第三届"粤港澳"核物理会议

多核子转移反应角分布的研究

广东·深圳

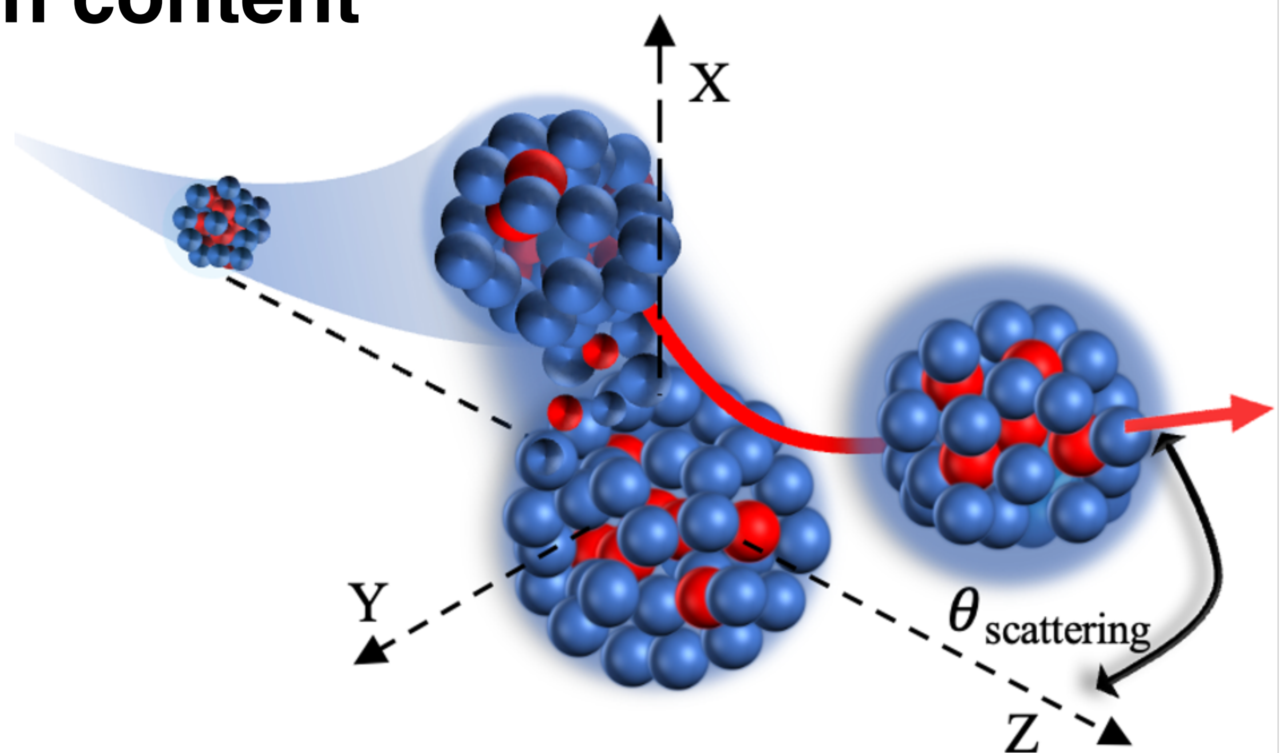
报告人： 廖泽鸿

导师 ： 祝龙

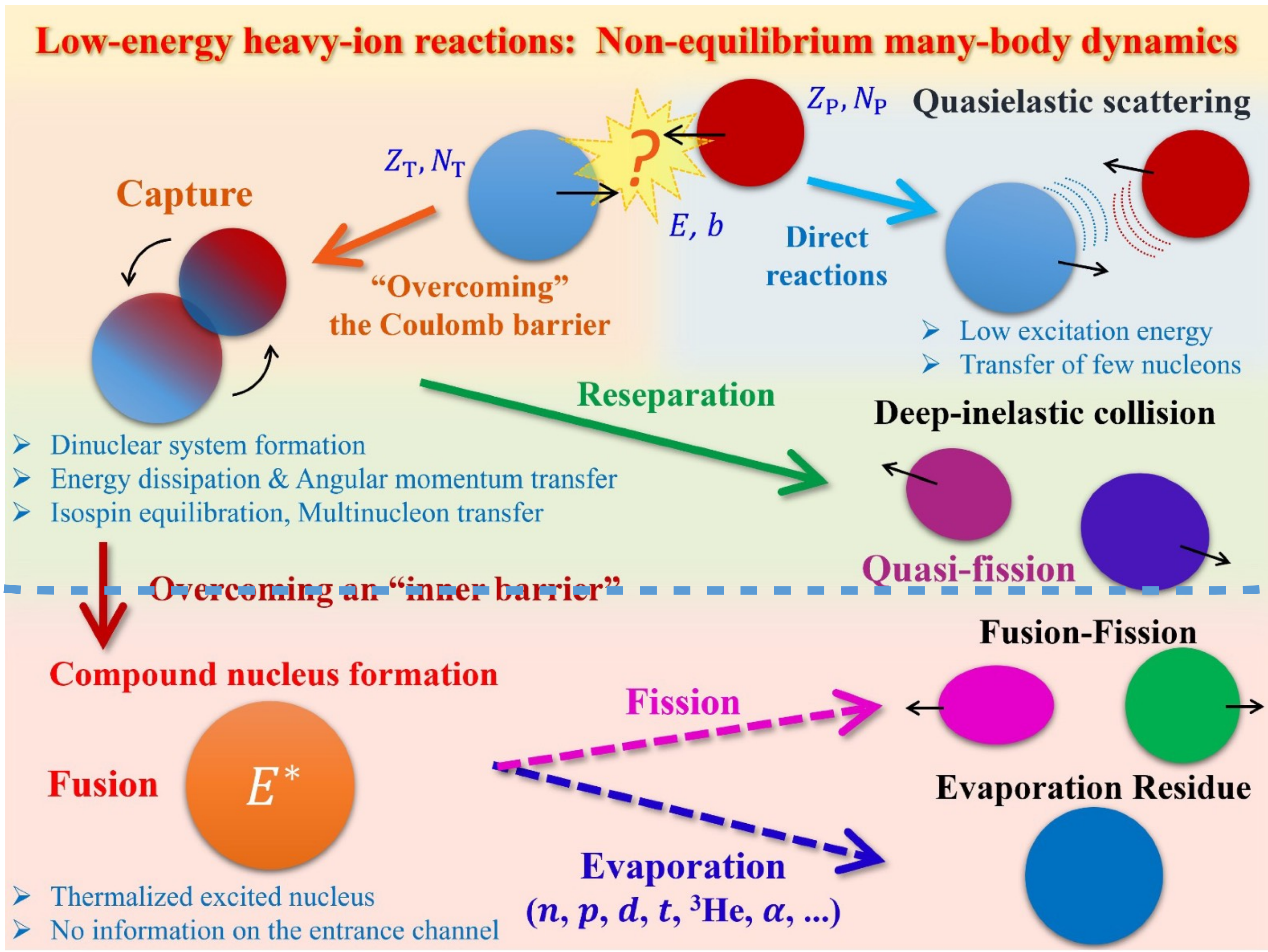
Sino-French Institute of Nuclear Engineering and Technology

Content

- **Background**
  - **Multinucleon transfer reaction (MNT)**
- **Methodology and research content**
  - **Dinuclear system model**
  - **MNT angular distribution**
- **Summary**



