Production of neutron-rich nuclides in multinucleon transfer reactions

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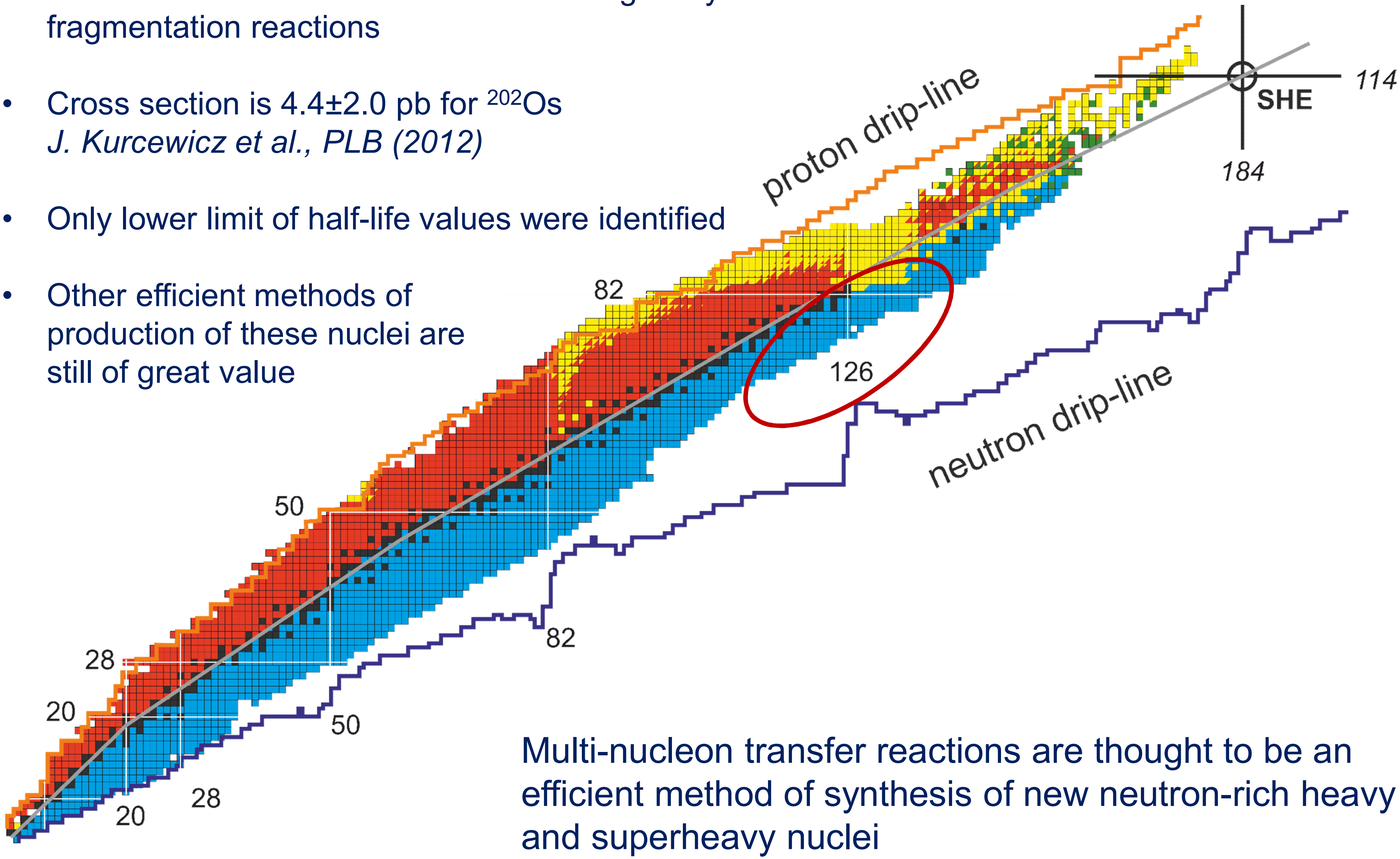
Motivation

- 3-4 neutron-rich nuclei were added during last years based on the fragmentation reactions
- Cross section is 4.4±2.0 pb for ^{202}Os
  J. Kurcewicz et al., PLB (2012)
- Only lower limit of half-life values were identified
- Other efficient methods of production of these nuclei are still of great value



Multi-nucleon transfer reactions are thought to be an efficient method of synthesis of new neutron-rich heavy and superheavy nuclei

Model

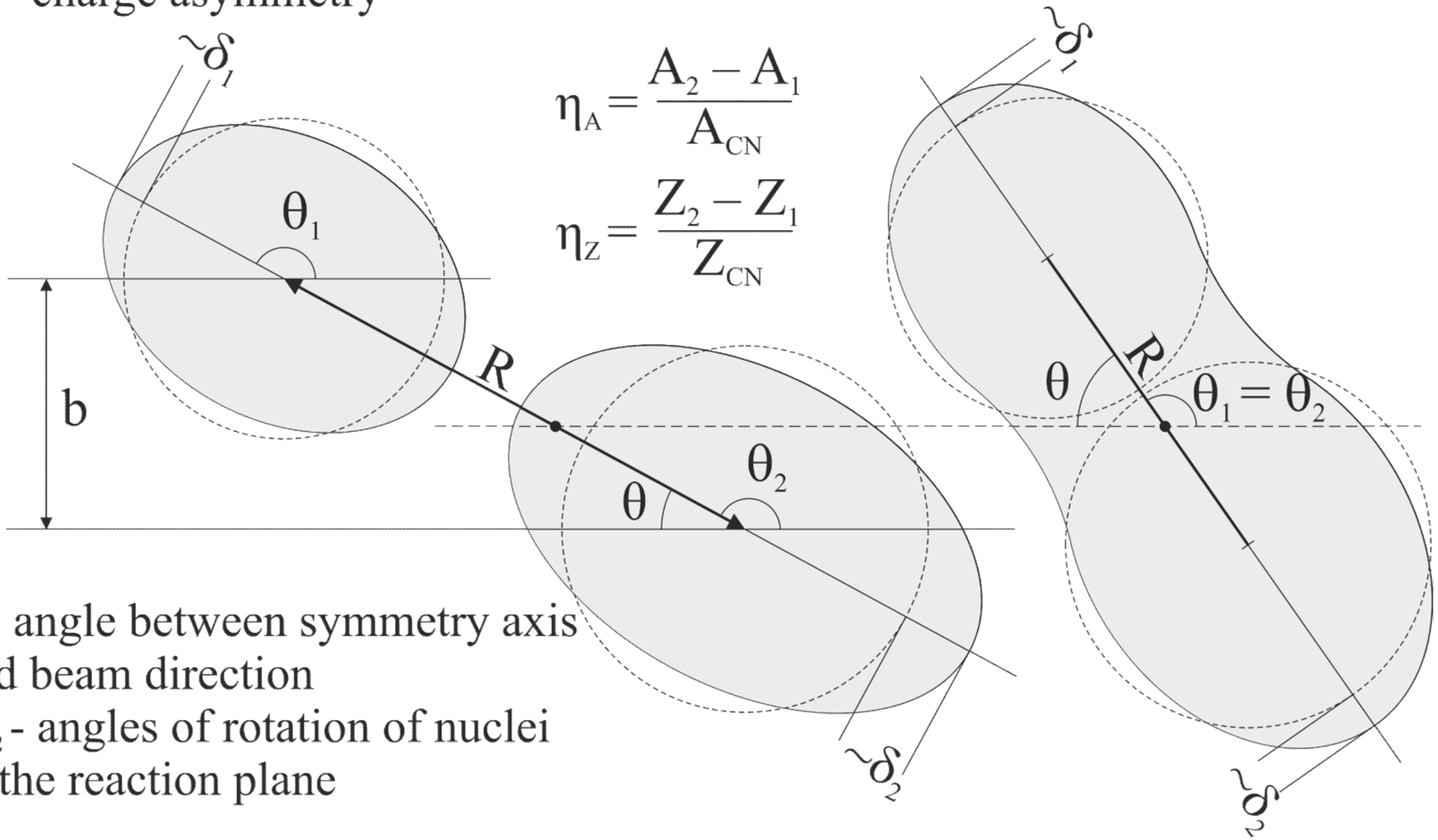
Degrees of freedom

R - distance between centers of nuclei (elongation)
$\boldsymbol{\delta}_{1,2}$ - surface deformations
$\boldsymbol{\eta}_A$ - mass asymmetry
$\boldsymbol{\eta}_Z$ - charge asymmetry

