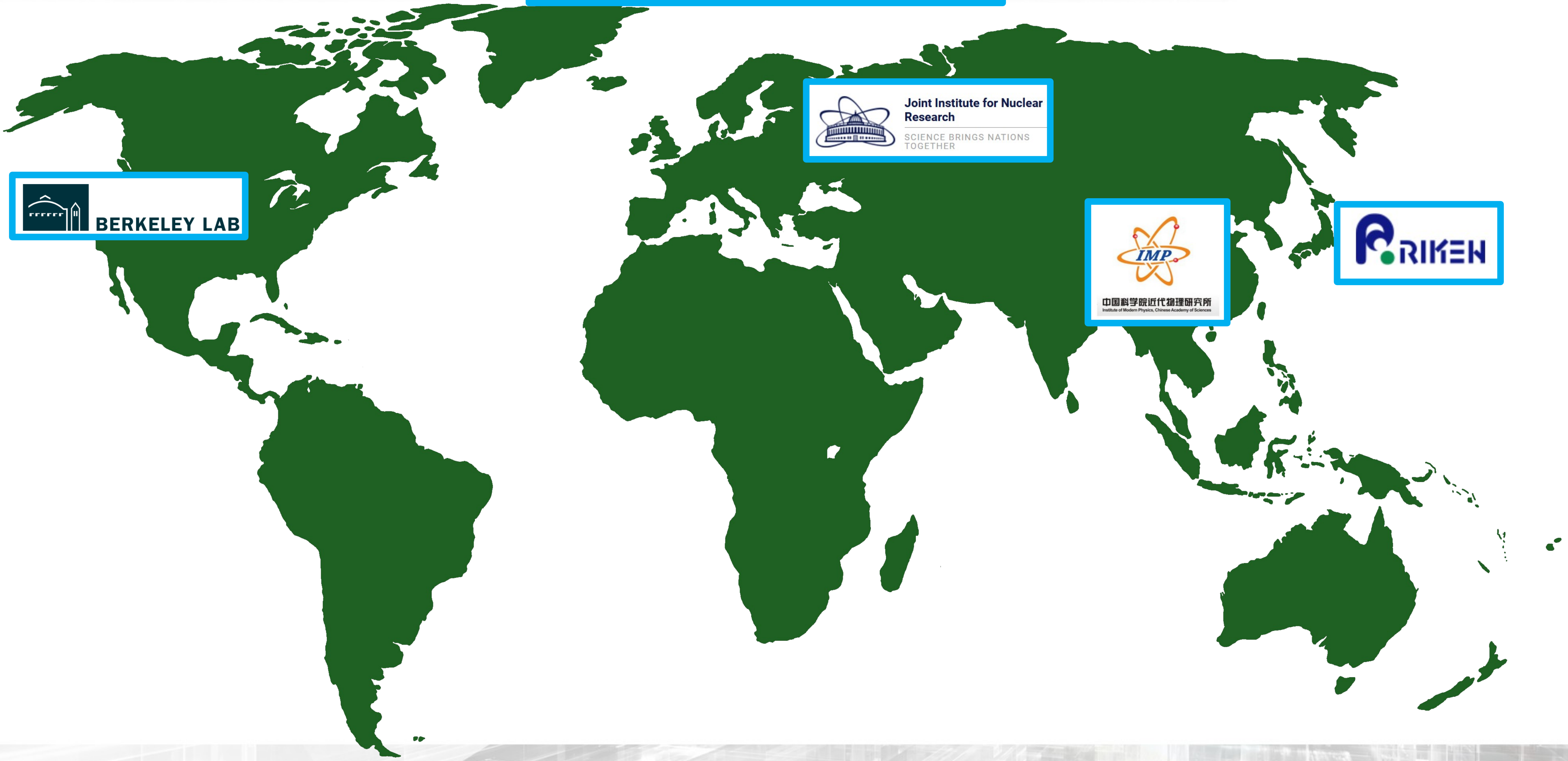
Colloque GANIL
Bussang, 21-25.09.26

Search for E119 and E120



Search for E119 and E120

BERKELEY LAB

- 50Ti + 244Pu → 290Lv + 4n, 2 events, 440 (+580/-280) fb
- First identification of Ac and No molecules with an atom-at-a-time technique (48Ca + 208Pb)
- 50Ti + 209Bi in xn, pxn channels
- 50Ti + 249Cf → 299Ubn*, search for E120 in 2027?

- J. M. Gates *et al.*, Phys. Rev. Lett. 133, 172502 (2024)
- J. L. Pore *et al.*, Nature 644, 376-380 (2025)
- M. Lykiardopoulou *et al.*, talk @ INPC2025

Search for E119 and E120

- 48Ca + 243Am → 288,287Mc + 3n or 4n,
  20 (3n) + 1 (4n) events, first SHE results from CAFE2
- 54Cr + 243Am→ 297Uue*, 60 fb limit for E119
- MNT studies in Ca, Cr + Am and Cr + U (58 isotopes)
- actinides studies (new isotopes of Bk and Am)
- … and more …

中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

- X. Y. Huang *et al.*, Chin. Phys. Lett., 43, 010101 (2026)
- Z. Gan *et al.*, talk @ TASCA26
- G. Xie *et al.*, Chin. Phys. C 50, 064001 (2026)

Search for E119 and E120

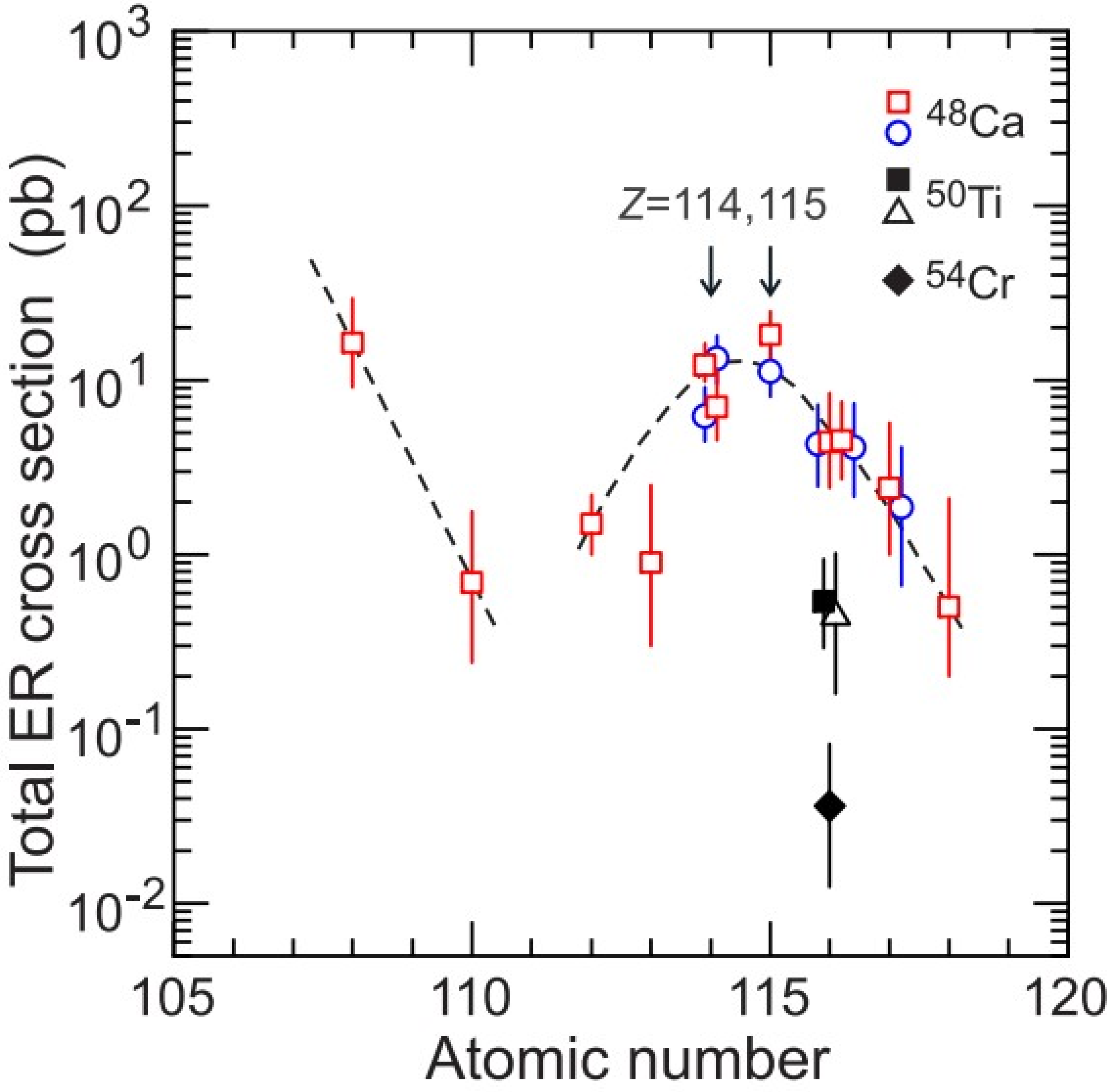
- 54Cr + 238U → 288Lv + 4n, 2 events, 36 (+46/-24) fb
- 50Ti + 242Pu → 289,288Lv + 3n or 4n
  3 (3n) and 2 (4n) events, 320 (+340/-180) fb, 220 (+270/-150) fb
- p2n observation in Ti + Pu, 1 event, 110 (+260/-90) fb
  (no pxn in 25 years of 48Ca reactions)
- 48Ca + 237Np → 282,281Nh + 3n (known ch.) or 4n (new ch.),
  isotopes needed for E119 identification in Cr+Am decay chain
- 50Ti + 249Bk → 299Uue*, search for E119 has already started
  (exp. limit is 65 fb measured @ GSI by Khuyagbaatar *et al.*, PRC 102, 064602 (2020))
- … and much more ….

- Yu. Ts. Oganessian *et al.*, Phys. Rev. C 112, 014603 (2025)
- JINR Annual Report 2025
- jinrmag.jinr.ru

- 50Ti + 248Cm → 298Og*, no events, upper limit of 270 fb
- 51V + 248Cm → 299Uue*, no events, upper limit of 4.85 fb
- pxn and axn channels in heavy elements synthesis (51V+159Tb, ...)
- ... new results (not with the Ca beam) will be soon published:)

RIKEN

- B. Gall *et al.*, J. Phys. Soc. Jpn. 94, 094201 (2025)
- K. Morimoto *et al.*, submitted to J. Phys. Soc. Jpn.
- P. Brionnet *et al.*, Phys. Rev. C 110, 064601 (2024).
- P. Brionnet *et al.*, private communication



Addopted from Yu. Ts. Oganessian *et al*.,
Phys. Rev. C 112, 014603 (2025)

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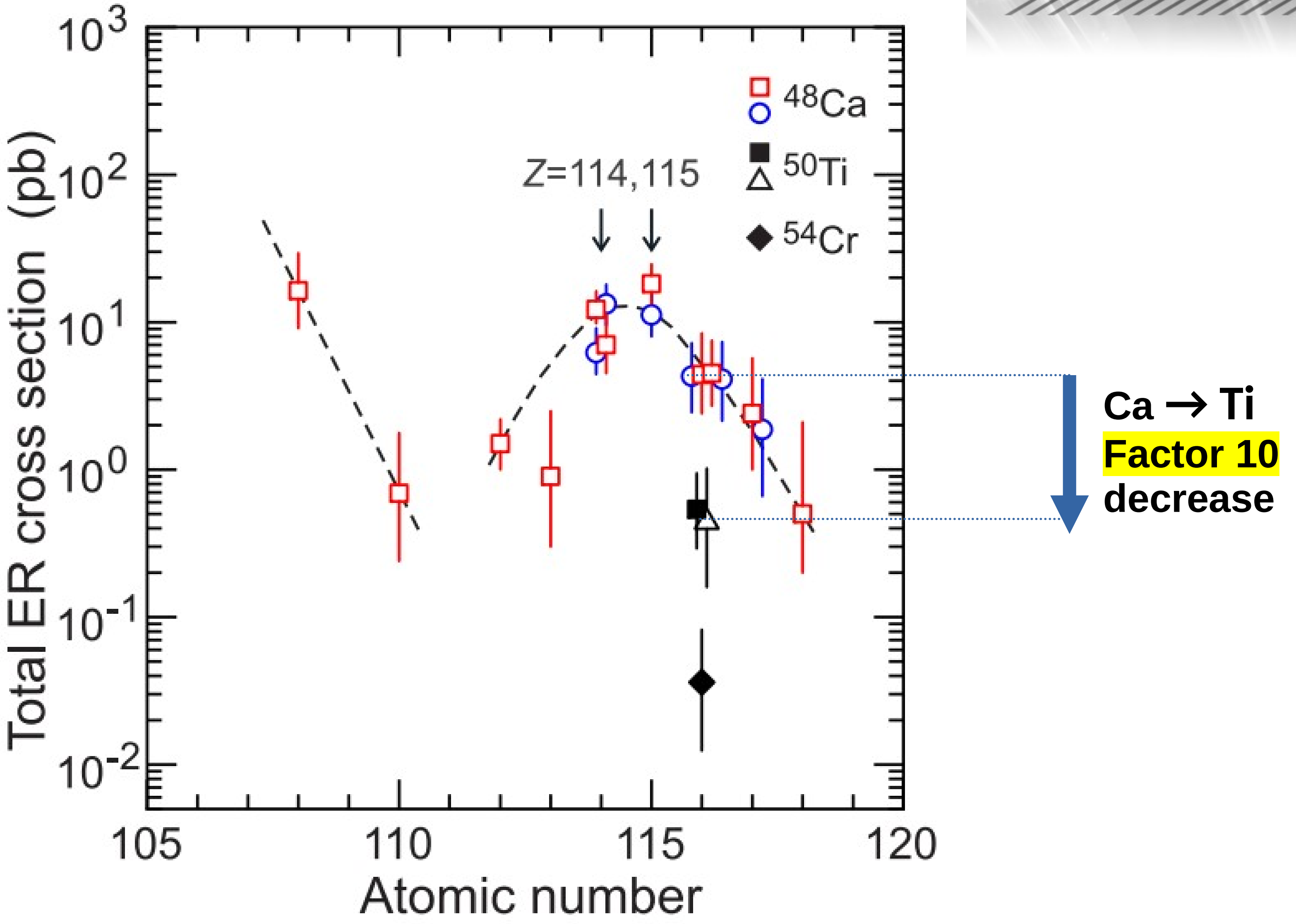

