

多核子转移反应产生 $N=126$ 丰中子 核素的理论研究

答辩人： 廖泽鸿

指导教师： 祝龙（教授）



中山大学博士学位答辩

2026年5月19日

目录

■ 研究背景与理论方法

- **N=126 核素特殊结构效应与r 过程**
- **N=126 核素合成与多核子转移反应**
- 模型与理论框架

■ 研究内容

- 低能核反应提取核结构信息的研究
- N=126 核素的多核子转移反应非平衡演化的研究
- N=126 核素的多核子转移反应产物角分布的研究
- N=126 核素的多核子转移反应准弹性转移机制

■ 总结与展望

N=126 核素 · r 过程

Rev. Mod. Phys. 29 547–650 (1957).
 REVIEWS OF
MODERN PHYSICS
 VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

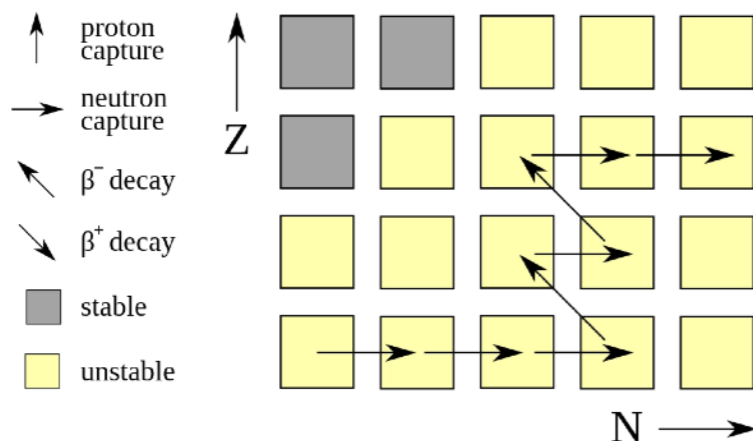
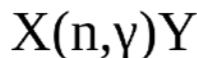
*Kellogg Radiation Laboratory, California Institute of Technology, and
 Mount Wilson and Palomar Observatories, Carnegie Institution of Washington,
 California Institute of Technology, Pasadena, California*

“It is the stars, The stars above us, govern our conditions”;
 (*King Lear*, Act IV, Scene 3)

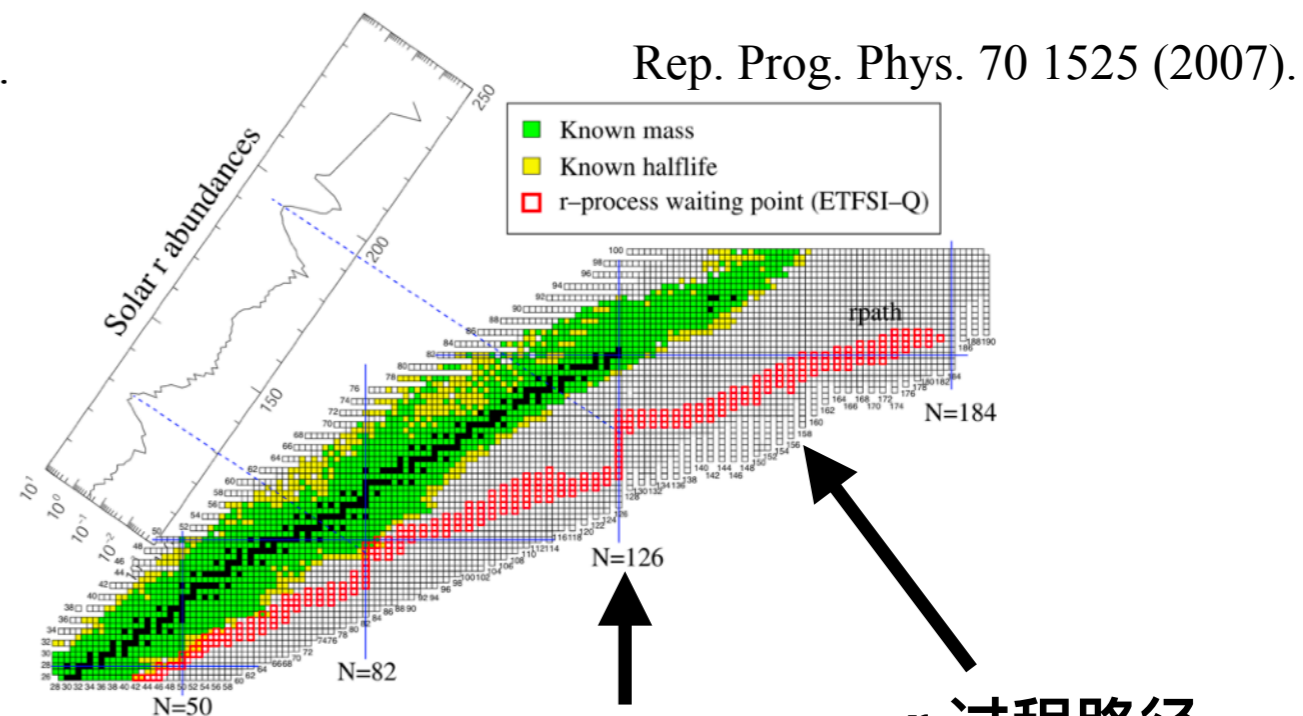
but perhaps

“The fault, dear Brutus, is not in our stars, But in ourselves,”
 (*Julius Caesar*, Act I, Scene 2)

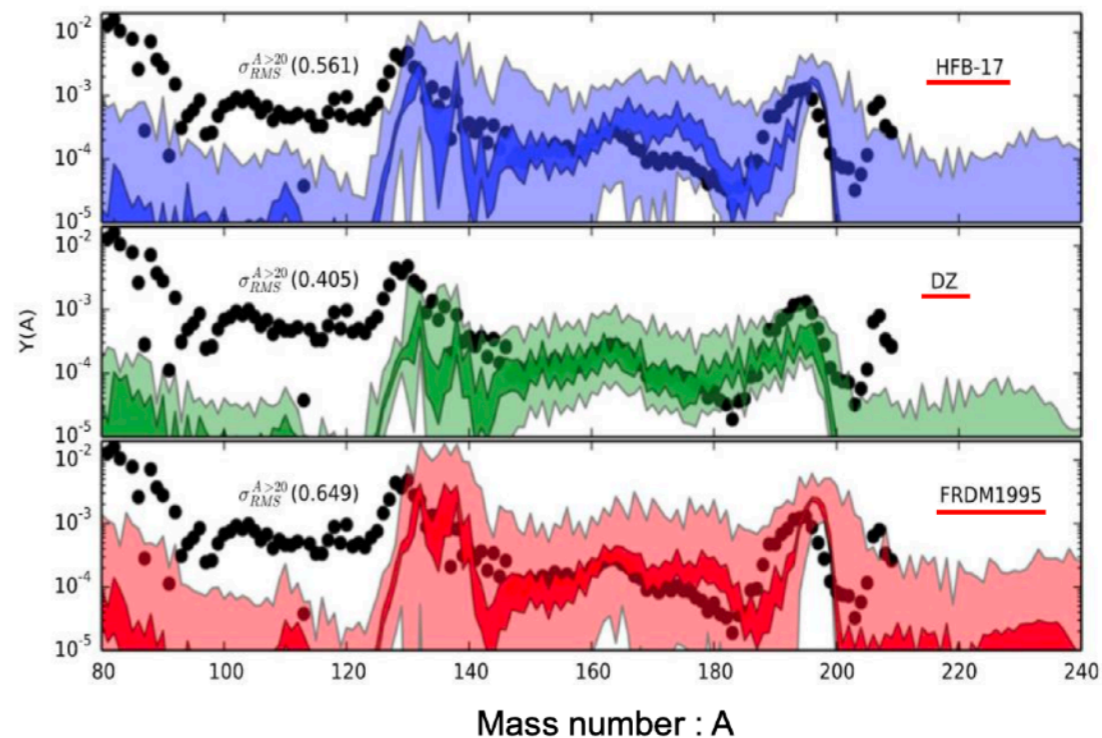
r-process
 rapid neutron captures



synthesis of neutron-rich nuclei
 A > 60



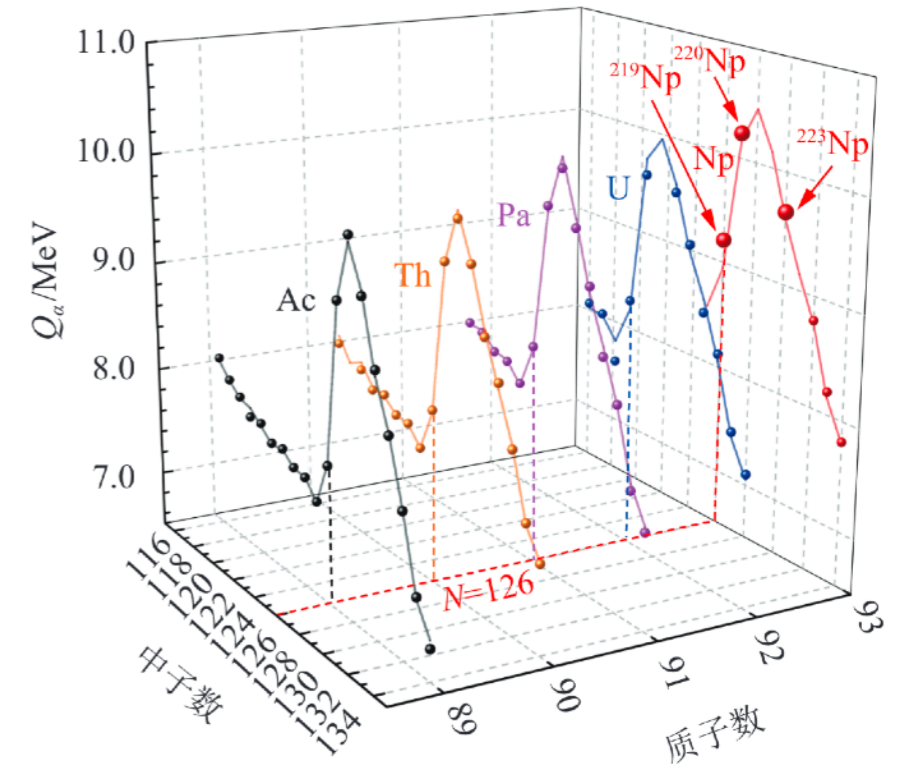
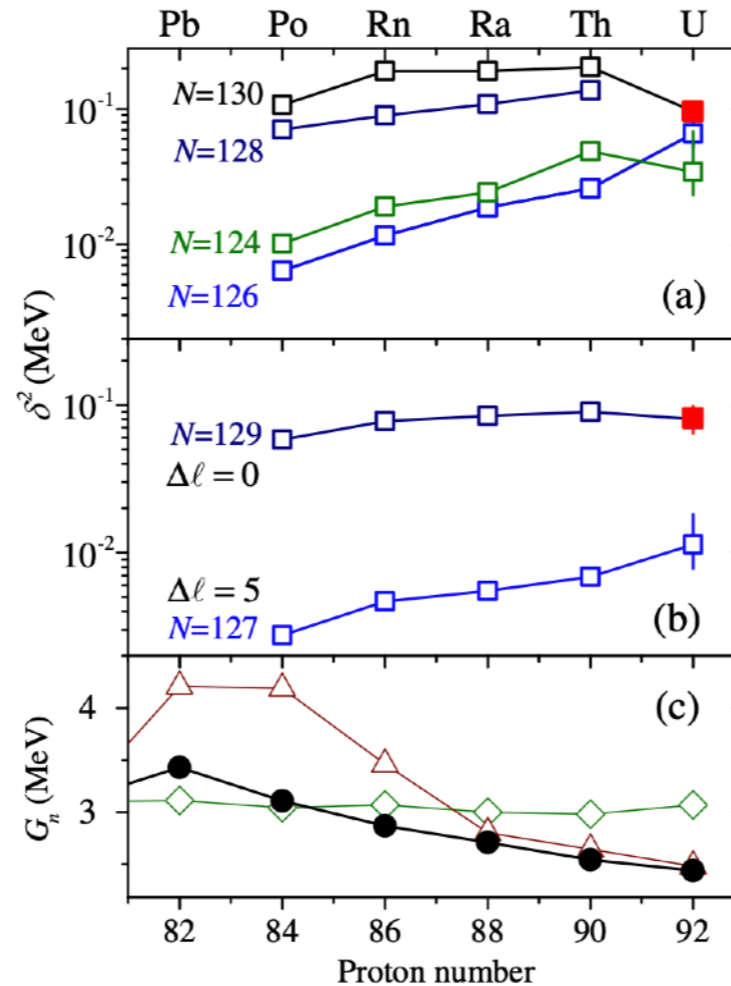
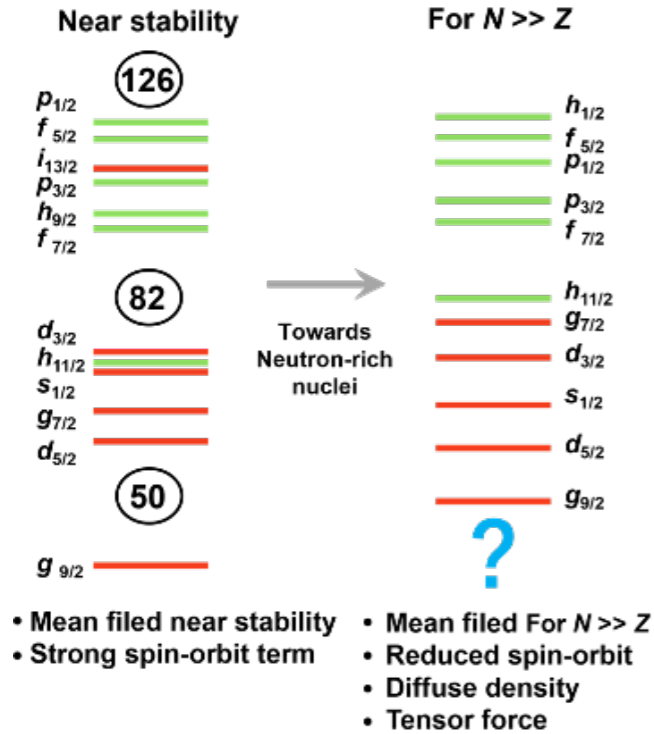
中子俘获与 β 衰变竞争形成等待点 r 过程路径



- N=126 核素性质 促进 理解重元素起源
- N=126 核素性质 决定 R 过程的演化路径 与 宇宙丰度分布

N = 126 核素的特殊结构效应

Shell evolution



当逐渐远离稳定核素，
N=126 壳的效应是否还存在？

α 衰变宽度分析

PhysRevLett. 115, 242502 (2015)

基态 α 衰变Q值系统性规律分析

PhysRevLett. 122, 192503 (2019)

PhysRevLett. 125, 032502 (2020)

■ 探索极丰质子或丰中子核素的性质对理解核力、壳结构演化具有重要意义

N = 126 核素合成 · 多核子转移反应 (MNT)

■ 熔合-蒸发反应:

- + 任意元素 (概率问题)
- 缺乏中子

■ 碎裂反应:

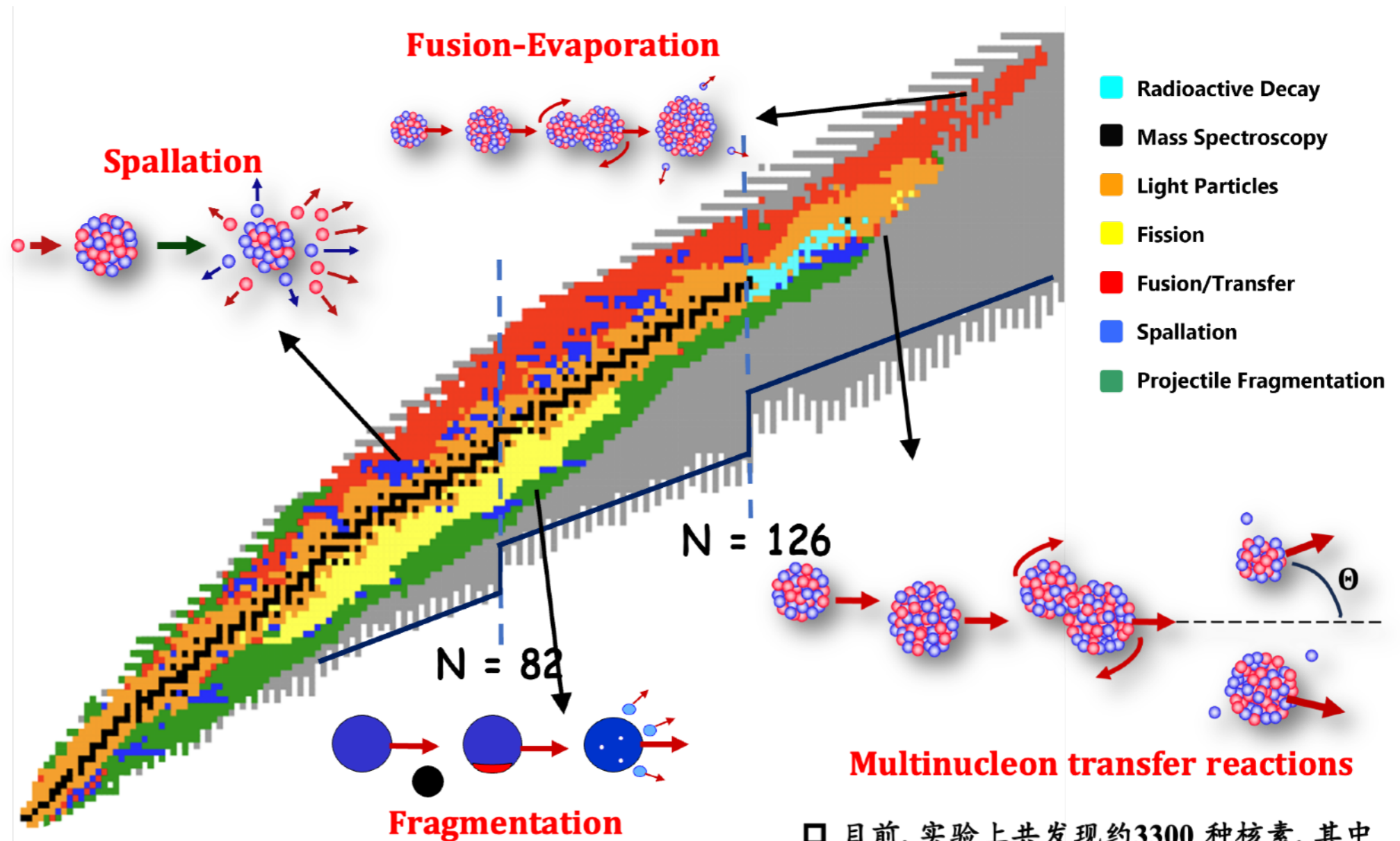
- + 非常高效且通用
- 产物比 ^{238}U 轻

■ 原子核裂变:

- + 丰中子产物
- 产物远轻于 ^{238}U

■ 多核子转移反应:

- + 探索未知区域的方法
- 技术上非常复杂
- 缺乏实验数据



<https://people.nsl.msui.edu/~thoennes/isotopes/>

□ 目前, 实验上共发现约3300种核素, 其中自然存在的核素有339种, 其余都是人工核反应合成的。而理论预言可能存在6000-9000种核素, 已知的核素还不到预测核素的一半。

因此合成远离稳定线的新核素、探索原子核存在的极限是原子核物理的重点研究课题。 5

N = 126 核素合成 · 多核子转移反应

PRL 115, 172503 (2015)

PHYSICAL REVIEW LETTERS

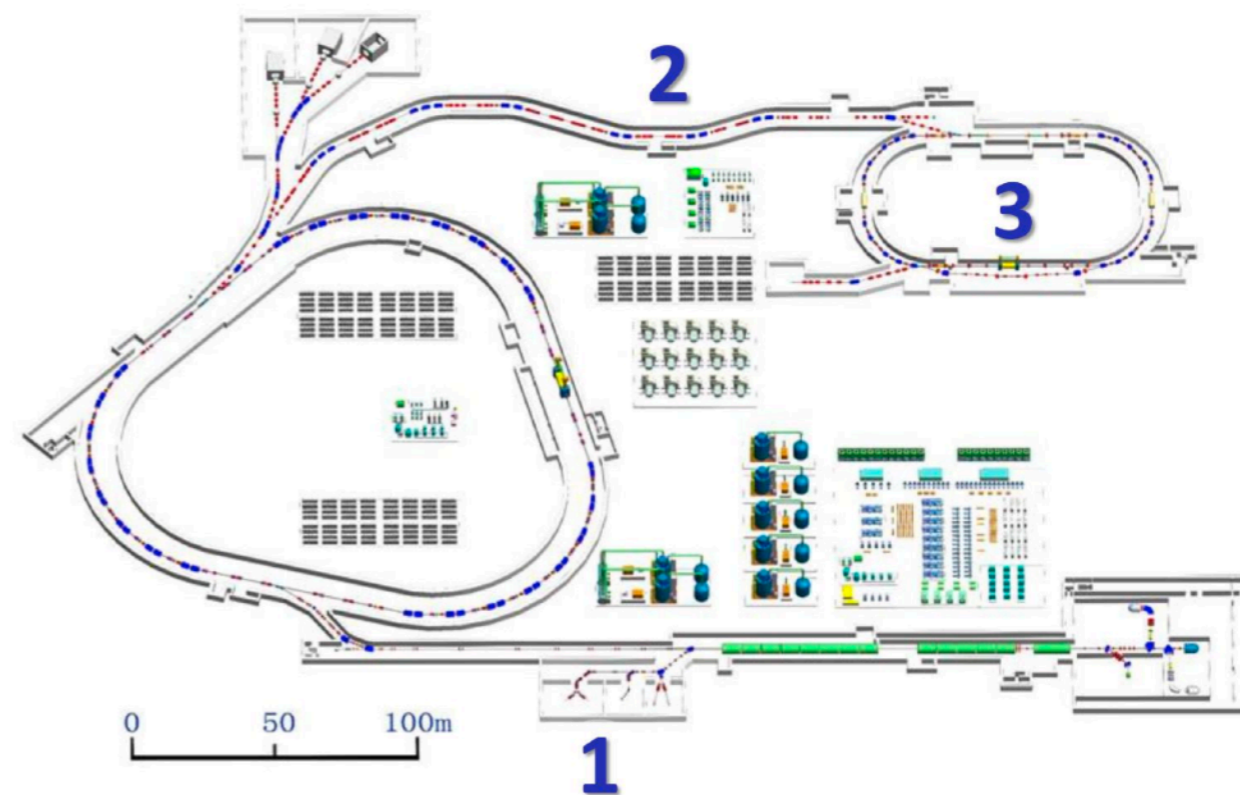
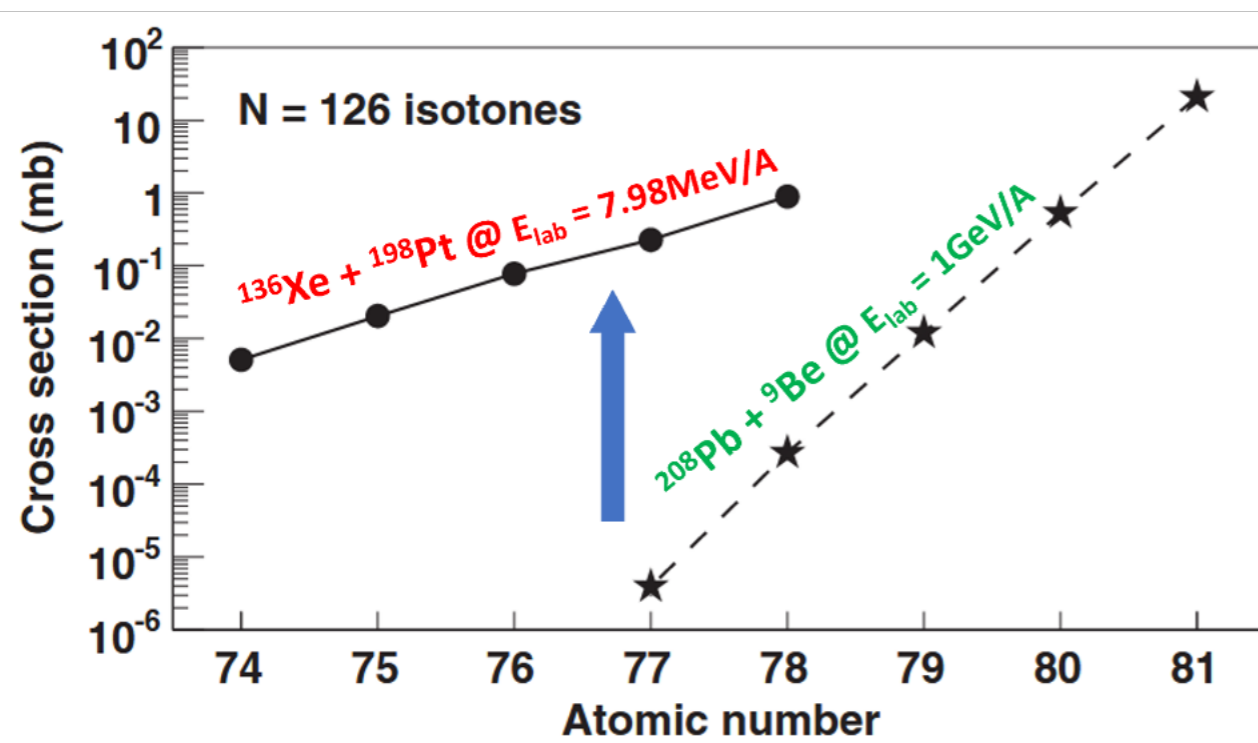
week ending
23 OCTOBER 2015

Pathway for the Production of Neutron-Rich Isotopes around the $N = 126$ Shell Closure

Y. X. Watanabe,^{1,*} Y. H. Kim,^{2,3,†} S. C. Jeong,^{1,‡} Y. Hirayama,¹ N. Imai,^{1,§} H. Ishiyama,^{1,‡} H. S. Jung,¹ H. Miyatake,¹ S. Choi,^{2,3} J. S. Song,^{2,3,4} E. Clement,⁵ G. de France,⁵ A. Navin,^{5,||} M. Rejmund,⁵ C. Schmitt,⁵ G. Pollarolo,⁶ L. Corradi,⁷ E. Fioretto,⁷ D. Montanari,⁸ M. Niikura,^{9,¶} D. Suzuki,^{9,**} H. Nishibata,¹⁰ and J. Takatsu¹⁰

¹Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan

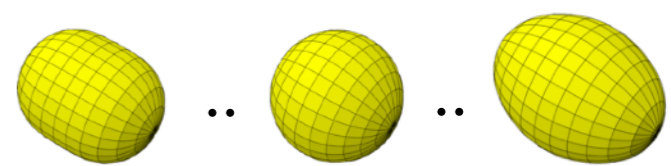
HIAF 实验终端建设



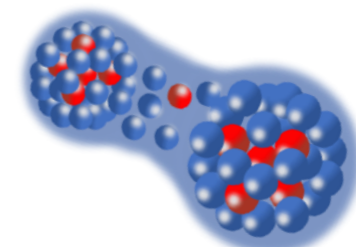
博士论文的研究内容



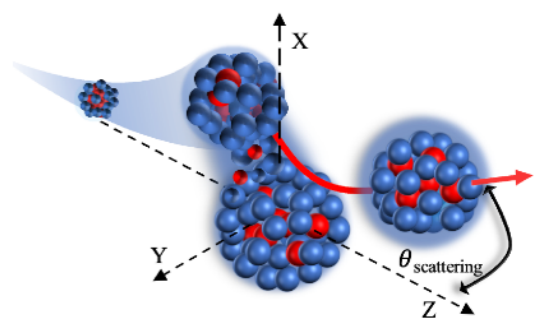
低能核反应是否可以作为提取核形变的探针?



