Key physical quantities in SHE synthesis prediction

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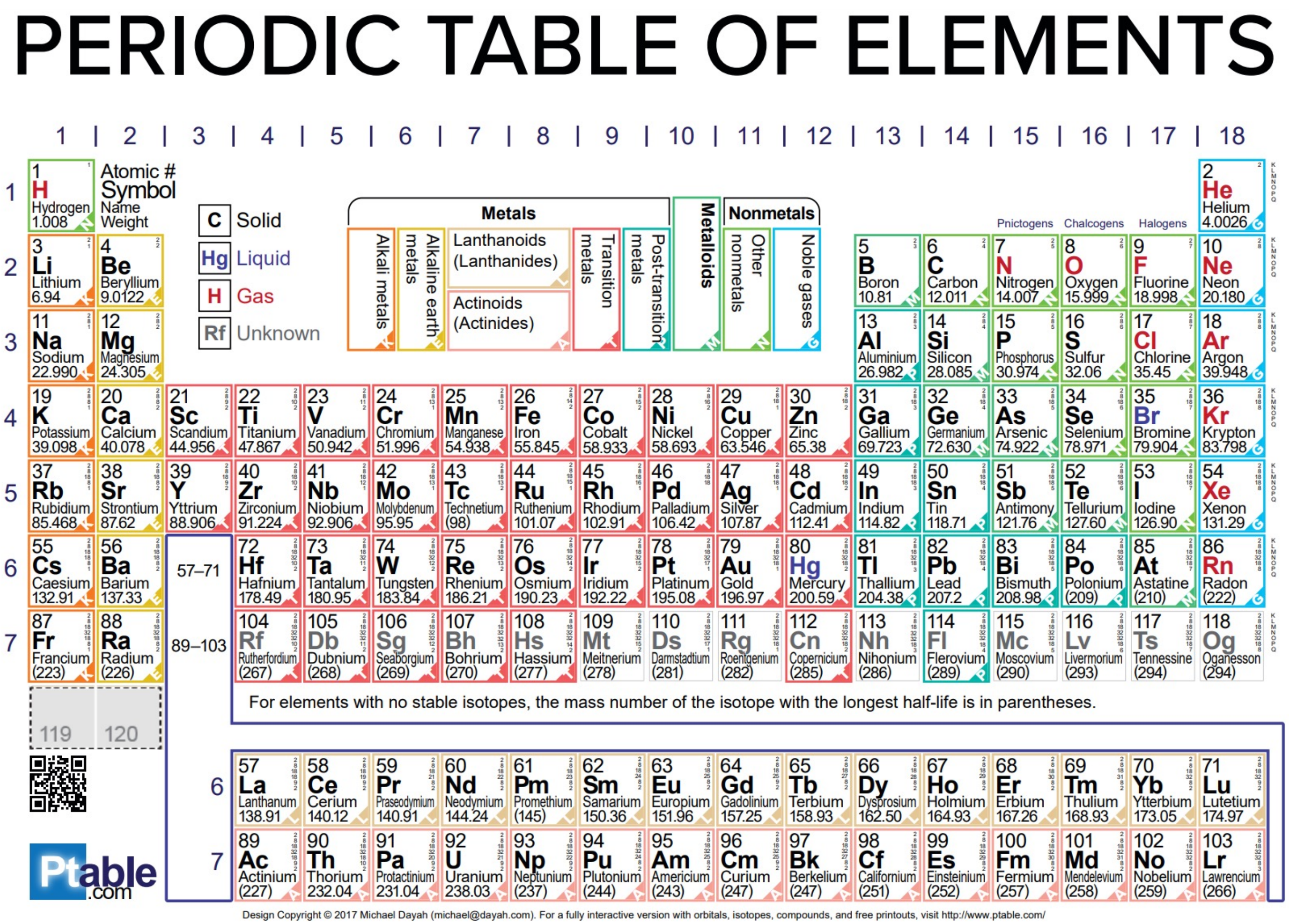
Outline

- **Background**
- **Theory model**
- **Results and Discussion**
  - ✓The prediction cross section of SHE errors caused by different nuclear mass models;
  - ✓The prediction cross section of SHE errors caused by the uncertainty of shell damping factor.
- **Acknowledge**

Periodic table of elements



Nation named elements:

钌，Ruthenium，俄罗斯

锗，Germanium，德国

钋，Polonium，波兰（居里夫人）

钫，Francium，法国

镅，Americium，美国

鉨，Nihonium，日本

重离子加速器合成的新元素：

美：Md, No, Lr (101~103), Sg (106)

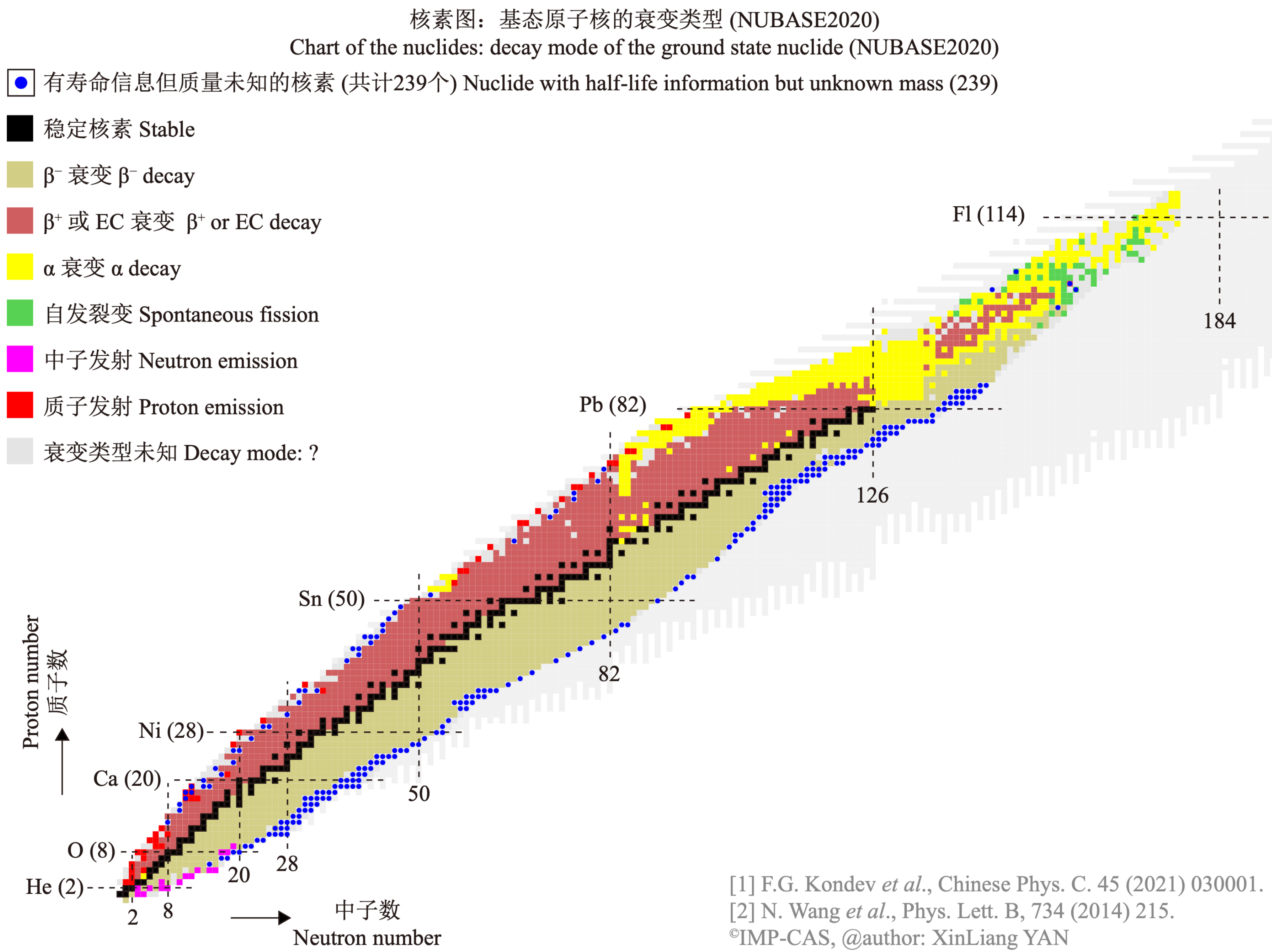
俄（苏）：Rf (104), Db (105),

Fl, Mc, Lv, Ts, Og (114~118)

德：Bh, Hs, Mt, Ds, Rg, Cn (107~112)