8 degrees of freedom

$$\eta_A = \frac{A_2 - A_1}{A_{CN}}$$

$$\eta_Z = \frac{Z_2 - Z_1}{Z_{CN}}$$



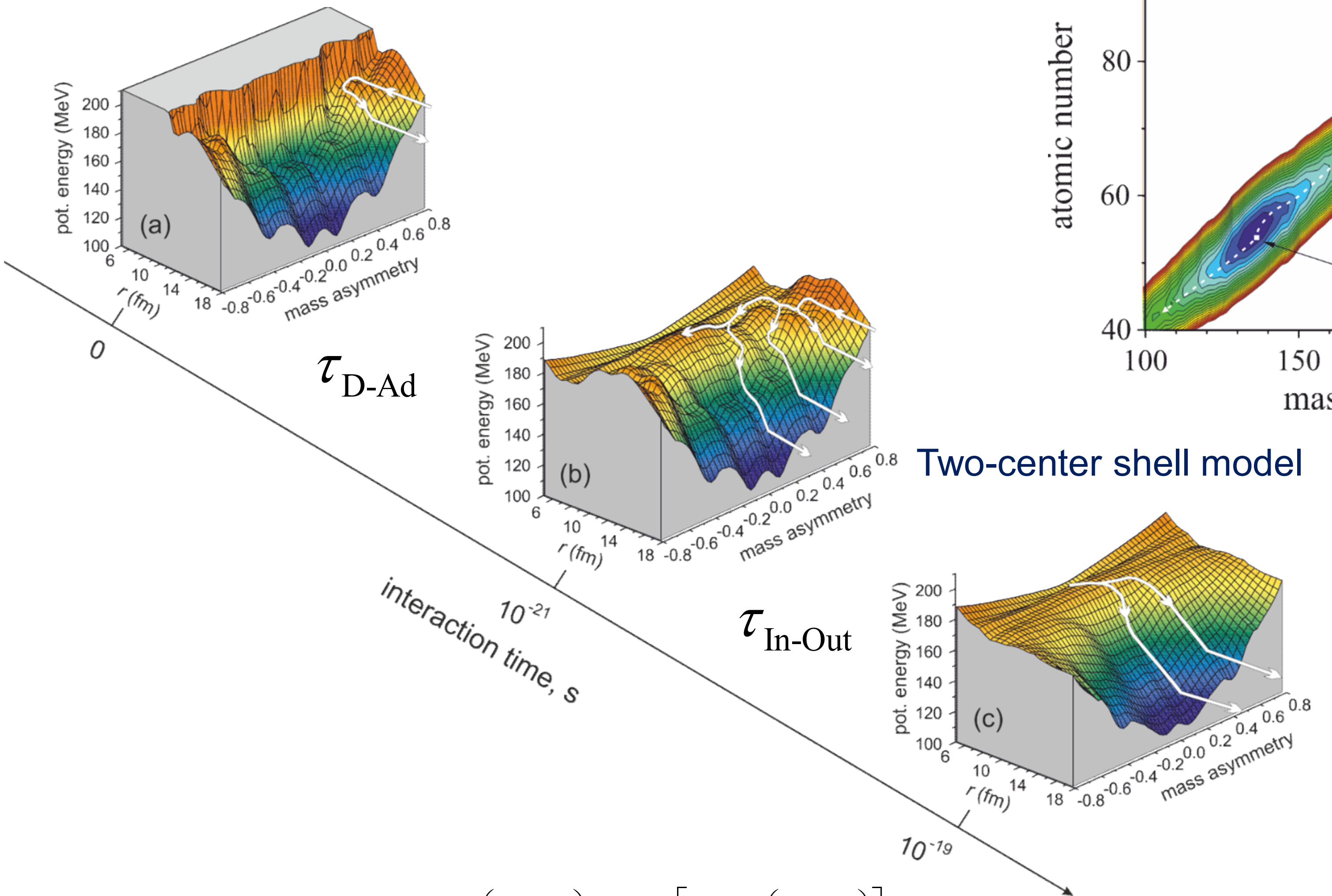
θ - angle between symmetry axis and beam direction
$\boldsymbol{\theta}_{1,2}$ - angles of rotation of nuclei in the reaction plane

A.V. Karpov and V.V. Saiko, Phys. Rev. C 96, 024618 (2017)

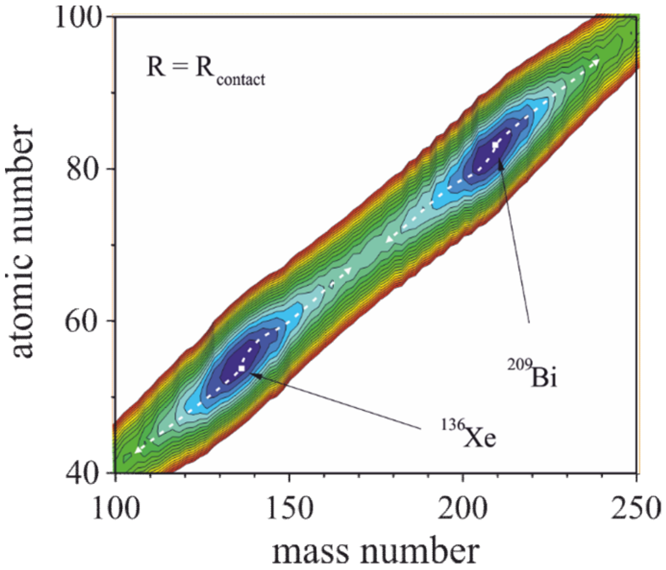
Potential energy

A.V. Karpov, EXON (2006)
V.I. Zagrebaev, A.V. Karpov, et al. PEPAN (2007)

Double-folding potential with Migdal forces



Two-center shell model



$$V_{\text{pot}}(r,\vec{\beta},\eta;A_P,Z_P,A_T,Z_T;\tau)=V_{\text{diab}}\cdot\exp\left(-\frac{\tau}{\tau_{\text{D-Ad}}}\right)+V_{\text{adiab}}\cdot\left[1-\exp\left(-\frac{\tau}{\tau_{\text{D-Ad}}}\right)\right]$$

$$\tau_{\text{D-Ad}}\sim 10^{-22}\text{ s}$$

Equations of motion

$$\left.\begin{aligned}\frac{dq_i}{dt} &= \mu_{ij} p_j \\ \frac{dp_i}{dt} &= F_i^{driving} + F_i^{dissipation} + F_i^{random}\end{aligned}\right\}$$

Traditional approach
based on Langevin equations

Variables:	$\{R \quad \delta_1 \quad \delta_2 \quad \eta_A \quad \eta_Z \quad \theta \quad \theta_1 \quad \theta_2 \}$
Momenta:	$\{p_R \quad p_{\delta 1} \quad p_{\delta 2} \quad p_{\eta_A} \quad p_{\eta_Z} \quad l \quad L_1 \quad L_2 \}$

$$F_i^{driving} = T\left(\frac{\partial S}{\partial q_i}\right)_{E_{tot}} \xrightarrow{T\to 0} -\frac{\partial V}{\partial q_i} - \sum_{j,k}\frac{p_j p_k}{2}\frac{\partial \mu_{jk}}{\partial q_i}$$

$$F_i^{dissipation} = -\sum_{j,k}\gamma_{ij}\mu_{jk}p_k$$

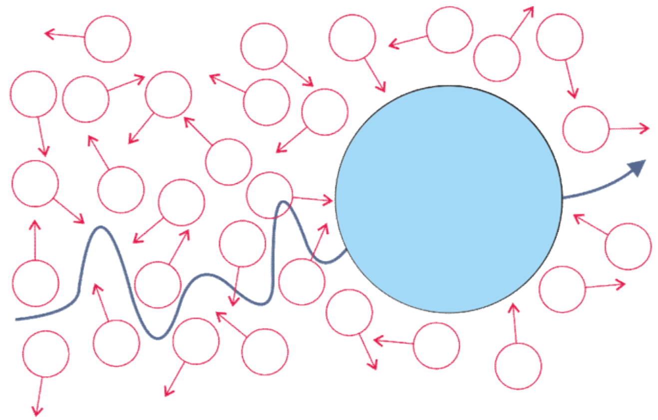
$$F_i^{random} = \sum_j \theta_{ij}\xi_j, \quad \sum_k \theta_{ik}\theta_{kj} = T^*\gamma_{ij}, \qquad T^* \begin{cases} \xrightarrow{T\to 0} \dfrac{\hbar\omega}{2} \\ \xrightarrow{T\to\infty} T \end{cases}$$

$\|\mu_{ij}\| = \|m_{ij}\|^{-1}$ - mass tensor

γ_{ij} - dissipation tensor

ξ_i - random value

θ_{ij} - amplitude of random force



abstract **Brownian particle** (slow)

$\downarrow\uparrow$

nucleus collective degrees of freedom

heat medium (fast)

$\downarrow\uparrow$

single-particle degrees of freedom

Equations of motion (R, δ_1, δ_2, η_A, η_Z, θ_1, θ_2, θ)

$$\frac{dR}{dt} = p_R \sum_i \mu_{Ri}$$

$$\frac{d\delta_1}{dt} = p_{\delta_1} \sum_i \mu_{\delta_1 i}$$

$$\frac{d\delta_2}{dt} = p_{\delta_2} \sum_i \mu_{\delta_2 i}$$

$$\frac{d\eta_A}{dt} = p_{\eta_A} \sum_i \mu_{\eta_A i}$$

$$\frac{d\eta_Z}{dt} = p_{\eta_Z} \sum_i \mu_{\eta_Z i}$$

$$\frac{d\theta}{dt} = \frac{l}{\mu_R R^2}$$

$$\frac{d\theta_1}{dt} = \frac{L_1}{\Im_1}$$

$$\frac{d\theta_2}{dt} = \frac{L_2}{\Im_2}$$

$$\frac{dp_R}{dt} = -\frac{\partial V}{\partial R} + T^2 \frac{\partial a}{\partial R} + \frac{l^2}{R^3}\mu_R + \sum_i \frac{L_i^2}{2\Im_i^2}\frac{\partial \Im_i}{\partial R} - \sum_{j,k} \frac{p_j p_k}{2}\frac{\partial \mu_{jk}}{\partial R} - \sum_{j,k} \gamma_{Rj}\mu_{jk} p_k + \sum_j \xi_{Rj}\Gamma_j(t)$$

$$\frac{dp_{\delta_1}}{dt} = -\frac{\partial V}{\partial \delta_1} + T^2 \frac{\partial a}{\partial \delta_1} + \sum_i \frac{L_i^2}{2\Im_i^2}\frac{\partial \Im_i}{\partial \delta_1} - \sum_{i,j} \frac{p_i p_j}{2}\frac{\partial \mu_{ij}}{\partial \delta_1} - \sum_{j,k} \gamma_{\delta_1 j}\mu_{jk} p_k + \sum_j \xi_{\delta_1 j}\Gamma_j(t)$$

$$\frac{dp_{\delta_2}}{dt} = -\frac{\partial V}{\partial \delta_2} + T^2 \frac{\partial a}{\partial \delta_2} + \sum_i \frac{L_i^2}{2\Im_i^2}\frac{\partial \Im_i}{\partial \delta_2} - \sum_{i,j} \frac{p_i p_j}{2}\frac{\partial \mu_{ij}}{\partial \delta_2} - \sum_{j,k} \gamma_{\delta_2 j}\mu_{jk} p_k + \sum_j \xi_{\delta_2 j}\Gamma_j(t)$$