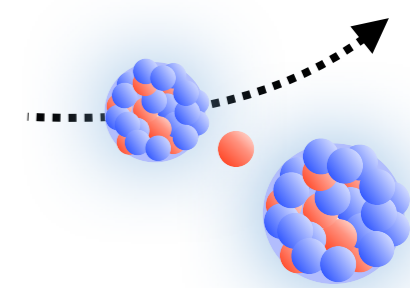
核结构性质是否对产生 N=126 丰中子核素有影响?



探测未知 N=126 丰中子核素的探测最佳条件?



提升预测 N=126 丰中子核素的模型准确性



目录

■ 研究背景与理论方法

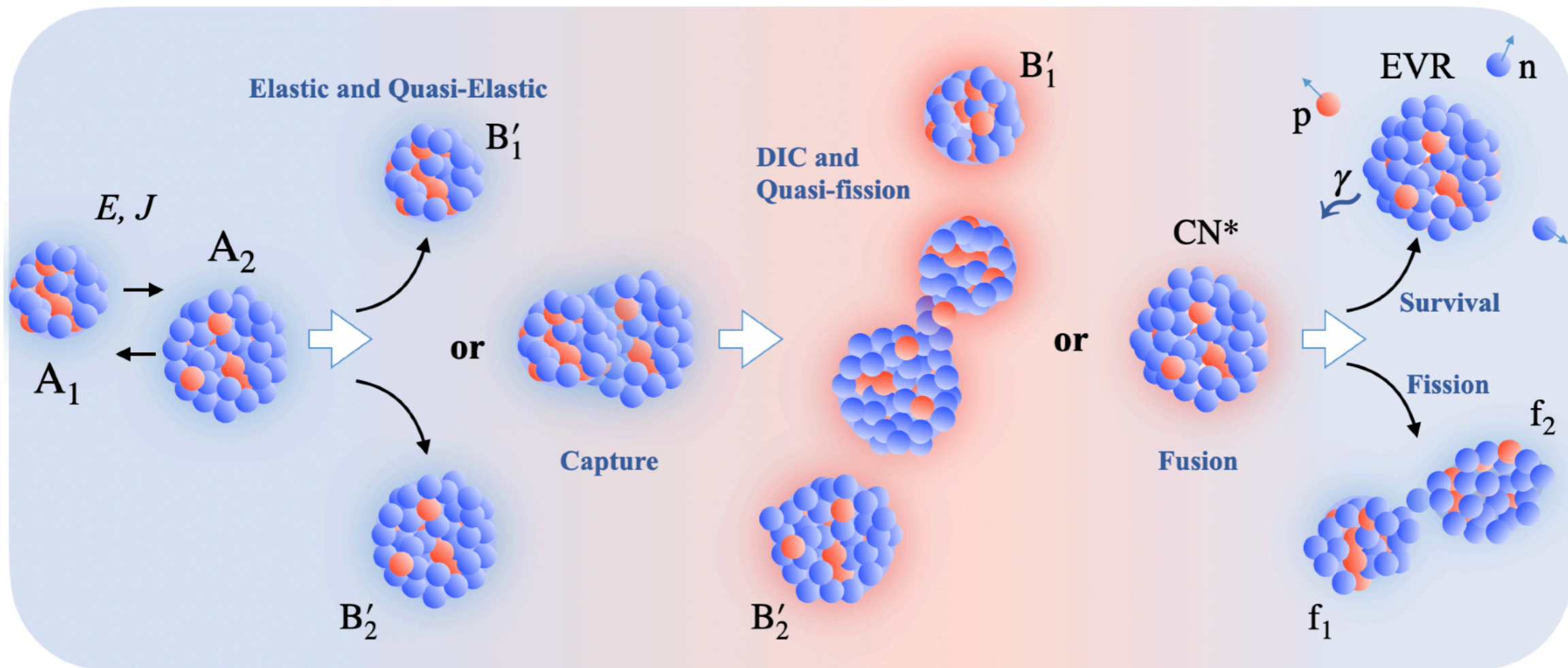
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■ 总结与展望

理论框架



俘获阶段

双核系统阶段

退激阶段

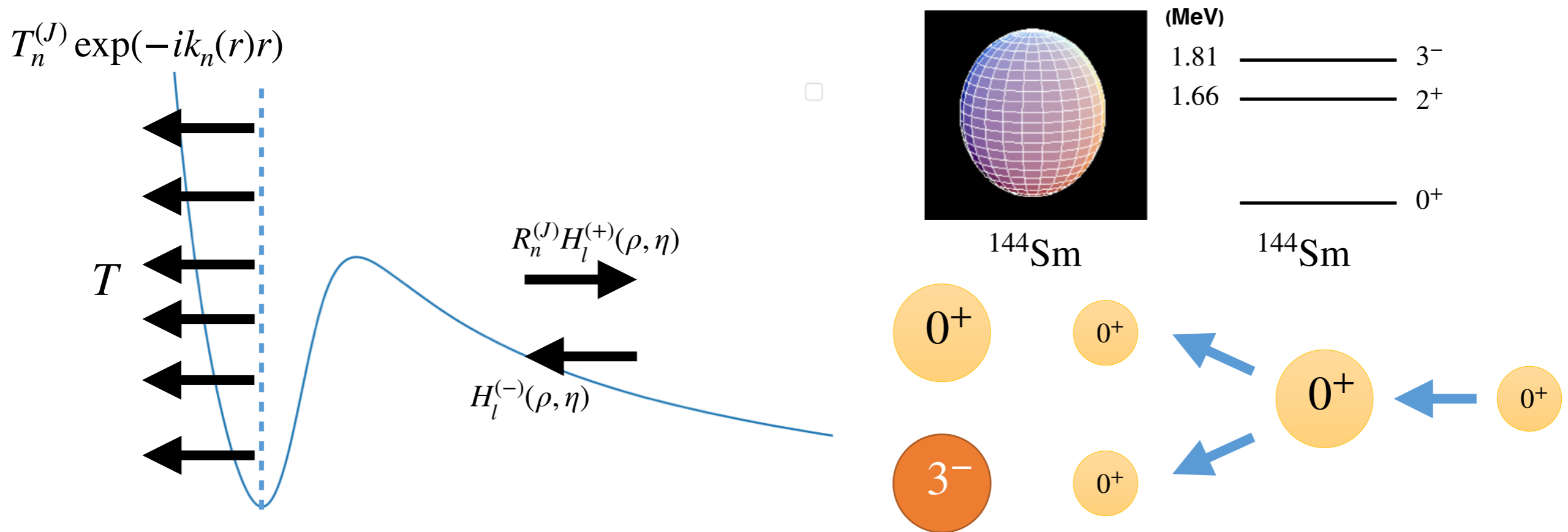
$$\sigma(Z_f, N_f) = \frac{\pi \hbar^2}{2\mu E_{c.m.}} \sum_{J=0}^{J_{max}} (2J+1) P_{cap}(J) \sum_{Z_1, N_1} P(Z_1, N_1; J^*, E^*) W(Z_1, N_1 \rightarrow Z_f, N_f; J^*, E^*),$$

耦合道模型

双核系统模型

统计蒸发模型

俘获阶段-耦合道模型

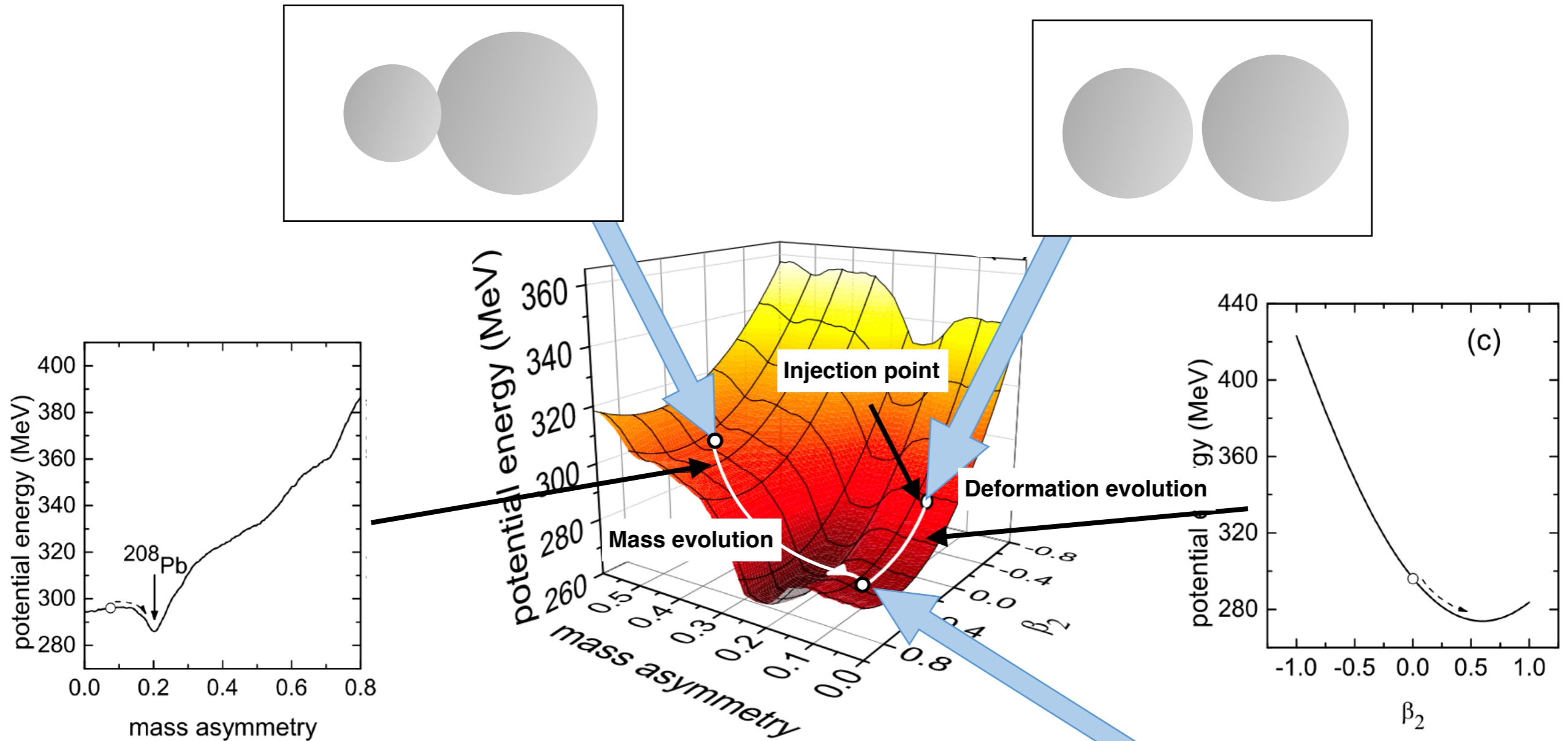


哈密顿量: $H = -\frac{\hbar^2}{2\mu} \nabla^2 + V^{(0)}(r) + H_{\text{int}}(\xi) + V_{\text{coup}}(r, \xi)$ 波函数: $\Psi(r, \xi) = \sum_n \frac{\phi_n(r)}{r} |n(\xi)\rangle$

耦合道方程: $\left[-\frac{\hbar^2}{2\mu} \frac{d^2}{dr^2} + \frac{J(J+1)\hbar^2}{2\mu r^2} + V_N^{(0)}(r) + \frac{Z_p Z_T e^2}{r} + \epsilon_n - E \right] \psi_n(r) + \sum_m V_{nm}(r) \psi_m(r) = 0,$

俘获概率: $P_J(E) = \sum_n \frac{k_n(r_{\text{min}})}{k} |T_n^{(J)}|^2 = 1 - \sum_n \frac{k_n}{k} |R_n^{(J)}|^2.$

双核系统阶段-双核系统模型



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

X. J. Bao, Phys Lett B, 2022. 833: 137307.

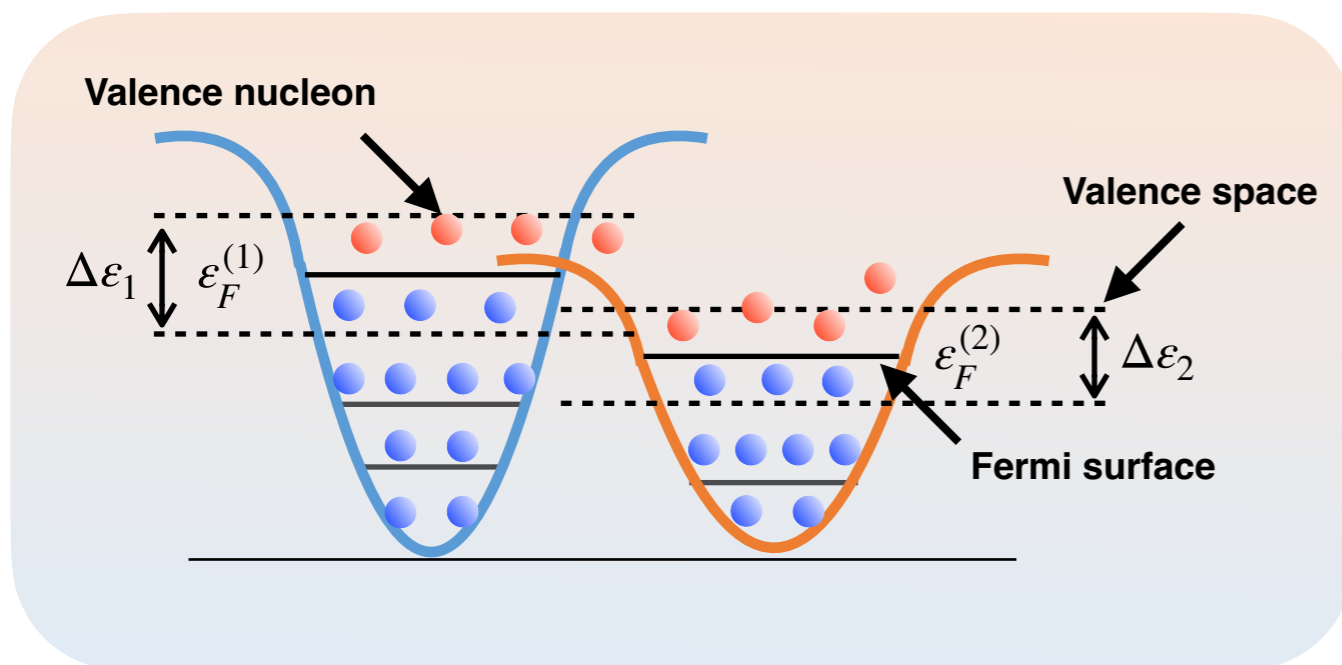
Long Zhu, Phys Lett B, 2021. 816: 136226. PhysRevC.98.034609

双核系统阶段-双核系统模型

主方程:

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

- N : 微观状态数.
- $P_N(t)$: 在状态为 $\{N\}$ 的时候的总概率.
- $w_{MN}(t)$: 从道 $n \in \{N\}$ 到道 $m \in \{M\}$ 的平均转移速率.



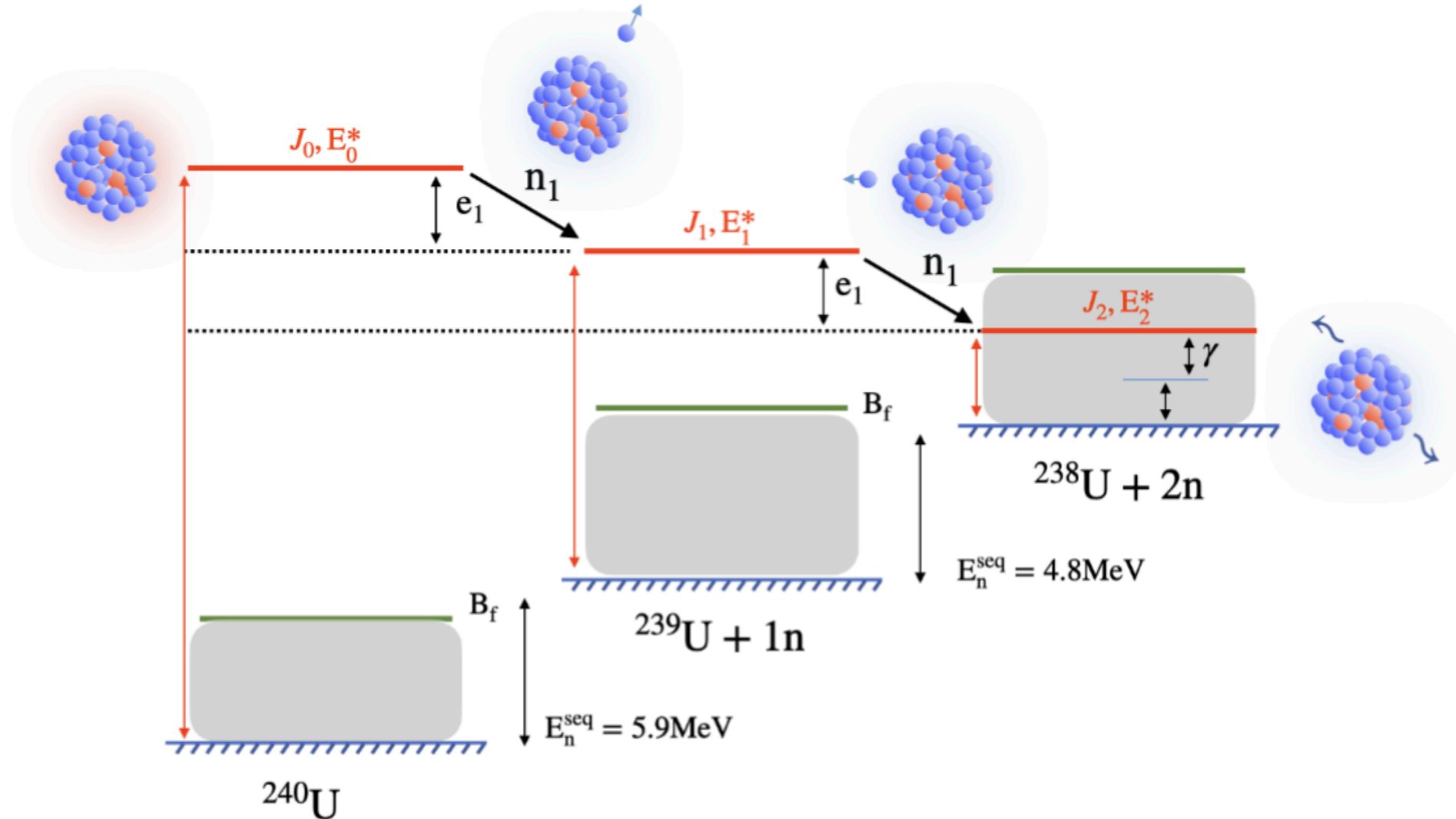
价核子空间:

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

微观状态数: $d(m_1, m_2) = \binom{N_1}{m_1} \binom{N_2}{m_2}$

核子转移概率:

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



在蒸发级联的每一个阶段，根据各个通道的衰变宽度随机选择一个衰变模式：

$$P_b = \frac{\Gamma_b}{\Gamma_{\text{tot}}}, \quad \text{其中} \quad \Gamma_{\text{tot}} = \sum_b \Gamma_b$$

轻粒子的蒸发过程采用 Hauser-Feshbach 理论形式：

$$\Gamma_i(E^*, J_{\text{CN}}) = \frac{1}{2\pi\rho_{\text{CN}}(E^*, J_{\text{CN}})} \int d\varepsilon \sum_{J_d=0}^{\infty} \sum_{J=|J_{\text{CN}}-J_d|}^{J_{\text{CN}}+J_d} \sum_{l=|J-S_i|}^{J+S_i} T_l(\varepsilon)\rho_d(E^* - B_i - \varepsilon, J_d)$$

Bohr-Wheeler 衰变宽度：

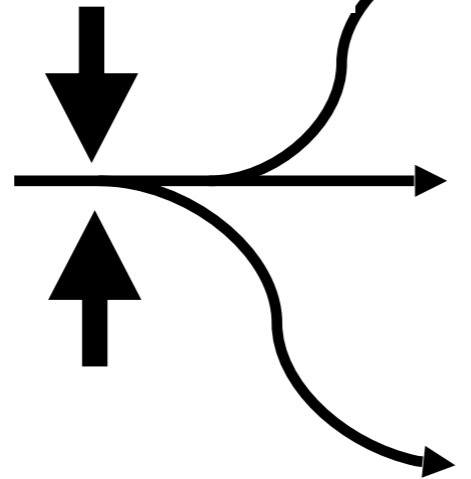
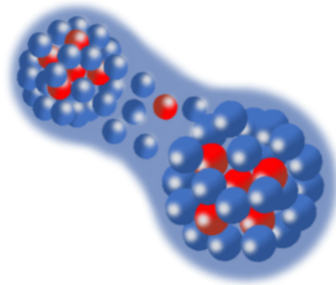
$$\Gamma_{\text{BW}}(E^*, J) = \frac{1}{2\pi\rho_{\text{CN}}(E^*, J)} \int_0^{E^* - B_f(J)} \rho_s(E^* - B_f(J) - \varepsilon, J) d\varepsilon$$

理论框架

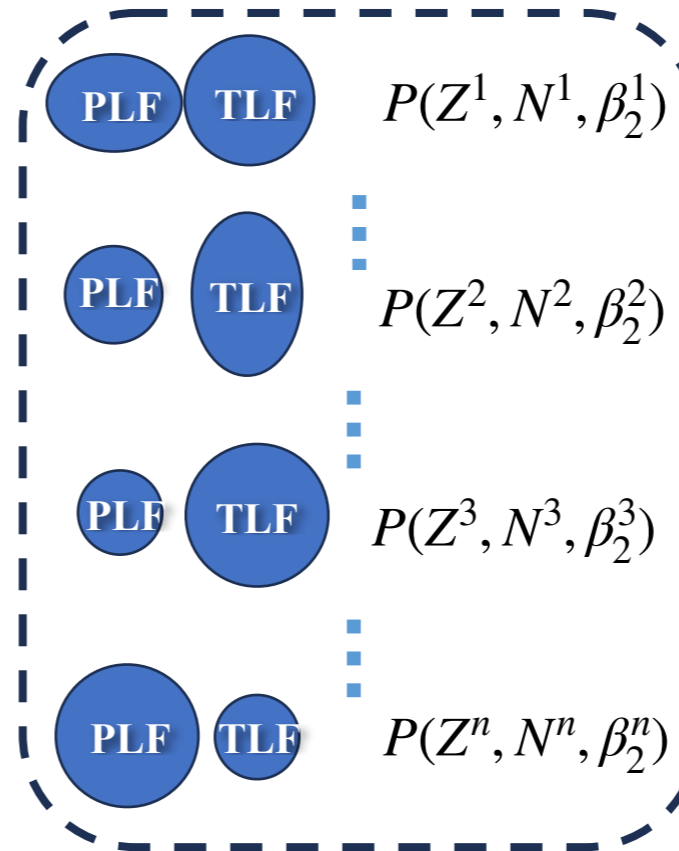
- PLF: projectile like fragment
- TLF: target like fragment

• 势能面:

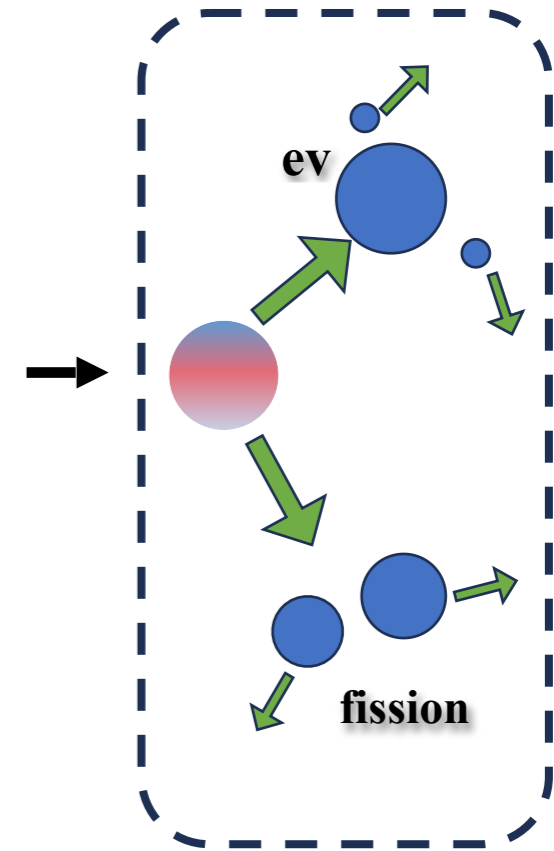
$$U(Z_1, N_1, \beta_2, J, r = R_{\text{cont}}) = \Delta(Z_1, N_1) + \Delta(Z_2, N_2) + V(Z_1, N_1, \beta_2, J, r = R_{\text{cont}}) + \frac{1}{2}C_1(\delta\beta_1^1)^2 + \frac{1}{2}C_2(\delta\beta_2^2)^2.$$



• 不同组态概率分布:

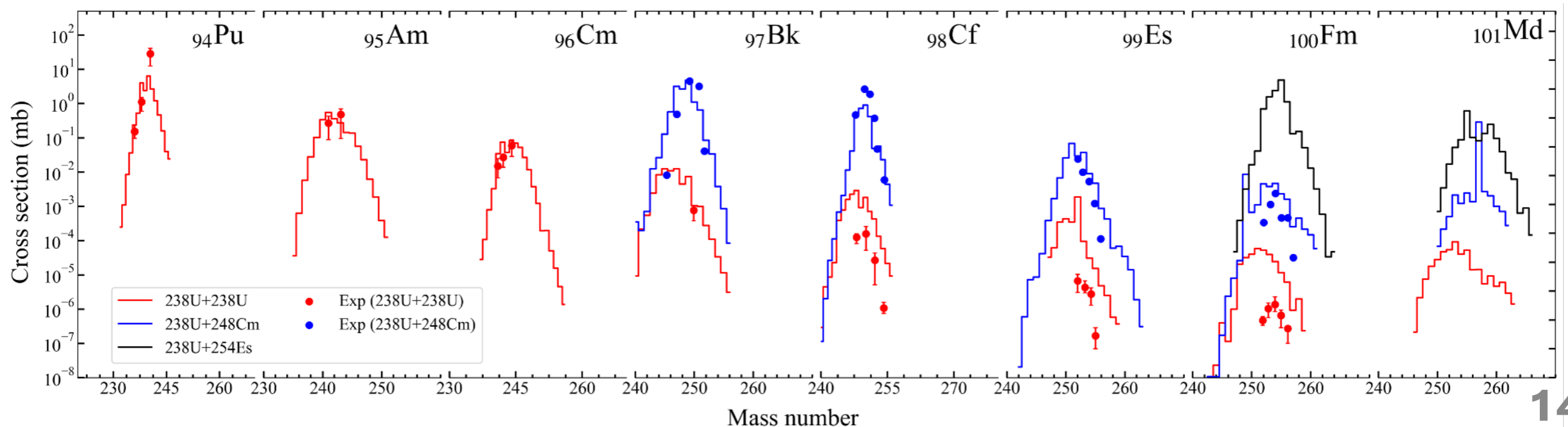


• 统计蒸发模型:



