Probing the fission-landscape of superheavy nuclei

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Superheavy nuclei and fission-stability

LDM + Shell effect

"Collective" (Mass surface) – T_{SF} (even-even) / P_{ECDF}

+

Single particle configuration – T_{SF} (even-odd / odd-even)

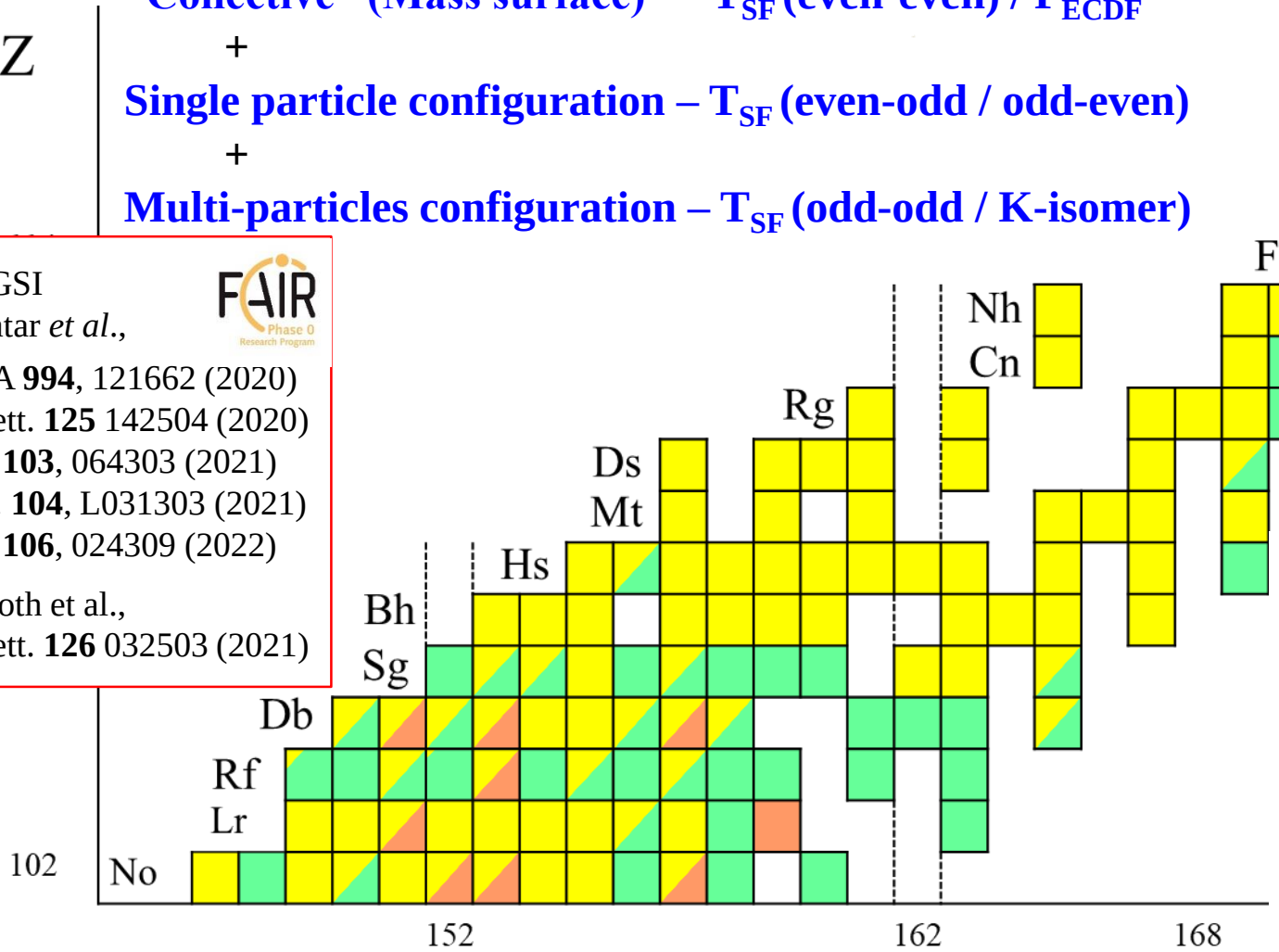
+

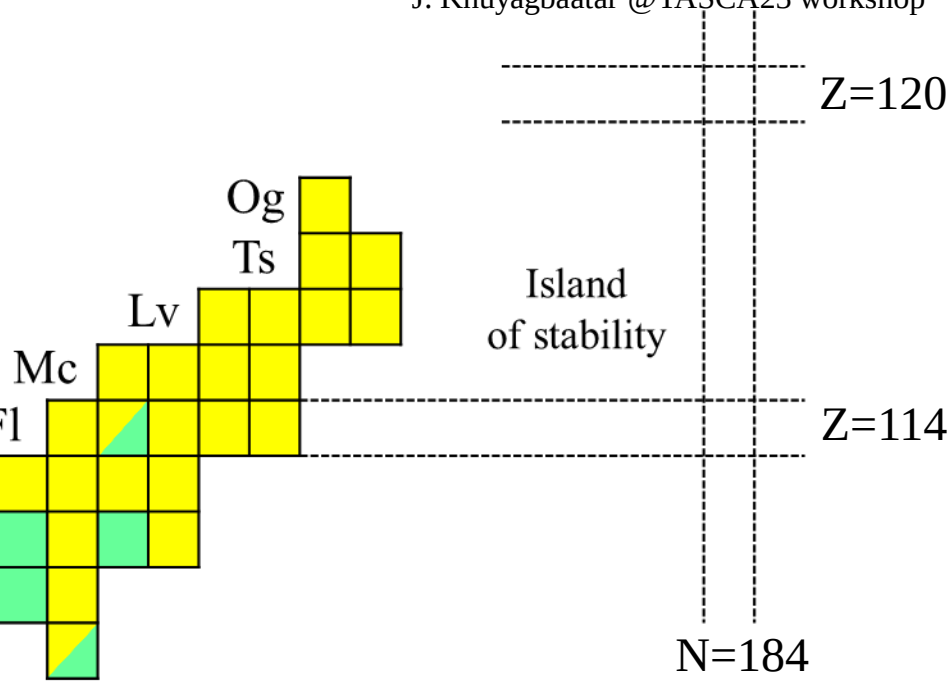
Multi-particles configuration – T_{SF} (odd-odd / K-isomer)

@**TASCA**, GSI
J. Khuyagbaatar *et al.*,

Nucl. Phys . A **994**, 121662 (2020)
Phys. Rev. Lett. **125** 142504 (2020)
Phys. Rev. C **103**, 064303 (2021)
Phys. Rev. C. **104**, L031303 (2021)
Phys. Rev. C **106**, 024309 (2022)

