5 May 2023

SHE research at RIKEN Nishina Center

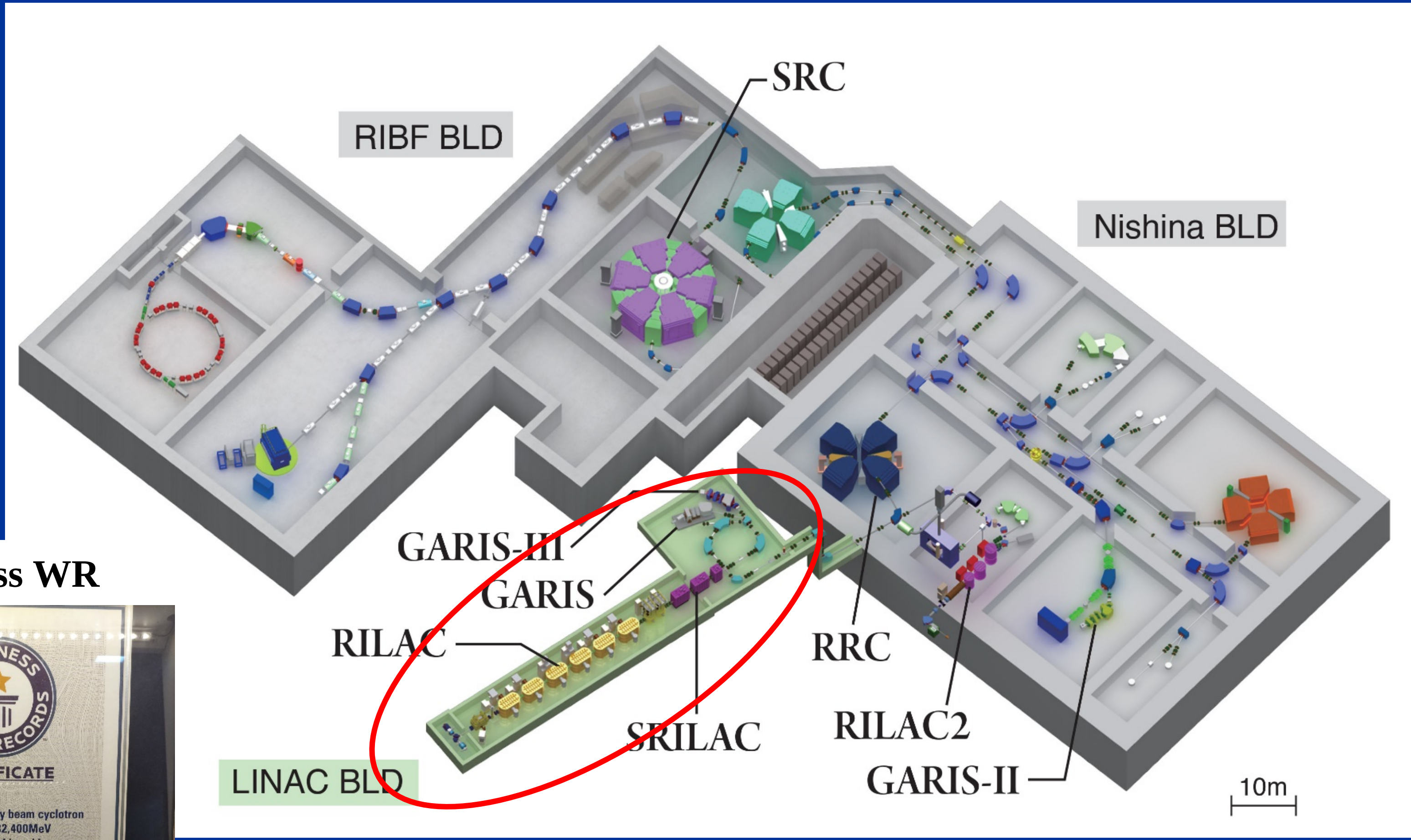
H. Sakai for nSHE research group

RIKEN Nishina Center

SHE research at RIKEN Nishina Center

1. Introduction
    - RIKEN Nishina Center (RNC) & discovery of nihonium (Nh Z=113)
2. SHE Project
    - SRILAC, SCECRIS, GARIS-III construction
      H. Sakai et al., Eur. Phys. J. A (2022) 58 :238
    - Key elements: S/N α-decay meas., ^{248}Cm target preparation
3. ^{51}V+^{248}Cm: Quasi-elas. barrier distribution measurement
    - Choice of E_{opt}(^{51}V)
      M. Tanaka et al., JPSJ 91 (2022) 084201
4. ^{248}Cm (^{51}V, xn)$^{299-x}$119 reaction (x=3 and 4)
    - Present status
5. ^{51}V+^{159}Tb reaction
    - Fusion reaction mechanism (deformation effect)
      Pierre Brionnet, in preparation
6. Summary

1. RIKEN Nishina Center (RNC)



RNC

- 5 cyclotrons
  2 linacs
  SCRIT (e microtron)