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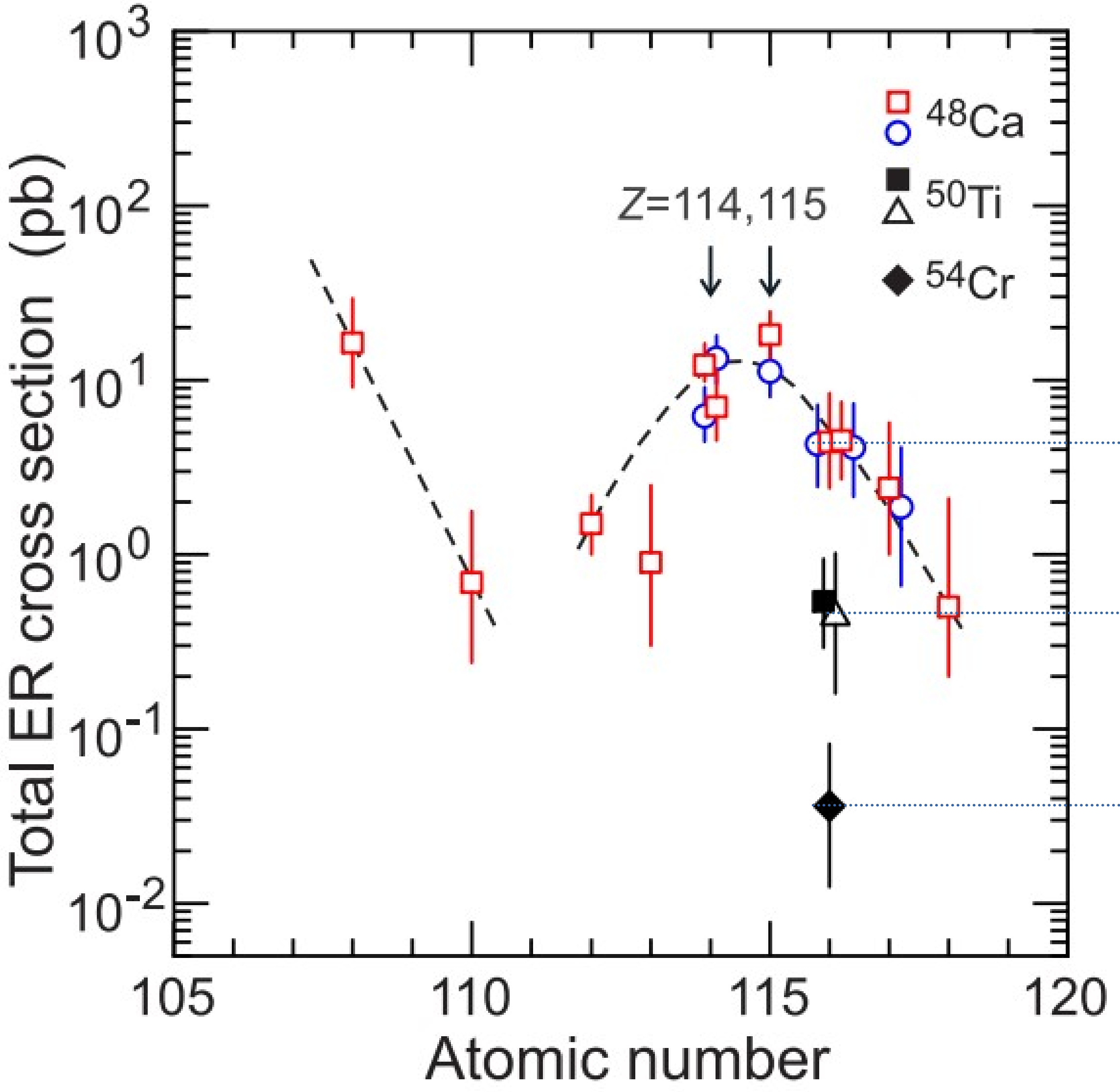
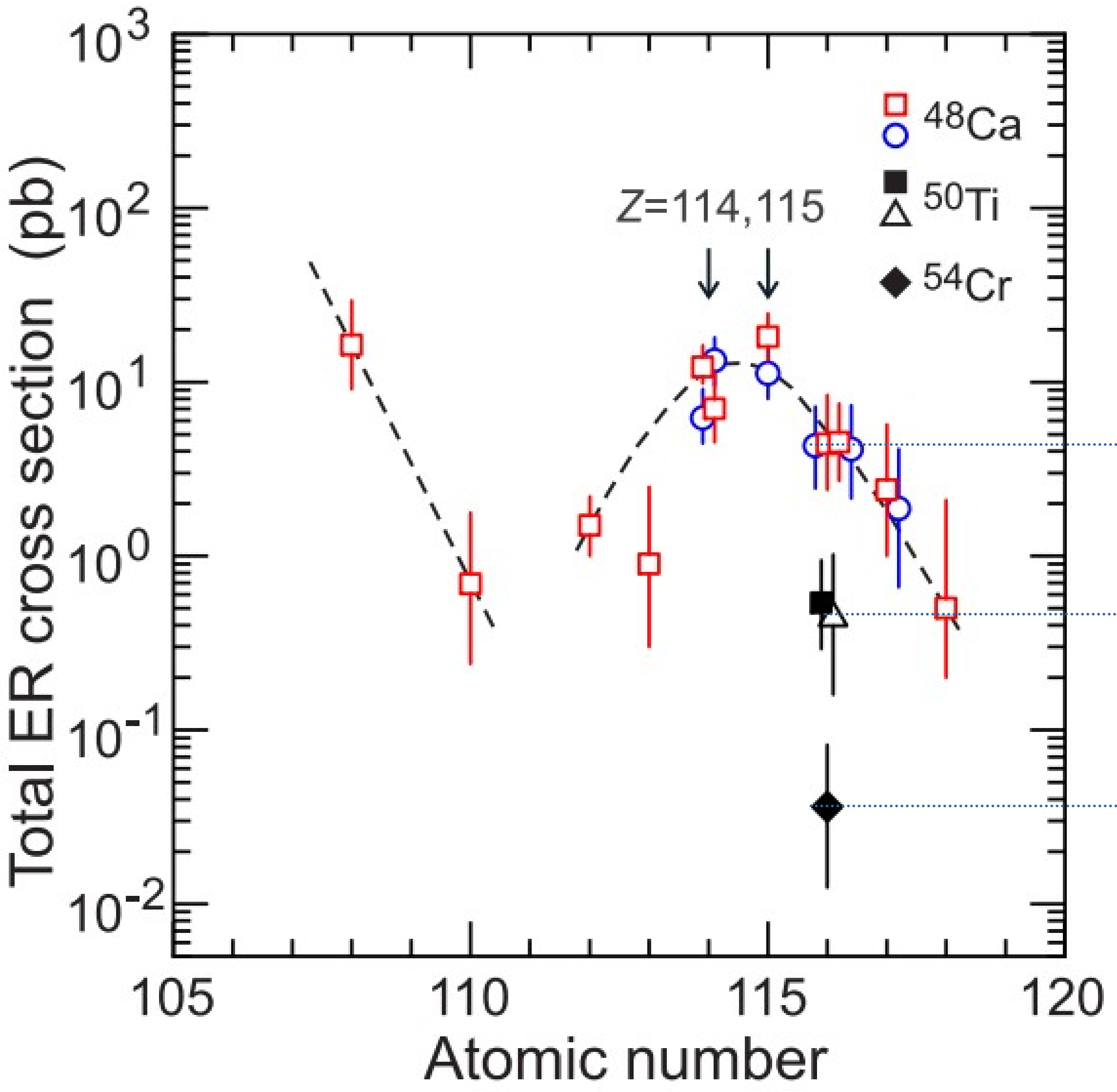


Ca → Ti
Factor 10
decrease

Ca → Cr
Factor 150
decrease

Addopted from Yu. Ts. Oganessian *et al.*,
Phys. Rev. C 112, 014603 (2025)



Addopted from Yu. Ts. Oganessian *et al.*,
Phys. Rev. C 112, 014603 (2025)

- 48Ca + 248Cm → 296Lv* (3n,4n)
- 48Ca + 245Cm → 293Lv* (2n,3n)
- 50Ti + 244Pu → 294Lv* (4n)
- 50Ti + 242Pu → 292Lv* (3n,4n)
- 54Cr + 238U → 292Lv* (4n)

Ca → Ti
Factor 10
decrease

Ca → Cr
Factor 150
decrease

… it is not that simple

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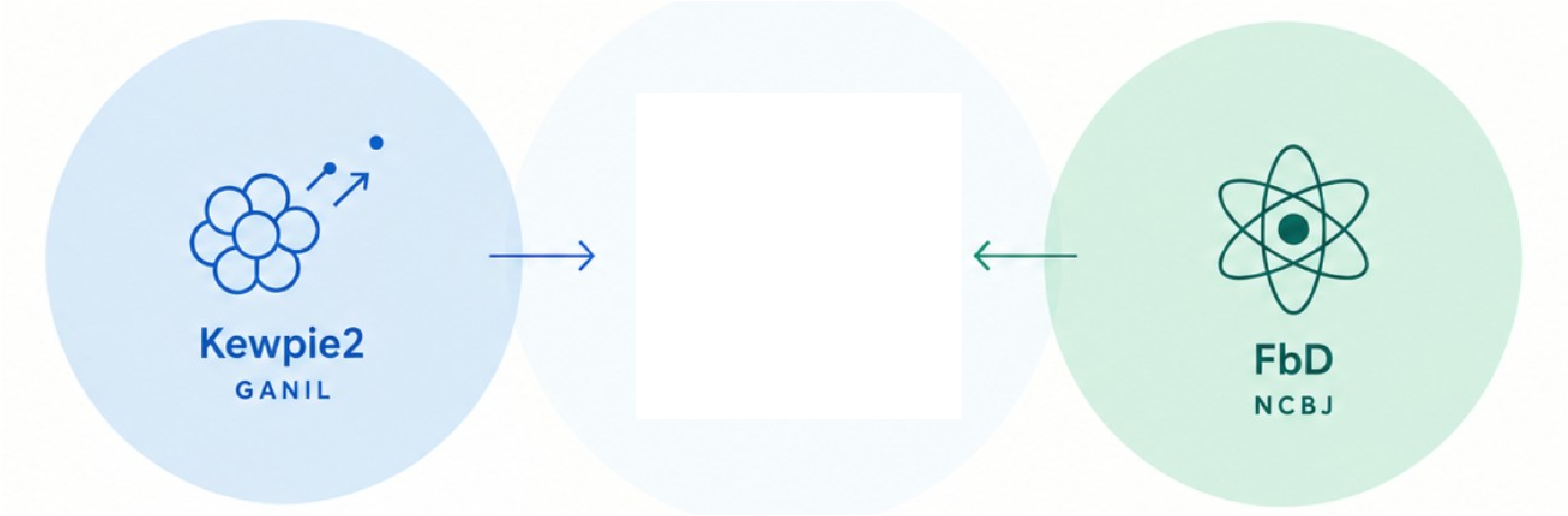
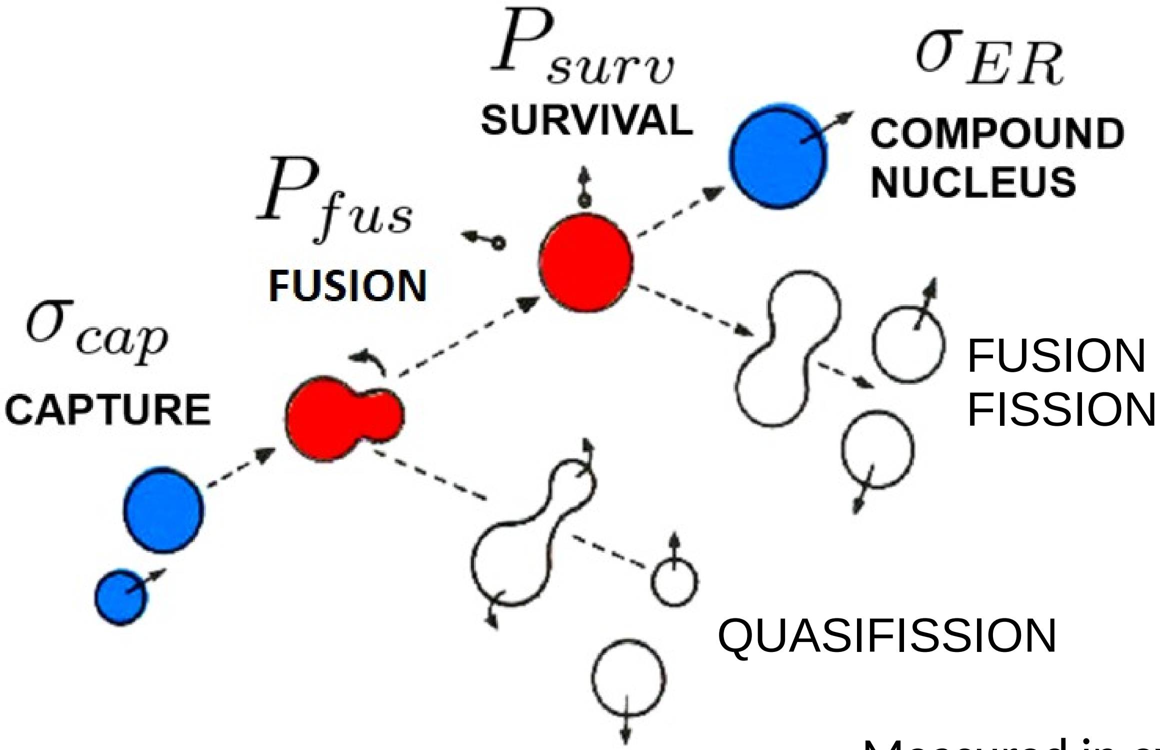
Fusion of two models...



H. Donglo, F. Agert, D. Boilley, T. Cap, M. Kowal, D. Ackermann, paper in preparation



Synthesis of SHN can be described as a **3** step process:

$$\sigma_{\mathrm{ER}} = \sigma_{\mathrm{cap}} \times P_{\mathrm{fus}} \times P_{\mathrm{surv}}$$

Measured in experiments, can be calculated using various models

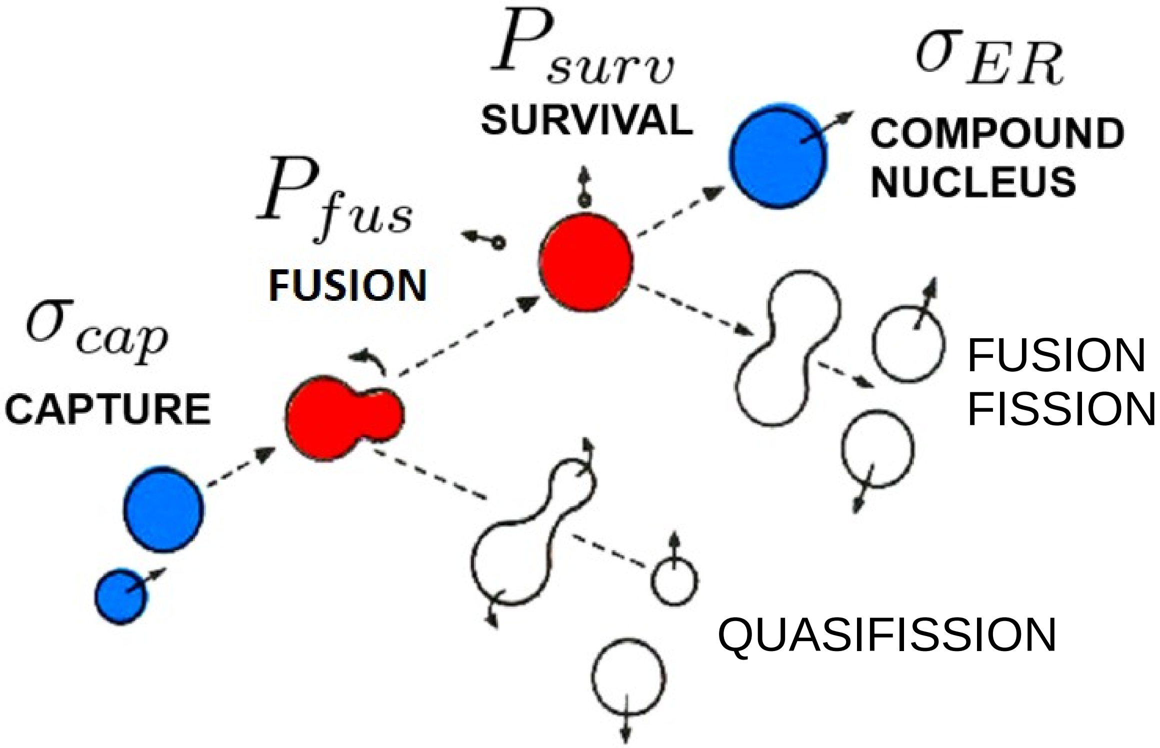
Not measured directly, difficult to calculate

