Verification of the mechanism for synthesizing a doubly magic superheavy nucleus

First part: Related to reaching the **island of stability**
Second part: Synthesis of **new superheavy elements** (Z = 119)

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TASCA 25
GSI Helmholtzzentrum für Schwerionenforschung GmbH
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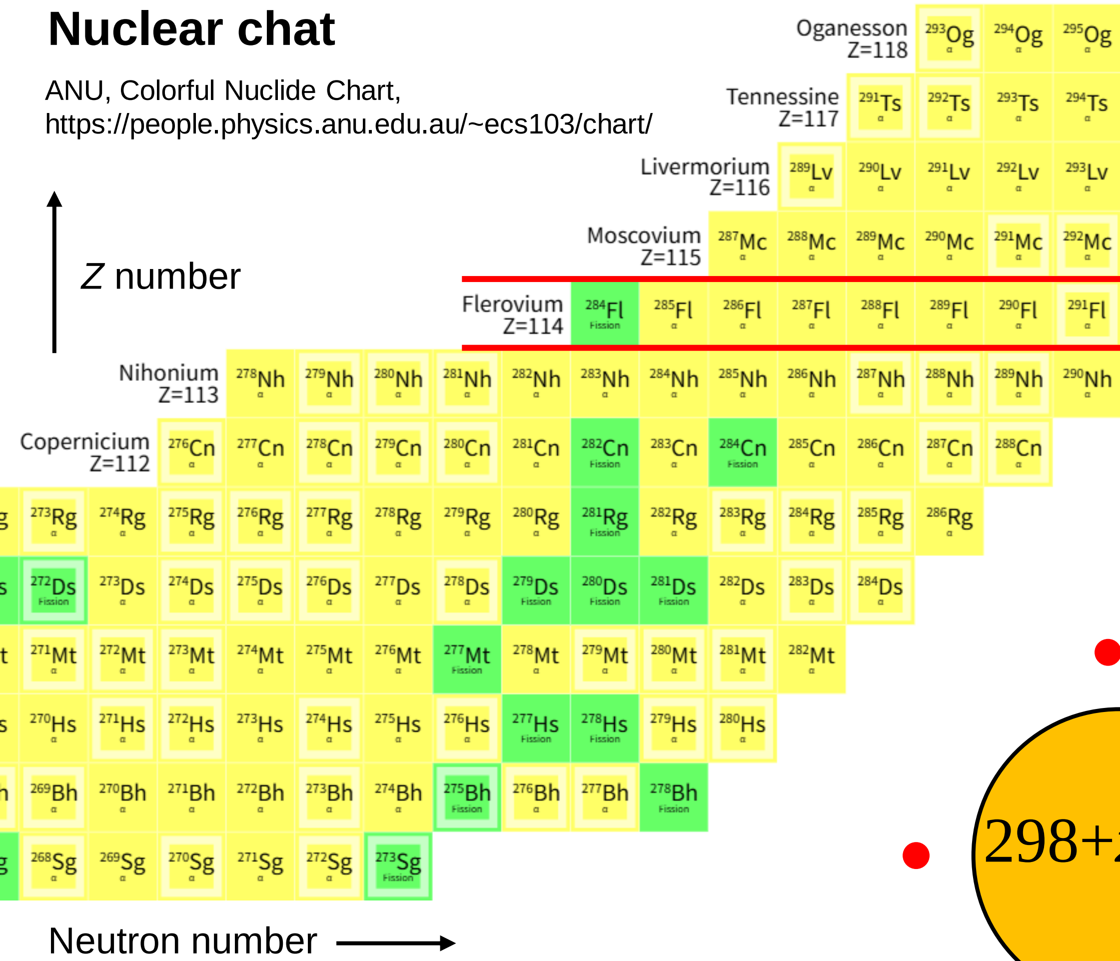
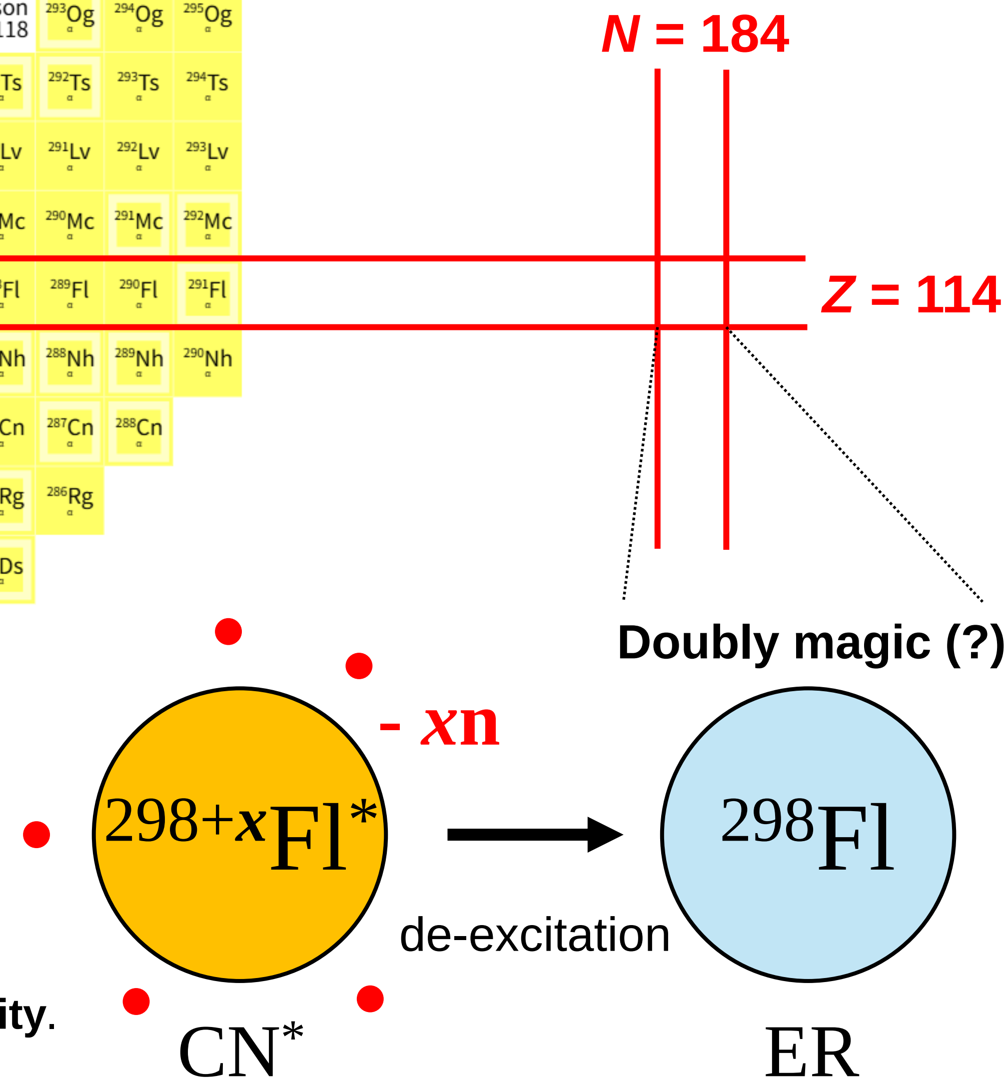
Background

