IV International Conference on Nuclear Structure and Dynamics (NSD2019)
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Time-Dependent Hartree-Fock Theory for Multinucleon Transfer Reactions: Very recent results

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Today’s topics

MNT

Towards N=126

QF & SHE

Towards Z=120

Today’s topics

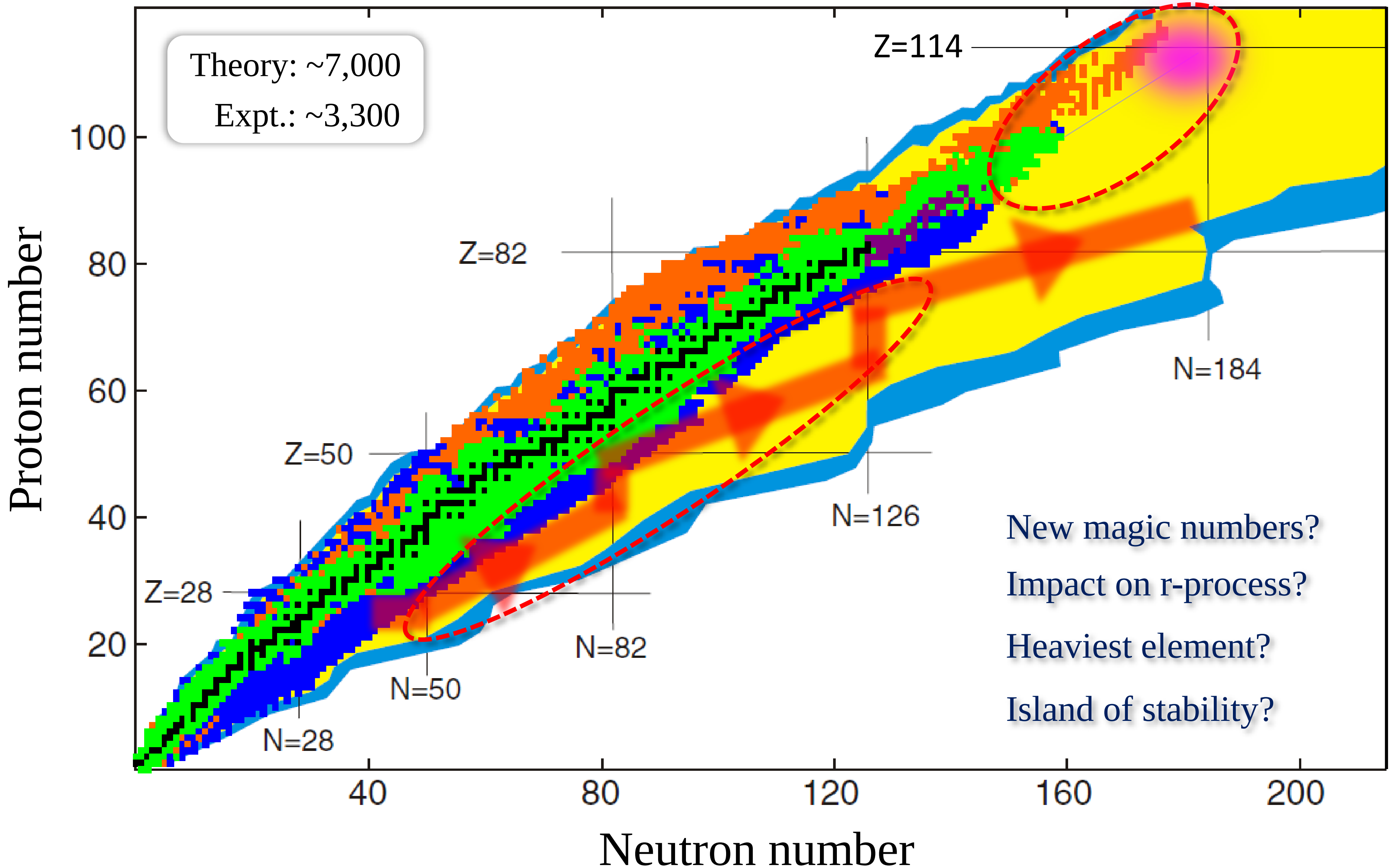
MNT

Towards *N*=126

QF & SHE

Towards Z=120

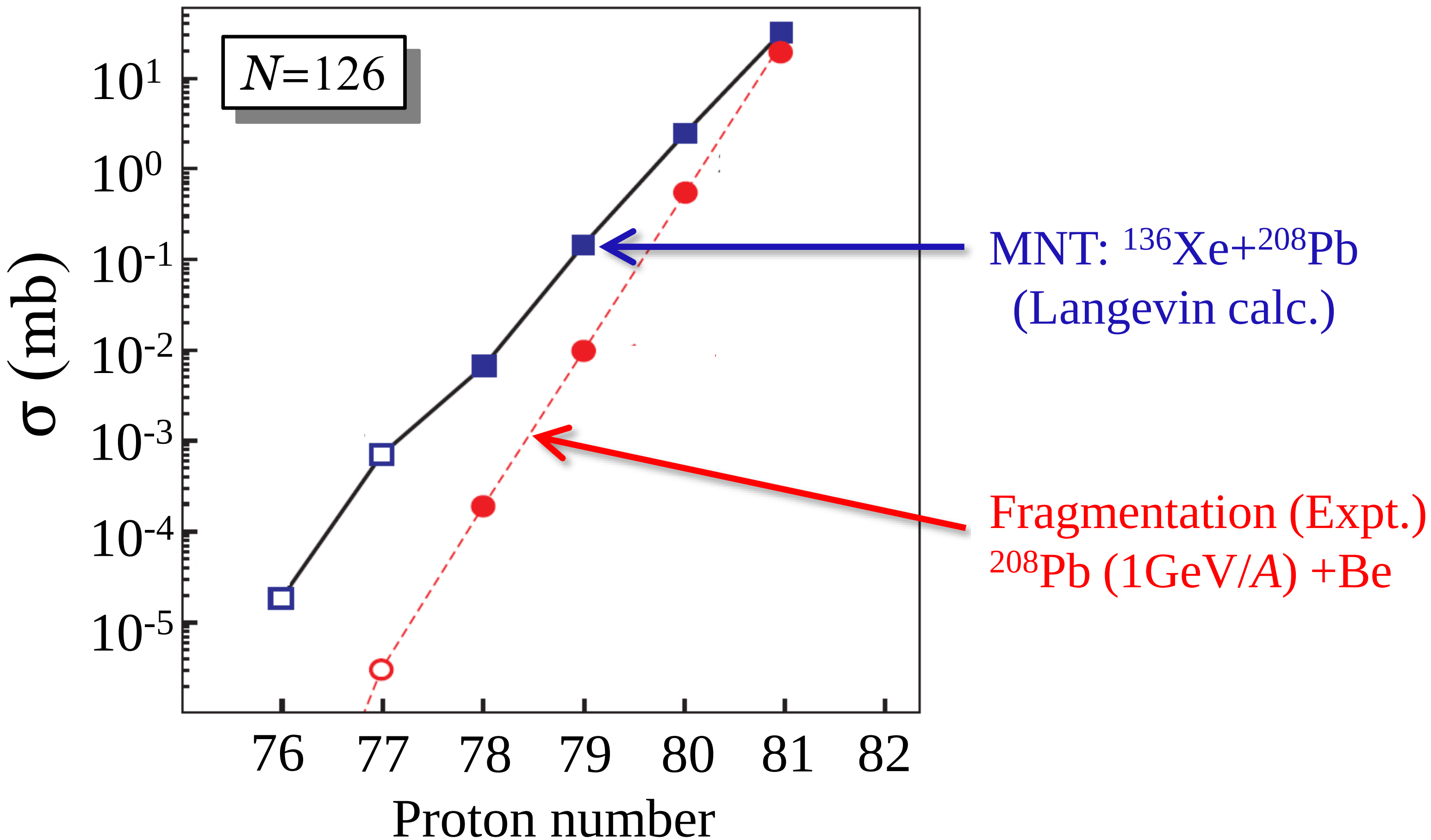
How can we create yet-unknown neutron-rich nuclei?



M. Thoennessen, Rep. Prog. Phys. **76**, 056301 (2013)

Multinucleon transfer reaction is expected to be a promising tool

Production cross section for N=126 isotones in ^{136}Xe + ^{208}Pb

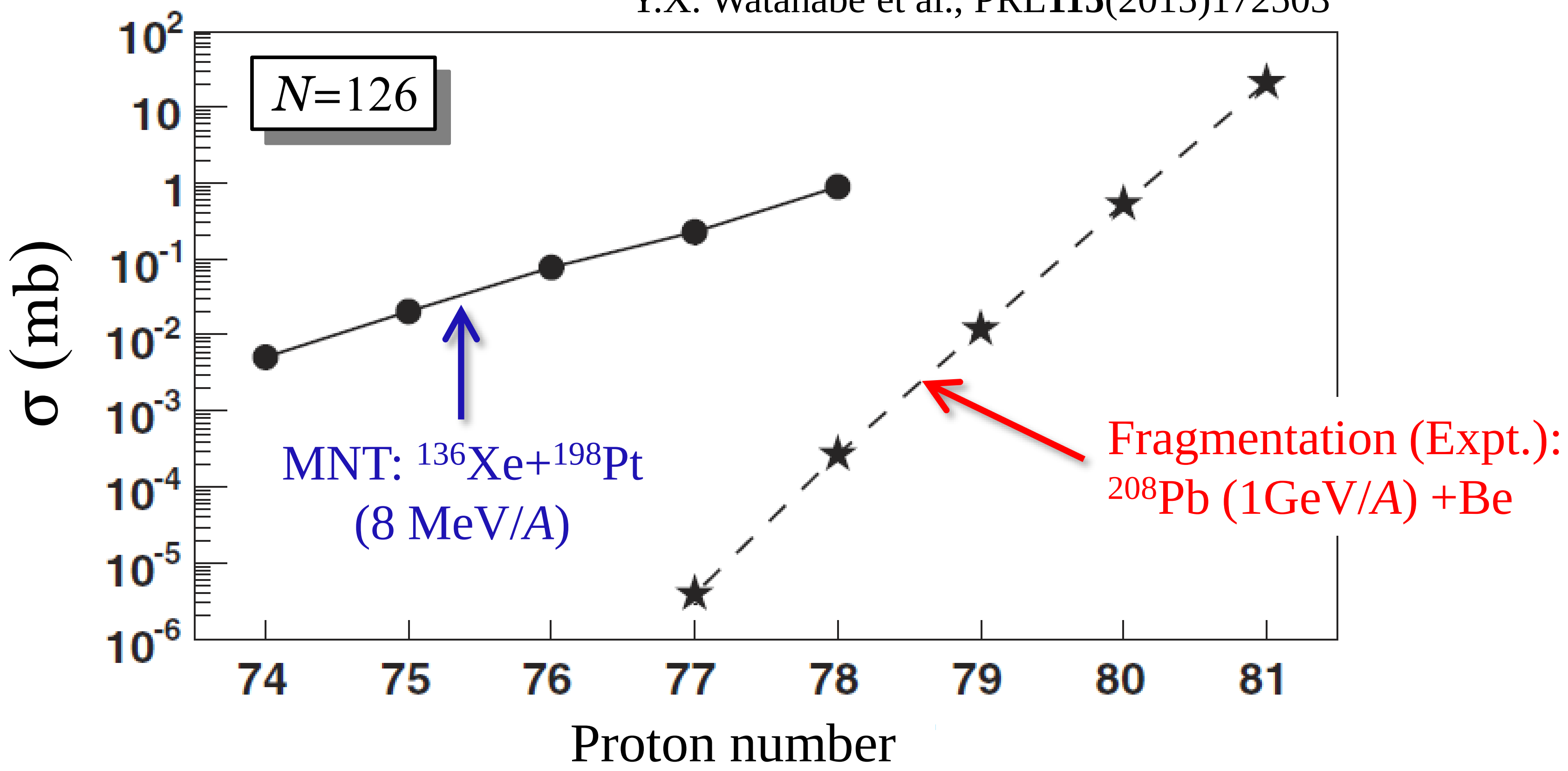


Langevin: V.I. Zagrebaev and W. Greiner, PRC**83**(2011)044618
Fragmentation: T. Kurtukian-Nieto et al., PRC**89**(2014)024616

