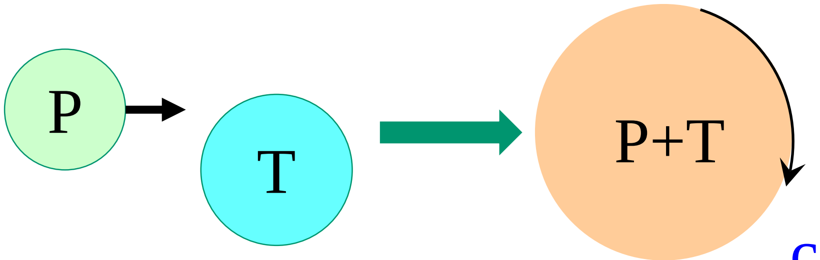
Recent progress and future perspectives of fusion and fission dynamics: from nuclear astrophysics to superheavy nuclei

Kouichi Hagino
Kyoto University, Kyoto, Japan

1. Introduction: fusion reactions
2. $^{12}C+^{12}C$ fusion
3. Fusion for superheavy elements
4. Fusion of neutron-rich nuclei
5. Fission
6. Summary

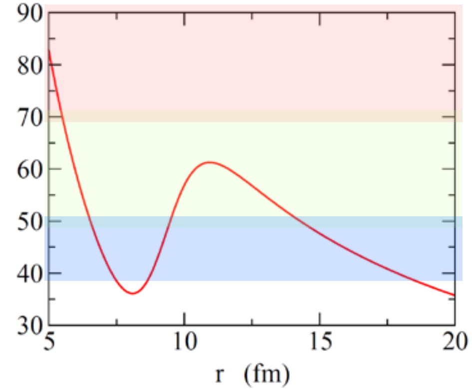
A3 Foresight Program Joint Annual Meeting, 2020.11.18-19, online

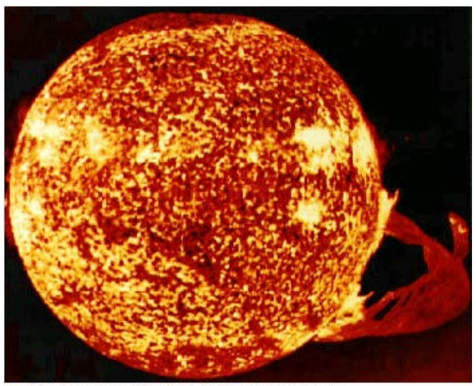
Introduction: Fusion reactions



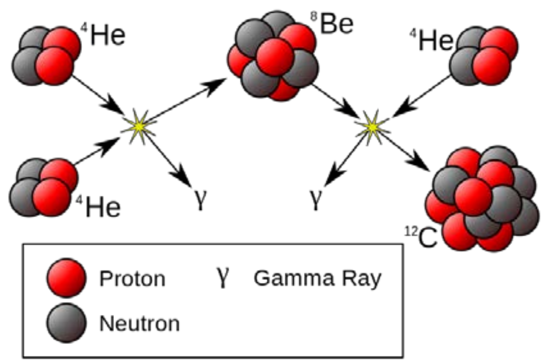
compound nucleus

barrier dynamics (tunneling, diffusion)

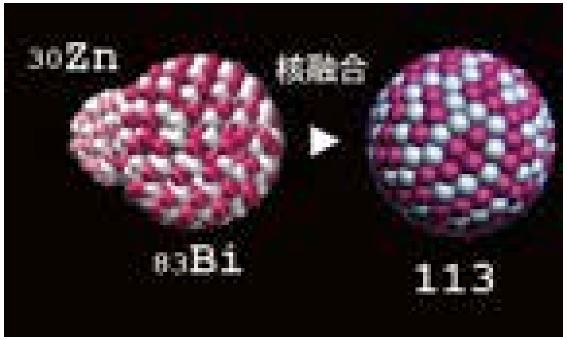




energy production in stars



nucleosynthesis



superheavy elements

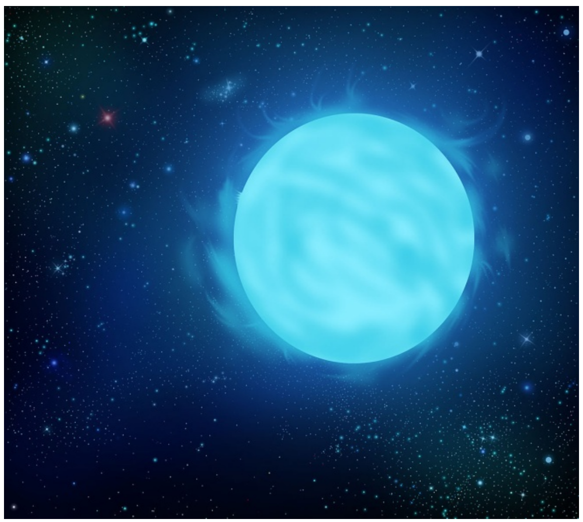
Fusion and fission: large amplitude motions

⟵ microscopic understanding: an ultimate goal of nuclear physics

$^{12}C + ^{12}C$ fusion reaction

$^{12}C + ^{12}C$ fusion : a key reaction in nuclear astrophysics

Carbon burning
in massive stars



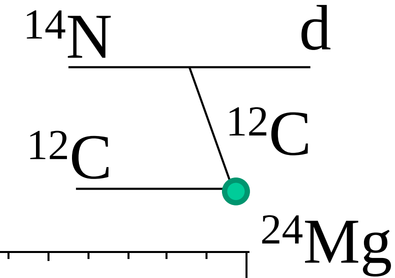
$^{12}C + ^{12}C \rightarrow \alpha + ^{20}Ne$

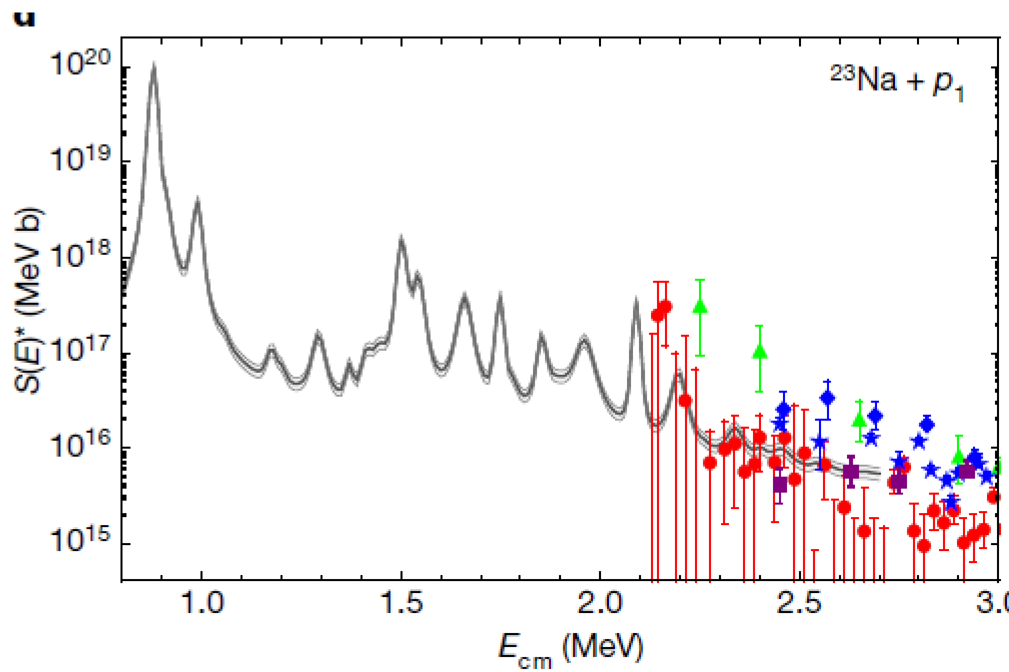
$^{12}C + ^{12}C \rightarrow p + ^{23}Na$

also

- ✓ Type Ia supernovae
- ✓ X-ray superburst

Trojan Horse Method



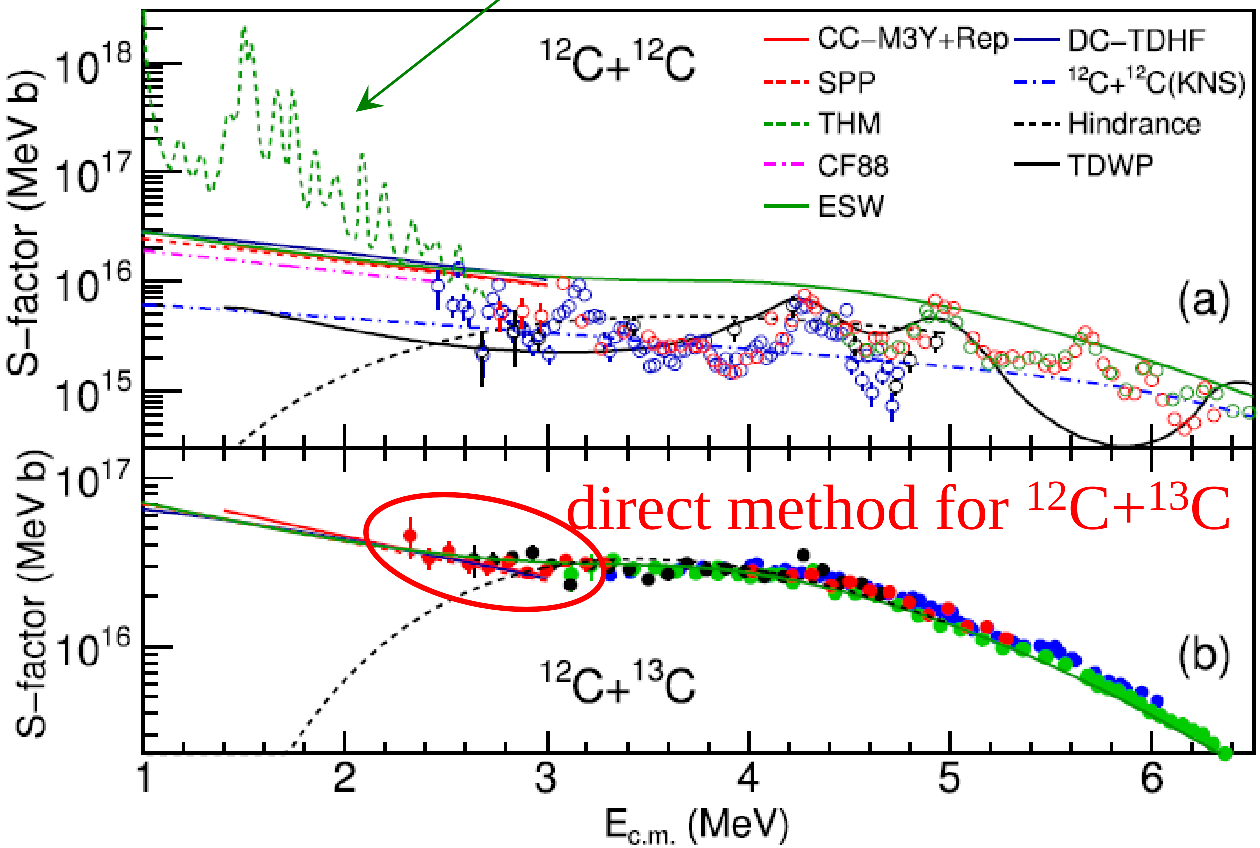


A. Tumino et al., Nature557 (‘18) 687

~ 25 times larger than before
→ lots of debates

$^{12}C+^{12}C$ fusion reaction

Trojan Horse Method



The THM data are not supported.

PWIA→DWIA?