W. D. Myers and W. J. Swiatecki, Nucl. Phys. 81, 1 (1966).

Nuclear chat

ANU, Colorful Nuclide Chart, https://people.physics.anu.edu.au/~ecs103/chart/

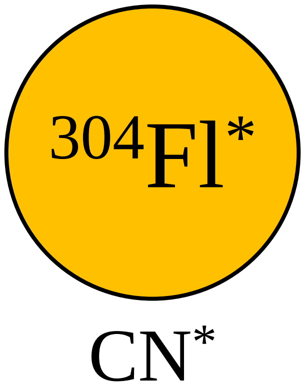


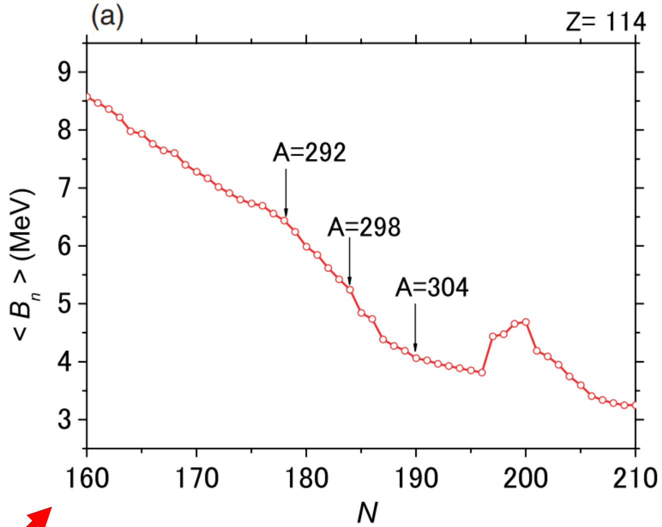


We need to **go beyond the island of stability**.
(need to produce more neutron-rich CN)