Well established theory and formulas
Monte Carlo Statistical model

Diffussed barrier formula (Entrance channel barrier is given by a Gaussian distribution)

Langevin or Smoluchowski Diffusion Equation

masses, fission barriers, deformations from Warsaw Micro-Macro model



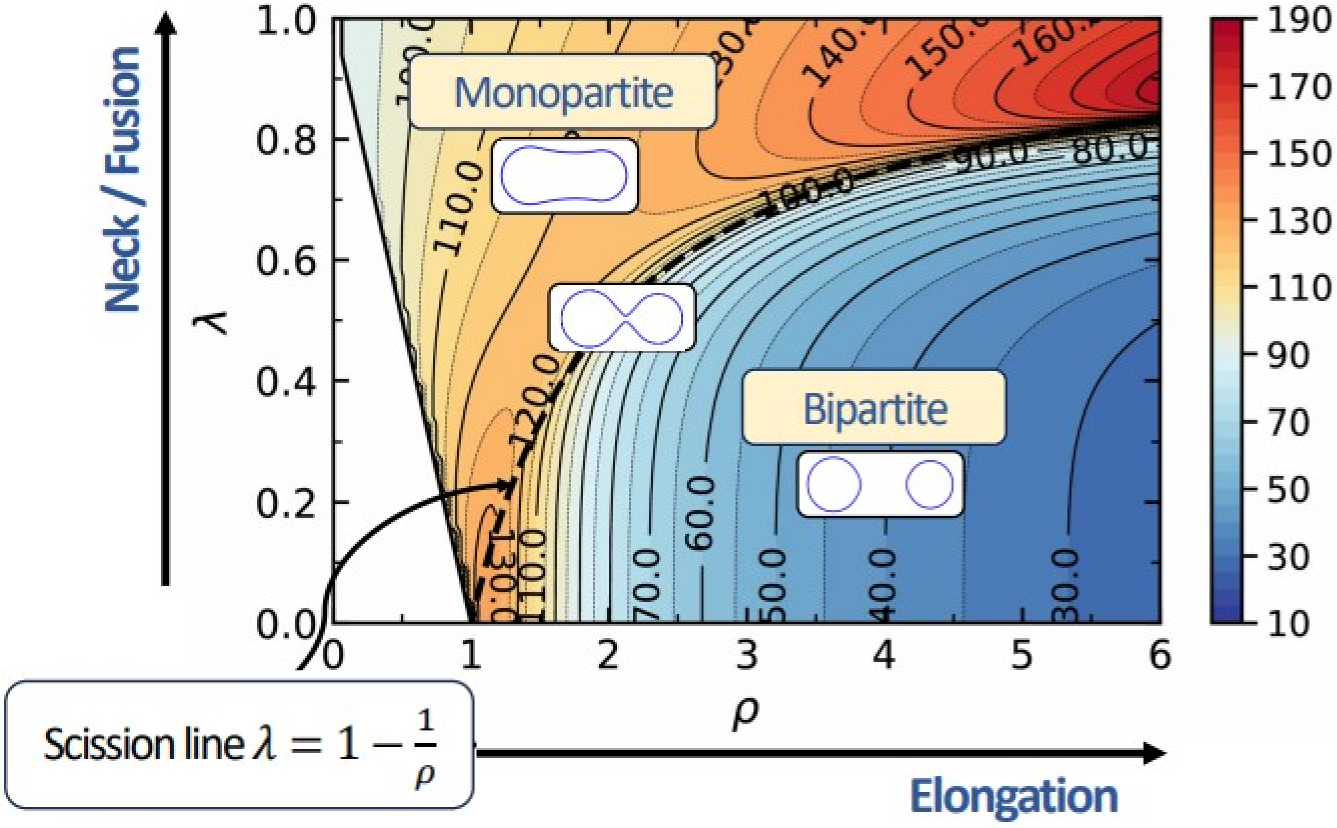
Synthesis of SHN can be described as a **3** step process:

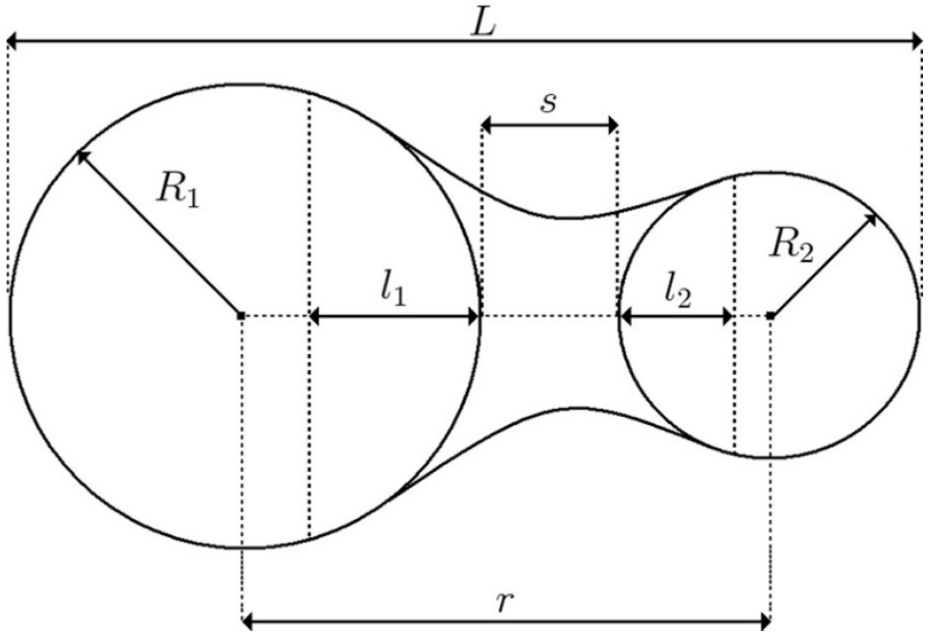
$$\sigma_{\mathrm{ER}} = \sigma_{\mathrm{cap}} \times P_{\mathrm{fus}} \times P_{\mathrm{surv}}$$

ℓ-dependent formula

$$\sigma_{\mathrm{ER}} = \pi \lambda\!\!\!^{-2} \sum_{l=0}^{\infty} (2l+1) T(l) \times P_{\mathrm{fus}}(l) \times P_{\mathrm{surv}}^{\mathrm{xn}}(l)$$

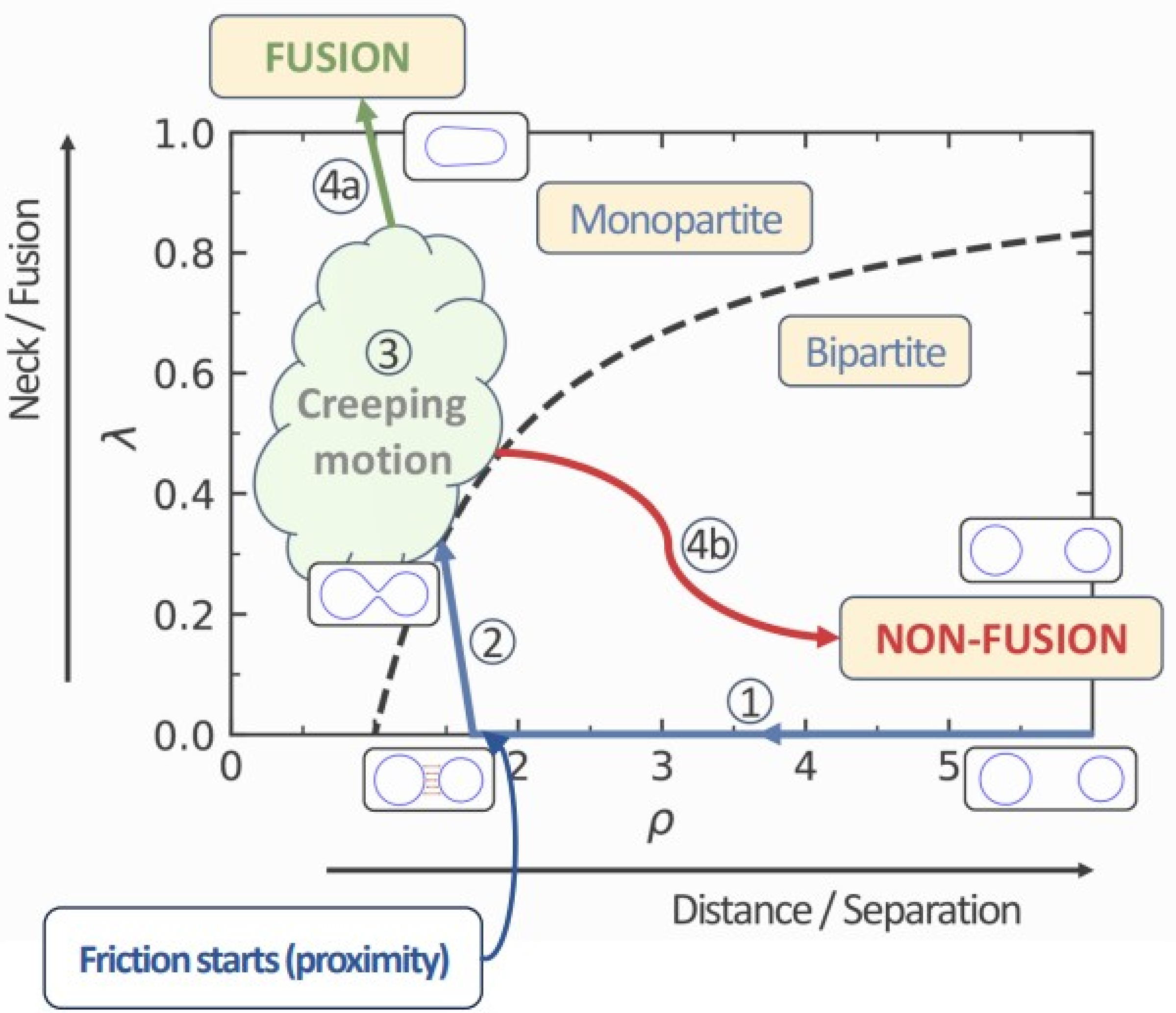
Macroscopic deformation energies are calculated using
the parameterization of the nuclear shapes by two spheres joined smoothly by a third quadratic surface of revolution.





J. Błocki, H. Feldmeier and W. J. Świątecki, Nucl. Phys. A 459 (1986) 145

Courtesy of Y. Jaganathen



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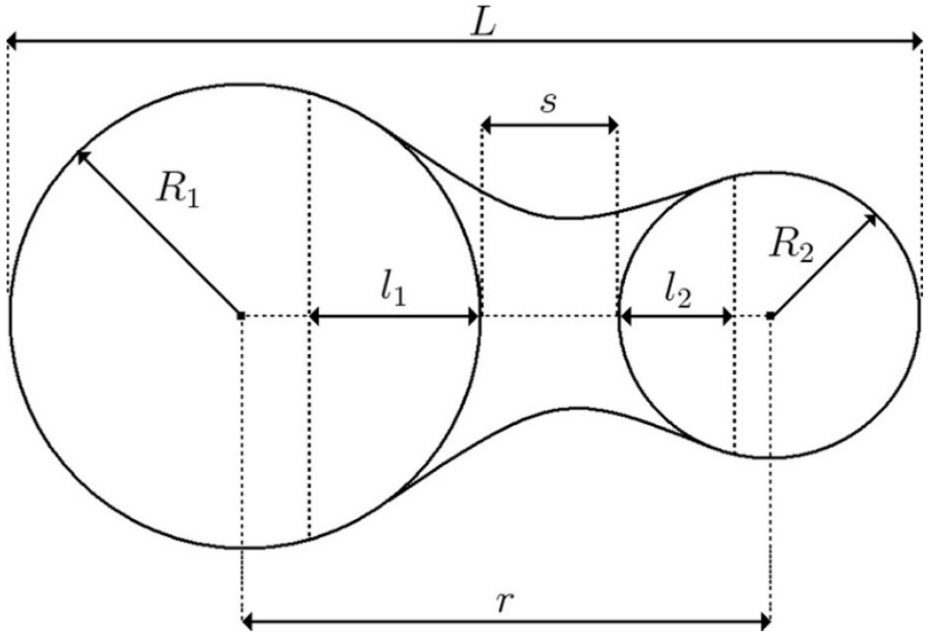

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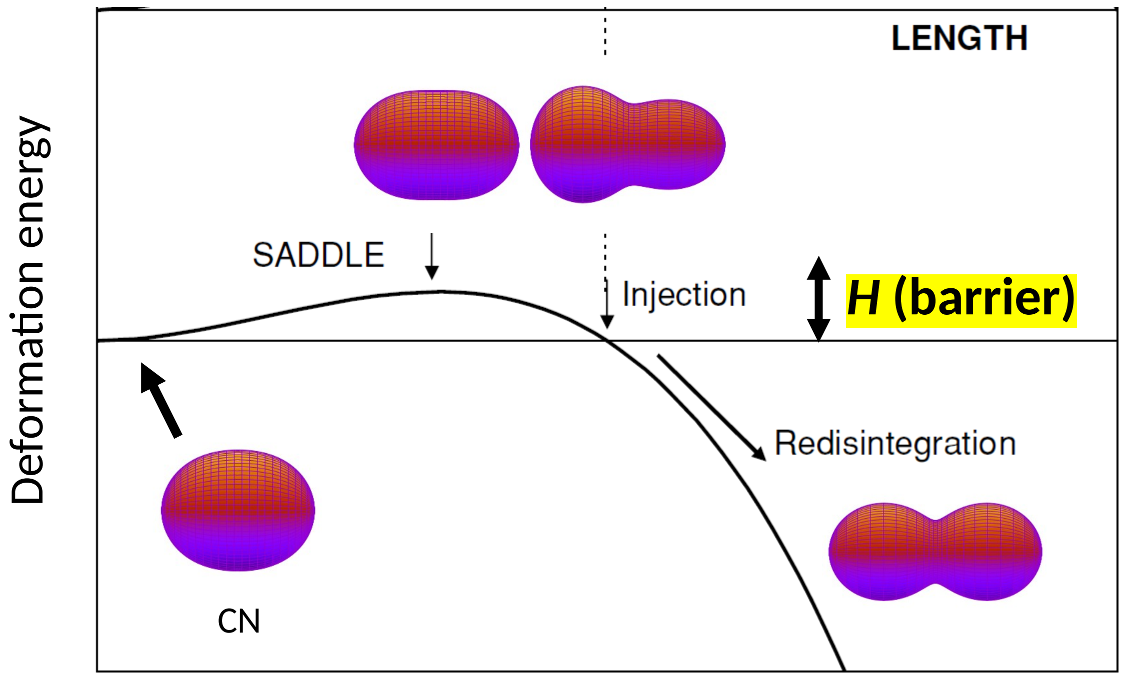
1D motion approximation

The system must overcome an internal barrier ***H*** to fuse.