• 3D 主方程

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

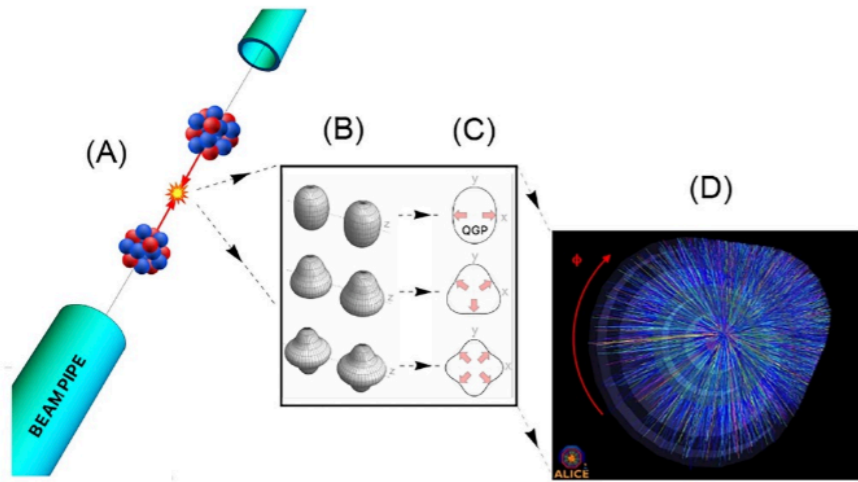


○ 低能核反应提取核形变结构信息的研究

Zehong Liao, K. Hagino*, Long Zhu* et. al.; *Physical Review C* 113, 044611 (2026)

低能俘获过程可以作为提取原子核形变的探针

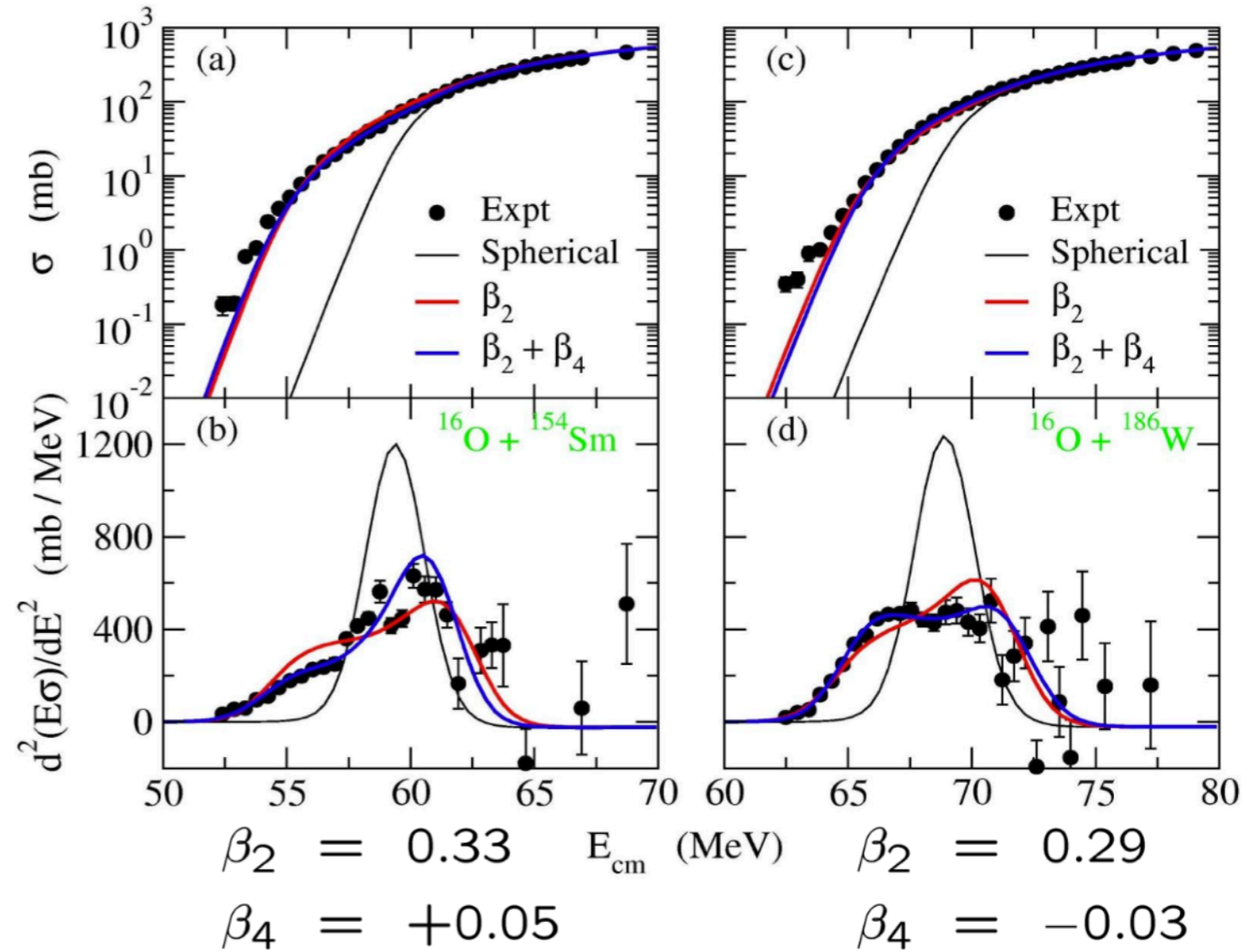
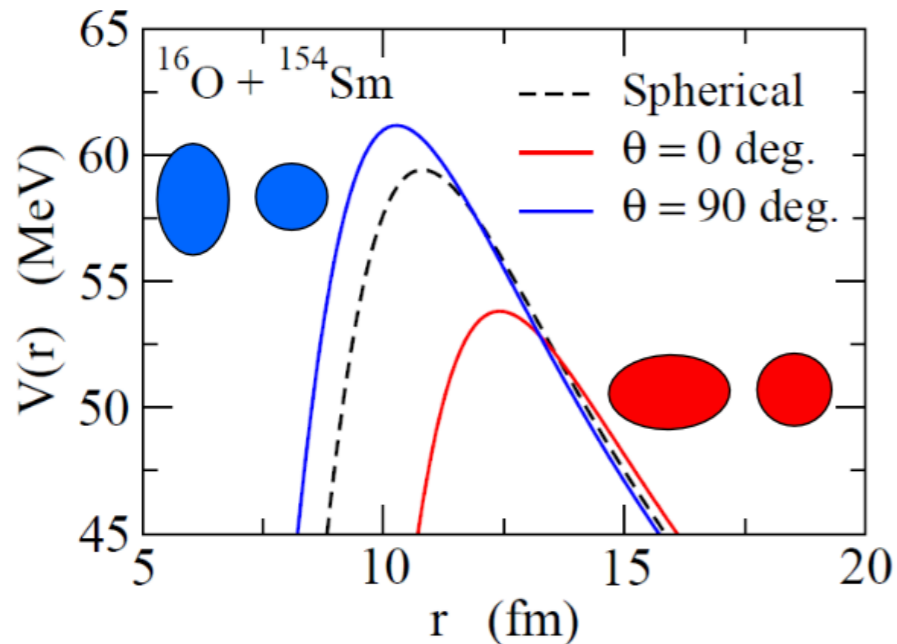
形变核的相对论重离子碰撞



J. Jia et al.,
Nucl. Sci. Tech. 35, 220 (2024)

increasing interests in recent years

形变核的低能重离子碰撞



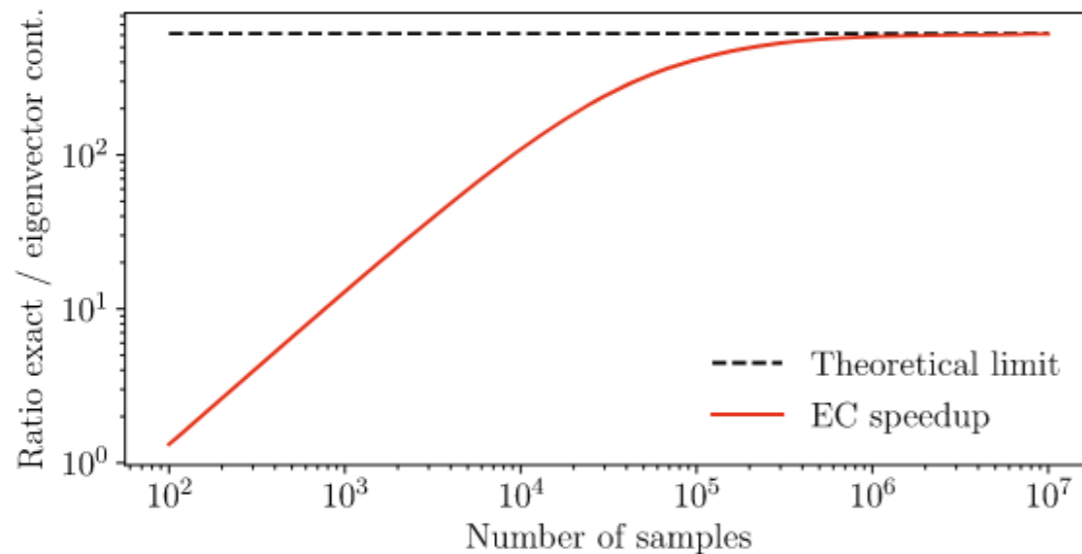
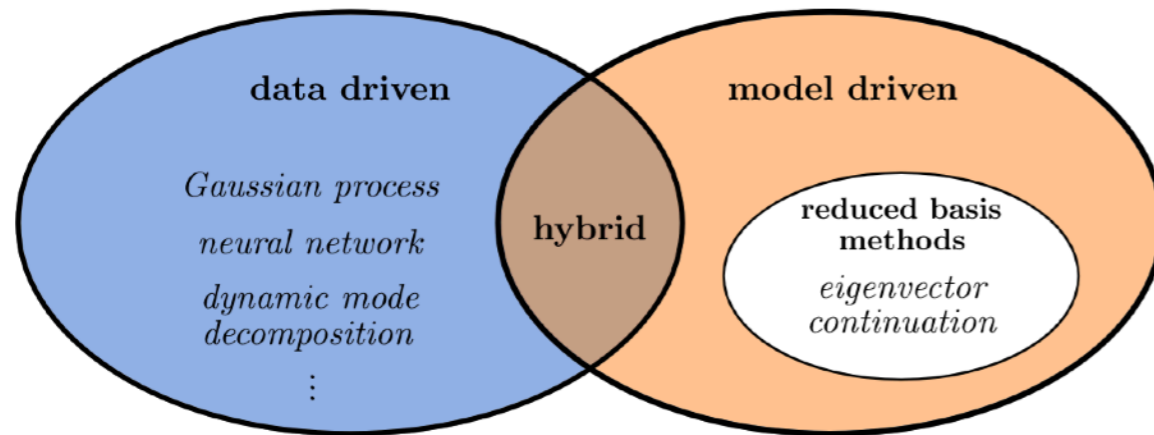
但该提取过程需要进行大量的重复计算！

K. Hagino' talk in INPC 2025

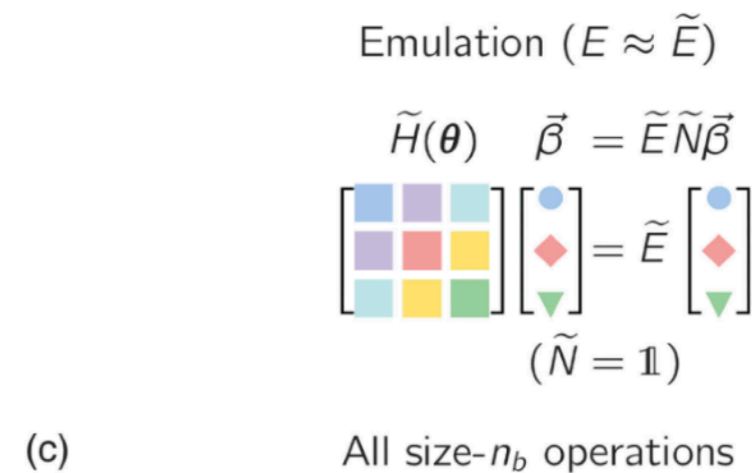
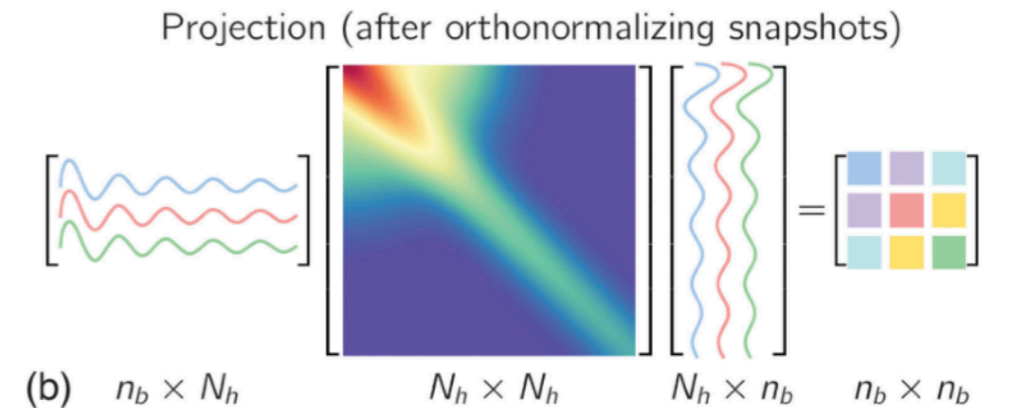
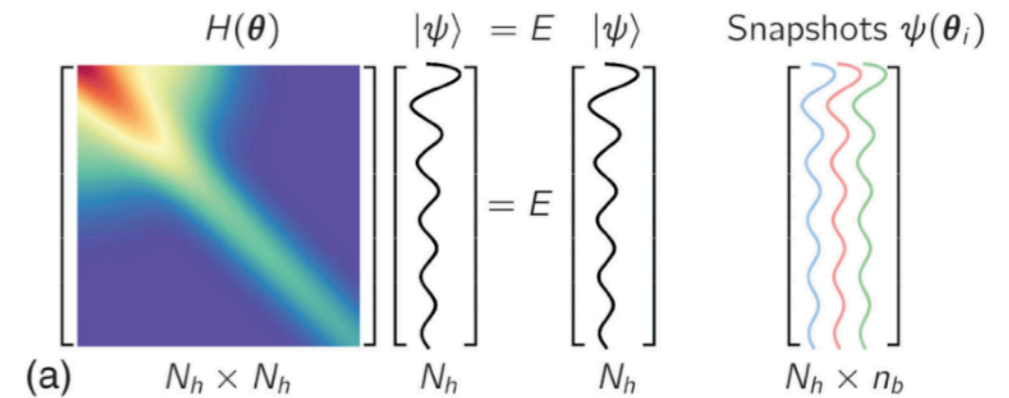
J.R. Leigh et al., PRC52 ('95) 3151

本征向量延拓 Reduce basis method

reduced order models

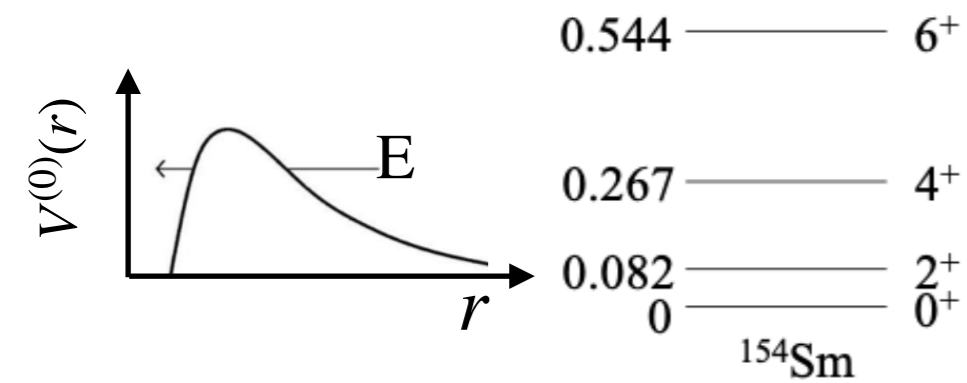


第一性原理no-core shell-model计算：
 ^4He ground-state energy

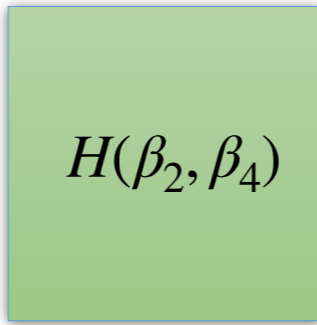


耦合道模型模拟器

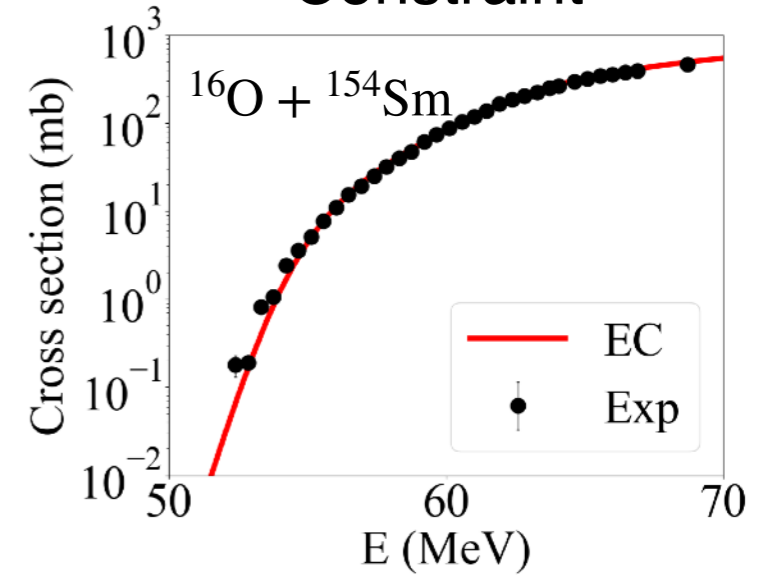
$$H = -\frac{\hbar^2}{2\mu}\nabla^2 + V^{(0)}(r) + H_{\text{int}}(\xi) + V_{\text{coup}}(r, \xi)$$



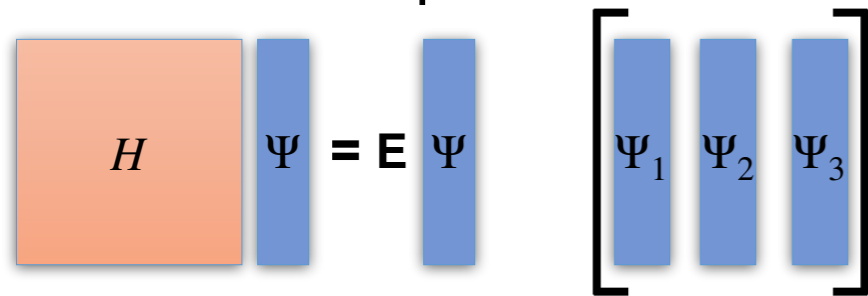
Emulation



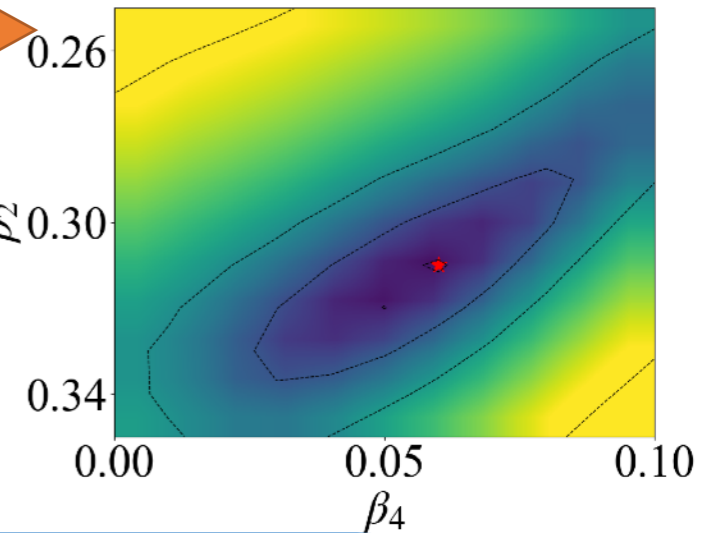
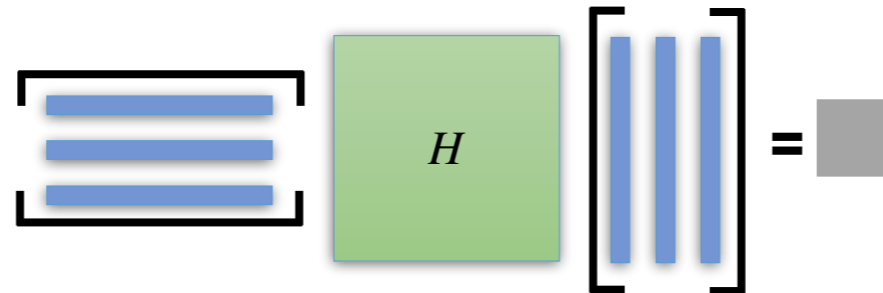
Constraint



Snapshot



Projection



物理模型哈密顿量

投影得到子空间

快速求取本征值

精确求取EC的基矢

目标参数的哈密顿量

实验观测量约束

耦合道模型模拟器

比较在不同轨道角动量下俘获概率的精度与速度

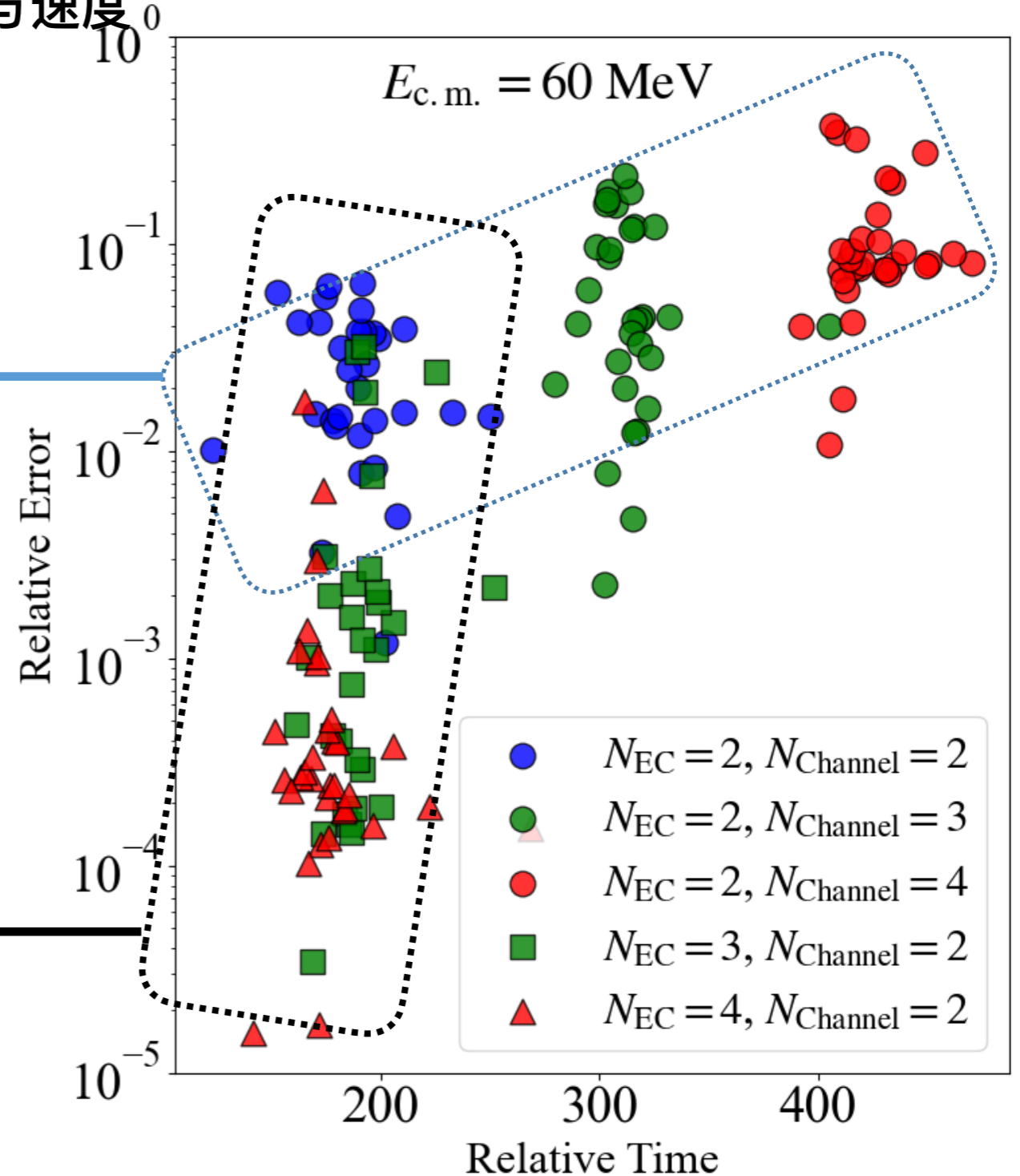
完整计算哈密顿量空间的大小

~ 900 for $N_{\text{Channel}} = 2$ channels

~ 1300 for $N_{\text{Channel}} = 3$ channels.