A. Samark-Roth et al.,
Phys. Rev. Lett. **126** 032503 (2021)





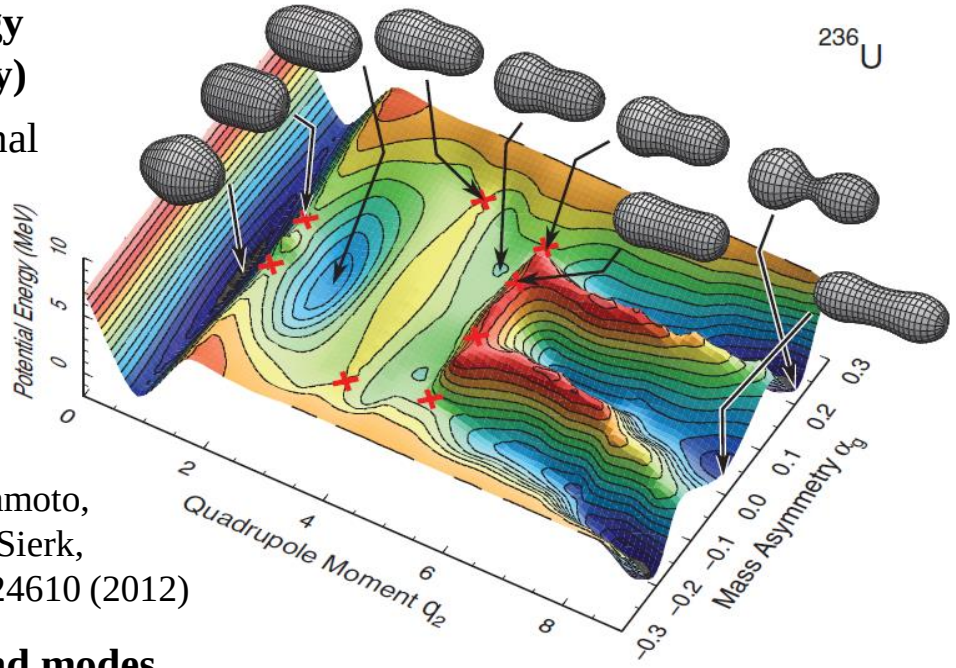
Experimental data on **fission**

@SHIP, GSI
P. Mosat et al., Phys. Rev. C **101**, 034310 (2020)
F.P. Hessberger et al., Eur. Phys. J. A 58, 11 (2022).
@RITU, JYFL
J. Kallunkathariyil et al., Phys. Rev. C **101**, 011301(R) (2020)
@SHELLS, FLNR, JINR
A. Lopez-Martens et al., Phys. Rev. C. **105**, L021306 (2021)
M. S. Tezekbayeva et al., Eur. Phys. J. A **58**, 52 (2022)
A.V. Isaev et al., PPNL **18**, 449 (2020)
@DGFRS II, FLNR, JINR
Yu.Ts. Oganessian et al., Phys. Rev. C **106**, L031301 (2022)
Yu.Ts. Oganessian et al., Phys. Rev. C **106**, 064306 (2022)
…