Multinucleon transfer reaction is expected to be a promising tool

Production cross section for N=126 isotones in ^{136}Xe + ^{198}Pt

Y.X. Watanabe et al., PRL**115**(2015)172503



Fragmentation: T. Kurtukian-Nieto et al., PRC**89**(2014)024616

Theoretical models for the MNT reactions

Various models have been extensively developed and applied:

- **Langevin approach**

  V. Zagrebaev and W. Greiner, J. Phys. G **31**(2005)825; **34**(2007)1, 2265
  A.V. Karpov and V.V. Saiko, PRC**96**(2017)024618; PRC**99**(2019)014613

- **Improved quantum molecular dynamics model (ImQMD)**

  K. Zhao et al., PRC**92**(2015)024613; PRC**94**(2016)024601
  C. Li et al., PRC**93**(2016)014618

- **Dinuclear system model (DNS)**

  M.H. Mun et al., PRC**89**(2014)034622; PRC**91**(2015)054610;
  L. Zhu et al., J. Phys. G **42**(2015)085102; PLB**767**(2017)437; PRC**96**(2017)024606

- **GRAZING**

  A. Winther, NPA**572**(1994)191; NPA**594**(1995)203
  R. Yanez and W. Loveland, PRC**91**(2015)044608 (GRAZING-F)
  P.W. Wen et al., PRC**99**(2019)034606 (GRAZING w/ GEMINI++)

You may also see my mini-review article: KS, Front Phys. **7**, 20 (2019)

✓ There is no adjustable parameter on reaction dynamics

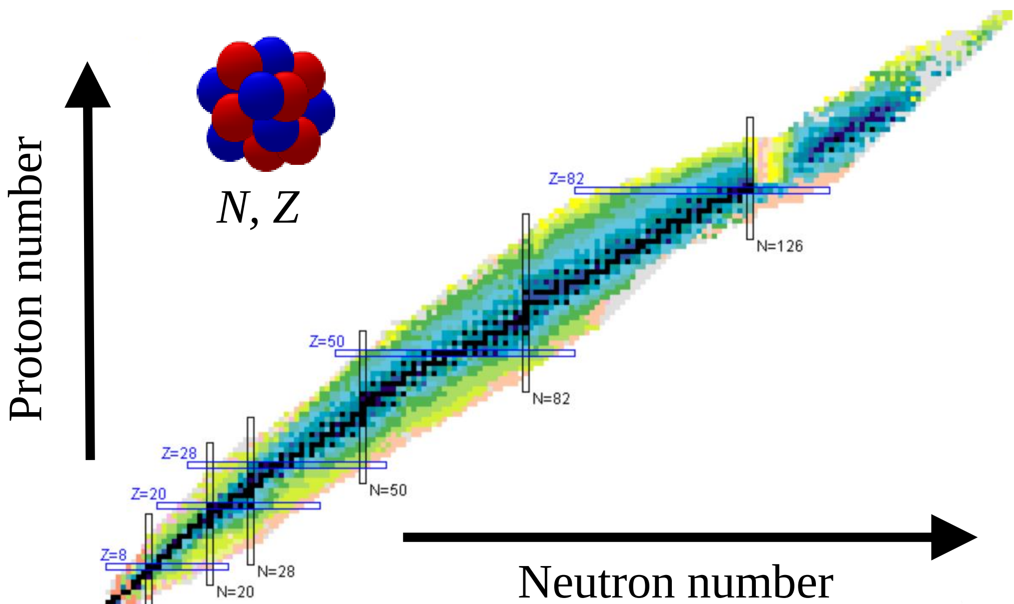
$$S = \int_{t_0}^{t_1} dt \left(i\hbar \sum_i \langle \phi_i(t) | \frac{\partial}{\partial t} | \phi_i(t) \rangle - \boxed{E[\rho(t)]} \right)$$

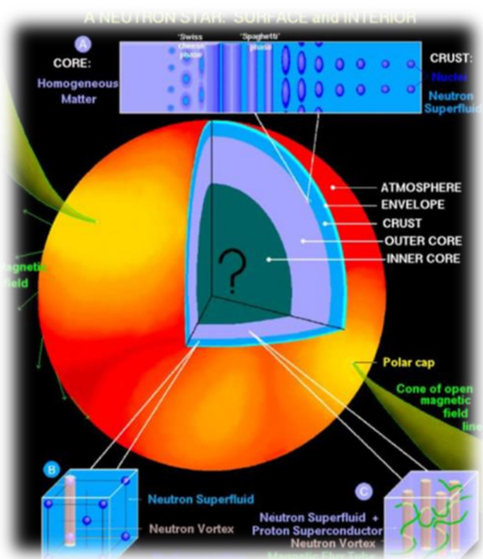
$$\boxed{i\hbar \frac{\partial \phi_i(\boldsymbol{r}\sigma q, t)}{\partial t} = \hat{h}[\rho(t)]\phi_i(\boldsymbol{r}\sigma q, t) \quad \text{: TDHF eq.}}$$

Effective interaction

$$E[\rho] = \langle \Phi | \hat{H} | \Phi \rangle$$

Energy Density Functional (EDF)

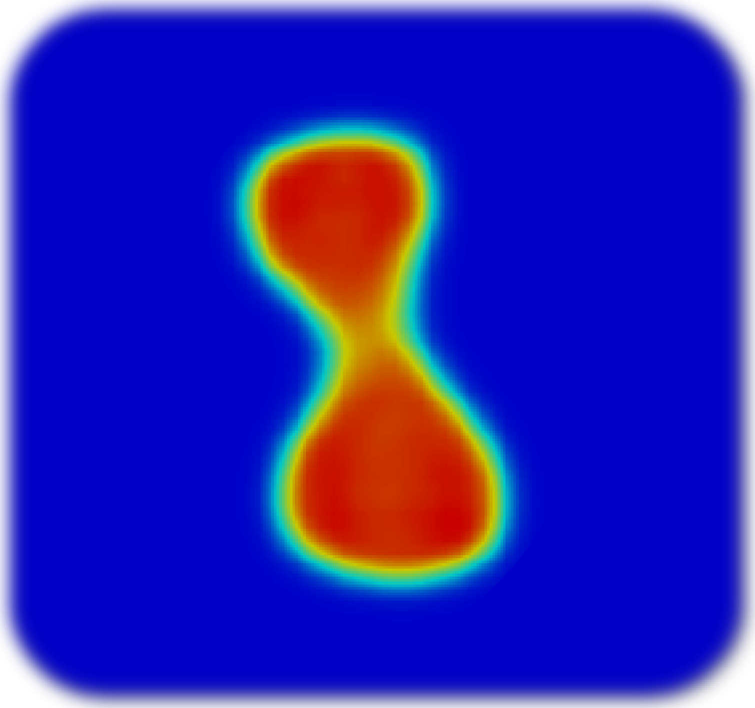




How to compute production cross sections?

We have developed: **TDHF + PNP + GEMINI**

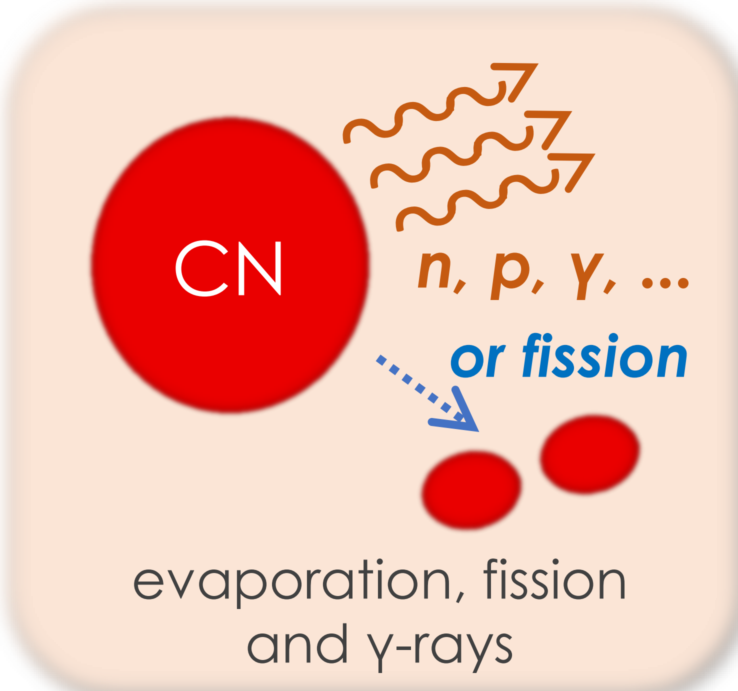
TDHF



Reaction dynamics
(10^{-21}-10^{-20} sec)

+

GEMINI++

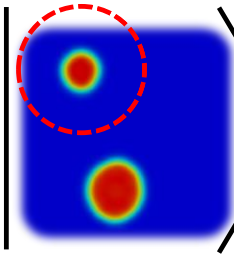


De-excitation
(10^{-18}-10^{-16} sec)

We have developed: **TDHF + PNP + GEMINI**

✓ Particle number projection (PNP)

C. Simenel, PRL**105**(2010)192701

$$\left|\Phi_{N,Z}(b)\right\rangle = \hat{P}_N \hat{P}_Z \left|\Phi(b)\right\rangle = \hat{P}_N \hat{P}_Z \Big|$$  $$\Big\rangle$$

PNP operator:

$$\hat{P}_n = \frac{1}{2\pi}\int_0^{2\pi} e^{i(n-\hat{N}_V)\theta} d\theta$$

- Transfer probabilities and cross sections

KS and K. Yabana, PRC**88**(2013)014614

$$P_{N,Z}(b) = \left\langle \Phi_{N,Z}(b) \middle| \Phi_{N,Z}(b) \right\rangle = P_N(b) P_Z(b)$$

$$\sigma_{N,Z} = 2\pi \int b\, P_{N,Z}(b) db$$

- Expectation values

KS and K. Yabana, PRC**90**(2014)064614

$$\mathcal{O}_{N,Z}(b) = \frac{\left\langle \Phi_{N,Z}(b) \middle| \hat{\mathcal{O}}_V \middle| \Phi_{N,Z}(b) \right\rangle}{\left\langle \Phi_{N,Z}(b) \middle| \Phi_{N,Z}(b) \right\rangle}$$

$$J_{N,Z}(b),\ E^*_{N,Z}(b)$$

Inputs for a statistical model

- Secondary deexcitation processes

KS, PRC**96**(2017)014615

Evaporation/Fission/Gamma by GEMINI++ [R.J. Charity, PRC**82**(2010)014610]

✓ **Other groups also adopted GEMINI for TDHF:**

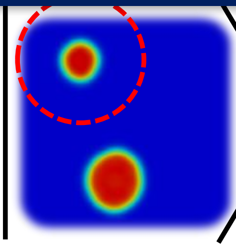
A.S. Umar, C. Simenel, and W. Ye, PRC**96**(2017)024625