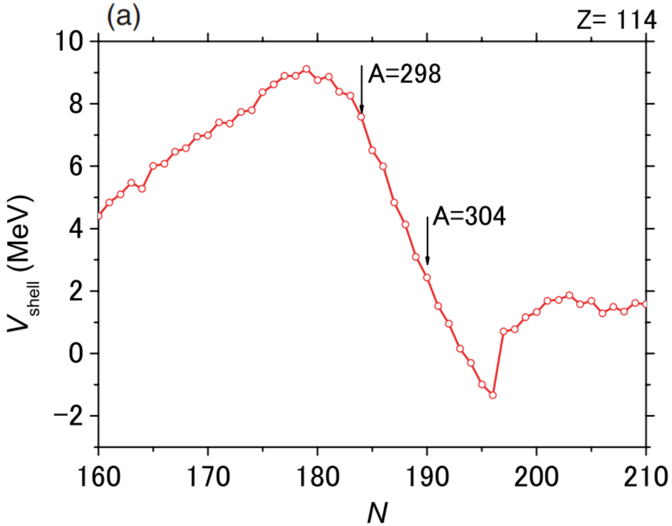
Background (previous study)

Some advantages in decay process Y. Aritomo, Phys. Rev. C **75**, 024602 (2007)





N binding energy vs ***N*** number



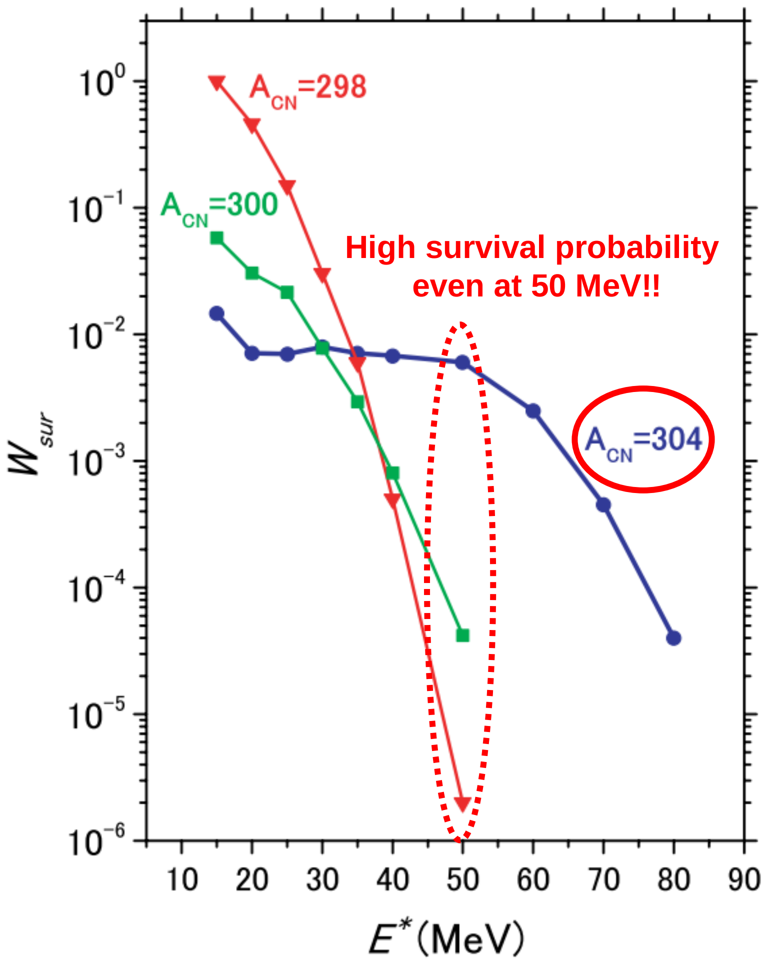
V_{shell} vs ***N*** number

1. **Low neutron binding energy**
→ Neutrons evaporate easily
→ **Rapid cooling**

2. As neutrons evaporate, **the fission barrier (Shell correction energy) increases**.
→ **Prevent the decrease in survival probability** of the compound nucleus.