Fission: theory vs experiment

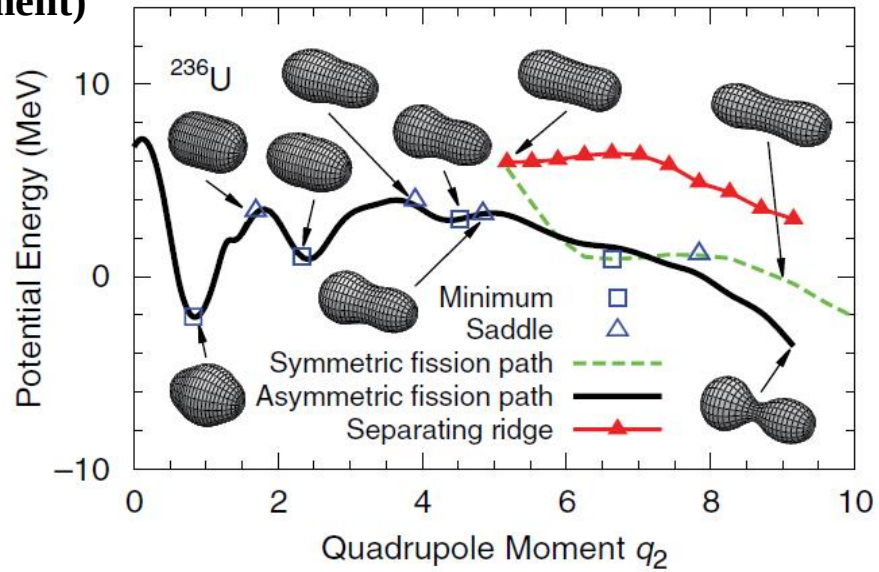
Potential energy surface (theory)

multi-dimensional
Z, N, E*, <L>



T. Ichikawa, A. Iwamoto, P. Möller, and A.J. Sierk, Phys. Rev. C **86**, 024610 (2012)

Fission paths and modes (theory/experiment)



Nucleus-shape can evolve in different ways:
Different paths toward the fission

@Low excitation energy:
Dynamical process (before "scission")

Fission probability (WKB)
$P \approx [1 + \exp(2S(L))]^{-1}$
Action integral S(L) along a **trajectory L**

trajectory L ~ fission barrier

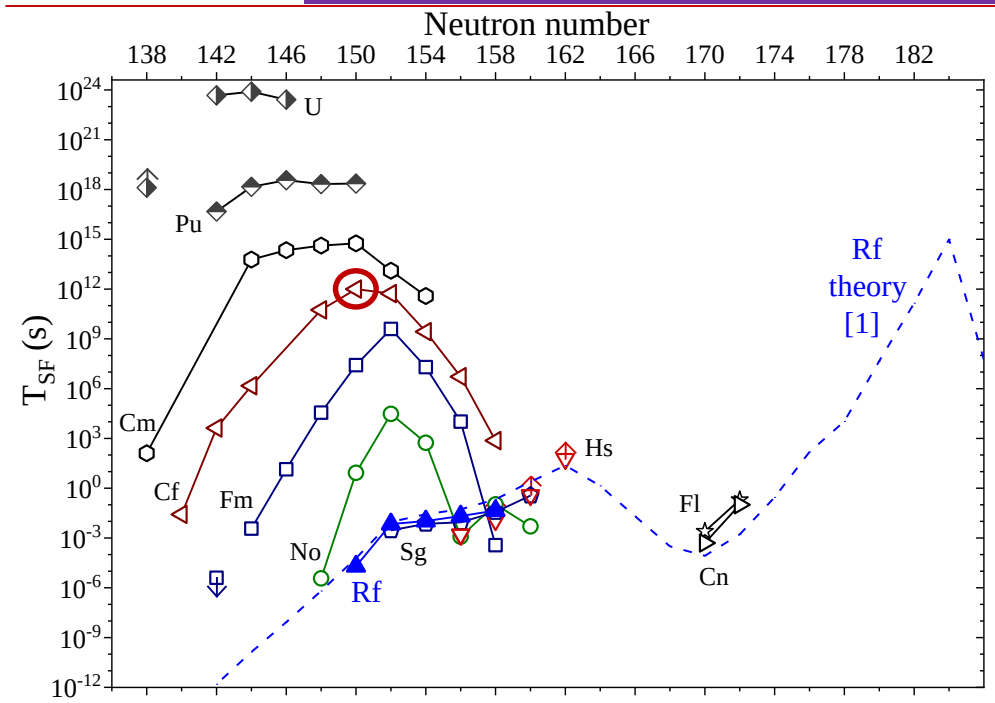
Height and shape ~ dynamics

Experimental fission observables:
e.g., T_{SF} ~ Height and shape

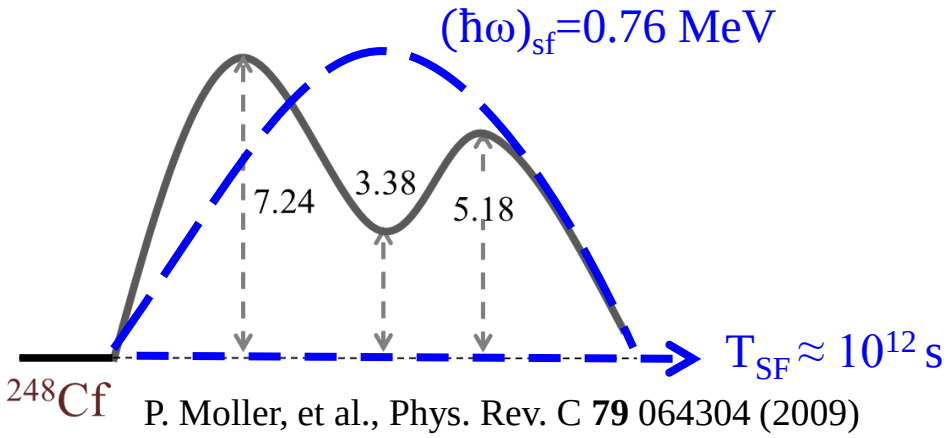
Experiment vs Theory
Shape: Local variable
B_f (Height): Global variable

"Semi-empirical" systematics (for T_{SF}) by using B_f
V.E. Viola and B.D. Wilkins, Nucl. Phys. 82, 65 (1966).