X. Jiang and N. Wang, Chin. Phys. C **42**(2018)104105

Z. Wu and Lu Guo, private communication.

We have develope

✓ Particle number projection (PNP)

$$\left|\Phi_{N,Z}(b)\right\rangle = \hat{P}_N \hat{P}_Z \left|\Phi(b)\right\rangle = \hat{P}_N \hat{P}_Z \Big|$$  $$\Big\rangle$$

PNP operator:

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$$P_{N,Z}(b) = \left\langle \Phi_{N,Z}(b) \middle| \Phi_{N,Z}(b) \right\rangle = P_N(b) P_Z(b)$$

$$\sigma_{N,Z} = 2\pi \int b\, P_{N,Z}(b) db$$

- Expectation values

KS and K. Yabana, PRC**90**(2014)064614

$$\bar{E}^*_{N,Z} = \frac{N+Z}{A_{\mathrm{CN}}} \bar{E}^*_{\mathrm{tot}} \qquad \bar{E}^*_{\mathrm{tot}} = E_{\mathrm{c.m.}} - \mathrm{TKE} + Q_{\mathrm{gg}}$$

$$\bar{J}(b), \bar{E}^*_{N,Z}(b)$$

Inputs for a statistical model

- Secondary deexcitation processes

KS, PRC**96**(2017)014615

Evaporation/Fission/Gamma by GEMINI++ [R.J. Charity, PRC**82**(2010)014610]

Recent experimental data:

- ✓ $^{136}Xe+^{198}Pt$, $E_{c.m.}= 645$ MeV — Y.X. Watanabe et al., PRL**115**(2015)172503 @GANIL
- $E_{c.m.}= 450$ MeV — V.V. Desai et al., PRC**99**(2019)044604 @Argonne
- ✓ $^{136}Xe+^{208}Pb$, $E_{c.m.}= 423, 526, 617$ MeV — E.M. Kozulin et al., PRC**86**(2012)044611 @Flerov Lab
- $E_{c.m.}= 450$ MeV — J.S. Barrett et al., PRC**91**(2015)064615 @Argonne
- ✓ $^{204}Hg+^{198}Pt$, $E_{c.m.}= 619$ MeV — T. Welsh et al., PLB**771**(2017)119 @Argonne

➢ **TDHF calculations were carried out for:**

$^{136}Xe+^{198}Pt$: $E_{c.m.}= 450, 564, 645, 726, 806$ MeV

$^{144}Xe+^{198}Pt$: $E_{c.m.}= 564, 645, 726, 806$ MeV

$^{132}Sn+^{208}Pb$: $E_{c.m.}= 565, 646, 727, 808$ MeV

$^{136}Xe+^{208}Pb$: $E_{c.m.}= 450, 617, 740, 822$ MeV

$^{204}Hg+^{198}Pt$: $E_{c.m.}= 619, 703, 804, 904, 1005$ MeV

Comparison with the experimental data (1):

the $^{136}Xe+^{198}Pt$ reaction

Preliminary

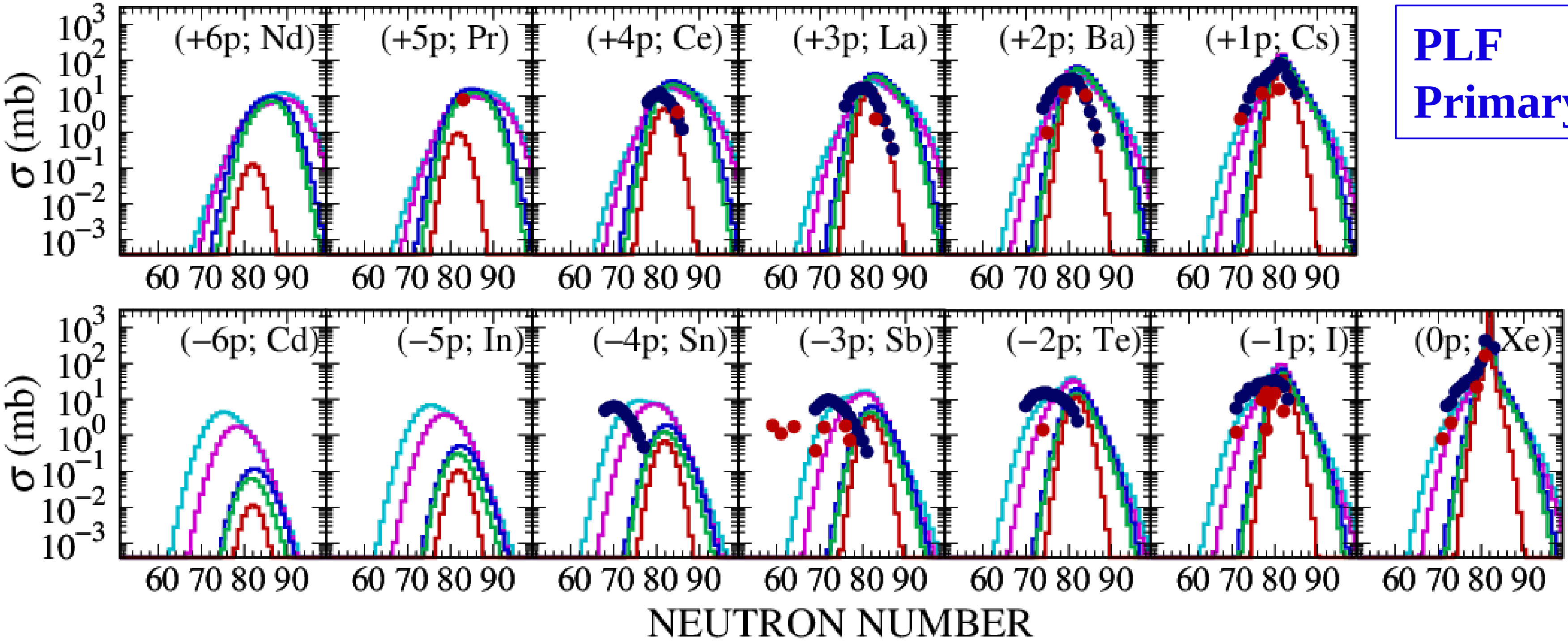
Isotopic distributions in the ^{136}Xe+^{198}Pt reaction

Experiment

- Watanabe et al. ($E_{c.m.}$=645MeV) PRL**115**(2015)172503
- Desai et al. ($E_{c.m.}$=450 MeV) PRC**99**(2019)044604

TDHF

- $E_{c.m.}$=806 MeV
- $E_{c.m.}$=726 MeV
- $E_{c.m.}$=645 MeV
- $E_{c.m.}$=564 MeV
- $E_{c.m.}$=450 MeV



PLF Primary

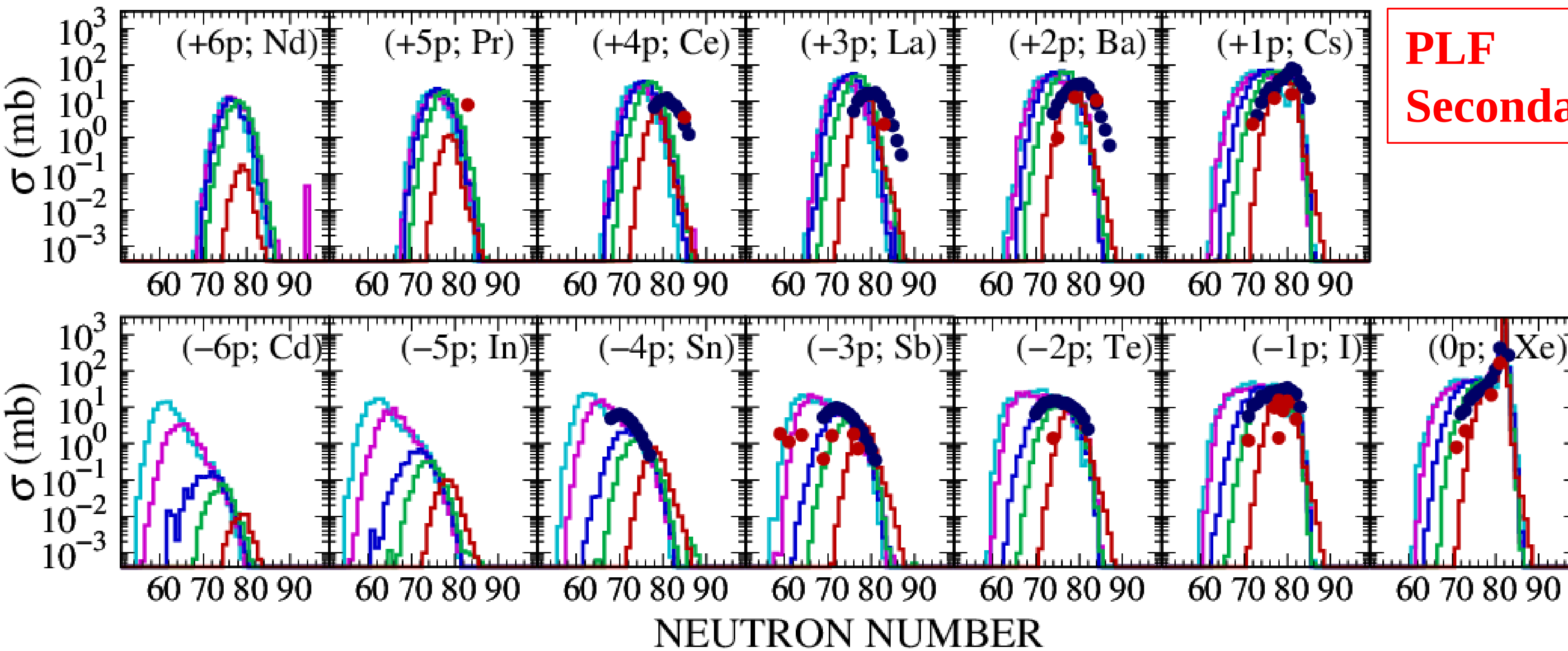
Preliminary

Isotopic distributions in the ^{136}Xe+^{198}Pt reaction

Experiment
- Watanabe et al. ($E_{\mathrm{c.m.}}$=645MeV) PRL**115**(2015)172503
- Desai et al. ($E_{\mathrm{c.m.}}$=450 MeV) PRC**99**(2019)044604

TDHF+GEMINI
- $E_{\mathrm{c.m.}}$=806 MeV
- $E_{\mathrm{c.m.}}$=726 MeV
- $E_{\mathrm{c.m.}}$=645 MeV
- $E_{\mathrm{c.m.}}$=564 MeV
- $E_{\mathrm{c.m.}}$=450 MeV

PLF Secondary



Preliminary

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- Desai et al. ($E_{c.m.}$=450 MeV) PRC**99**(2019)044604