$$\frac{dp_{\eta_A}}{dt} = -\frac{\partial V}{\partial \eta_A} + T^2 \frac{\partial a}{\partial \eta_A} + \sum_i \frac{L_i^2}{2\Im_i^2}\frac{\partial \Im_i}{\partial \eta_A} - \sum_{i,j} \frac{p_i p_j}{2}\frac{\partial \mu_{ij}}{\partial \eta_A} - \sum_{j,k} \gamma_{\eta_A j}\mu_{jk} p_k + \sum_j \xi_{\eta_A j}\Gamma_j(t)$$

$$\frac{dp_{\eta_Z}}{dt} = -\frac{\partial V}{\partial \eta_Z} + T^2 \frac{\partial a}{\partial \eta_Z} + \sum_i \frac{L_i^2}{2\Im_i^2}\frac{\partial \Im_i}{\partial \eta_Z} - \sum_{i,j} \frac{p_i p_j}{2}\frac{\partial \mu_{ij}}{\partial \eta_Z} - \sum_{j,k} \gamma_{\eta_Z j}\mu_{jk} p_k + \sum_j \xi_{\eta_Z j}\Gamma_j(t)$$

$$\frac{dl}{dt} = -\gamma_{\text{tang}}\left(\frac{l}{\mu_R R} - \frac{L_1}{\Im_1}a_1 - \frac{L_2}{\Im_2}a_2\right)R + R\sqrt{\gamma_{\text{tang}} T}\,\Gamma_{\text{tang}}(t)$$

$$\frac{dL_1}{dt} = \gamma_{\text{tang}}\left(\frac{l}{\mu_R R} - \frac{L_1}{\Im_1}a_1 - \frac{L_2}{\Im_2}a_2\right)a_1 + a_1\sqrt{\gamma_{\text{tang}} T}\,\Gamma_{\text{tang}}(t)$$

$$\frac{dL_2}{dt} = \gamma_{\text{tang}}\left(\frac{l}{\mu_R R} - \frac{L_1}{\Im_1}a_1 - \frac{L_2}{\Im_2}a_2\right)a_2 + a_2\sqrt{\gamma_{\text{tang}} T}\,\Gamma_{\text{tang}}(t)$$

Cross section calculation

For each trajectory we know:

- Z and A of two fragments (*primary, final*),
- angles θ (*cm, lab*),
- kinetic energies (*TKE, lab*),
- time
- ...

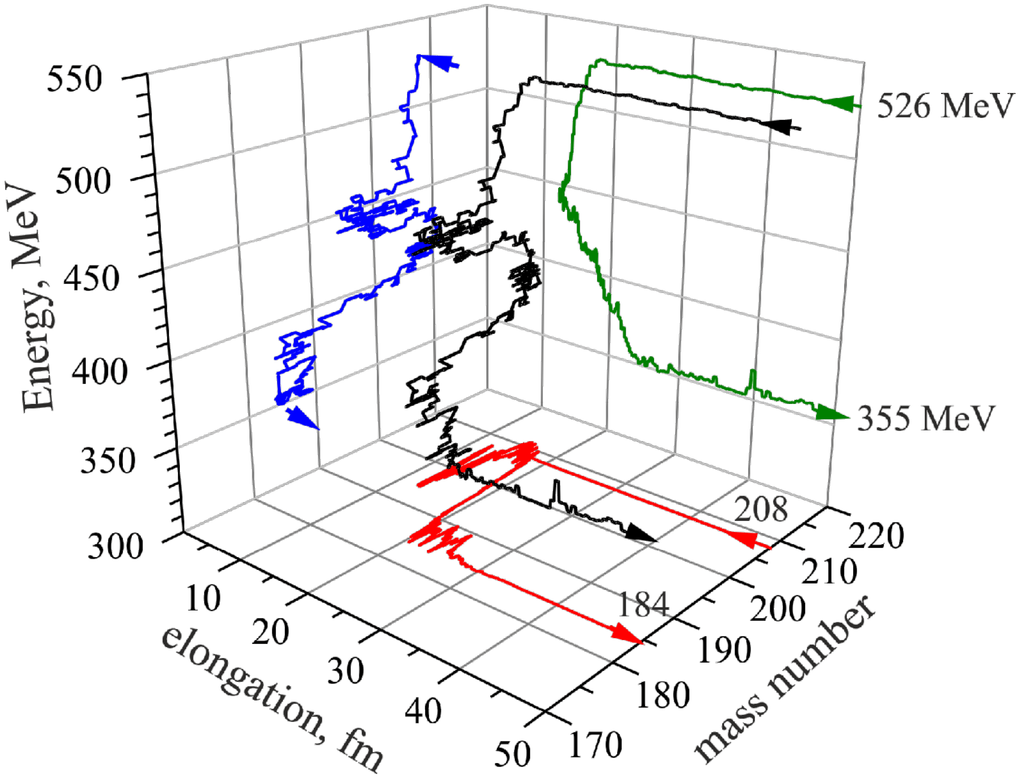
Langevin model simulations:

1. A number trajectories are calculated for impact parameter $0 < b < b_{max}$

2. Trajectories are selected according to experimental conditions: energy, angle, atomic and mass numbers ranges

3. cross sections are calculated as

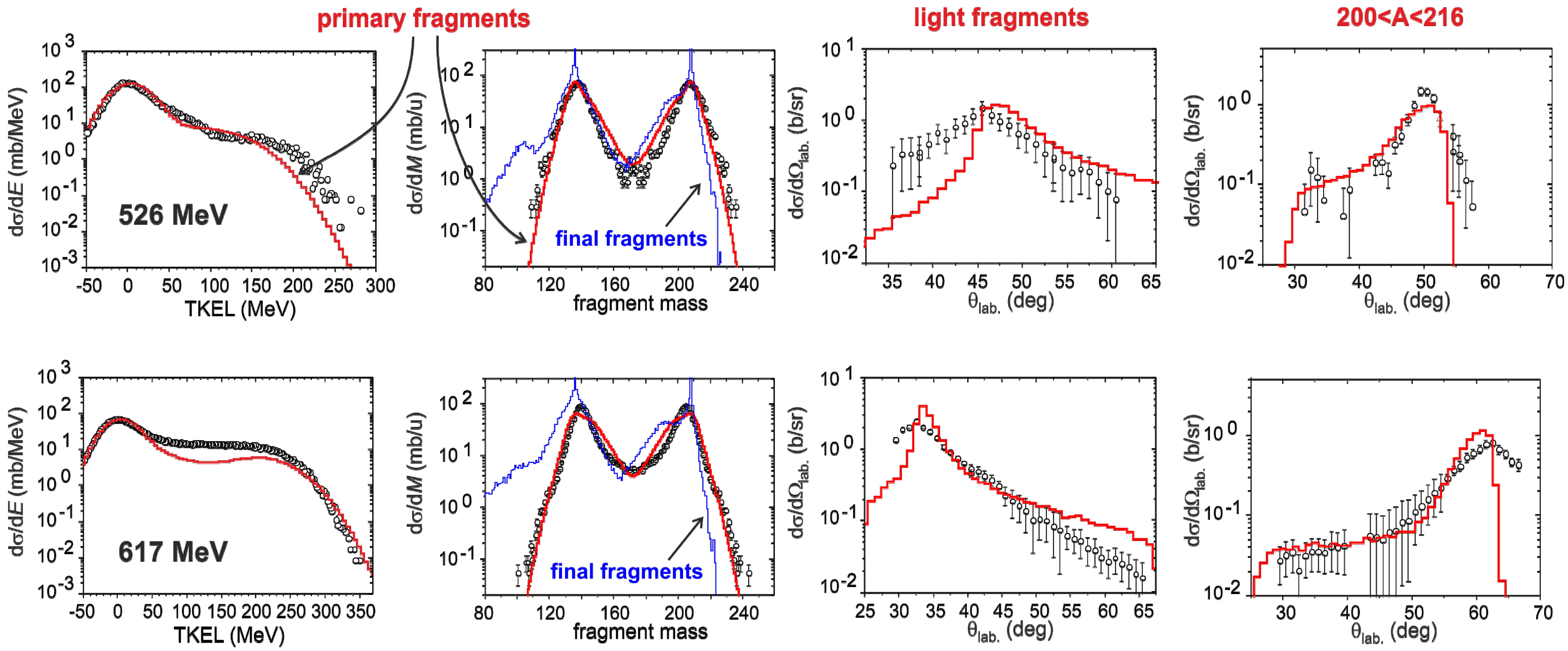
$$\frac{d^4\sigma}{d\Omega dE dA dZ}(E,\theta) = \int_0^\infty \frac{\Delta N(b,E,\theta)}{N_{tot}(b)} \frac{1}{\sin\theta \Delta\theta \Delta E \Delta A \Delta Z} b db$$