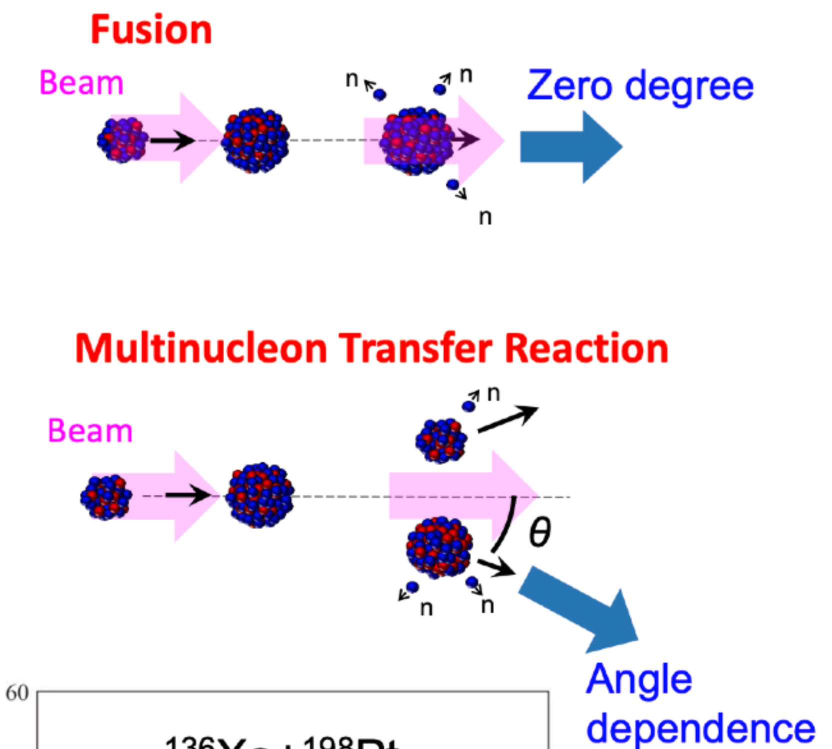
MNT · Low-energy heavy-ion reaction

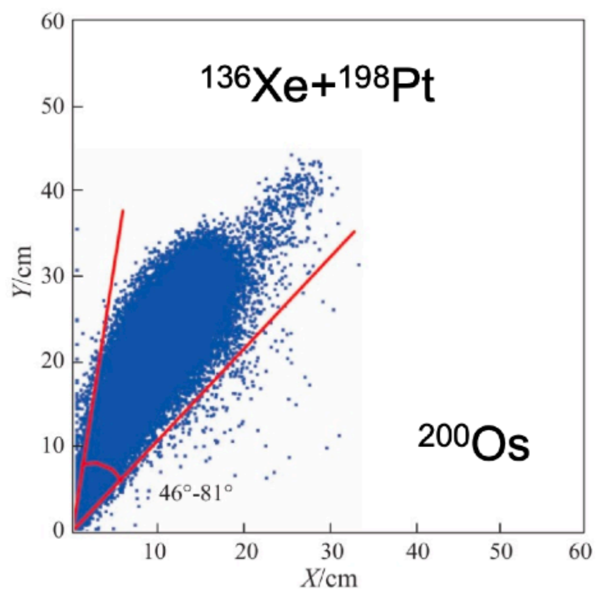


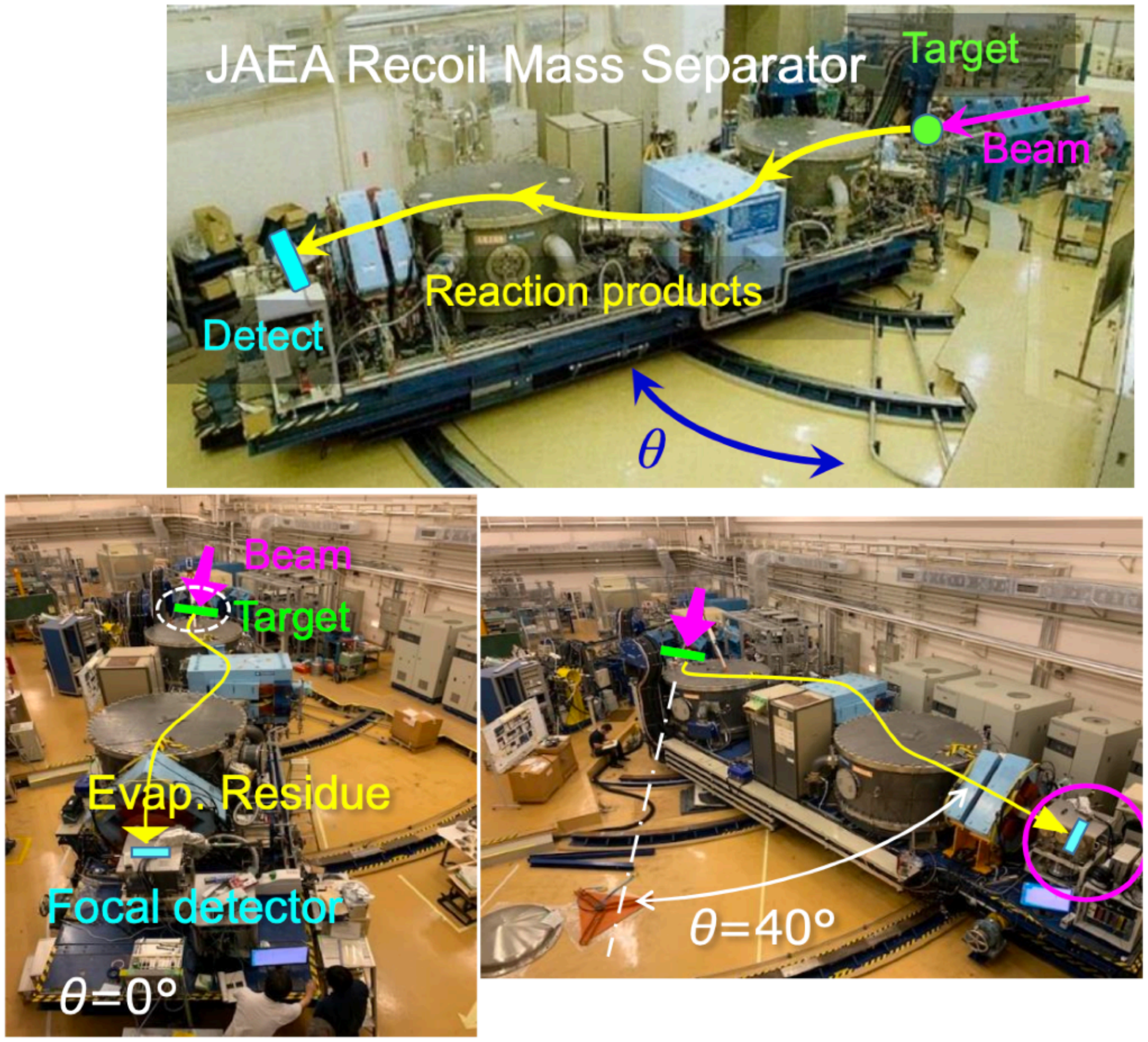
Complex quantum non-equilibrium evolution process with multiple reaction mechanisms and wide time scale

Sekizawa's talk

MNT ·Angular Distribution







Wenxue Huang et al. Nucl. Phys. Rev. (2017)

H. Ikezoe et al., Nucl. Instrum. Meth. A 376, 420 (1996).

- The emission of MNT reaction products in the laboratory system is not in the forward direction near 0°, but covers a wide range of cone angles.

- This brings great difficulties to the collection and separation of the Multinucleon transfer reaction products that we are interested in, and requires theoretical support.

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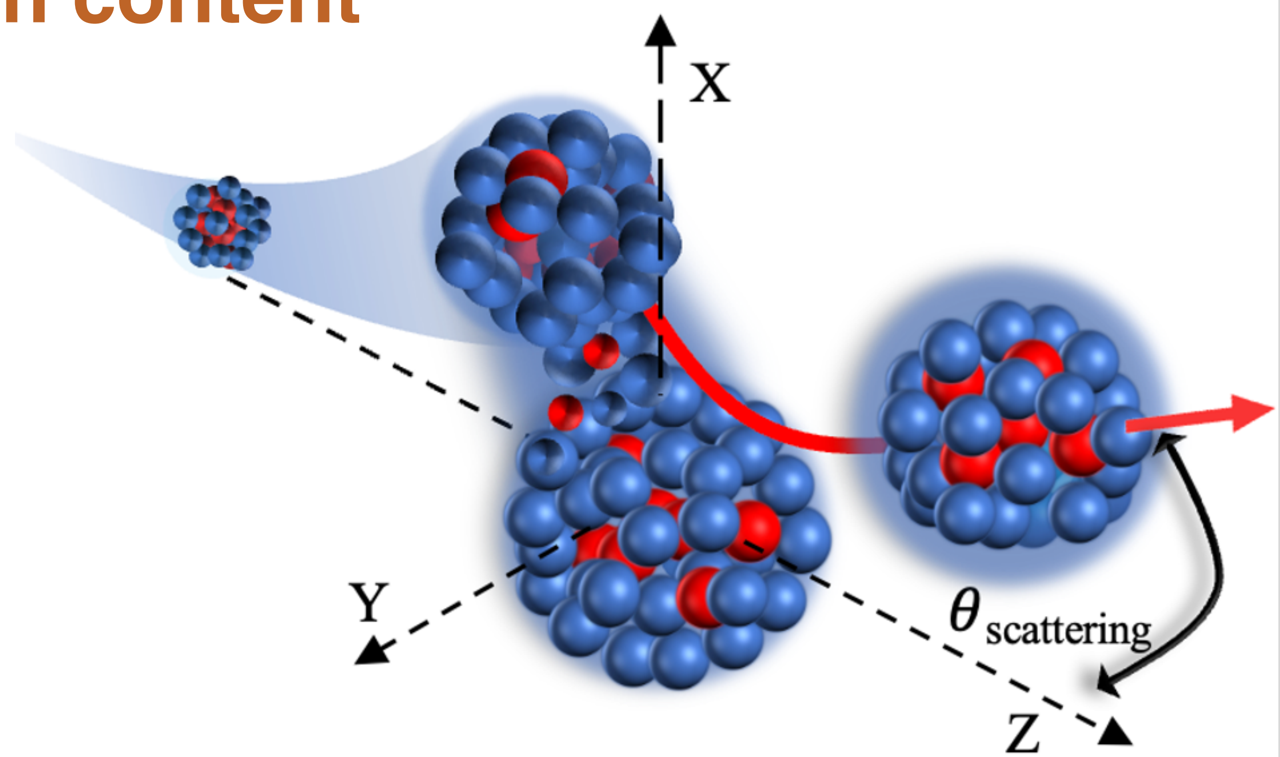
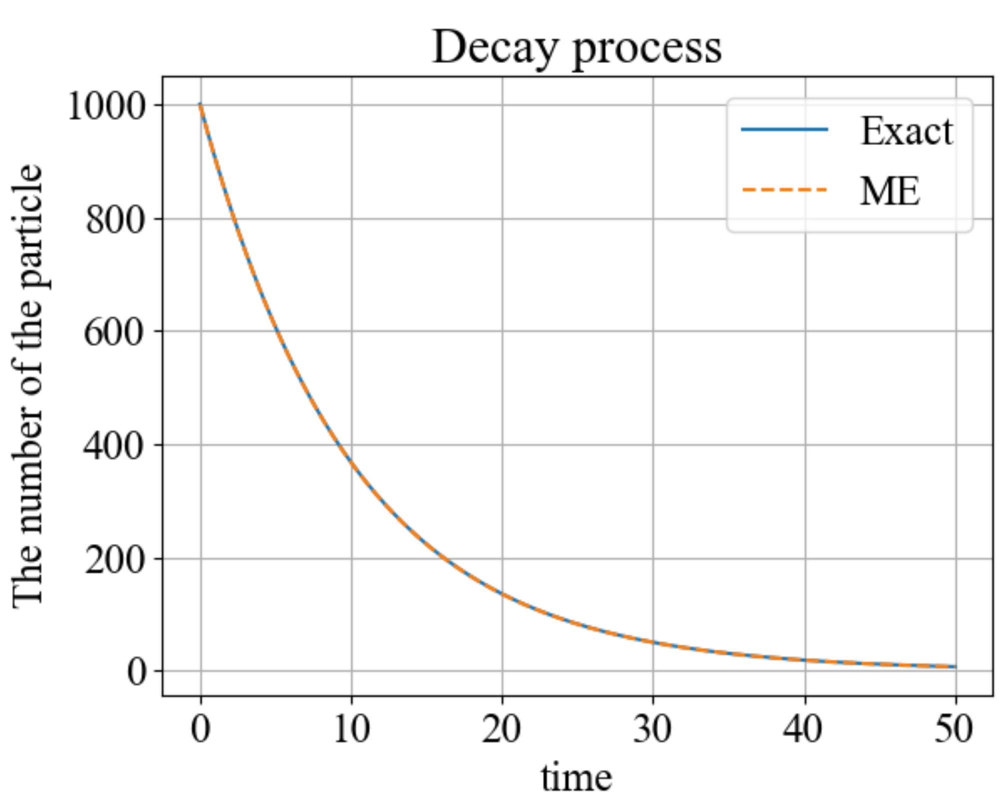


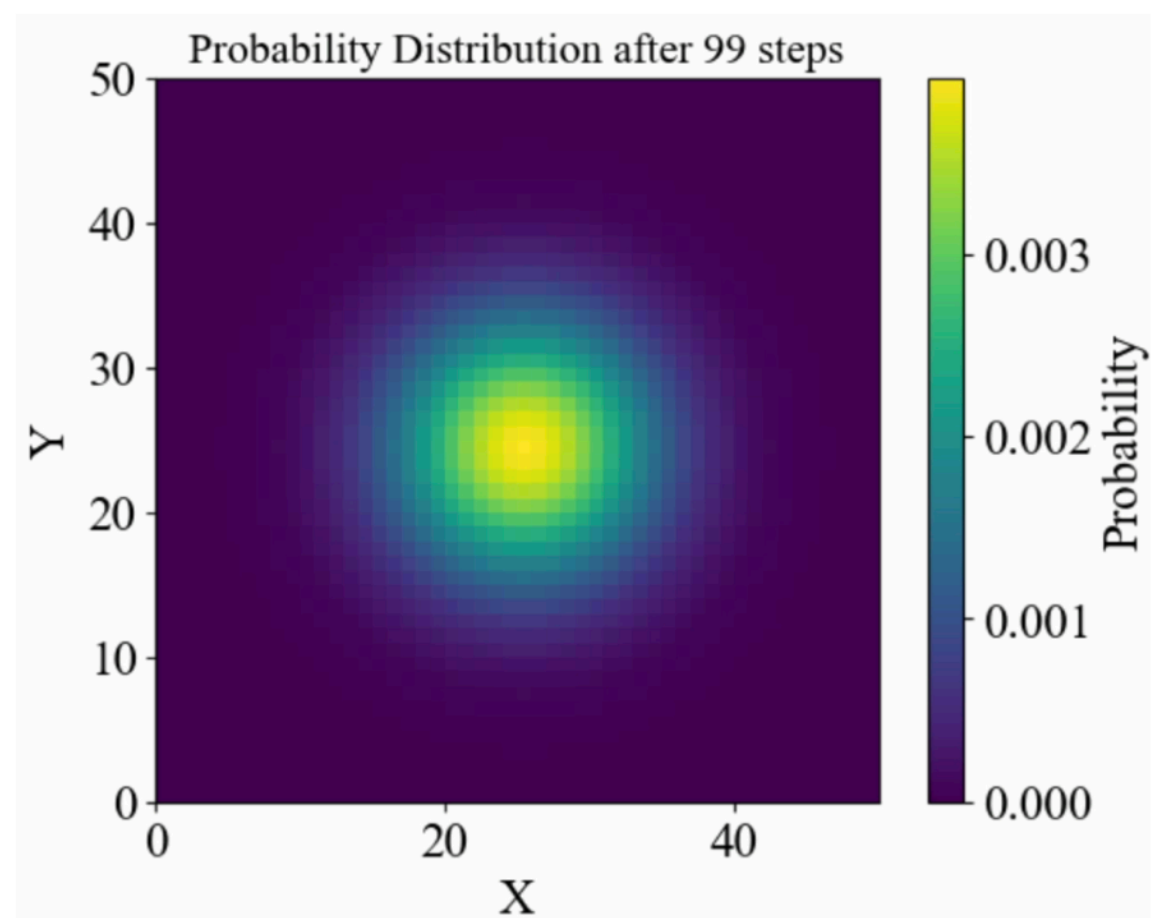
Master equation

A master equation is a phenomenological set of first-order differential equations describing the time evolution of (usually) the probability of a system to occupy each one of a discrete set of states with regard to a continuous time variable t.