随着反应通道数 N_{Channel} 增加，其加速能力也在增加

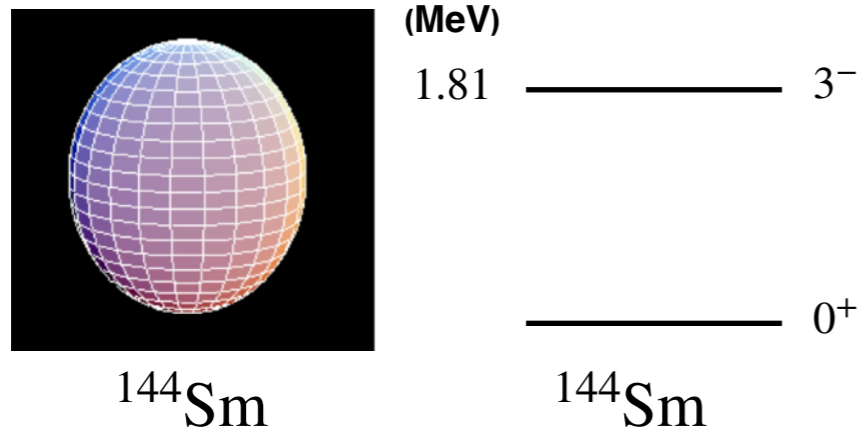
随着 EC 基矢的数量增加 N_{EC} ，其误差在减小



$$\text{Relative error} = |P_{\text{Ec}}(E = 60\text{MeV}, J) - P_{\text{Exact}}(E = 60\text{MeV}, J)| / P_{\text{Exact}}(E = 60\text{MeV}, J)$$

$$\text{Relative time} = \tau_{\text{Exact}}(E = 60\text{MeV}, J) / \tau_{\text{Ec}}(E = 60\text{MeV}, J)$$

$^{16}\text{O} + ^{144}\text{Sm}$



β^λ 可以通过实验测得的跃迁几率转化得到

$$\beta^\lambda = \frac{4\pi}{3ZR^\lambda} \left[\frac{B(E\lambda)}{e^2} \right]^2$$

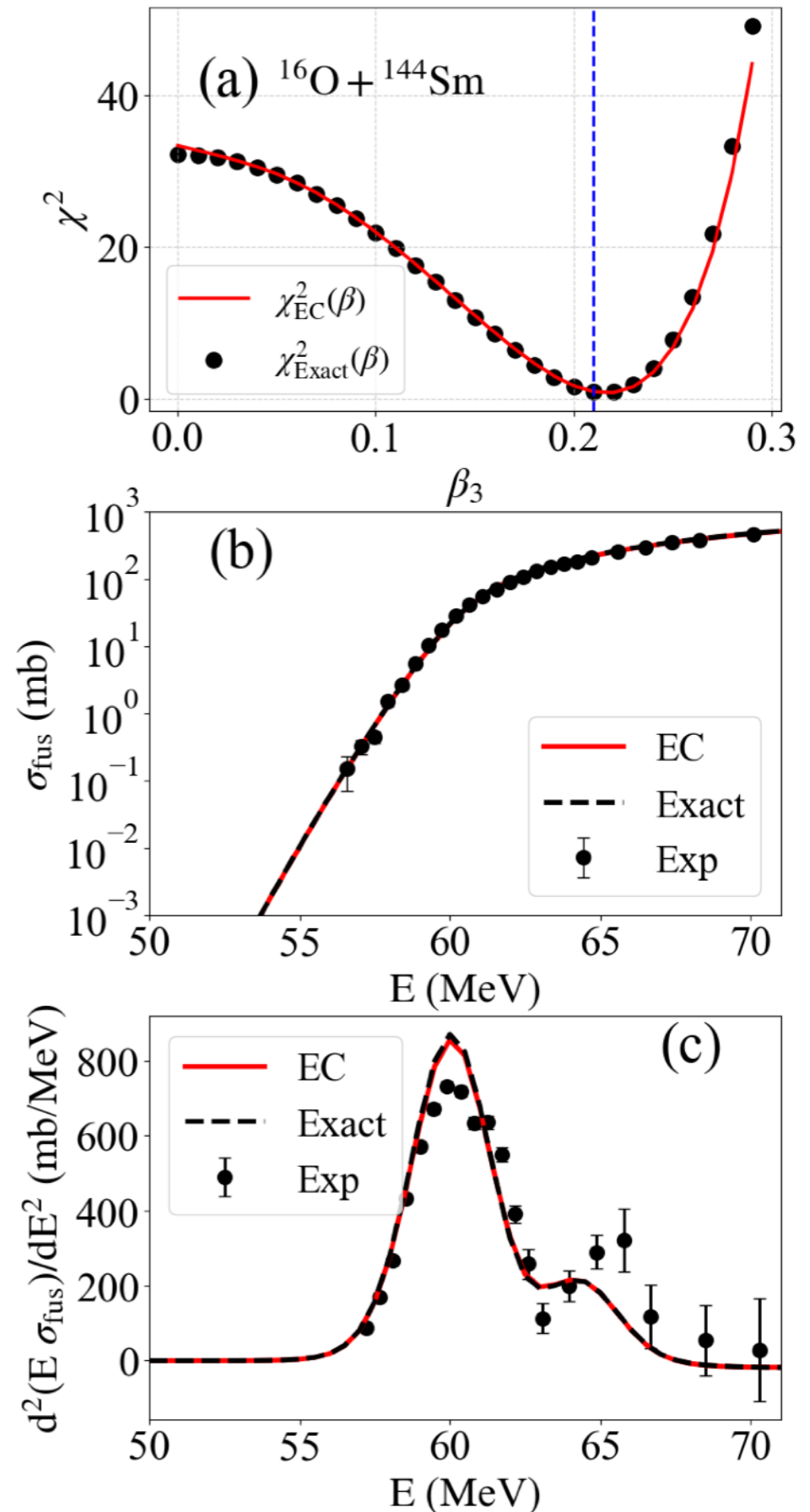
cf. : $\beta_3 = 0.21$,

A.T. Kruppa et. al. Nucl. Phys. A560, 845 (1993)

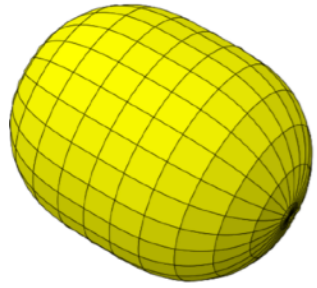
CCFULL 模型得到的最优形变参数 $\beta_3 = 0.21$

The emulator Consist 5 basis

($\beta_3 = \{0.10, 0.15, 0.20, 0.25, 0.30\}$).

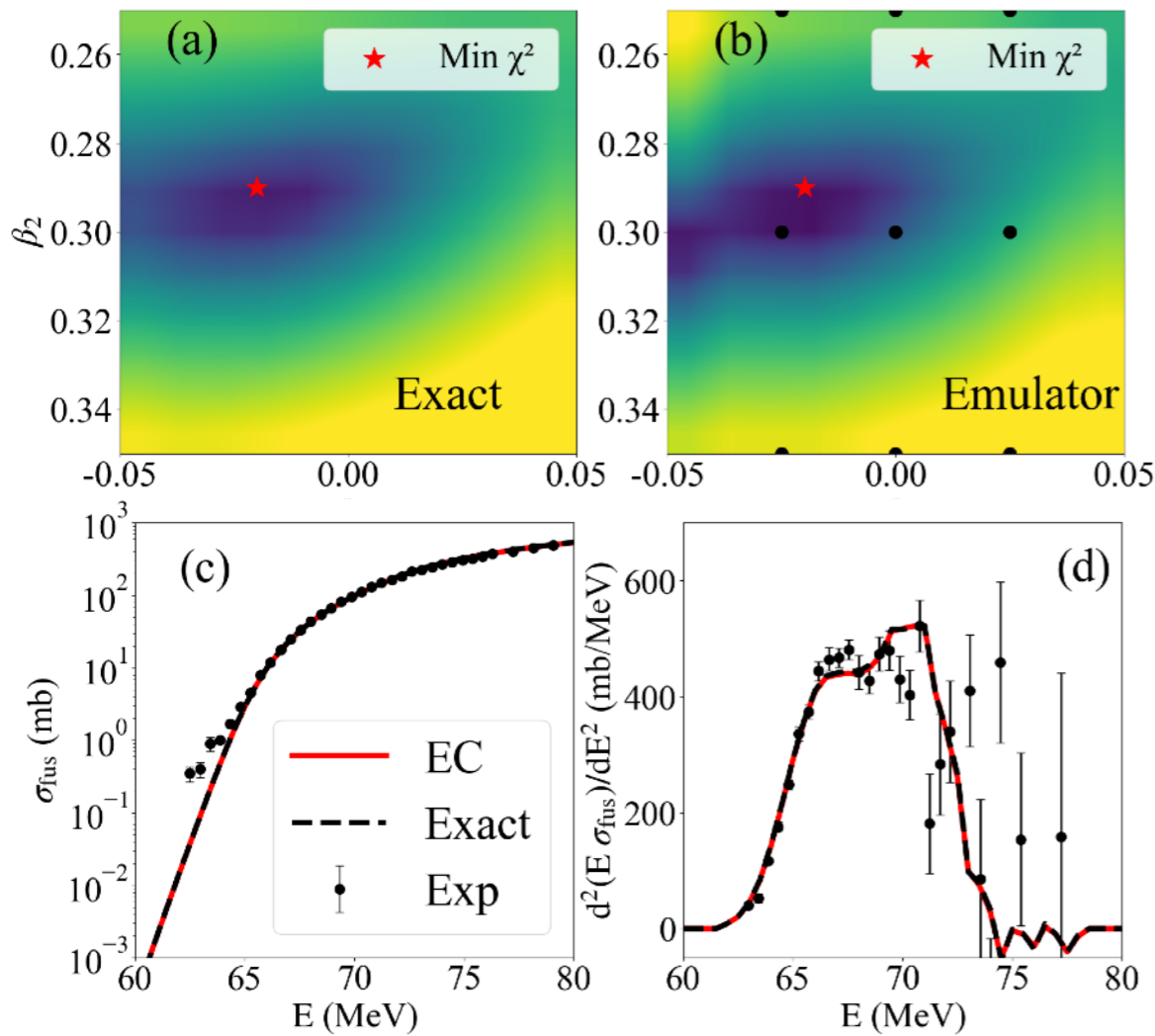


$^{16}\text{O} + ^{154}\text{Sm}, ^{186}\text{W}$



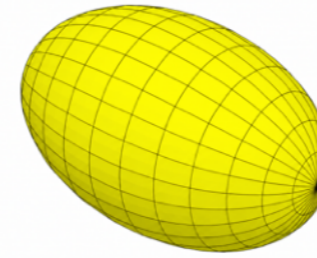
^{186}W

The emulator Consist 9 basis
 $(\beta_2 = \{0.25, 0.30, 0.35\},$
 $\beta_4 = \{-0.025, 0.0, 0.025\}).$



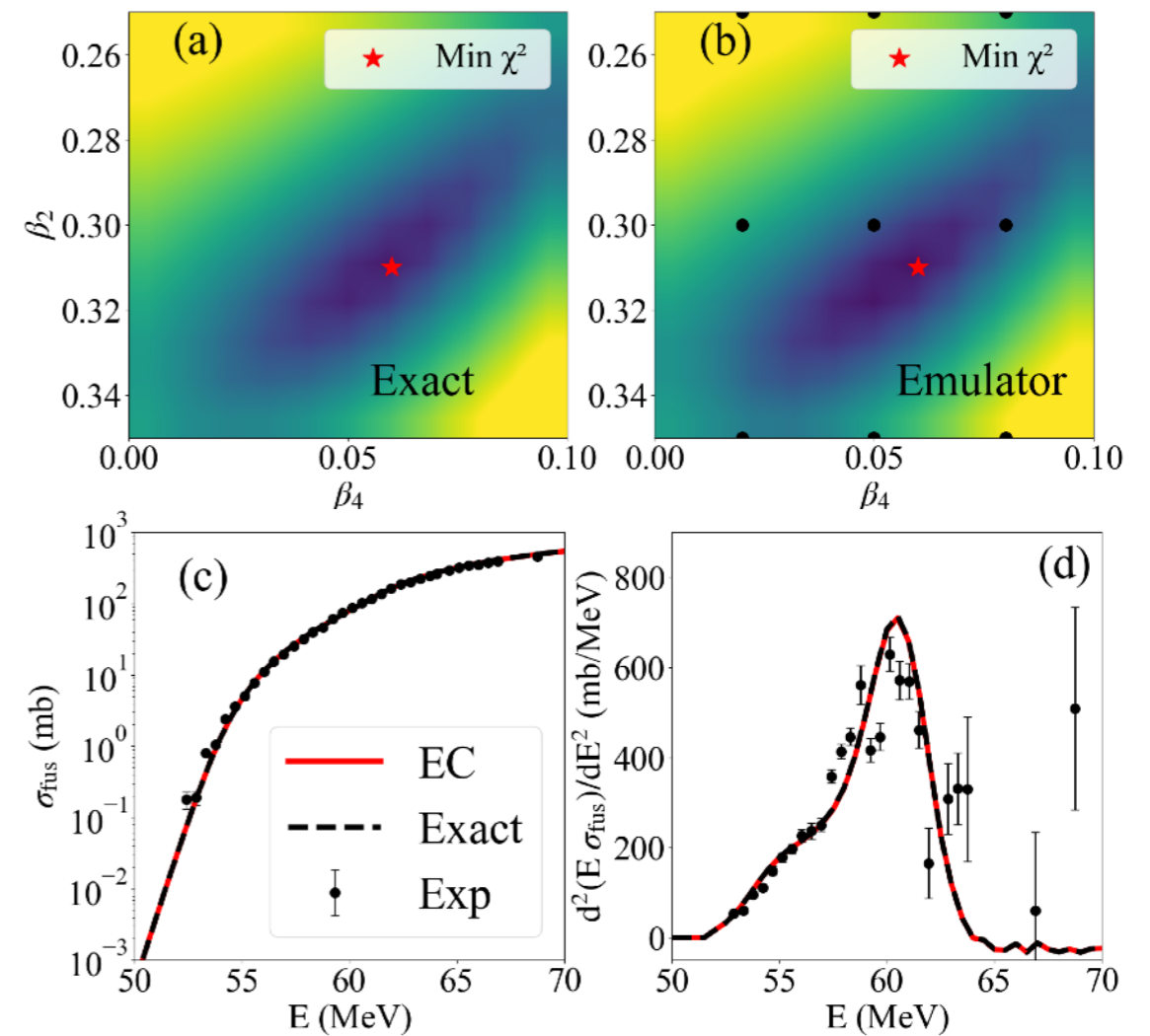
CCfull Exact result: $\beta_2 = 0.29, \beta_4 = -0.2$
CCfull Ec result: $\beta_2 = 0.29, \beta_4 = -0.2$

re-analysis by radius parameter $r = 1.06$ fm
 cf. (Mass calculation) : $\beta_2 = 0.25$ and $\beta_4 = -0.117$
 cf. (Neutron scattering): $\beta_2 = 0.203$ and $\beta_4 = -0.057$



^{154}Sm

The emulator Consist 9 basis
 $(\beta_2 = \{0.25, 0.30, 0.35\},$
 $\beta_4 = \{0.02, 0.05, 0.08\}).$

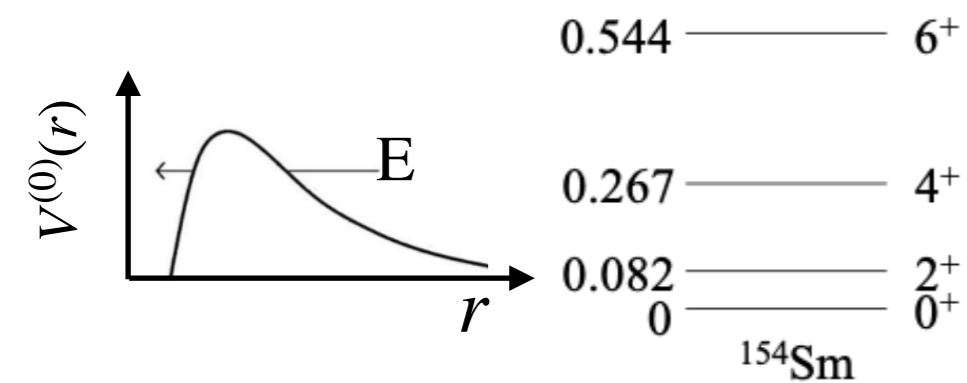


CCfull Exact result: $\beta_2 = 0.31, \beta_4 = 0.06$
CCfull Ec result: $\beta_2 = 0.31, \beta_4 = 0.06$

re-analysis by radius parameter $r = 1.06$ fm
 cf. (α scattering) : $\beta_2 = 0.317$ and $\beta_4 = 0.07$

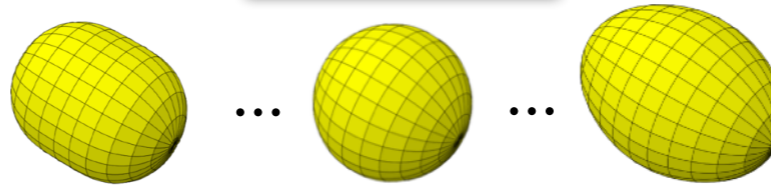
Summary

$$H = -\frac{\hbar^2}{2\mu}\nabla^2 + V^{(0)}(r) + H_{\text{int}}(\xi) + V_{\text{coup}}(r, \xi)$$

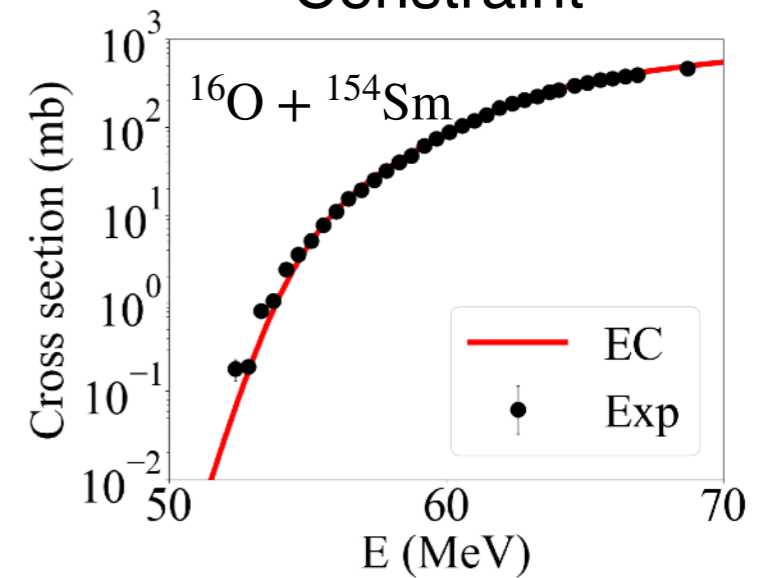


Emulation

$$H(\beta_2, \beta_4)$$



Constraint

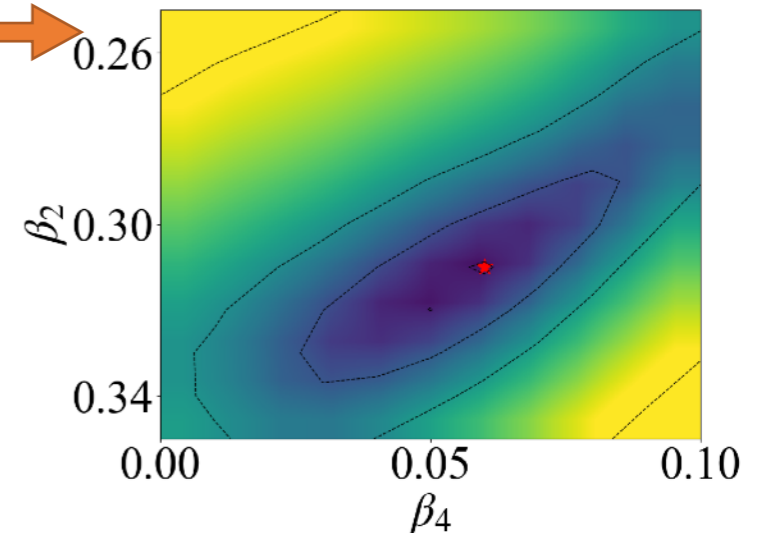


Snapshot

$$H \Psi = E \Psi \quad \left[\begin{array}{c} \Psi_1 \\ \Psi_2 \\ \Psi_3 \end{array} \right]$$

Projection

$$\left[\begin{array}{c} \Psi_1 \\ \Psi_2 \\ \Psi_3 \end{array} \right]^\dagger H \left[\begin{array}{c} \Psi_1 \\ \Psi_2 \\ \Psi_3 \end{array} \right] = \text{Matrix}$$



- 我们构建了Ec-CCFULL 的模拟器，并提出了通过低能核反应提取原子核形变的方法
- 我们基于该方法，成功提取出了 ^{144}Sm , ^{154}Sm , ^{186}W 的原子核形变

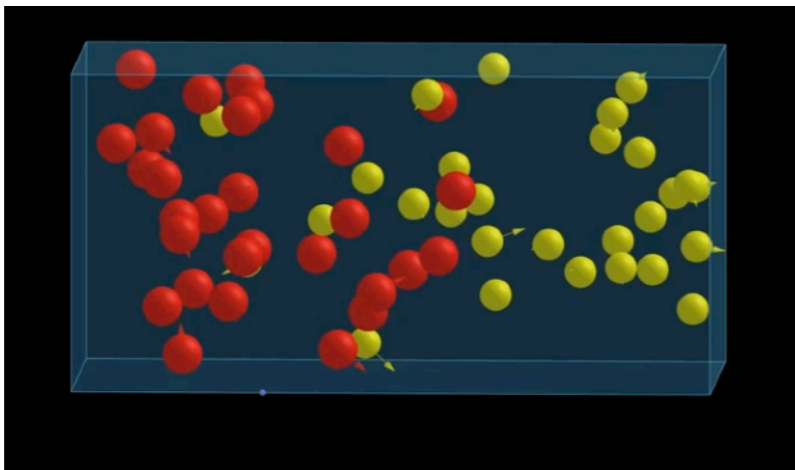
○ **N=126 核素的多核子转移反应非平衡演化的研究**

Zehong Liao, Long Zhu*; *Physical Review C* 107, 014614 (2023)

Zehong Liao, Long Zhu*; *Physical Review C* 109, 054612 (2024)

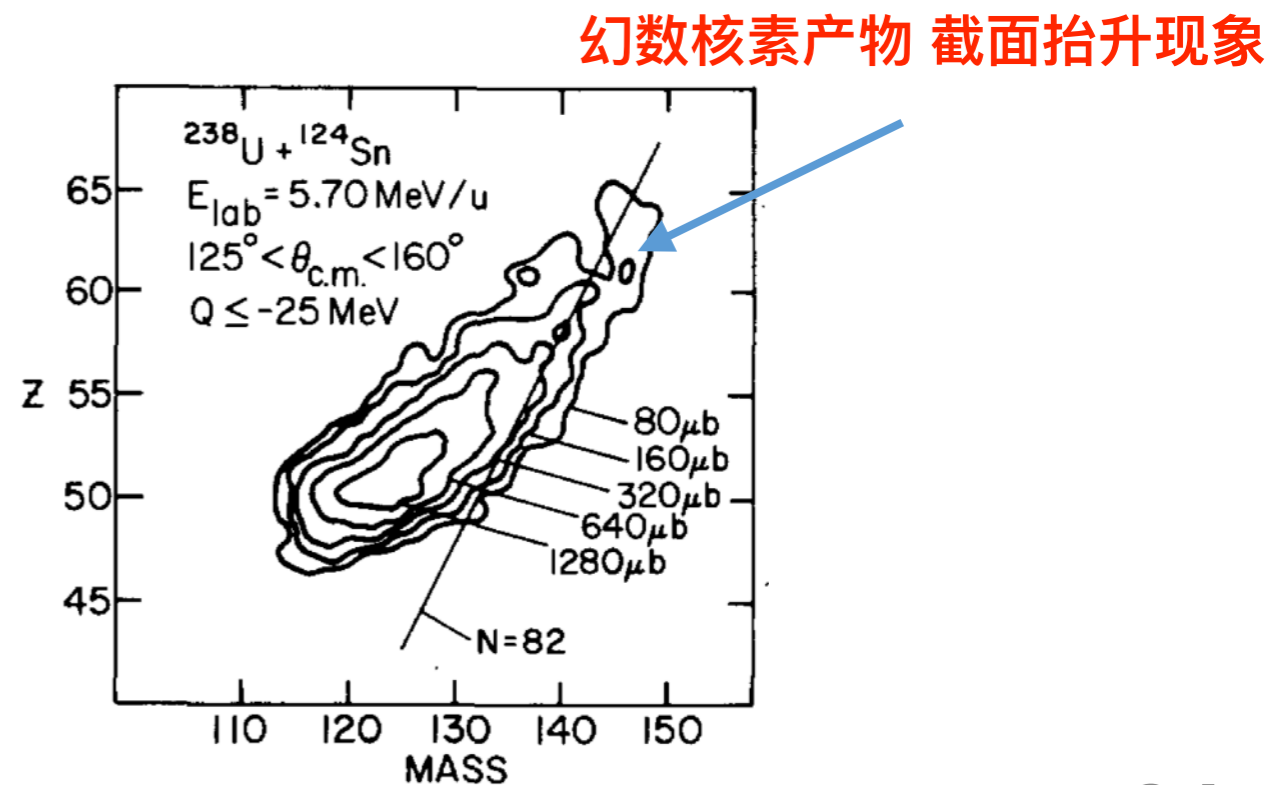
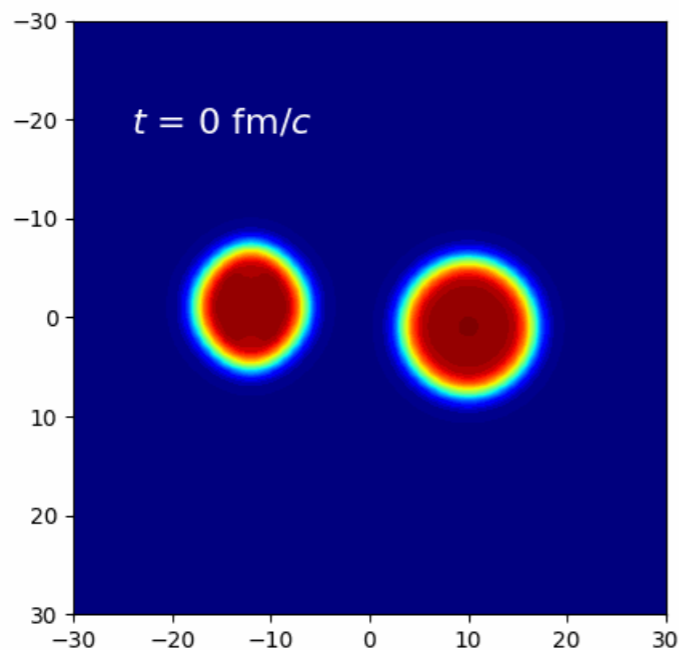
非平衡演化的普遍现象