$^{136}Xe + ^{208}Pb$, $E_{c.m.} = 526$ MeV

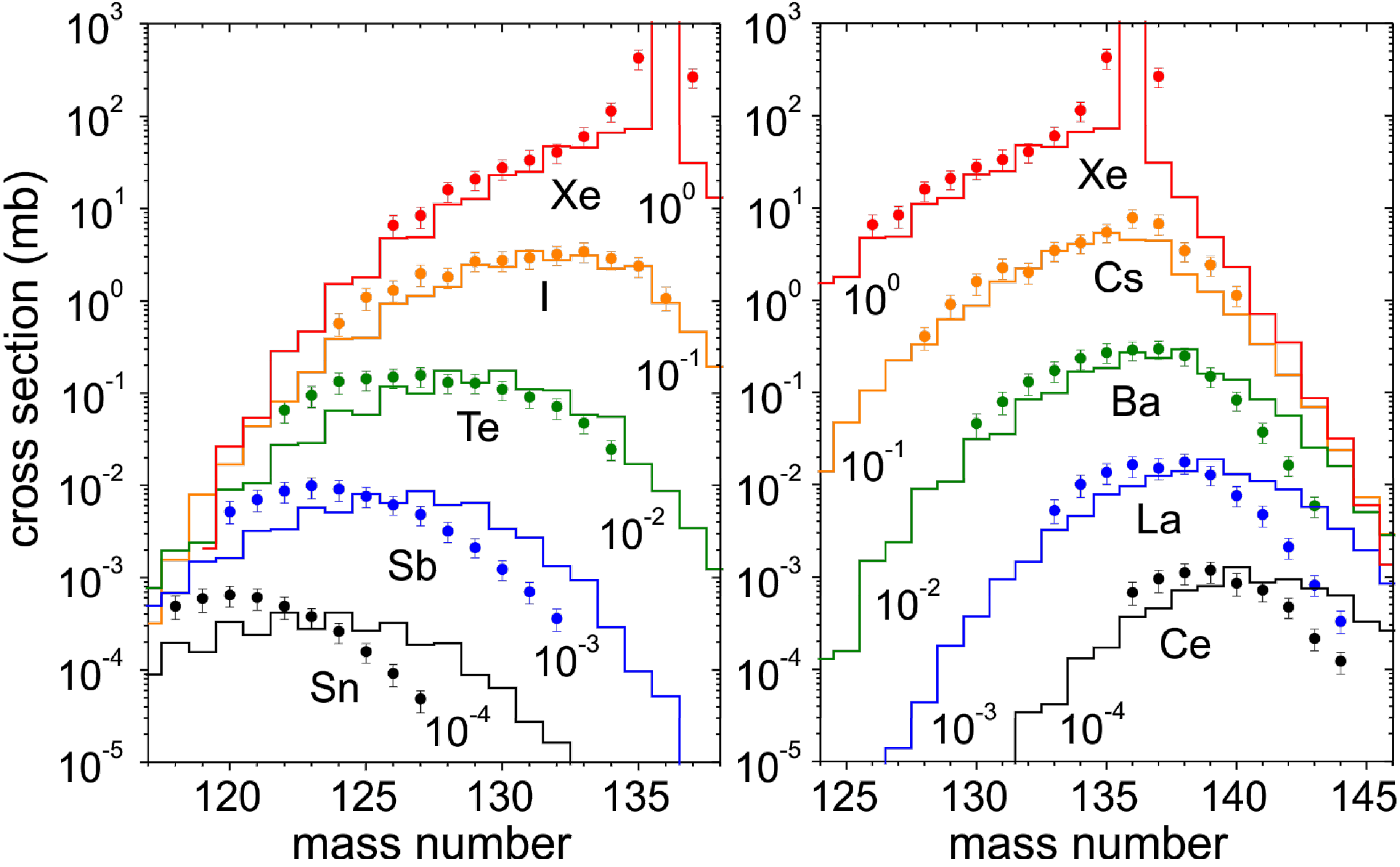
$^{136}Xe+^{208}Pb$

experiment: E.M. Kozulin, et al., PRC (2012)

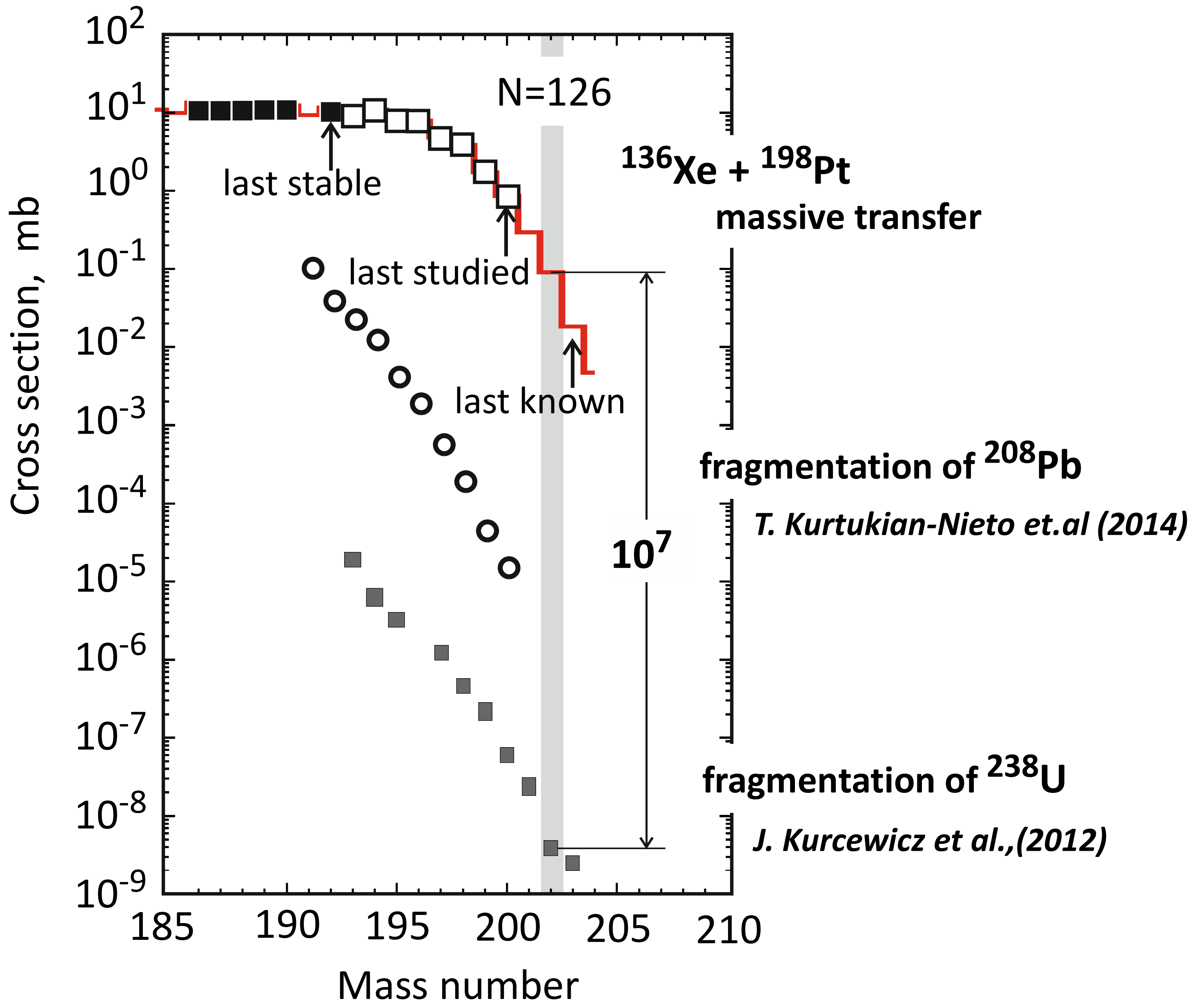


$^{136}Xe+^{198}Pt$ @ 643 MeV

experiment: Y. X. Watanabe, et al., PRL (2015)