TDHF
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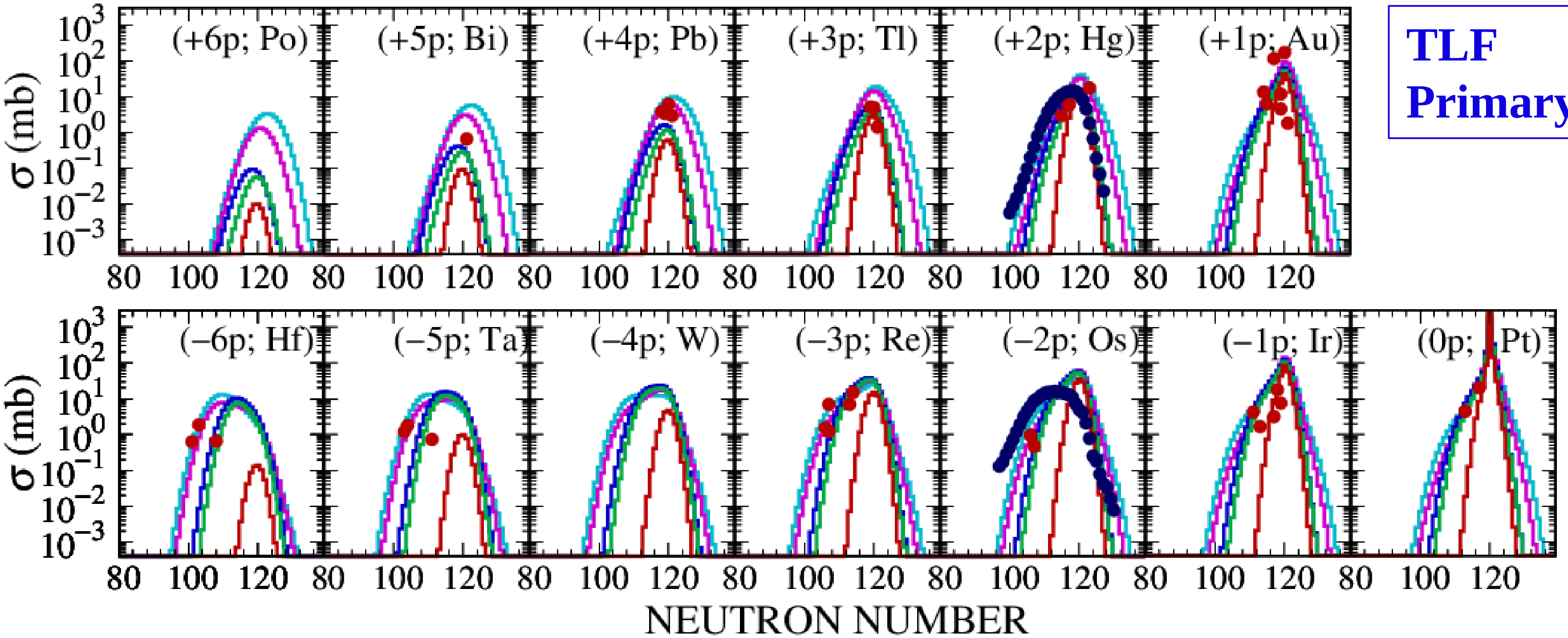
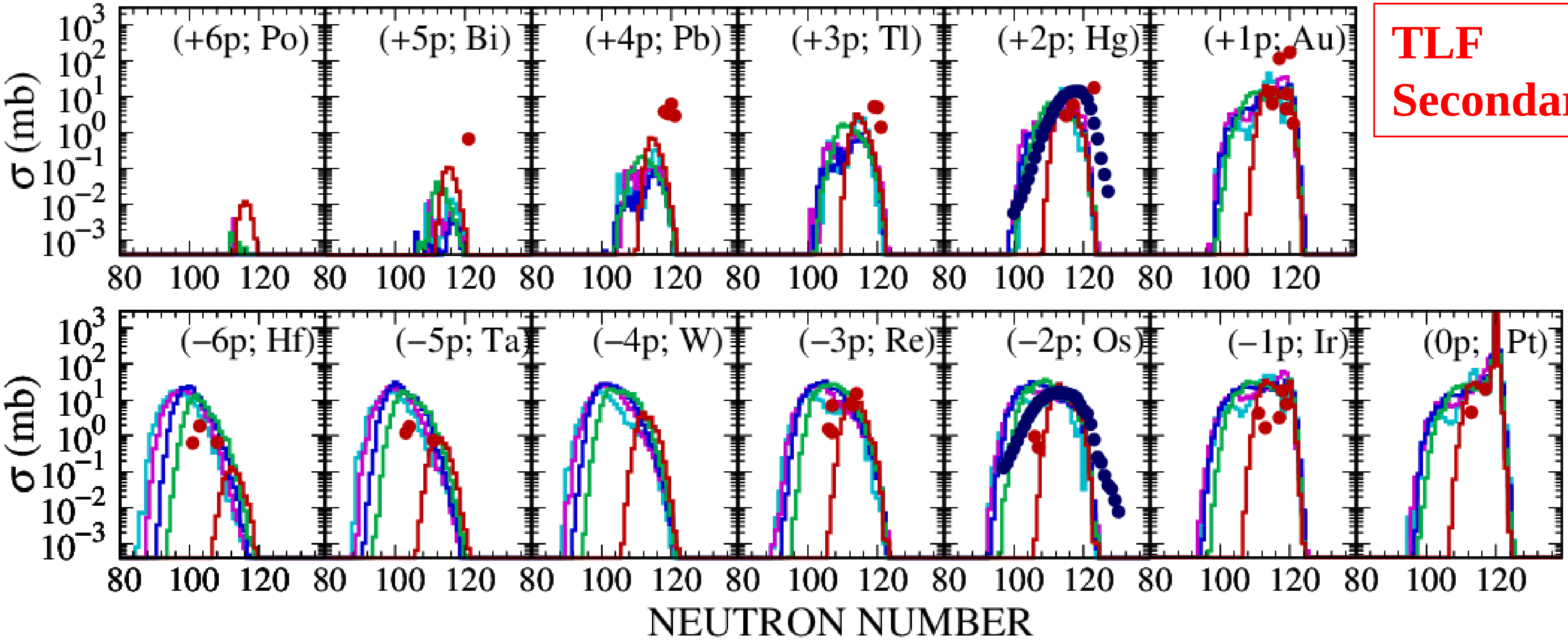


TLF Primary

Isotopic distributions in the ^{136}Xe+^{198}Pt reaction

Experiment
- Watanabe et al. ($E_{c.m.}$=645MeV) PRL**115**(2015)172503
- Desai et al. ($E_{c.m.}$=450 MeV) PRC**99**(2019)044604

TDHF+GEMINI
- $E_{c.m.}$=806 MeV
- $E_{c.m.}$=726 MeV
- $E_{c.m.}$=645 MeV
- $E_{c.m.}$=564 MeV
- $E_{c.m.}$=450 MeV



TLF Secondary

Comparison with the experimental data (2):

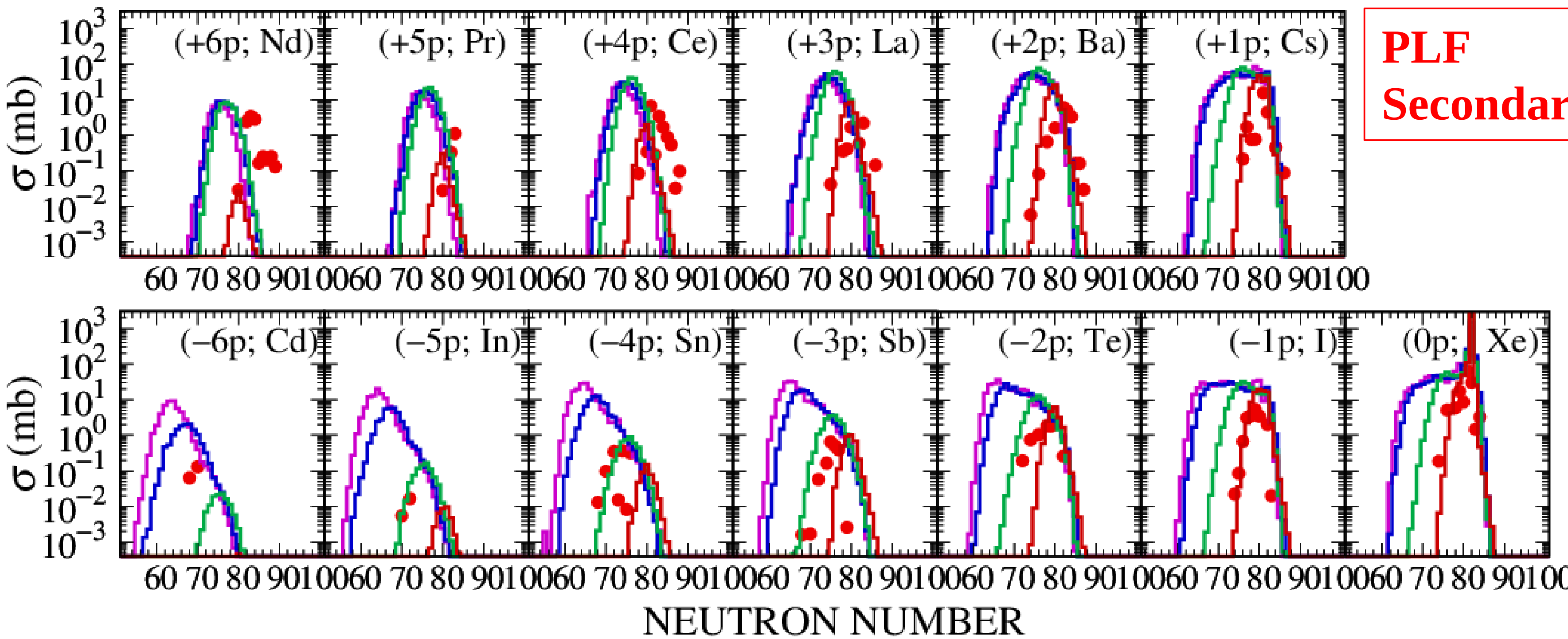
the $^{136}Xe+^{208}Pb$ reaction

Preliminary

Isotopic distributions in the ^{136}Xe+^{208}Pb reaction

Experiment
- Barrett et al. ($E_{c.m.}$=450 MeV) PRC**91**(2015)064615

TDHF+GEMINI
- $E_{c.m.}$=822 MeV
- $E_{c.m.}$=740 MeV
- $E_{c.m.}$=617 MeV
- $E_{c.m.}$=450 MeV

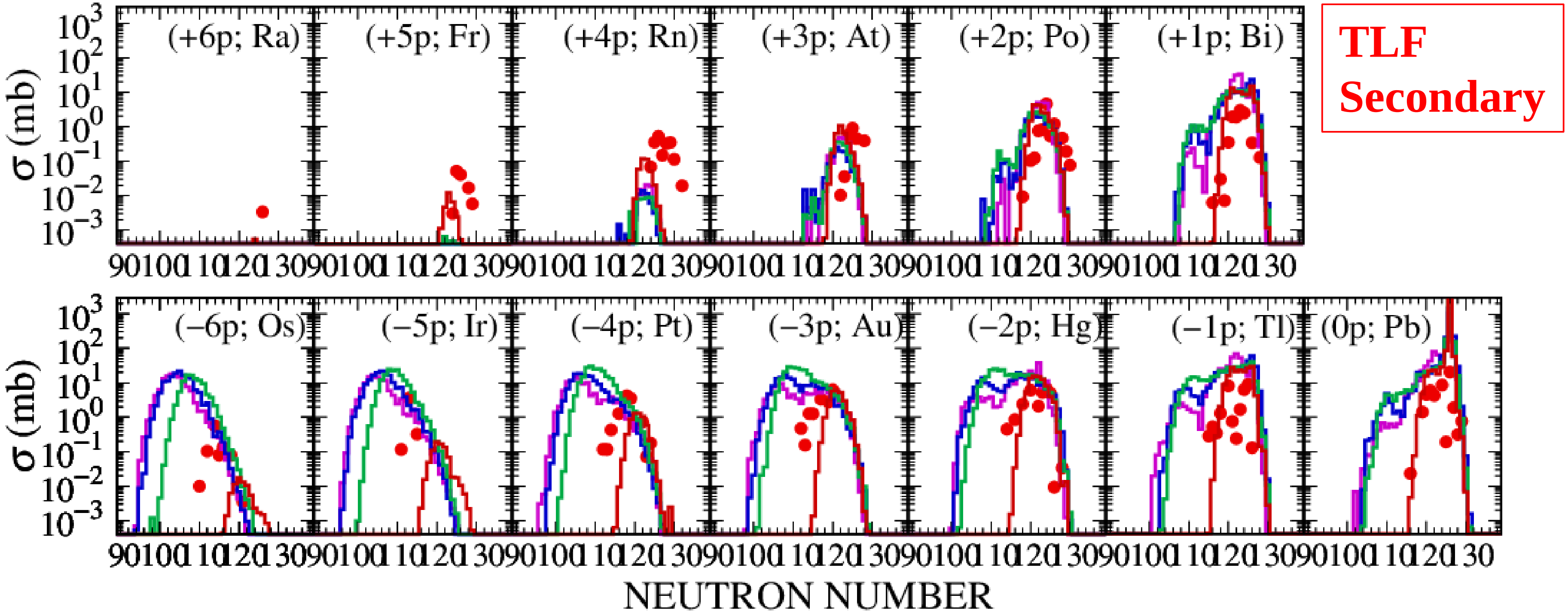


PLF Secondary

Isotopic distributions in the ^{136}Xe+^{208}Pb reaction

Experiment { ● Barrett et al. ($E_{c.m.}$=450 MeV) PRC**91**(2015)064615

TDHF+GEMINI { $E_{c.m.}$=822 MeV, $E_{c.m.}$=740 MeV, $E_{c.m.}$=617 MeV, $E_{c.m.}$=450 MeV