经典宏观系统



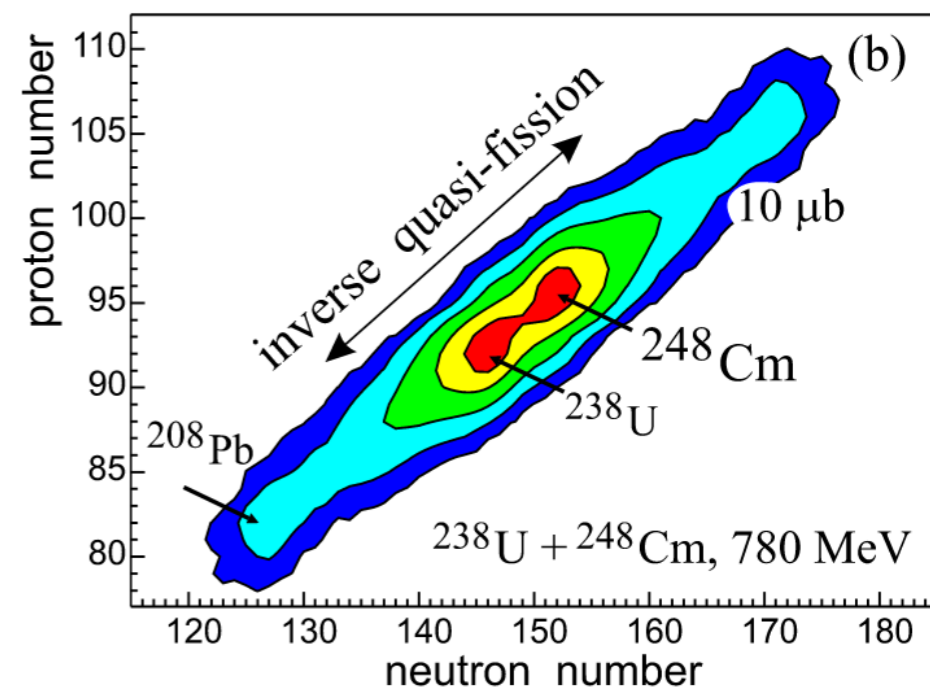
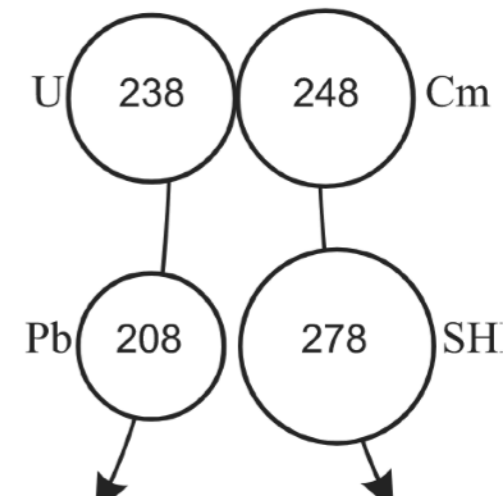
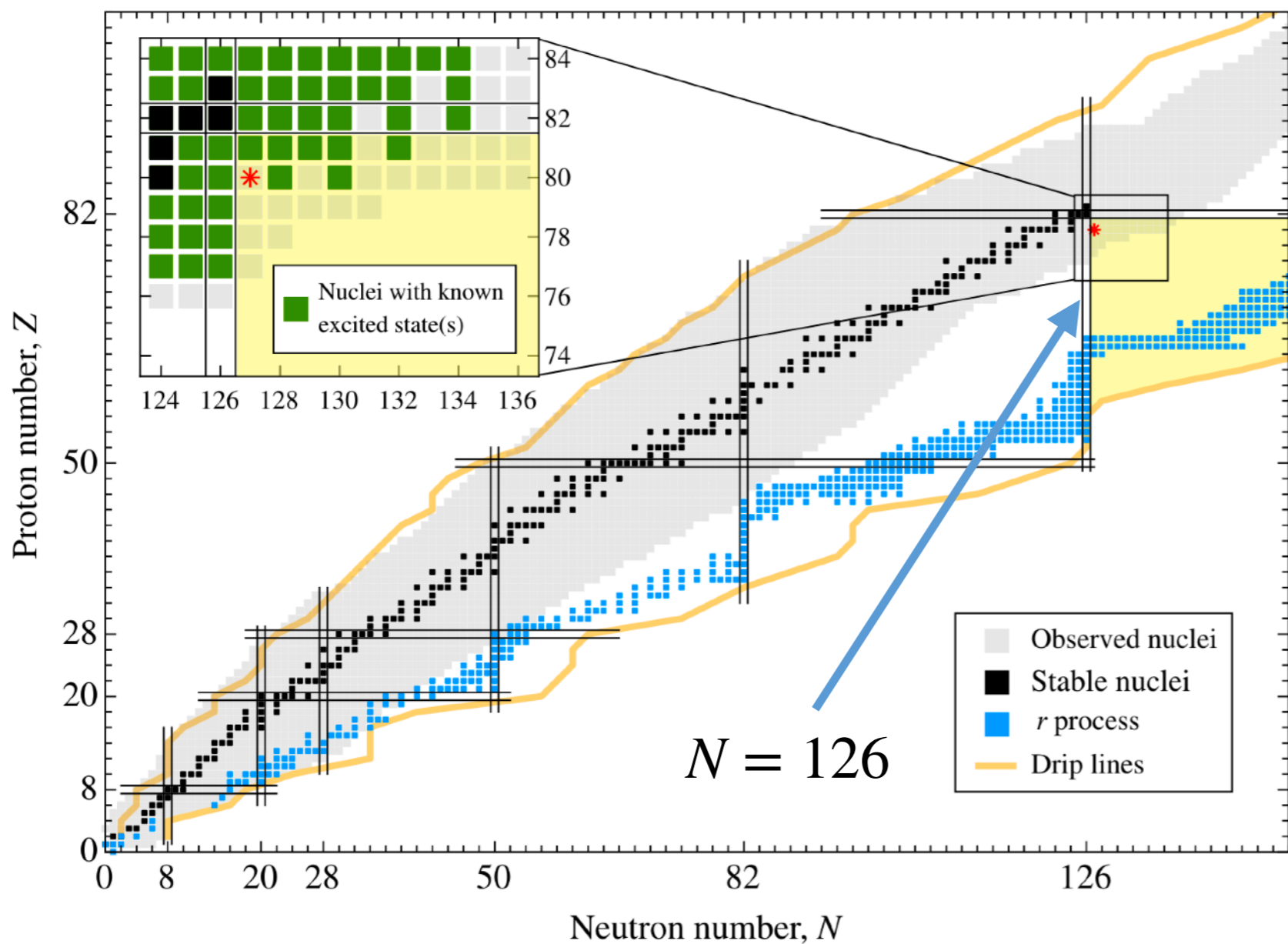
- 能否趋向平衡，如何趋向平衡，是否存在远离平衡的稳定态等，都是非平衡物理中的核心问题

原子核尺度系统



- 如果原子核反应看作一个非平衡演化问题，如何到达一个我们关心的稳定态

多核子转移反应非平衡演化的研究



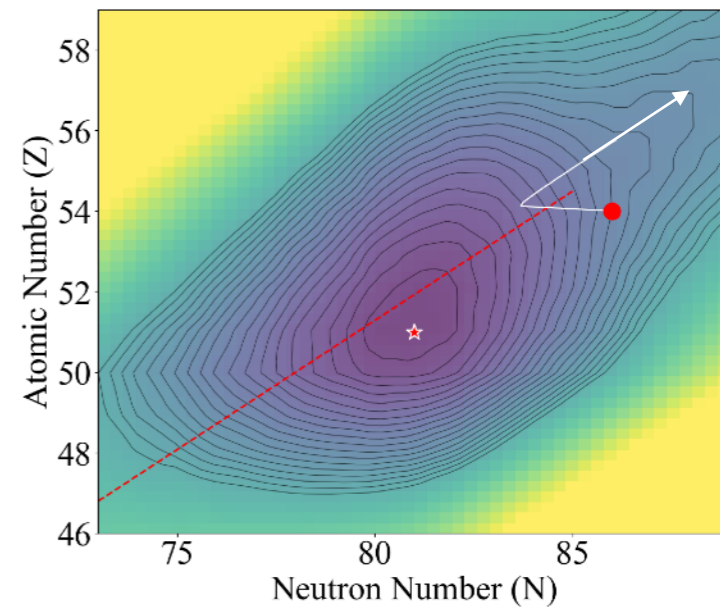
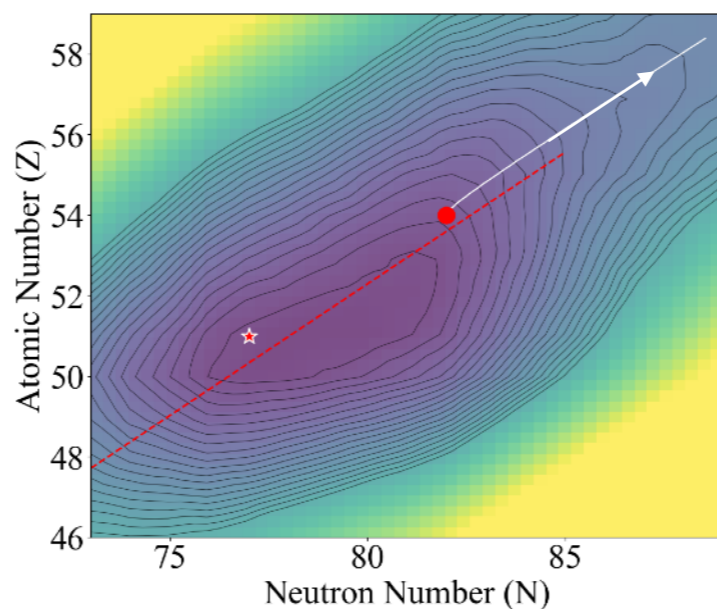
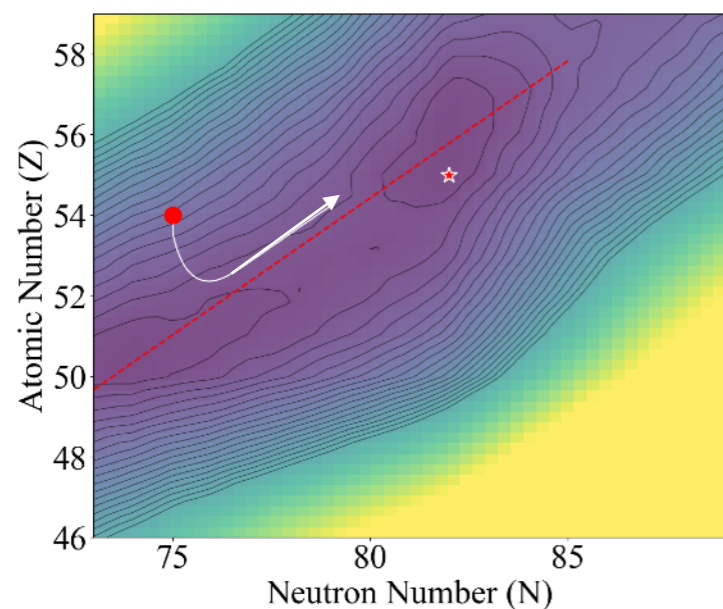
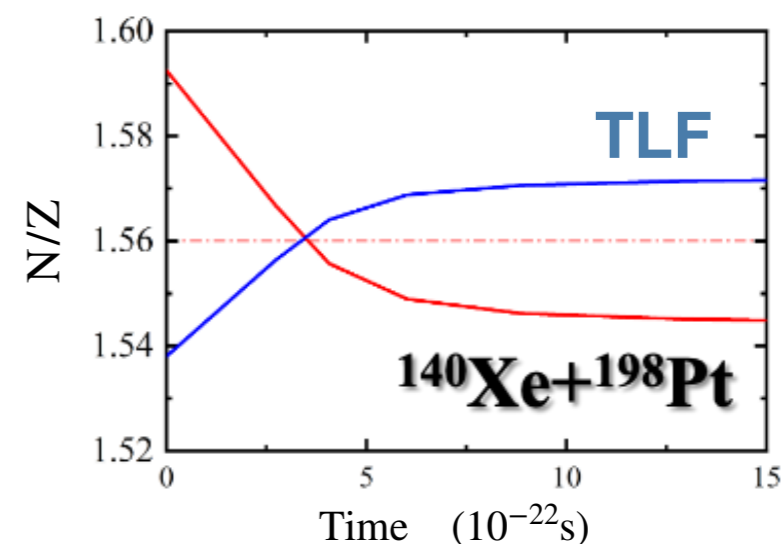
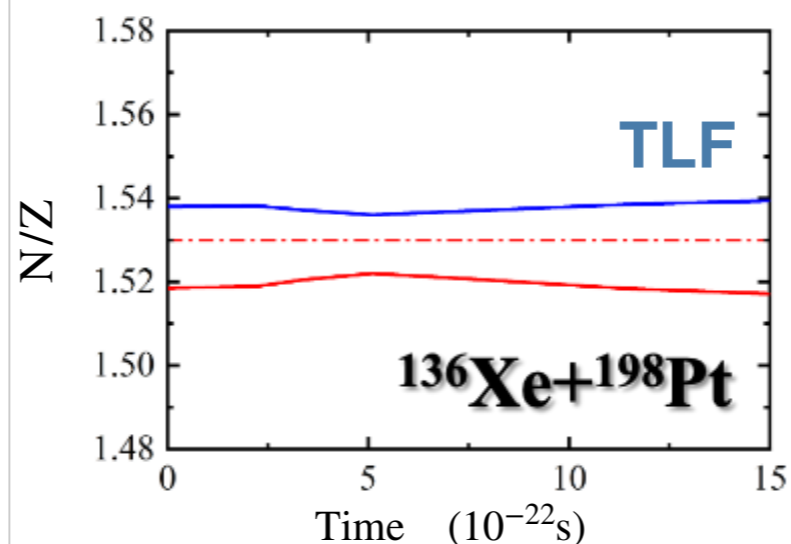
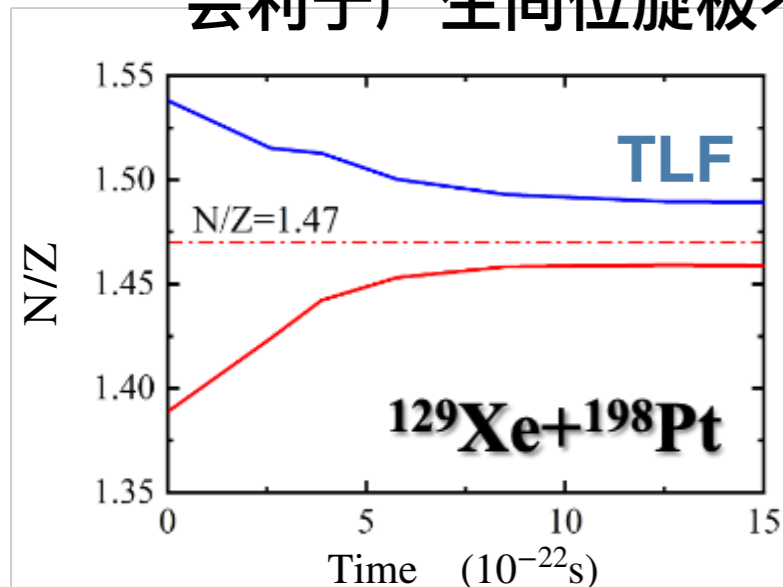
- 什么样的反应会利于产生同位旋极不对称的核素?
- 在高激发能下, 壳效应对非平衡过程的调控作用是否会衰弱?

多核子转移反应中的中质比平衡

Q: 对于产生极端丰中子的核素, 什么样的反应会利于产生同位旋极不对称的核素?

$$\bar{Z}_1(t) = \langle Z_1(t) \rangle = \sum_{Z_1} \sum_{N_1} \sum_{\beta_2} Z_1 \times P(Z_1, N_1, \beta_2, t)$$

$$\bar{N}_1(t) = \langle N_1(t) \rangle = \sum_{Z_1} \sum_{N_1} \sum_{\beta_2} N_1 \times P(Z_1, N_1, \beta_2, t)$$

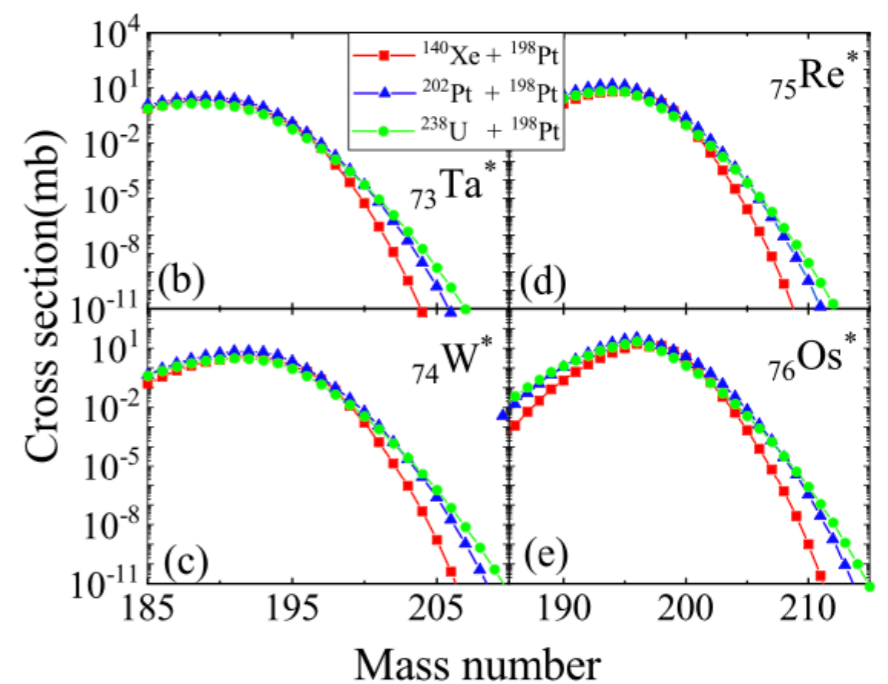
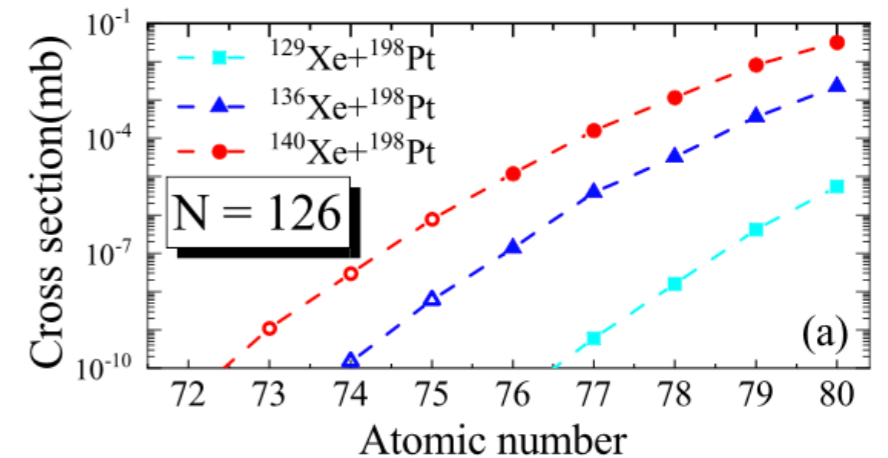
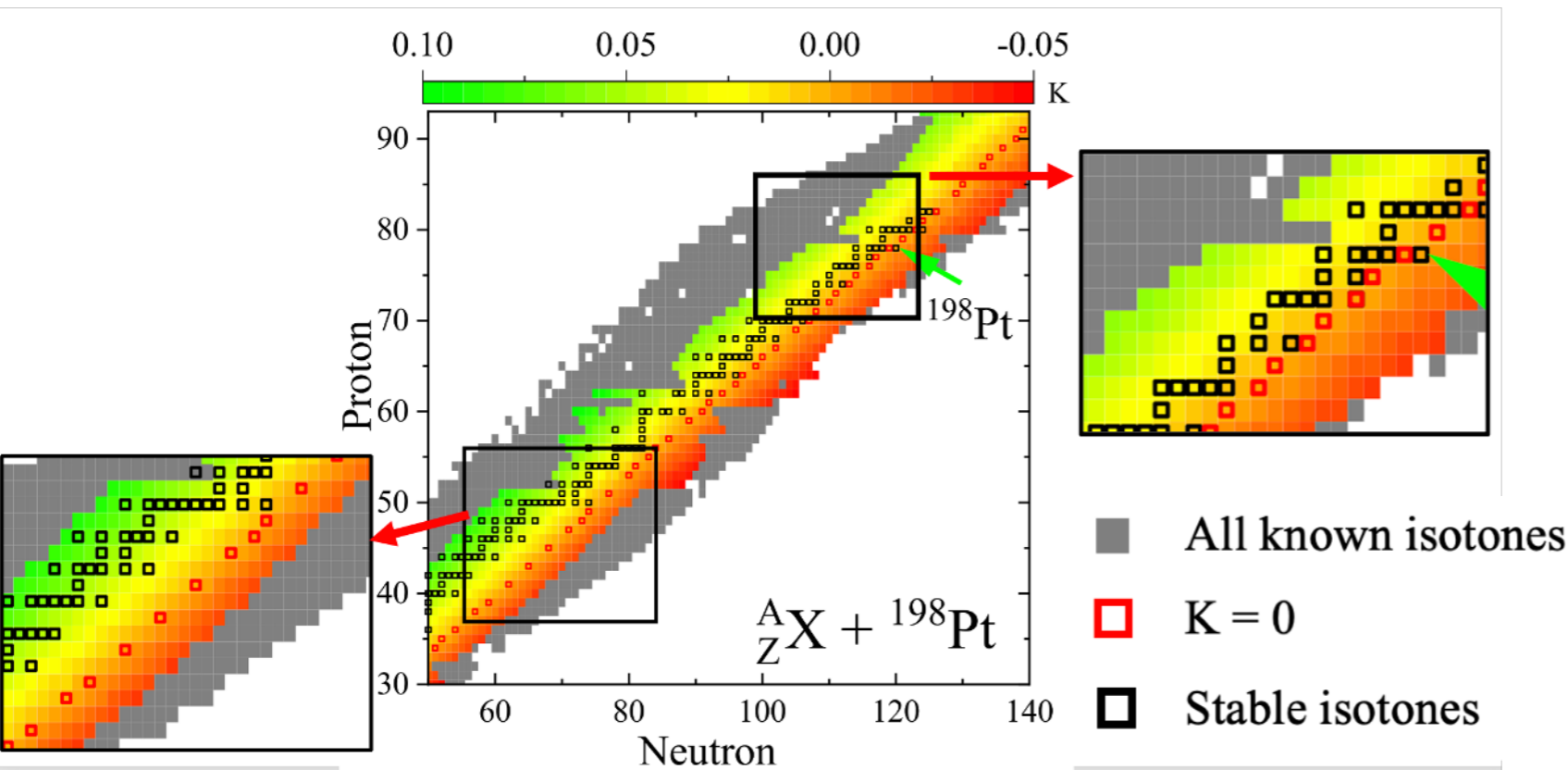


- 丰中子弹核素, 利于产生更加丰中子的 TLF 核素
- 发现了逆中质比平衡现象

同位旋平衡与质量平衡对丰中子核素产生

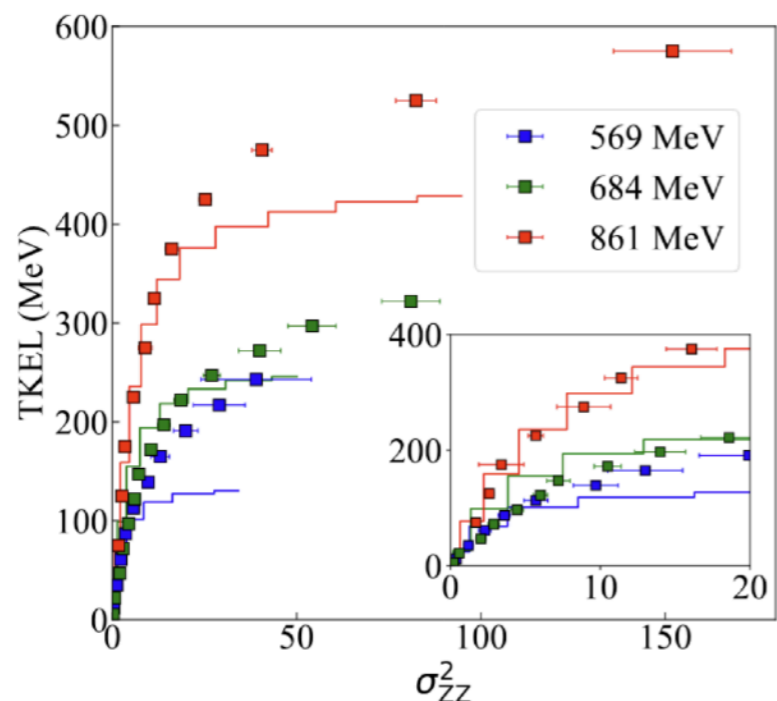
以 ^{198}Pt 为靶核，选取近1200个弹核，提取在不同体系中对 ^{198}Pt 的影响

$$K = \frac{\langle N/Z \rangle_{\text{TLF}} - \langle N/Z \rangle_{^{198}\text{Pt}}}{\langle N/Z \rangle_{\text{CN}}}$$

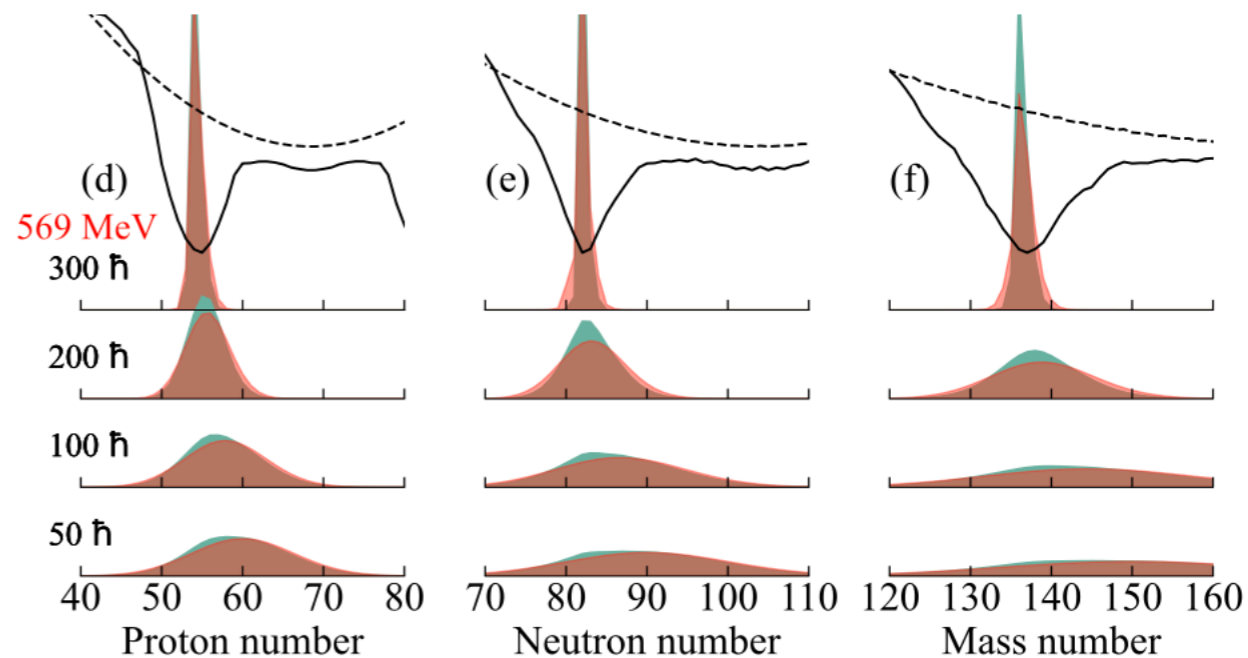
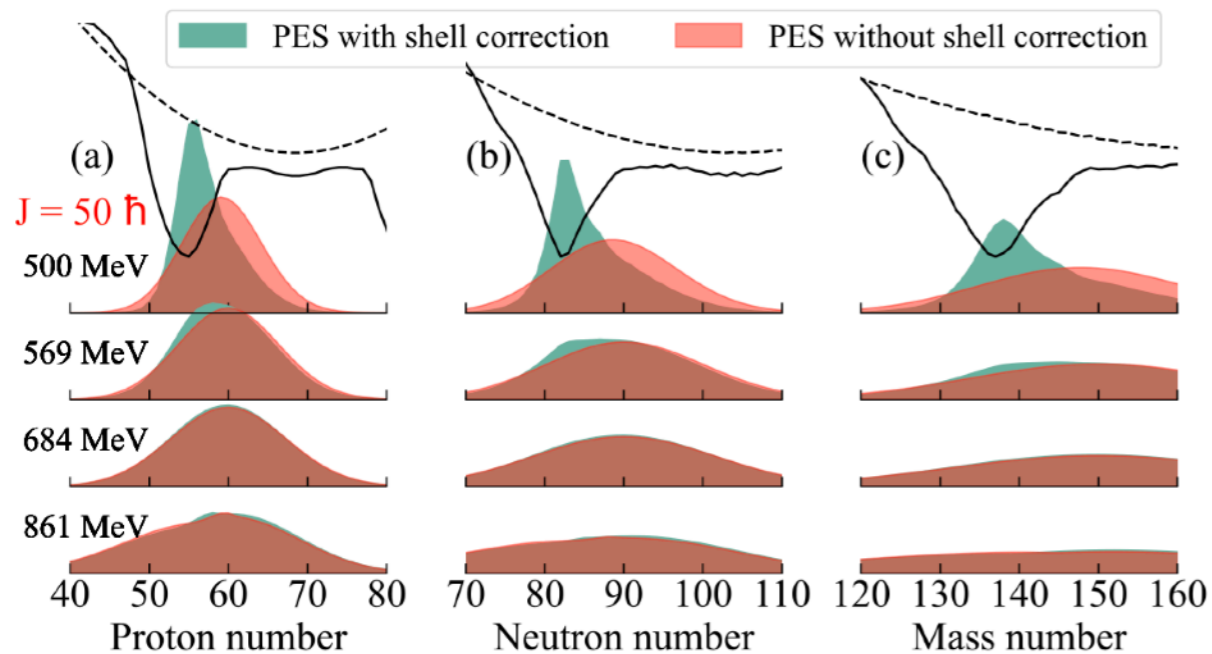
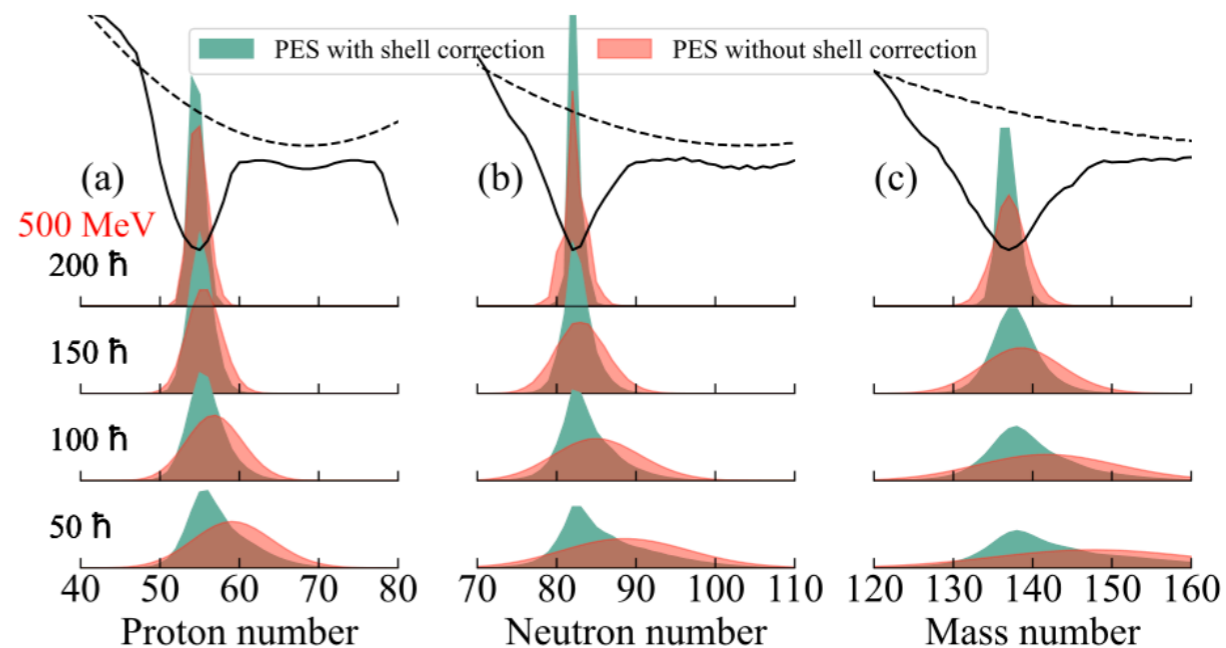