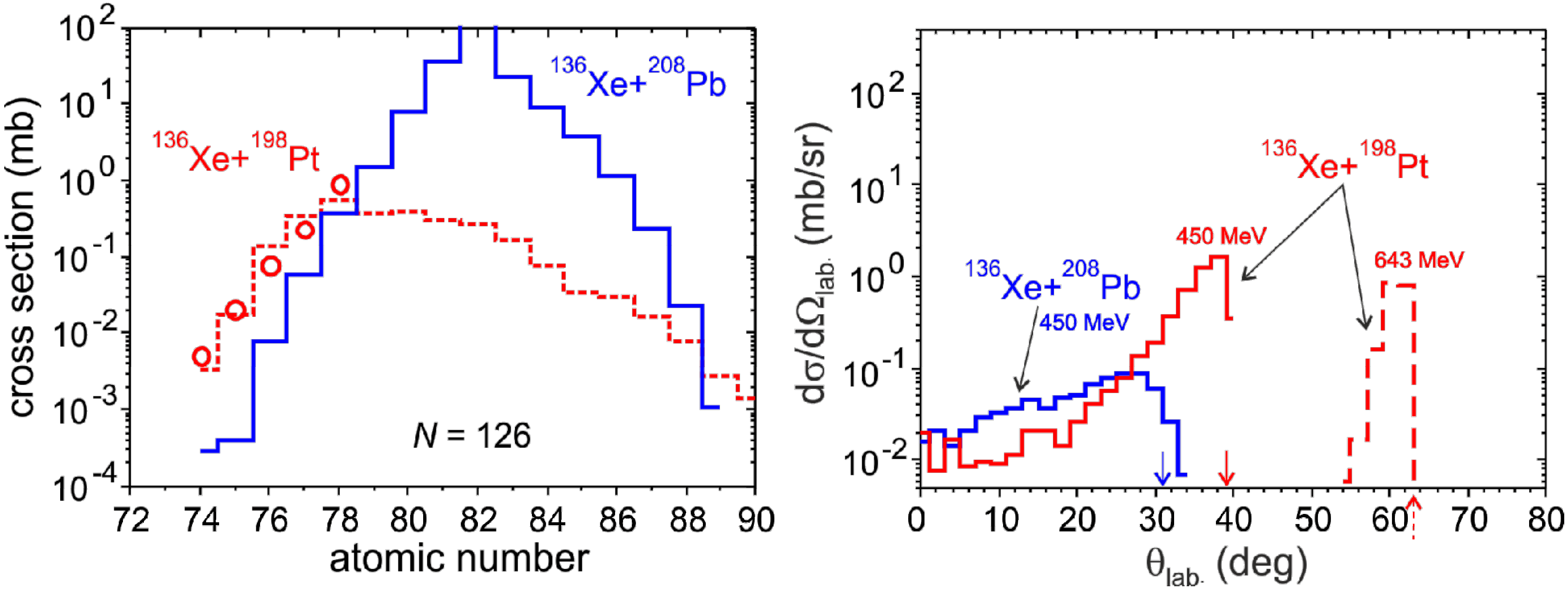


Production of neutron-rich Os-isotopes



Production of *N*=126 nuclides

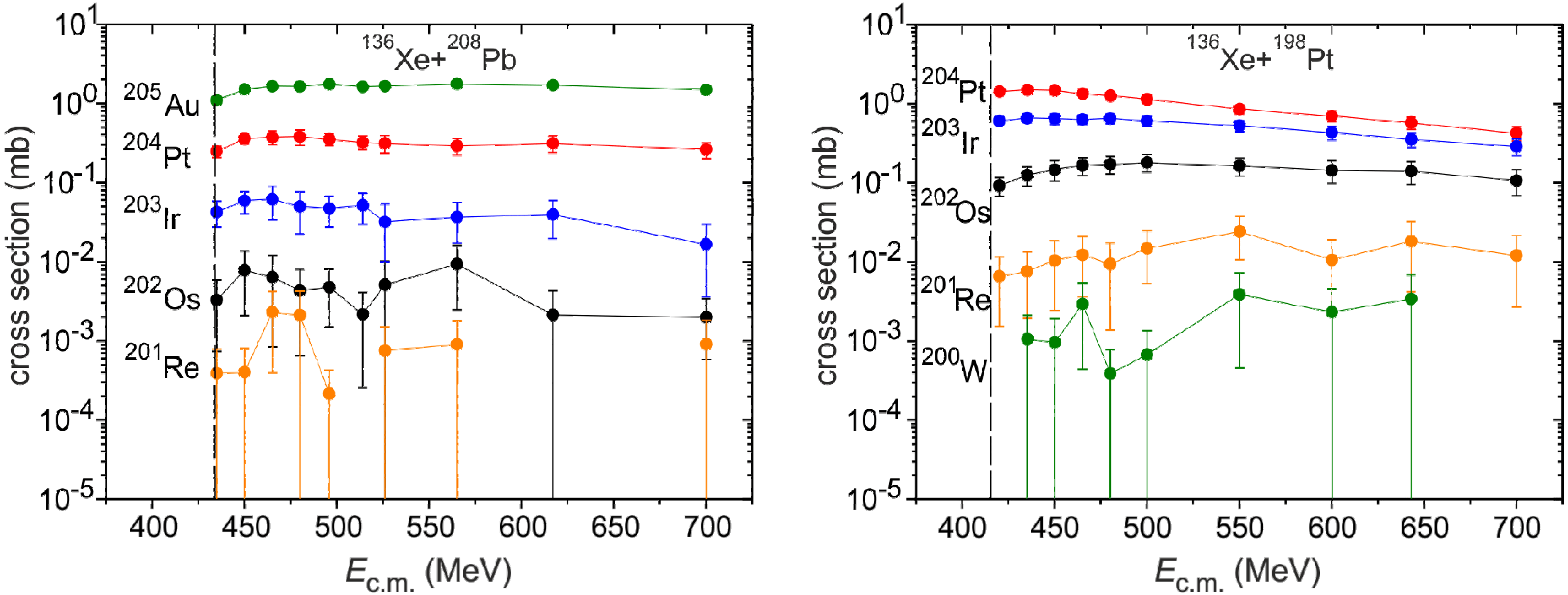
Optimal reaction and detection angles



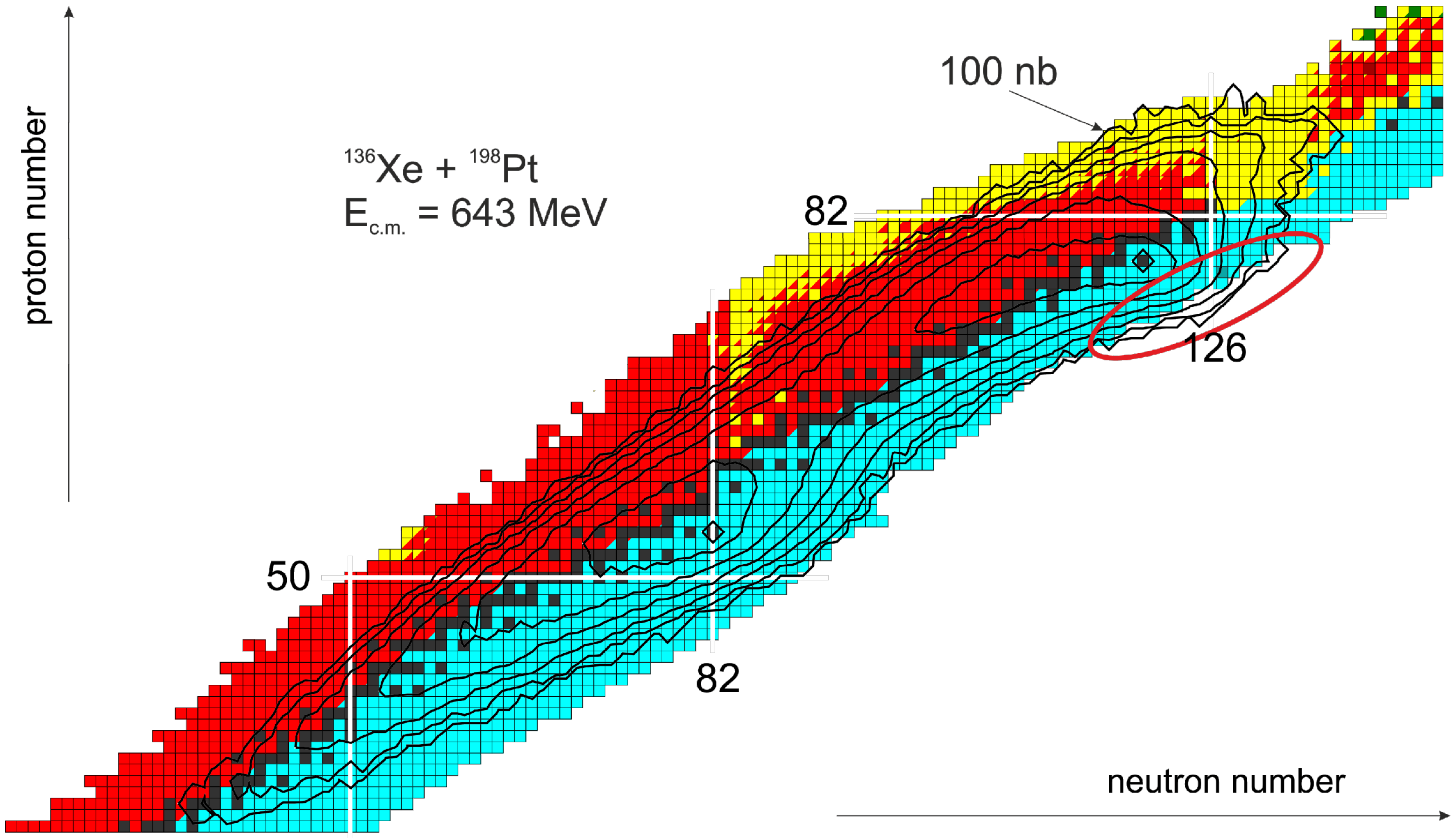
experiment: Y. X. Watanabe, et al., PRL (2015)