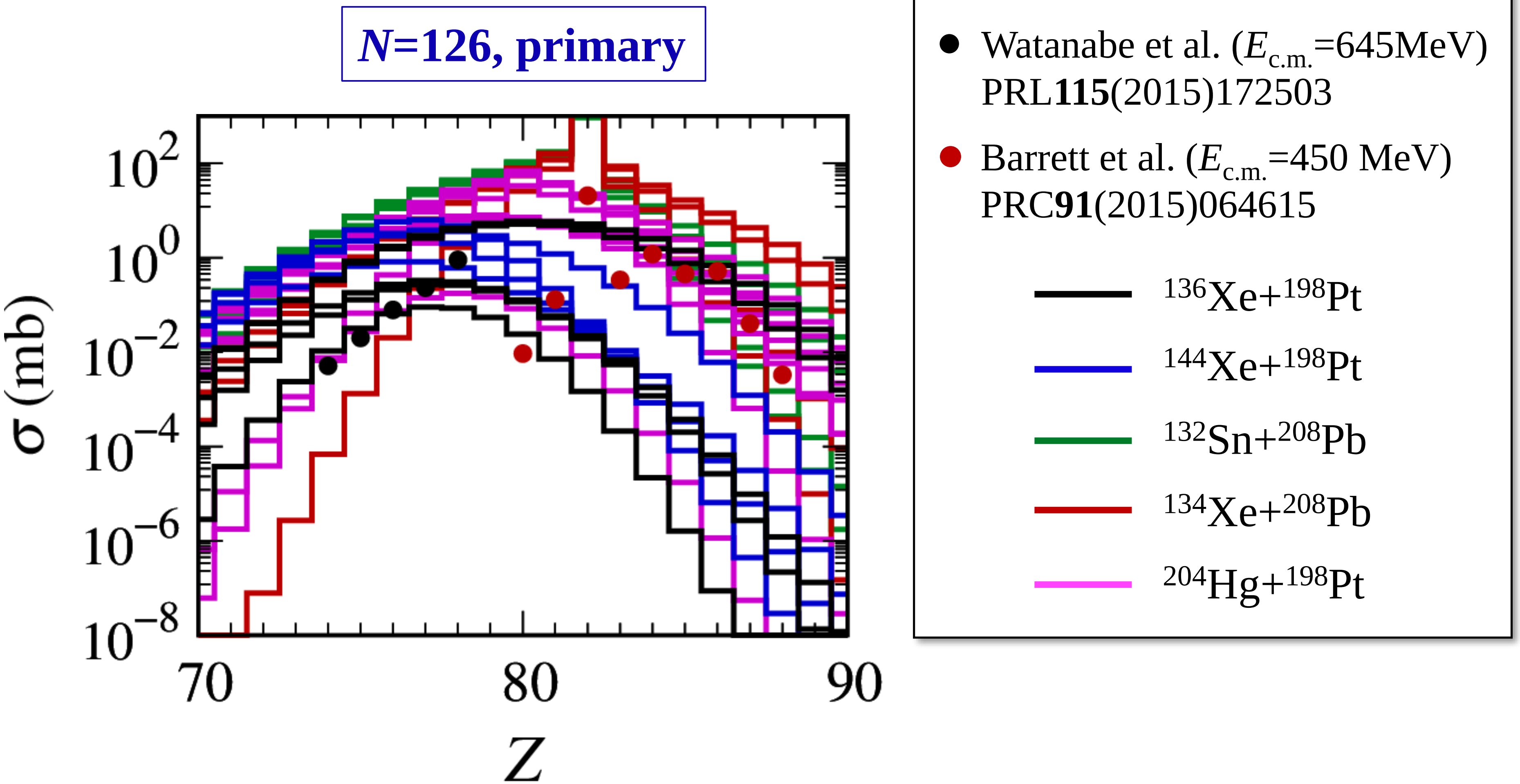


Finally, let’s see the most important plots:

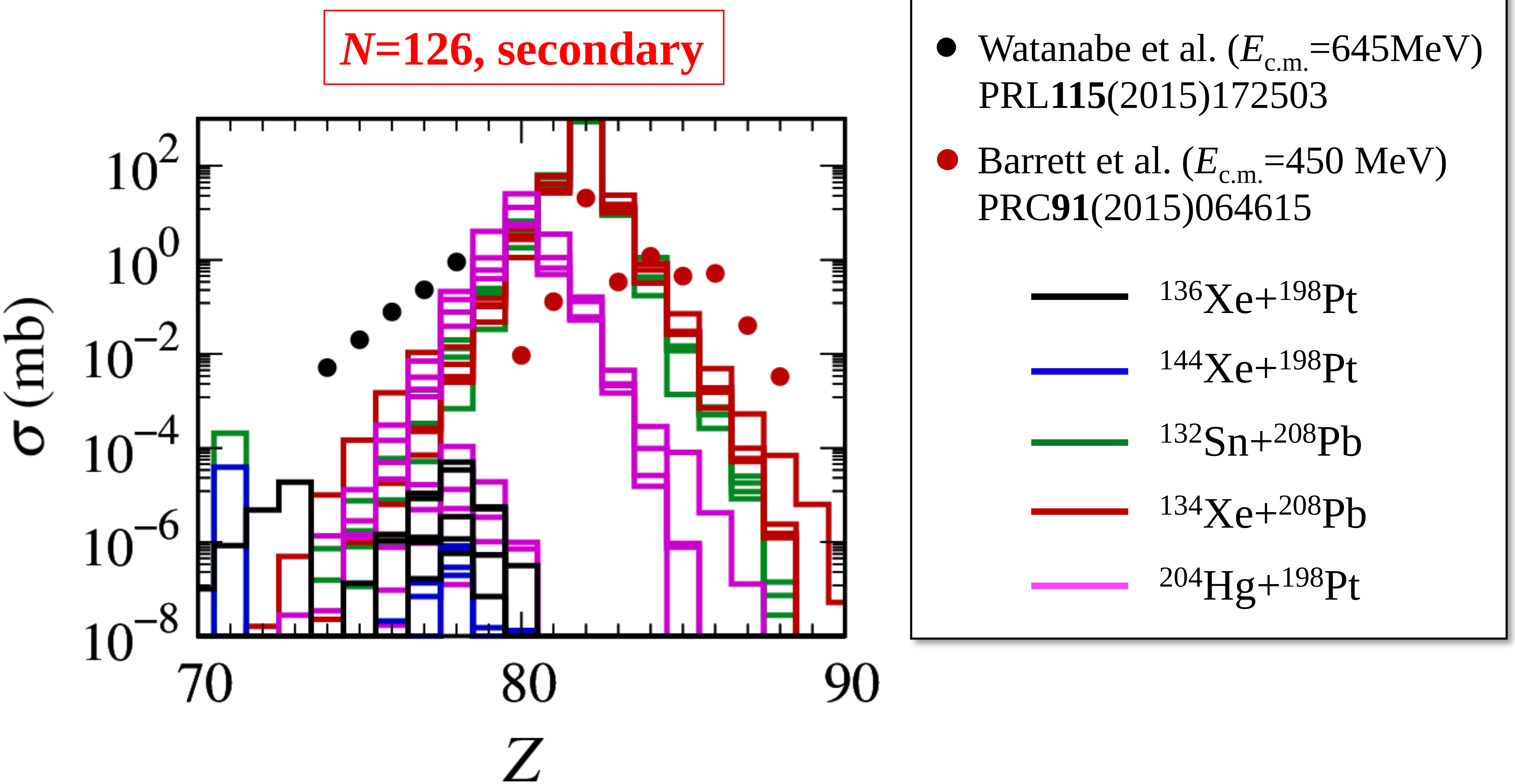
Production cross sections for N=126 isotones