Semi-empirical approach: Fission-barrier shape for the ground-state



J. Khuyagbaatar, Eur. Phys. J. A 55, 134 (2019).



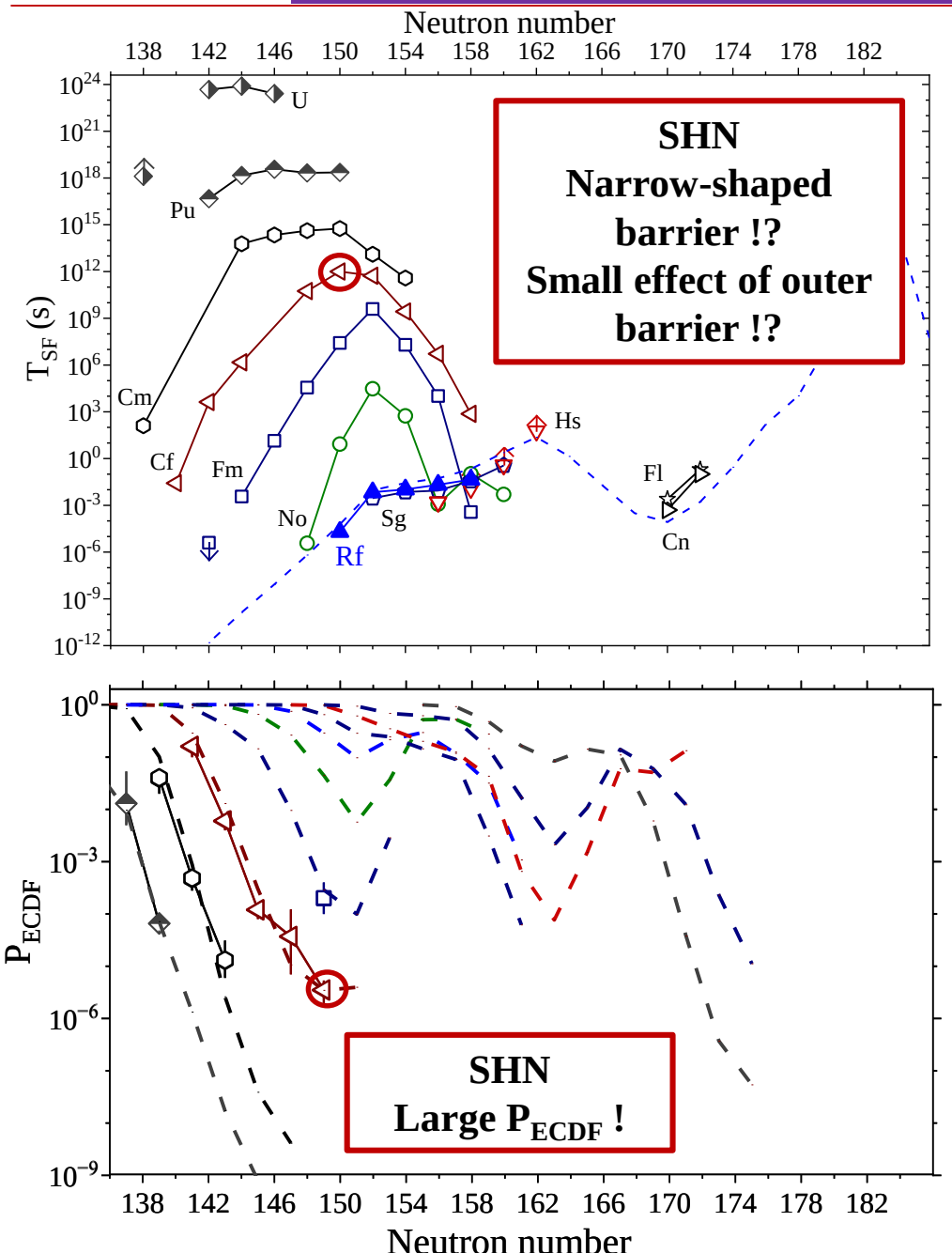
P. Moller, et al., Phys. Rev. C **79** 064304 (2009)

Fission probability (parabolic-shaped barrier)