Background (previous study)

Y. Aritomo, Phys. Rev. C **75**, 024602 (2007)



Confirmation with ^{304}Fl is not yet possible due to **synthesis difficulties**.

This mechanism can be confirmed in **known compound nuclei**.

$^{40}Ar + ^{238}U \rightarrow ^{278}Ds^*$

$^{48}Ca + ^{232}Th \rightarrow ^{280}Ds^*$

Yu. Ts. Oganessian, et al., Phys. Rev. C **108**, 024611 (2023)
Yu. Ts. Oganessian, et al., Phys. Rev. C **109**, 054307 (2024)

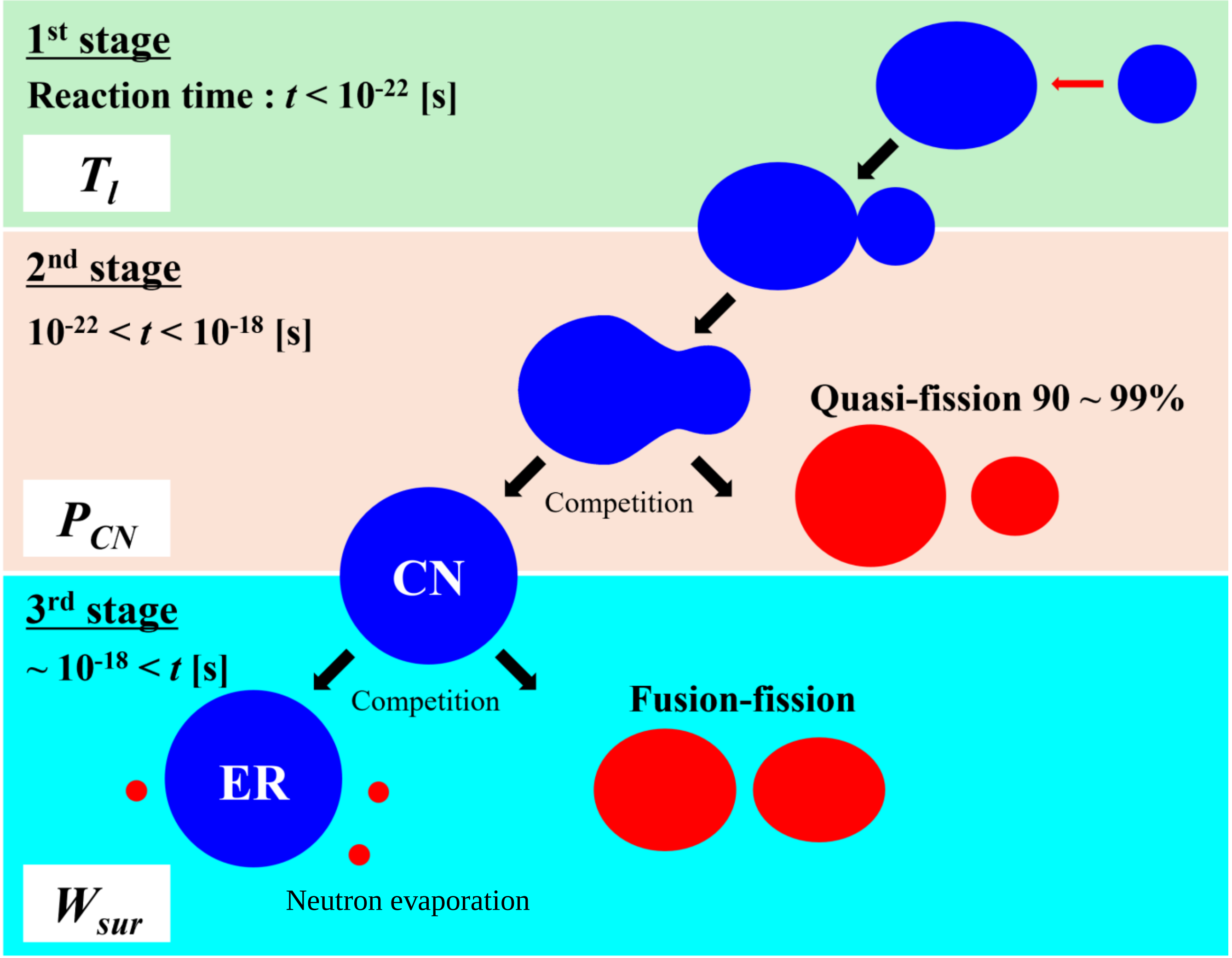
a road in Wako, near RIKEN

in front of RIKEN's entrance
(Not related to the presentation.)