- **SRC (2006) of RIBF**
  Milestone: ^{238}U 345 MeV/u
  82.4 GeV ,
  ~100pnA

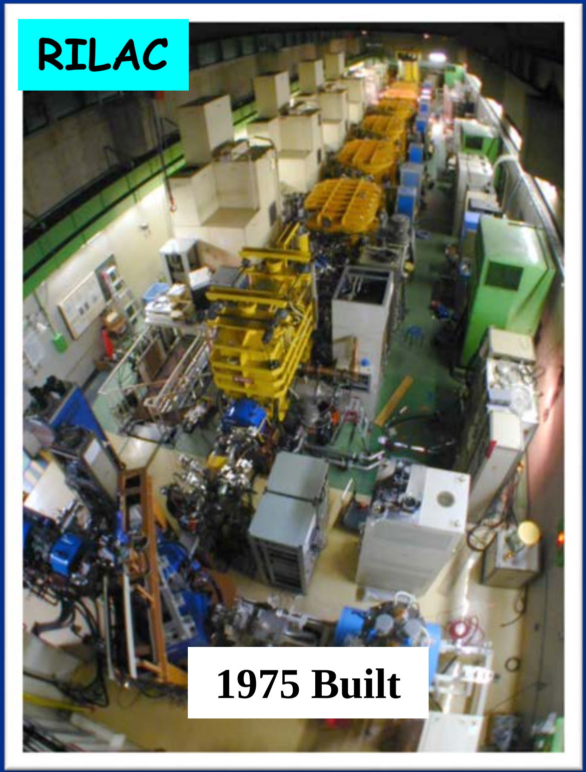
Gunness WR

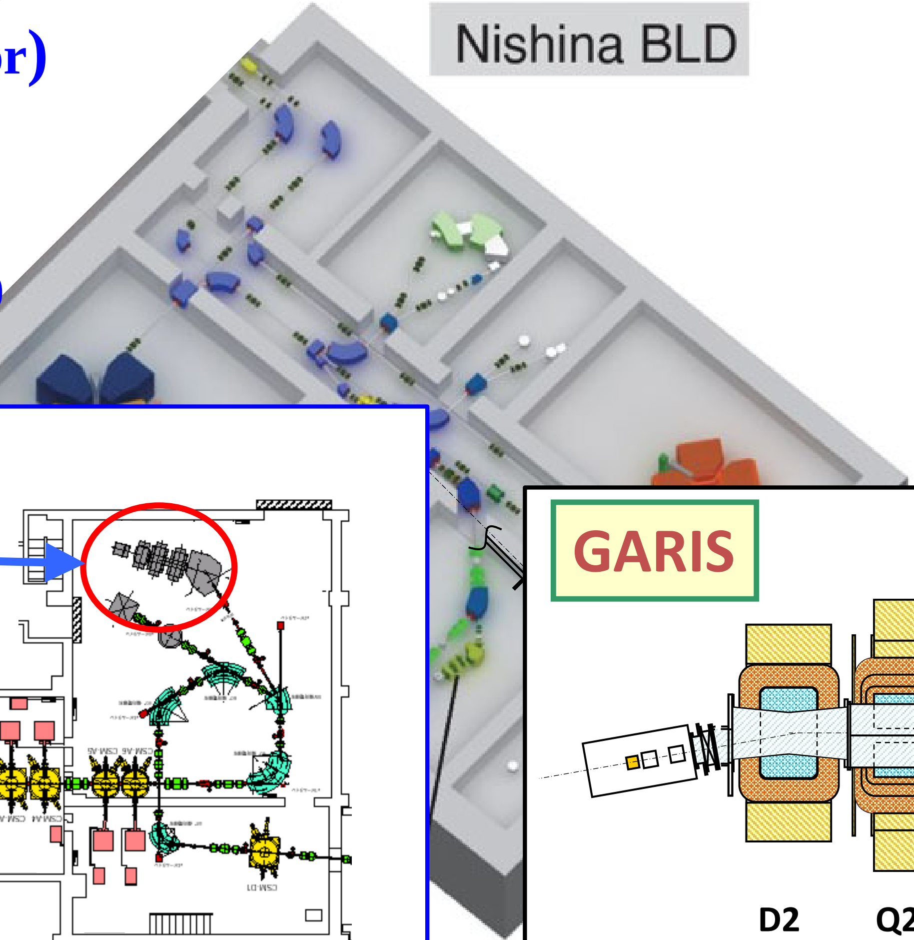