Production of *N*=126 nuclides

Optimal energy

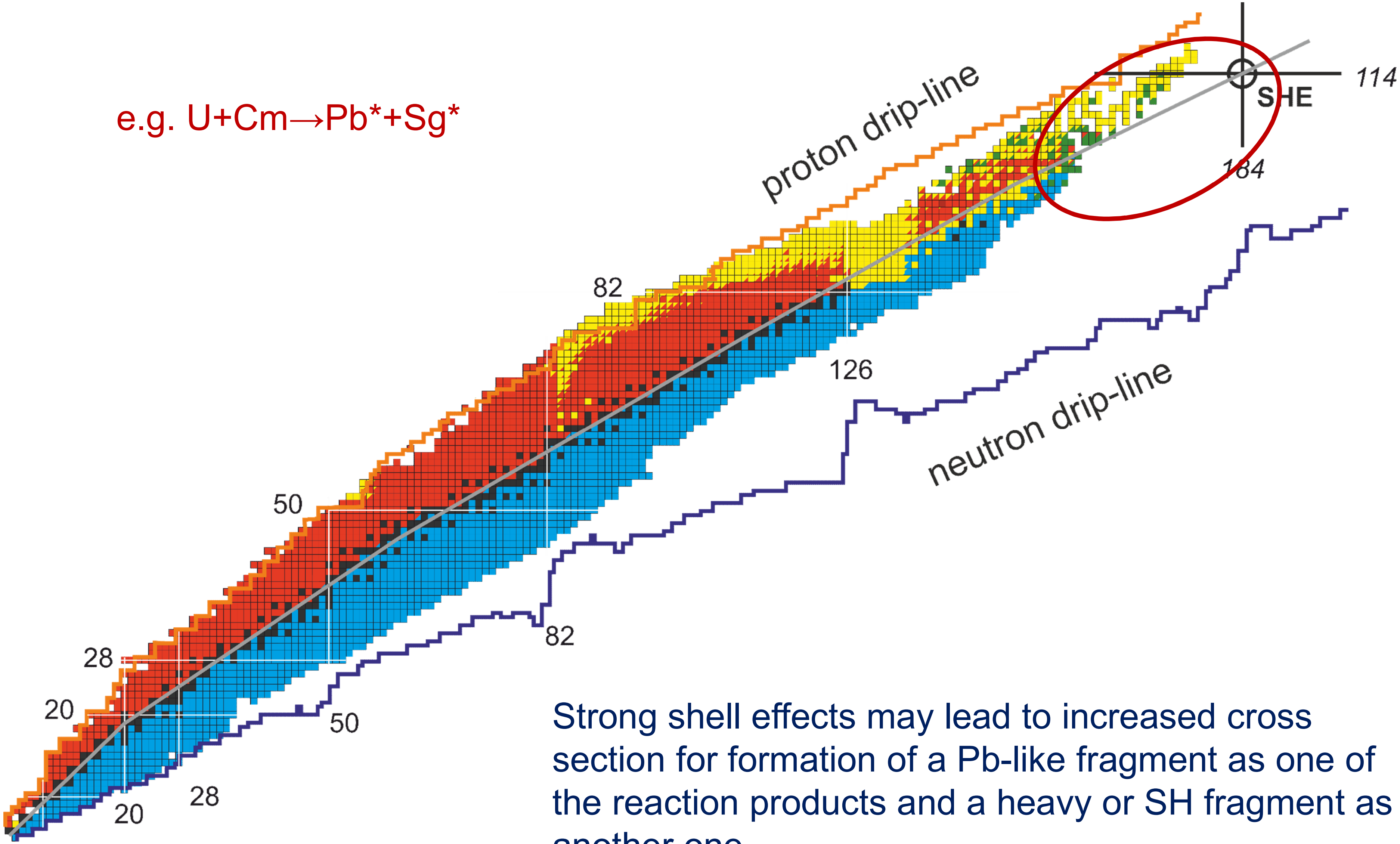


Production cross section



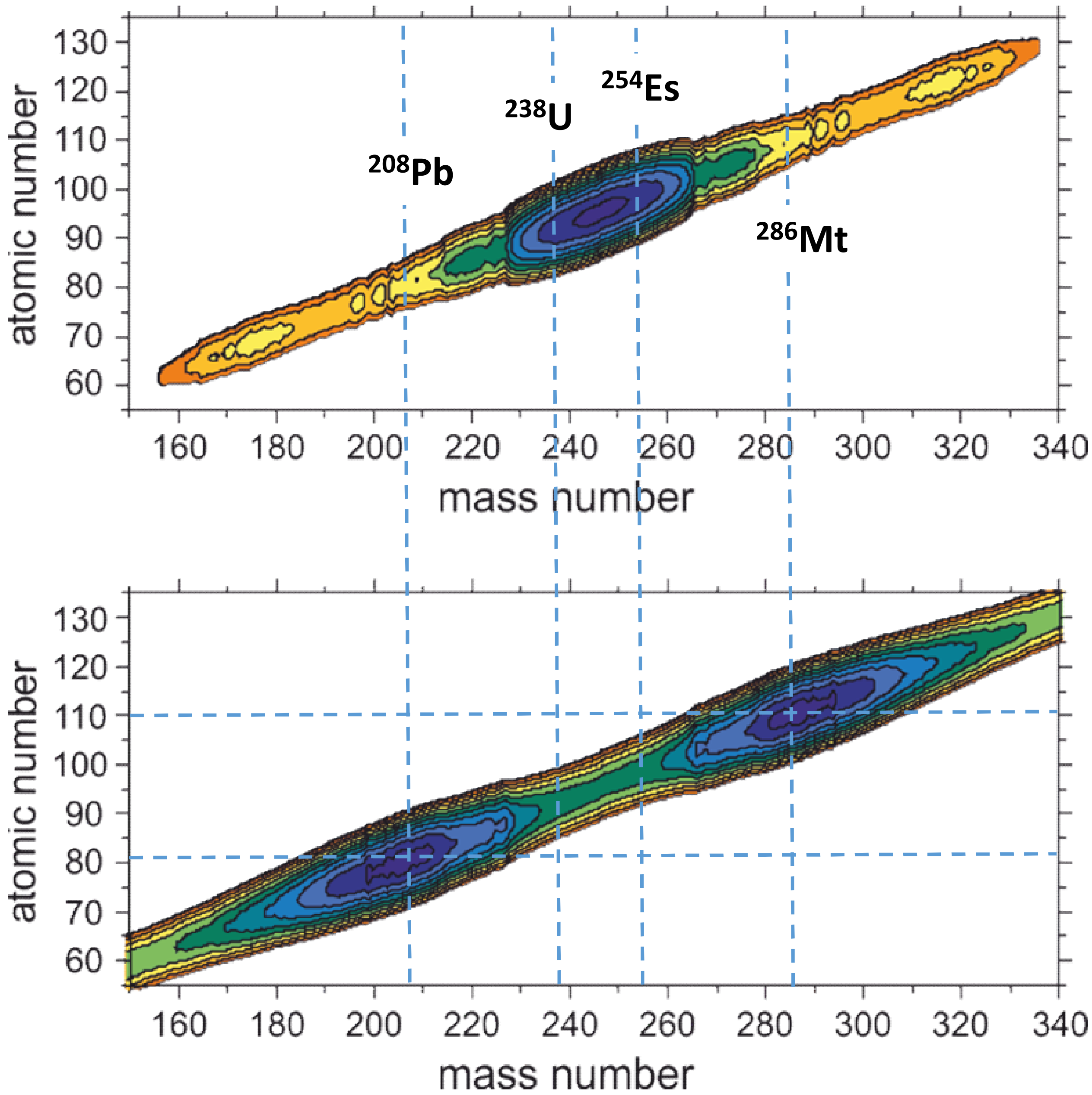
Production of neutron-rich heavy and SH nuclei in actinide-actinide collisions (U+smth.)

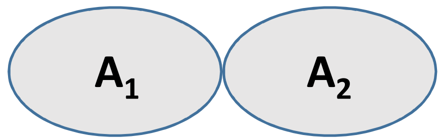
e.g. U+Cm→Pb*+Sg*

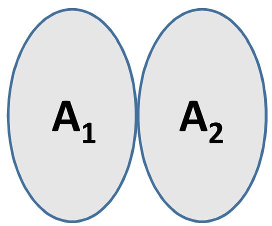


Strong shell effects may lead to increased cross section for formation of a Pb-like fragment as one of the reaction products and a heavy or SH fragment as another one

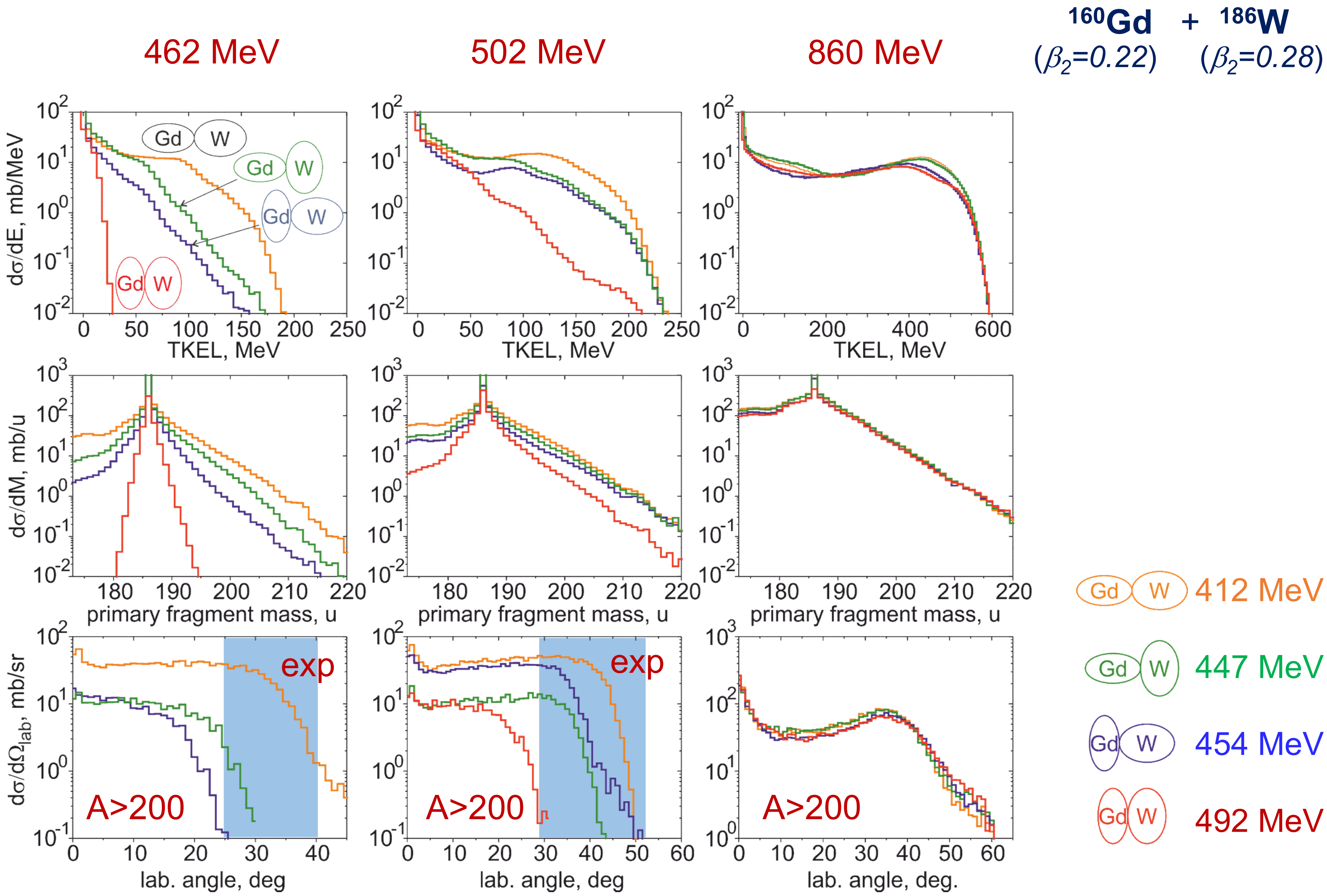
Collisions of actinides. Potential energy @ contact point: $^{238}U+^{254}Es$ case