Models

$$\sigma_{\rm ER} = \frac{\pi\hbar}{2\mu_0 E_{\rm c.m.}} \sum_{\ell=0}^{\infty} (2\ell+1) T_\ell(E_{\rm c.m.},\ell) P_{\rm CN}(E^*,\ell) W(E^*,\ell)$$

: **ER cross section**



Touching probability

$T_\ell(E_{\rm c.m.})$

Coupled-channel

×

Formation probability

$P_{\rm CN}(E^*)$

Langevin approach

×

Survival probability

$W(E^*)$

Statistical model

Models of each reaction stages

Coupled-channel method (1st stage)

K. Hagino, et al., Computer Phys. Comm. 123 (1999), 143 – 152.
Y. Aritomo, K. Hagino, *et al.*, Phys. Rev. C **85**, 044614 (2012).

$$T_\ell(E_{\mathrm{c.m.}}) = \int_0^1 d(\cos\theta) T_\ell(E_{\mathrm{c.m.}};\theta)$$ ← **CCFULL (K. Hagino)**

$$\sigma_{\mathrm{cap}}(E_{\mathrm{c.m.}}) = \frac{\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)T_\ell(E_{\mathrm{c.m.}})$$

$$V_{CC}(r,\theta) = V^{(N)}(r,\theta) + V^{(C)}(r,\theta)$$

- σ_{cap} : Capture cross section
- $E_{\mathrm{c.m.}}$: Incident energy (center-of-mass frame)
- θ : Angle of deformed target to the incident beam
- l : Angular momentum
- k : Wave number of the incident flux
- T_l : Capture probability
- $V_{CC}(r,\theta)$: Angle dependent internucleon potential
- $V^{(N)}$: Nuclear potential (Woods-Saxson)
- $V^{(C)}$: Coulomb potential

Langevin equation (2nd stage)

V. Zagrebaev and W. Greiner, Journal of Phys. G: Nuclear and Particle Physics 31, 825 (2005).
Y. Aritomo, K. Hagino, *et al.*, Phys. Rev. C **85**, 044614 (2012).

$$\frac{dq_i}{dt} = (m^{-1})_{ij} p_j$$

$$\frac{dp_i}{dt} = -\frac{\partial V}{\partial q_i} - \frac{1}{2}\frac{\partial}{\partial q_i}(m^{-1})_{jk} p_j p_k - \gamma_{ij}(m^{-1})_{jk} p_k + g_{ij} R_j(t) q_i$$

$\langle R_i(t)\rangle = 0,\ \langle R_i(t_1)R_j(t_2)\rangle = 2\delta_{ij}\delta(t_1 - t_2)$: white noise

$\sum_k g_{ij} g_{jk} = T\gamma_{ij}$: Einstein relation

- q_i : Two-center parametrization
- p_i : Momentum
- m_{ij} : Hydrodynamical mass (inertia mass)
- γ_{ij} : Wall and Window (one-body) dissipation (friction)
- g_{ij} : Strength of Random force

Statistical model (3rd stage)

R. Vandenbosch and J. R. Huizenger, Nuclear Fission, 1973, p.233.
M. Ohta, Proceedings on Fusion Dynamics at the Extremes, 110 (2001).

$$W = \prod_{i=1}^{N} \frac{\Gamma_n^{(i)}}{\Gamma_f^{(i)}}$$

$$\boldsymbol{B_f = -V_{shell}}\ \textbf{(FRDM2012)}$$

$$\frac{\Gamma_n}{\Gamma_f} = \frac{k_{coll}(gr.st.)}{k_{coll}(saddle)\cdot k_{\mathrm{Kramers}}} A_0 \exp\left[2\sqrt{a_n E_n^*} - 2\sqrt{a_f E_f^*}\right]$$

$$E_n^* = E_{int}^* - B_n\ ,\quad E_f^* = E_{int}^* - \boldsymbol{B_f}$$

- Γ_n : Decay width of neutron emission
- Γ_f : Decay width of fission
- a_n : Level density parameter (Neutron evaporation)
- a_f : Level density parameter (Fission)
- E_{int}^* : Intrinsic excitation energy
- B_n : Neutron binding energy
- $\boldsymbol{B_f}$: Fission barrier height