A.M. Mukhamedzhanov et al., PRC99 ('19) 064618

cf. recent direct measurement for $^{12}C+^{12}C$:

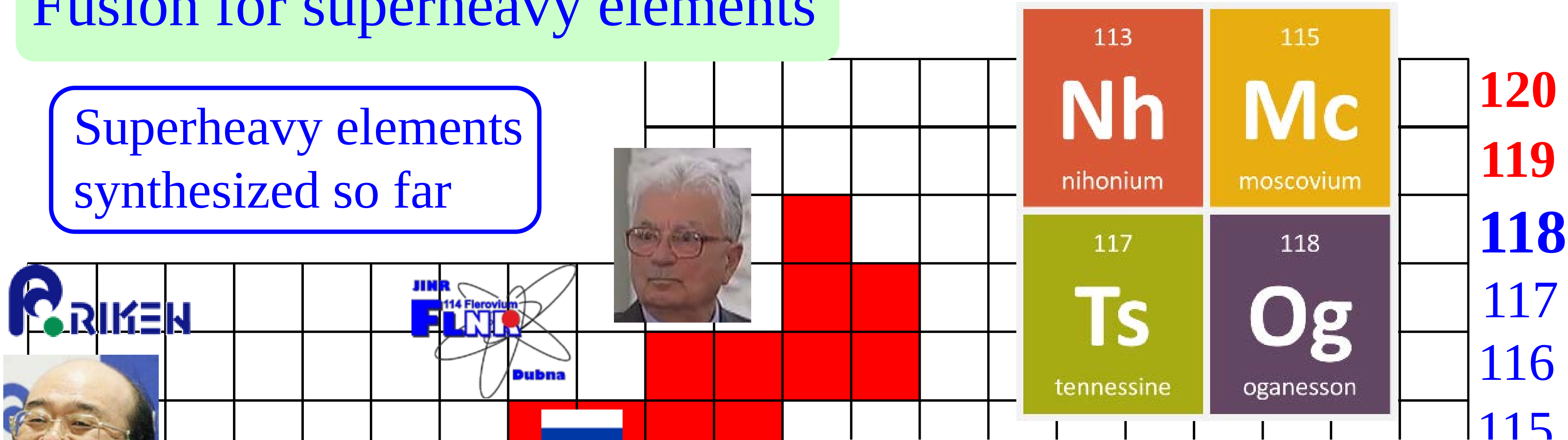
W.P. Tan et al., PRL124 ('20) 192702

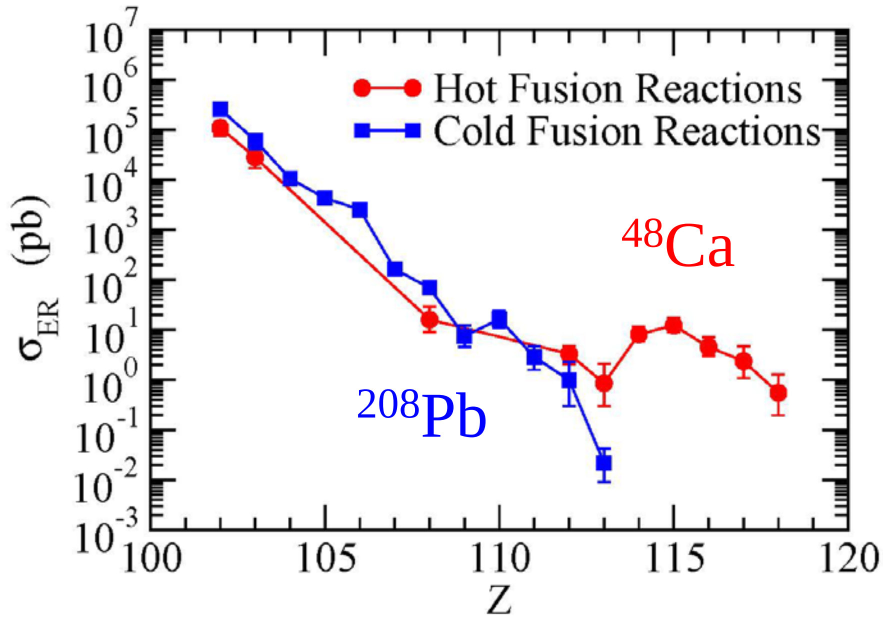
N.T. Zhang,…, K.H., S. Kubono, …., C.J. Lin,….

XiaoDong Tang (IMP) et al., Phys. Lett. B801 (2020) 135170

Fusion for superheavy elements

Superheavy elements synthesized so far

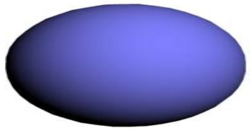




RIKEN (2018-)
$^{51}V + ^{248}Cm \rightarrow 119$

✓ optimum bombarding energy?
✓ ^{51}V rather than ^{48}Ca?

optimum bombarding energy

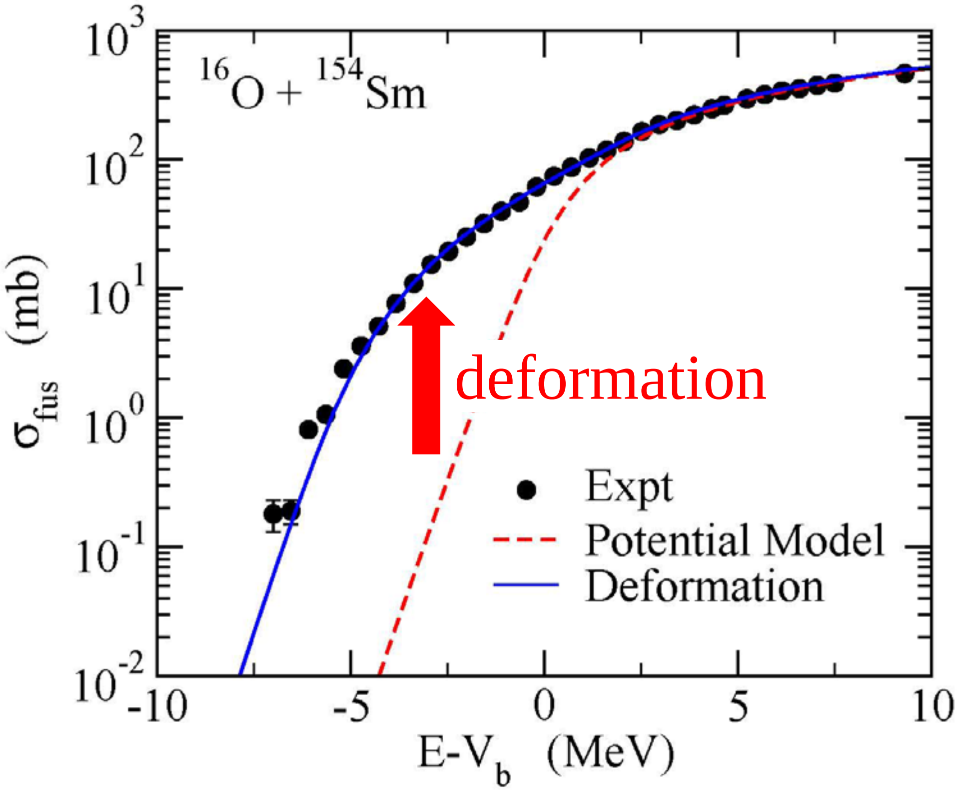


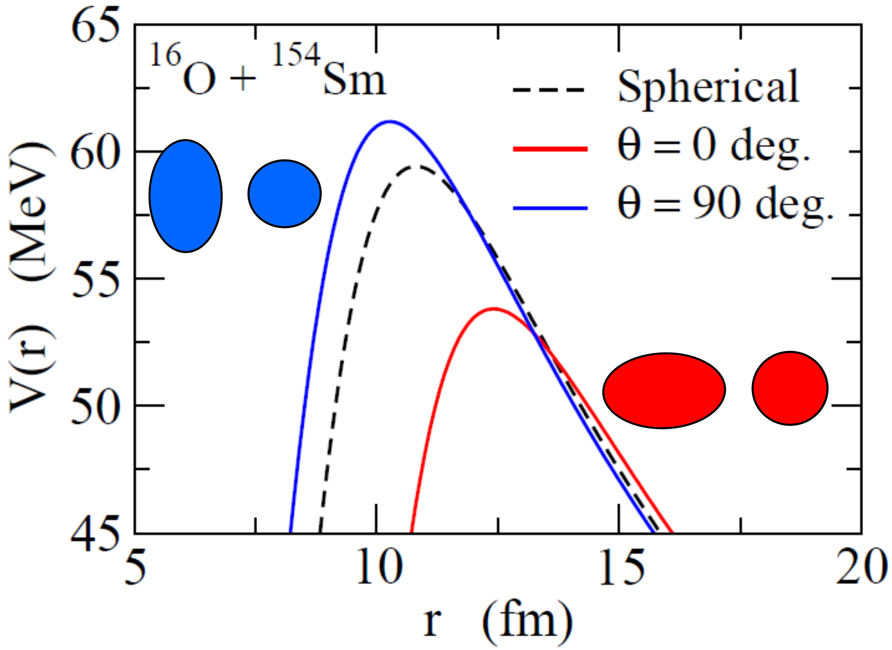
hot fusion: ^{48}Ca + deformed target

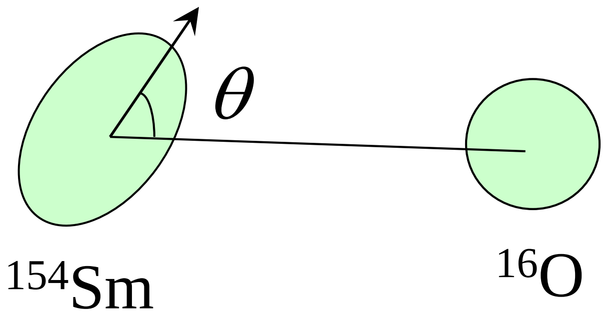
the role of deformation in heavy-ion reactions?