Preliminary

Isotonic distributions for various systems

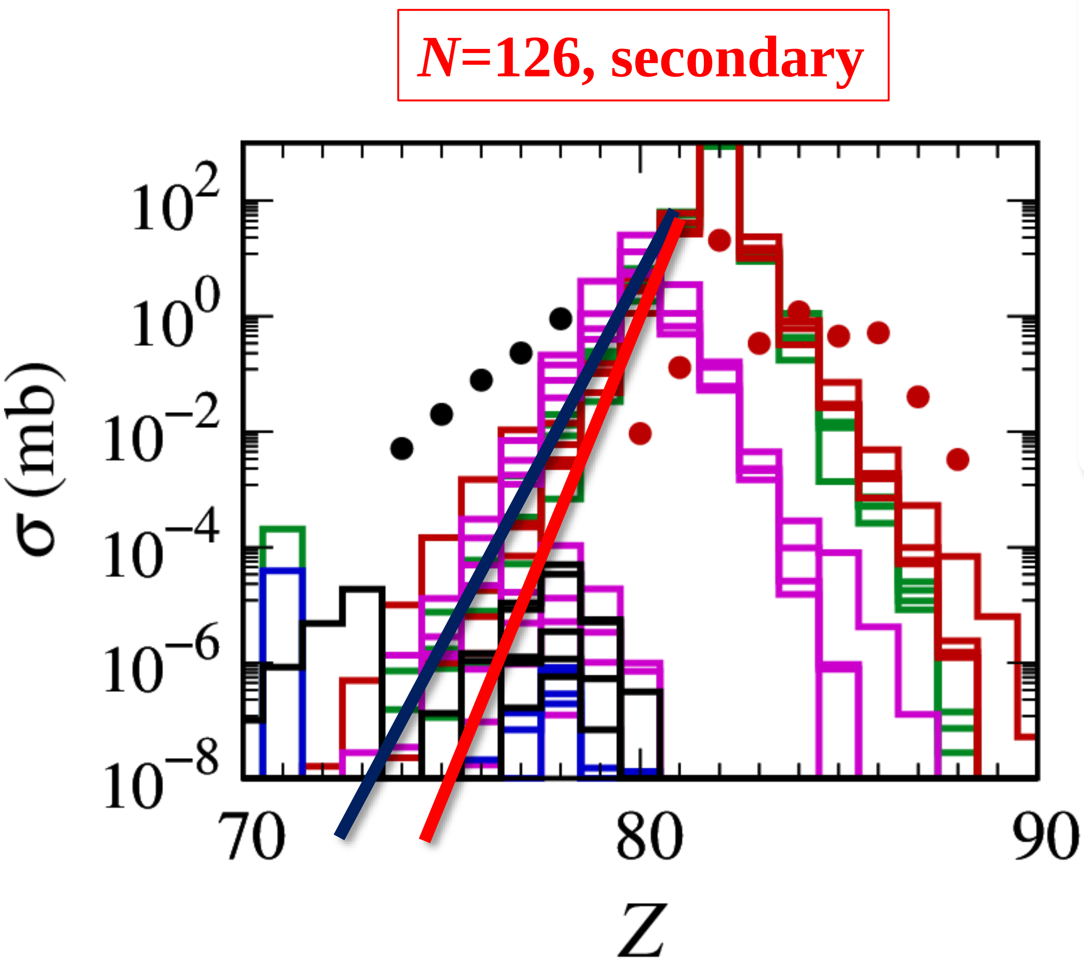


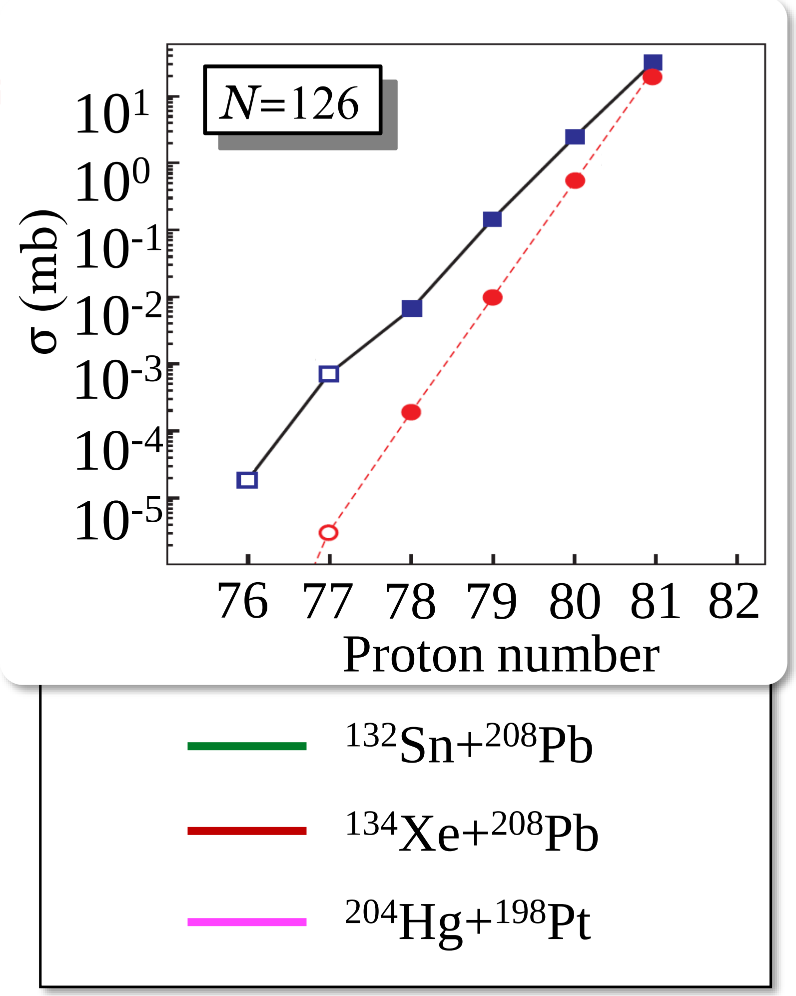
Isotonic distributions for various systems



Preliminary

Isotonic distributions for va



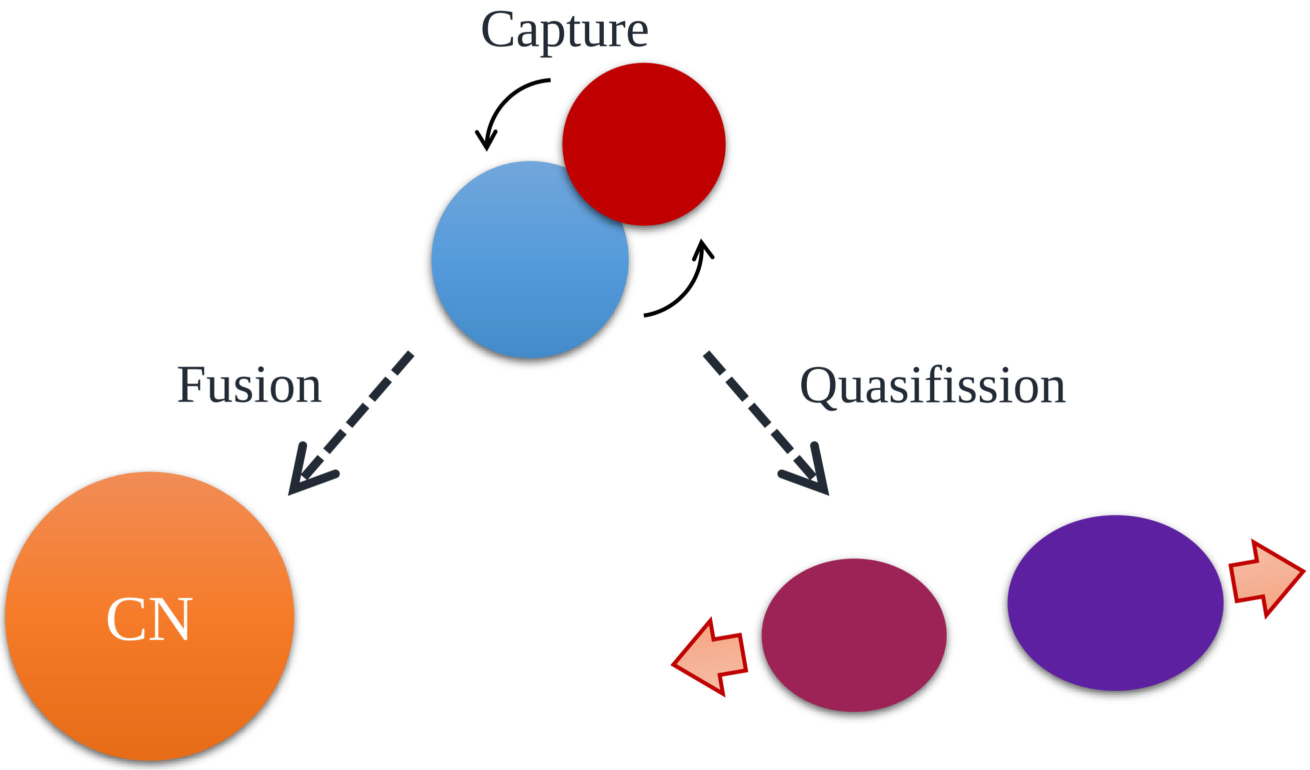


QF & SHE

Towards Z=120

Quasifission process

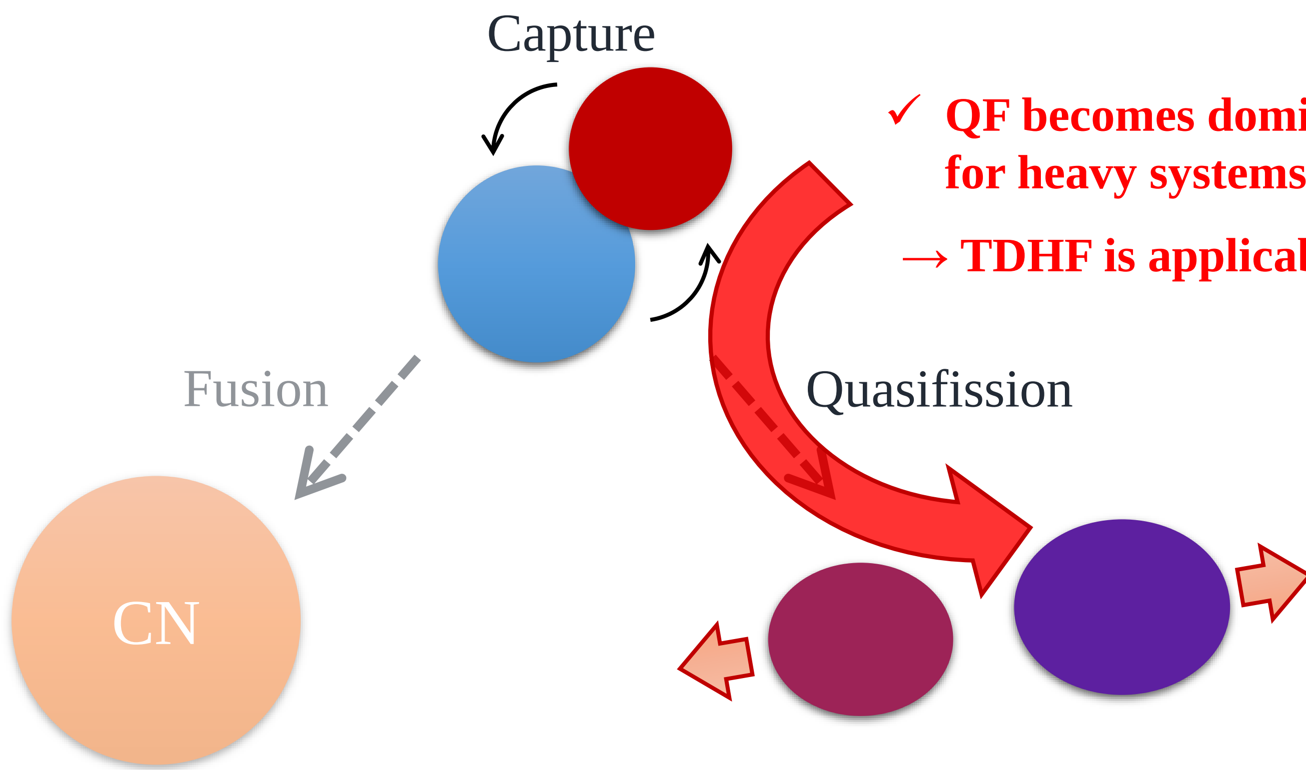
A fast (~10^{-21}-10^{-20} sec) fission process before compound nucleus formation (fusion)



$$\sigma_{\mathrm{ER}} \sim W_{\mathrm{surv}} * \sigma_{\mathrm{cap}} * P_{\mathrm{CN}}$$

Quasifission process

A fast (~10^{-21}-10^{-20} sec) fission process before compound nucleus formation (fusion)



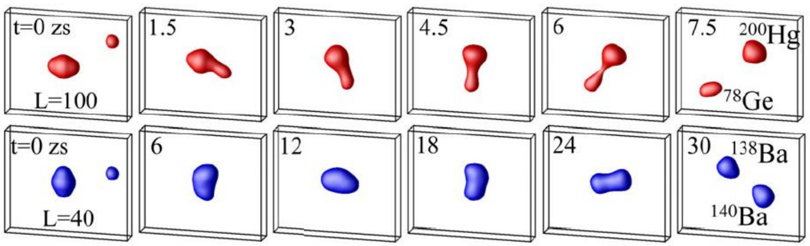
✓ **QF becomes dominant for heavy systems**

→ TDHF is applicable!

$$\sigma_{\rm ER} \sim W_{\rm surv} * \sigma_{\rm cap} * P_{\rm CN}$$

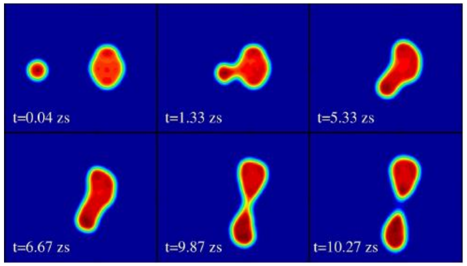
Quasifission dynamics in TDHF have been investigated in last 5 years