L is the effective elongation (along the fusion path)

Macroscopic deformation energies are calculated using
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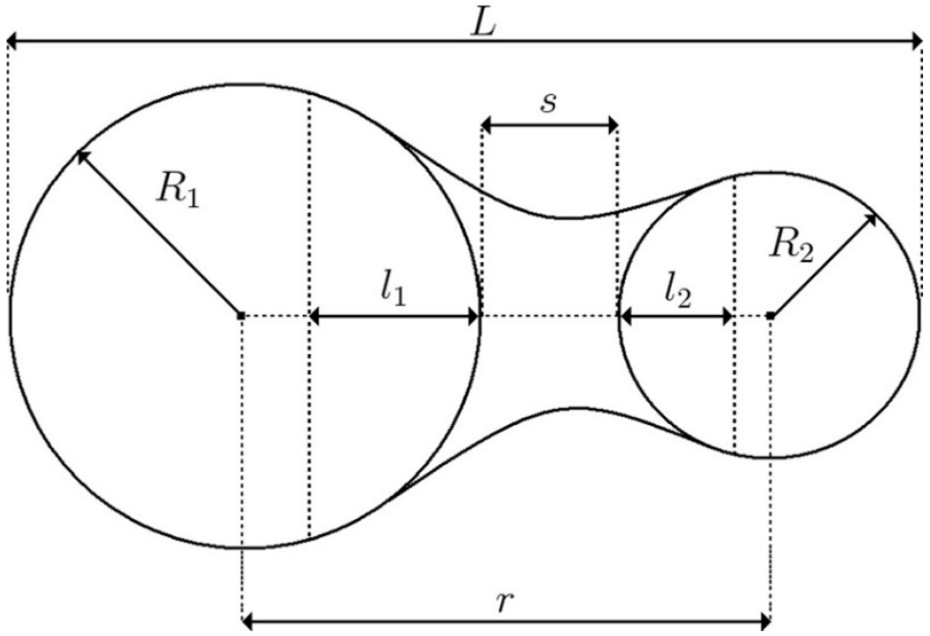

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1D motion approximation

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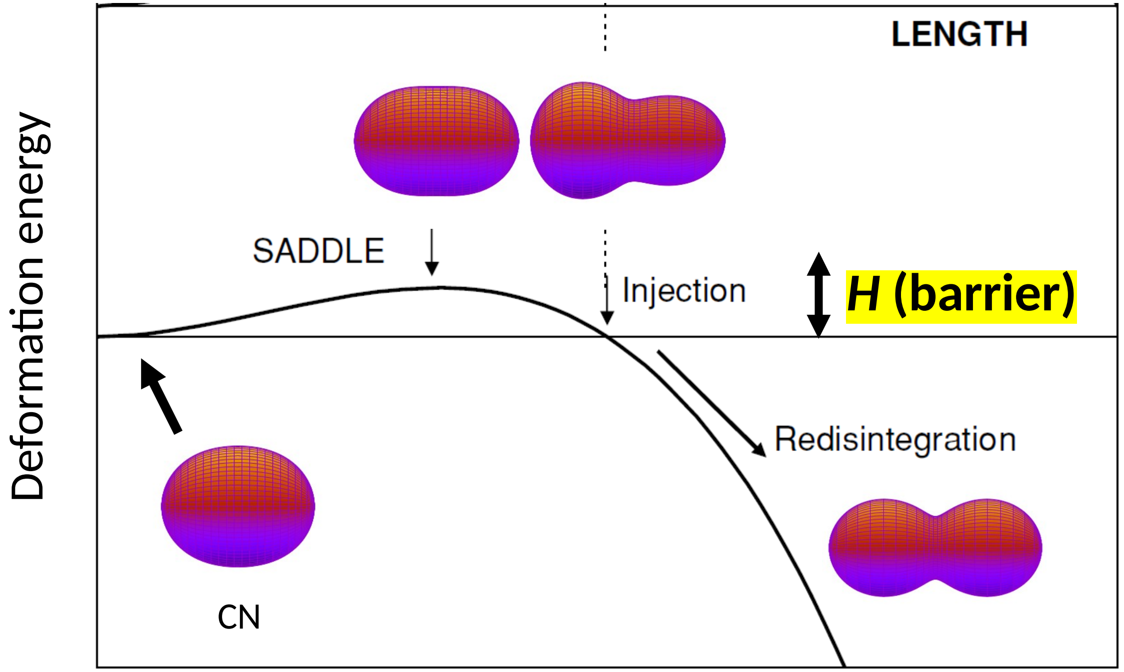
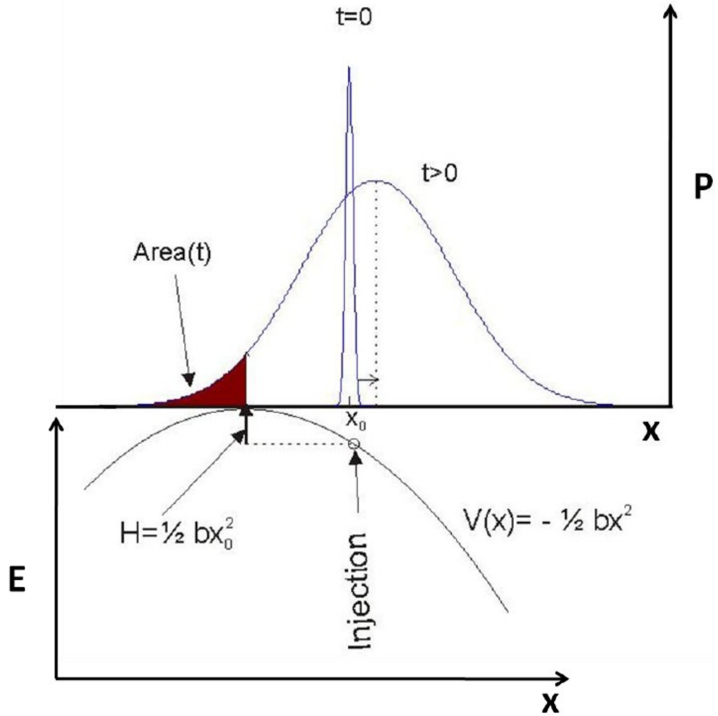


L is the effective elongation (along the fusion path)

P_{fus} is calculated by solving
1D Smoluchowski Diffusion Equation

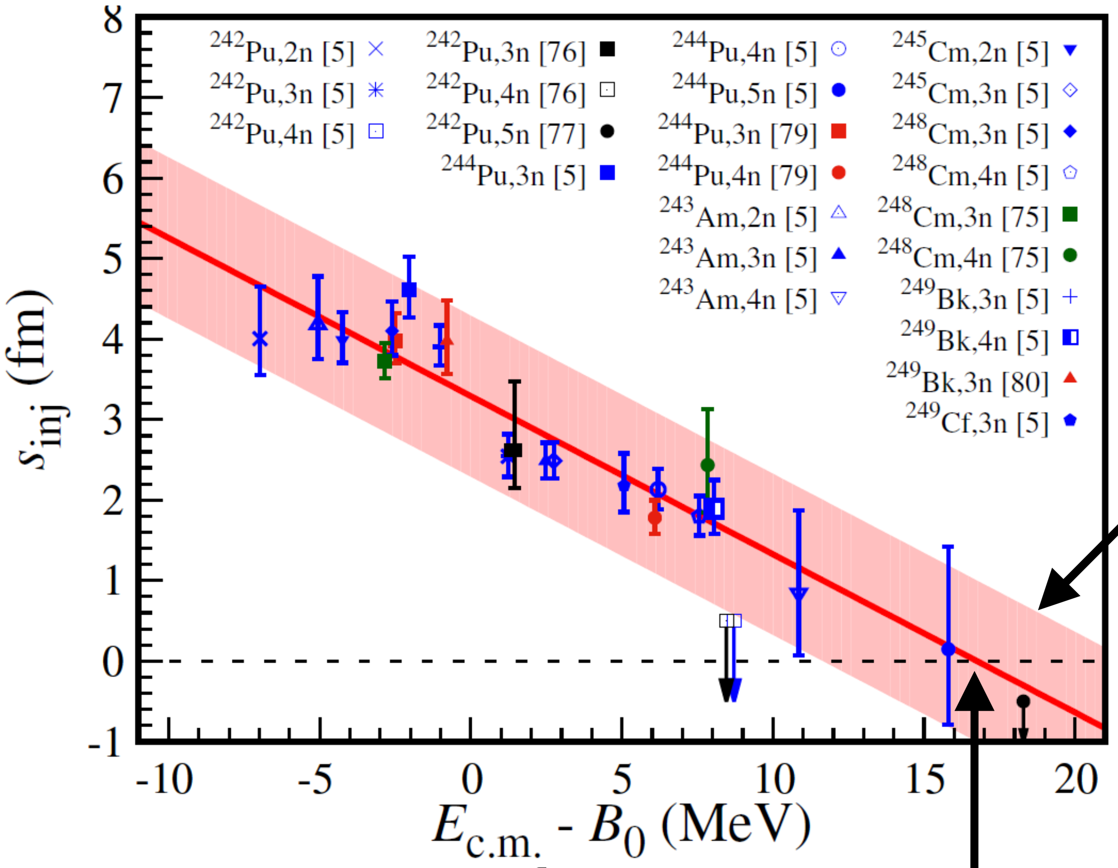


$$P_{fus}(l) = \frac{1}{2}\left(1 - \mathrm{erf}\sqrt{\frac{H(l)}{T}}\right) \text{ when } L_{inj} \geq L_{saddle}$$

H(L) – the function of angular momentum and bombarding energy
T – the temperature depends on available energy

Yu. Ts. Oganessian and V. K. Utyonkov. Rep. Prog. Phys. 78(3):036301, 2015

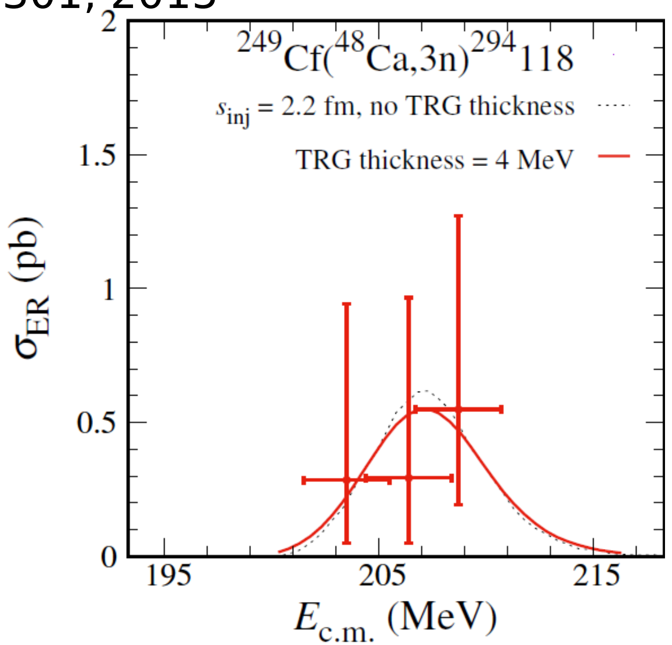
$$s_{\mathrm{inj}} = 3.291\ \mathrm{fm} - 0.196 \times (E_{\mathrm{c.m.}} - B_0)\ \mathrm{fm/MeV}$$



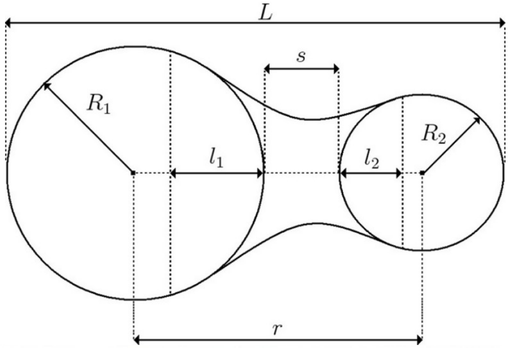
Error corridor
± 1 fm

Energy relative to the entrance channel barrier B_0

Tangent Configuration
$s_{\mathrm{inj}} = 0$ fm



The distance between the nuclear surfaces of two colliding nuclei at the **injection point s_{inj}** is the adjustable parameter of the model.



s_{inj} distance was parametrized by analyzing 24 hot fusion reactions with ^{48}Ca (2n-5n channels) .

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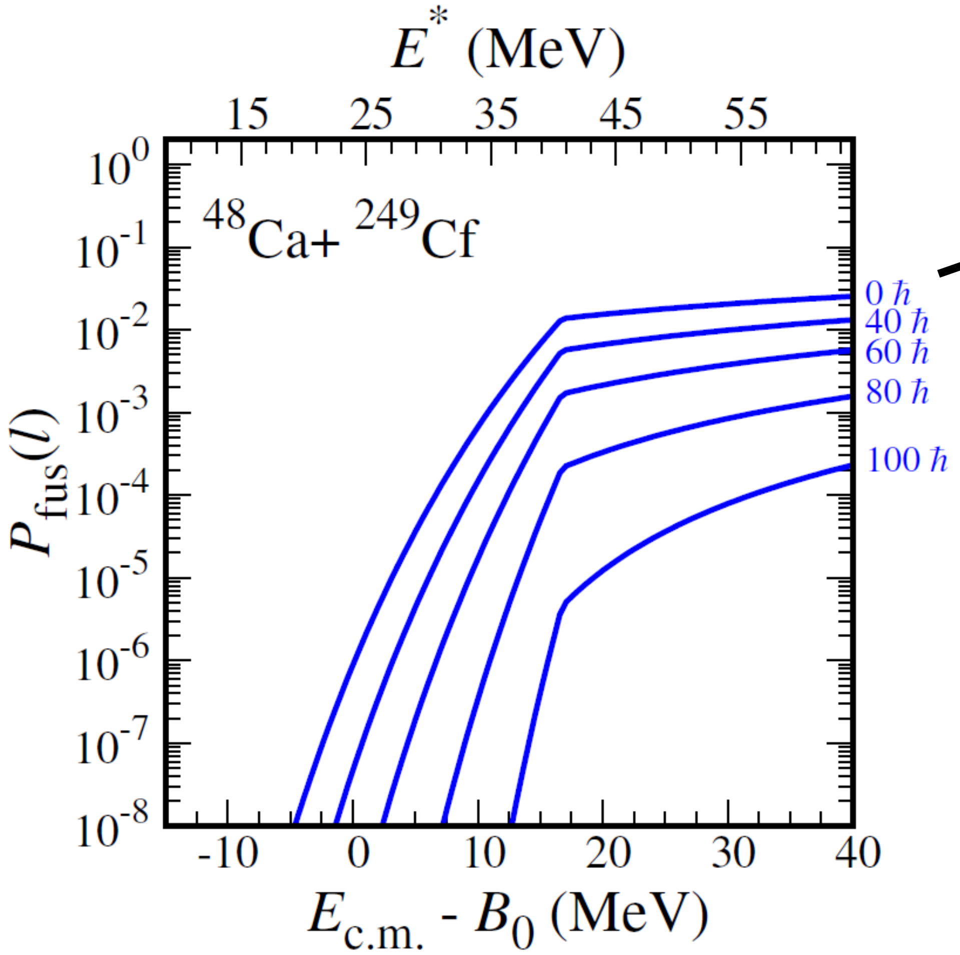
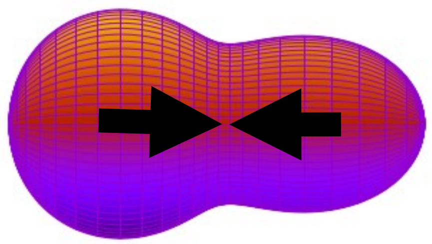


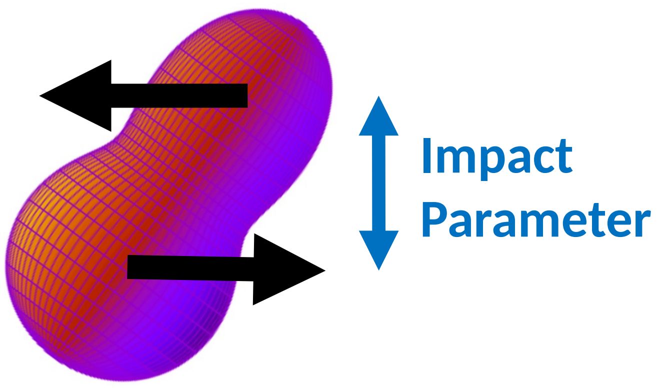
Energy relative to the entrance channel barrier B_0