Nuclear deformation → a large sub-barrier enhancement of fusion (capture) cross sections

$^{16}O+^{154}Sm$

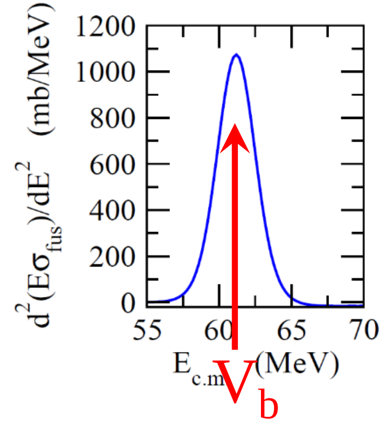




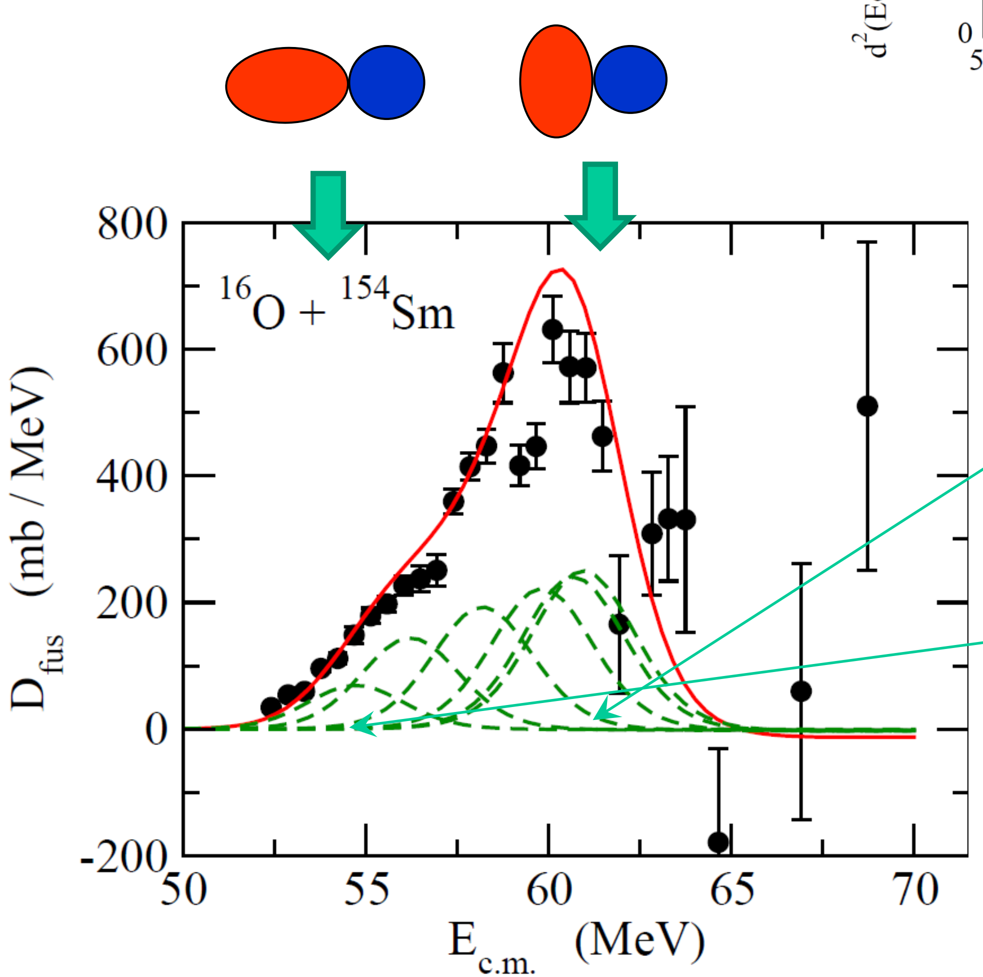


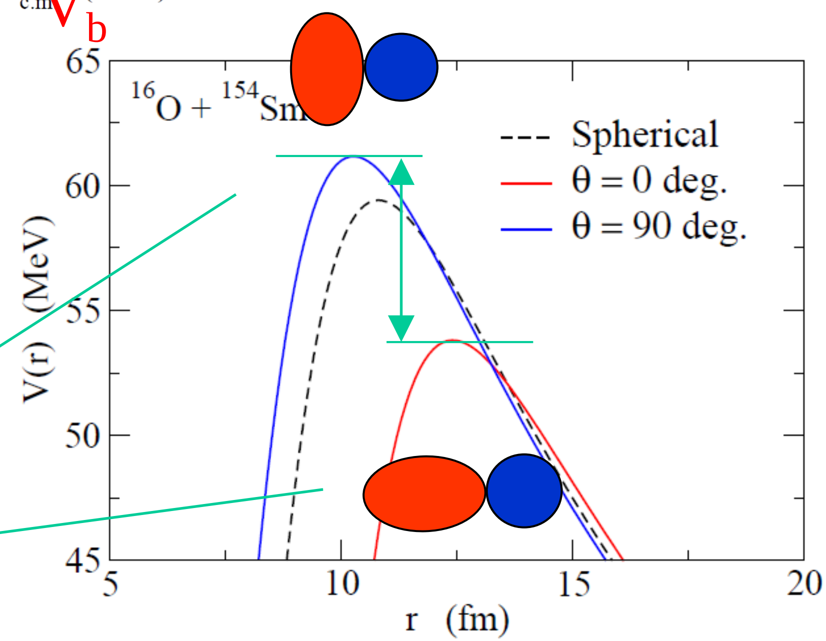
✓ Fusion barrier distribution (Rowley, Satchler, Stelson, PLB254('91))

$$D_{\mathsf{fus}}(E) = \frac{d^2(E\sigma_{\mathsf{fus}})}{dE^2}$$



single channel

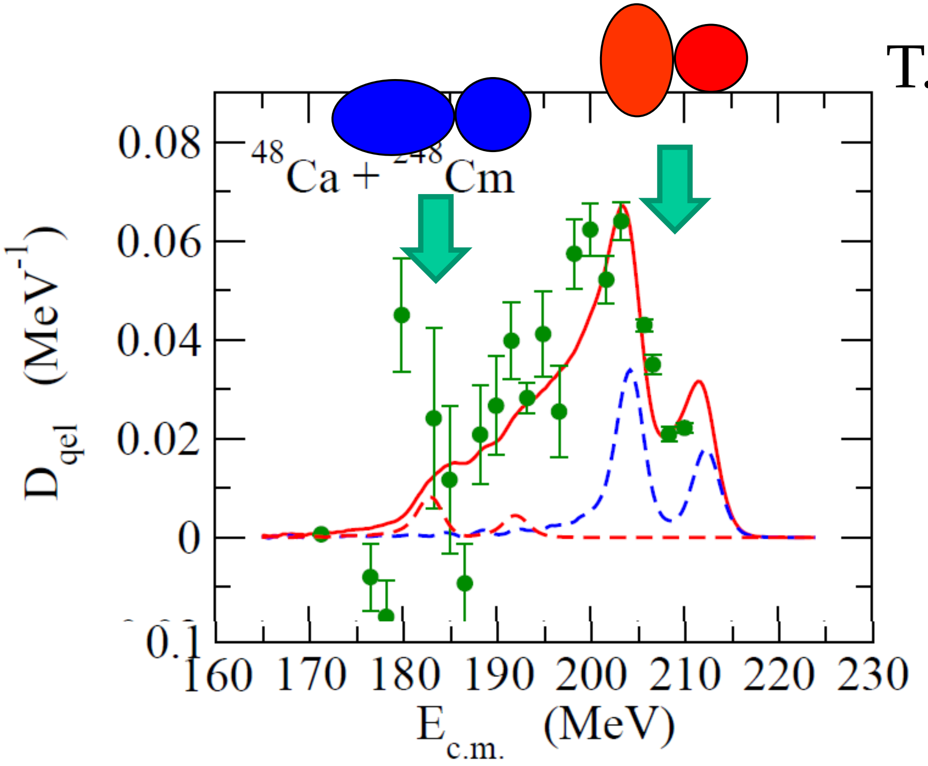




can be used to identify
the side/tip collisions

Application to hot fusion reactions

$^{48}Ca + ^{248}Cm \rightarrow {}^{296}_{116}Lv^*$



T. Tanaka,..., K.H., et al.,
JPSJ 87 ('18) 014201
PRL124 ('20) 052502

capture barrier distribution

Application to hot fusion reactions

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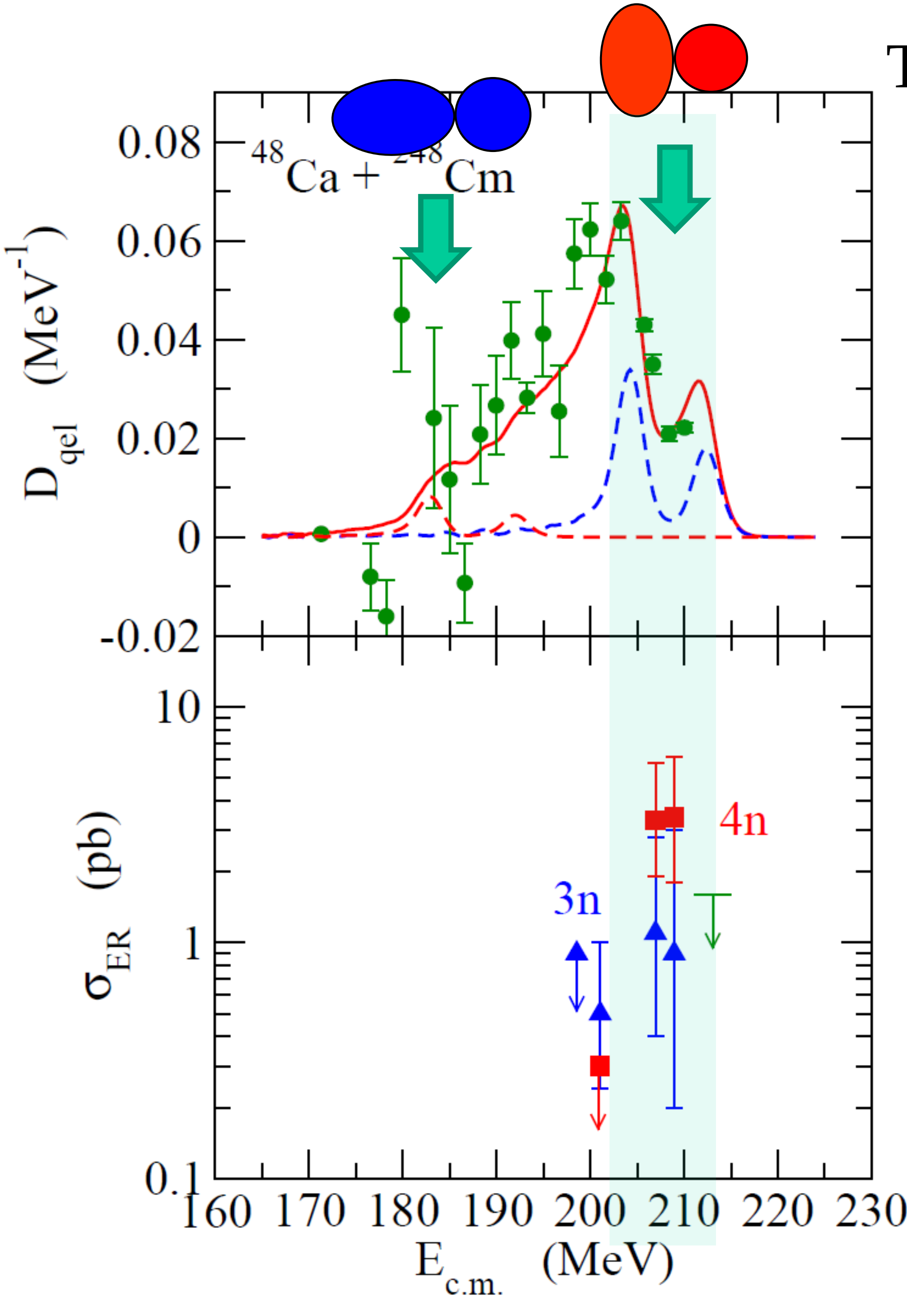
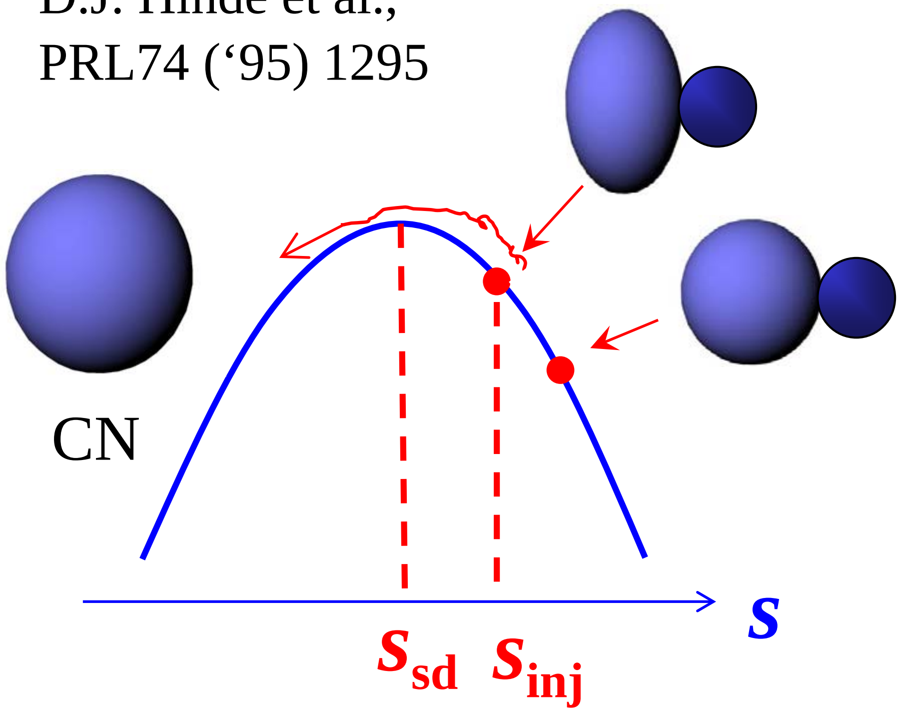