Uncertainty of reaction Q-value (mass)

$$\sigma_{\mathrm{ER}} = \frac{\pi\hbar}{2\mu_0 E_{\mathrm{c.m.}}} \sum_{\ell=0}^{\infty} (2\ell+1) T_\ell(\boldsymbol{E}_{\mathbf{c.m.}}, \ell) P_{\mathrm{CN}}(\boldsymbol{E}^*, \ell) W(\boldsymbol{E}^*, \ell)$$

Measured (AME2020)

$$E^* = E_{\mathrm{c.m.}} + \boldsymbol{Q}, \quad \boldsymbol{Q} = \{\boldsymbol{M}_{\boldsymbol{CN}} - (M_{\mathrm{P}} + M_{\mathrm{T}})\}c^2$$

Dependent on mass table (with uncertainty)

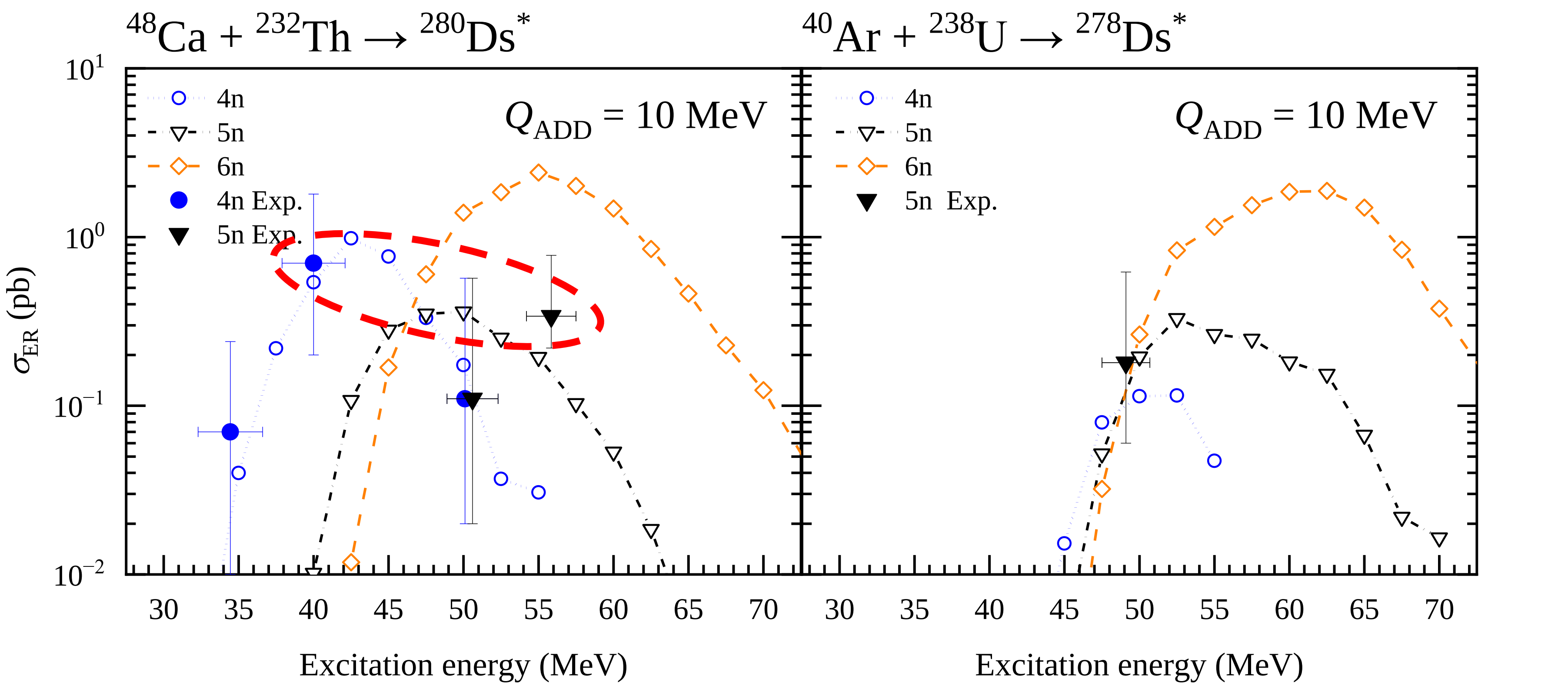
Table: Reaction Q-value (MeV)