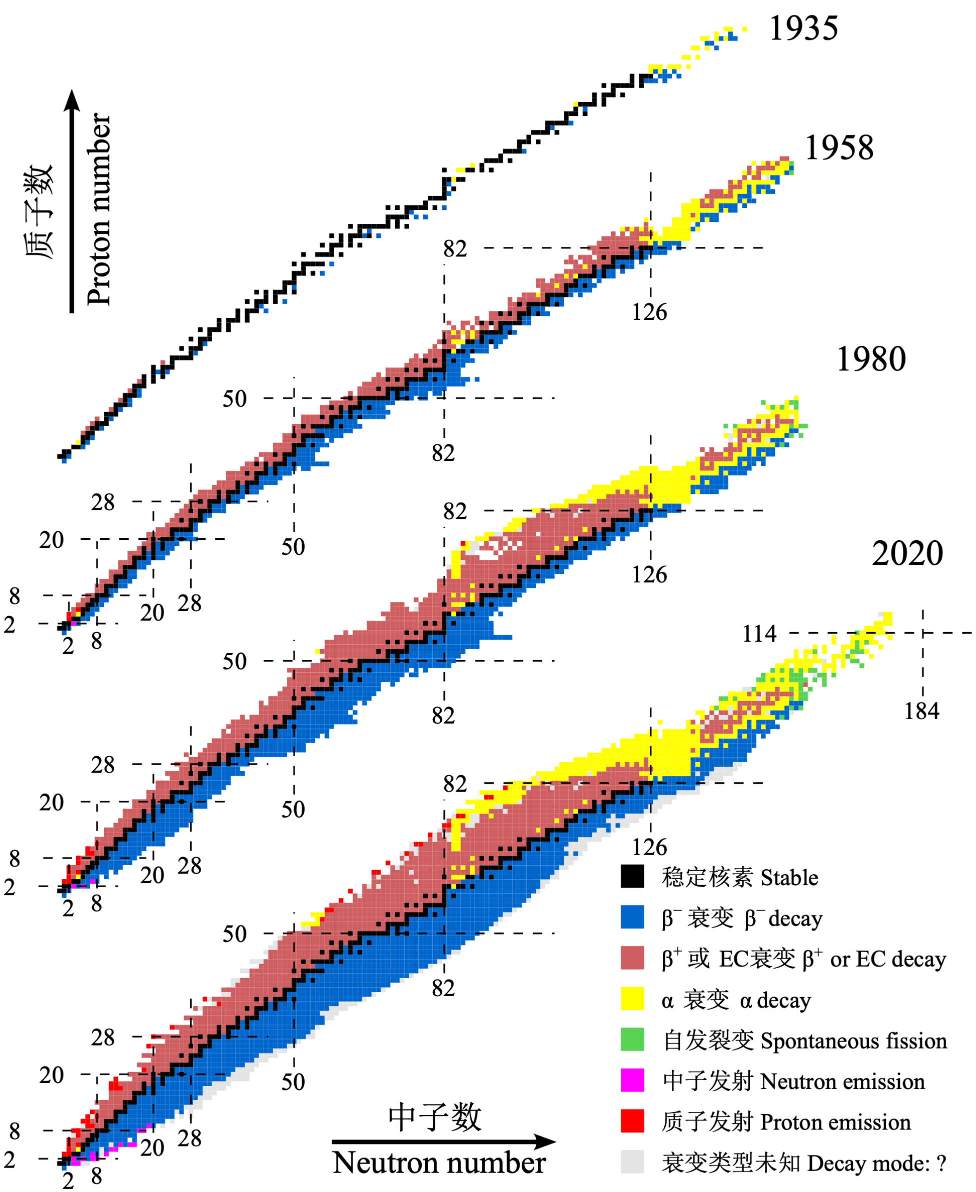
日：Nh (113)

Nuclide chart



[1] F.G. Kondev *et al.*, Chinese Phys. C. 45 (2021) 030001.
[2] N. Wang *et al.*, Phys. Lett. B, 734 (2014) 215.

Nuclide chart in history



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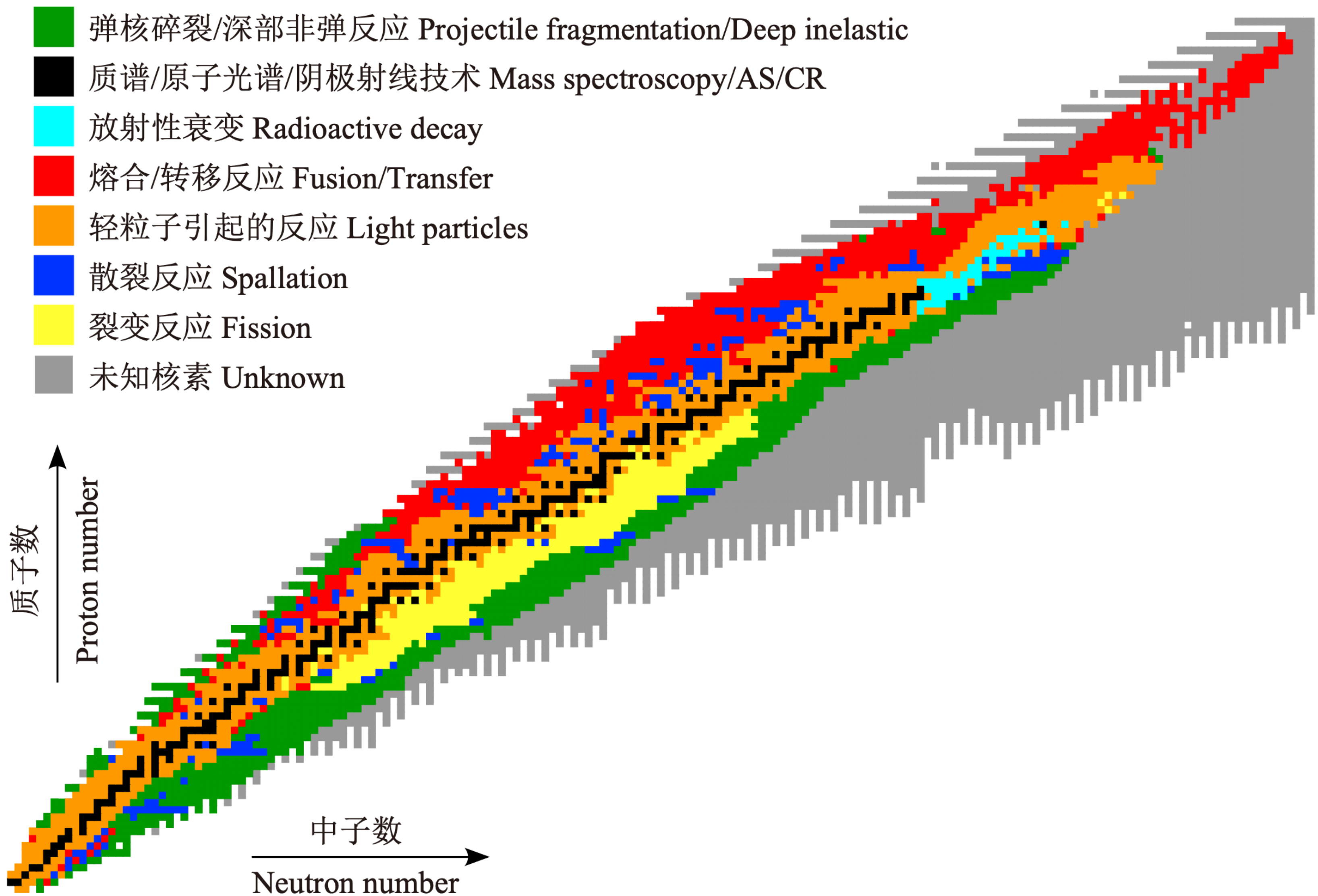
- New isotopes in 2020 (4):
  ^{235}Cm, ^{211}Pa, ^{222}Np, ^{244}Md.
- New isotopes in 2021 (15):
  ^{101}Br, ^{102}Kr, ^{105}Rb, ^{106}Rb, ^{108}Sr, ^{110,111}Y, ^{114}Zr, ^{117}Nb, ^{13}F, ^{214}U, ^{249}No, ^{150}Yb, ^{18}Mg.
- New isotopes in 2022 (11):
  ^{149}Lu, ^{207}Th, ^{264}Lr, ^{166}Pm, ^{168}Sm, ^{170}Eu, ^{172}Gd, ^{204}Ac, ^{251}Lr, ^{39}Na, ^{286}Mc.
- New isotopes in 2023(13)：
  ^{241}U, ^{190}At, ^{276}Ds, ^{272}Hs, ^{268}Sg, ^{27}O, ^{28}O, ^{189}Lu, ^{191}Hf, ^{192}Hf, ^{9}N, ^{156}W, ^{160}Os
- New isotopes in 2024(34):
  ^{203}Ac, ^{275}Ds, ^{84}Cu , ^{86,87}Zn, ^{88,89}Ga, ^{45,46}Si, ^{227}Pu ^{91,92}Ge, ^{93,94,95}As, ^{96,97}Se, ^{99,100}Br , ^{103}Kr , ^{255}Db

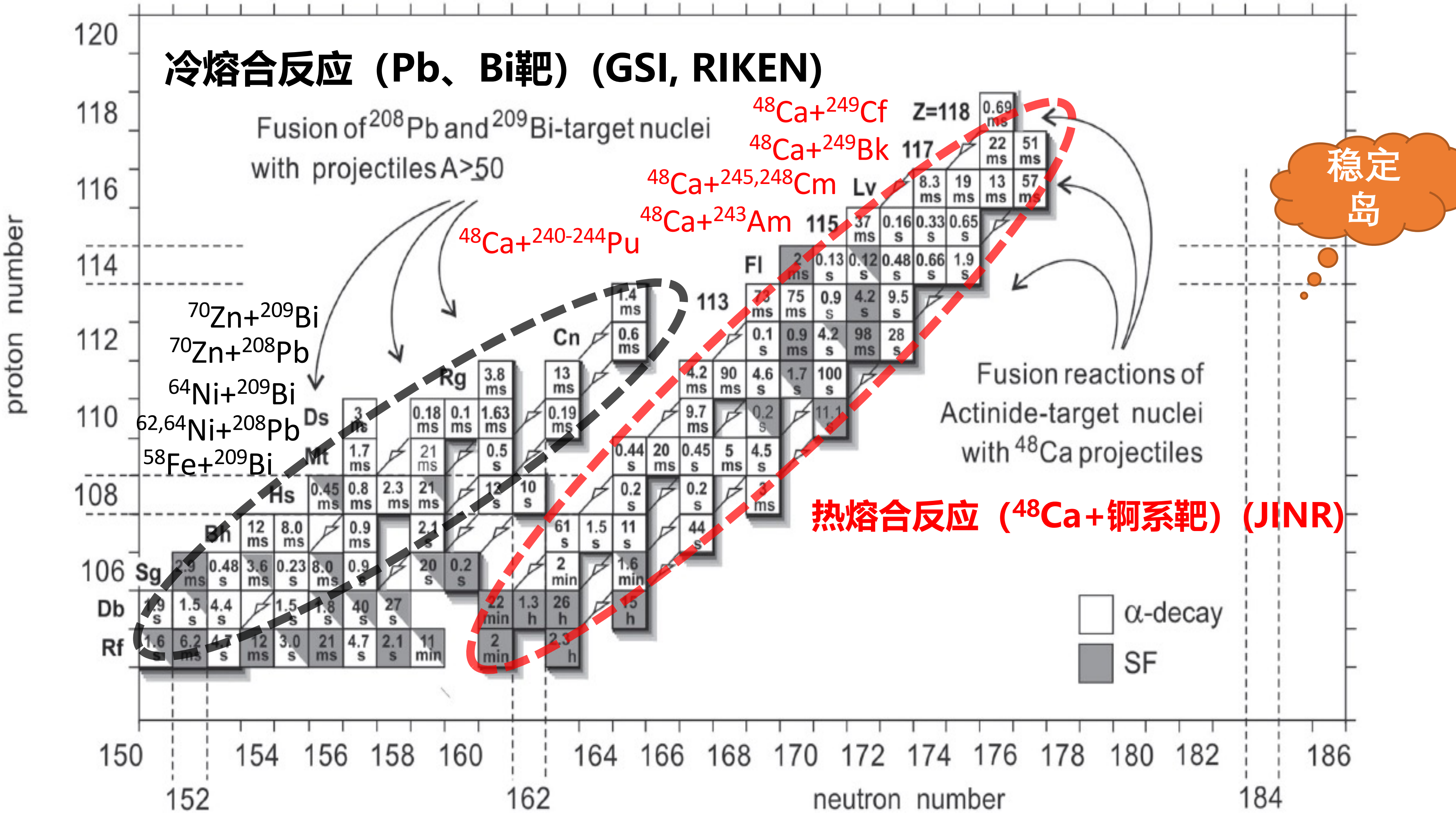
New isotopes in 2025(3+):
^{257}Sg, ^{98}Sn, ^{252}Rf ,……