T. Tanaka,..., K.H., et al.,
JPSJ 87 ('18) 014201
PRL124 ('20) 052502

capture barrier distribution

cf. notion of compactness:

D.J. Hinde et al.,
PRL74 ('95) 1295



Application to hot fusion reactions

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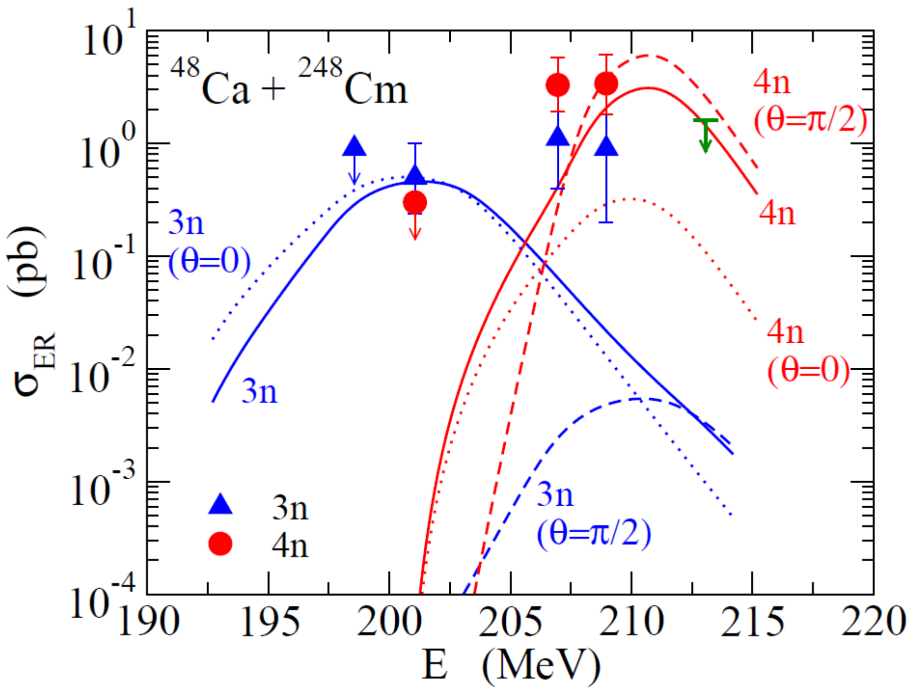
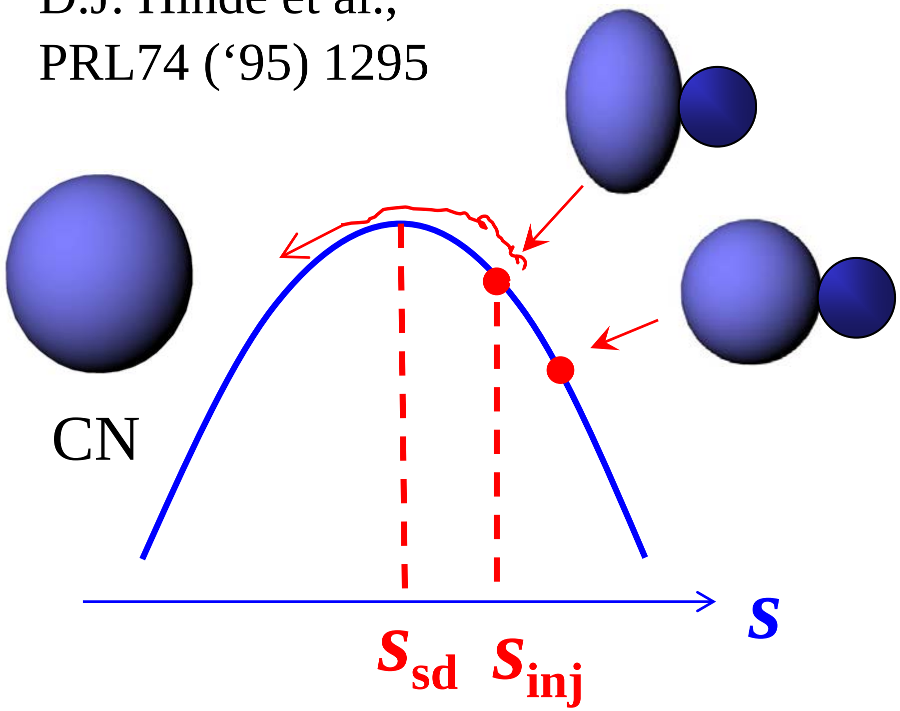


K. Hagino, PRC98 ('18) 014607

capture barrier distribution

cf. notion of compactness:

D.J. Hinde et al.,
PRL74 ('95) 1295



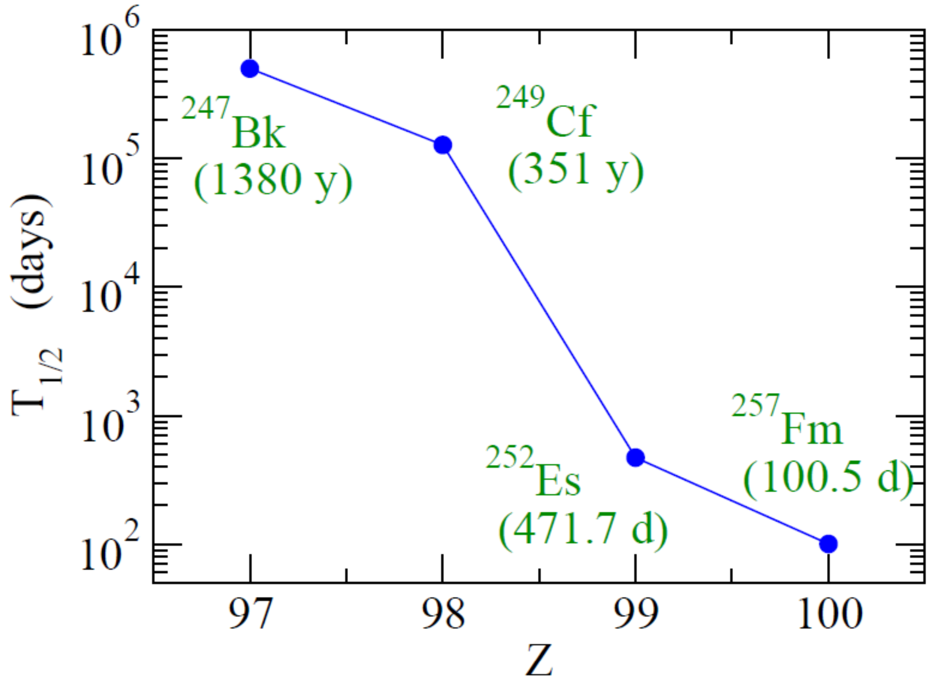
Hot fusion towards Z=119 and 120 nuclei

hot fusion reactions with ^{48}Ca:

$^{48}_{20}Ca + {}_{99}Es \rightarrow 119$

$^{48}_{20}Ca + {}_{100}Fm \rightarrow 120$

short lived →not available with sufficient amounts



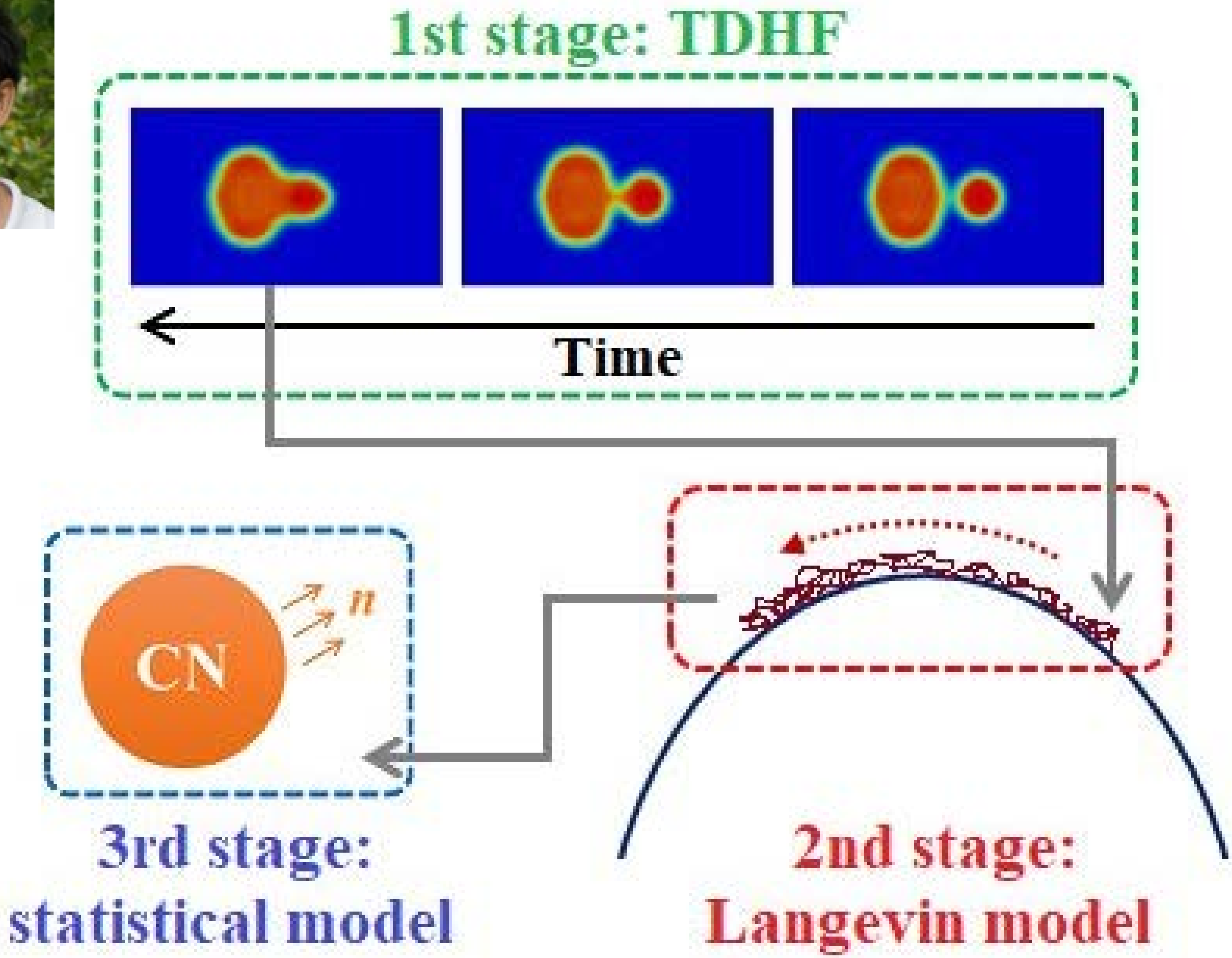
$^{48}Ca \rightarrow {}^{50}_{22}Ti, {}^{51}_{23}V, {}^{54}_{24}Cr$ projectiles

closed shell → open shells

how much will cross sections be affected?