Highest beam energy cyclotron

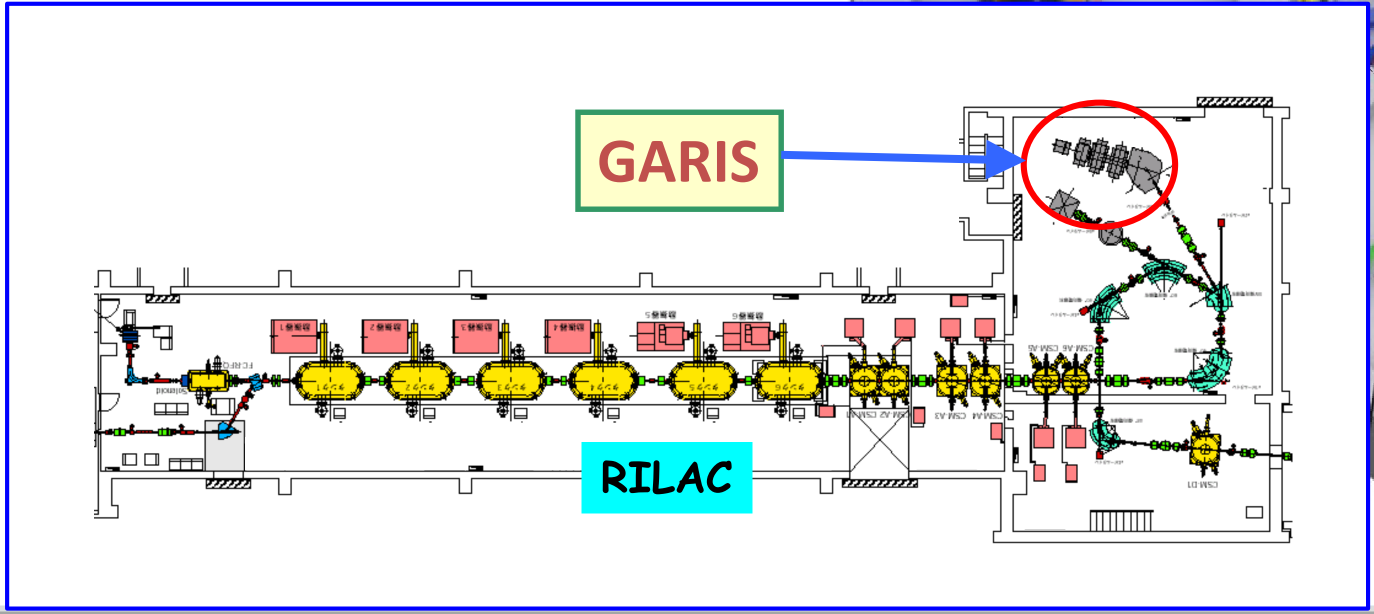
Discovery of nihonium

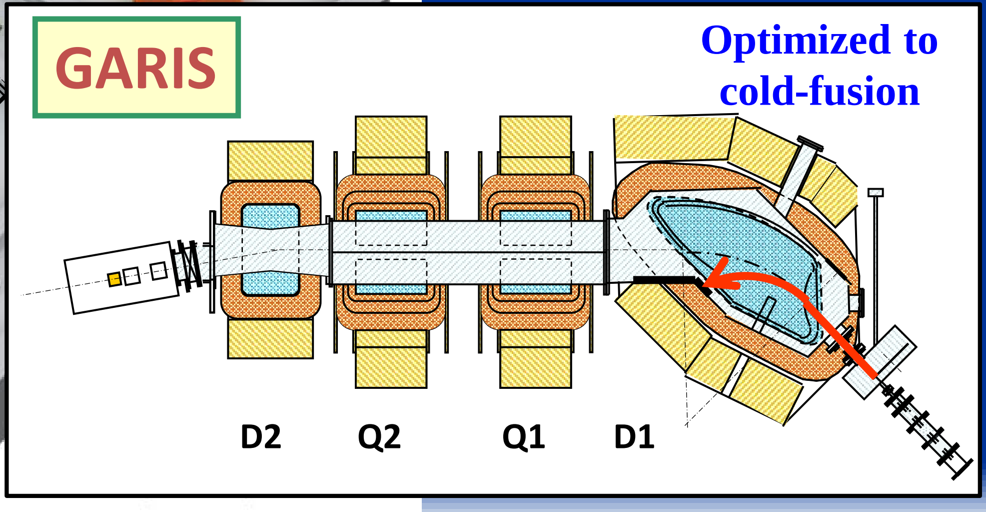
- $^{209}Bi(^{70}Zn,n)\,^{278}113$: cold fusion reaction
- Morita Group
- RILAC(RIKEN Linear Accelerator)
- GARIS(gas-filled recoil ion separator)

- Nh discovered (2016)
- 3 events / 575 days (2004,2005,2012)
- Production cross section ~22 fb