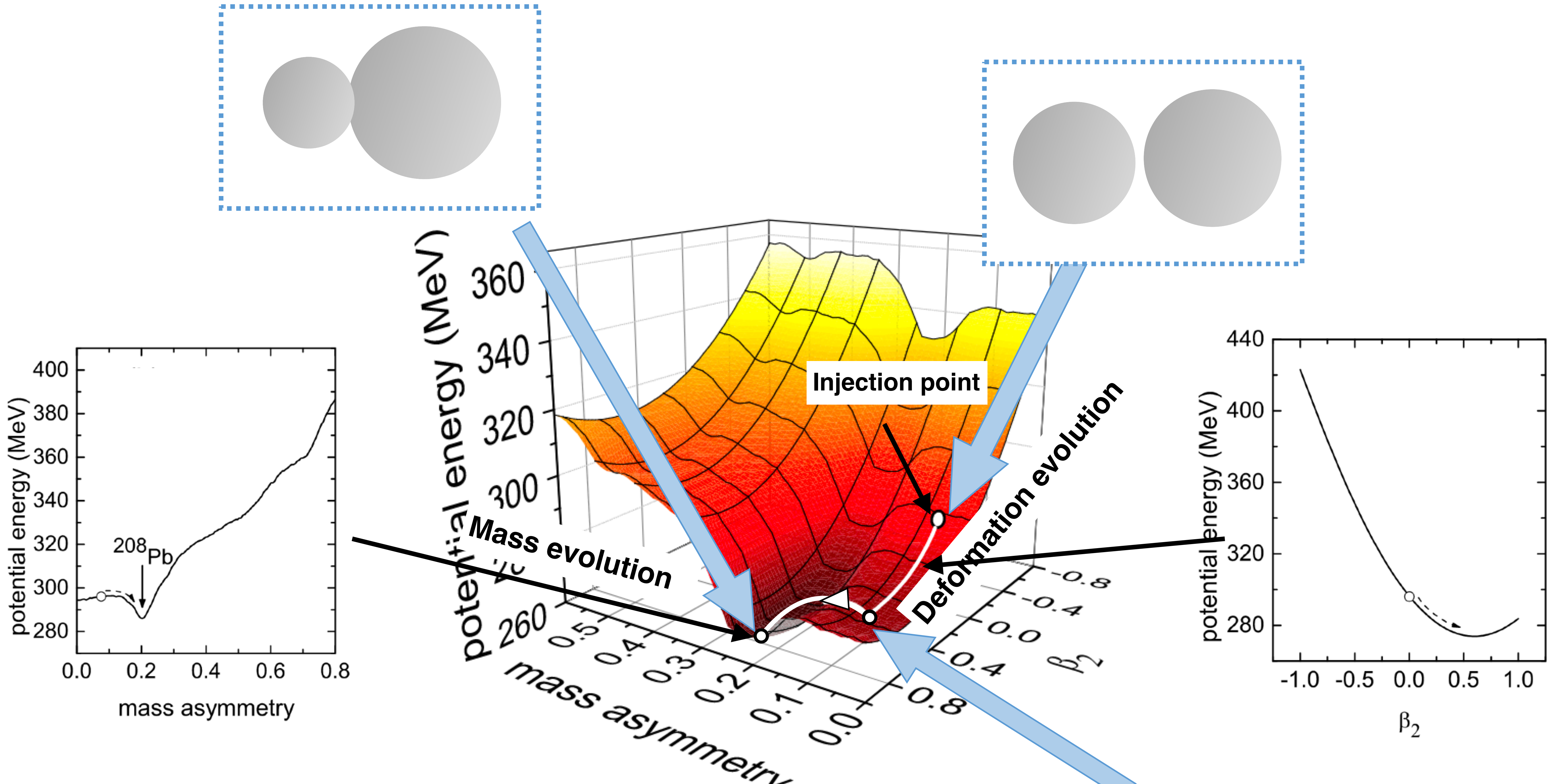
$$dP_N(t)/dt = \sum_M w_{MN}(t)\{NP_M(t) - MP_N(t)\}$$

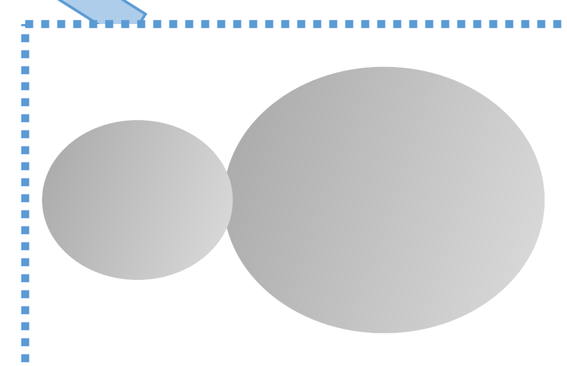
Many physical problems in classical, quantum mechanics and problems in other sciences, can be reduced to the form of a master equation, thereby performing a great simplification of the problem





Potential energy Surface (PES)





PES:

$$U = \Delta(Z_1, N_1) + \Delta(Z_2, N_2) + V(Z_1, N_1, \beta_2, J, r = R_{\text{cont}}) + \frac{1}{2}C_1\left(\delta\beta_2^1\right)^2 + \frac{1}{2}C_2\left(\delta\beta_2^2\right)^2.$$

Mass excess **Effective interaction** **Deformation energy**

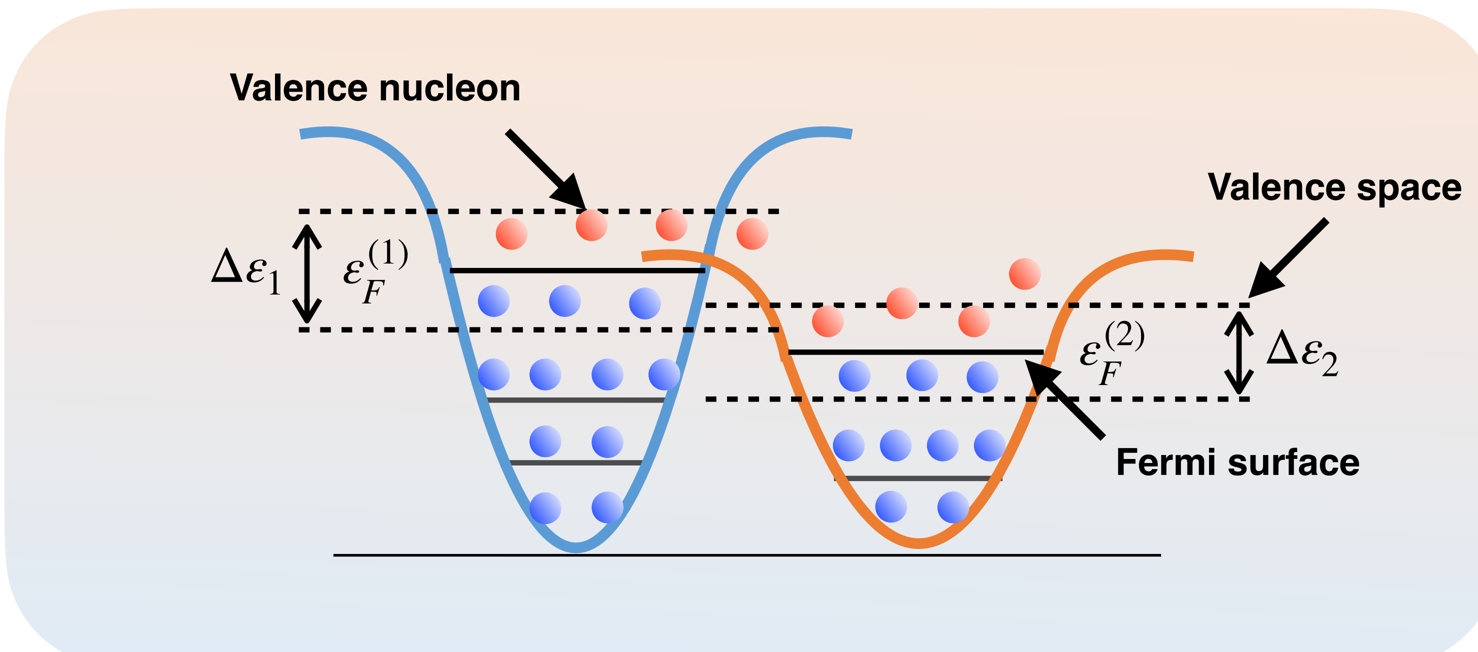
Long Zhu, Phys Lett B, 2021. 816: 136226. PhysRevC.98.034609

Master equation

Master Equation:

$$dP_N(t)/dt = \sum_M w_{MN}(t)\{NP_M(t) - MP_N(t)\}$$

- N : the number of channels.
- $P_N(t)$: the sum over all occupation probabilities of the channels in the subset $\{N\}$.
- $w_{MN}(t)$: the mean transition probability from a channel $n \in \{N\}$ to a channel $m \in \{M\}$.



Valence nucleon:

$$\Delta\varepsilon_K = \sqrt{\frac{4\varepsilon_K^*}{g_K}}, \quad \varepsilon_K^* = \varepsilon^* \frac{A_K}{A}, \quad g_K = \frac{A_K}{12},$$

- ε_K^* means the local excitation energy.
- g_K denotes single nucleon energy density.

Nucleon transfer probability:

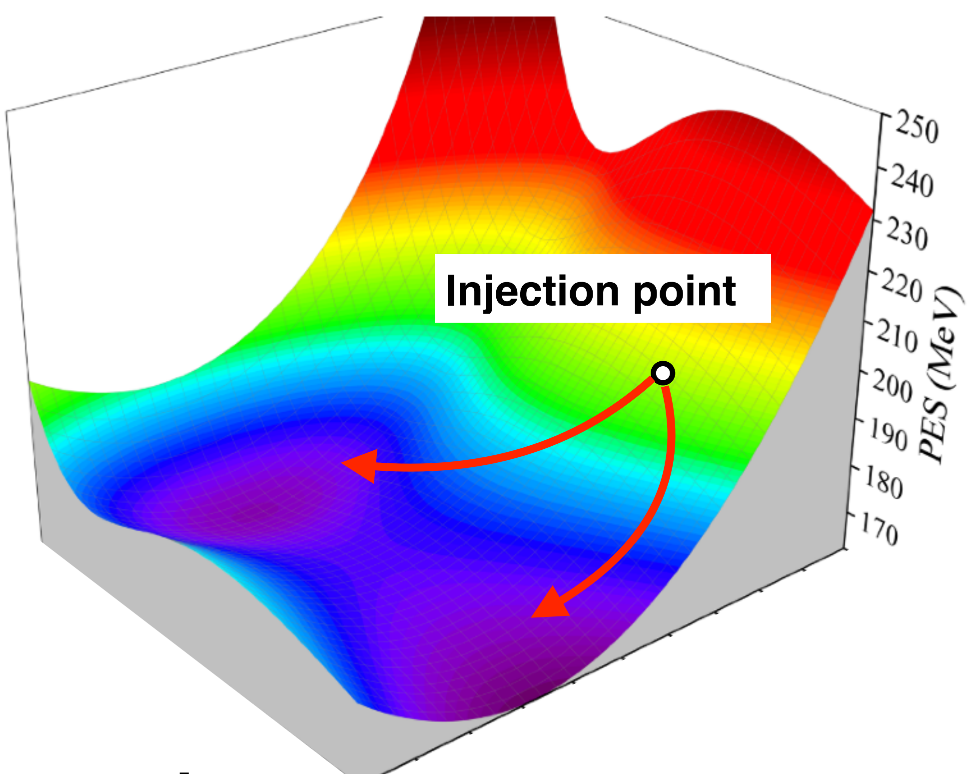
$$W_{A_1,A_1'}(t) = \frac{\tau_{mem}\left(A_1, E_1, A_1', E_1'; t\right)}{\hbar^2 d_{A_1} d_{A_1'}} \sum_{ii'} \left| \left\langle A_1', E_1', i' \,|\, V(t) \,|\, A_1, E_1, i \right\rangle \right|^2$$