New hybrid model: TDHF + Langevin approach

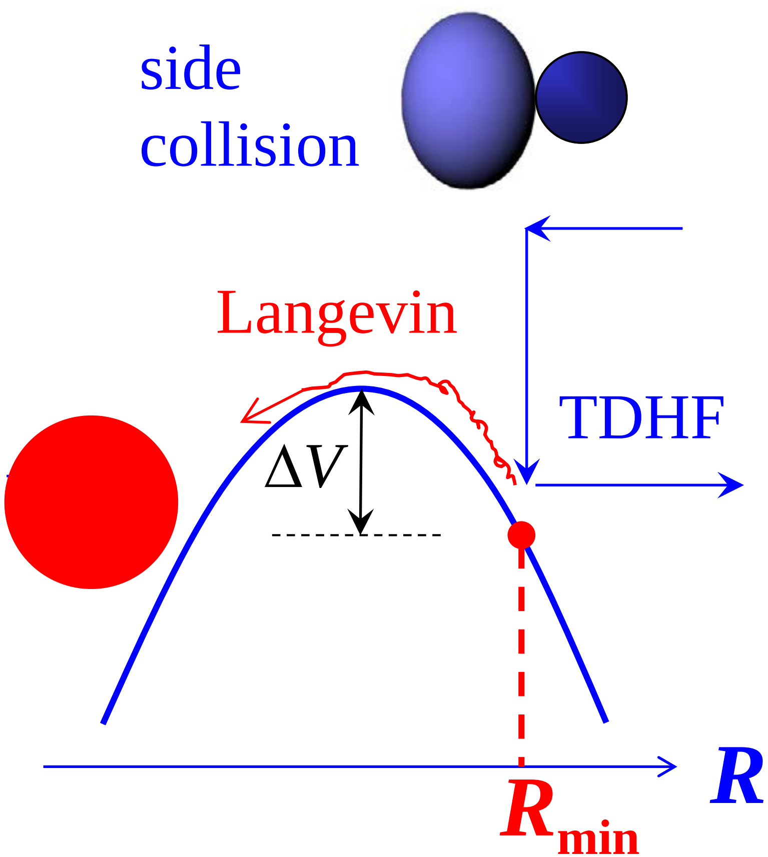
K. Sekizawa and K.H., PRC99 (2019) 051602(R)



Furthermore : TDHF + Langevin approach and quantum friction

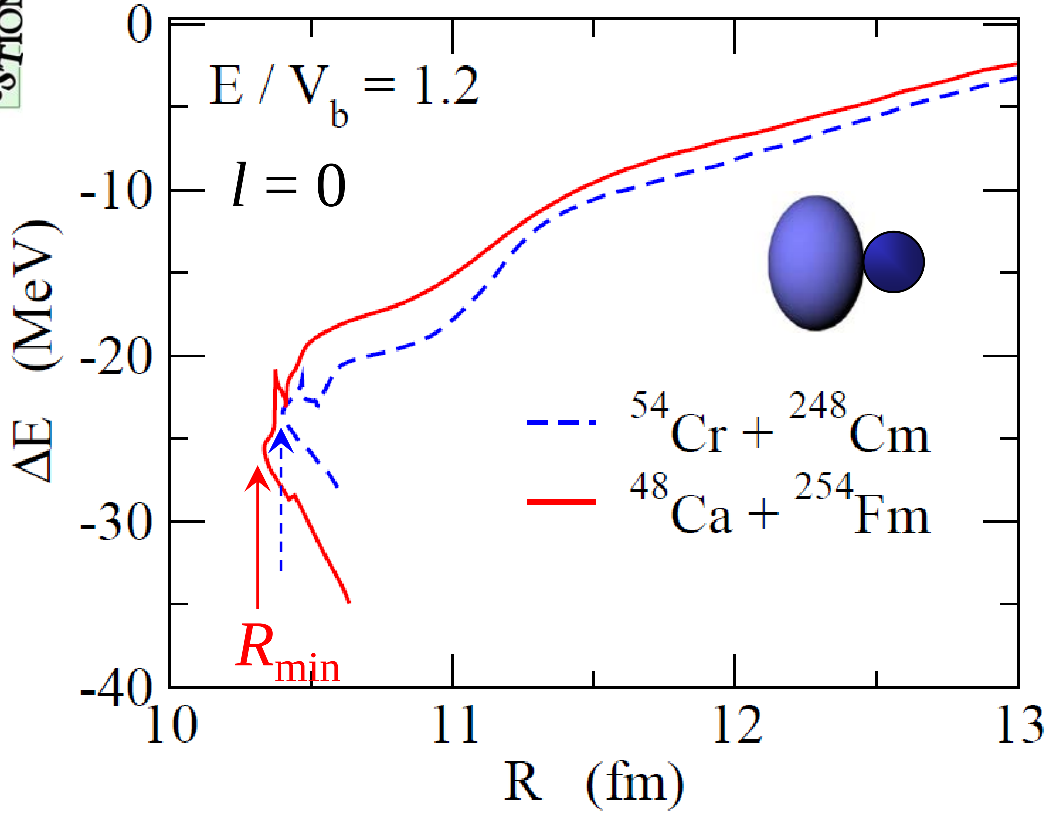
TDHF + Langevin approach :

K. Sekizawa and K. H., PRC99 (2019) 051602(R)



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

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



→ Langevin caluclation

New model for fusion for SHE: TDHF + Langevin approach

K. Sekizawa and K.H., PRC99 (2019) 051602(R)

how special is ^{48}Ca ?

System	CN	E^* (MeV)	R_{min} (fm)	P_{CN} ($\times 10^4$)	W_{sur} ($\times 10^9$)	$P_{CN} W_{sur}$ ($\times 10^{13}$)
$^{48}Ca + ^{254}Fm$	$^{302}120$	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

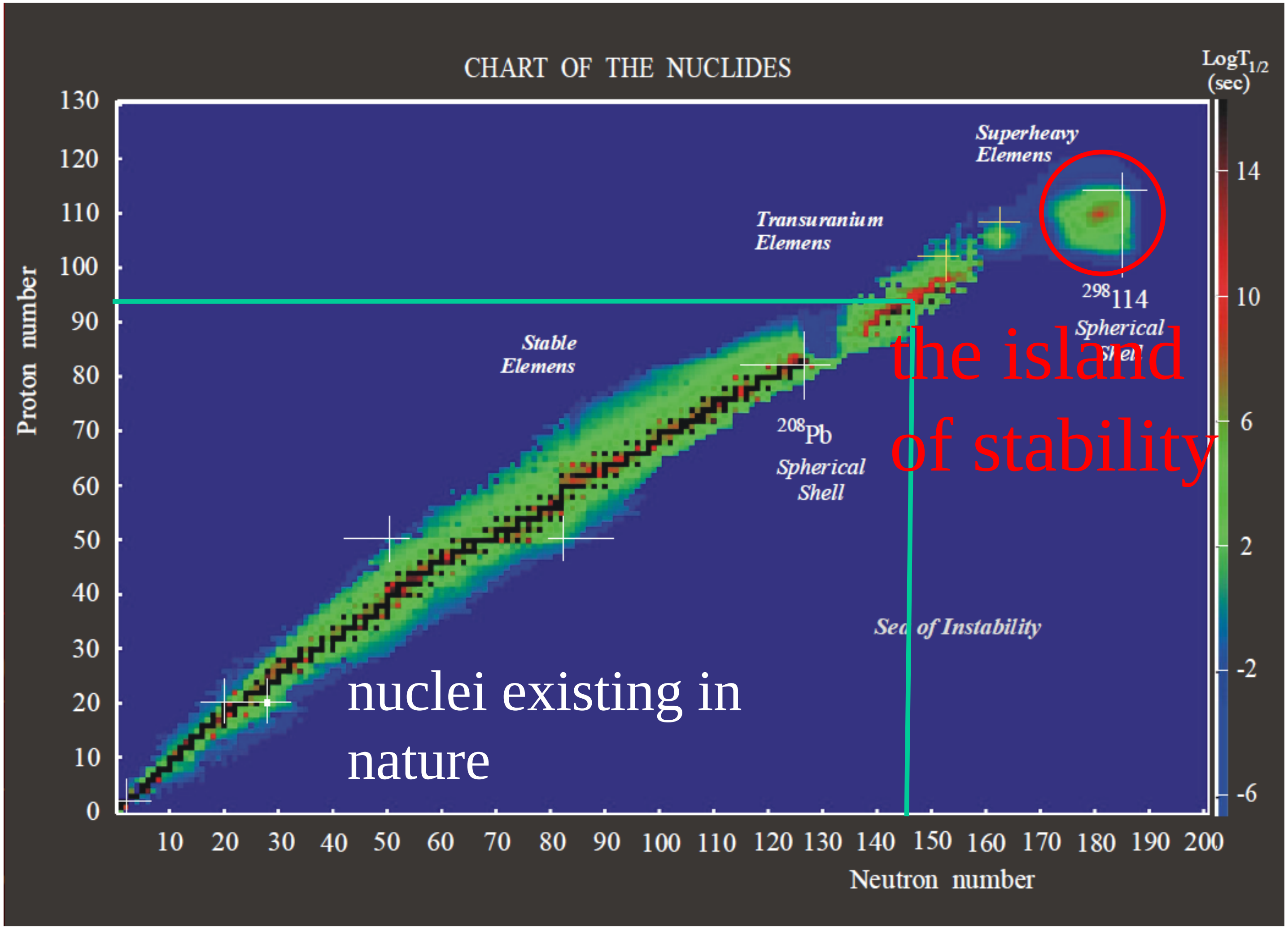
$$P_{ER} = P_{cap} \cdot P_{CN} \cdot W_{suv}$$

similar P_{CN}

✓ no special role of ^{48}Ca in the entrance channel

✓ non-^{48}Ca proj.: about 2 order of magnitude smaller due mainly to W_{sur}

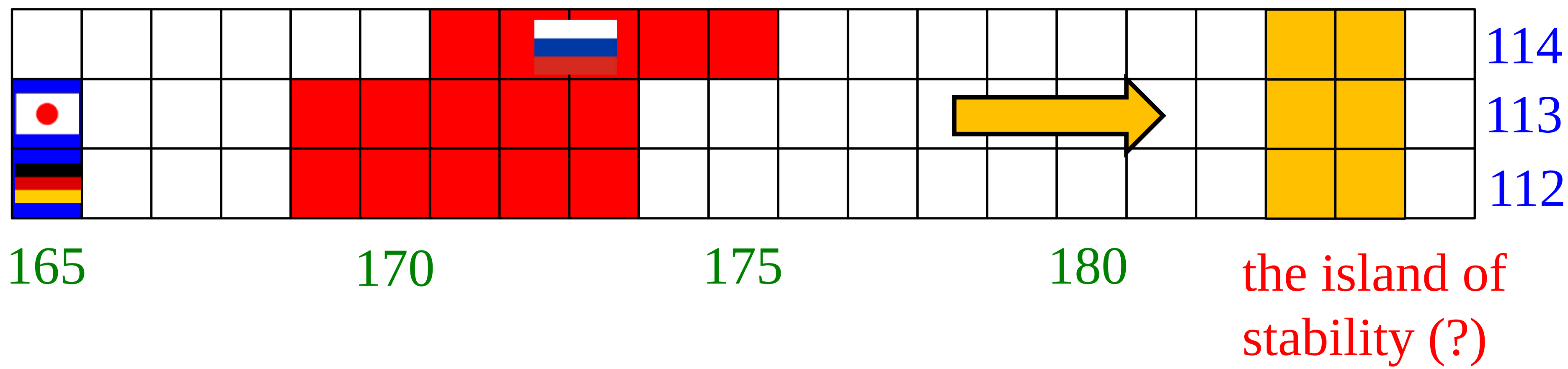
Fusion of neutron-rich nuclei



Yuri Oganessian

how to reach the island of stability?