B_0 = 202.23 MeV

l = 0
Central collision



Peripheral collisions



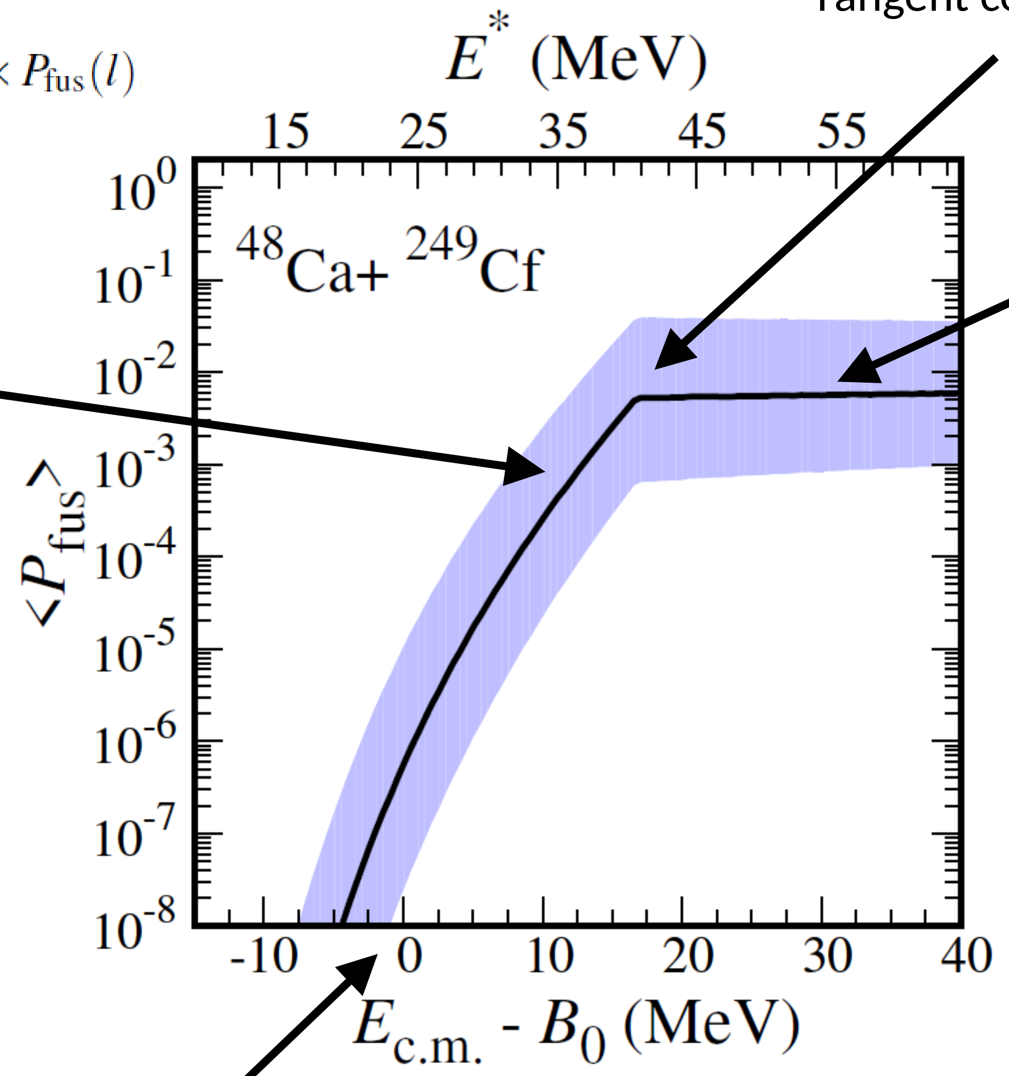
Higher partial waves l
=
Higher rotational energy
=
Higher barrier $H(l)$
=
Lower $Pfus(l)$

Fusion probability averaged over l

$$< P_{\text{fus}} > = \frac{1}{(l_{\text{max}}+1)^2} \sum_{l=0}^{l_{\text{max}}} (2l+1) \times P_{\text{fus}}(l)$$

Tangent configuration of projectile and target ($s_{\text{injection}}$ = 0 fm)

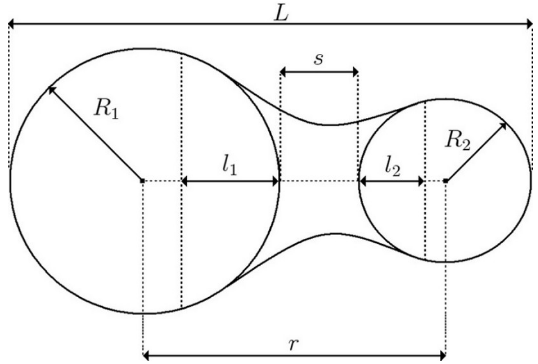
Below B_0, the $<P_{\text{fus}}>$ growth comes from the reduction in the height of the internal barrier opposing fusion.



The $<P_{\text{fus}}>$ saturation above B_0 results from suppression of the contributions from higher partial waves and can be linked to the critical angular momentum.

The difference between rotational energies in the fusion saddle and the contact (sticking) configuration plays a major role in CN formation at energies above B_0.

$s_{\text{injection}}$ > 0 fm



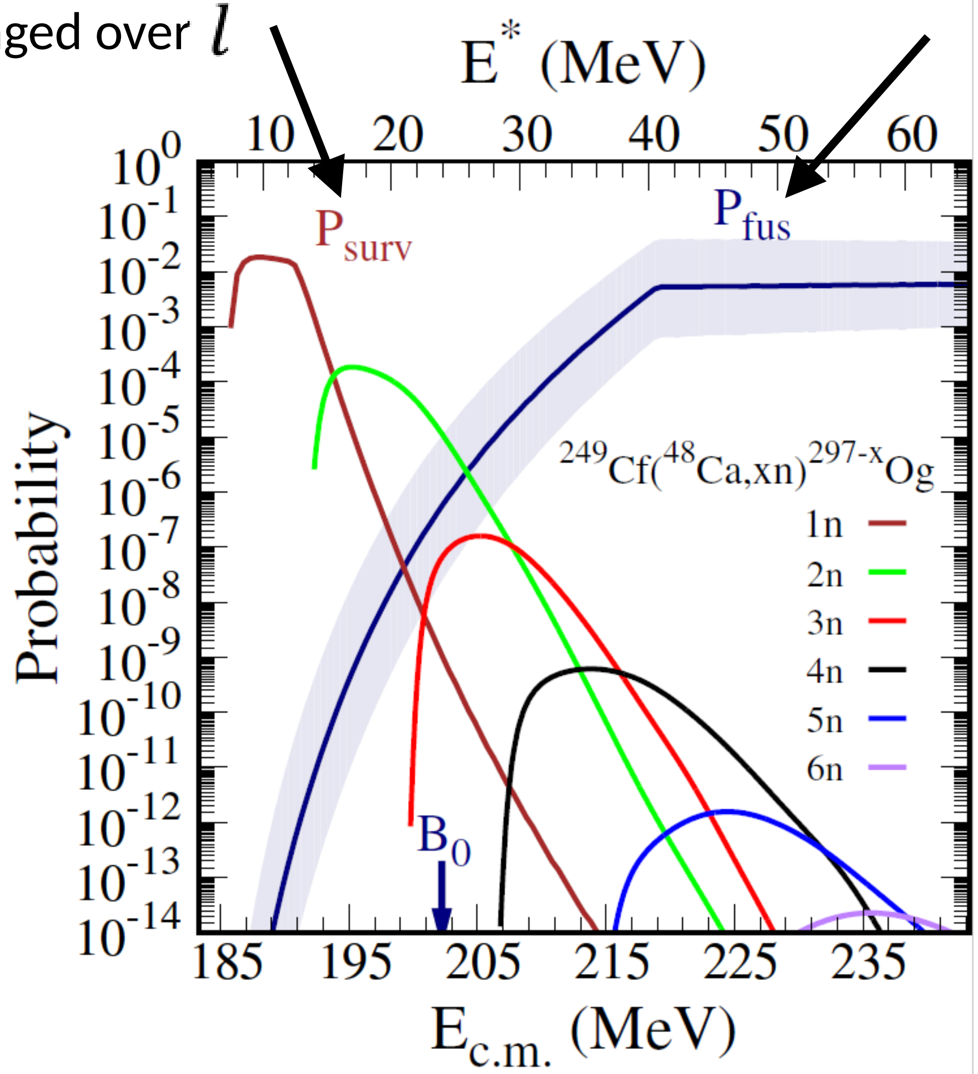
B_0 - entrance channel barrier (Coulomb + Nuclear potential)

$$< P_{\rm surv} > = \frac{1}{(l_{\rm max}+1)^2} \sum_{l=0}^{l_{\rm max}} (2l+1) \times P_{\rm surv}(l)$$

Survival probability averaged over l

Fusion probability averaged over l

$P_{\rm surv}$ is calculated using Monte Carlo methods



Competition between LCP, neutron emission and fission

Weisskopf formula

$$\Gamma_{\rm n} = \frac{g m_{\rm n} \sigma_{\rm n}}{\pi^2 \hbar^2 \rho_{\rm G.S.}} \int_0^{X_{\rm n}} \rho_{\rm n}(X_{\rm n} - \varepsilon_{\rm n}) \varepsilon_{\rm n} d\varepsilon_{\rm n}$$

Transition-state theory

$$X_{\rm n} = E^* - B_{\rm n} - E_{\rm rot}^{A-1}(l)$$
$$X_{\rm f} = E^* - B_{\rm f} - E_{\rm rot}^{sp}(l)$$

$$\Gamma_{\rm f} = \frac{1}{2\pi \rho_{\rm G.S.}} \int_0^{X_{\rm f}} \rho_{\rm f}(X_{\rm f} - \varepsilon_{\rm f}) d\varepsilon_{\rm f}$$

Properties of heaviest nuclei with $98 \leq Z \leq 126$ and $134 \leq N \leq 192$

P. Jachimowicz [a], M. Kowal [b,*], J. Skalski [b]

[a] Institute of Physics, University of Zielona Góra, Szafrana 4a, 65-516 Zielona Góra, Poland
[b] National Centre for Nuclear Research, Pasteura 7, 02-093 Warsaw, Poland

Adiabatic fission barriers

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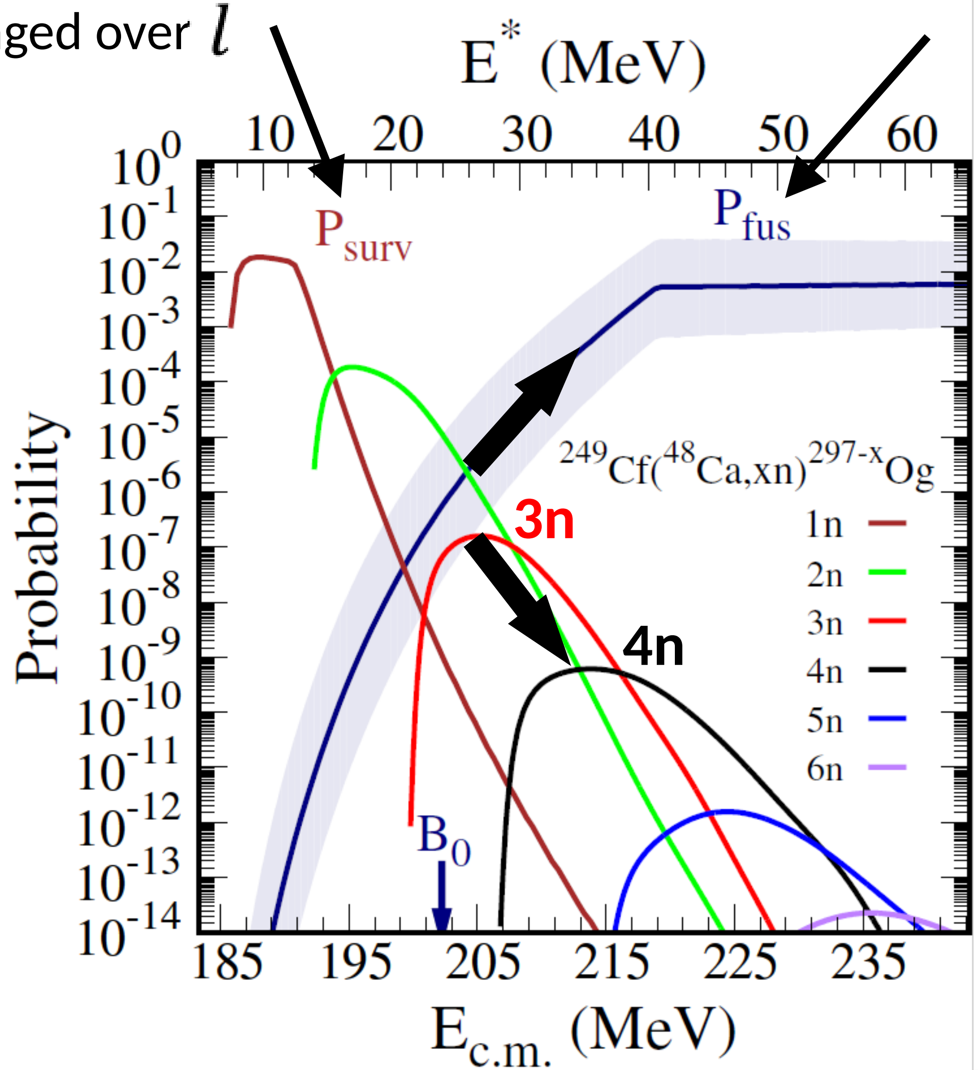
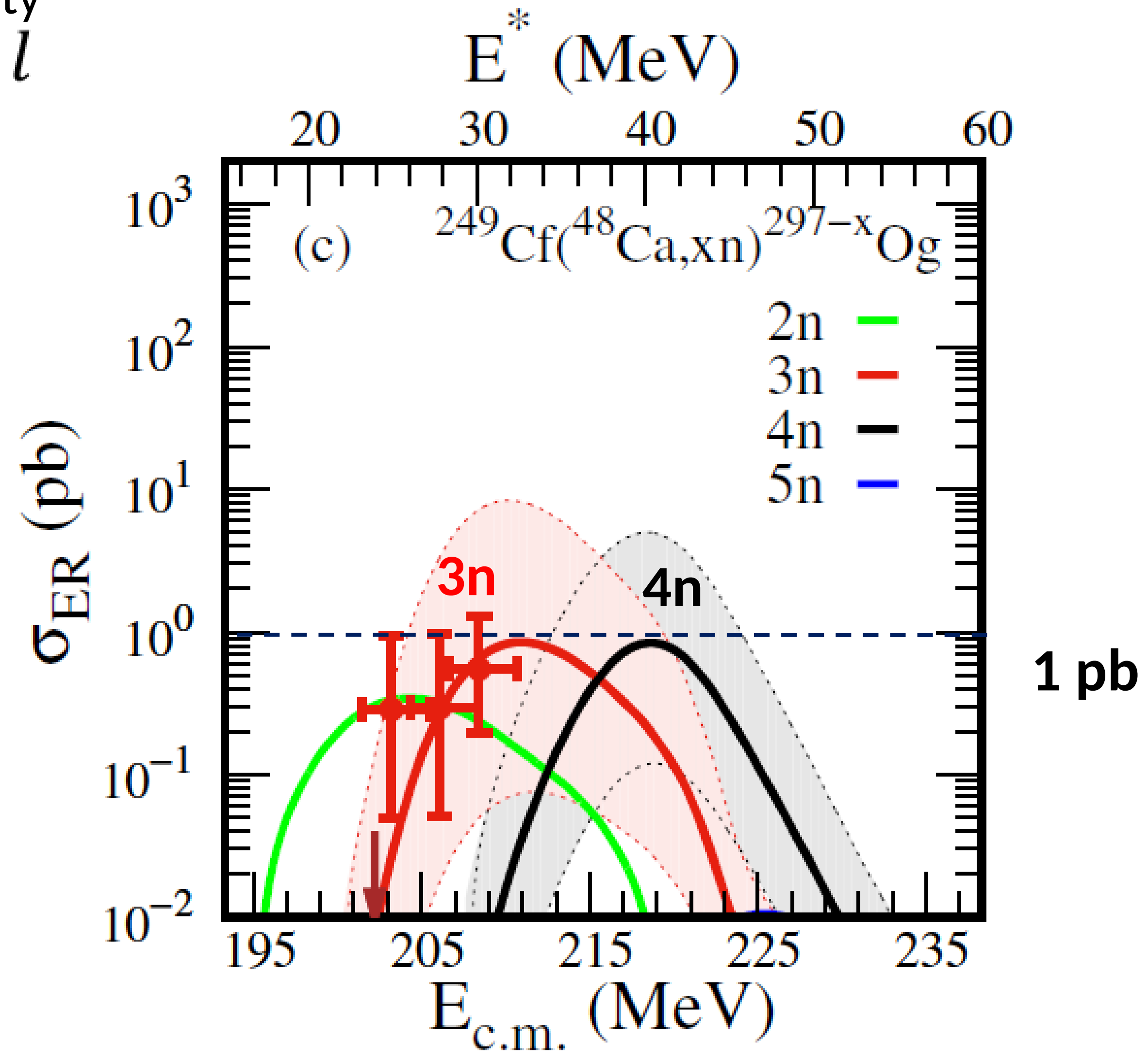
$$< P_{\rm surv} > = \frac{1}{(l_{\rm max}+1)^2} \sum_{l=0}^{l_{\rm max}} (2l+1) \times P_{\rm surv}(l)$$