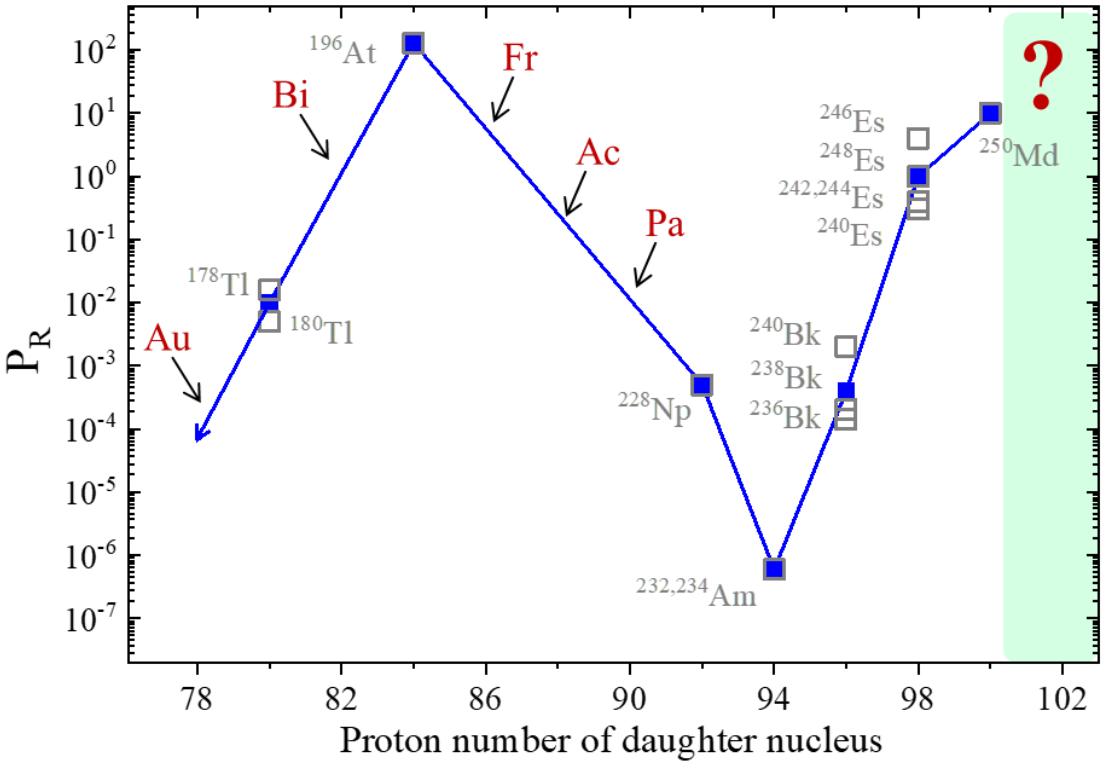
D. L. Hill and J. A. Wheeler, Phys. Rev. **89**, 1102 (1953).

$$T \approx \left[1 + \exp\left(\frac{2\pi(B_f - E)}{\hbar\omega_f}\right)\right]^{-1}$$

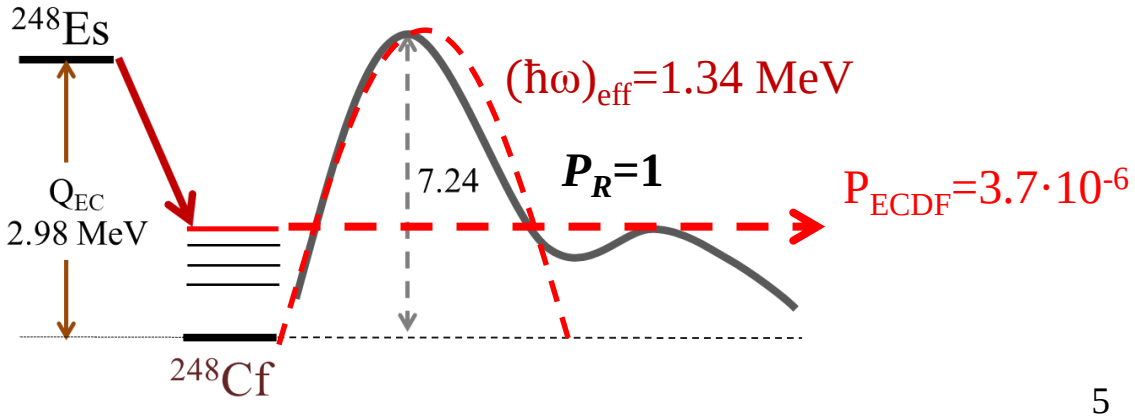
Semi-empirical approach: Fission-barrier shape for excited-state(s)