Fusion of neutron-rich nuclei



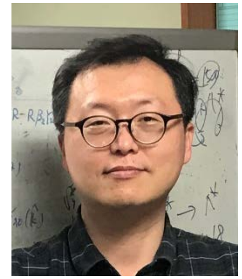
neutron-rich beams: indispensable

- how to deal with low beam intensity?
- reaction dynamics of neutron-rich beams?
  - ✓ capture: role of breakup and (multi-neutron) transfer?
  - ✓ diffusion: neutron emission during a shape evolution?
  - ✓ survival: validity of the statistical model?

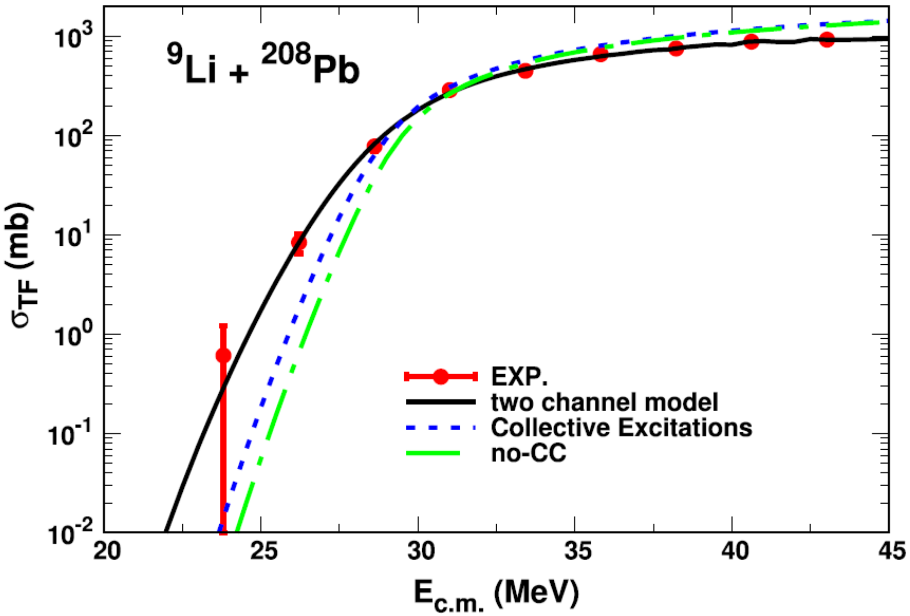
structure of exotic nuclei

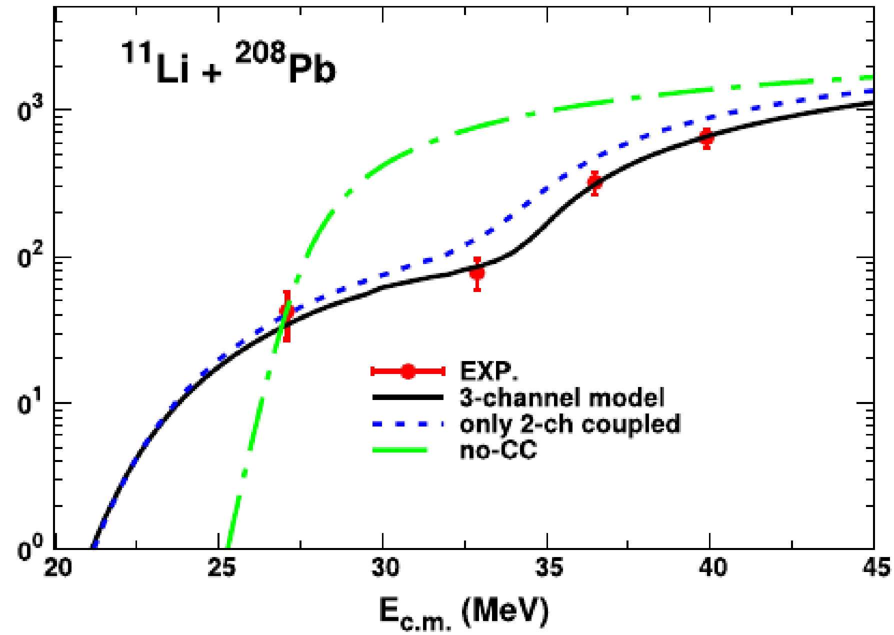
more studies are required

Fusion of neutron-rich nuclei



K.-S. Choi, M.-K. Cheoun, W.Y. So, K.H., and K.S. Kim, Phys. Lett. B780 ('18) 455



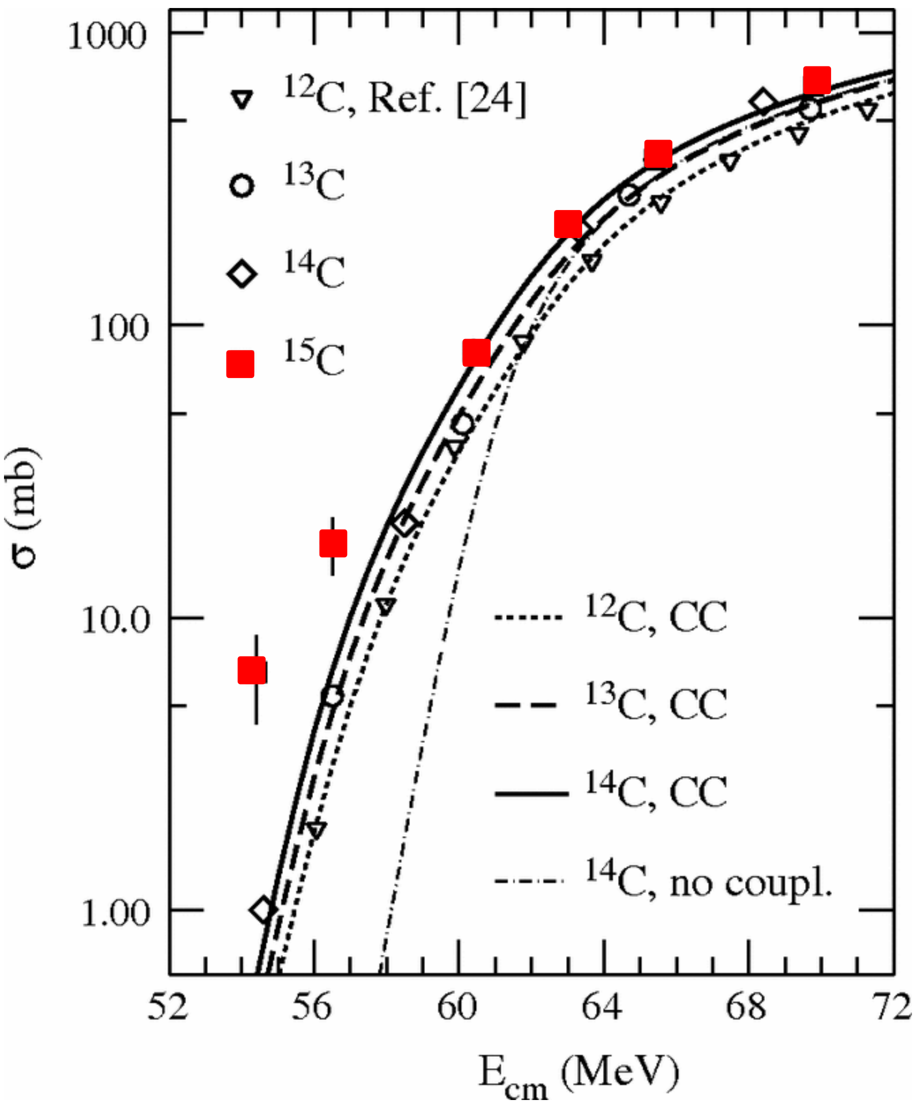


simultaneous explanation for $^9Li+^{208}Pb$ and $^{11}Li+^{208}Pb$ with:

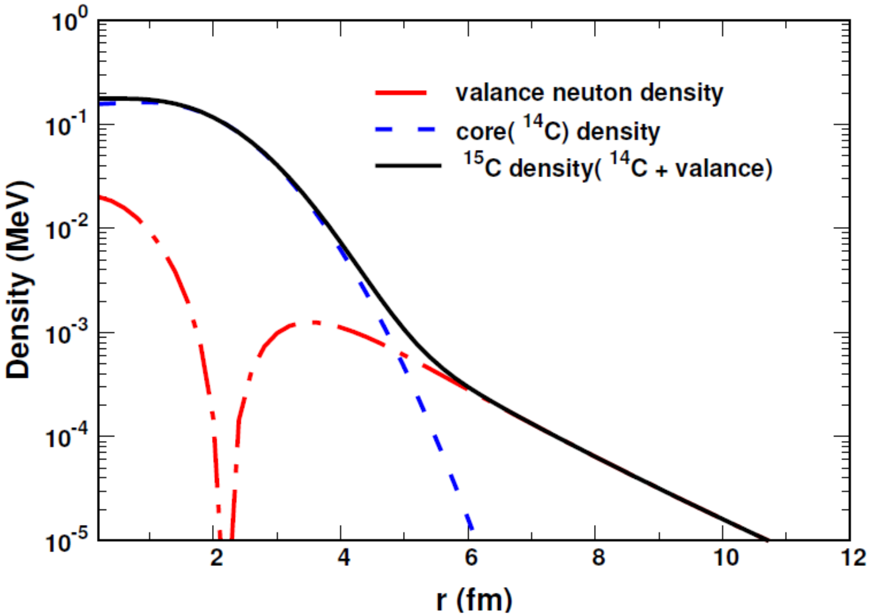
$^{11}Li+^{208}Pb \longleftrightarrow {}^9Li+^{210}Pb \longleftrightarrow {}^7Li+^{212}Pb$ transfer couplings