Shell/orientation effects, MAD: $^{40}Ca+^{238}U$



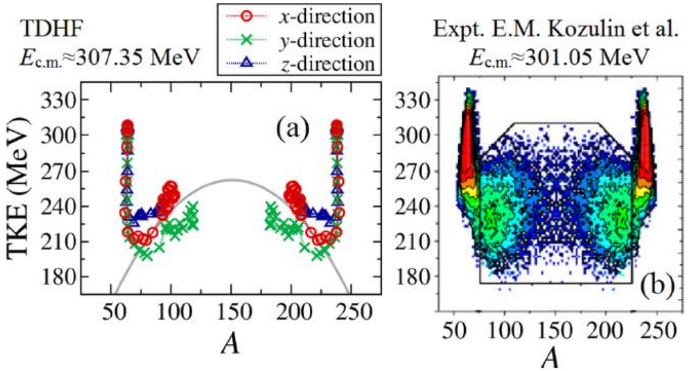
A. Wakhle, C. Simenel, D.J. Hinde et al., PRL**113**(2014)182502

Contact time, E^*, TKE: $^{40,48}Ca+^{238}U$



V.E. Oberacker, A.S. Umar, and C. Simenel, PRC**90**(2014)054605

Shell/orientation effects, TKE: $^{64}Ni+^{238}U$



KS and K. Yabana, PRC**93**(2016)054616

Other applications:

$^{48}Ca+^{249}Bk$ vs. $^{50}Ti+^{249}Bk$:

A.S. Umar, V.E. Oberacker, and C. Simenel, PRC**94**(2016)024605

$^{40}Ca+^{238}U$, EDF dependence:

H. Zheng et al., PRC**98**(2018)024622

$^{48}Ca+^{239,244}Pu$, isotope dependence:

Lu Guo et al., PRC**98**(2018)064609

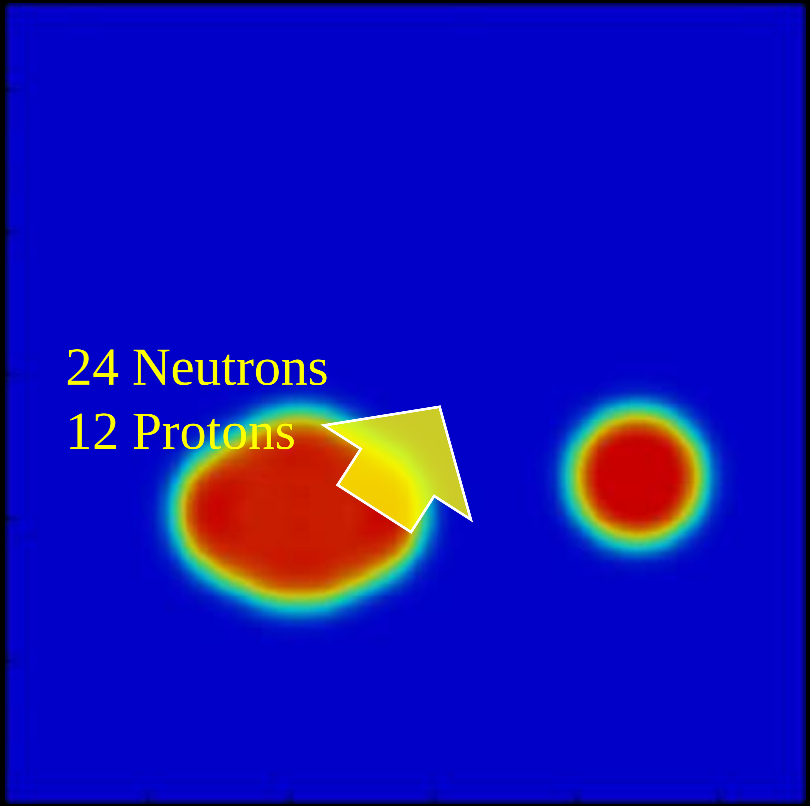
$^{64}Ni+^{238}U$ at E_{lab}=390 MeV

KS and K. Yabana, PRC**93**(2016)054616

Quasifission dynamics in TDHF

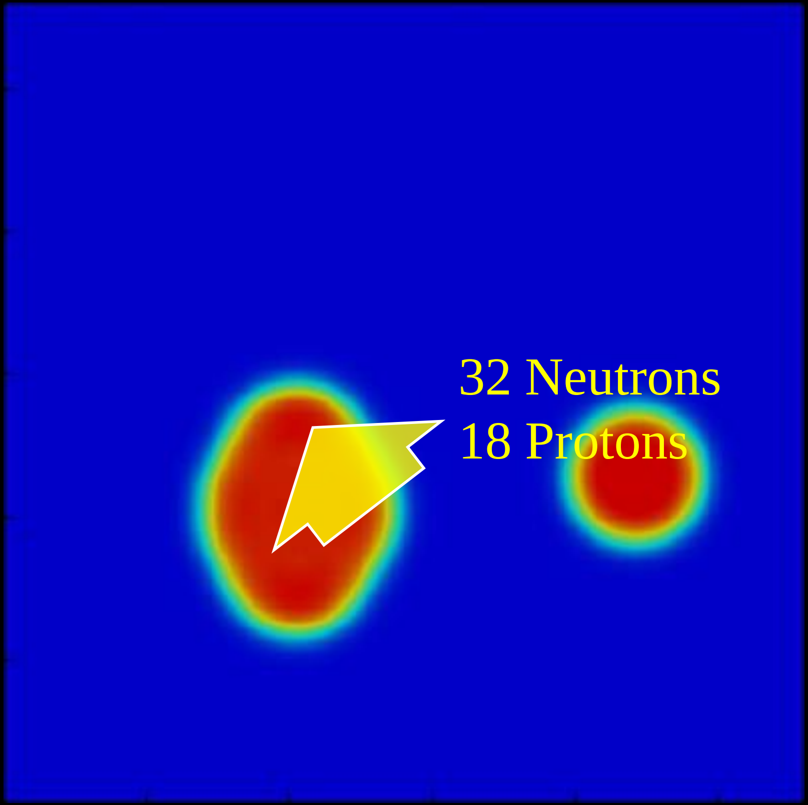
Tip collision

Shell effects of ^{208}Pb



Side collision

More mass-symmetric



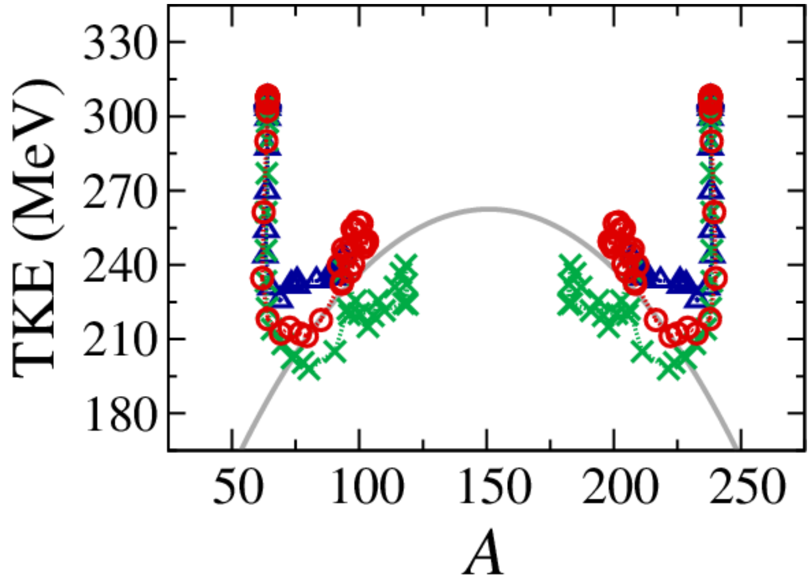
$^{64}Ni+^{238}U$ at E_{lab}=390 MeV

KS and K. Yabana, PRC**93**(2016)054616

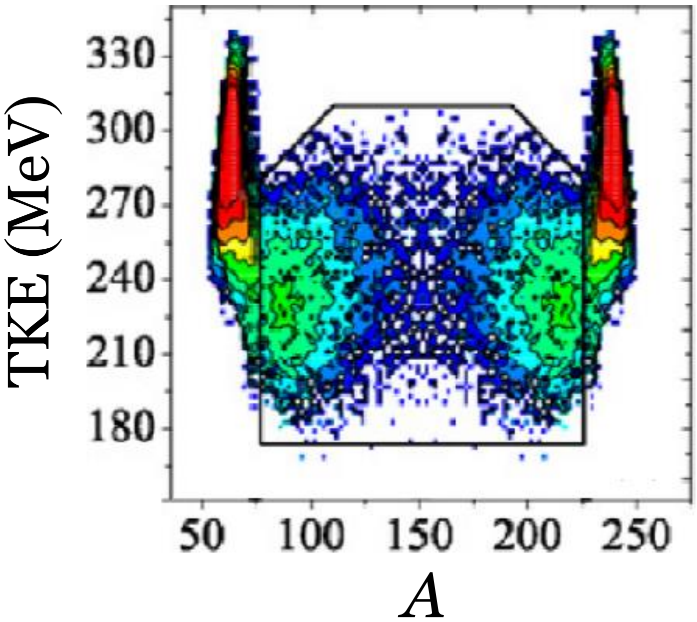
TDHF provides quantitative description of quasifission dynamics

TKE-*A* distribution: Comparison with experimental data

TDHF



Experiment



Expt.: E.M. Kozulin *et al.*, PLB**686**(2010)227

Recently, TDHF calculations were carried out for:

(head-on, tip & side collisions, E/V_B=0.95-1.2)

Z=118

^{50}Ti+^{248}Cm $\longrightarrow$ ^{298}Og

^{48}Ca+^{249}Cf $\longrightarrow$ ^{297}Og

^{54}Cr+^{240}Pu $\longrightarrow$ ^{294}Og

^{51}V+^{243}Am $\longrightarrow$ ^{294}Og

^{40}Ca+^{249}Cf $\longrightarrow$ ^{289}Og

Z=119

^{48}Ca+^{254}Es $\longrightarrow$ ^{302}119

^{51}V+^{248}Cm $\longrightarrow$ ^{299}119

^{50}Ti+^{249}Bk $\longrightarrow$ ^{299}119

Z=120

^{48}Ca+^{257}Fm $\longrightarrow$ ^{305}120

^{48}Ca+^{254}Fm $\longrightarrow$ ^{302}120

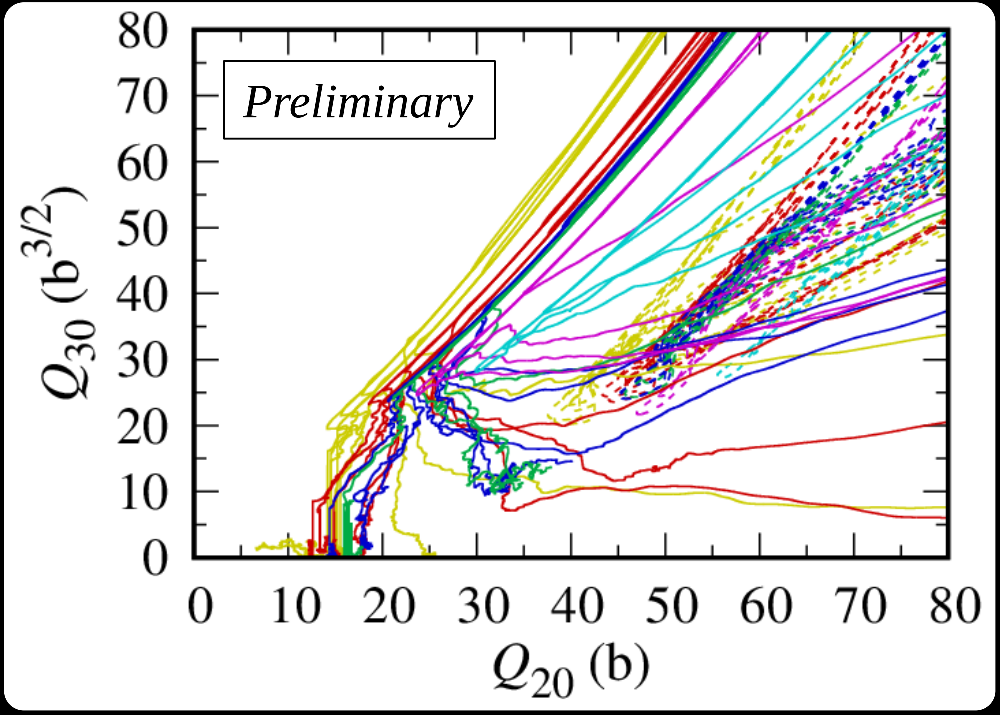
^{54}Cr+^{248}Cm $\longrightarrow$ ^{302}120