Mass Table	$^{40}Ar + ^{238}U \rightarrow ^{278}Ds$	$^{48}Ca + ^{232}Th \rightarrow ^{280}Ds$	$^{48}Ca + ^{238}U \rightarrow ^{286}Cn$	$^{48}Ca + ^{244}Pu \rightarrow ^{292}Fl$	$^{48}Ca + ^{248}Cm \rightarrow ^{296}Lv$	$^{48}Ca + ^{249}Cf \rightarrow ^{297}Og$
FRDM1995	**-132.74**	-155.50	-162.31	-160.72	-166.91	-174.34
FRDM2012	-133.07	**-154.72**	**-161.86**	**-160.44**	**-166.57**	**-174.18**
KTUY05	-135.70	-164.79	-171.46	-164.47	-169.10	-176.07
SKP	-141.07	-164.79	-171.03	-171.30	-175.32	-181.31
SkM	**-142.87**	**-169.16**	**-175.80**	**-176.44**	**-180.41**	**-186.42**
SV-min	-137.50	-161.15	-167.67	-167.76	-172.00	-178.13
UNEDF0	-133.48	-157.61	-164.27	-164.48	-168.90	-175.33

*Max and min marked with **yellow**

ER cross sections (CN: Ds)

Experimental values:
Yu. Ts. Oganessian, et al., Phys. Rev. C 108, 024611 (2023)
Yu. Ts. Oganessian, et al., Phys. Rev. C 109, 054307 (2024)



The cross sections remain **relatively large even at high excitation energy**.

Experiment: No significant difference between **40 MeV** and **55 MeV**. (Ca + Th)

Calculation: The **6n** evaporation channel has **a few pb** at **high excitation energies**.

Effect of the **increase in shell correction energy** due to **neutron evaporation**.

Background (Z = 119)

Hot fusion using ^{48}**Ca** is successful for many SHEs up to Og.

When making element **119** with ^{48}**Ca**, ……

$$^{48}\mathrm{Ca} + {}^{254}\mathrm{Es} \rightarrow {}^{302\text{-}x}119$$

Short half-life, Scarcity

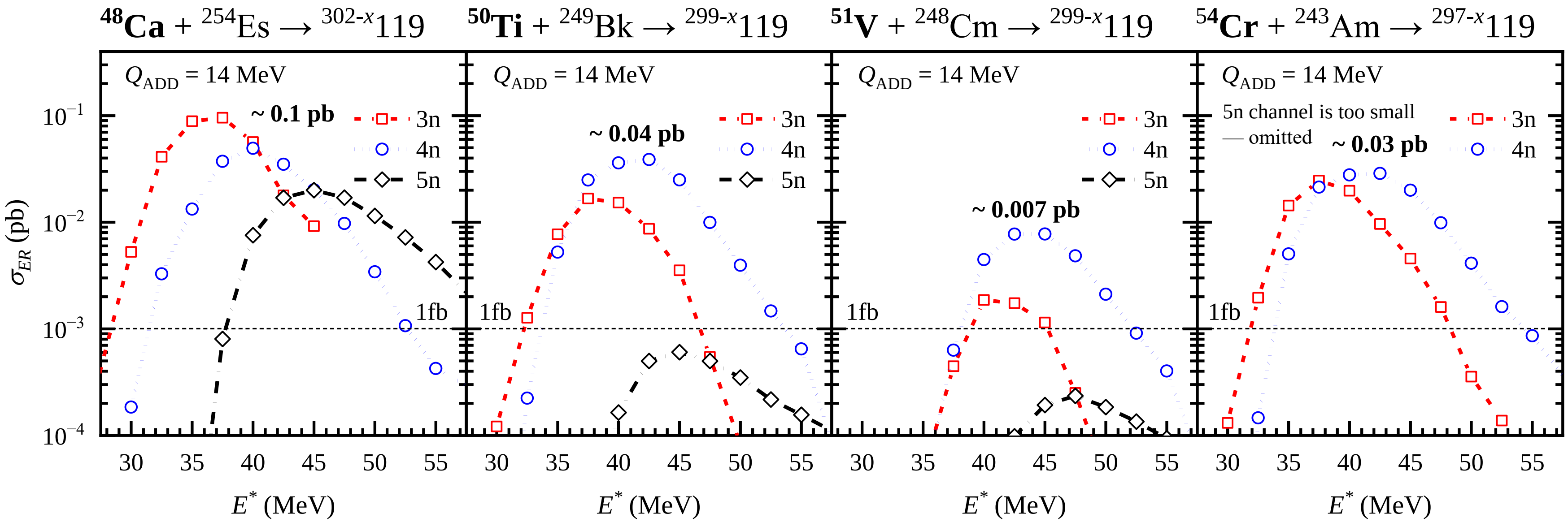
It is necessary to use **heavier projectiles** than ^{48}Ca.