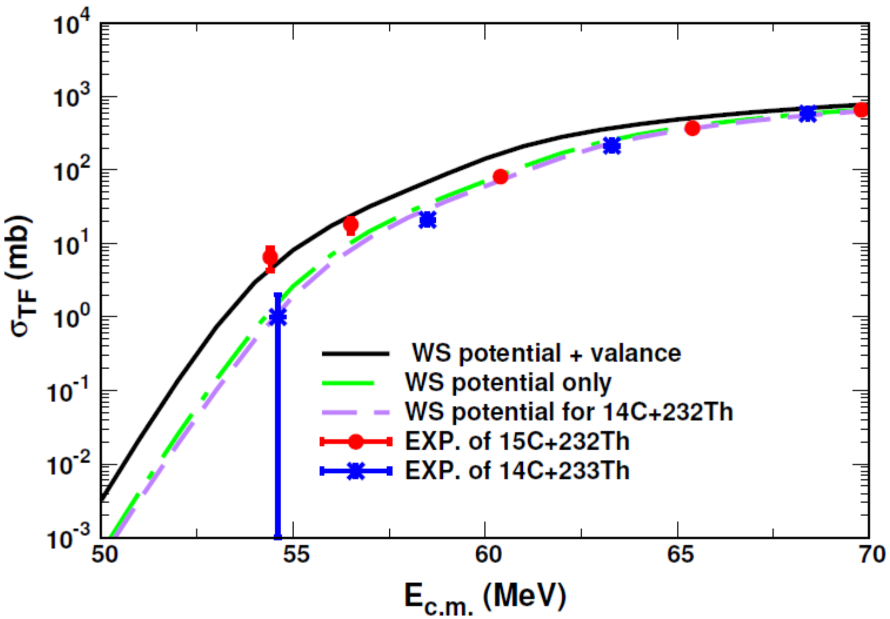
Fusion of neutron-rich nuclei

$^{12,13,14,15}C + {}^{232}Th$



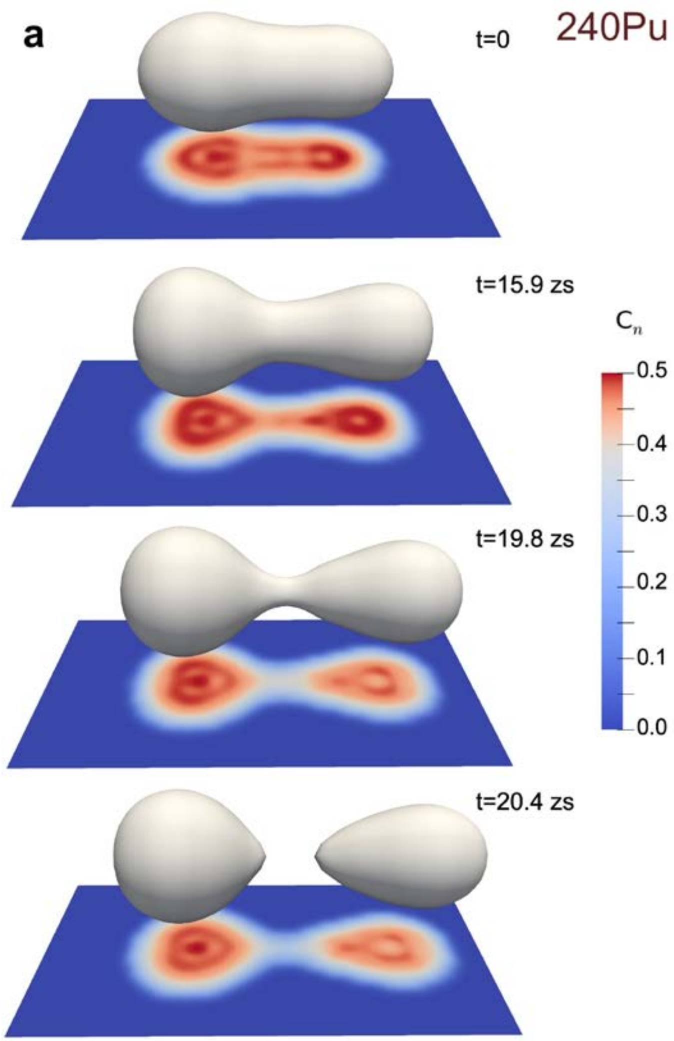
M. Alcorta et al., PRL106('11)





K.-S. Choi,…,K.H. et al., in preparation

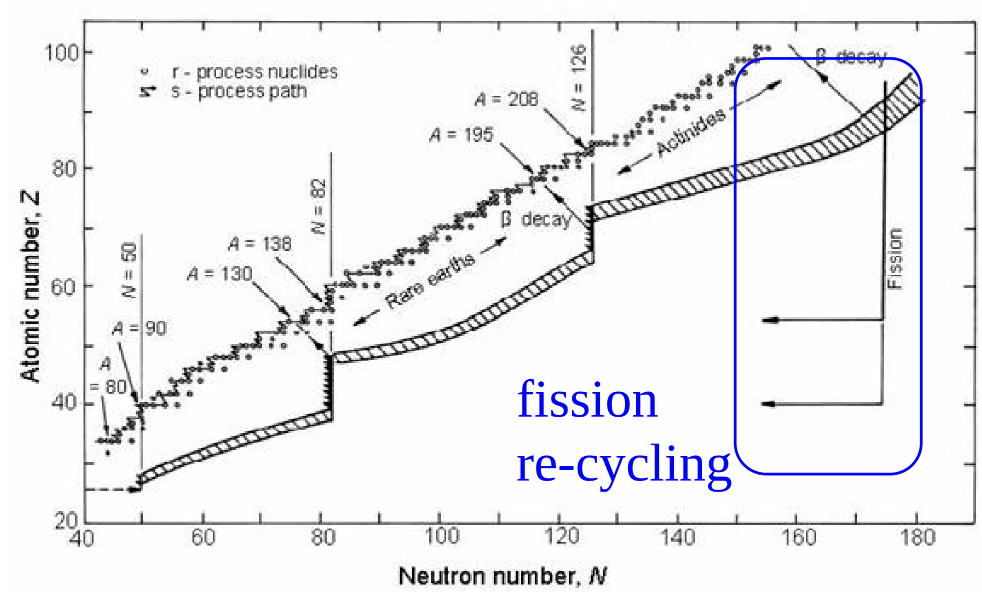
Fission



G. Scamps and C. Simenel, Nature 564 (2018) 382

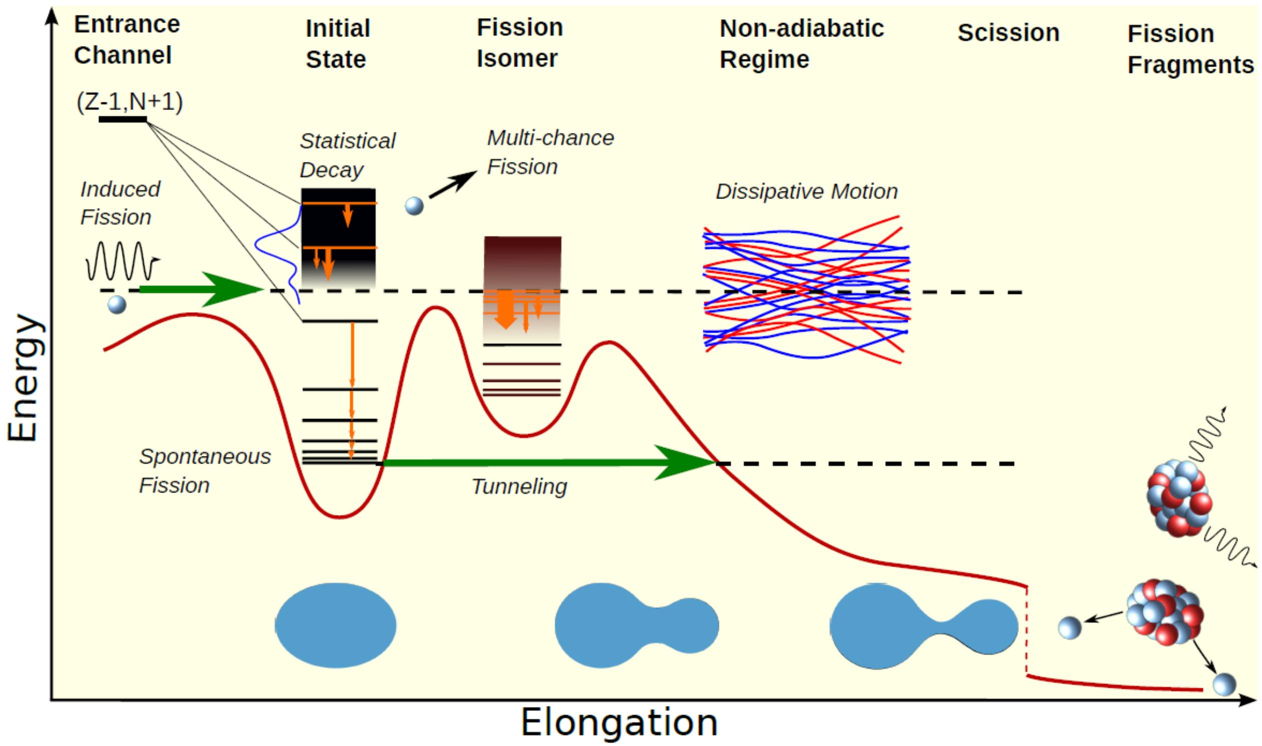
➢ important role in:

- energy production
- superheavy elements
- r-process nucleosynthesis
- production of neutron-rich nuclei



very complicated dynamics:

a microscopic understanding → far from complete



M. Bender et al., J. of Phys. G47, 113002 (2020) very complicated dynamics:

a microscopic understanding → far from complete

J. Phys. G: Nucl. Part. Phys. 47 (2020) 113002 (58pp) https://doi.org/10.1088/1361-6471/abab4f

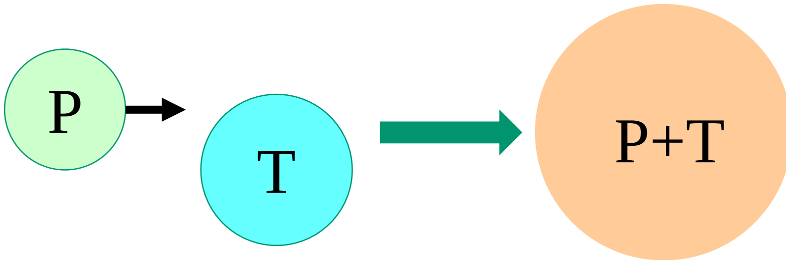
Topical Review

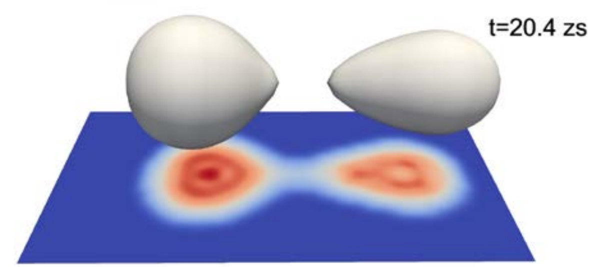
J. of Phys. G47, 113002 (2020)

Future of nuclear fission theory

Michael Bender[1], Rémi Bernard[2,3], George Bertsch[4], Satoshi Chiba[5], Jacek Dobaczewski[6,7,8], Noël Dubray[3,9], Samuel A Giuliani[10], Kouichi Hagino[11], Denis Lacroix[12], Zhipan Li[13], Piotr Magierski[14], Joachim Maruhn[15], Witold Nazarewicz[16], Junchen Pei[17], Sophie Péru[3,9], Nathalie Pillet[3,9], Jørgen Randrup[18], David Regnier[3,9], Paul-Gerhard Reinhard[19], Luis M Robledo[20,21], Wouter Ryssens[22], Jhilam Sadhukhan[23,24], Guillaume Scamps[25], Nicolas Schunck[26], Cédric Simenel[2], Janusz Skalski[27], Ionel Stetcu[28], Paul Stevenson[29], Sait Umar[30], Marc Verriere[26,28], Dario Vretenar[31], Michał Warda[32] and Sven Åberg[33]