W. Li et al 2003 EPL 64 750

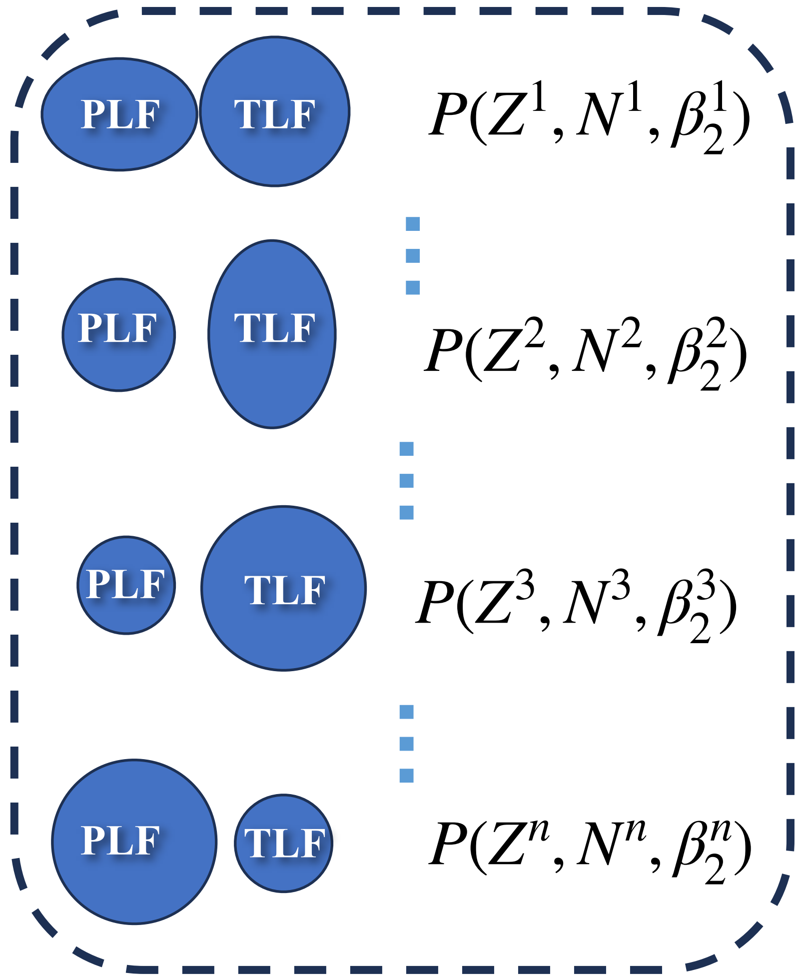
Dinuclear System model (DNS)

MNT nucleon transfer process

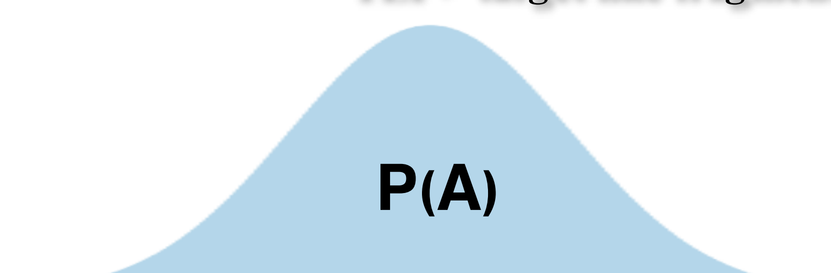
$$\frac{dP(Z_1,N_1,\beta_2,J,t)}{dt} = \sum_{Z_1'} W_{Z_1,N_1,\beta_2;Z_1',N_1,\beta_2}(t)\big[d_{Z_1,N_1,\beta_2}P(Z_1',N_1,\beta_2,J,t) - d_{Z_1',N_1,\beta_2}P(Z_1,N_1,\beta_2,J,t)\big] + \sum_{N_1'} W_{Z_1,N_1,\beta_2;Z_1,N_1',\beta_2}(t)\big[d_{Z_1,N_1,\beta_2}P(Z_1,N_1',\beta_2,J,t) - d_{Z_1,N_1',\beta_2}P(Z_1,N_1,\beta_2,J,t)\big] + \sum_{\beta_2'} W_{Z_1,N_1,\beta_2;Z_1,N_1,\beta_2'}(t)\big[d_{Z_1,N_1,\beta_2}P(Z_1,N_1,\beta_2',J,t) - d_{Z_1,N_1,\beta_2'}P(Z_1,N_1,\beta_2,J,t)\big].$$



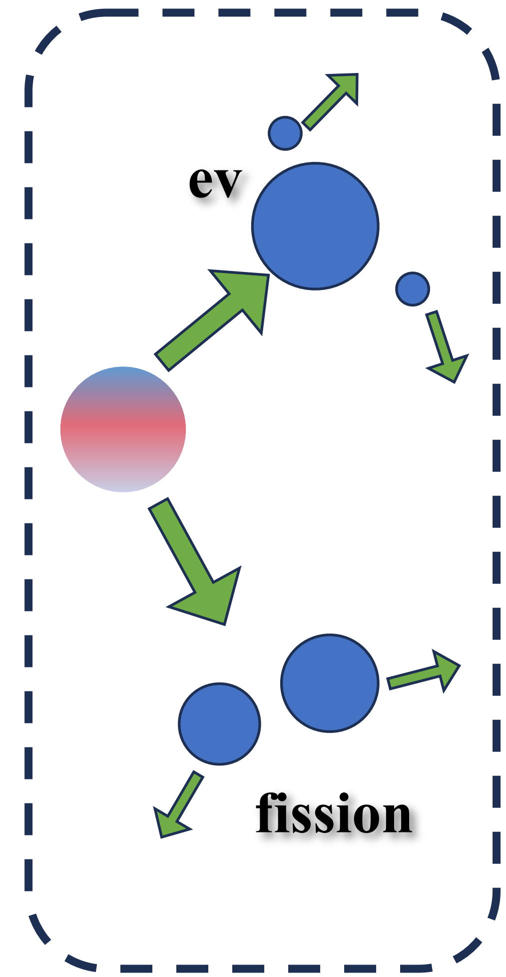
Configuration probability distribution

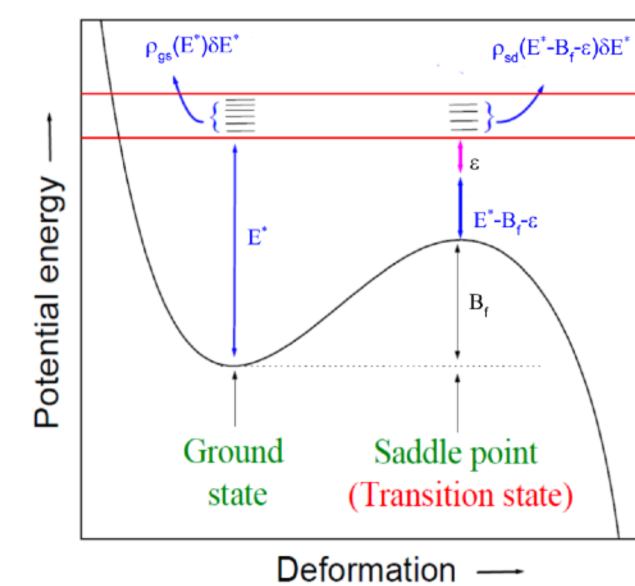


PLF: projectile like fragment
TLF: target like fragment



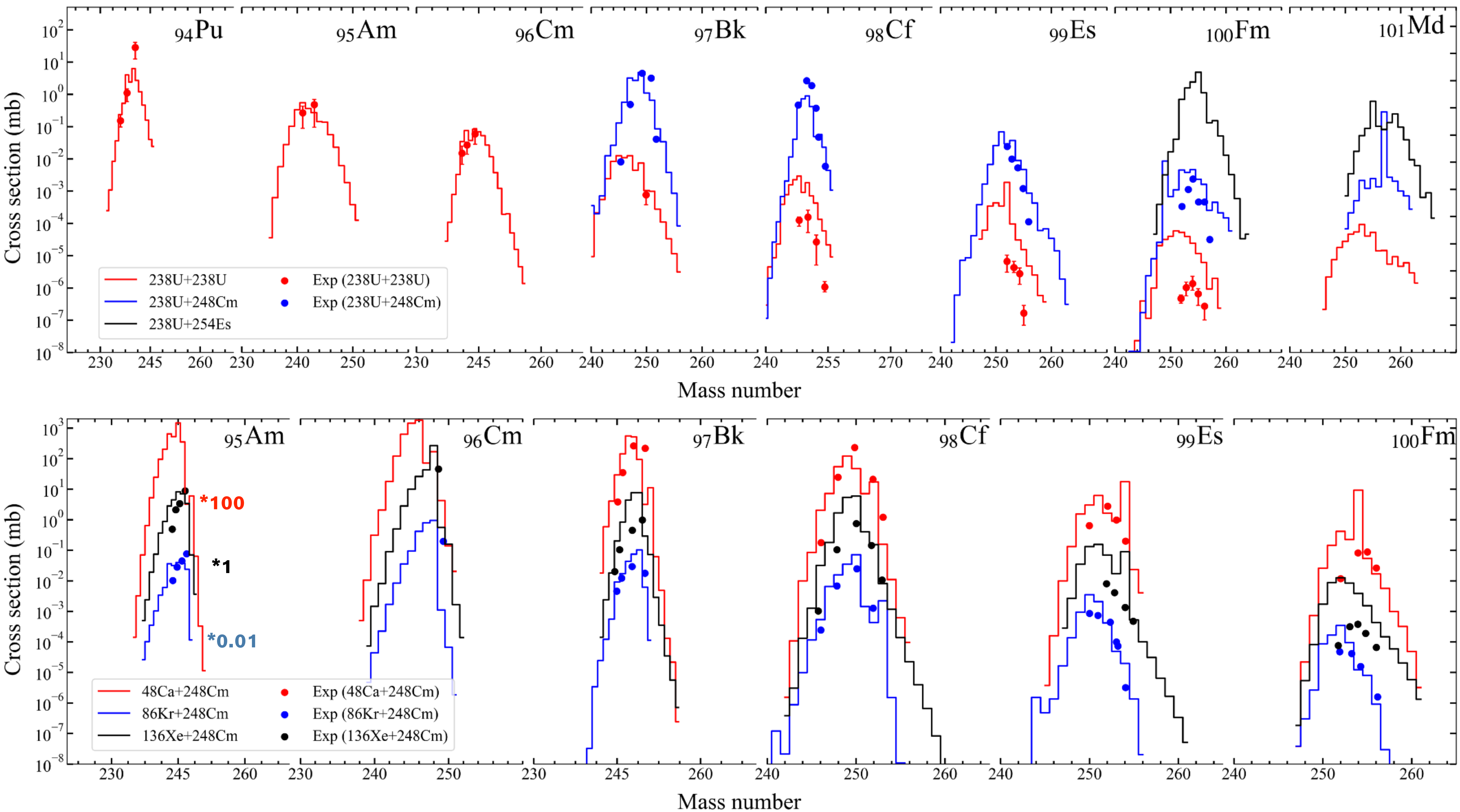
De-excitation Process





time

DNS model & Experiment Data



Ref: Phys. Rev. Lett. 41, 469 (1978).
Phys. Rev. Lett. 48, 852 (1982).
Phys. Rev. C 33, 1315 (1986).
Phys. Rev. C 88, 054615 (2013).
Phys. Rev. C 31, 1763 (1985).