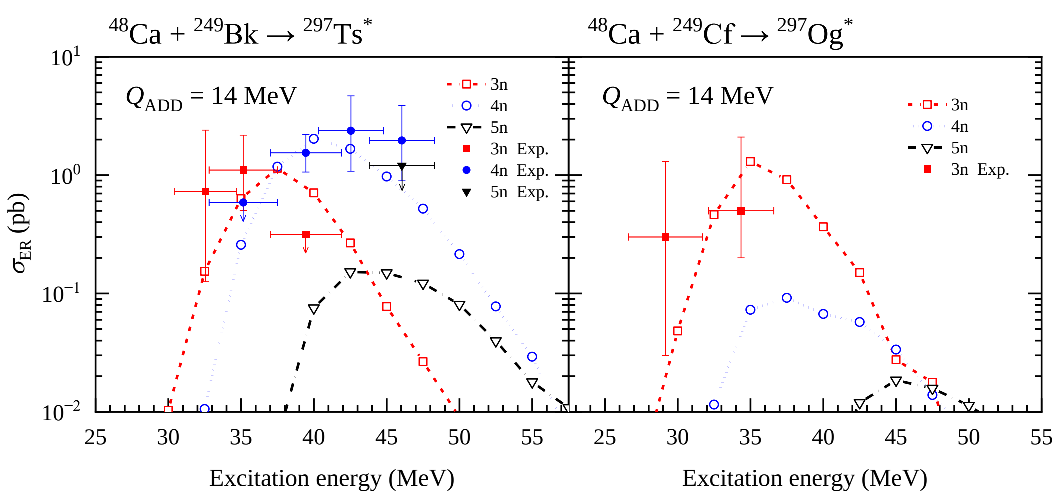
$$^{50}\mathbf{Ti} + {}^{249}\mathrm{Bk} \rightarrow {}^{299\text{-}x}119$$

$$^{51}\mathbf{V} + {}^{248}\mathrm{Cm} \rightarrow {}^{299\text{-}x}119 \quad \text{(RIKEN, Japan)}$$

$$^{54}\mathbf{Cr} + {}^{243}\mathrm{Am} \rightarrow {}^{297\text{-}x}119$$

ER cross sections for Z = 119





^{48}Ca > ^{50}Ti ≈ ^{54}Cr > ^{51}V

Effects of the **reaction Q-value** and **Coulomb barrier height!!**

Q_{ADD} = 14 MeV was determined by fitting to these experimental results.

Experimental values:
Yu. Ts. Oganessian, et al., Phys. Rev. C 87, 054621 (2013)
Yu. Ts. Oganessian, et al., Phys. Rev. C 74, 044602 (2006)

Summary

The effect of **increased shell correction energy** due to **neutron evaporation** is confirmed. (CN: $^{278,280}Ds^{*}$)

→ The **same mechanism** might be observed in the synthesis of **doubly magic superheavy nuclei**.

The relative relationship between **reaction Q-value** and **Coulomb barrier height** is important in comparing fusion reactions forming the **same compound nucleus**.

→ In the synthesis of element **119**, a **^{54}Cr projectile** might not be a bad choice. (^{243}Am is relatively easy to use!!)

However, the results of theoretical calculations are **highly dependent** on the **mass table**. (**Many uncertainly!!!**)

→ The absolute value is **open to discussion**. (Q, mass, V_{sh}, …)