J. Khuyagbaatar, Eur. Phys. J. A 55, 134 (2019).

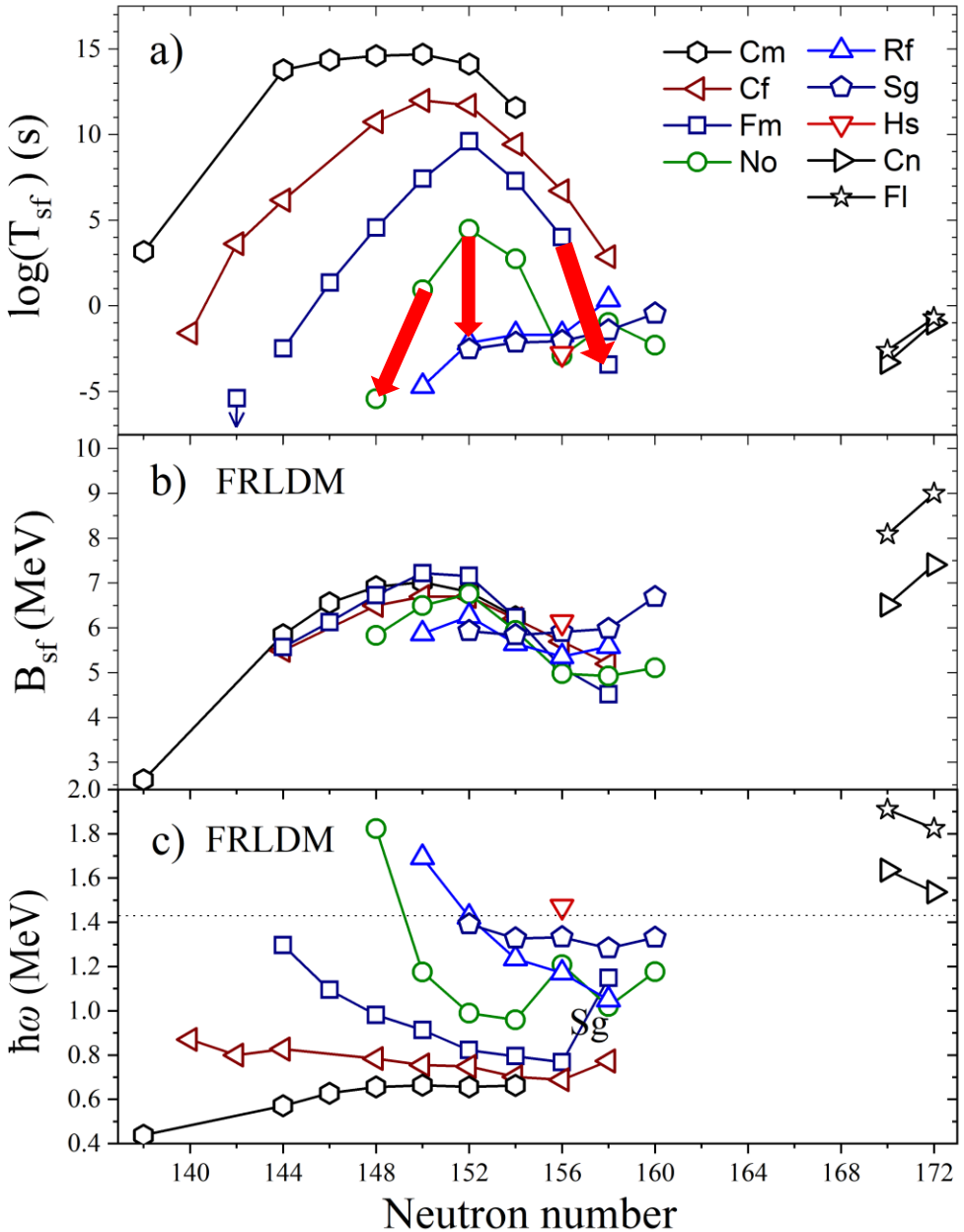


P_R ~ effect of outer barrier

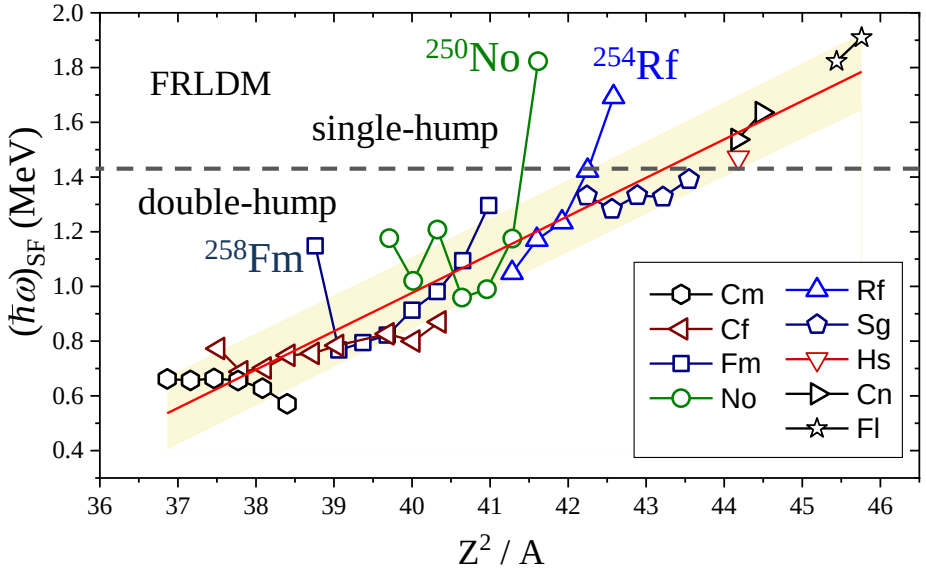


Semi-empirical approach: Ground-state barrier shapes of SHN

J. Khuyagbaatar Nucl. Phys. A **1002**, 121958 (2020).



SHN
Narrow-shaped barrier !?
Small effect of outer barrier !?



Outer barrier in ^{256}Rf is below the first well.
S.G. Nillson et al., Nucl. Phys. A **131**, 1 (1969)
Yu.Ts. Oganessian et al., Nucl. Phys. A **239**, 157 (1975).