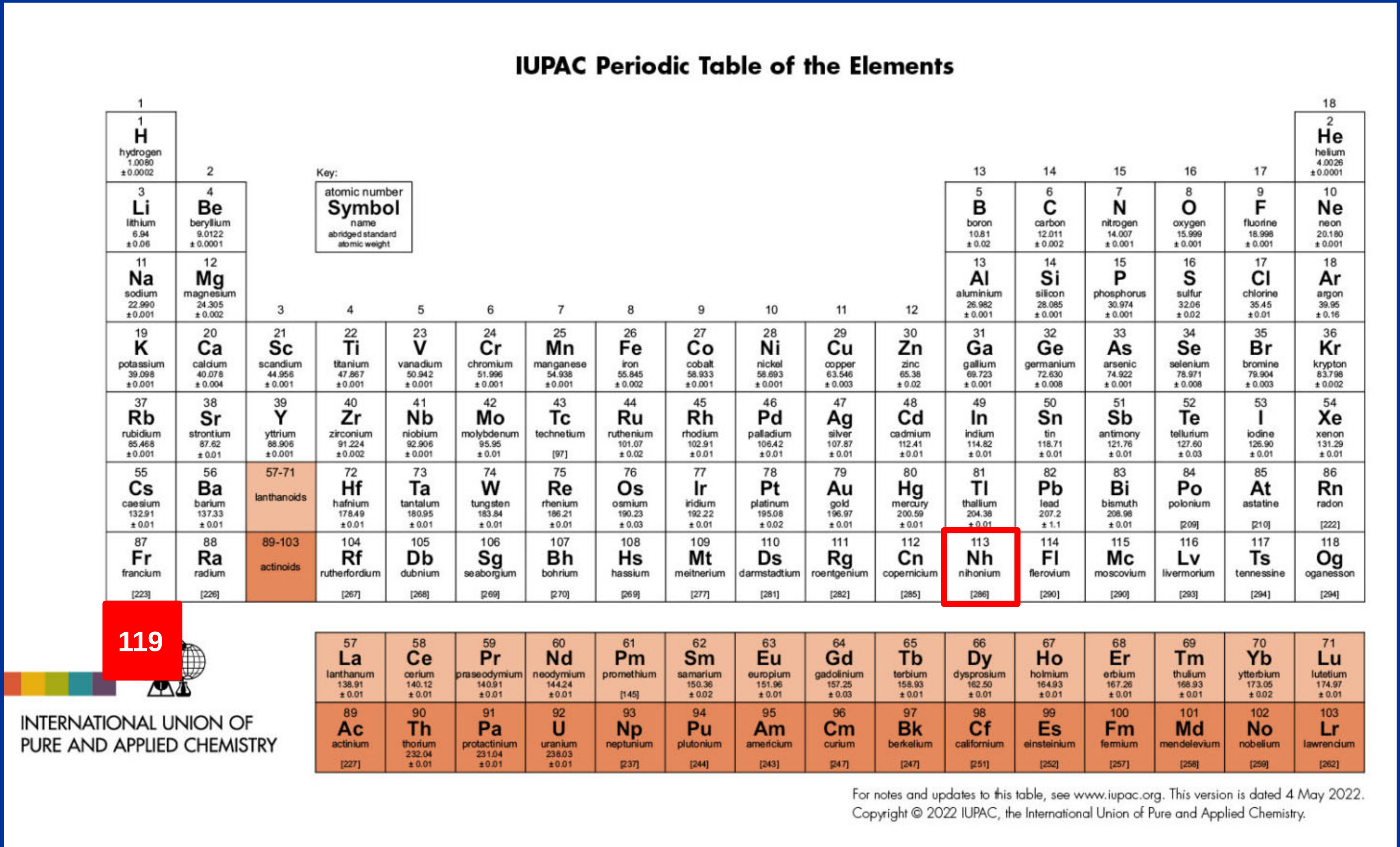








What is next?