https://people.nscl.msu.edu/~thoennes/isotopes/

Synthesis method



Experimental progress

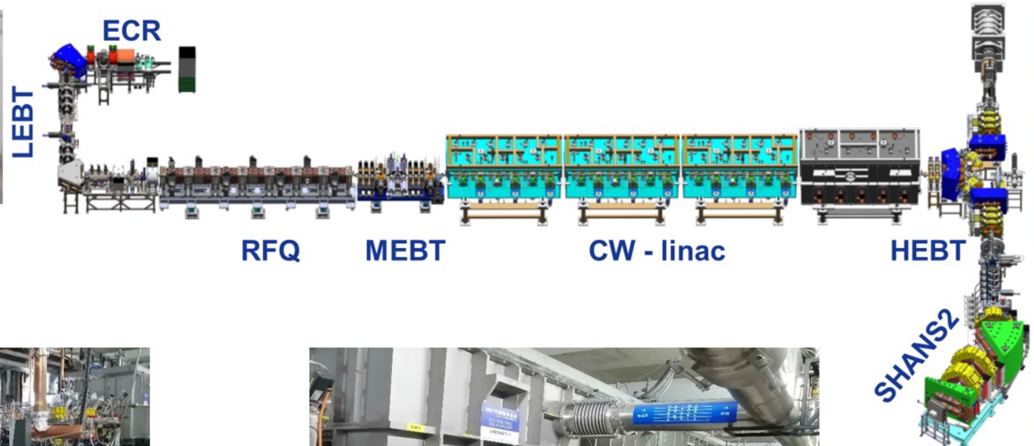


Experimental progress

中国超重元素研究加速器装置

China Accelerator Facility for Superheavy Elements (CAFE2)

电子回旋共振离子源
(ECR ion source)



参数	设计指标	单位
加速粒子	Ca ~ Zn	-
荷质比	1/3	-
束流能量	4.5-7	MeV/u
束流强度	5-10	pμA

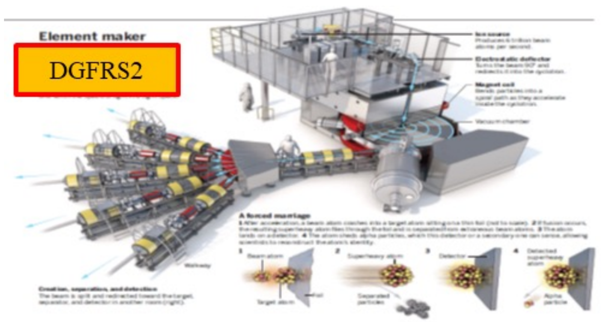
射频四极聚束器
(RFQ)

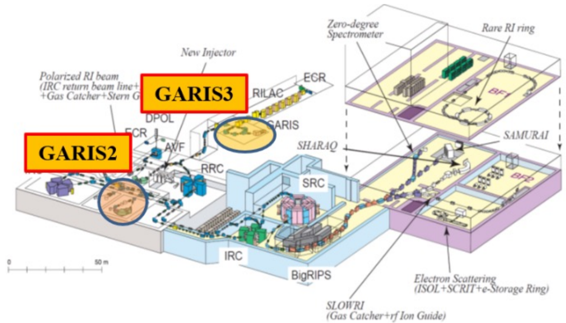
连续波超导直线加速器
(CW-LINAC)

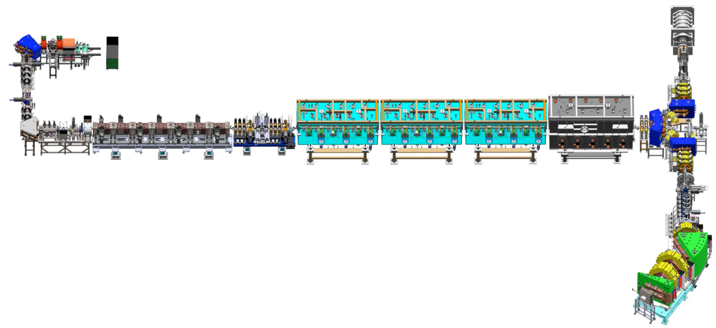
充气反冲核分离器
(SHANS2)

Russia's JINR, Japan's RIKEN, and China's IMP have all newly constructed experimental facilities, launching plans to synthesize new elements 119 or 120.

Experimental progress







俄罗斯JINR

SHE Factory + DGFRS2

日本RIKEN

RILAC + GARIS3

中国IMP-CAS

CAFE2 + SHANS2

国家	实验室	装置	最高流强 (粒子微安)	充气谱仪传输效率
俄罗斯	JINR	SHE Factory	~10	~59% ($^{48}Ca+^{206}Pb$)
日本	RIKEN	RILAC	3~4	~47% ($^{40}Ar+^{169}Tm$)
中国	**IMP-CAS**	**CAFE2**	**目前：3~5 目标：10~15**	**~58% ($^{40}Ar+^{169}Tm$)**

Key technical challenge:

Element synthesis for fb cross section generation

Higher beam intensity

Higher separation efficiency

Theory models

- Phenomenological Models:
  - ➢ Macroscopic dynamics model: pure dynamical fusion process;
    - Swiatecki, *Nul. Phys. A* **391**, 471 (1982).
  - ➢ Fluctuation-dissipation model: Fluctuation, shell correction;
    - Y. Abe, *Phys. Rev. C* **59**, 796 (1999).
  - ➢ Dinuclear system model (DNS): keep individuality, nucleon transfer;
    - G.G. Adamian, *Nul. Phys. A* **627**, 361 (1997); W. F. Li, N. Wang, et. al., *Eur. Lett.* 64 (2003) 750;
    - V. V. Volkov, G. G. Adamian, N. V. Antonenko, *Nuovo Cimento A* 110, 1127 (1997)
  - ➢ Nucleon collectivization model:
    - V.I. Zagrebaev, *Phys. Rev. C* **64**, 034606 (2001).

  ……
- Microscopic Models:
  - ➢ Improved quantum molecule model (ImQMD)
    - Kai Zhao, *Phys. Rev. C* **94**, 024601 (2016).
  - ➢ Time-depedent Hartree Fock model (TDHF)
    - Lu Guo, *Phys. Rev. C* **90**, 044609 (2014). *Com. Phys. C* 185, 2195 (2014)

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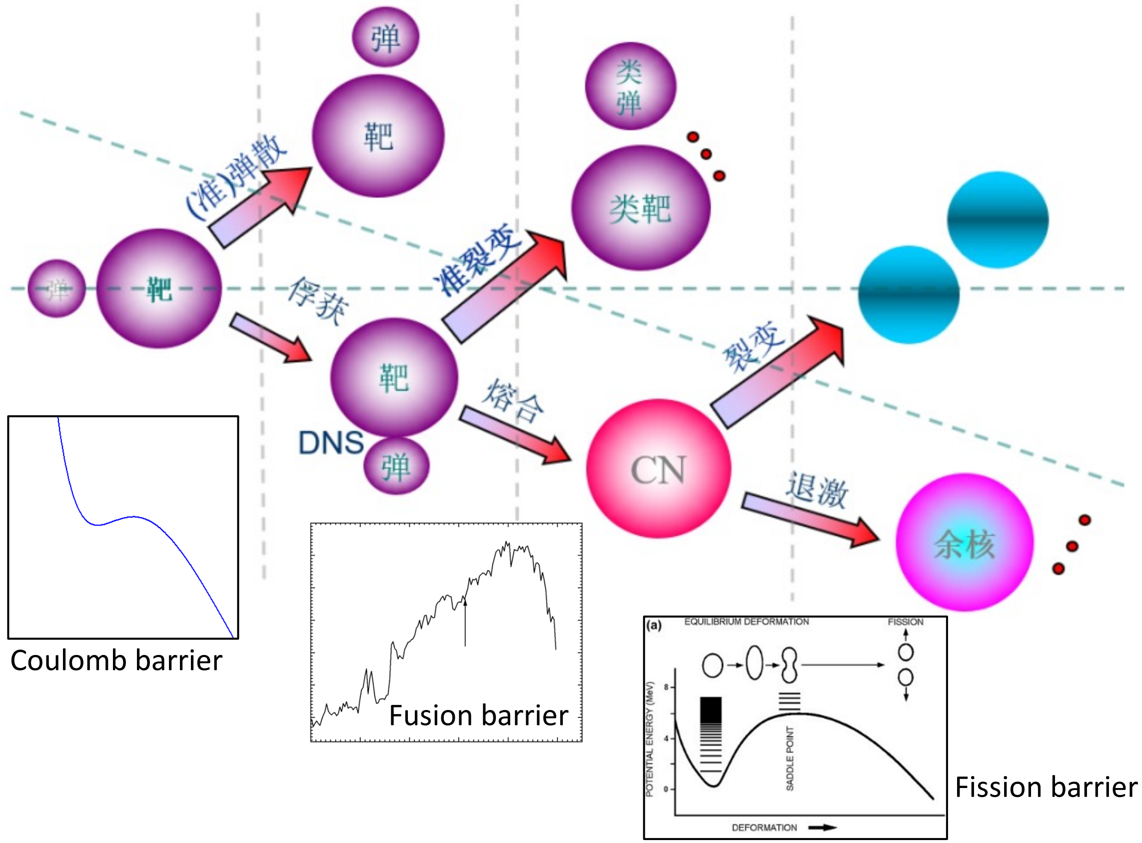
Dinuclear system model (DNS)