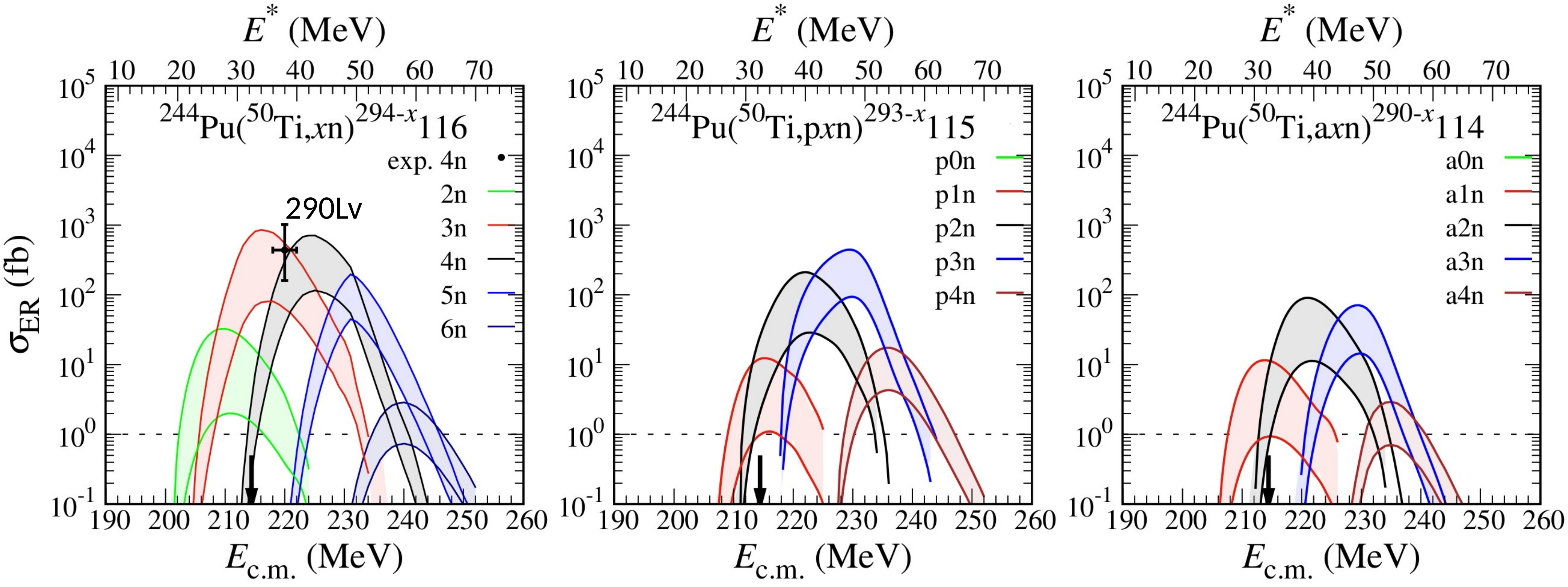
Survival probability averaged over l

Fusion probability averaged over l

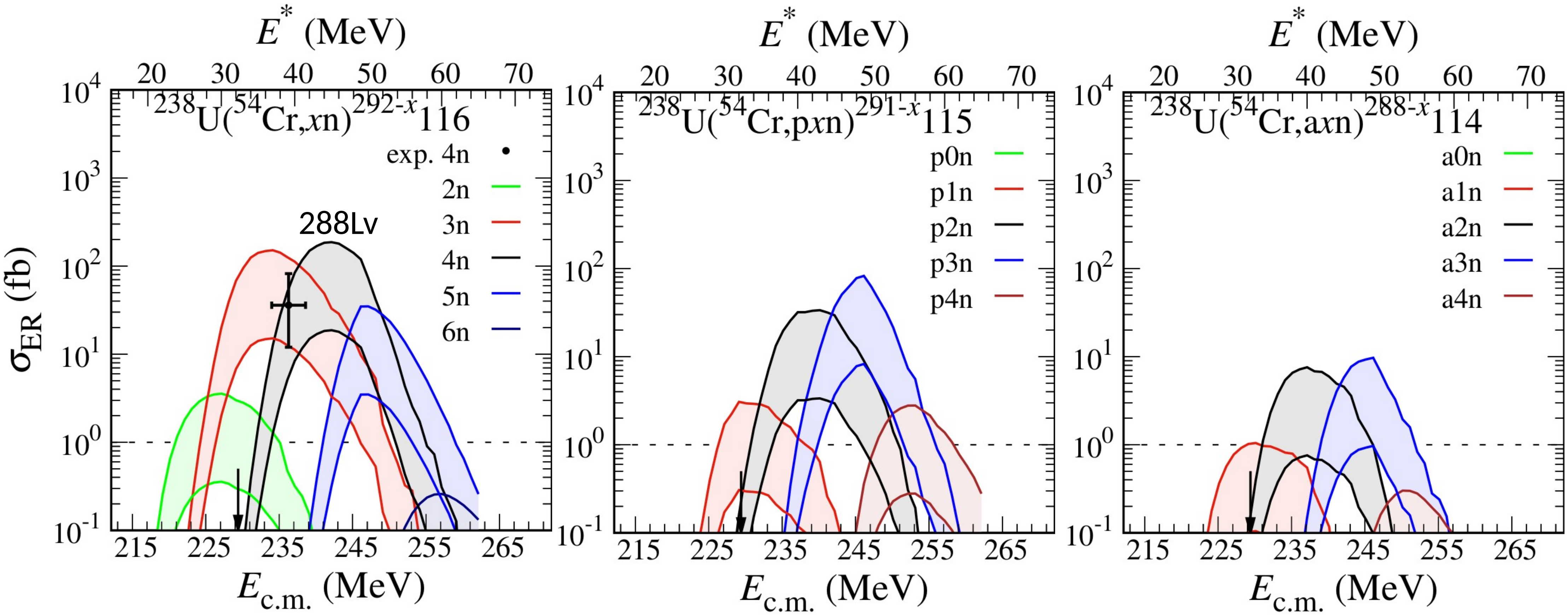




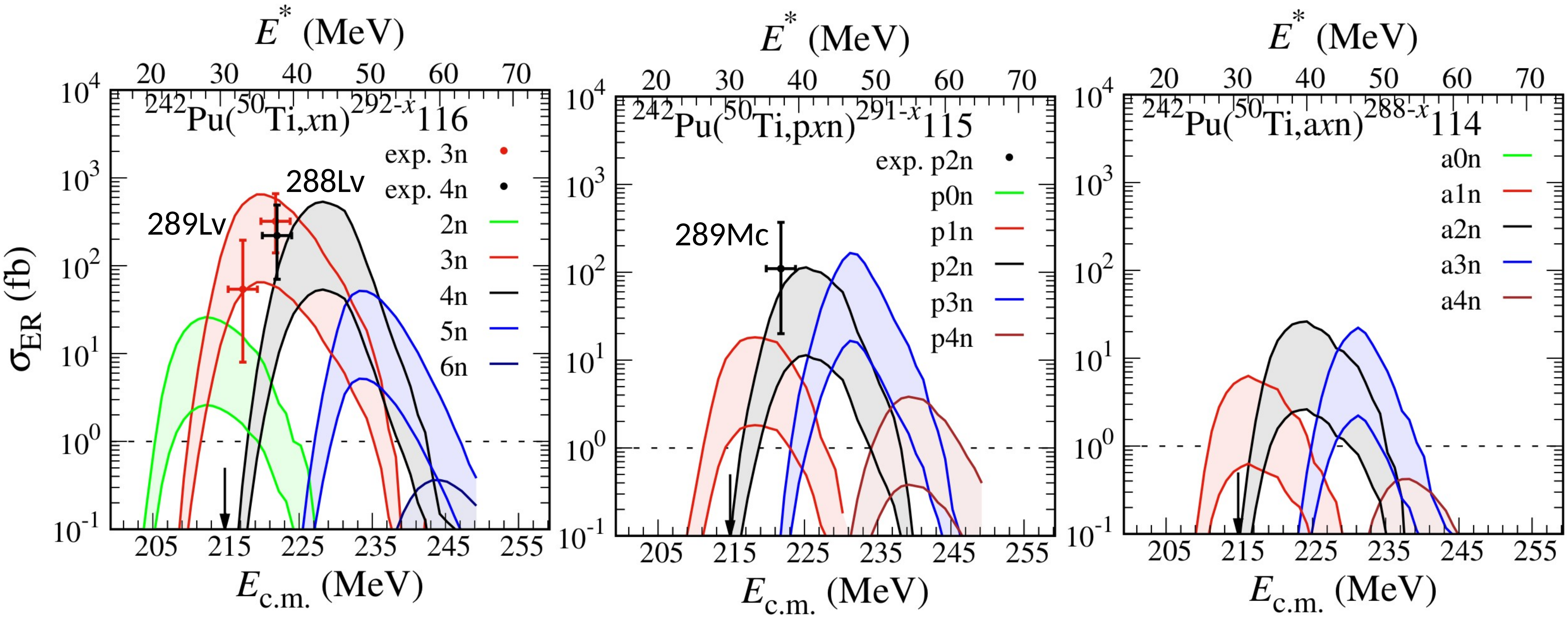
Yu. Ts. Oganessian and V. K. Utyonkov. Rep. Prog. Phys. 78(3):036301, 2015