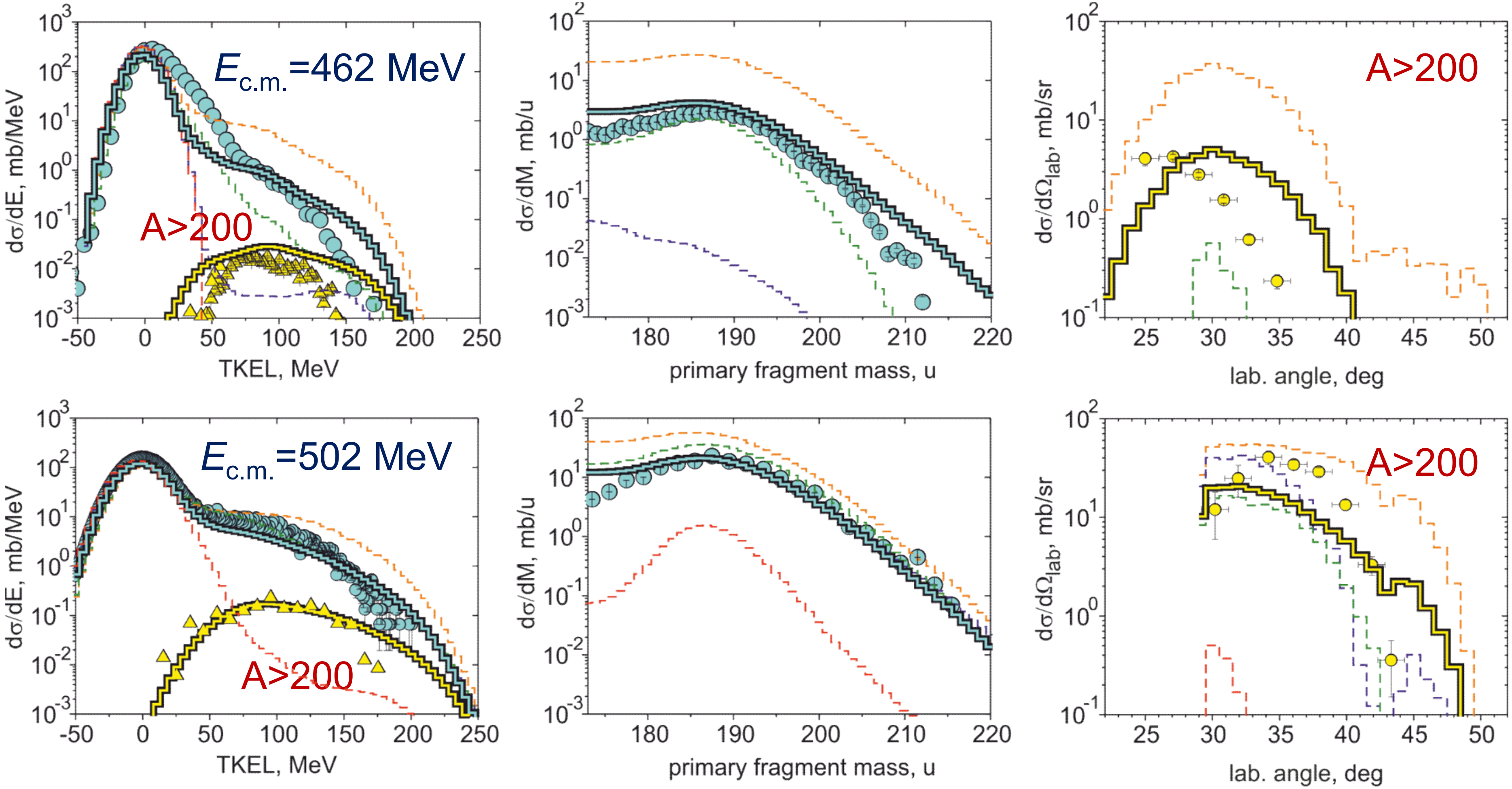
Orientation effects in nucleus-nucleus collisions



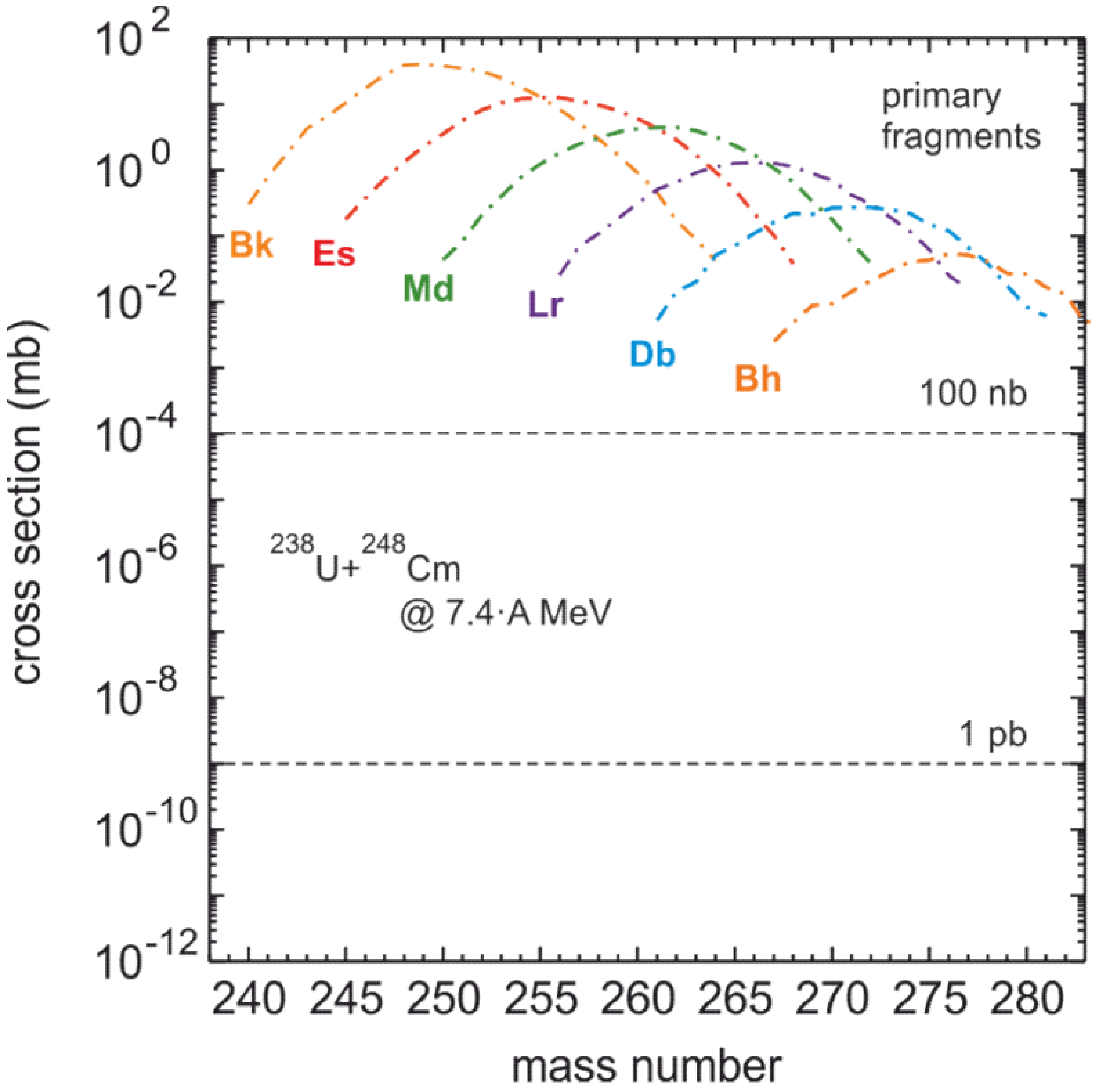
Orientation effects

$^{160}Gd + ^{186}W$

exp: E.M. Kozulin, et al. (2017)

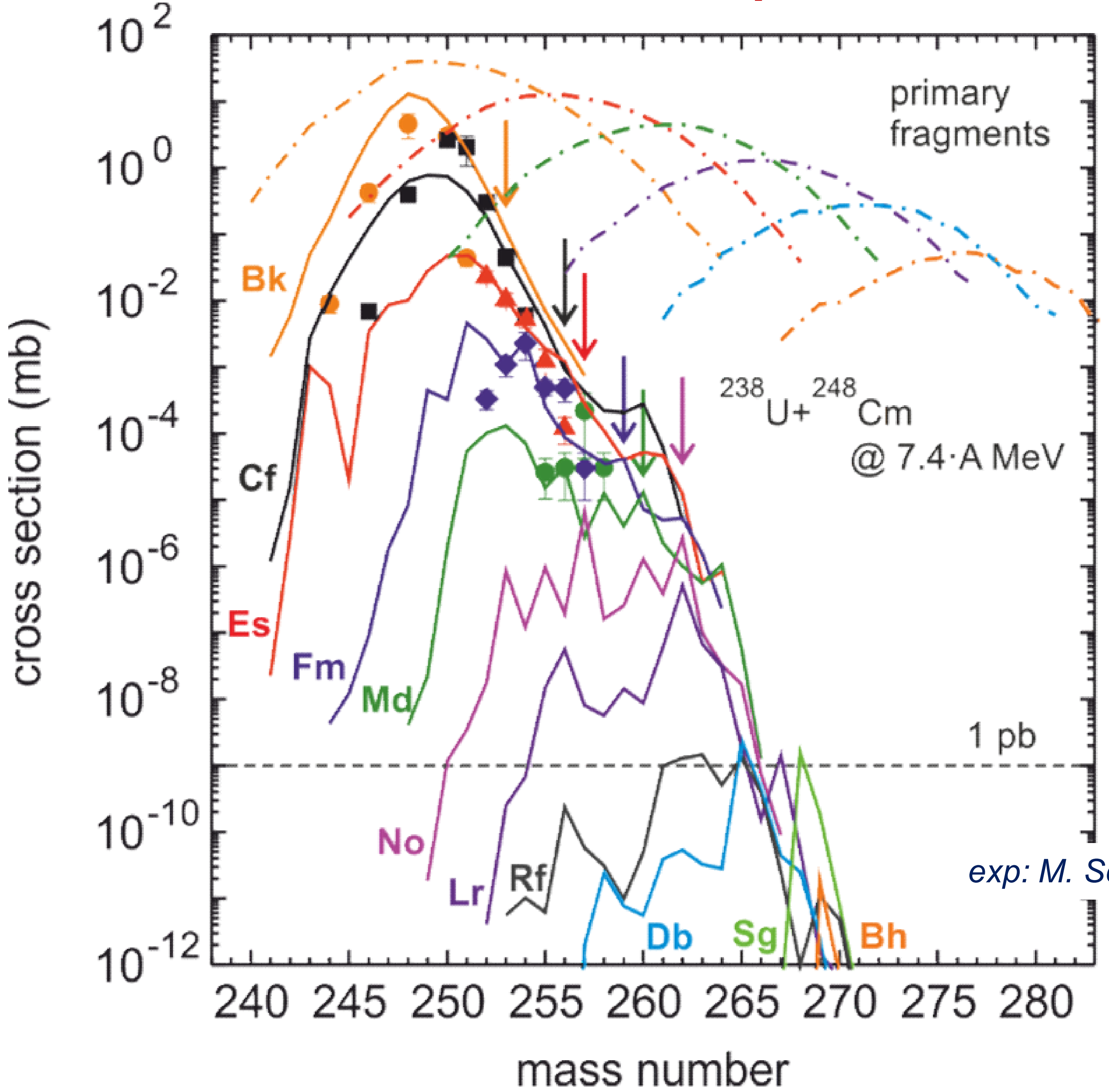


Collisions of actinides. A way to superheavies?