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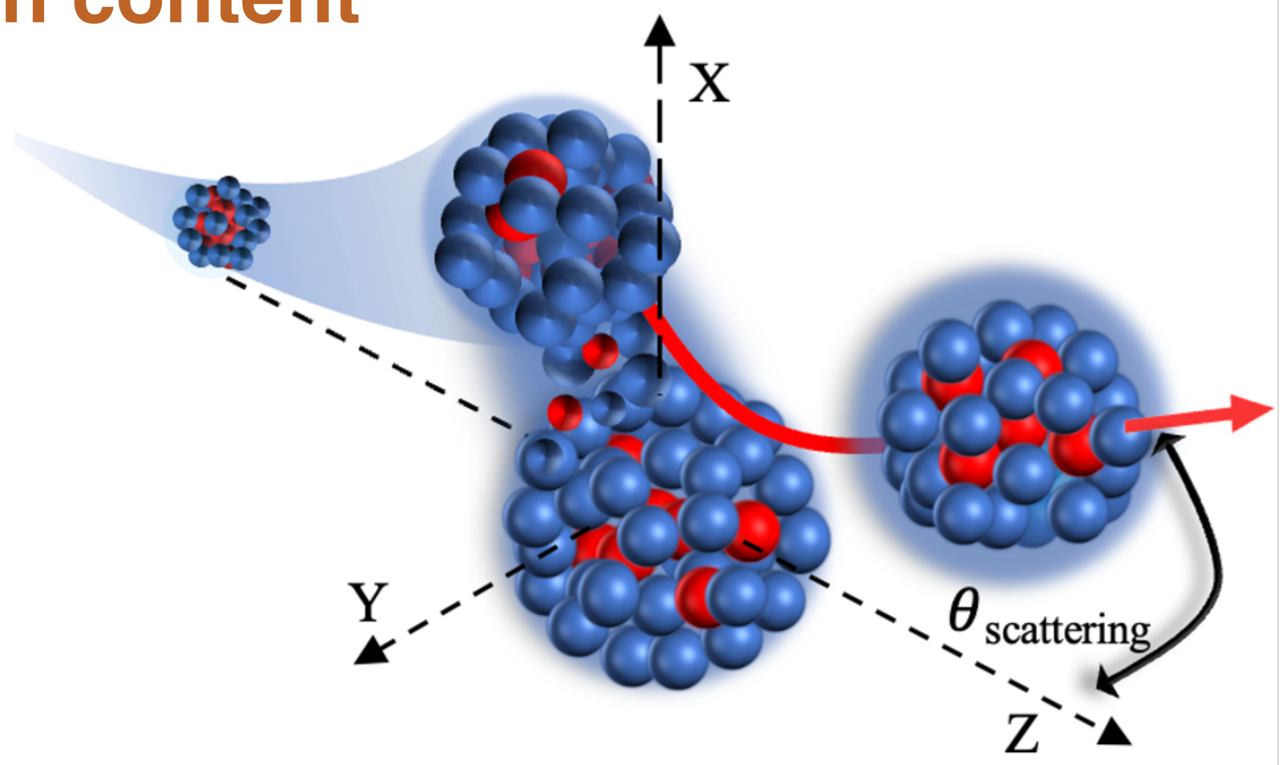
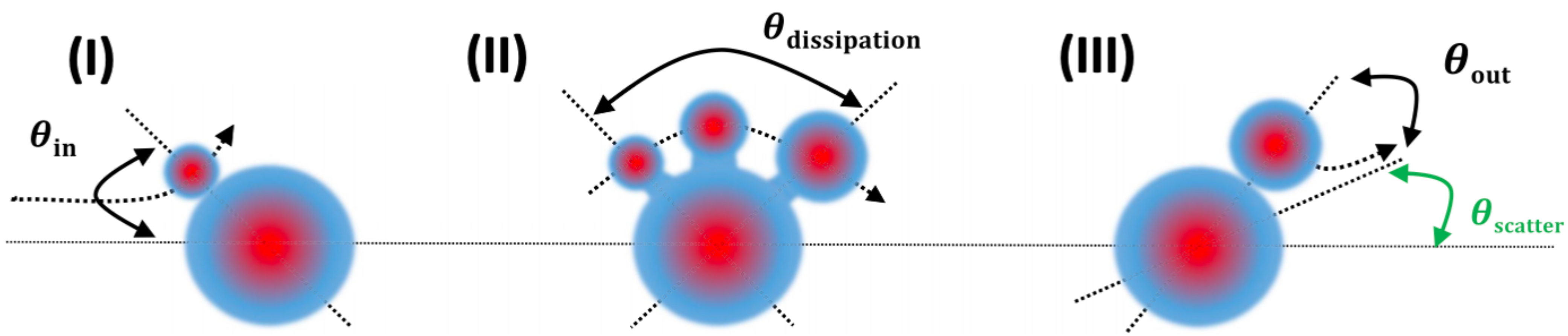


DNS model & scattering angle



◆ *Under the Center of mass frame*

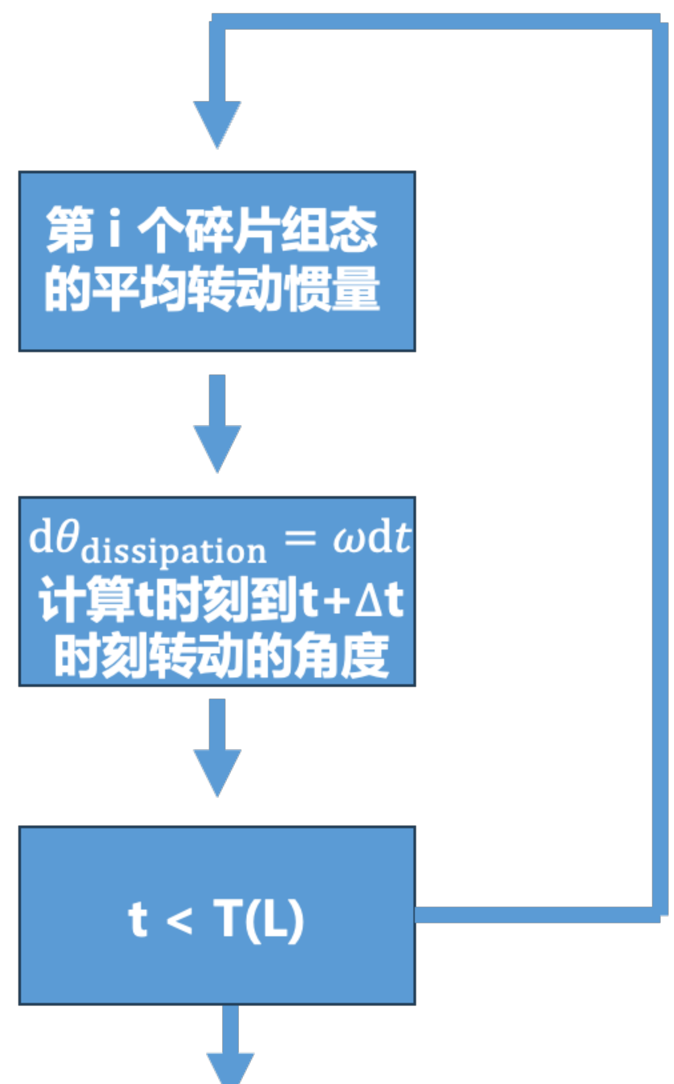
$$\theta_{\text{scatter}} = \pi - \theta_{\text{in}} - \theta_{\text{dissipation}} - \theta_{\text{out}},$$

$\theta_{\text{dissipation}}$ 由反应时间与转动速度决定

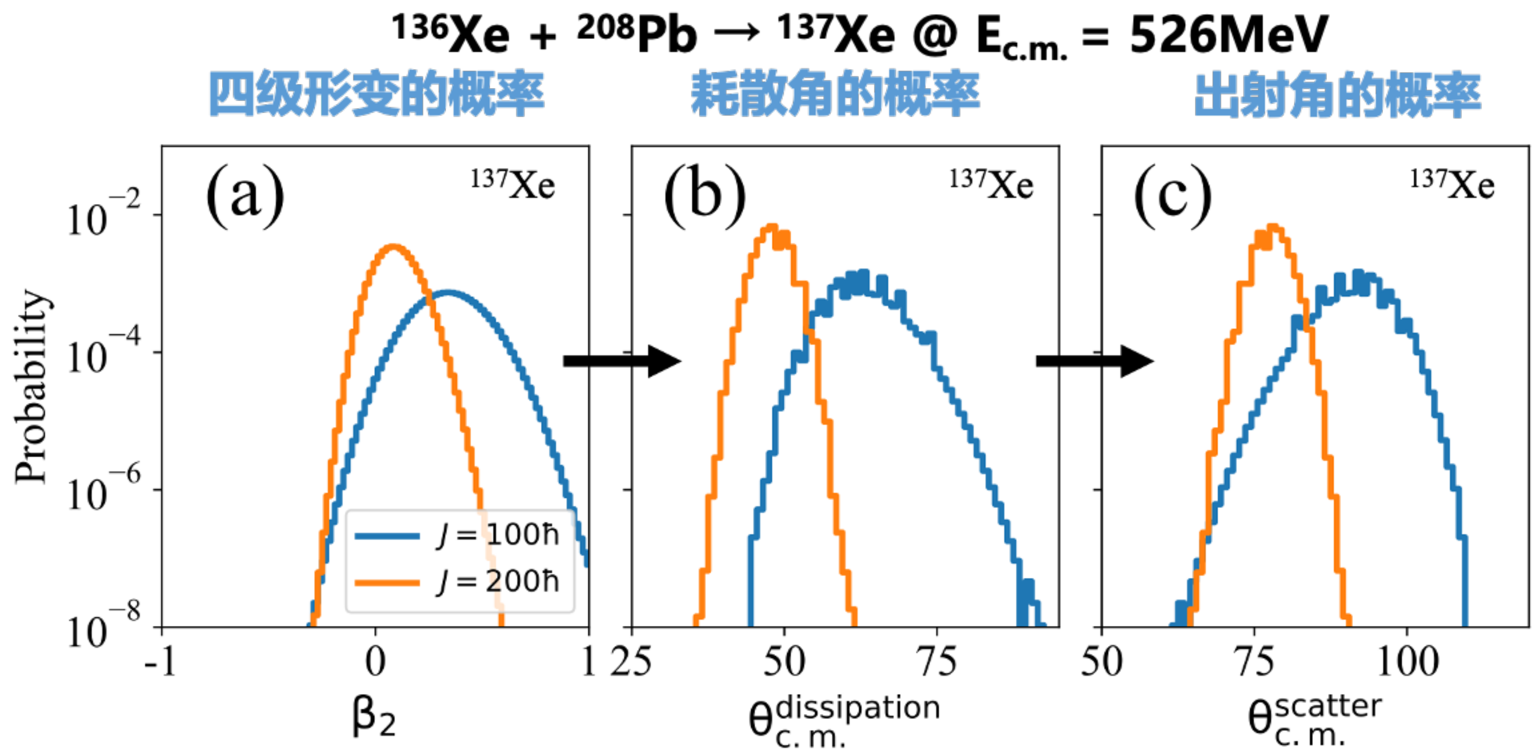
$$\theta_{\text{dissipation}} = \omega_{\text{DNS}} * t_s = \int^{t_s} \frac{J(t)\hbar}{\langle I \rangle} dt.$$