Summary



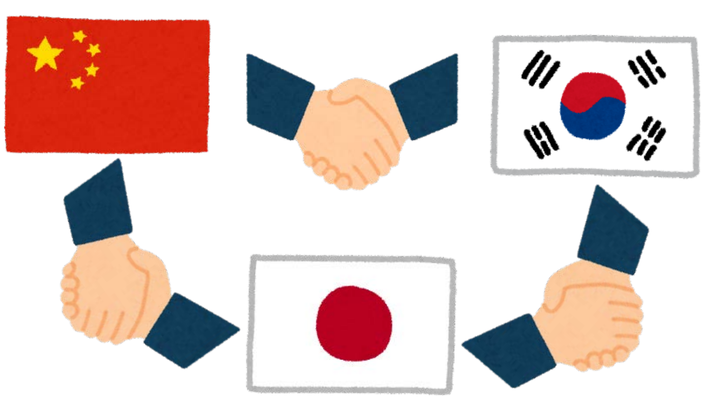


Fusion and fission dynamics

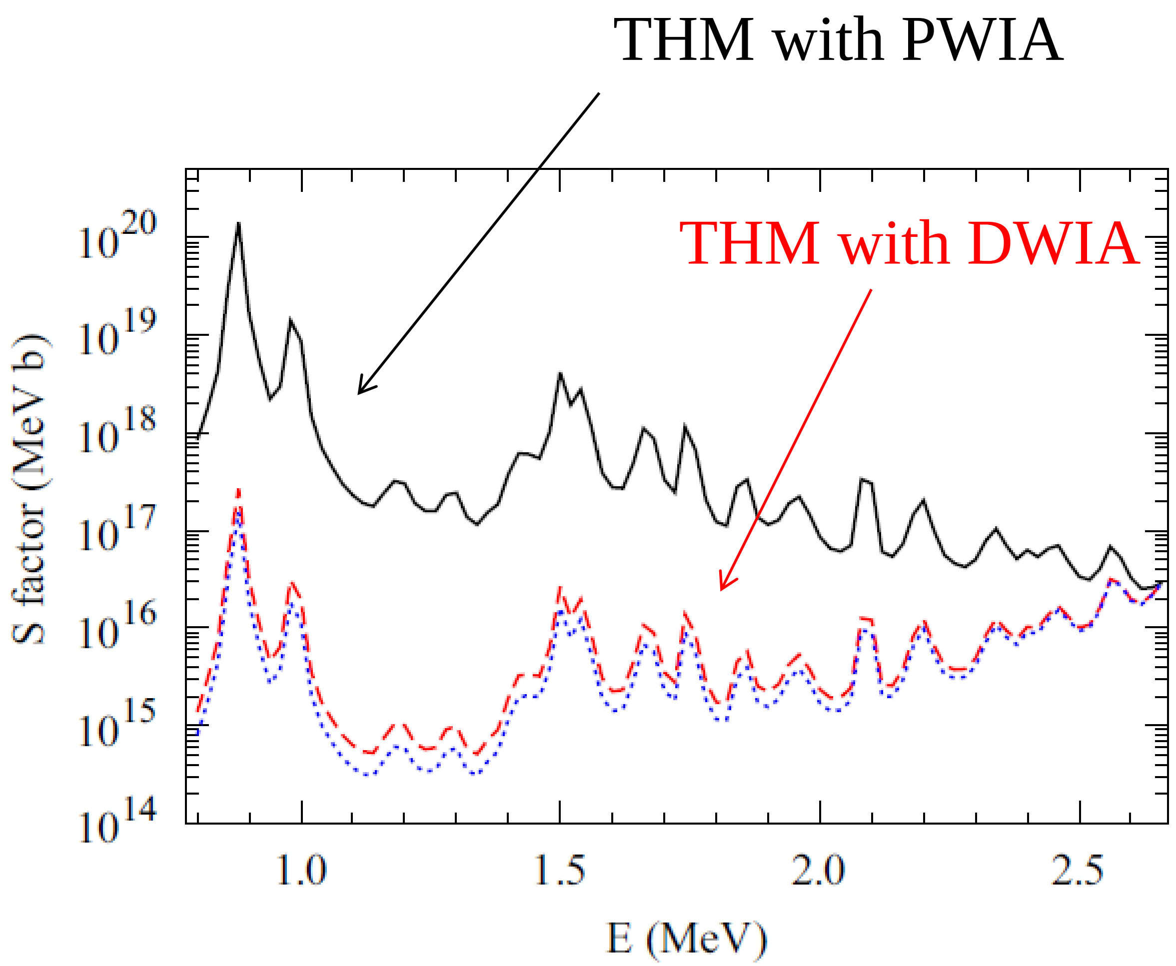
- Nuclear astrophysics
- Superheavy elements
- Neutron-rich nuclei

Many challenges

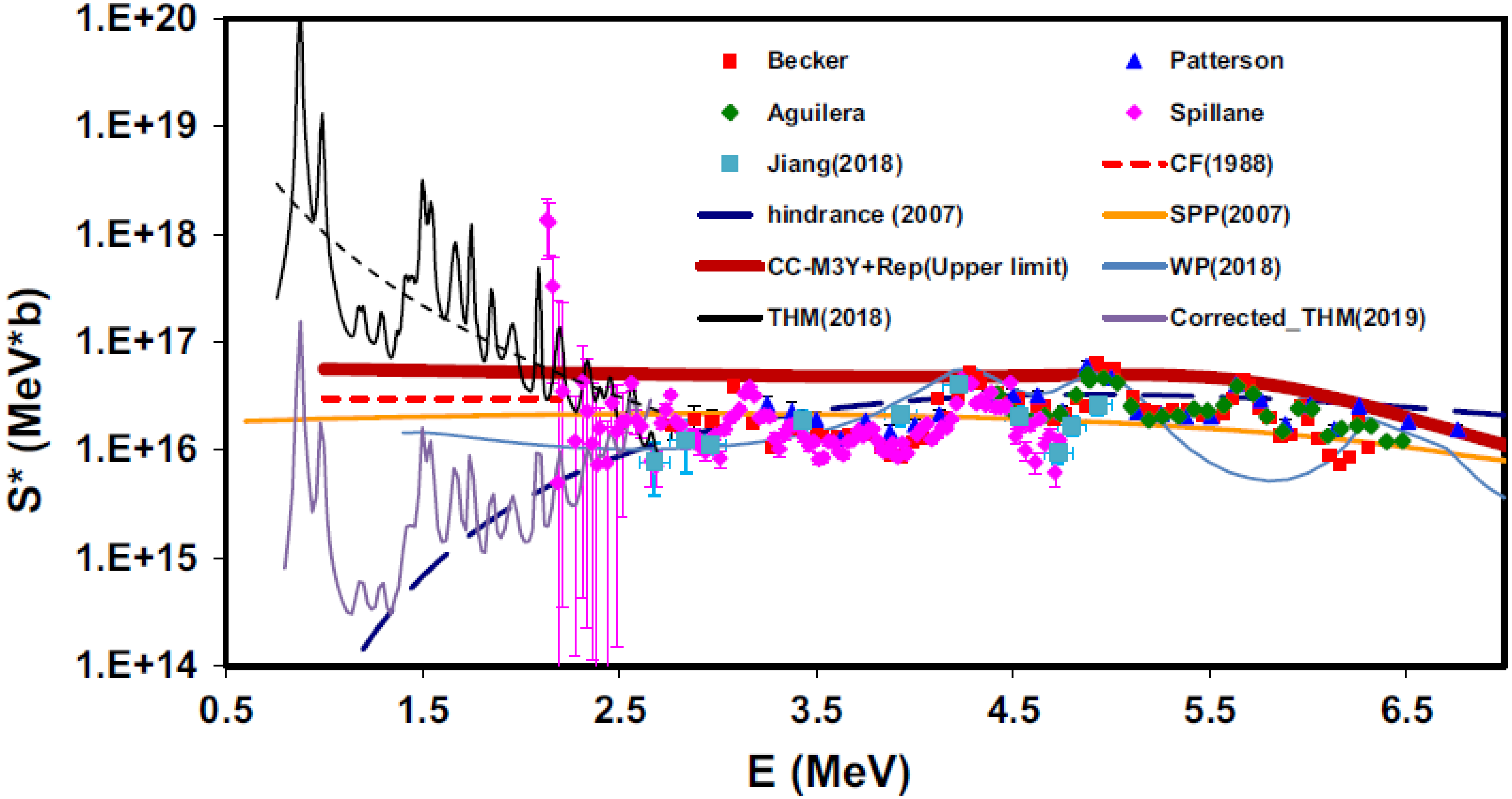
- reaction dynamics
- reliable prediction for SHE
- fusion of n-rich nuclei
- microscopic understanding of fission



lots of opportunities for collaborations

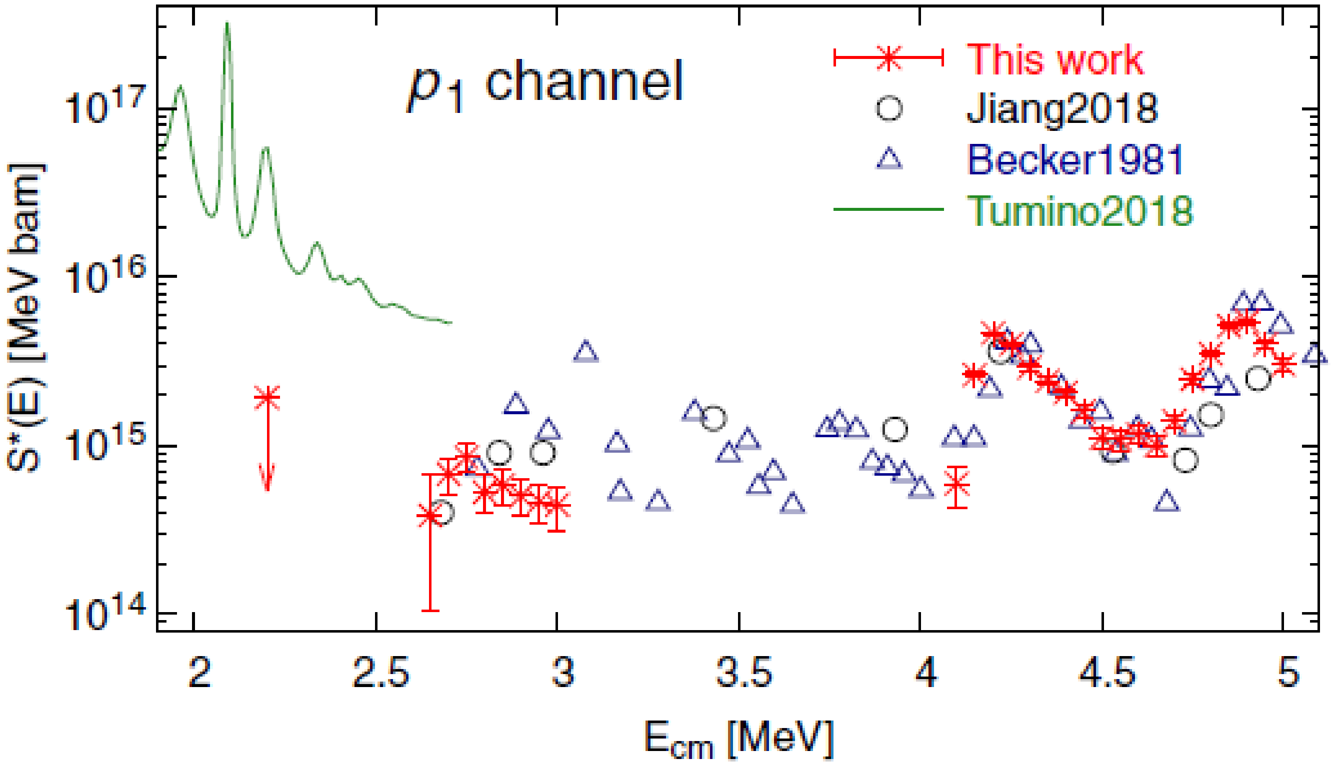


A.M. Mukhamedzhanov et al.,
PRC99 ('19) 064618



C. Beck, A.M. Muckhamedzhanov, and X. Tang, EPJA56 (2020) 87

Recent direct measurement for $^{12}C+^{12}C$



W.P. Tan et al., PRL124 (‘20) 192702

see also G. Fruet et al., PRL124 (‘20) 192701