- large production cross sections for primary reaction products
- $^{298}114^*$ (double magic) can be produced with the cross section ~10-100 nb

Collisions of actinides. Comparison with existing data: U+Cm



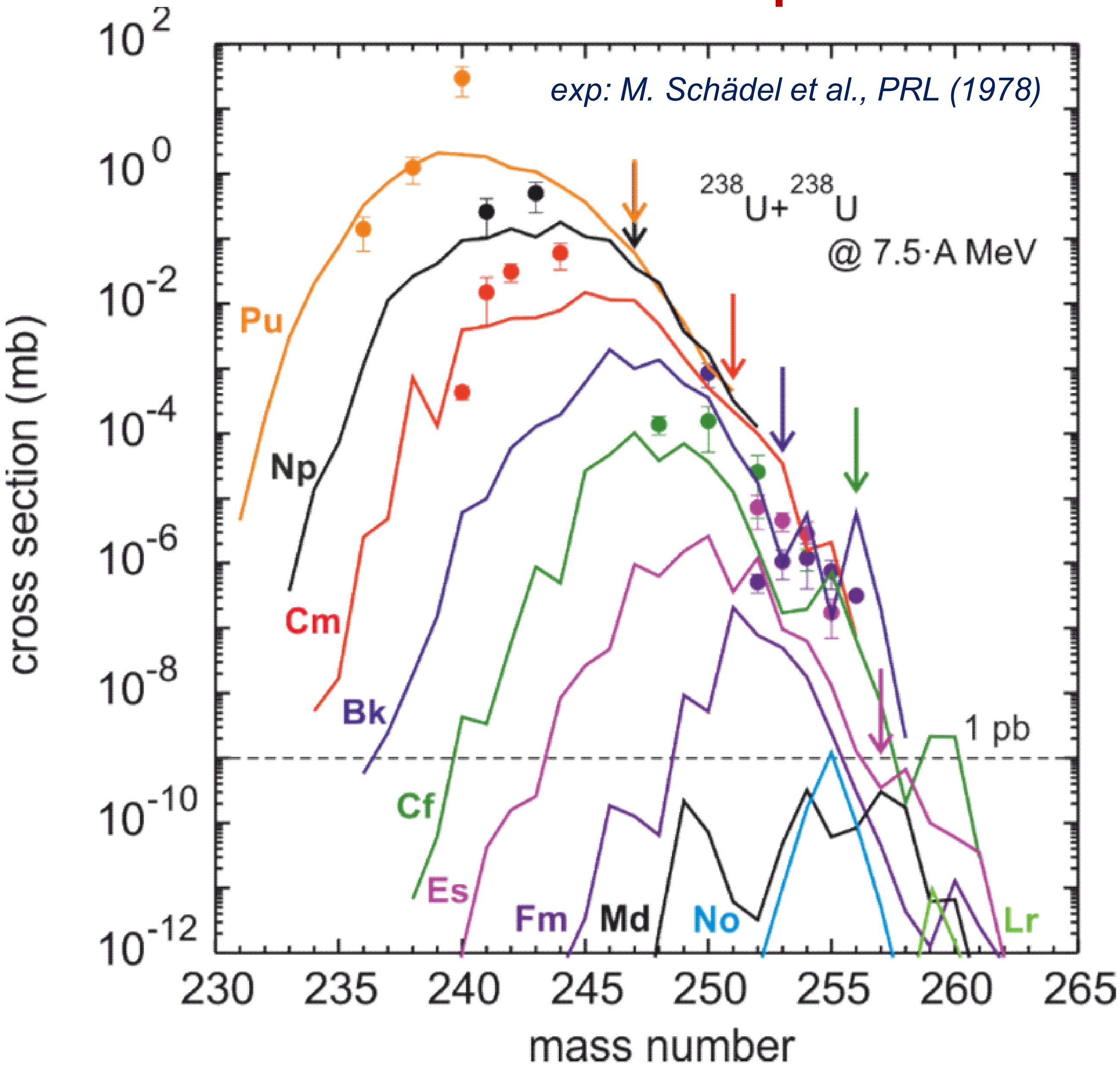
- cross sections for Z>103 are below 1 pb

but…

- new isotopes of elements with Z<103 can be produced with sufficiently large cross sections

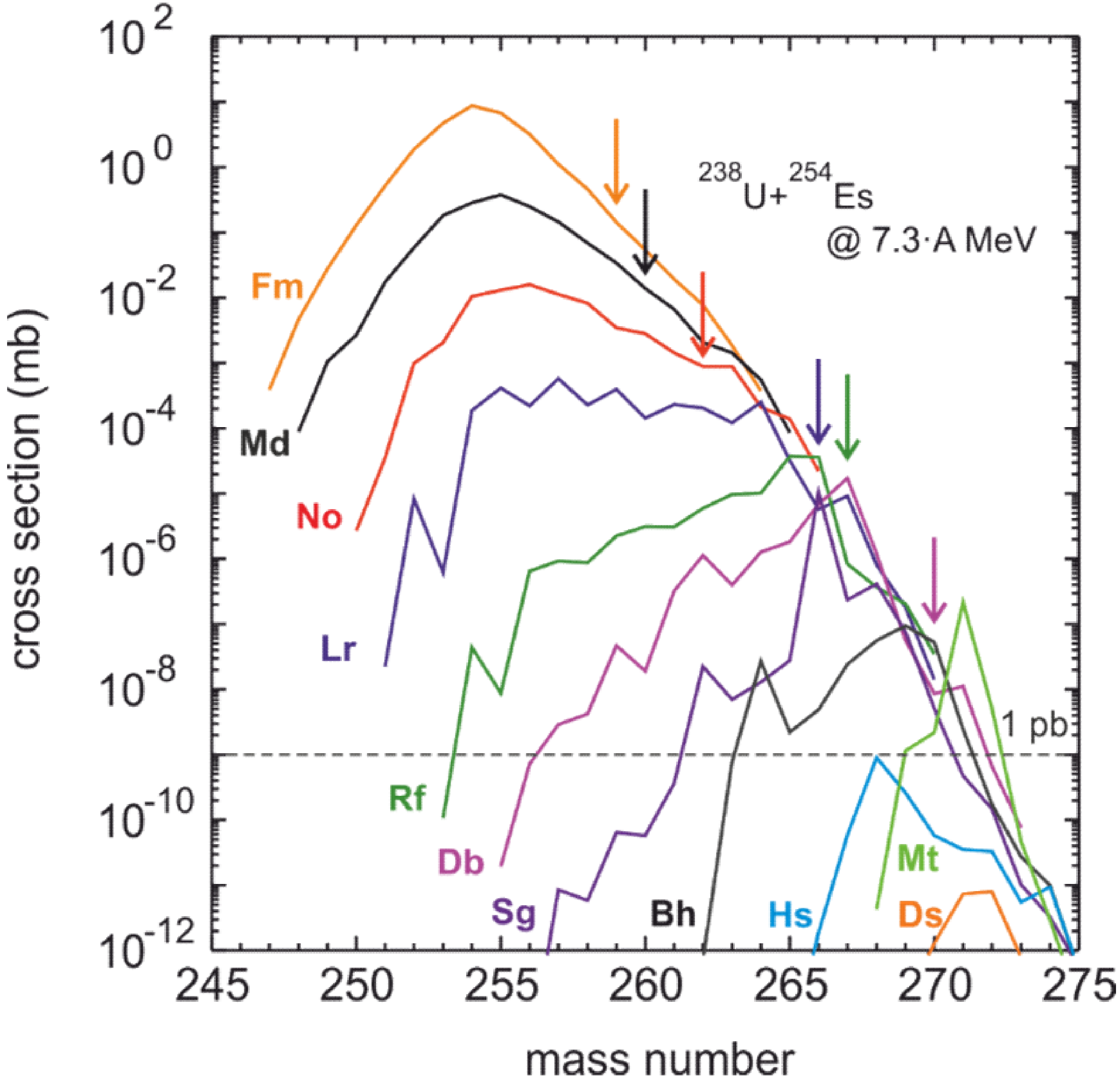
exp: M. Schädel et al., PRL (1982)

Collisions of actinides. Comparison with existing data: U+U



- cross sections for heavy products are lower than in the U+Cm case
- no significant influence of shell effects (parabola-like shapes)
- one should use the heaviest available target (^{254}Es)

Collisions of actinides: U+Es



- SH nuclei up to isotopes of Mt can be produced with cross sections larger than 1pb
- pronounced influence of shell effects on the production cross sections

Conclusions and Outlook

Co-author: ***Vyacheslav Saiko***

- PRODUCTION OF NEUTRON-RICH HEAVY NUCLEI (N=126)

Large cross sections (>100 nb) for yet-unknown nuclei. Weak energy dependence of the production cross sections of neutron-rich nuclei, but strong sensitivity of the angular distributions to the collision energy. (collisions of spherical nuclei)

A.V. Karpov and V.V. Saiko, Phys. Rev. C 96, 024618 (2017)

- ORIENTATION EFFECTS IN NUCLEUS-NUCLEUS COLLISIONS

Strong influence on the production cross sections as well as on the angular and energy distributions.

- PRODUCTION OF SH NUCLEI IN COLLISIONS OF ACTINIDES

Production cross sections drop down very quickly with increasing nucleon transfer due to small survival probabilities. One should use the heaviest available target (^{254}Es) to increase the production cross section of heaviest nuclei. Strong shell effects may give a real chance to produce new isotopes of heavy actinides.

In spite of a long history of studies of heavy-ion nucleus-nucleus collisions, systematic high-quality experiments are of great demand.