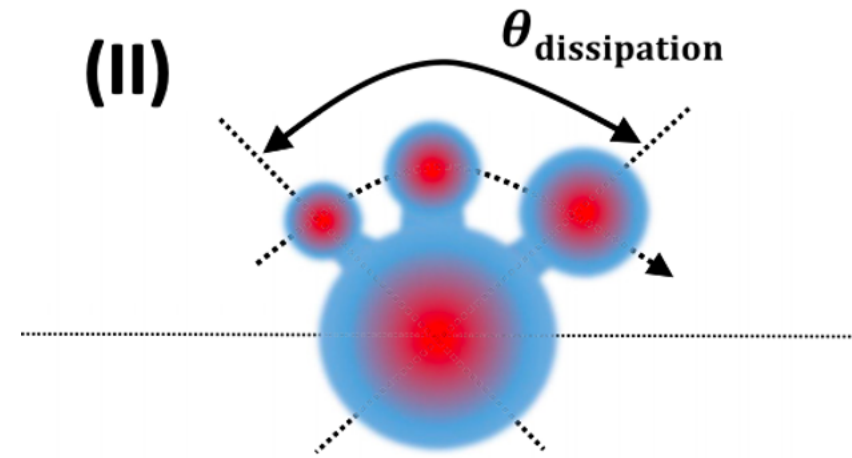
- 考虑角动量耗散的弛豫行为
- 考虑不同碎片组态的刚体转动惯量

PHYSICAL REVIEW RESEARCH 5, L022021 (2023)

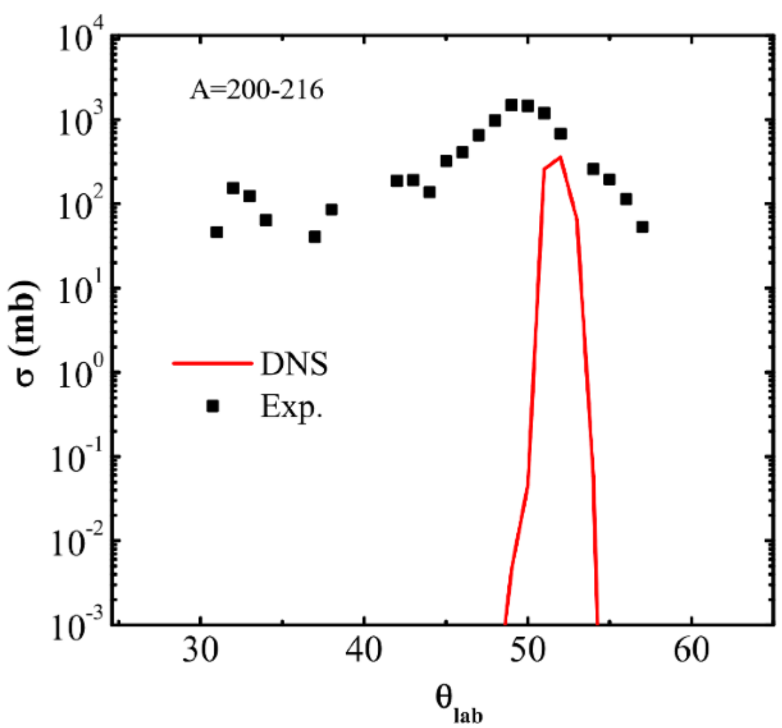


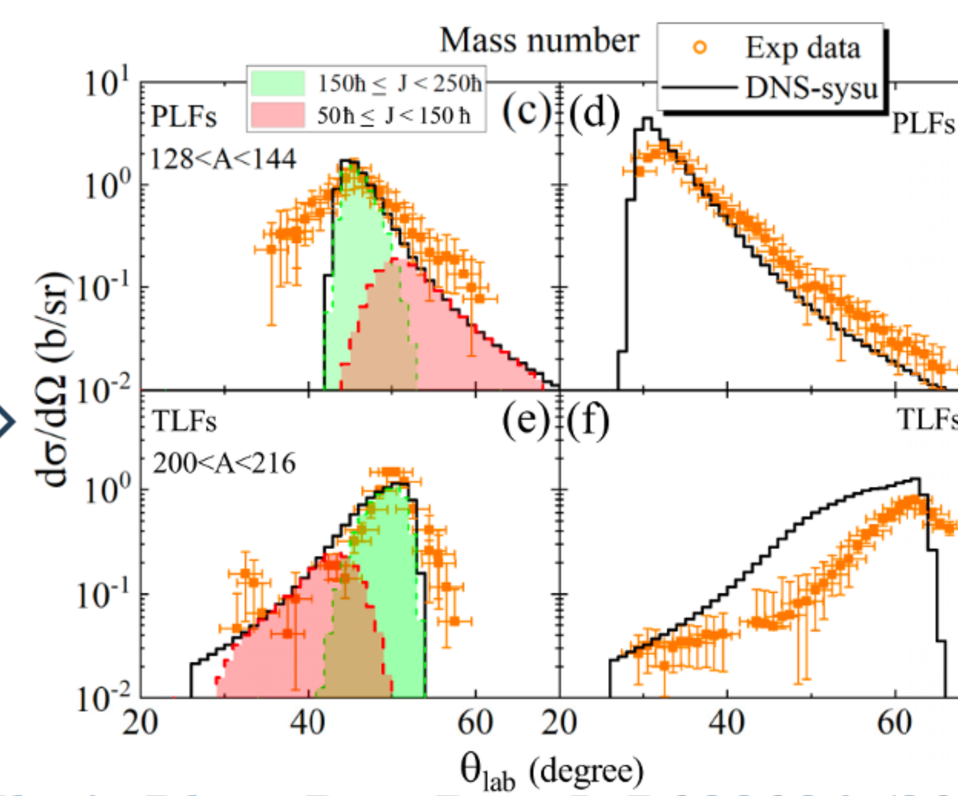
DNS model & scattering angle





■ In the DNS model, the introduction of the degree of freedom evolution of fragment deformation can self-consistently increase the fluctuation of the fragment exit angle.

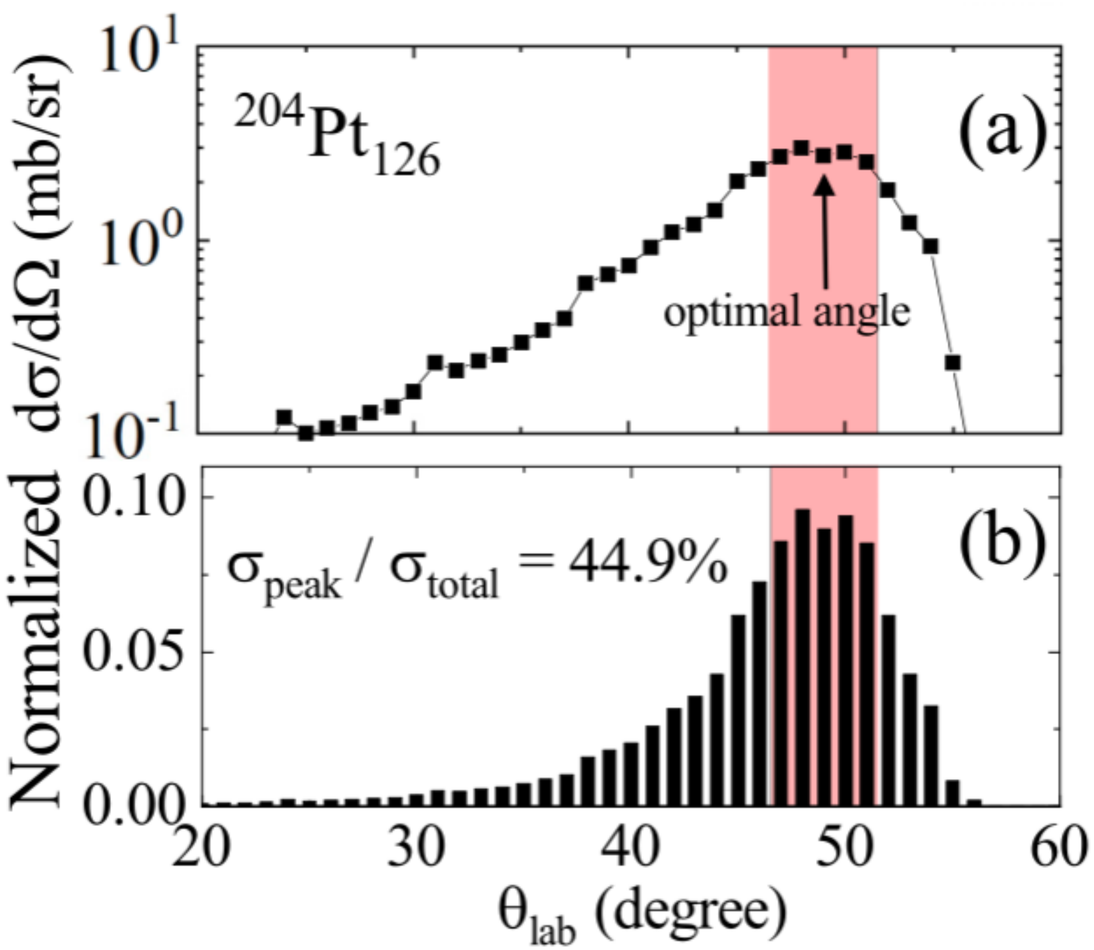


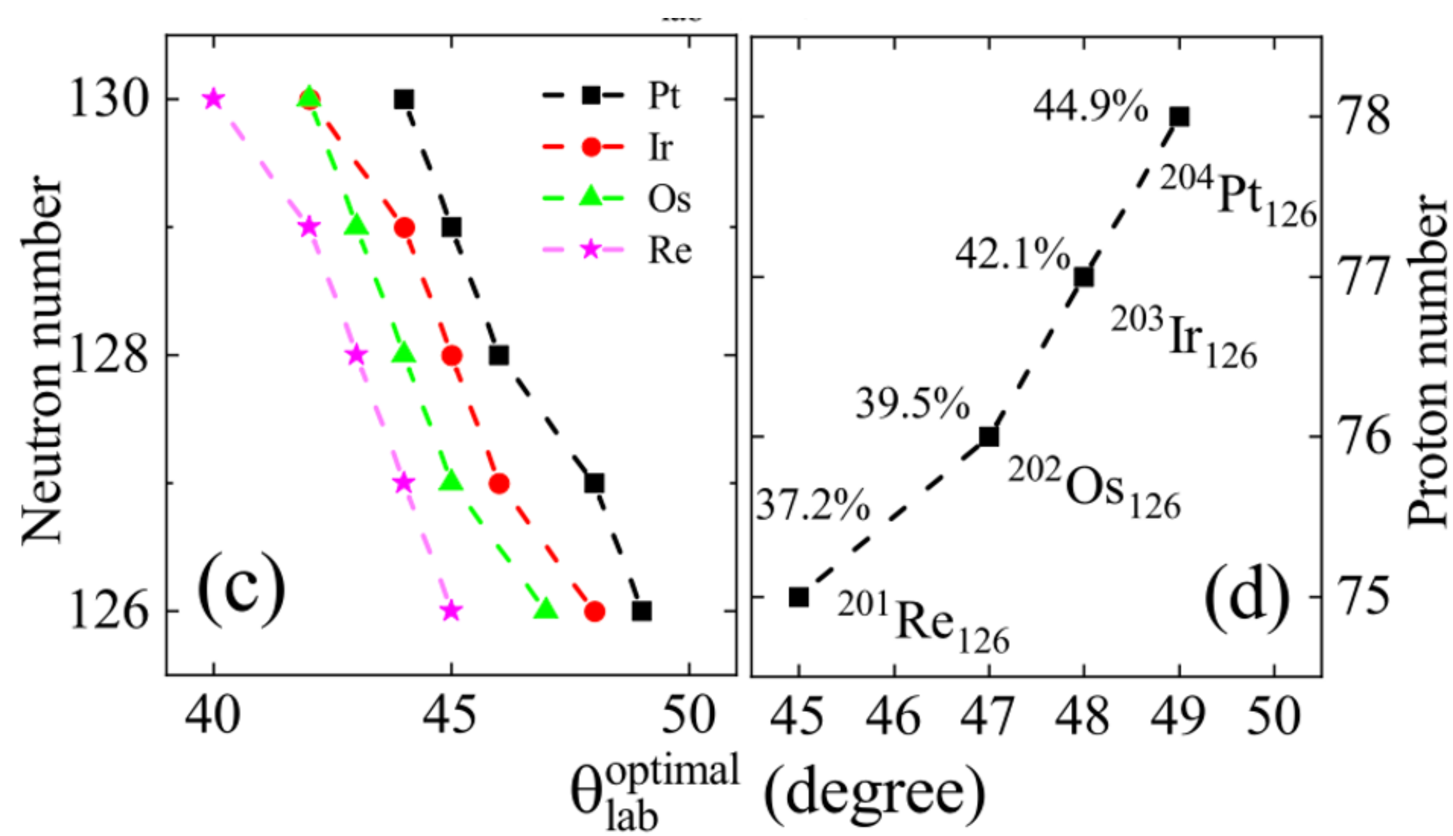


Liao, Zhu, Phys. Rev. Res. 5, L022021 (2023)*

DNS model & scattering angle

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





We found that a yield ratio of 44.9% can be detected within the range of 47°< θ_{lab}<51°. Nearly half of the production can be detected in the optimal angle .