IUPAC Periodic Table of the Elements
Key: atomic number Symbol name abridged standard atomic weight
57-71 lanthanoids
89-103 actinoids
113 Nh nihonium [286]
119
INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY
For notes and updates to this table, see www.iupac.org. This version is dated 4 May 2022.
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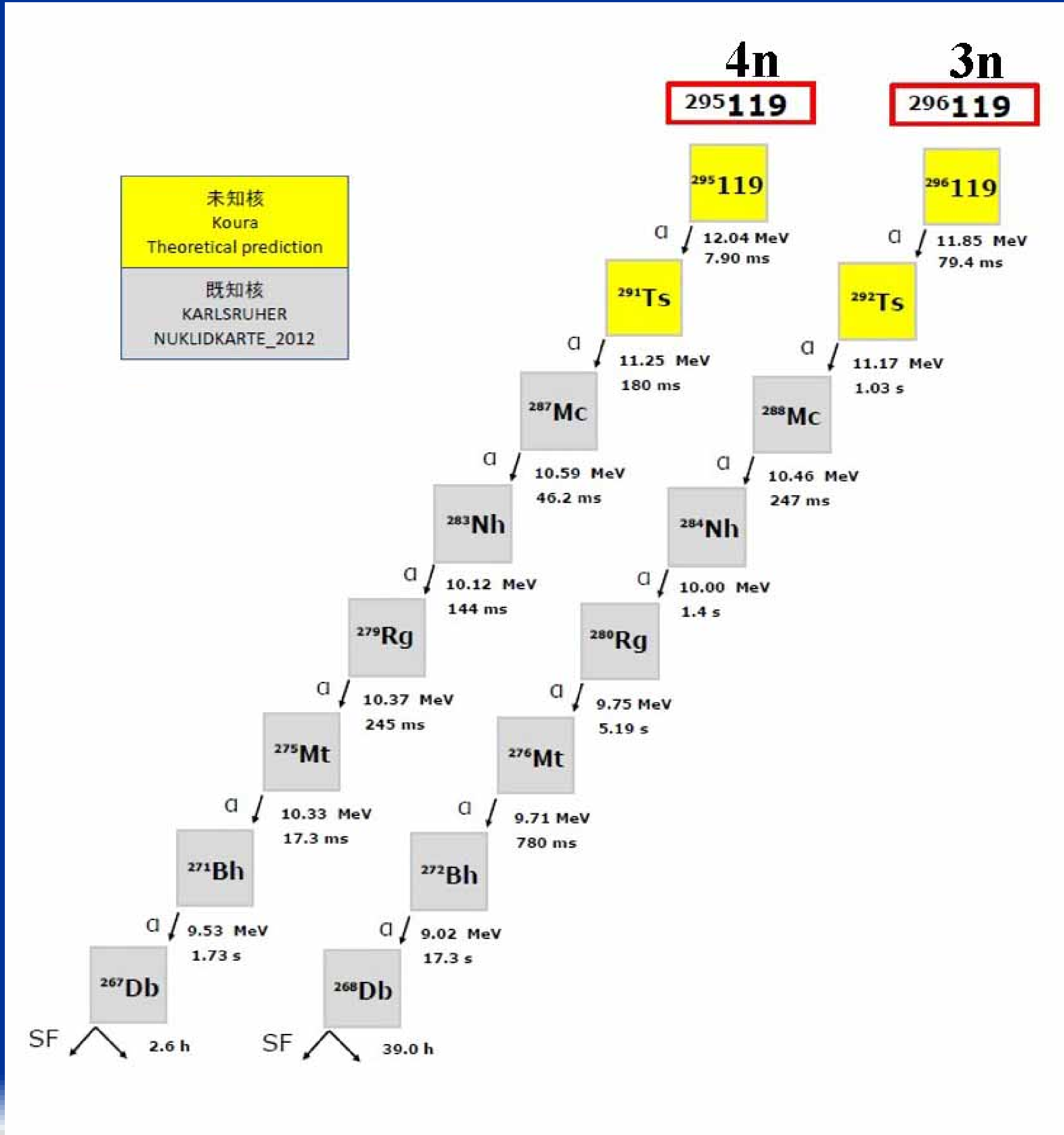
2. SHE Project (2016)

- **Goal: Discover new SHE Z=119**

- $^{248}Cm(^{51}V, xn)\,^{299-x}119$ **by hot fusion reaction**
- **Expected cross section ≤ 10 fb (10^{-38} cm^2) (heuristic guess!)**

^{248}Cm(^{51}V,xn)$^{299-x}$119 channel x	Cross section (fb) 3n	Cross section (fb) 4n
Ghahramany (2016)	20	100
Zhu (2016)	6	11