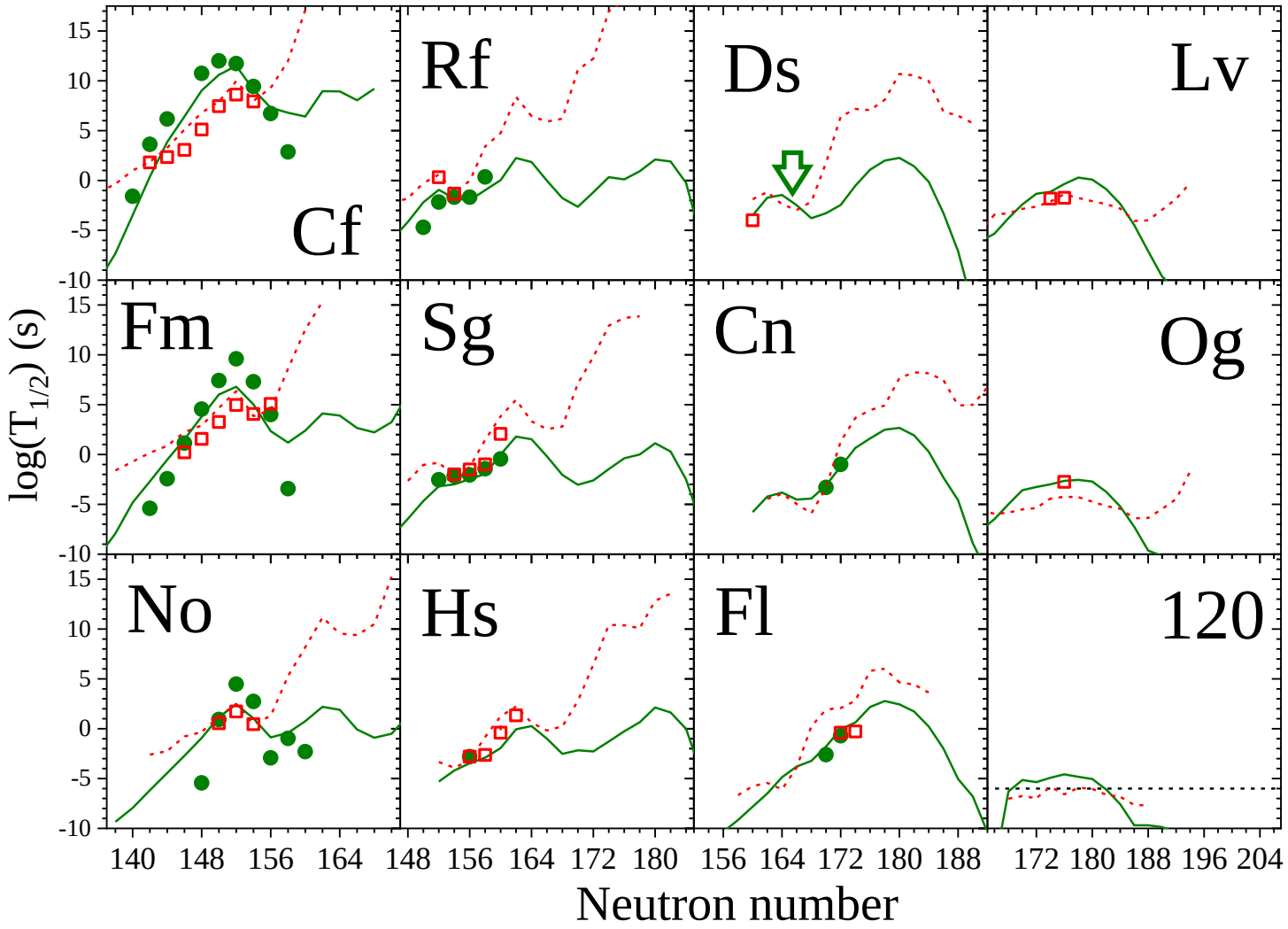
SHN
Narrow-shaped barrier !

Fission and α decay half-lives of SHN

J. Khuyagbaatar @TASCA23 workshop

J. Khuyagbaatar, Nucl. Phys. A 1002, 121958 (2020).

T_{SF}: Semi-empirical estimates with B_f from P. Möller, et al., Phys. Rev. C 91 (2015) 024310.
T_{α}: from P. Möller, et al., At. Data Nucl. Data Tables 66 (1997) 131.



News from SHE-Factory, FLNR, JINR

^{276}Ds: $T_{SF} \approx 0.15$ ms T_{SF} (est.) ≈ 3 ms
^{268}Sg: $T_{SF} \approx 11$ s T_{SF} (est.) ≈ 62 s

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^{282}Cn: $T_{SF} \approx 1$ ms [1] T_{SF} (est.) ≈ 1 ms

Direct fission from the even-even SHN (e.g., element 120) has to be considered in the SHE-synthesis !

J. Khuyagbaatar et al., Phys. Rev. C **102**, 064602 (2020).
S. Hofmann et al., Eur. Phys. J. A **52**, 180 (2016).
S. Hofmann et al., GSI Sci. Rep. **2009-1**, 131 (2009).
Yu.Ts. Oganessian et al., Phys. Rev. C **79**, 024603 (2009).

Z=120 with odd-N should still have predominant α-decay branching ! ?