- 对于质量较轻的弹核，只有丰中子的放射性弹核束流才能促使丰中子的类靶核产物产生
- 对于质量较重的弹核，更有利于丰中子的类靶核产物产生

壳效应对原子核核子交换涨落的影响

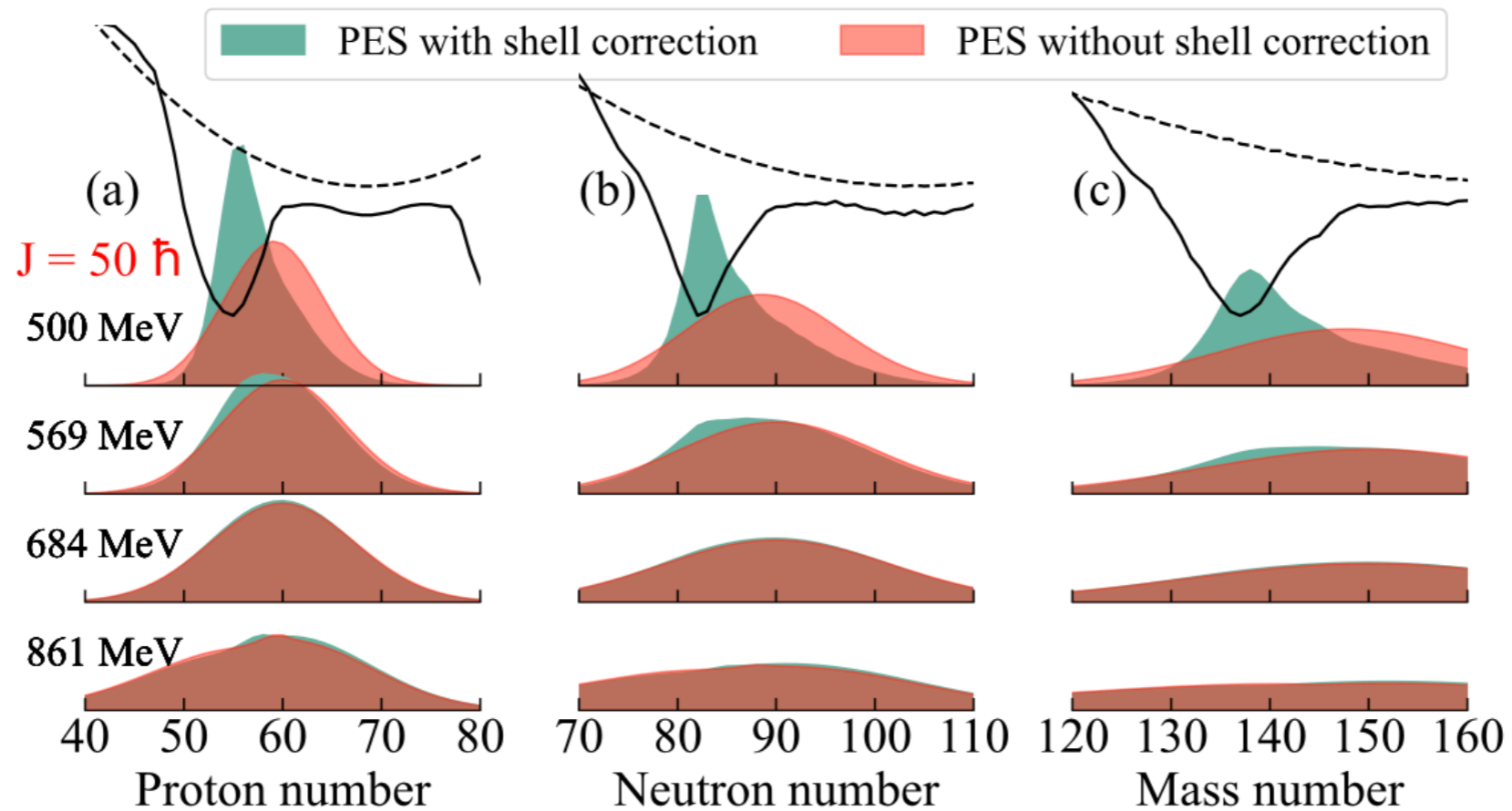


$$\sigma_{ZZ}^2(t) = \sum_{Z_1} \sum_{N_1} \sum_{\beta_2} (Z_1 - \bar{Z}_1(t))^2 \times P(Z_1, N_1, \beta_2, t)$$



- 在同一入射轨道角动量下，随着能量增加，核子交换的概率分布更加相似
- 低能情况下，壳修正效应明显，但能量更高情况下，该效应在消失

Summary



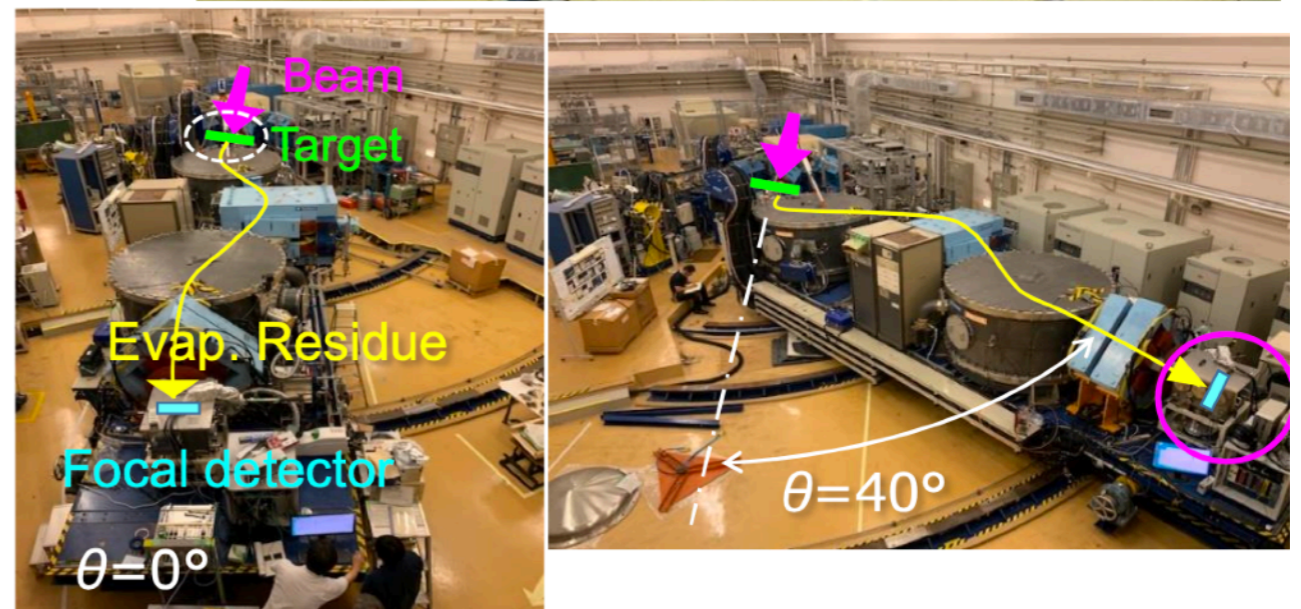
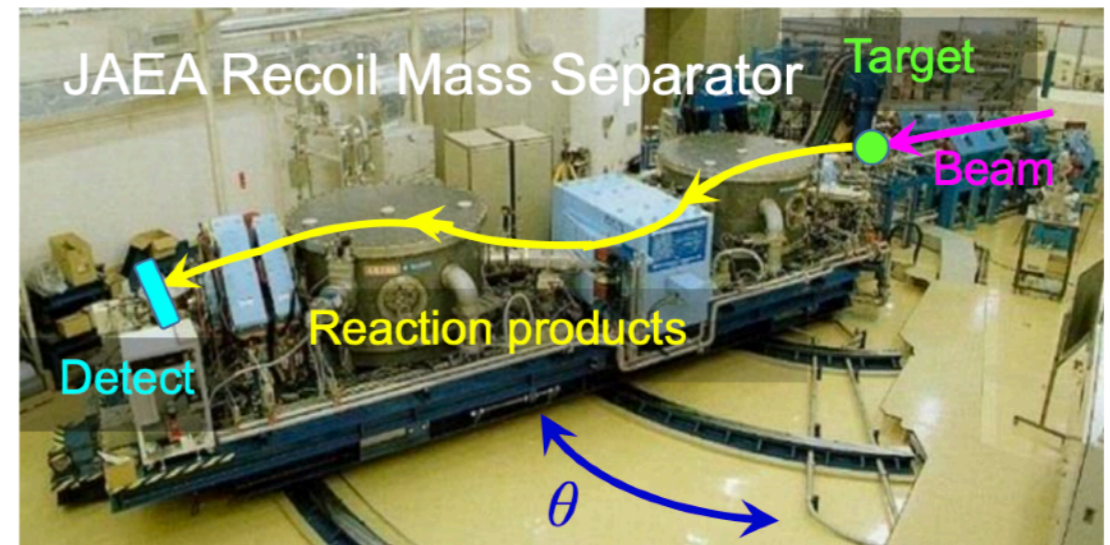
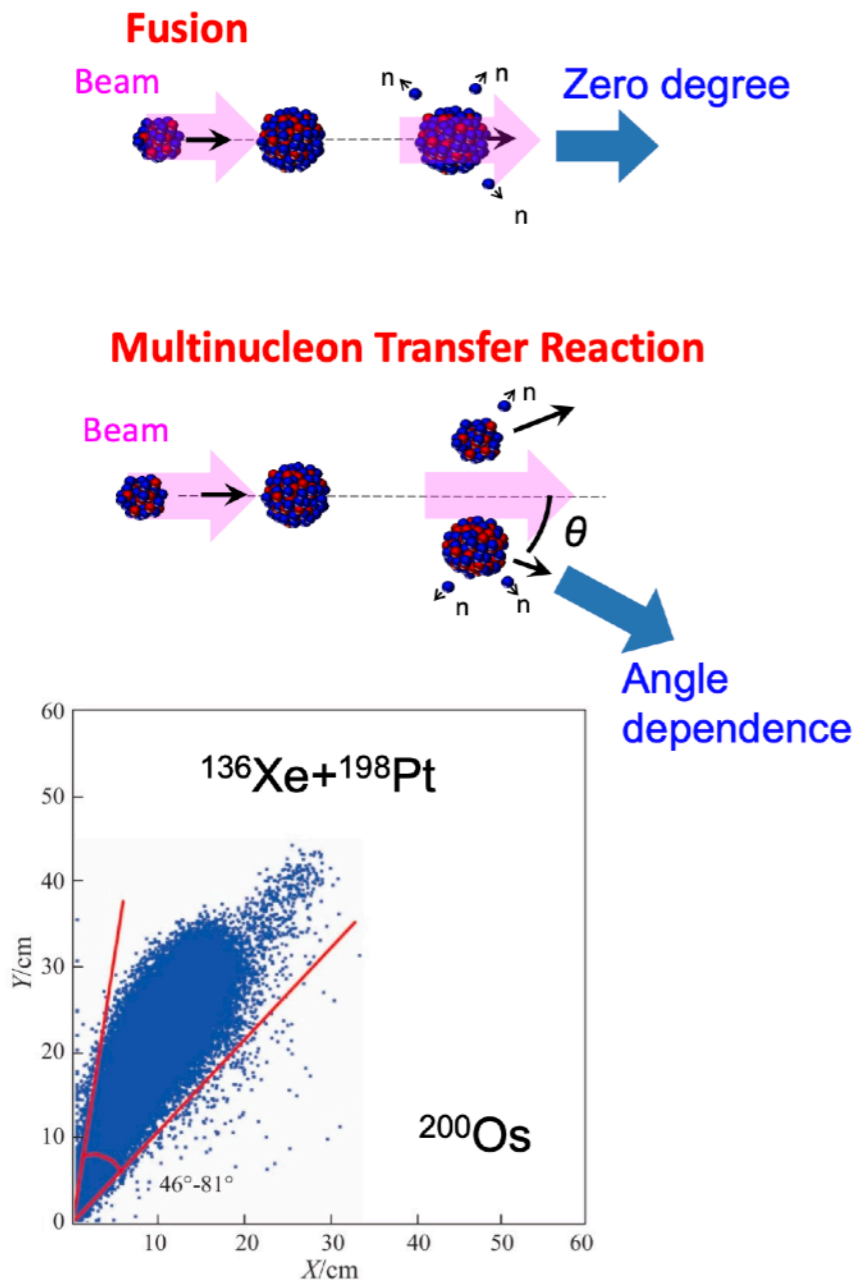
- 提取出了三种不同的 中质比平衡 模式。
- 定量计算了通过平衡模式对丰中子核素的影响，提出了 $^{238}\text{U} + ^{198}\text{Pt}$ 为最优反应体系。
- 分析了壳效应在核反应中对核子交换的影响。

○ **N=126 核素的多核子转移反应产物角分布的研究**

Zehong Liao, Long Zhu*; *Physical Review Research* 5, L022021 (2023) (Letter)

Zehong Liao, Long Zhu*; *Physical Review C* 111, 024605 (2025)

多核子转移反应产物角分布的复杂性

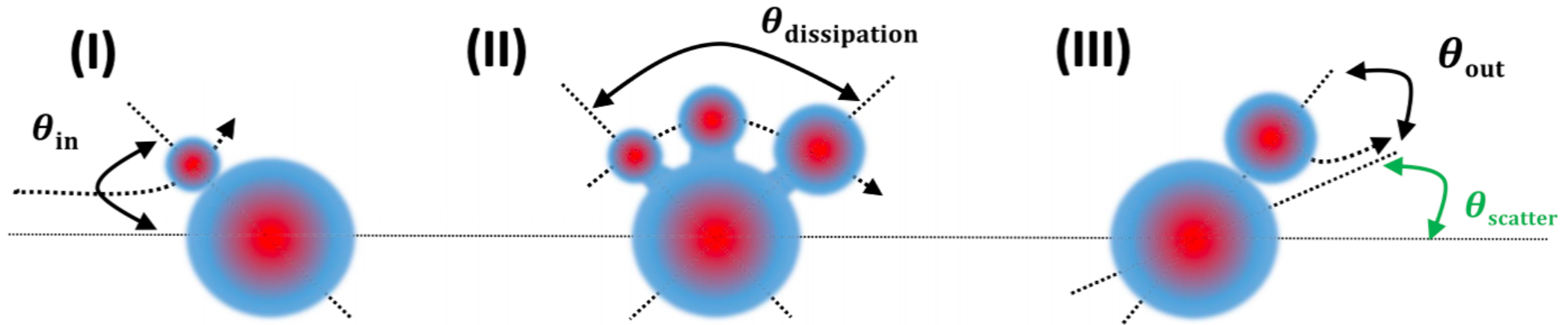


Wenxue Huang et al. Nucl. Phys. Rev. (2017)

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

- MNT 反应产物的出射并非集中在 0° 附近的前冲方向，而是覆盖了较宽的锥角范围。
- 这给我们所感兴趣的 MNT 反应产物的收集与分离带来了很大困难，因此需要理论支持。

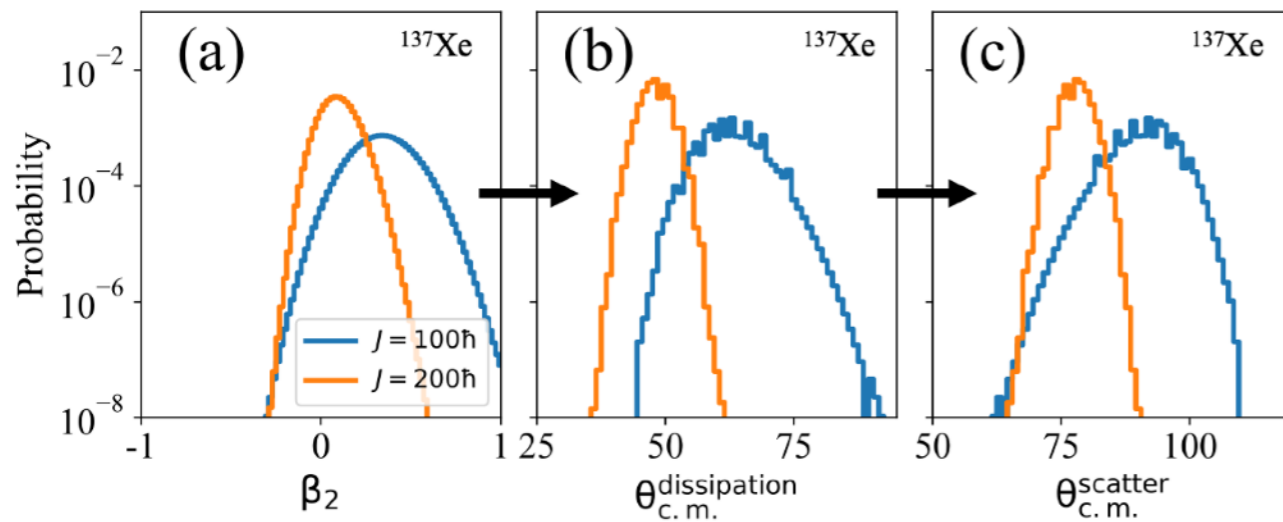
双核模型 - 角分布



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

◆ Under the Center of mass frame

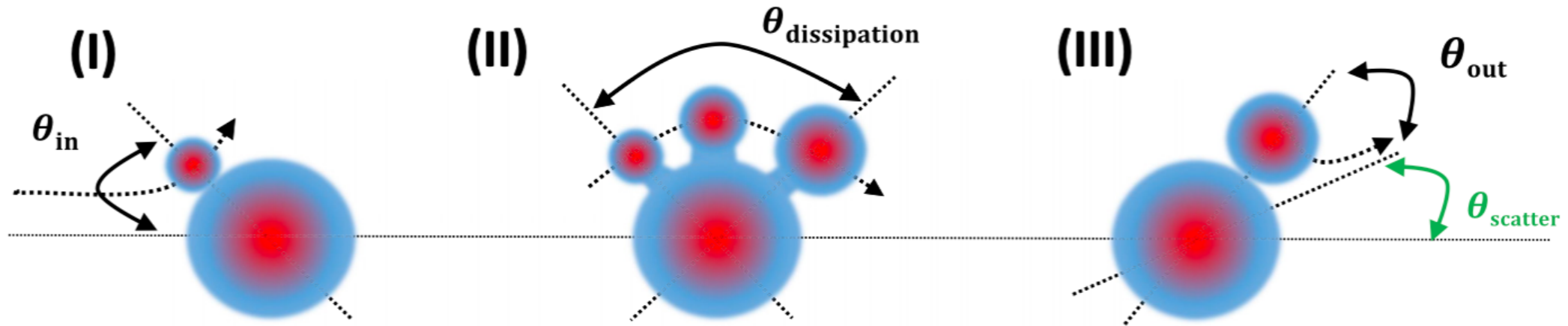
四级形变的概率 耗散角的概率 出射角的概率



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

- 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

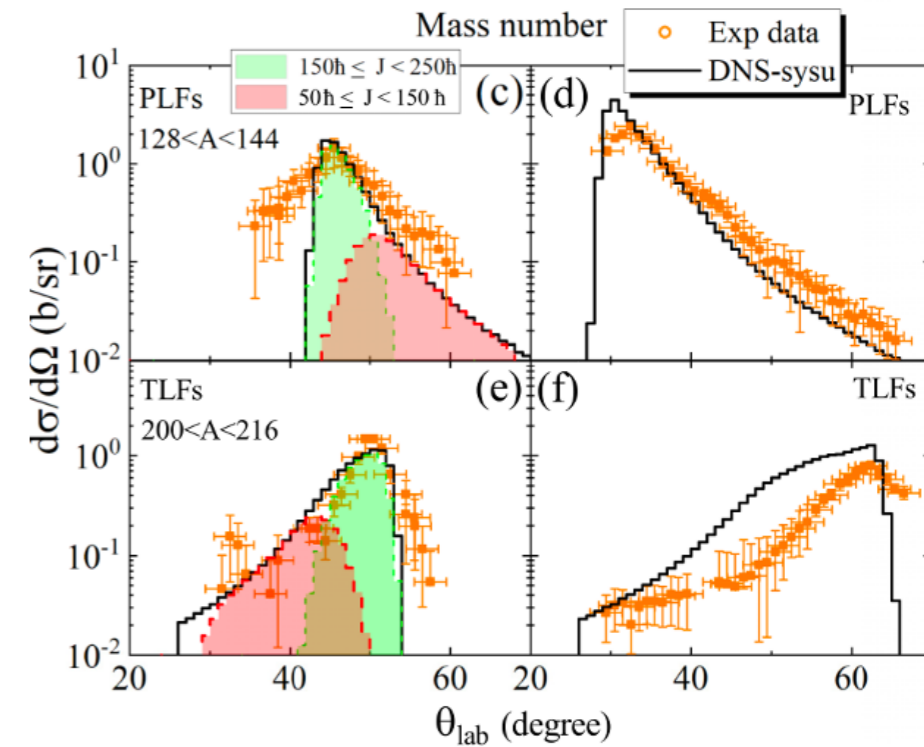
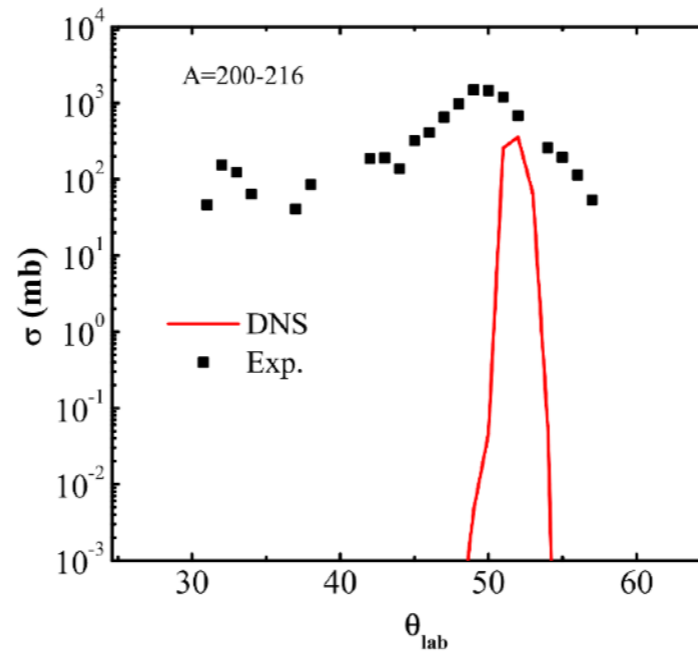
双核模型 - 角分布