- Three stages description of DNS: Phys. Rep. 44(1978)93



- Residual evaporation equation:

$$\sigma_{ER}(E_{c.m.}) = \frac{\pi\hbar^2}{2\mu E_{c.m.}} \sum_{J=0}^{J_{max}} (2J+1)\ T(E_{c.m.}, J)\ P_{CN}(E_{c.m.}, J)\ W_{sur}(E_{c.m.}, J)$$

Capture stage

- Barrier penetration probability: Hill-Wheeler formula

$$T(E_{\mathrm{c.m.}}, J) = \int f(B) \frac{1}{1+\exp(-\frac{2\pi}{\hbar\omega(J)}[E_{\mathrm{c.m.}} - B - \frac{\hbar^2}{2\mu R_B^2(J)} J(J+1)])} dB$$

D.L. Hill, J.A. Wheeler, Phys. Rev.**89**, 1102 (1953).

- Barrier distribution function: Asymmetric-Gauss function

$$f(B) = \begin{cases} \frac{1}{N}\exp[-(\frac{B-B_{\mathrm{m}}}{\Delta_1})] & B < B_{\mathrm{m}} \\ \frac{1}{N}\exp[-(\frac{B-B_{\mathrm{m}}}{\Delta_2})] & B > B_{\mathrm{m}} \end{cases}$$

$$B_{\mathrm{m}} = (B_0 + B_{\mathrm{s}})/2, \Delta_2 = (B_0 - B_{\mathrm{s}})/2, \Delta_2 - \Delta_1 = (2 \sim 4)\ \mathrm{MeV}$$

- Interaction potential: V_N double folding, V_C Wong Formula

$$V(R; \beta_1, \beta_2, \theta_1, \theta_2) = V_{\mathrm{C}} + V_{\mathrm{N}} + \frac{1}{2}C_1(\beta_1 - \beta_1^0)^2 + \frac{1}{2}C_2(\beta_2 - \beta_2^0)^2$$

Rowley, *Phys. Lett. B* **254** 25 (1991);Zagrebaev, *Phys. Rev. C* **64**, 034606 (2001). Feng, et al. *Nucl. Phys. A* **771**, 56 (2006).

Transfer/fusion stage

- Master equation *Eur. Lett.* 64 (2003) 750; *Phys. Rev. C 68* (2003) 034601

$$\frac{dP(Z_1,N_1,E_1,t)}{dt}=\sum_{Z_1'}W_{Z_1,N_1;Z_1',N_1}(t)[d_{Z_1,N_1}P(Z_1',N_1,E_1',t)-d_{Z_1',N_1}P(Z_1,N_1,E_1,t)]+$$
$$\sum_{N_1'}W_{Z_1,N_1;Z_1,N_1'}(t)[d_{Z_1,N_1}P(Z_1,N_1',E_1',t)-d_{Z_1,N_1'}P(Z_1,N_1,E_1,t)]$$
$$-[\Lambda^{\rm qf}_{A_1,E_1,t}(\Theta)+\Lambda^{\rm fis}_{A_1,E_1,t}(\Theta)]P(Z_1,N_1,E_1,t)$$

- Fusion probability P_{CN}

$$P_{\rm CN}(E_{\rm c.m},J)=\int f(B)\sum_{Z=1}^{Z_{\rm BG}}\sum_{N=1}^{N_{\rm BG}}P(Z,N,E_1,\tau_{\rm int}(E_{\rm c.m},J),B){\rm dB}.$$

- MNT cross section σ_{sur}

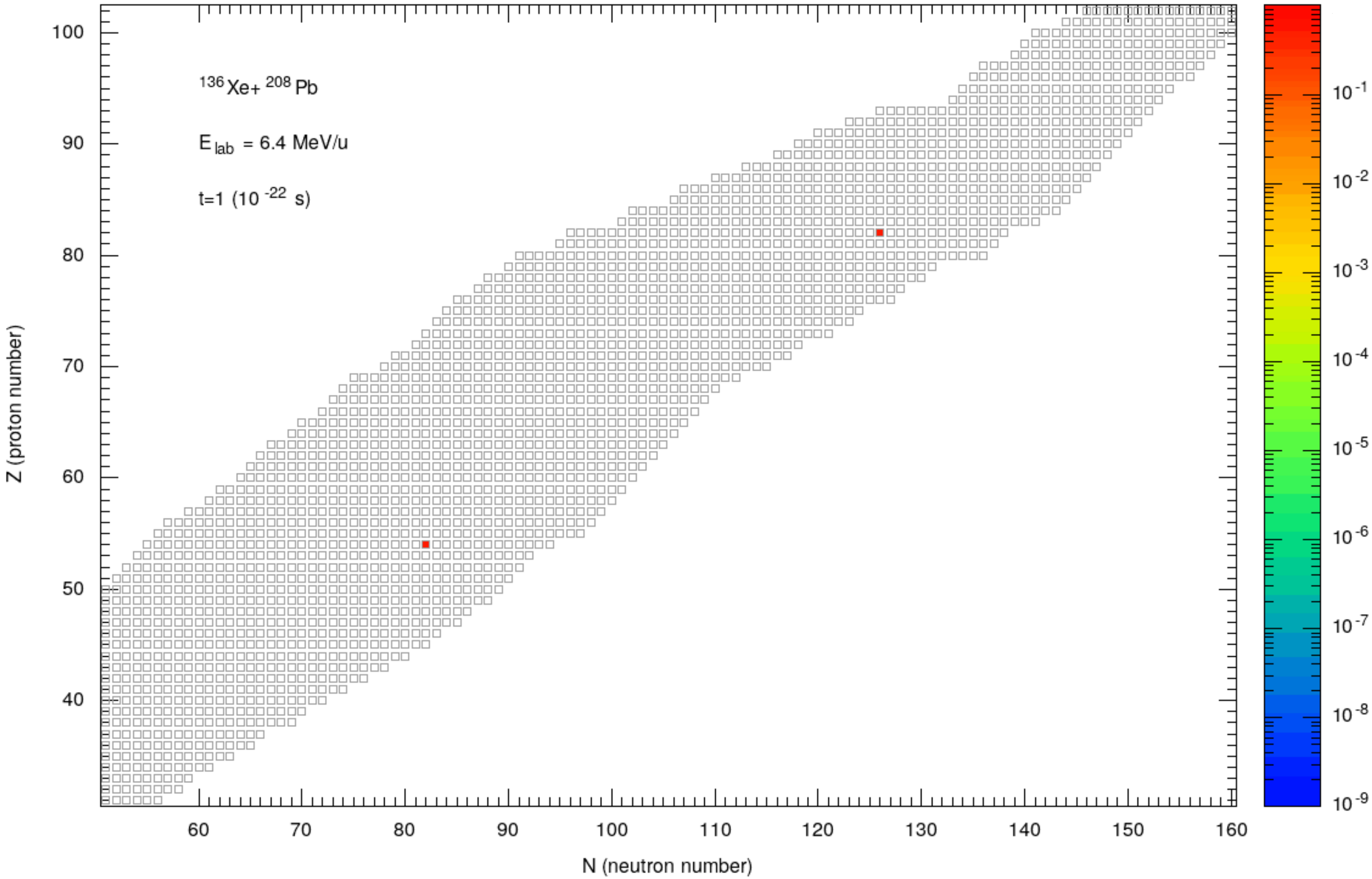
$$\sigma_{\rm sur}(Z_1,N_1,E_{\rm c.m.})=\sum_{J=0}^{J_{\max}}\sigma_{\rm cap}\int f(B)\times P(Z_1,N_1,E_1,J_1,B)W_{\rm sur}(E_1,J_1,s)dB.$$

- Fusion cross section σ_{fus}

$$\sigma_{\rm fus}(E_{\rm c.m.})=\frac{\pi\hbar^2}{2\mu E_{\rm m.c.}}\sum_{J=0}^{J_m}(2J+1)T(E_{\rm c.m.,J})P_{CN}(E_{\rm c.m.},J)$$

Feng, *Nucl.Phys. A* **816**, 33 (2009), *Phys.Rev. C* **76**, 044606 (2007)