^{64}Ni+^{238}U $\longrightarrow$ ^{302}120

^{51}V+^{249}Bk $\longrightarrow$ ^{300}120

^{50}Ti+^{249}Cf $\longrightarrow$ ^{299}120

^{40}Ca+^{257}Fm $\longrightarrow$ ^{297}120



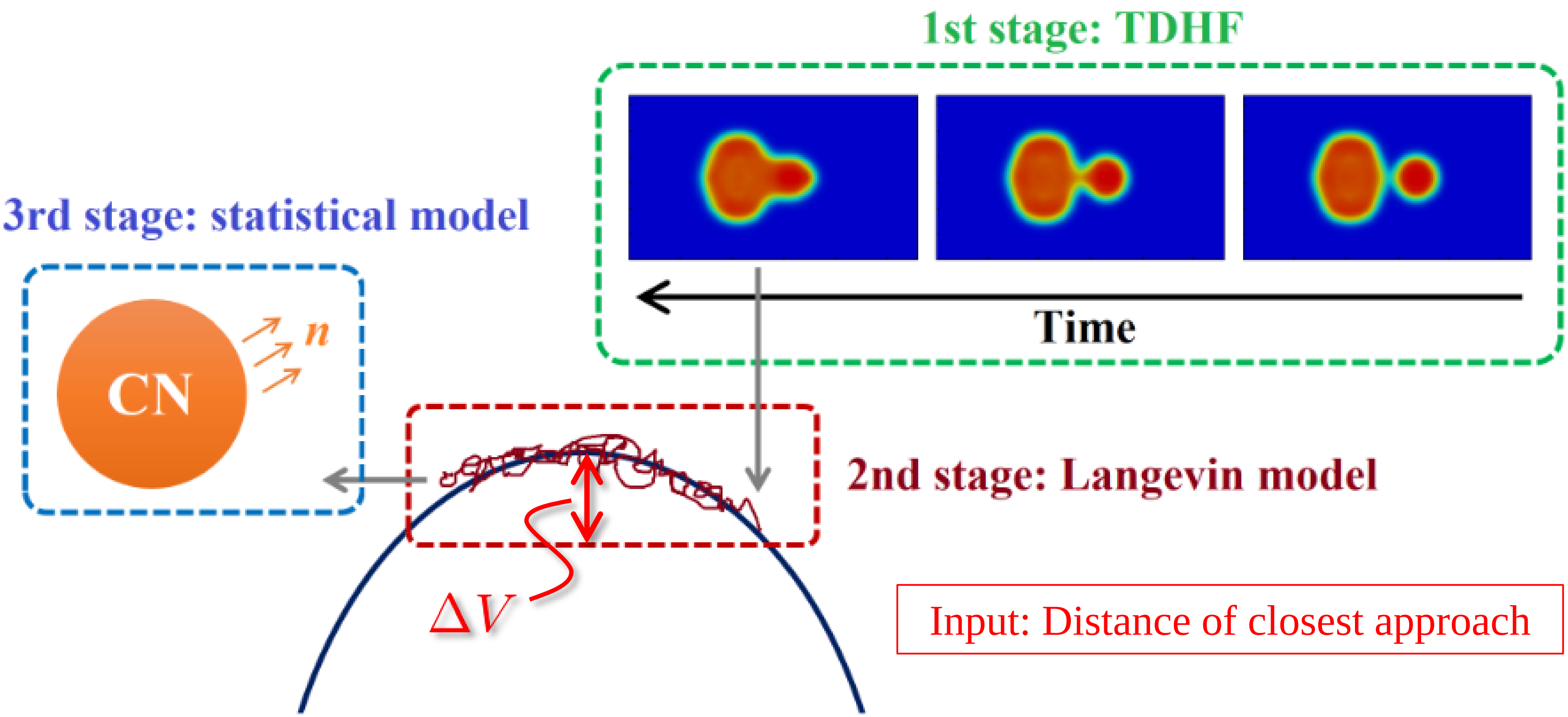
However, TDHF cannot be used to compute
the CN formation probability
(because it’s a very rare process)

↓

To study fusion reactions for SHE synthesis,
we have developed a “TDHF+Langevin” approach

KS and K. Hagino, Phys. Rev. C **99**, 051602(R) (2019)
Rapid Comm. with Editors' Suggestion

TDHF + Langevin approach: Idea



- **Analytical formula can be derived:**

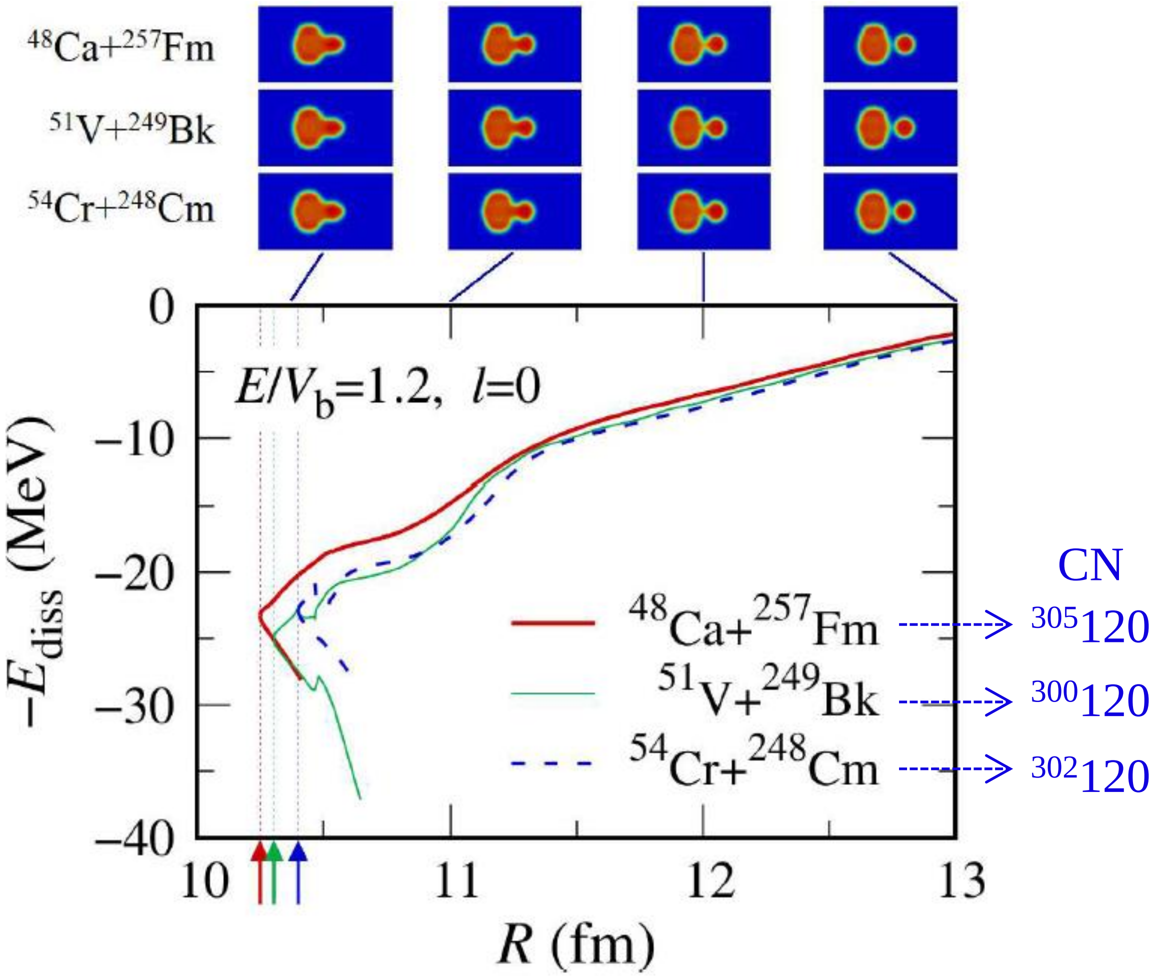
$$P_{\rm CN} = \frac{1}{2}\left[1 - {\rm erf}\left(\frac{\Delta V}{T}\right)\right]$$

We use fusion-by-diffusion model to describe the "up-hill diffusion" over the inner barrier

Fusion-by-diffusion model:
W.J. Świątecki, K. Siwek-Wilczyńska, and J. Wilczyński,
Acta Phys. Pol. B **34**(2003)2049; PRC**71**(2005)014602
K. Hagino, PRC**98**(2018)014607

KS and K. Hagino, Phys. Rev. C **99**, 051602(R) (2019)

Magicity of ^{48}Ca does not affect much the entrance-channel dynamics



Dissipated energy was evaluated by DD-TDHF: K. Washiyama et al., PRC**78**(2008)024610; **79**(2009)024609

KS and K. Hagino, Phys. Rev. C **99**, 051602(R) (2019)

Magicity of ^{48}Ca affects the survival probability via the lower excitation energy

			TDHF	FBD		
System	CN	E^* (MeV)	$R_{\rm min}$ (fm)	$P_{\rm CN}$ ($\times 10^4$)	$W_{\rm sur}$ ($\times 10^9$)	$P_{\rm CN}\,W_{\rm sur}$ ($\times 10^{13}$)
^{48}Ca+^{254}Fm	^{302}120	29.0	12.93	1.72	176	302
^{54}Cr+^{248}Cm	^{302}120	33.2	13.09	1.89	1.31	2.47
^{51}V+^{249}Bk	^{300}120	37.0	12.94	3.95	0.117	0.461
^{48}Ca+^{257}Fm	^{305}120	30.5	12.94	2.49	0.729	1.82

Very similar
for all systems

Thus, $P_{\rm CN}$ is
also similar
(higher E^*, larger $P_{\rm CN}$)

Note:
Survival probability also depends on the fission barrier height!

Summary and perspective

MNT

✓ Experimental and theoretical results have been accumulated.

➡ Detailed analysis will reveal what is enough (or not) in TDHF to describe multinucleon transfer reactions

➢ **It would be the time to go beyond the TDHF description**

QF

✓ Systematic TDHF calculations have been performed.

➡ It will provide us various information, e.g., contact time, fragment mass and charge, and equilibration time scale, etc.

SHE

✓ TDHF+Langevin approach has been developed for SHEs.

➡ We plan to combine a more realistic Langevin model to predict fusion reactions for Z=119, 120, and beyond.

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