Liao, Zhu, Phys. Rev. Res. 5, L022021 (2023)*

Two-parameter semi-empirical formula

Two-parameter semi-empirical formula：

$$\Theta(l_i) = 2\arctan\frac{Z_p Z_T e^2}{2E_{c.m.}b} - \beta\Theta_C^{gr}\frac{l_i}{l_{gr}}\left(\frac{\delta}{\beta}\right)^{l_i/l_{gr}}$$

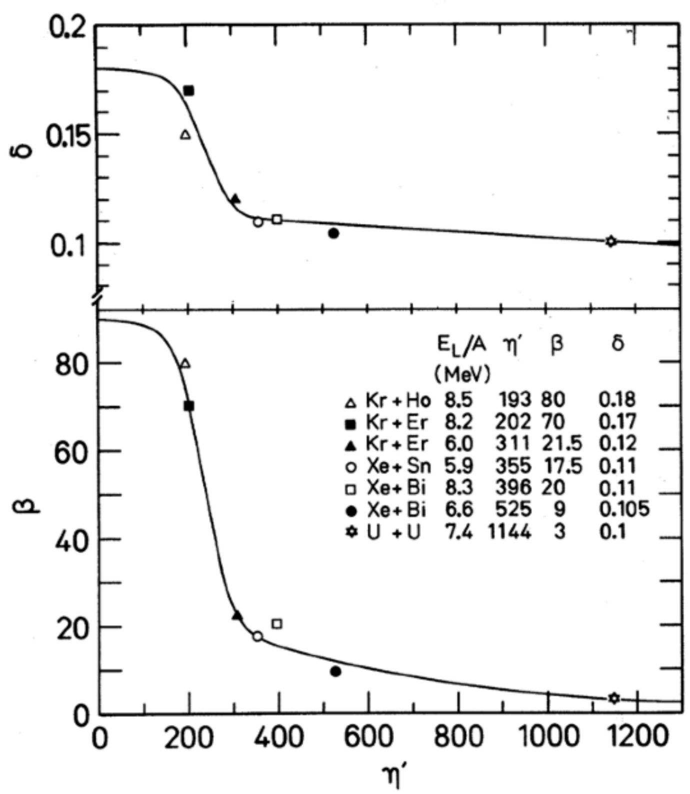
Here, β and δ are fitted through experimental data and are related to the reaction system and reaction energy.

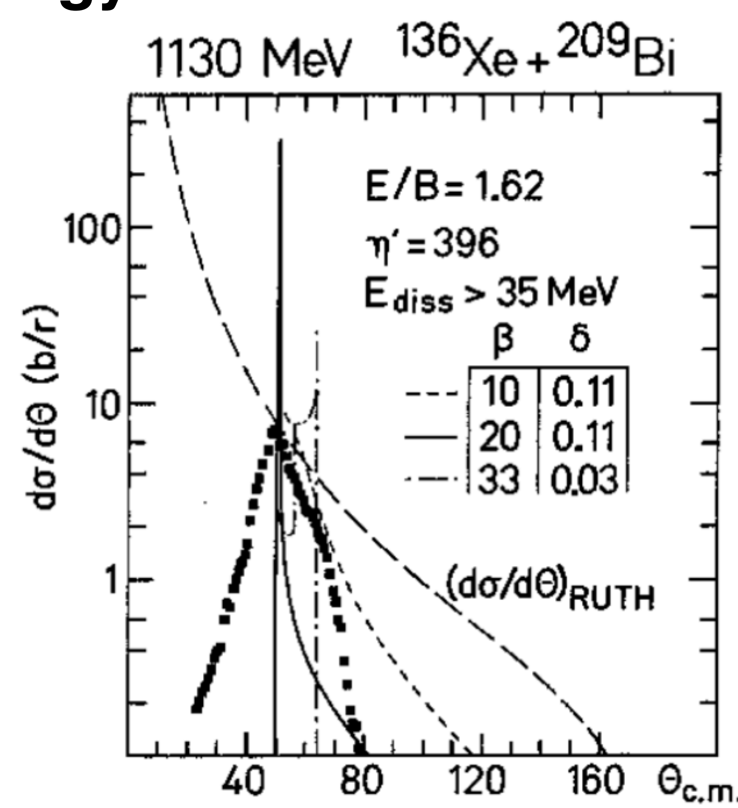
$$\frac{d\sigma}{d\Theta} = \frac{2\pi}{k^2}\sum_n l_n \left|\frac{dl}{d\Theta}\right|_{l=l_n}$$

$$\beta = 75f(\eta') + 15, \quad \eta' < 375$$
$$= 36\exp[-2.17\times10^{-3}\eta'], \quad \eta' \geq 375\ ,$$
$$\delta = 0.07f(\eta') + 0.11, \quad \eta' < 375$$
$$= 0.117\exp[-1.34\times10^{-4}\eta'], \quad \eta \geq 375\ ,$$

where

$$f(\eta') = \left[1 + \exp\left[\frac{\eta' - 235}{32}\right]\right]^{-1}.$$





Phys. Rev. C. 27, 590 (1983)

Z. Physik A 290, 47-55 (1979)

It is better to describe the peak value of experimental data, but cannot describe the broadening of experimental data.

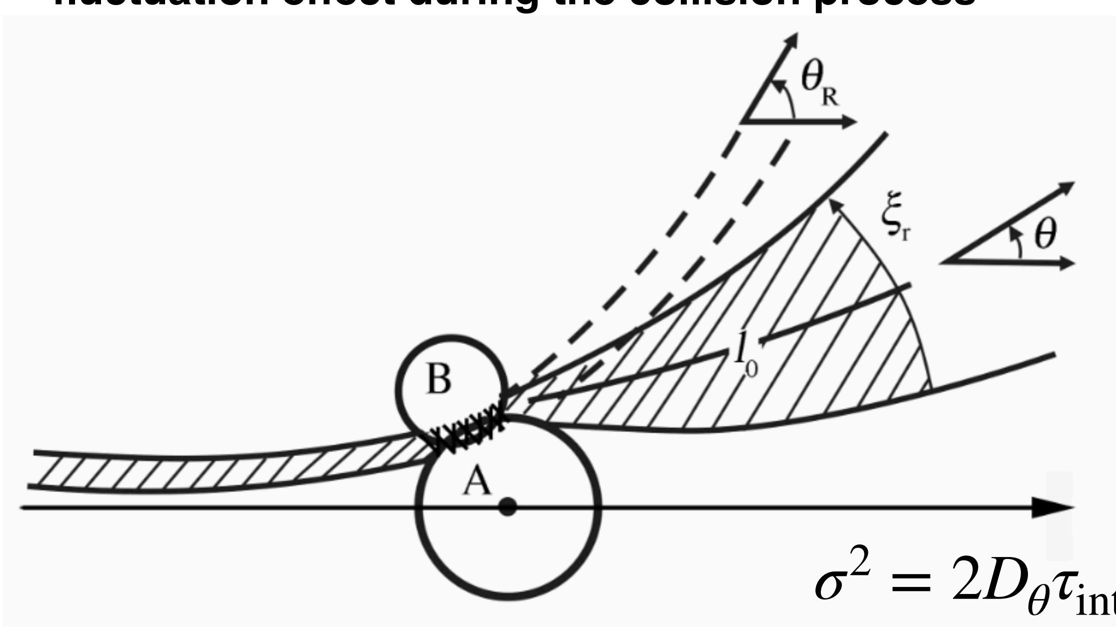
Three-parameter semi-empirical formula

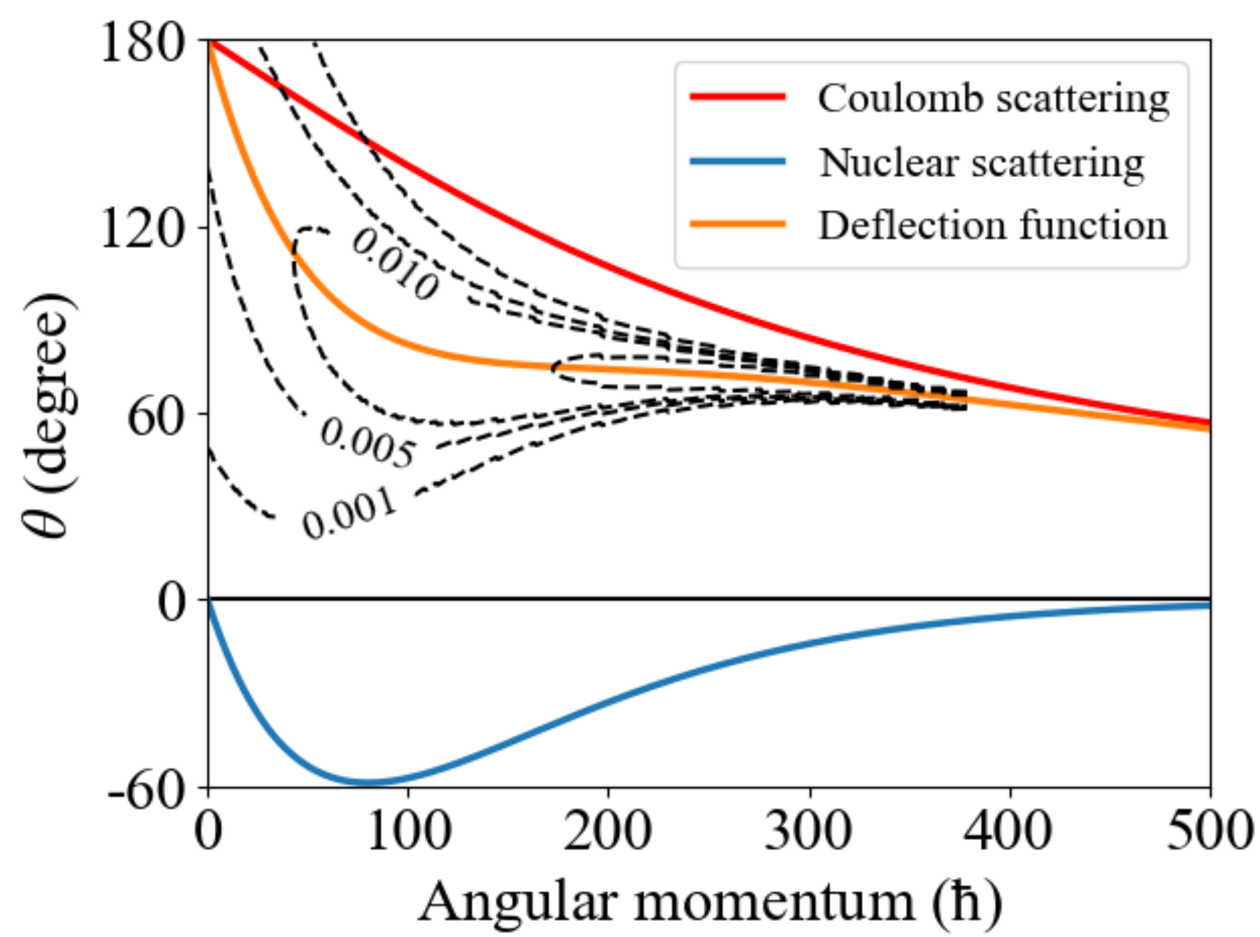
Three-parameter semi-empirical formula:

$$\Theta(l_i) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(\Theta-\overline{\Theta})^2}{2\sigma^2}\right)\left(2\arctan\frac{Z_\mathrm{p}Z_\mathrm{T}e^2}{2E_\mathrm{c.m.}b}-\beta\Theta_\mathrm{C}^\mathrm{gr}\frac{l_i}{l_\mathrm{gr}}\left(\frac{\delta}{\beta}\right)^{l_i/l_\mathrm{gr}}\right)$$