Probability diffusion process



Derived by Master Equation

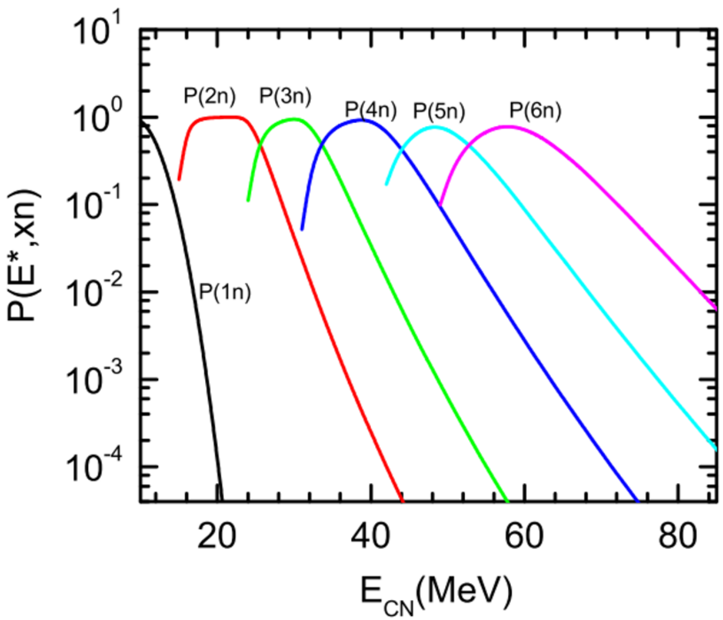
Survival stage

- Survival probability

V. Weisskopf, *Phys. Rev.* **52**, 250 (1937).

$$W_{\mathrm{sur}}(E^*_{\mathrm{CN}}, x, J) = P(E^*_{\mathrm{CN}}, x, J) \prod_{i=1}^{x_n} \frac{\Gamma_n(E^*_i, J)}{\Gamma_{\mathrm{tot}}(E^*_i, J)} \prod_{j=1}^{x_p} \frac{\Gamma_p(E^*_j, J)}{\Gamma_{\mathrm{tot}}(E^*_j, J)} \prod_{k=1}^{x_\alpha} \frac{\Gamma_\alpha(E^*_k, J)}{\Gamma_{\mathrm{tot}}(E^*_k, J)}$$

- Realization probability



$$P(E^*_{CN}, 1, J) = \exp\left(-\frac{(E^*_{\mathrm{CN}} - B_{\mathrm{n}} - E_{\mathrm{rot}} - 2T)^2}{2\sigma^2}\right)$$

$$P(E^*_{\mathrm{CN}}, x, J) = I(\Delta_x, 2x-3) - I(\Delta_{x+1}, 2x-1)$$

$$I(z, m) = \frac{1}{m!} \int_0^z u^m e^{-u} du$$

$$\Delta_x = \frac{E^*_{\mathrm{CN}} - \sum_{i=1}^{x} B^n_i - E_{rot}}{T_i}$$

Feng. *Nucl. Phys. A* **771**, 56 (2006).

G.G. Adamian, *Nul. Phys. A* **627**, 361 (1997)

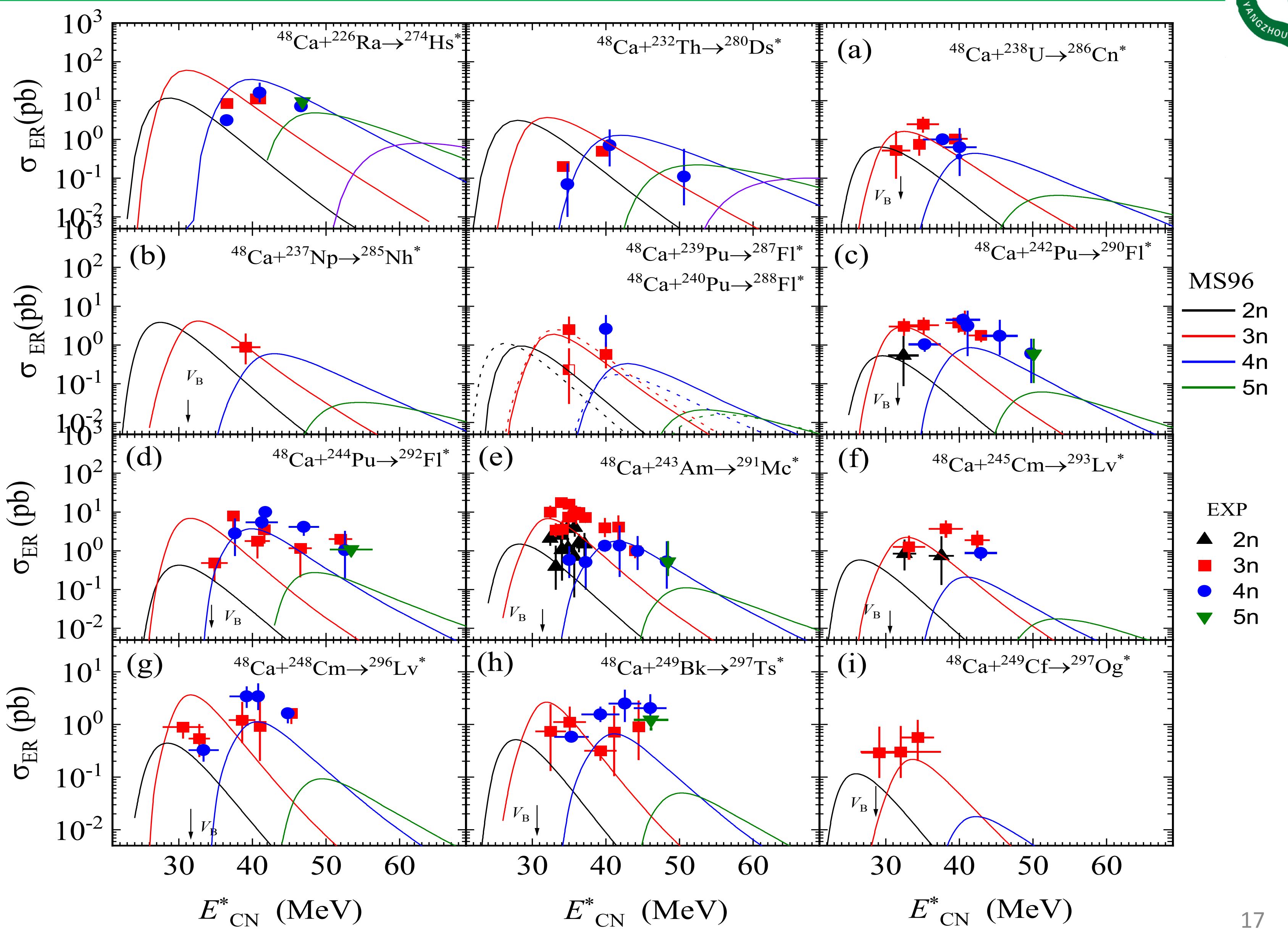
1. The prediction cross-section errors caused by different nuclear mass models.

Five nuclear mass models:

- ✓ FRDM12, the finite-range droplet model, P. Moller, et.al. ADND 109-110, 1 (2016);
- ✓ KUTY05, Koura-Tachibana-Uno-Yamada model, H. Koura, et.al., PTP 113, 305 (2005);
- ✓ WS4, Weizsäcker-Skyrme mass models, N. Wang, et.al., PLB 734, 215 (2014);
- ✓ MS96, the Little Droplet model, W. D. Myers, et.al. Nucl. Phys. 81, 1 (1966);
- ✓ HFB02, Hartree-Fock-Bogoliubov approaches, Y. El Bassem,et.al. NPA 957, 22 (2017).

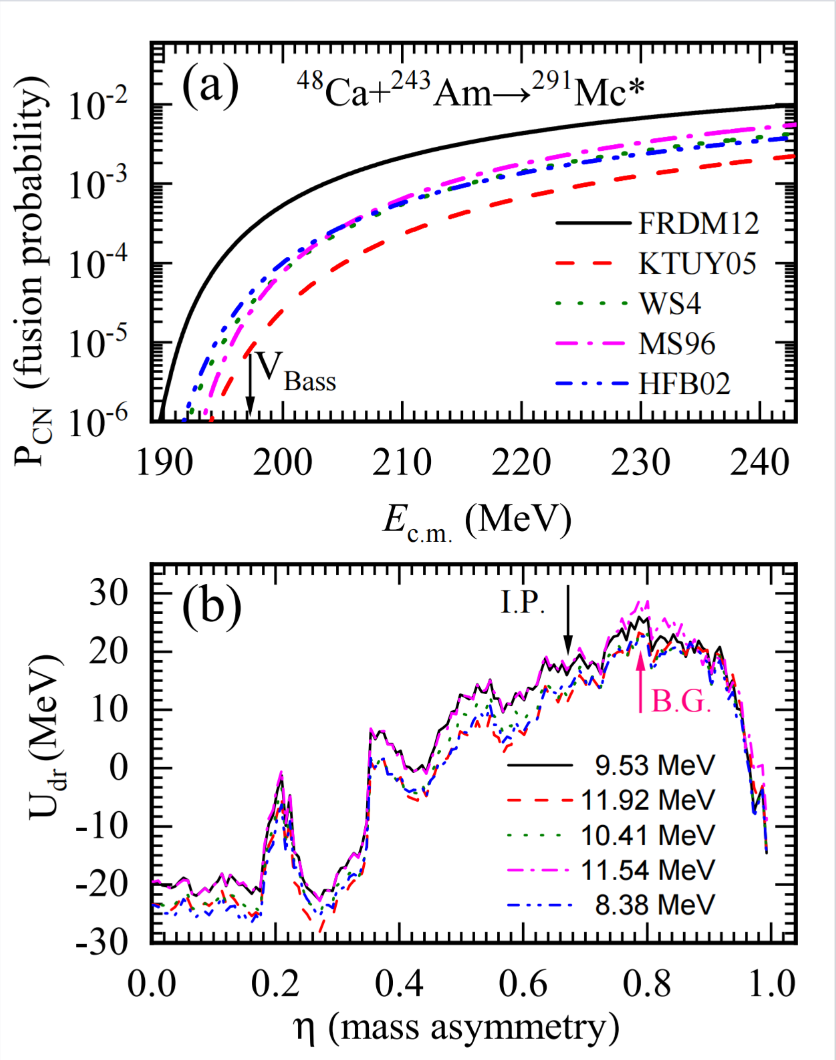
PRC **109** 054611(2024)