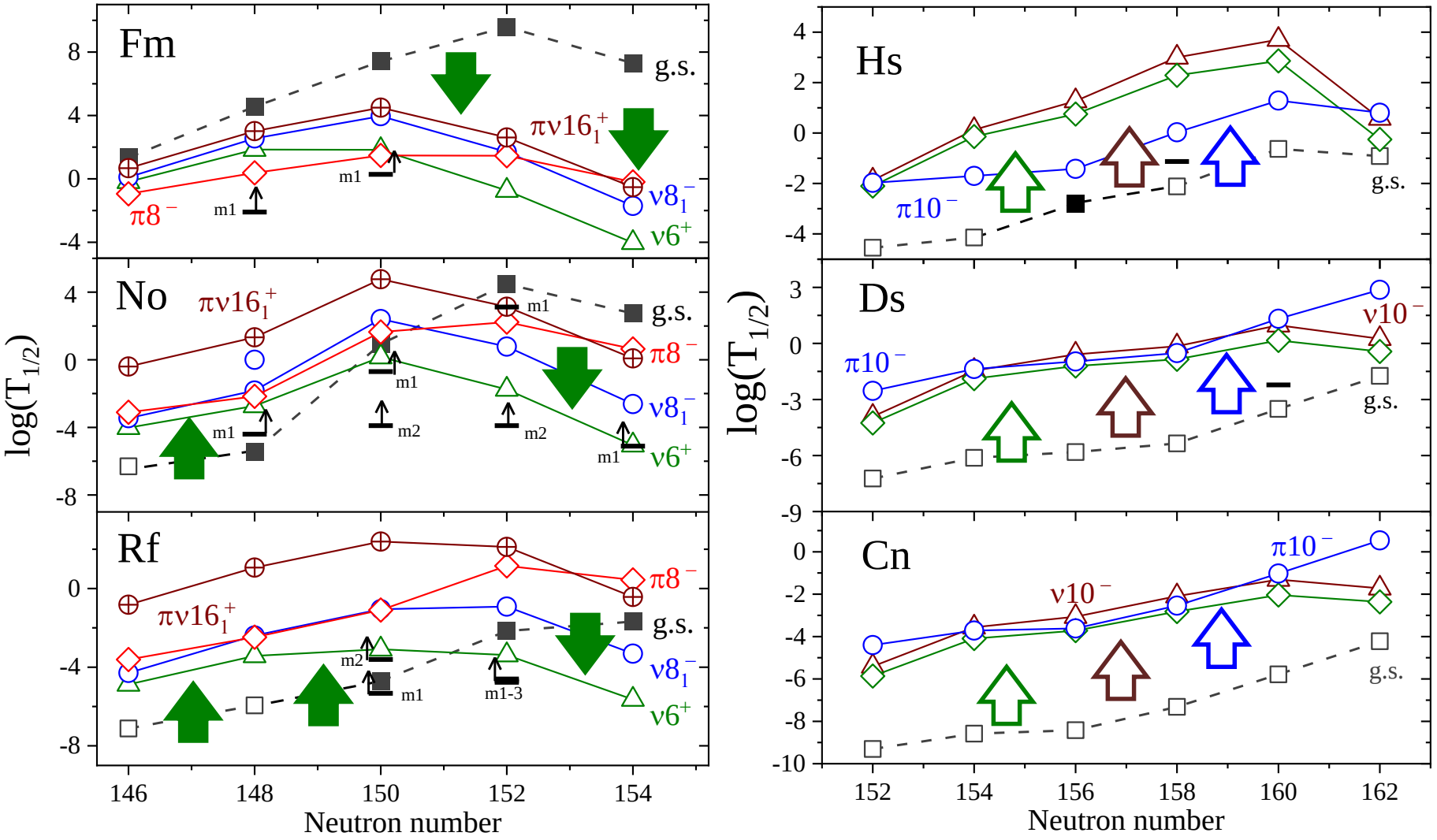
Fission hindrance
single-particle configuration
multi-particle configuration
quasi-particle configuration

[1] A. Samark-Roth et al., Phys. Rev. Lett. **126** 032503 (2021)

Semi-empirical approach: Fission hindrance of quasi-particle configuration

Fission-stability of high-*K* states in superheavy nuclei

J. Khuyagbaatar, Eur. Phys. J. A 58, 243 (2022).



Experimental T_{SF} : filled square
F.P. Hessberger, Eur. Phys. J. A 53, 75 (2017).
Theoretical half-lives: open symbols

Inversion of fission-stability
Z ≈ 102

The "minimum" on the PES is not anymore the most stable configuration against fission in the deformed SHN !

SHN:
Fission from K-isomeric state has T_{SF} longer than the ground state !

Fission hindrance
single-particle configuration
multi-particle state configuration
quasi-particle state configuration

Predictions on high K-states are taken from H. L. Liu et al., Phys. Rev. C 89, 044304 (2014).

Summary and conclusion

- A semi-empirical approach for probing the fission-barrier shape within the macroscopic-microscopic model was proposed
- Fission-barrier shape: One of the global variable for understanding the fission process.
- In heavy nuclei fission barrier width becomes
  - narrow as a function of the fissility parameter
  - broader with presence of unpaired nucleon
  - broader with presence of coupled “unpaired” nucleons (e.g., quasi-particle states)
  - narrow as a function of an excitation energy …
- A high-K states in SHN are more stable against the fission than their ground states.
- More experimental data on fissions from odd-A and odd-odd SHN …

Thank you for your attention!