- **J. M. Gates *et al.*, Phys. Rev. Lett. 133, 172502 (2024)**

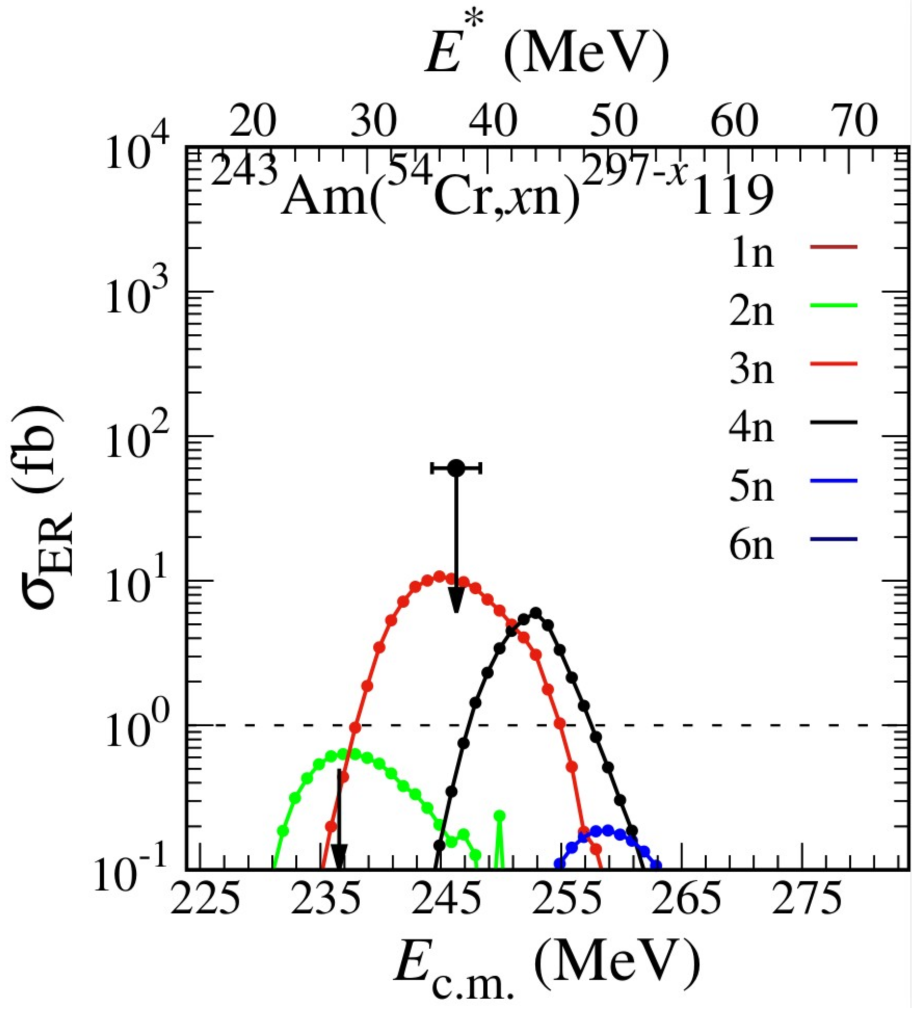


- **Yu. Ts. Oganessian *et al.*, Phys. Rev. C 112, 014603 (2025)**

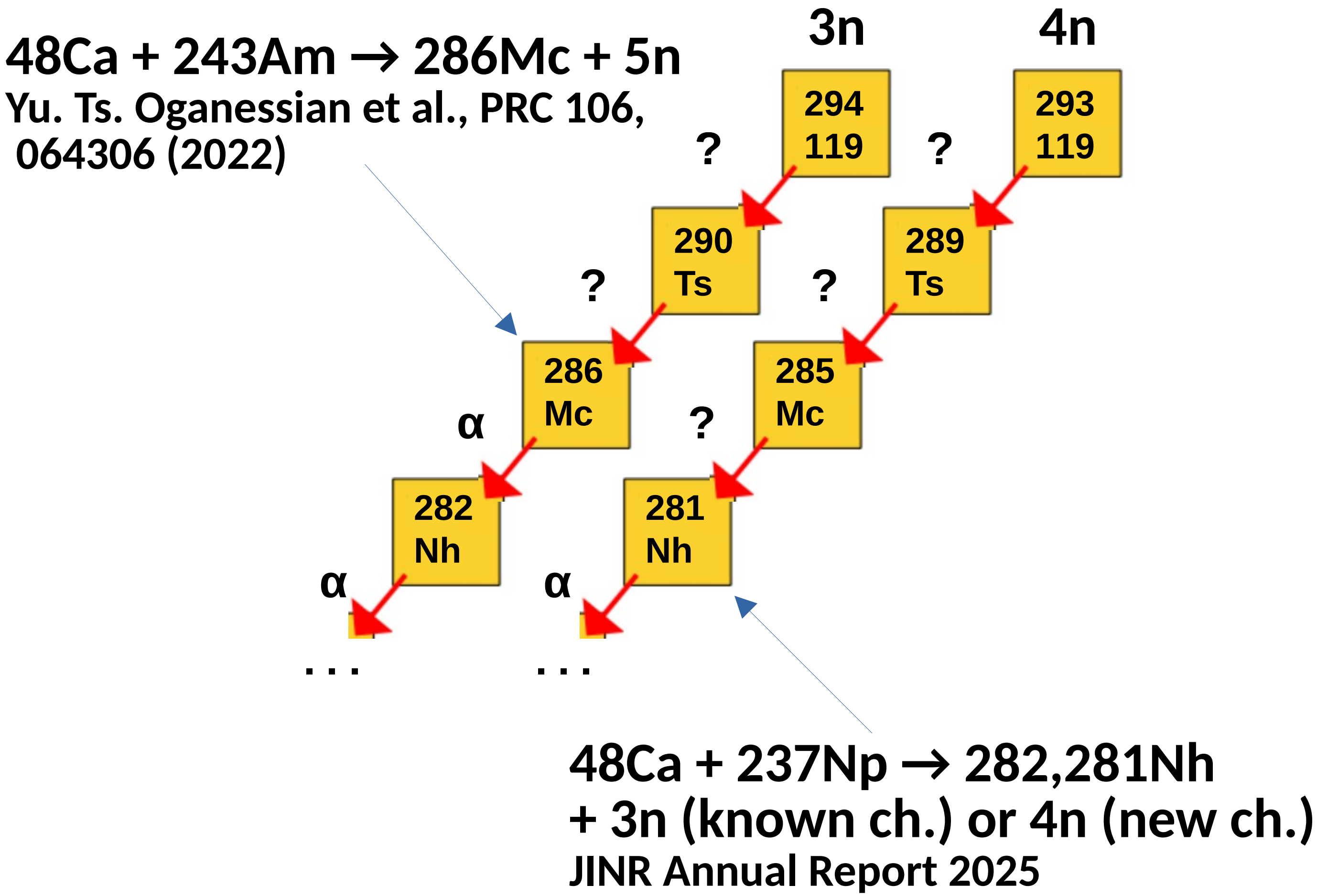


- **Yu. Ts. Oganessian *et al.*, Phys. Rev. C 112, 014603 (2025)**
- **Yu. Ts. Oganessian *et al.*, Phys. Rev. C 113, 014614 (2026)**

- $^{54}Cr + ^{243}Am \rightarrow ^{297}119^*$ **< 60 fb** ongoing experiment at IMP (Z. Gan *et al.*, talk @ TASCA26)



11 fb for 3n ch.



Calculations with a lower limit of the fusion probability only

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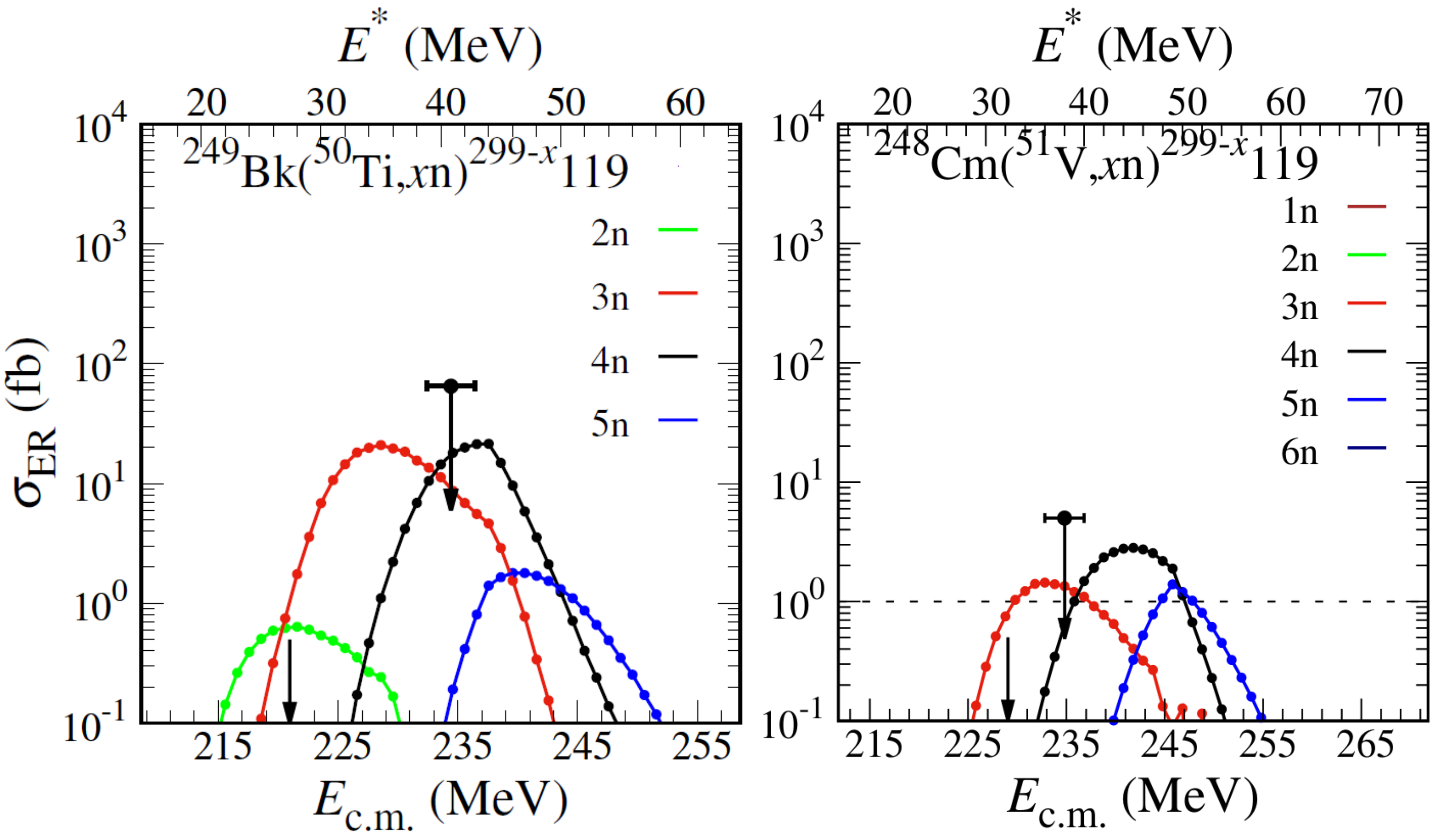
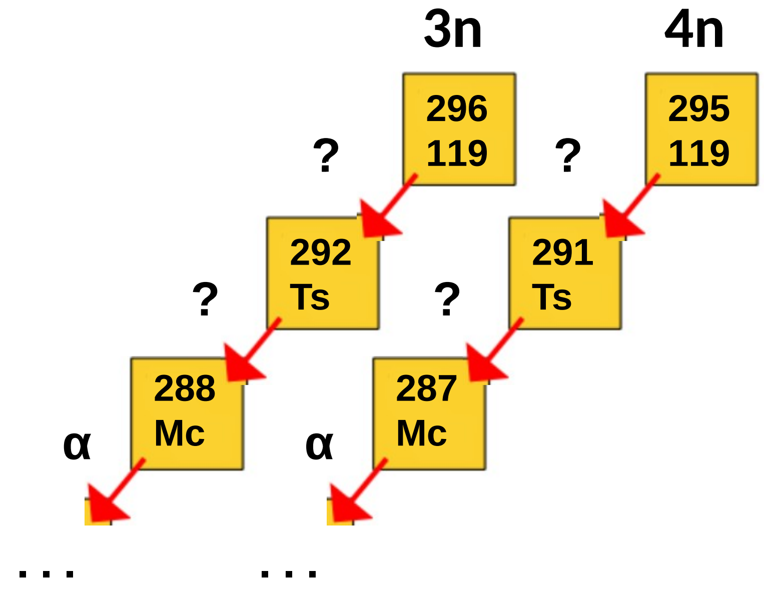
$^{50}Ti + ^{249}Bk \rightarrow ^{299}119^{*}$ Limit of 65 fb J. Khuyagbaatar *et al.*, Phys. Rev. C **102**, 064602 (2020)

$^{51}V + ^{248}Cm \rightarrow ^{299}119^{*}$ Limit of 4.85 fb K. Morimoto *et al.*, submitted to J. Phys. Soc. Jpn.



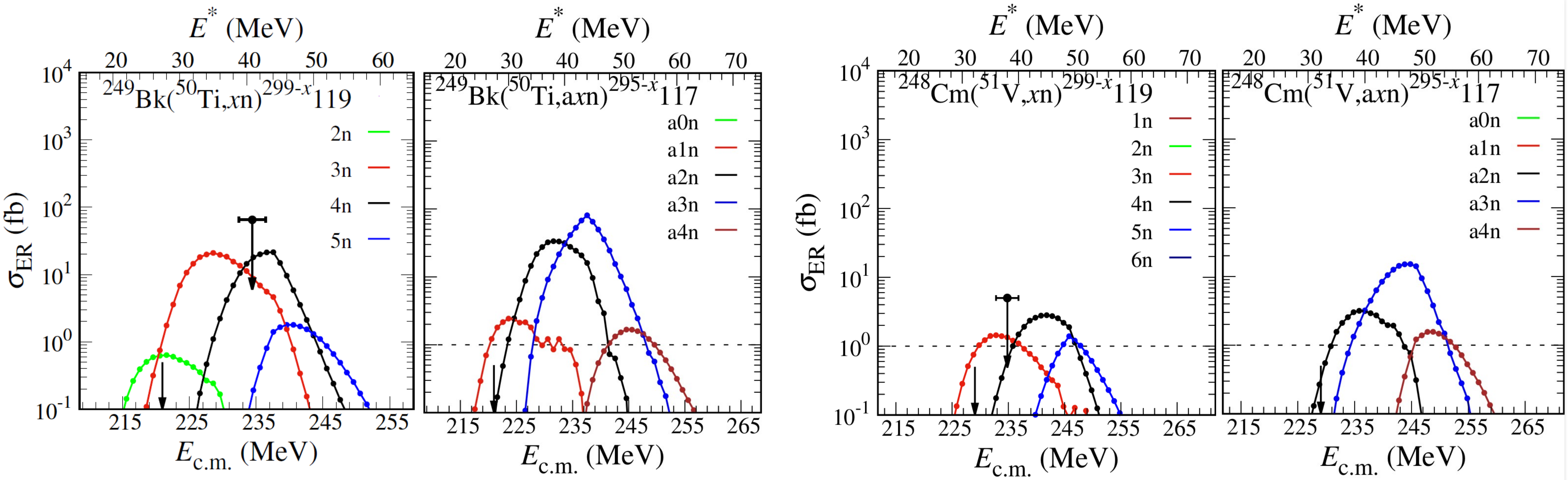


292Ts can be obtained in 51V+244Pu in 3n ch. or in 48Ca+249Bk in 5n ch.

291Ts in 51V+244Pu in 4n ch.

^{50}**Ti** + ^{249}**Bk** → ^{299}**119*** Limit of 65 fb J. Khuyagbaatar *et al.*, Phys. Rev. C **102**, 064602 (2020)

^{51}**V** + ^{248}**Cm** → ^{299}**119*** Limit of 4.85 fb K. Morimoto *et al.*, submitted to J. Phys. Soc. Jpn.



axn might exceed xn cross section

@ E* = 38 MeV

Fission	$\Gamma_f/\Gamma_{TOT} \approx 0.992$	> 99%
Neutron	$\Gamma_n/\Gamma_{TOT} \approx 0.008$	< 1%
Alpha	$\Gamma_a/\Gamma_{TOT} \approx 0.00014$	< 0.02%
Proton	$\Gamma_p/\Gamma_{TOT} \approx 1.6 \times 10^{-5}$	< 0.002%

Q_{alpha} = 12.9 MeV while the coulomb barier is 23.3 MeV high (Parker)

W. Parker *et al.*, Phys. Rev. C **44**, 774 (1991).

$\Gamma_{TOT} \approx \Gamma_f + \Gamma_n$ thus addition of LCP does not change the predictions for xn ch.

Example

		0.8%				0.8%				0.8% × 0.01		
$^{299}119$	$\rightarrow$	n	$\rightarrow$	$^{298}119$	$\rightarrow$	n	$\rightarrow$	$^{297}119$	$\rightarrow$	n	$\rightarrow$	$^{296}119$
38 MeV				≈28 MeV				≈19 MeV				G.S.

Probability that the last neutron takes enough energy to stop the cascade

Survival in 3n channel = 0.8% × 0.8% × 0.8% × 0.01 ≈ 10^{-9}

Example

$$\begin{array}{ccccccc} & 0.8\% & & 0.8\% & & 0.8\% \times 0.01 & \\ {}^{299}119 & \rightarrow n \rightarrow & {}^{298}119 & \rightarrow n \rightarrow & {}^{297}119 & \rightarrow n \rightarrow & {}^{296}119 \\ 38\ \text{MeV} & & \approx 28\ \text{MeV} & & \approx 19\ \text{MeV} & & \text{G.S.} \end{array}$$

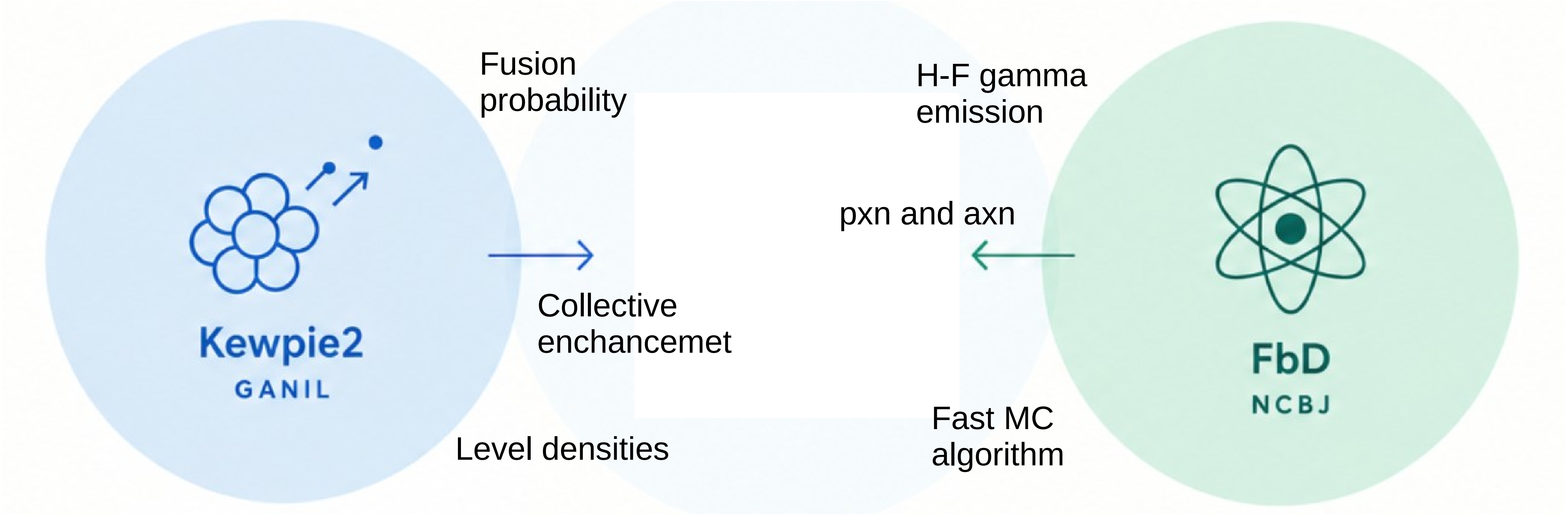
Probability that the last neutron takes enough energy to stop the cascade

Survival in 3n channel = $0.8\% \times 0.8\% \times 0.8\% \times 0.01 \approx 10^{-9}$

$$\begin{array}{ccccccc} & 0.014\% & & 1.4\ \% & & 3\% \times 0.02 & \\ {}^{299}119 & \rightarrow a \rightarrow & {}^{295}117 & \rightarrow n \rightarrow & {}^{294}117 & \rightarrow n \rightarrow & {}^{293}117 \\ 38\ \text{MeV} & & \approx 24\ \text{MeV} & & \approx 16\ \text{MeV} & & \text{G.S.} \\ & & B_n \approx B_f & & B_n < B_f\ ! & & \end{array}$$

Survival in a2n channel = $0.014\% \times 1.4\% \times 3\% \times 0.02 \approx 10^{-9}$

Fusion of two models...