SHN synthesis cross-section predictions VS Exp. data

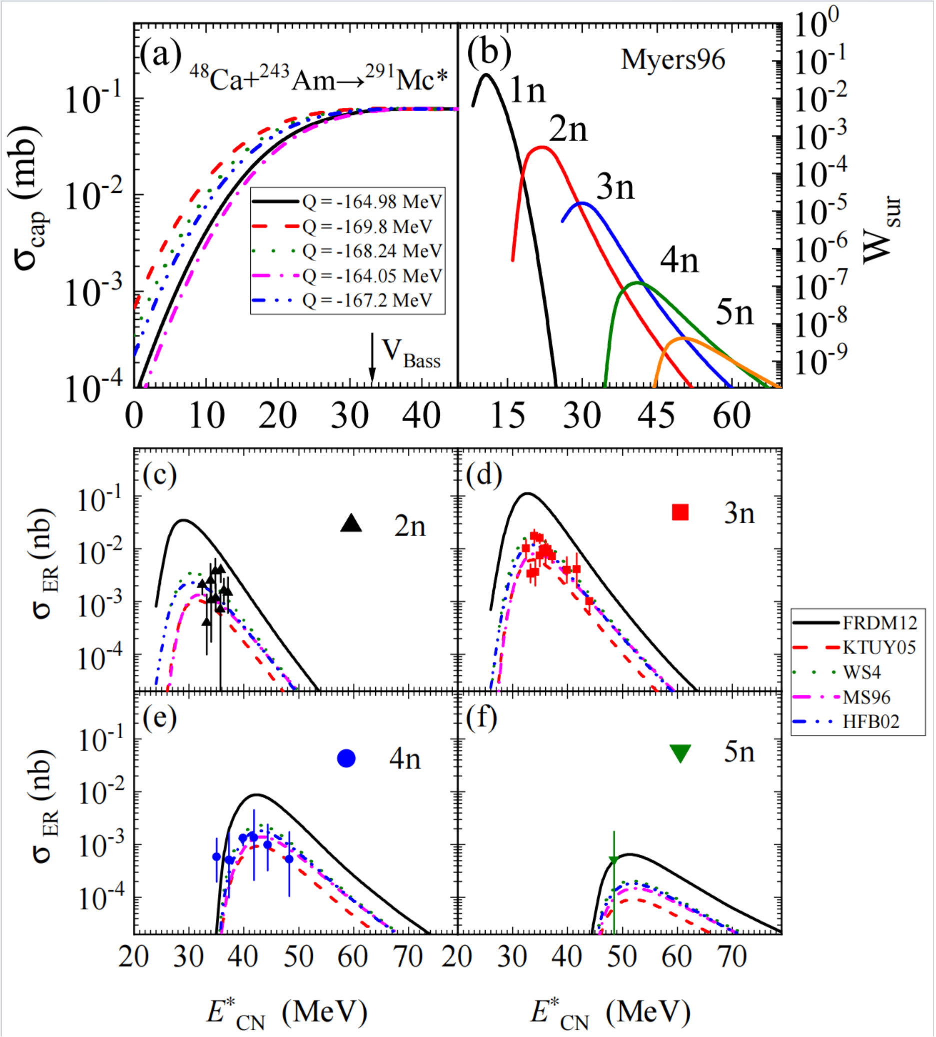


$^{48}Ca + ^{243}Am@E_{lab}=5.6MeV/u$

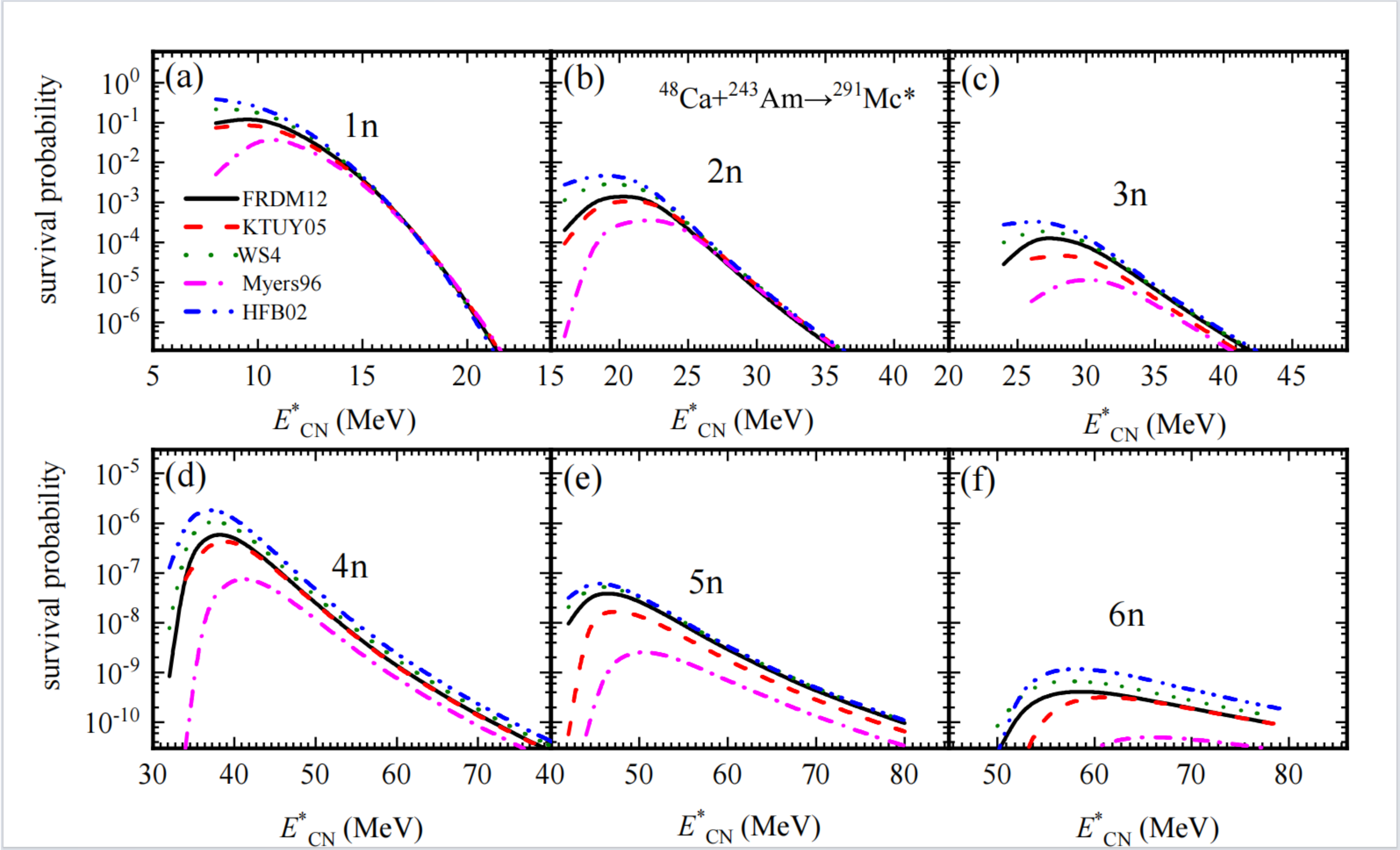
driver potential and fusion probability



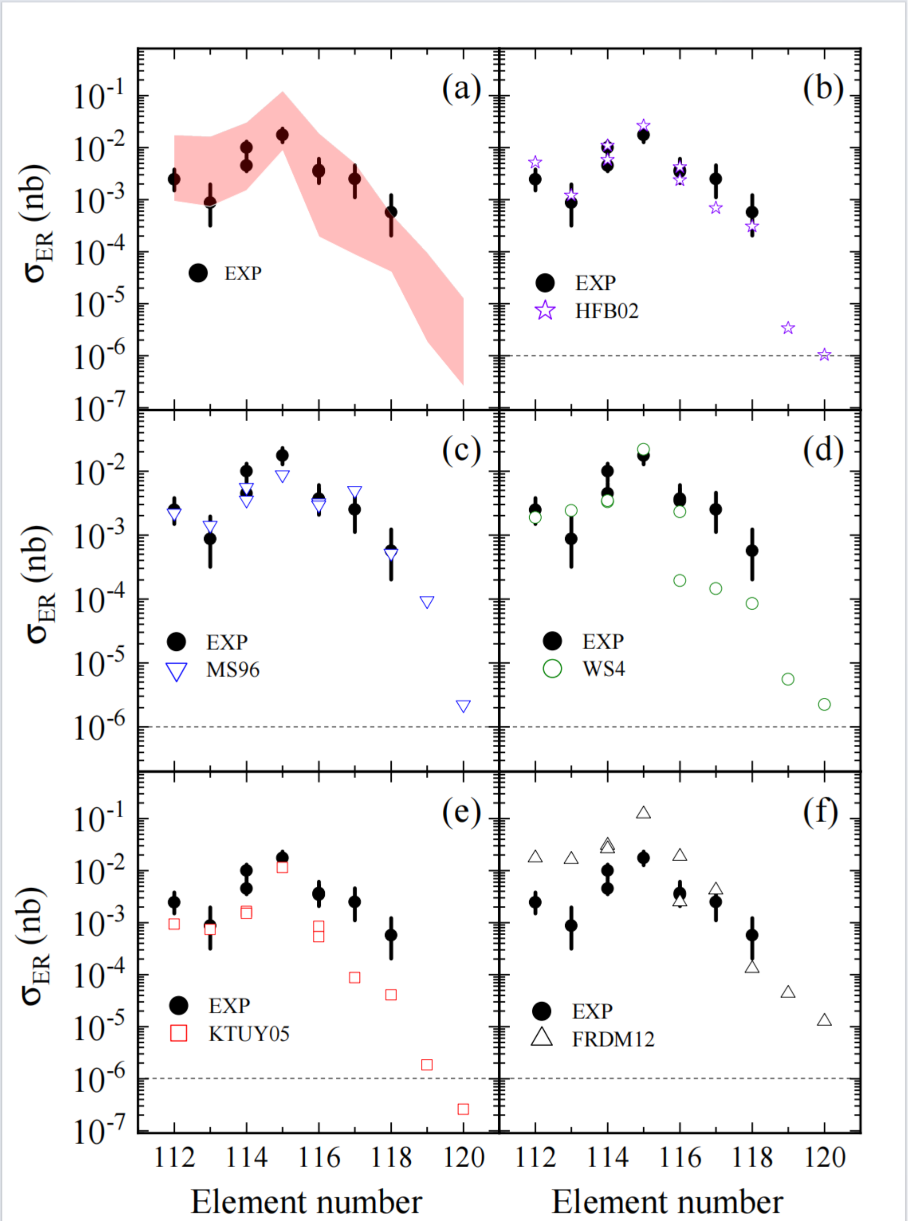
calculation and experimental data



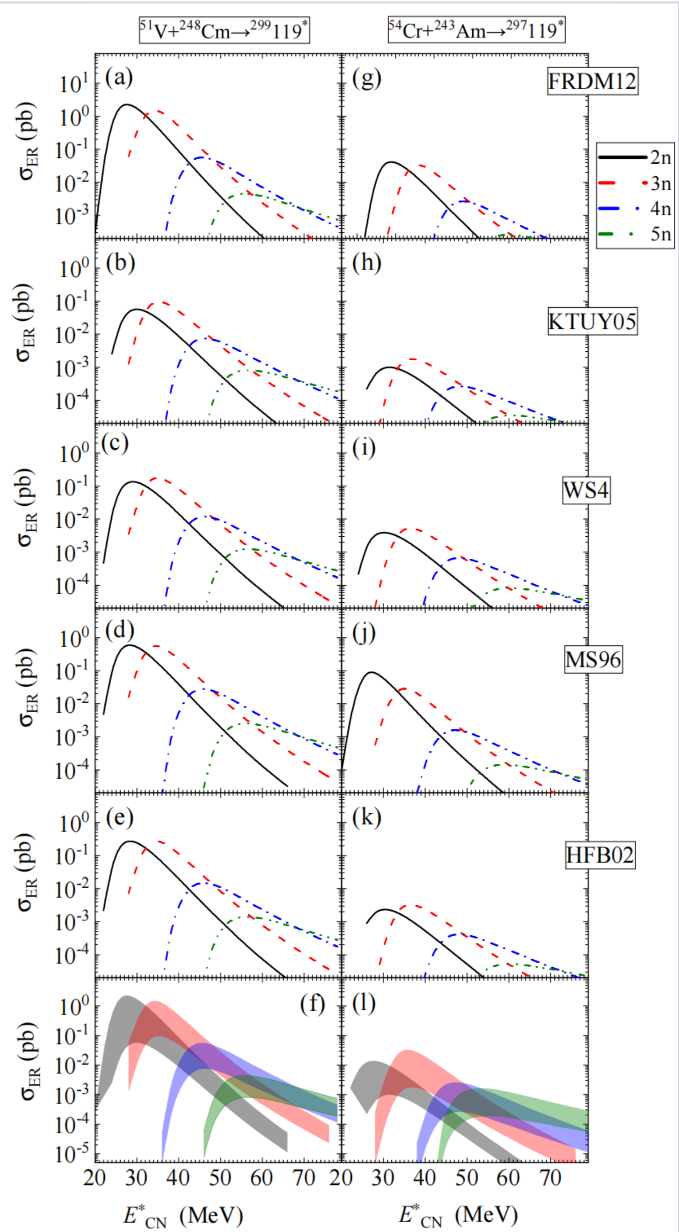
Evaluate survival probability via different mass models