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

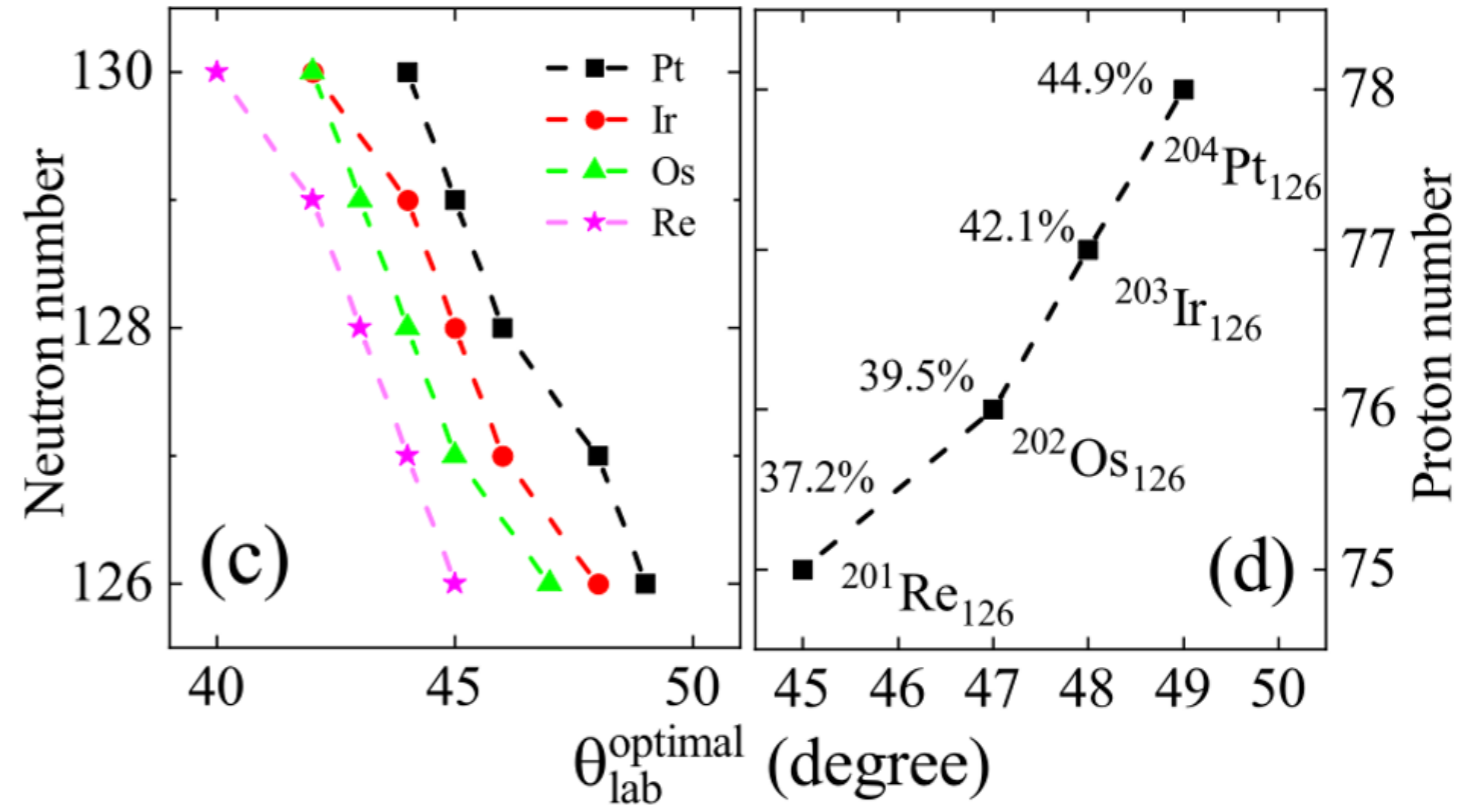
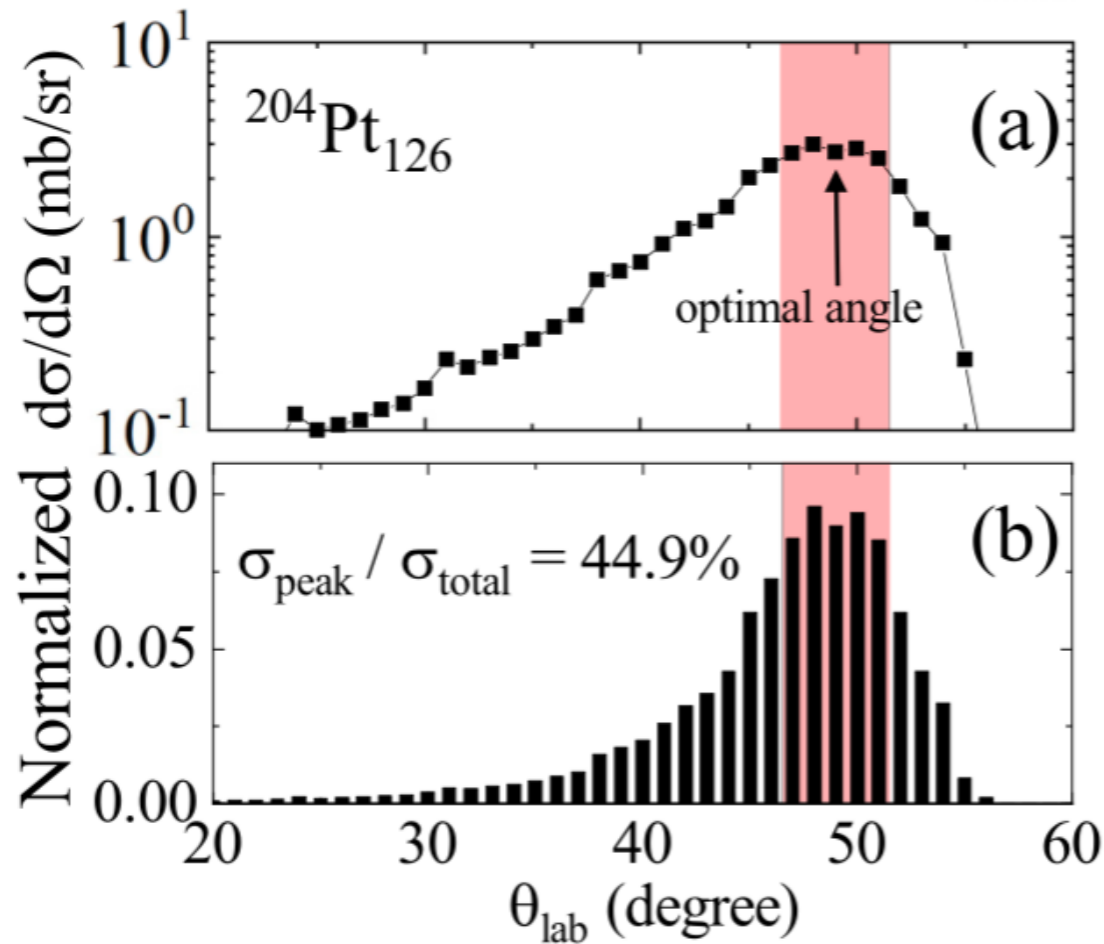
$$\theta_{\text{dissipation}} = \omega_{\text{DNS}} * t_s = \int^{t_s} \frac{J(t)\hbar}{\langle I \rangle} dt.$$

- 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



多核子转移反应产物的角分布

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



- 我们发现，在 47° 到 51° 的角度范围内，可以探测到 44.9% 的产额。在最佳角度下，近一半的反应产物都能够被探测到。

三参数 半经验公式

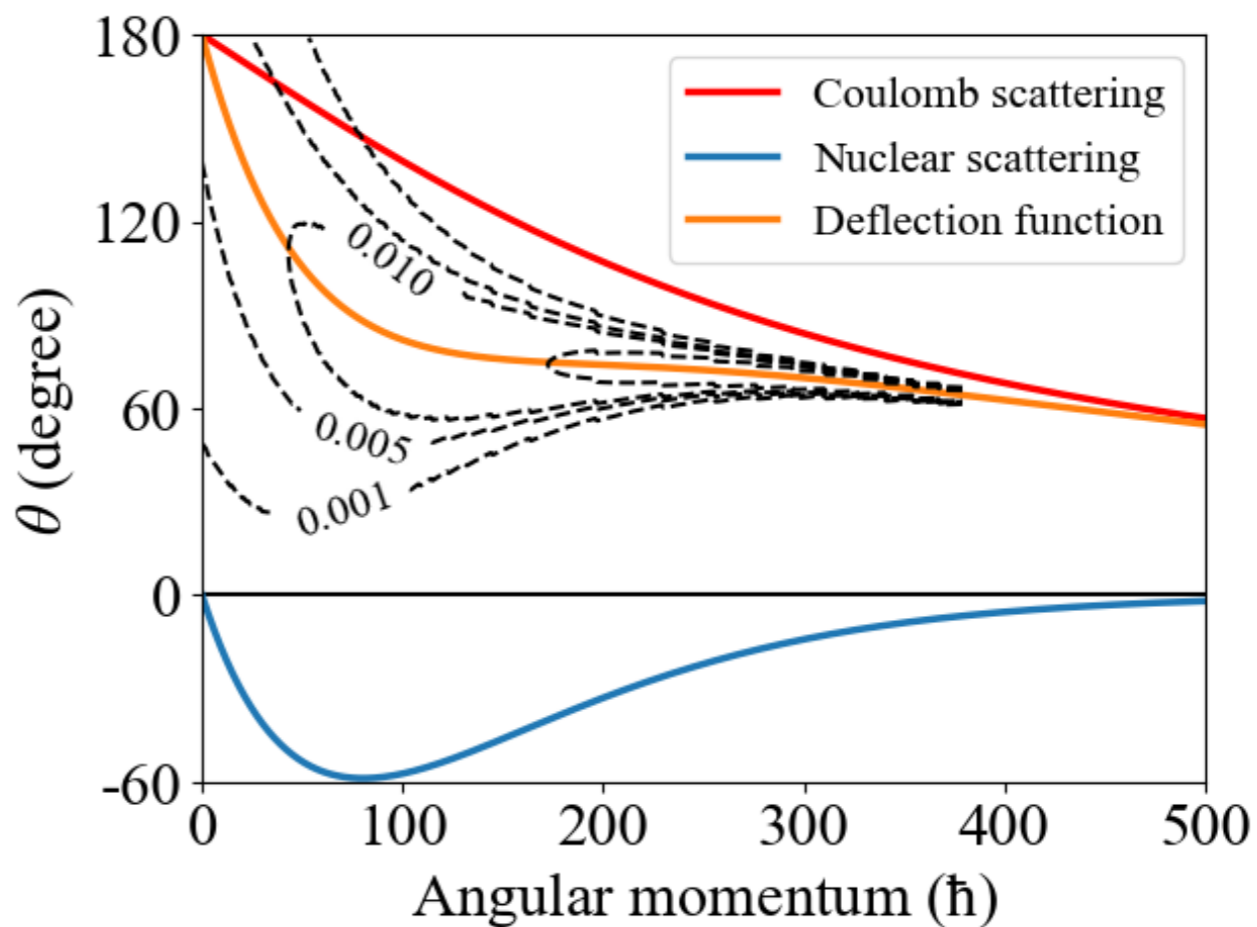
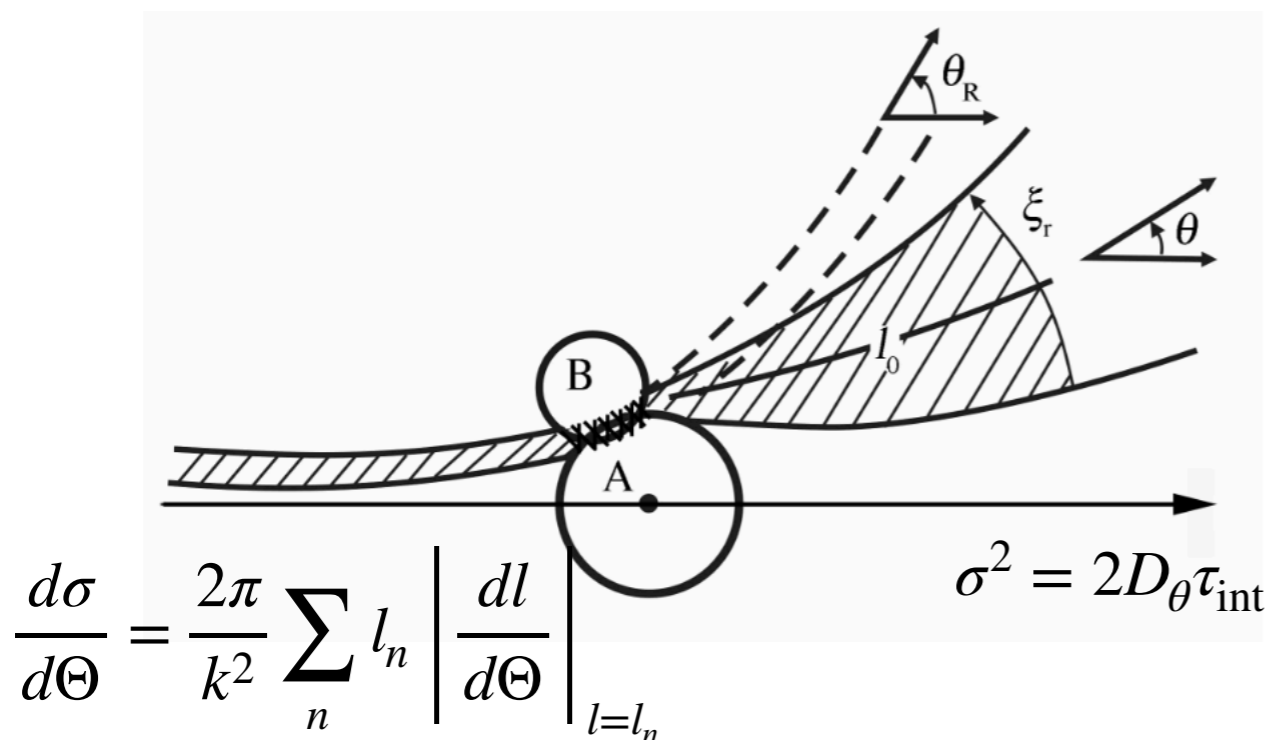
$$\Theta(l_i) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(\Theta - \bar{\Theta})^2}{2\sigma^2}\right) \left(2 \arctan \frac{Z_p Z_T e^2}{2E_{c.m.} b} - \beta \Theta_C^{gr} \frac{l_i}{l_{gr}} \left(\frac{\delta}{\beta}\right)^{l_i/l_{gr}} \right)$$

高斯分布

库伦偏转角

参数化核势偏转角

引入高斯分布来考虑碰撞过程中的涨落效应



参数 σ 、 β 和 δ 通过实验体系与反应能量进行拟合

三参数 半经验公式

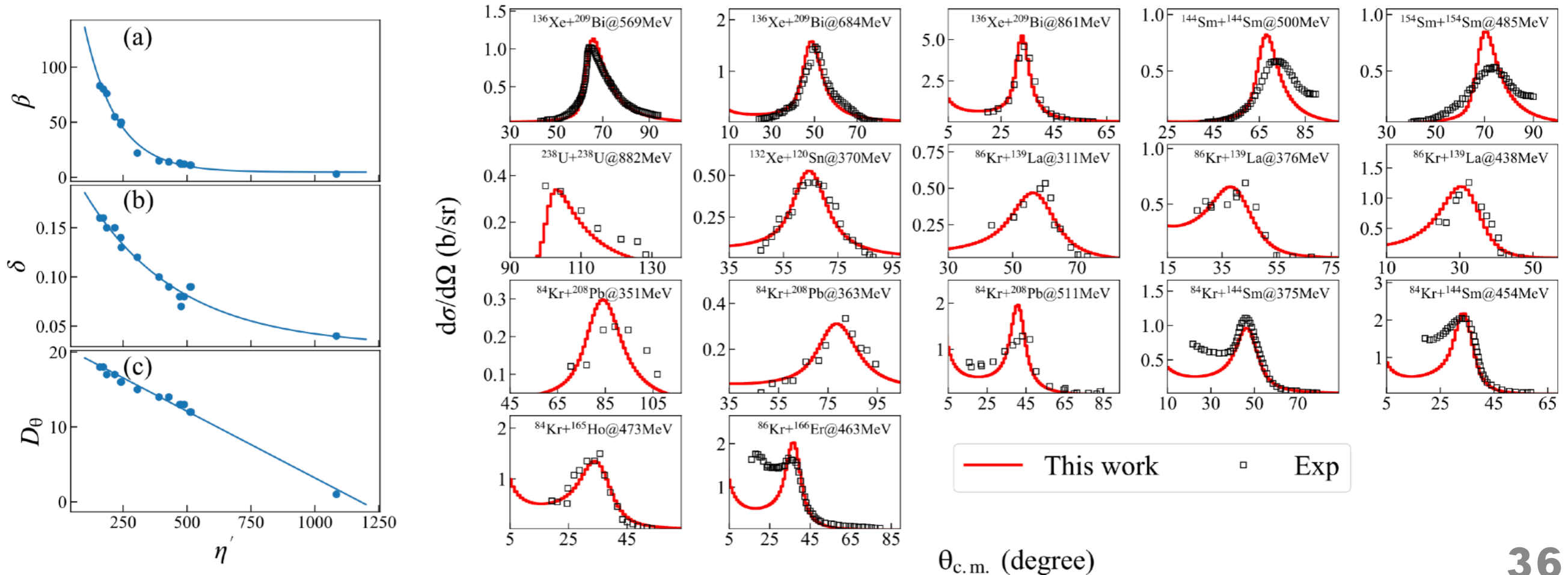
$$\Theta(l_i) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(\Theta - \bar{\Theta})^2}{2\sigma^2}\right) \left(2 \arctan \frac{Z_p Z_T e^2}{2E_{c.m.} b} - \beta \Theta_C^{gr} \frac{l_i}{l_{gr}} \left(\frac{\delta}{\beta}\right)^{l_i/l_{gr}}\right)$$

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

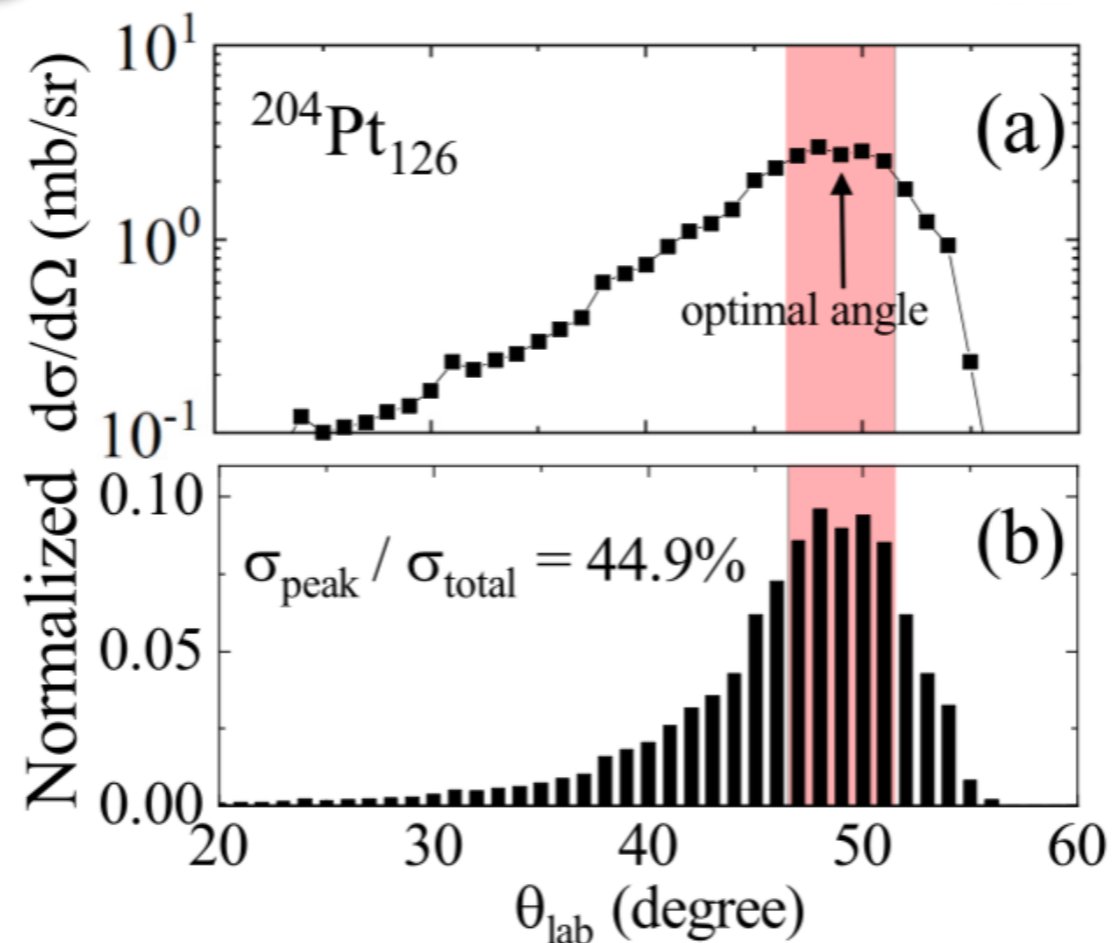
$$\delta(\eta) = 0.029 + 0.127 * \exp[-(\eta - 176.3)/364]$$

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

$$\eta' = Z_1 Z_2 e^2 / v', \quad v' = [2/A_{red}(E_{c.m.} - V(R_{int}))]^{1/2}$$



Summary

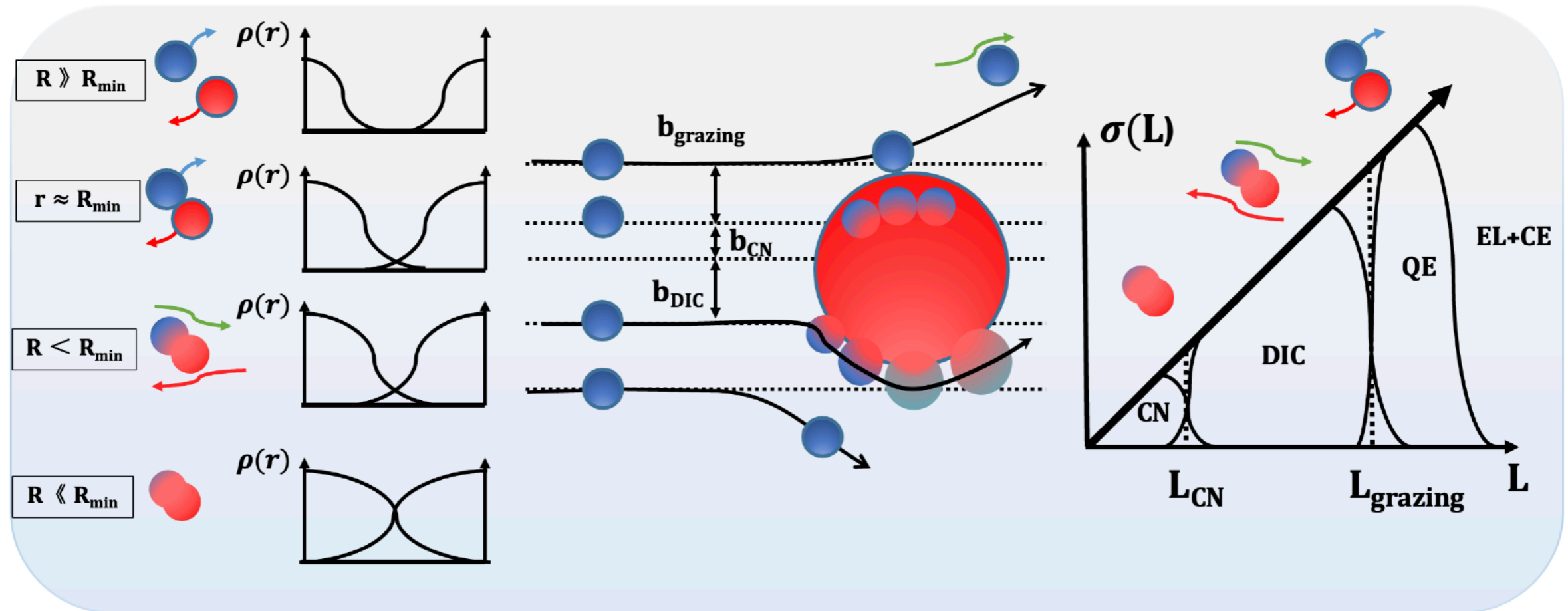


- 基于 **DNS** 模型框架，我们提出了一种构建散射角分布的方法。以 $^{136,144}\text{Xe} + ^{208}\text{Pb}$ 反应为例，计算结果与现有实验数据吻合良好。
- 针对入射能量为 $E_{\text{c.m.}} = 526 \text{ MeV}$ 的 $^{136}\text{Xe} + ^{208}\text{Pb}$ 反应，我们预测了 $N = 126$ 丰中子核素（如 ^{204}Pt , ^{203}Ir , ^{202}Os , ^{201}Re ）的最佳探测角度范围为实验室系 $45^\circ \leq \theta_{\text{lab}} \leq 50^\circ$ 。
- 我们也提出了一套半经验计算 MNT 反应的角分布公式，可以避免计算核反应模型的演化过程，快速计算反应的角分布。

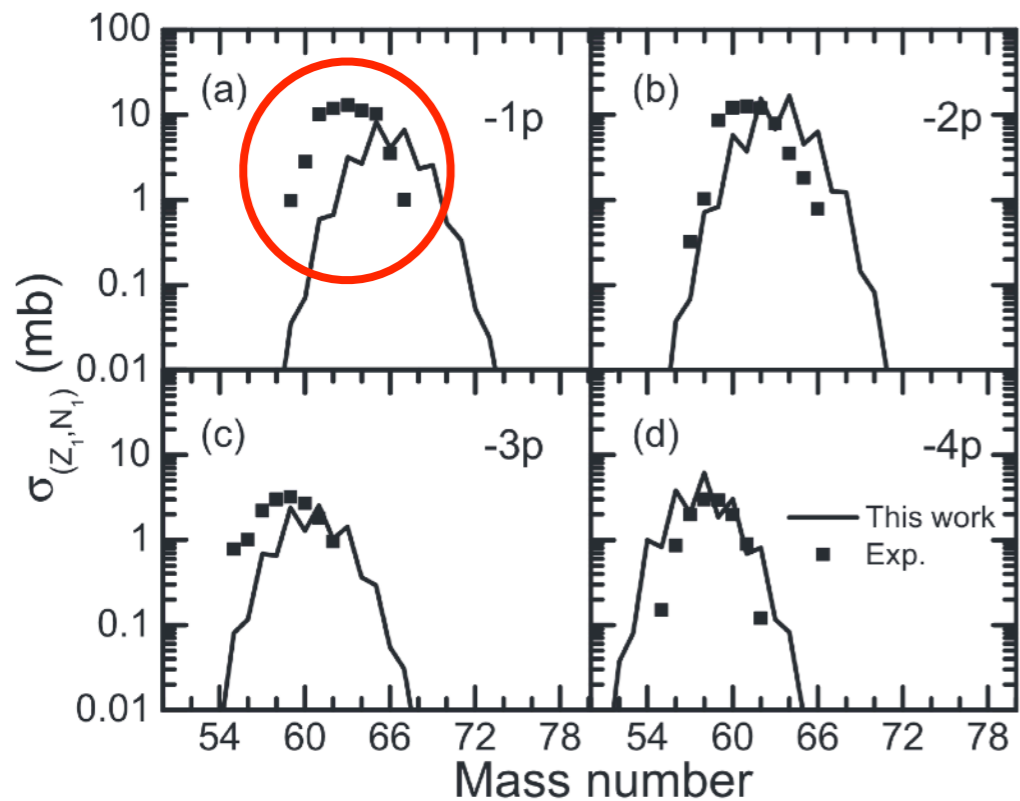
○ **N=126 核素的多核子转移反应准弹性转移机制**

Zehong Liao, Long Zhu*; *Physical Review C* 112, L051601 (2025) (Letter)