H. Donglo, F. Agert, D. Boilley, T. Cap, M. Kowal, D. Ackermann, paper in preparation

Thank you for your attention

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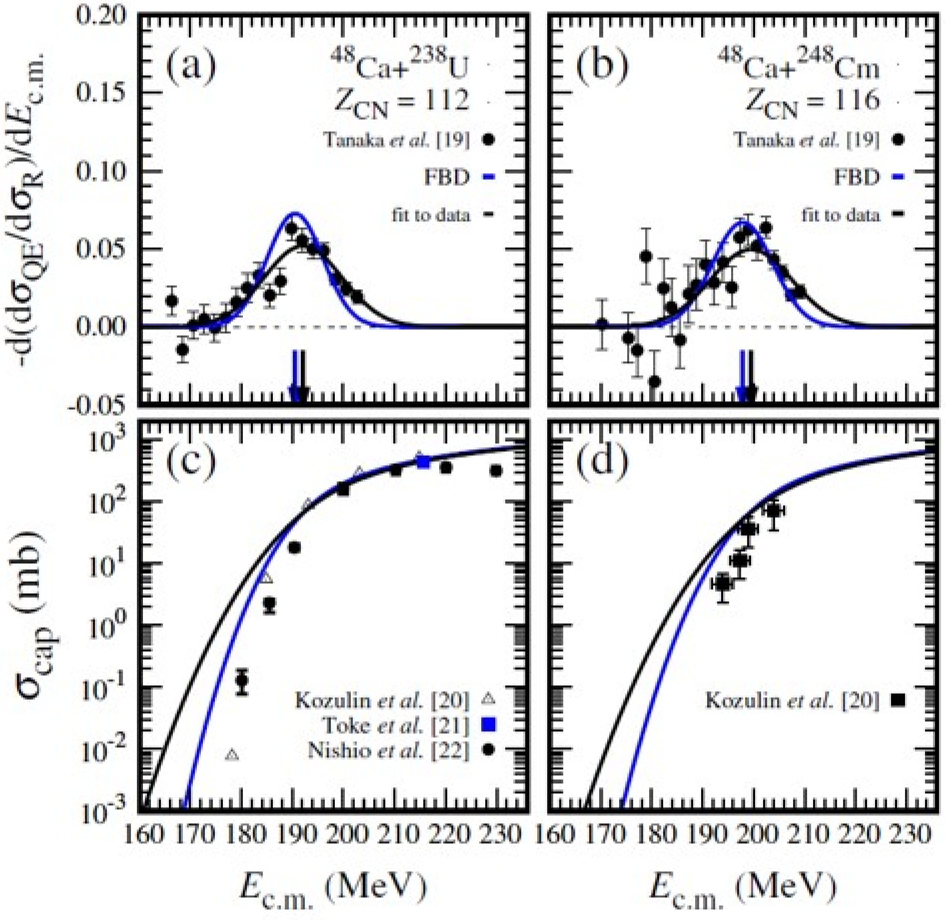
www.ncbj.gov.pl

Capture cross section

$$D(B) = \frac{1}{\sqrt{2\pi}\omega} \exp\left(-\frac{(B-B_0)^2}{2\omega^2}\right)$$



$$X = \frac{E_{\mathrm{c.m.}} - B_0}{\sqrt{2}w}$$

$$\sigma_{\mathrm{cap}}(E_{\mathrm{c.m.}}) = \pi R^2 \frac{w}{\sqrt{2\pi}E_{\mathrm{c.m.}}}\left[\sqrt{\pi}X(1+\mathrm{erf}\,X) + \exp(-X^2)\right]$$

Barrier dist. data taken from:
T. Tanaka *et al.*, J. Phy. Soc. Jpn 87, 014201, 2018
T. Tanaka *et al.*, PRL 124, 052502, 2020

K. Siwek-Wilczyńska and J. Wilczyński, PRC 69, 024611 (2004)
T. Cap et al., PRC 2011

The cross section range in the most probable xn channel.

Target	^{50}Ti	^{51}V	^{54}Cr
^{238}U	3 - 26 fb	< 9 fb	19 - 171 fb
^{237}Np			41 - 462 fb
^{244}Pu	120 - 860 fb	23 - 125 fb	8 - 60 fb
^{242}Pu	70 - 640 fb	13 - 102 fb	11 - 94 fb
^{243}Am	0.11 - 1.14 pb	3 - 22 fb	11 - 135 fb
^{241}Am	0.14 - 1.41 pb	4 - 43 fb	8 - 94 fb
^{248}Cm	36 - 205 fb	2 - 22 fb	< 2 fb
^{245}Cm	36 - 263 fb	3 - 18 fb	1.4 - 16 fb
^{249}Bk	21 - 252 fb	< 3 fb	
^{251}Cf	2 - 11 fb	< 2 fb	
^{249}Cf	4 - 45 fb	1.4 - 9.2 fb	
^{254}Es			

Hot fusion synthesis experiments leading to elements 119 and 120

^{48}Ca + ^{254}Es → ^{302}119*	Limit of 300 nb	R. W. Lougheed *et al*., Phys. Rev. C **32**, 1760 (1985)
^{50}Ti + ^{249}Bk → ^{299}119*	Limit of 65 fb	J. Khuyagbaatar *et al*., Phys. Rev. C **102**, 064602 (2020)
^{51}V + ^{248}Cm → ^{299}119*		ongoing experiment at RIKEN
^{54}Cr + ^{243}Am → ^{297}119*		ongoing experiment at IMP
^{50}Ti + ^{249}Cf → ^{299}120*	Limit of 200 fb	J. Khuyagbaatar *et al*., Phys. Rev. C **102**, 064602 (2020)
		planned experiment at LBNL
^{58}Fe + ^{244}Pu → ^{302}120*	Limit of 400 fb	Yu. Ts. Oganessian *et al*., Phys. Rev. C **79**, 024603 (2009)
^{64}Ni + ^{238}U → ^{302}120*	Limit of 90 fb	S. Hoffmann *et al*., GSI Report 2009-1
^{54}Cr + ^{248}Cm → ^{302}120*	Limit of 580 fb	S. Hoffmann *et al*., Eur. Phys. J. A 52, 180 (2016)
		planned experiment at JINR

Entrance channel effects in E119

$^{48}Ca + {}^{254}Es$

Z_1Z_2 = 1980

Q = -179.37 MeV

B_0 = 203.56 MeV

$E^*(B_0)$ = 24.20 MeV

$^{50}Ti + {}^{249}Bk$

Z_1Z_2 = 2134

Q = -193.58 MeV

B_0 = 220.96 MeV

$E^*(B_0)$ = 27.38 MeV

$^{51}V + {}^{248}Cm$

Z_1Z_2 = 2208

Q = -196.8 MeV

B_0 = 225.6 (229.04) MeV

$E^*(B_0)$ = 28.8 (32.24) MeV

For V + Cm reaction B_0 is more than 22 MeV higher than for Ca + Es system.

Q value differ by 17.4 MeV

E^* at $E_{C.M.} = B_0$ is 8 MeV higher

NARODOWE CENTRUM BADAŃ JĄDROWYCH ŚWIERK

$^{48}Ca + ^{254}Es$

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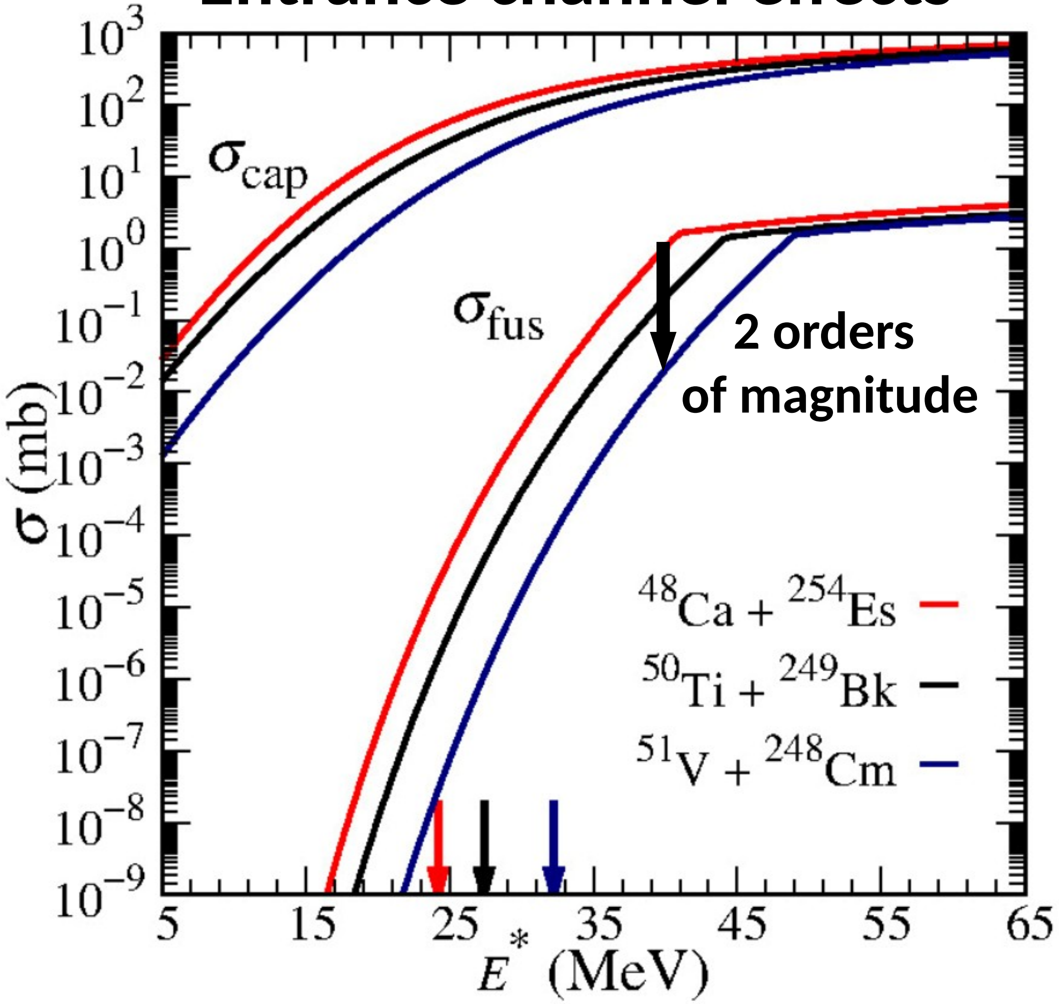
Entrance channel effects



Fusion probabilities based on Ca systematics

NARODOWE CENTRUM BADAŃ JĄDROWYCH ŚWIERK

^{48}**Ca +** ^{254}**Es**

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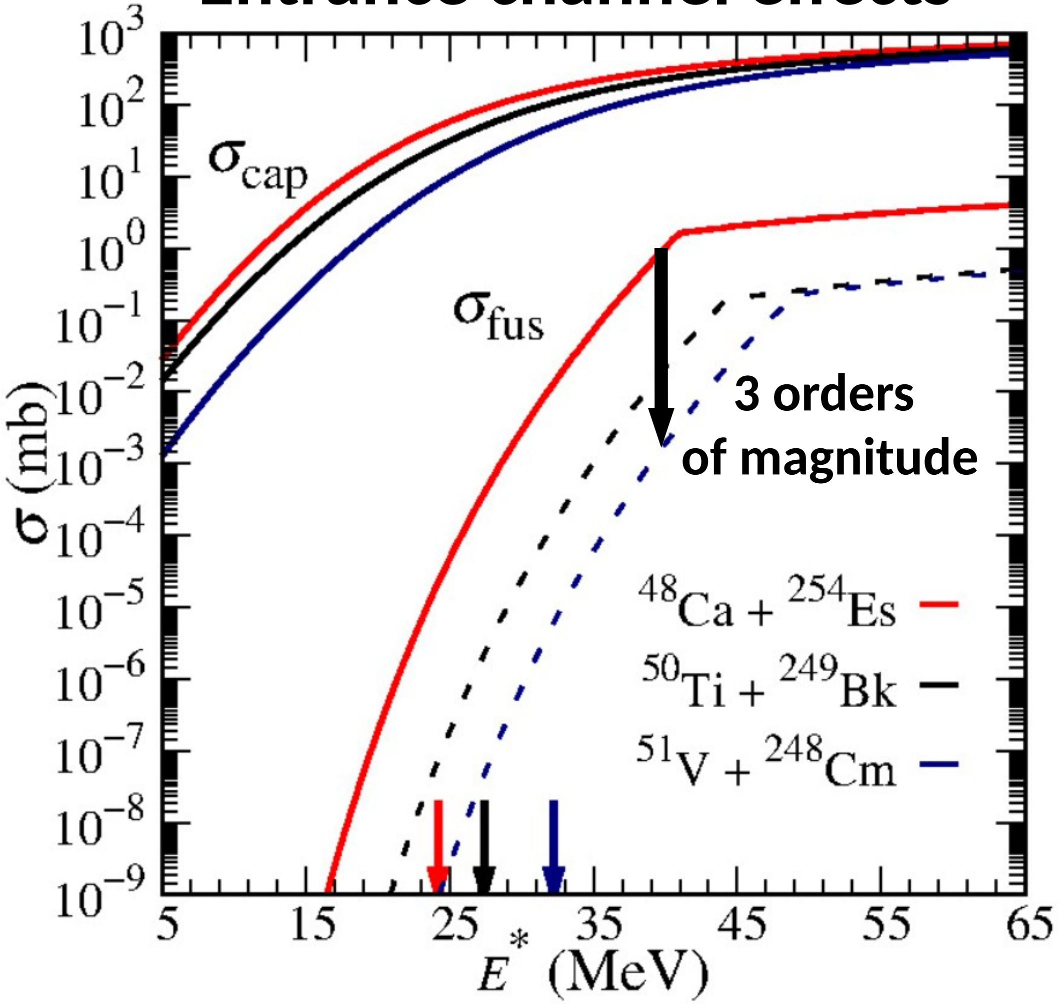
Entrance channel effects



Lower (more realistic) values of the fusion probabilities

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