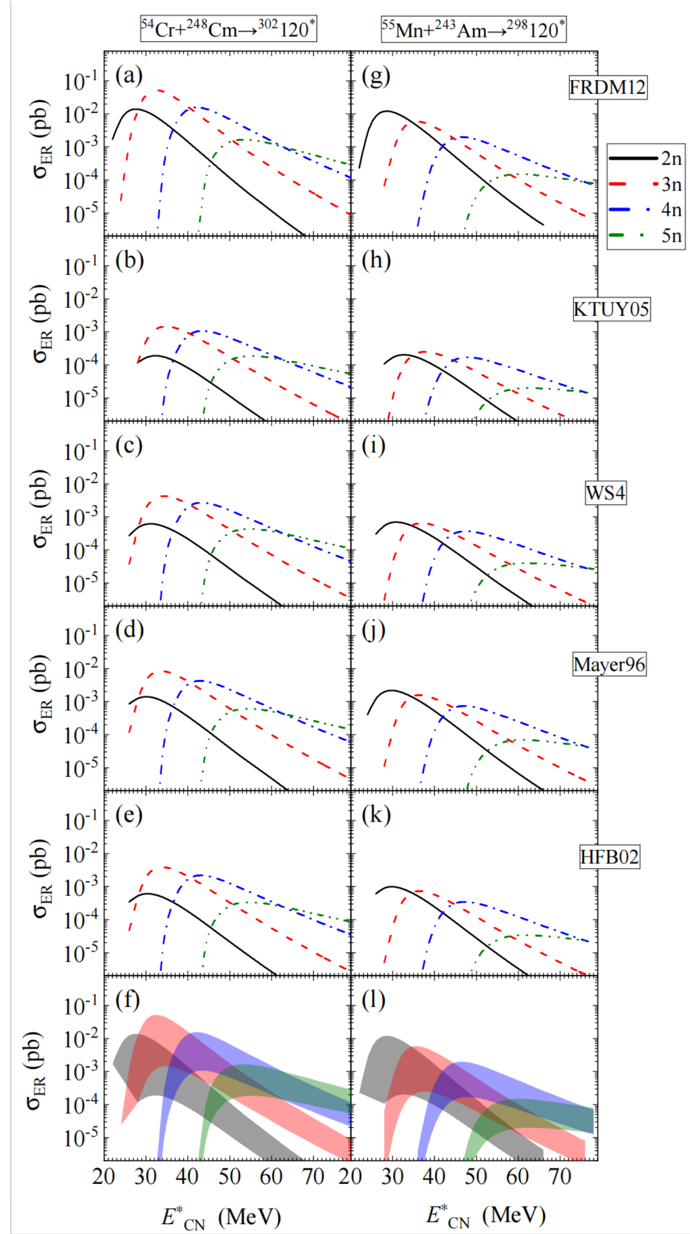


Prediction cross section of SHN via different mass models, Exp. data

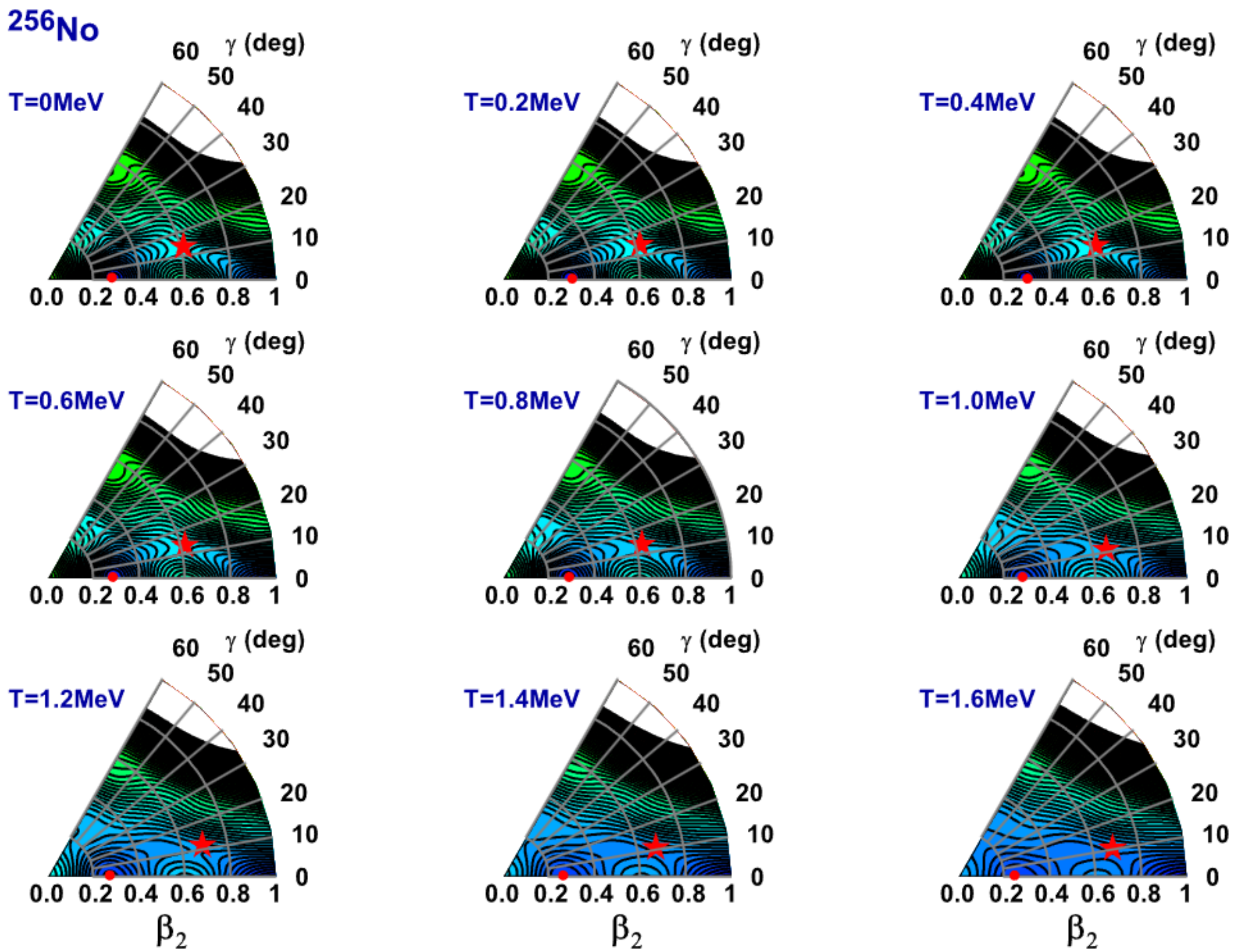


Prediction cross section of SHE with Z=119-120 via different mass models



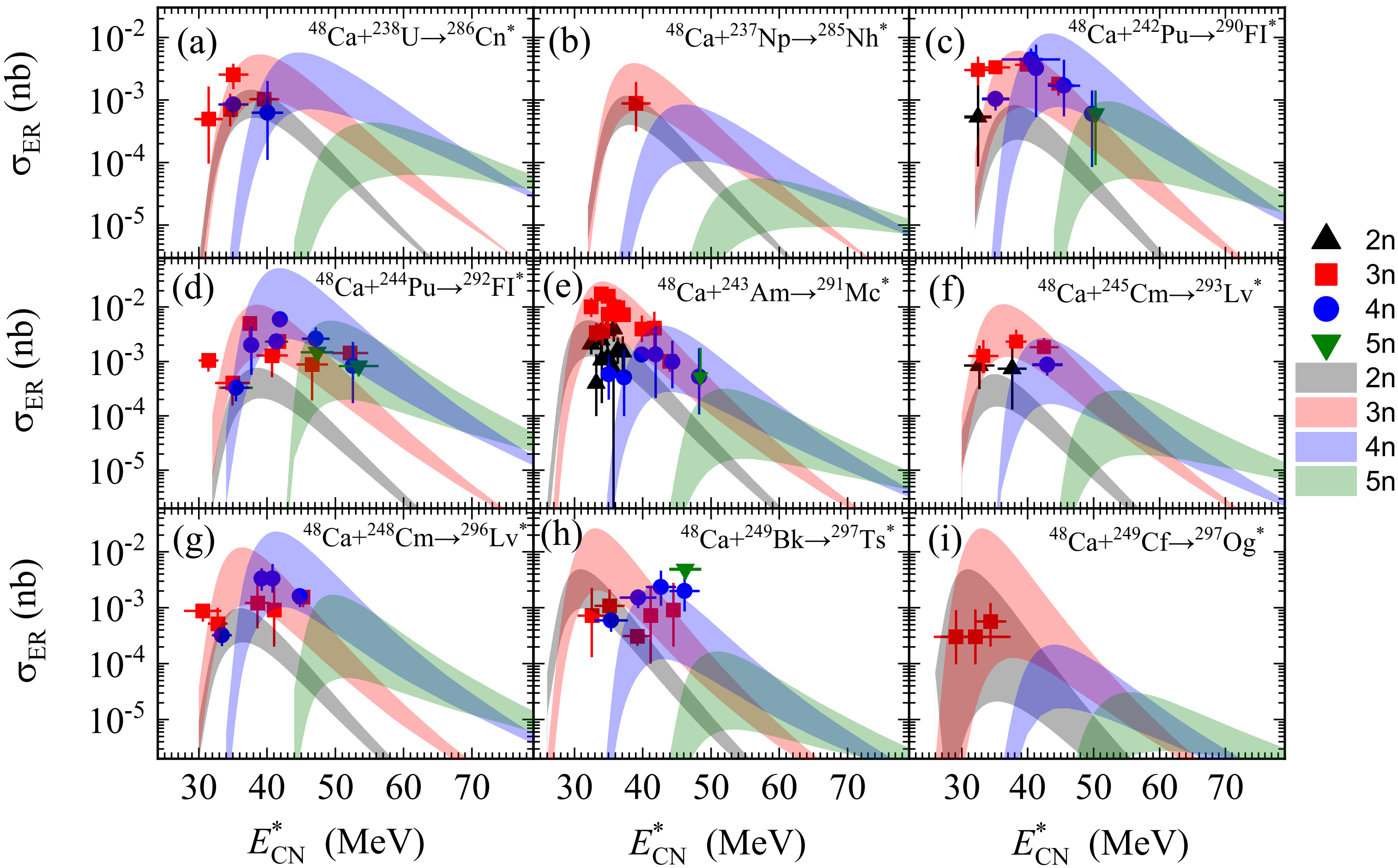


2. The prediction cross-section errors caused by shell damping factor



EPJoC 3**06** 01033(2024)

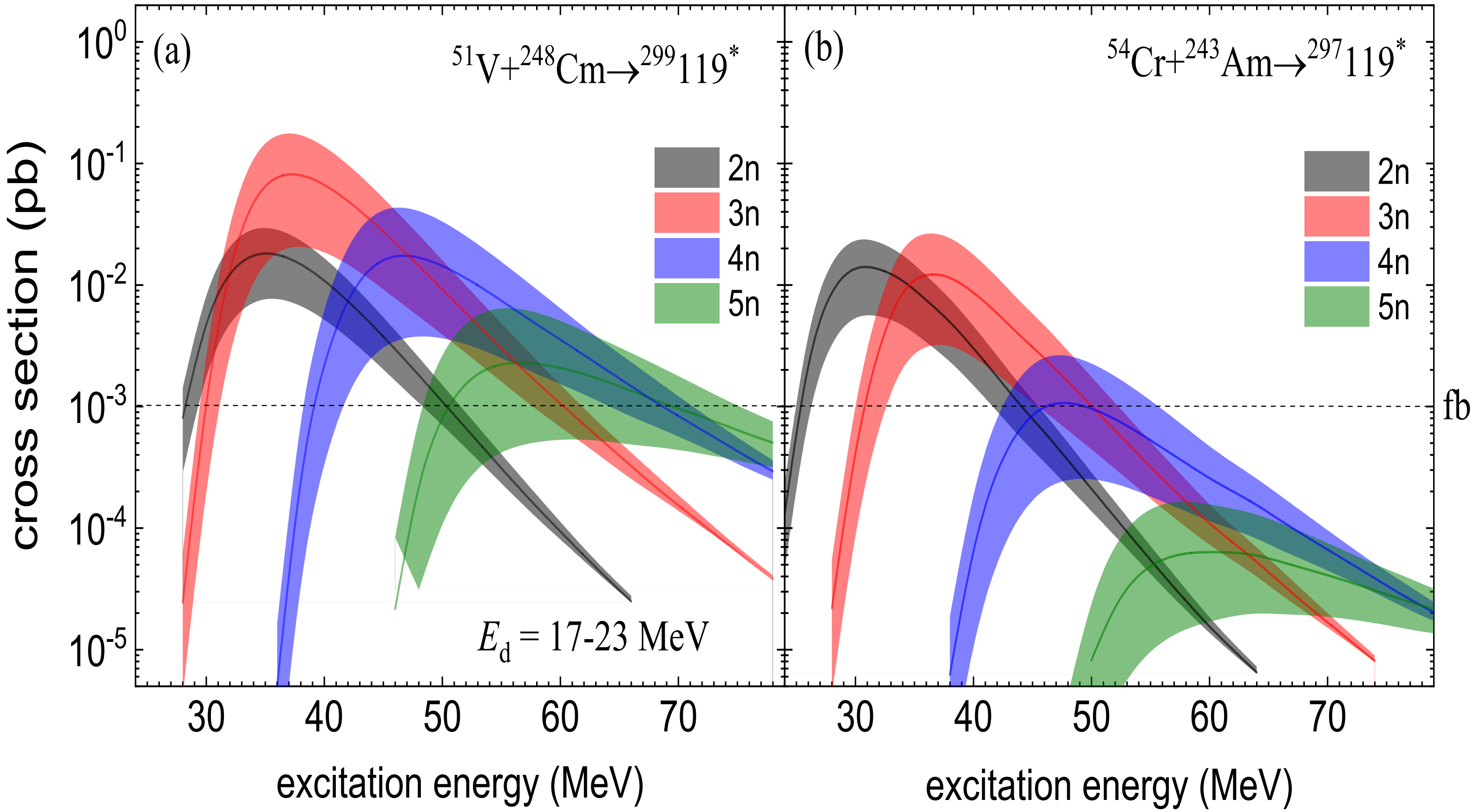
Constraint E_D from Exp. data



$$B_f(E^*, J) = B_f^{Mac} + B_f^{Mic}(E^* = 0, J)\exp(-E^*/E_D),$$

E_D=13-25 MeV → E_D=17-23 MeV

Predict cross section of new SHE with Z=119



E_D=17-23 MeV

Summary and prospect

■ Summary:

- The calculated cross-sections using different nuclear mass tables can reasonably reproduce the experimental data of hot fusion reactions;
- The predicted synthesis cross-sections show strong dependence on nuclear masses, with uncertainties within one order of magnitude;