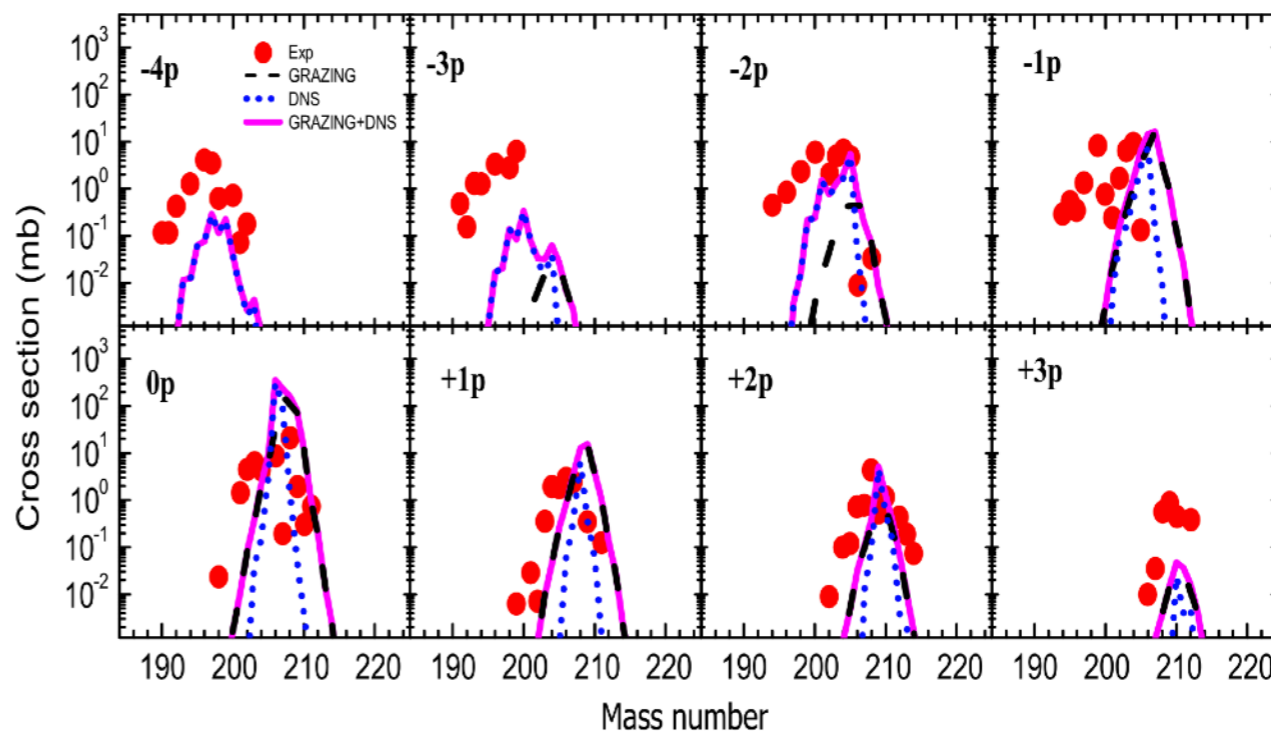
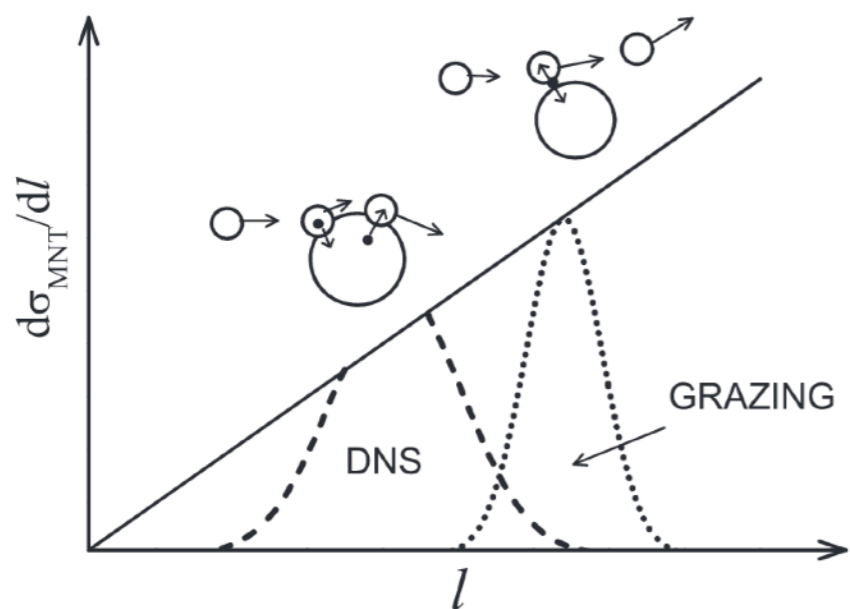
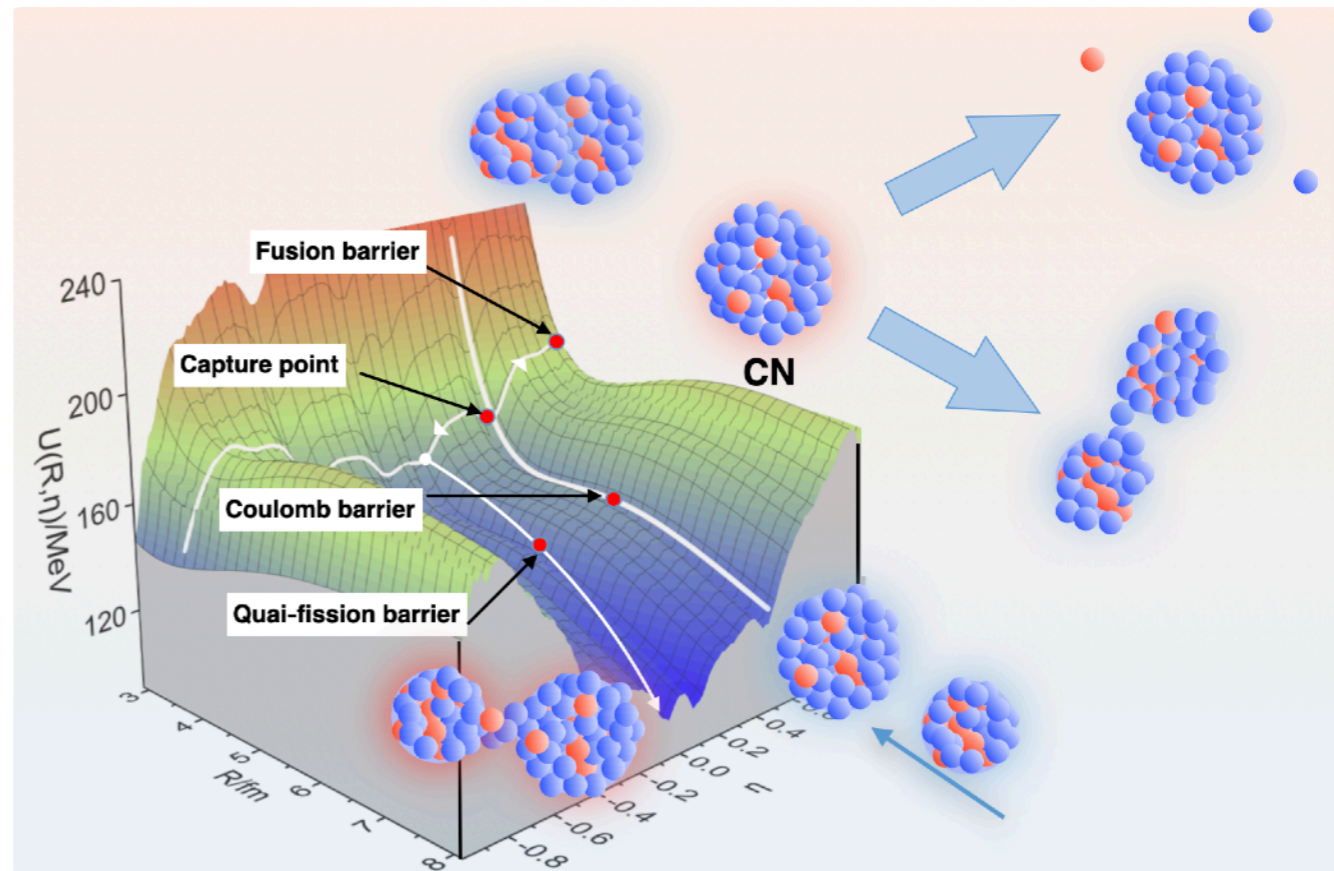
准弹性转移



双核系统模型 低估 准弹性转移道的贡献



PHYSICAL REVIEW C 102, 054613 (2020)



J. Phys. G: Nucl. Part. Phys. 44 (2017) 115101

单核子转移概率

Z. Phys.A - AtomicNuclei 326,463-481 (1987)

Brink [25]. We will consider the barrier to be static and we assume that the nucleon tunnels between two levels with the same energy (binding energy E_B). In a WKB and first order approximation the probability for the transmission through the barrier between two points x_1 and x_2 is given by (see Fig. 16)

$$P = \exp(-2Q) \quad (14)$$

with

$$Q = \int_{x_1}^{x_2} \left(\frac{2m}{\hbar^2} (V(x) - E_B) \right)^{1/2} dx; \quad x_d = x_1 - x_2. \quad (15)$$

$V(x)$ is the potential barrier and x_d is the distance between the two potential edges x_1 and x_2 .

If we assume $V(x)$ to be constant ($\equiv 0$), we immediately obtain with $\alpha = (2m/\hbar^2 |E_B|)^{1/2}$, the exponential dependence used as an approximation to our data

$$P \simeq \exp(-2\alpha x_d). \quad (16)$$

$$W^\pm = \lambda_0 \sqrt{\frac{\rho(A \pm 1)}{\rho(A)}} P_{tr}(R, \beta, A \rightarrow A \pm 1)$$

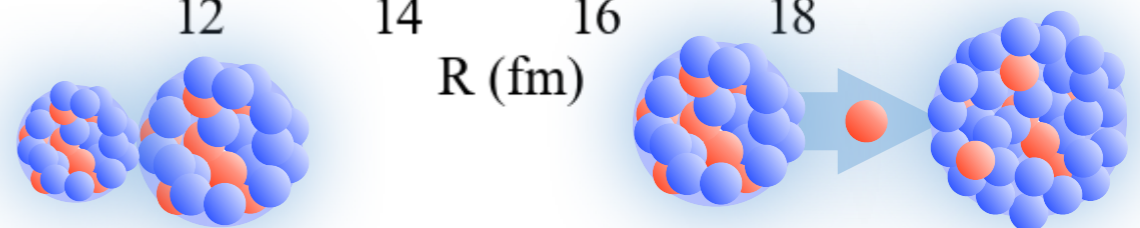
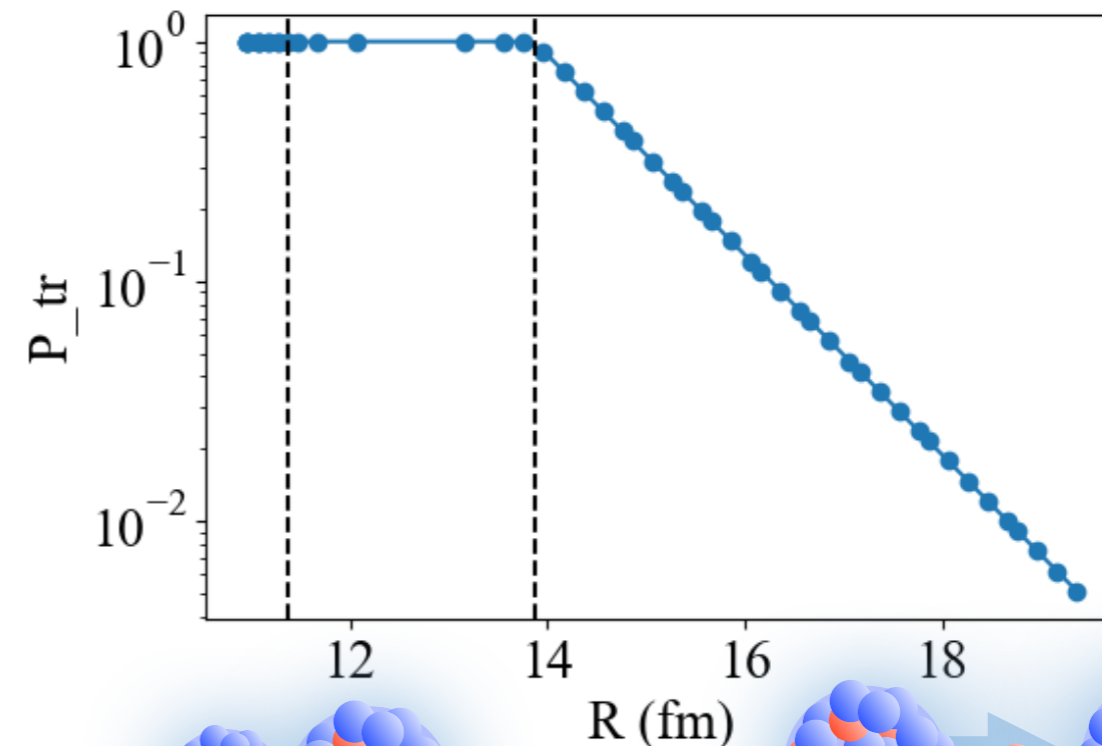


Probability of a nucleon transfer

$$P_{tr}(R, \beta, A \rightarrow A \pm 1) = \exp(-2k[r_c - r_0])$$

中子 $k = \sqrt{M(-\epsilon_F)/2\hbar^2} + \sqrt{M(-\epsilon'_F)/2\hbar^2} \quad [1/\text{fm}]$

质子 $k = \sqrt{M(-\epsilon_F + Z_T e^2/R_T)/2\hbar^2} + \sqrt{M(-\epsilon'_F + Z_P e^2/R_P)/2\hbar^2} \quad [1/\text{fm}]$



单核子转移概率

$$W^\pm = \lambda_0 \sqrt{\frac{\rho(A \pm 1)}{\rho(A)}} P_{tr}(R, \beta, A \rightarrow A \pm 1)$$

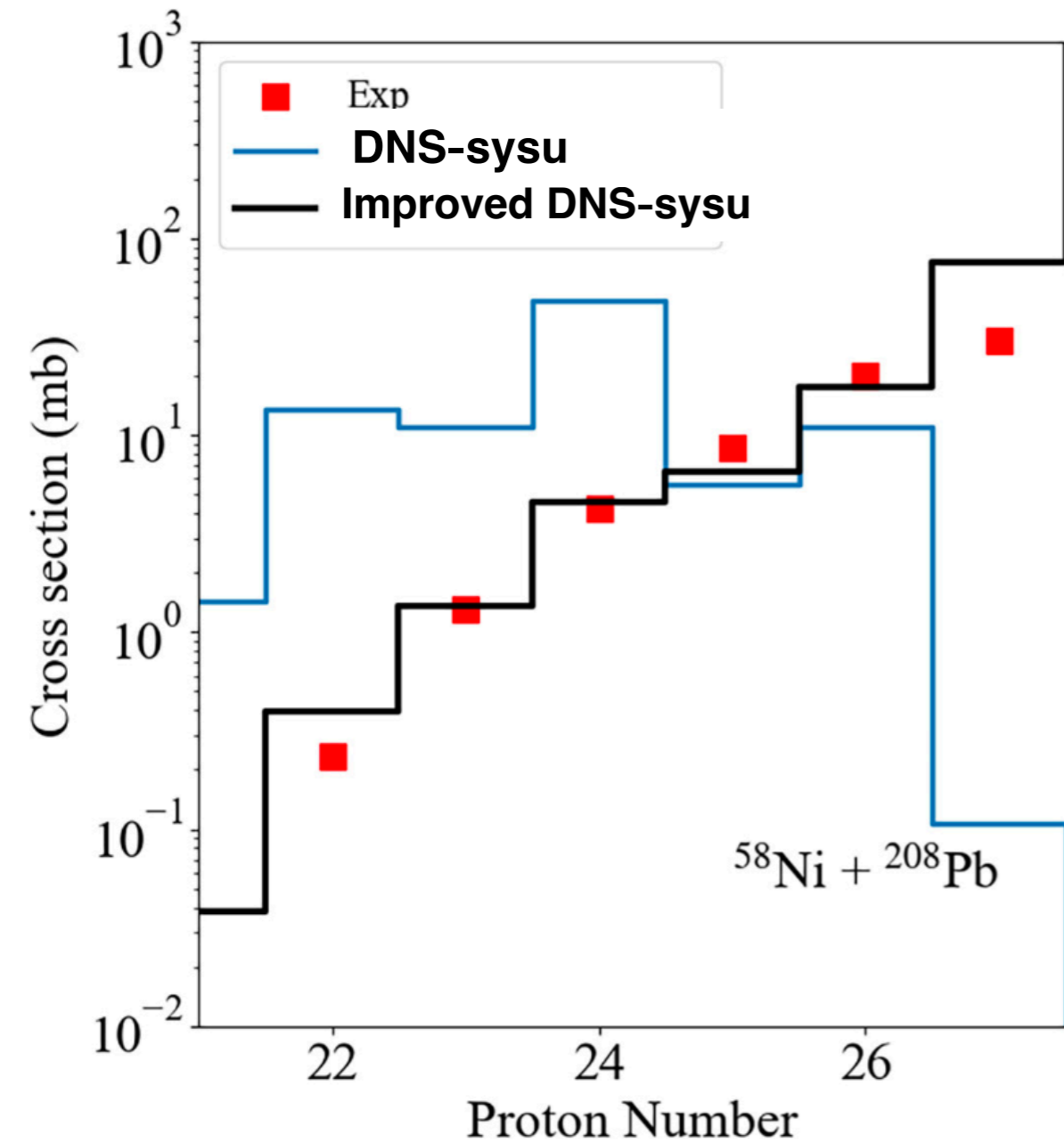
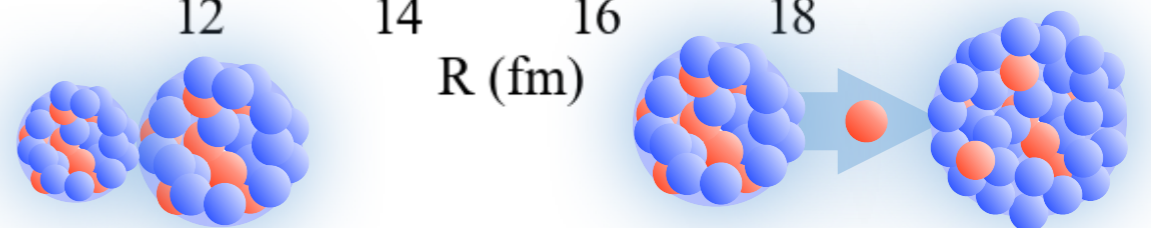
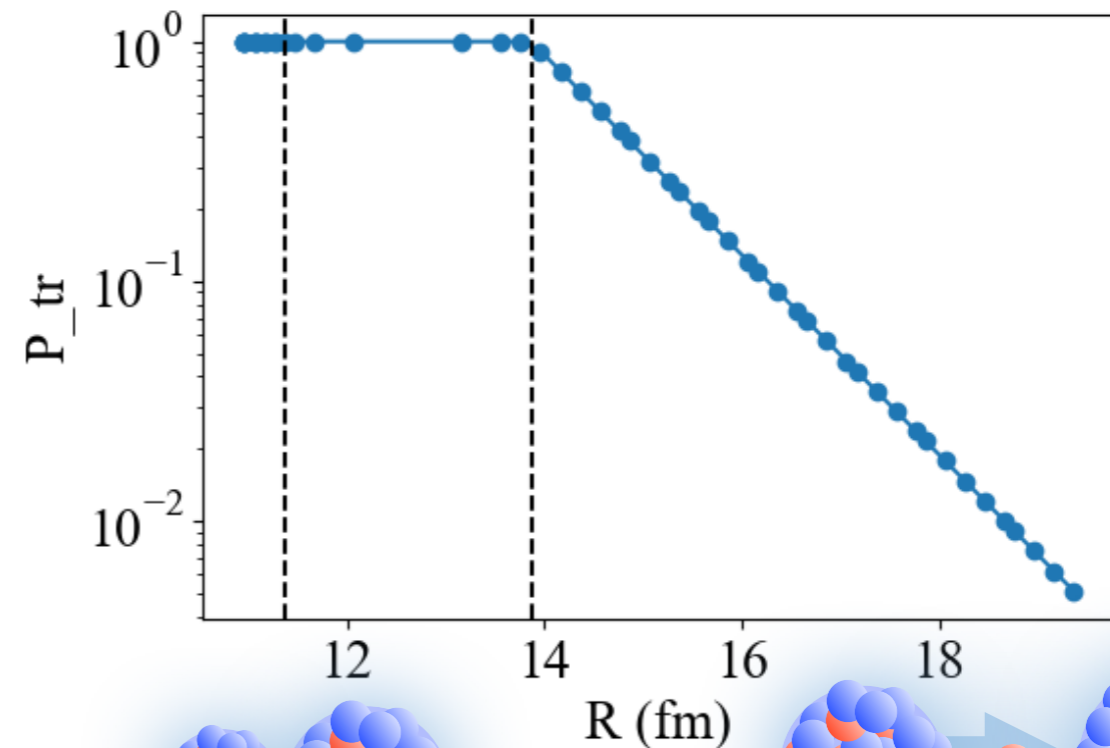


Probability of a nucleon transfer

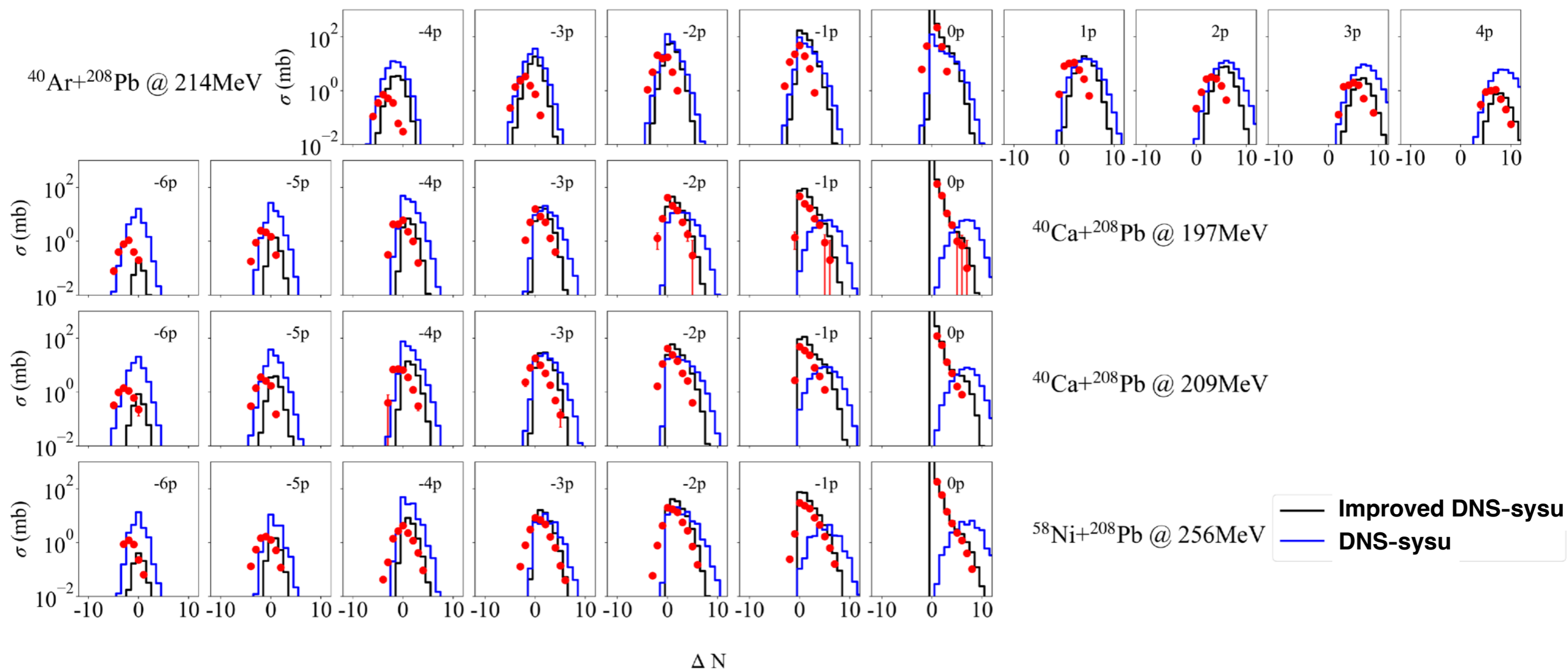
$$P_{tr}(R, \beta, A \rightarrow A \pm 1) = \exp(-2k[r_c - r_0])$$

中子 $k = \sqrt{M(-\epsilon_F)/2\hbar^2} + \sqrt{M(-\epsilon'_F)/2\hbar^2}$ [1/fm]

质子 $k = \sqrt{M(-\epsilon_F + Z_T e^2/R_T)/2\hbar^2} + \sqrt{M(-\epsilon'_F + Z_P e^2/R_P)/2\hbar^2}$ [1/fm]



Summary



- 基于双核系统模型，我们考虑了距离依赖的核子转移概率。
- 有效地改进双核系统模型在描述少核子转移的能力。

目录

■ 研究背景与理论方法

- N=126 核素特殊结构效应与r 过程
- N=126 核素合成与多核子转移反应
- 模型与理论框架

■ 研究内容

- 低能核反应提取核结构信息的研究
- N=126 核素的多核子转移反应非平衡演化的研究
- N=126 核素的多核子转移反应产物角分布的研究
- N=126 核素的多核子转移反应准弹性转移机制

■ 总结与展望

总结与展望

总结：

- 通过低能核反应约束原子核形变探索核反应与核结构的关联
- 探究非平衡演化过程中，结构性质对演化影响，进而对 N=126 反应体系优化选取
- 理论MNT反应角分布预言，为探测 N=126 核素提供最佳的角度选取
- 改进的模型合理地描述准弹性碰撞，解决了对少核子转移截面长期低估模型问题。

展望：

- 将EC-CCFULL利用到 ^{238}U 上，该核素是三轴形变核素
- 探究 MNT 反应中的 Mpemba effect
- 发展耦合主方程与郎之万方程，主方程描述核子转移，郎之万方程描述形状演化

攻读博士学位期间发表的学术论文

- (1) **Zehong Liao**, Long Zhu*, Jun Su, Cheng Li; Dynamics of charge equilibration and effects on producing neutron-rich isotopes around $N = 126$ in multinucleon transfer reactions; **Physical Review C** 107, 014614 (2023)
- (2) **Zehong Liao**, Long Zhu*, Zepeng Gao, Jun Su, Cheng Li; Optimal detection angles for producing $N = 126$ neutron-rich isotones in multinucleon transfer reactions; **Physical Review Research** 5, L022021 (2023) (**Letter**)
- (3) **Zehong Liao**, Zepeng Gao, Yu Yang, Long Zhu*, Jun Su; Shell effects on the drift and fluctuation in multinucleon transfer reactions; **Physical Review C** 109, 054612 (2024)
- (4) **Zehong Liao**, Zepeng Gao, Yu Yang, Yueping Fang, Long Zhu*, Jun Su; Quantifying angular distributions in multinucleon transfer reactions with a semiclassical method; **Physical Review C** 111, 024605 (2025)
- (5) **Zehong Liao**, Yu Yang, Zepeng Gao, Jun Su, Long Zhu*; Mechanism of the quasielastic scattering based on the dinuclear system concept; **Physical Review C** 112, L051601 (2025) (**Letter**)
- (6) **Zehong Liao**, K. Hagino*, Long Zhu*, S. Yoshida, K. Uzawa; Determination of nuclear deformations with an emulator for sub-barrier fusion reactions; **Physical Review C** (2026)
- (7) K. Hagino, **Zehong Liao**, S. Yoshida, M. Kimura, K. Uzawa; Emulating multichannel scattering based on eigenvector continuation in the discrete-basis formalism; **Physical Review C** 112, 024618 (2025)
- (8) Yu Yang, **Zehong Liao**, Zepeng Gao, Long Zhu*, Jun Su, Cheng Li; New insight into the N/Z and mass equilibration in heavy-ion collisions; **Physical Review C** 111, 024602 (2025)
- (9) Zimeng Shen, **Zehong Liao**, Long Zhu*; Correlation of multiple physical quantities in multinucleon transfer reactions: Insight into production of isotopes near the shell closure $N = 152$; **Physical Review C**, accepted (3 December 2025) (**Editor's Suggestion**) (**Letter**)
- (10) Yu Yang, Long Zhu*, **Zehong Liao**, Zepeng Gao, Yueping Fang, Jun Su, Zhong Liu, Dongsheng Hou, Hao Huang, Cheng Li, Fengshou Zhang; Production of actinide isotopes near $\theta_{lab} = 0^\circ$ in multinucleon transfer reaction $^{238}\text{U} + ^{248}\text{Cm}$; **Physics Letters B** 862, 139318 (2025)
- (11) Zepeng Gao, Yinu Zhang, Long Zhu*, **Zehong Liao**, Yu Yang, Chenchen Guo, Jun Su; Role of the isospin diffusion on the cluster transfer in $^{12,14}\text{C} + ^{209}\text{Bi}$ reactions; **Physical Review C** 109, L041605 (2024) (**Letter**)
- (12) Yueping Fang, Zepeng Gao, Yinu Zhang, **Zehong Liao**, Yu Yang, Jun Su, Long Zhu*; Bayesian uncertainty quantification for synthesizing superheavy elements; **Physics Letters B** 858, 139069 (2024)
- (13) Zepeng Gao, Siyu Liu, Peiwei Wen, **Zehong Liao**, Yu Yang, Jun Su, Yongjia Wang, Long Zhu*; Constraining the WoodstSaxon potential in fusion reactions based on neural networks; **Physical Review C** 109, 024601 (2024)

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