Gaussian distribution

Introduce Gaussian distribution and consider the fluctuation effect during the collision process





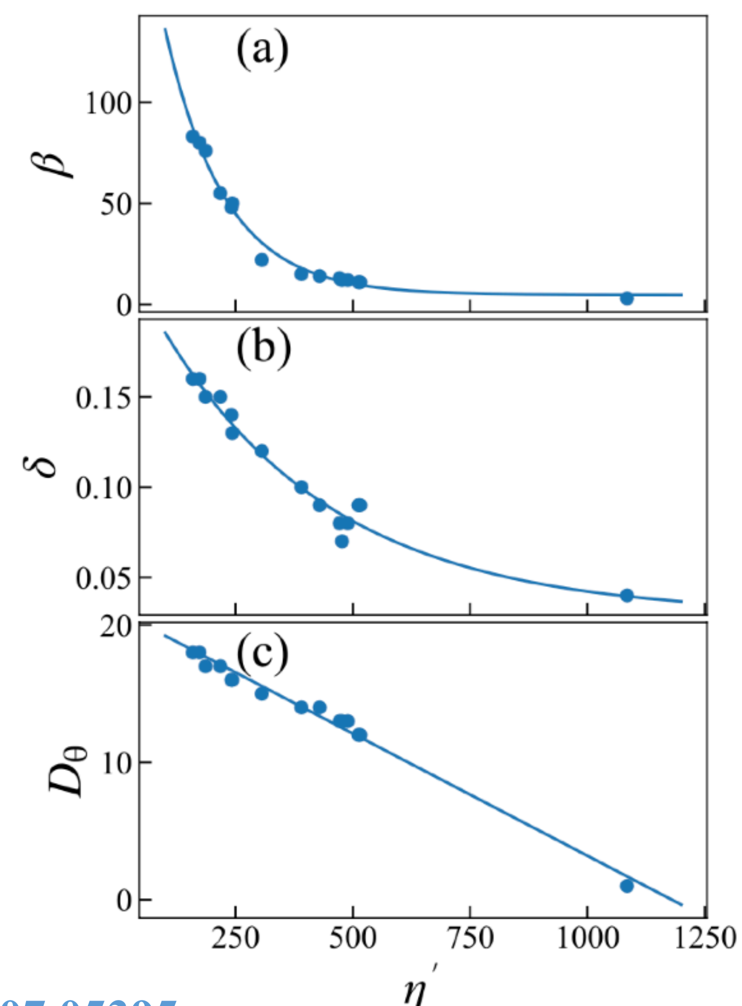
Here, σ、β and δ are fitted through experimental data and are related to the reaction system and reaction energy

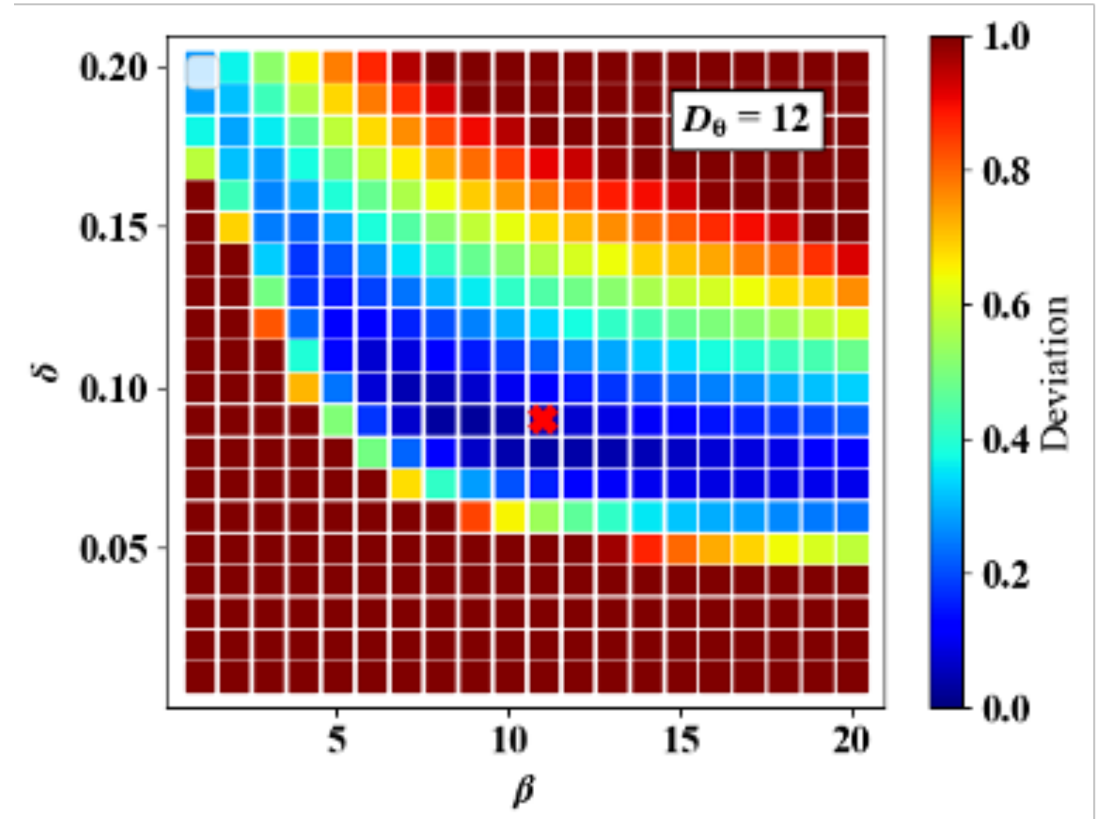
arXiv:2407.05395

Optimal parameter selection

- **In order to quantitatively describe the deviation of the calculation from the experimental value, we introduce the average deviation by：**

$$\mathfrak{D} = \frac{1}{n}\sum_{i=1}^{n}\left[\log\left(\frac{\sigma_{th}(\theta_i)}{\sigma_{exp}(\theta_i)}\right)\right]^2$$





$$\beta(\eta) = 4.7 + 81.2 * \exp[-(\eta - 160.8)/126.5]$$

$$\delta(\eta) = 0.029 + 0.127 * \exp[-(\eta - 176.3)/364]$$

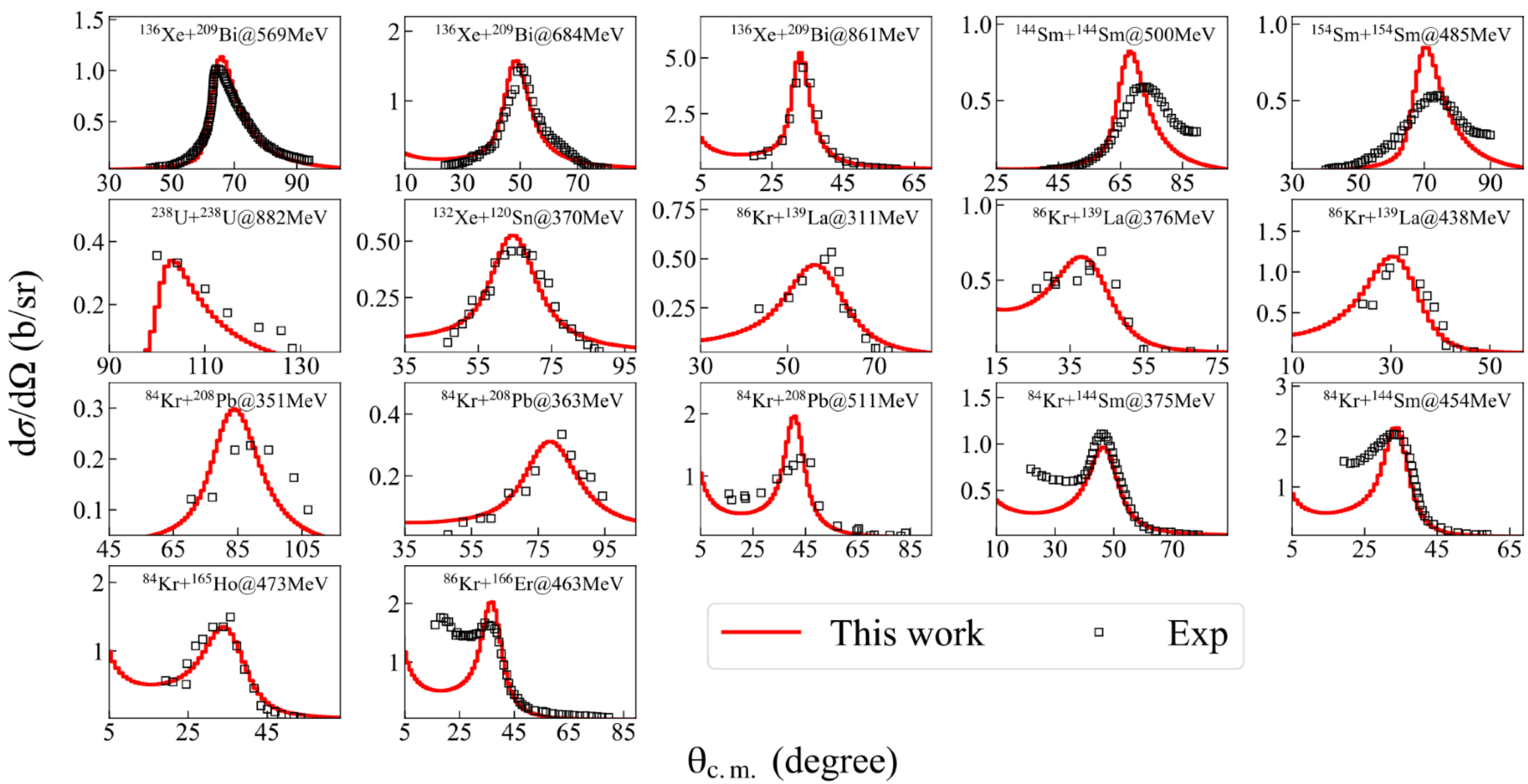
$$D_{\Theta}(\eta) = 21 - 0.0178\eta$$

arXiv:2407.05395

Three-parameter semi-empirical formula

Three-parameter semi-empirical formula:

$$\Theta(l_i) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(\Theta - \overline{\Theta})^2}{2\sigma^2}\right)\left(2\arctan\frac{Z_p Z_T e^2}{2E_{c.m.}b} - \beta\Theta_C^{gr}\frac{l_i}{l_{gr}}\left(\frac{\delta}{\beta}\right)^{l_i/l_{gr}}\right)$$



Bypassing the complex dynamical calculations underlying the MNT process

arXiv:2407.05395

Summary

- 在双核模型框架下，通过引入形变自由度，我们可以自洽的描述多核子转移的角分布。
- 我们改进了偏转函数，通过引入唯象的涨落形式，可以用三参数的偏转函数很好的描述多核子转移反应的角分布。

Thank you for your attention!