- Z=119: $^{54}Cr(^{243}Am,3n)^{294}119$~2-35 fb, $^{51}V(^{248}Cm,3n)^{296}119$~0.1-1 pb.
- Z=120: $^{55}Mn(^{243}Am,3n)^{295}120$~0.2-6 fb, $^{54}Cr(^{248}Cm,3n)^{299}120$~1-55 pb.

■ Prospect:

- In the DNS model, Systematic evaluation of model parameter effects on superheavy nucleus synthesis cross-section predictions;
- In the DNS model, develop a dynamical potential energy surface based on the multi-dimensional adiabatic approximation.

C. Geng, P. H. Chen*, X. H. Zeng, Z. Q. Feng, *Phys. Rev. C* **109**, 054611 (2024)
P. H. Chen*, H. Wu, Z. X. Yang, X. H. Zeng, Z. Q. Feng, *Nucl. Sci. Tech.* **34**, 7 (2023)
P. H. Chen*, Chang. Geng, Z. X. Yang, X. H. Zeng, Z. Q. Feng, *Nucl. Sci. Tech.* **34**, 160(2023)
P. H. Chen*, F. Niu, X. H. Zeng, Z. Q. Feng, *Phys. Rev. C* **105**, 054601 (2022)
P. H. Chen*, C. Geng, X. H. Zeng, Z. Q. Feng, *Phys. Rev. C* **106**, 034610 (2022)

Group members at YZU

Acknowledge