Z=119 expected decays via. ^{248}Cm(^{51}V, xn)   x=3 and 4



- **7 generations (successive α emissions)**
- **5-α-decay chain known**

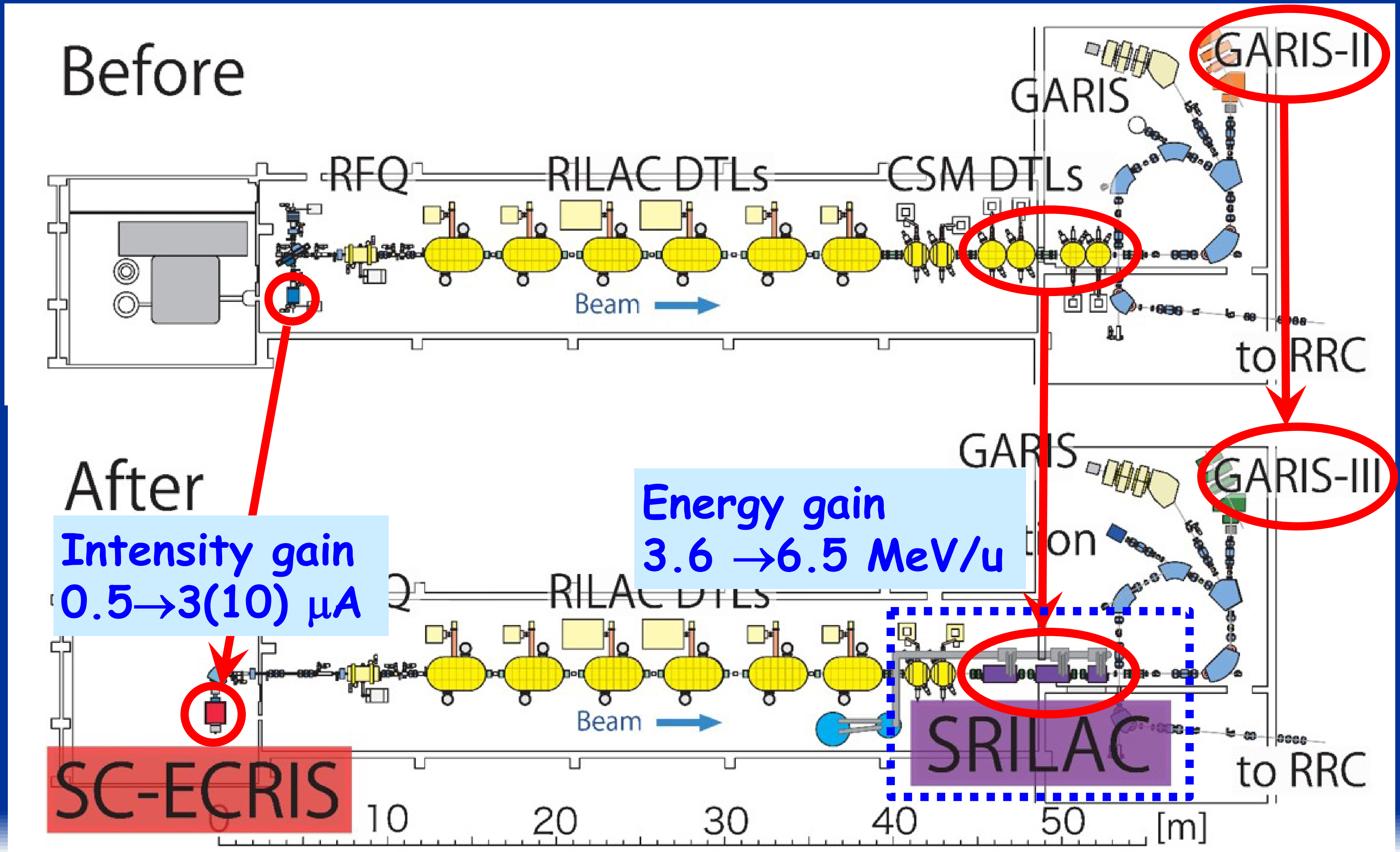
SHE Project (2016)

- Goal: Synthesis new SHE Z=119
- $^{248}Cm(^{51}V, xn)\ ^{299-x}119$ by hot fusion reaction
- Expected cross section ≤ 10 fb (10^{-38} cm^2)
- SRILAC:~6 MeV/*u* ^{51}V beam (RILAC 5.5 MeV/*u*)
- SC-ECRIS: High-intensity beam
- $^{248}Cm_2O_3$ material: Collaboration with ORNL
- GARIS-III: Spectrometer + Focal plane det. Electronics etc.

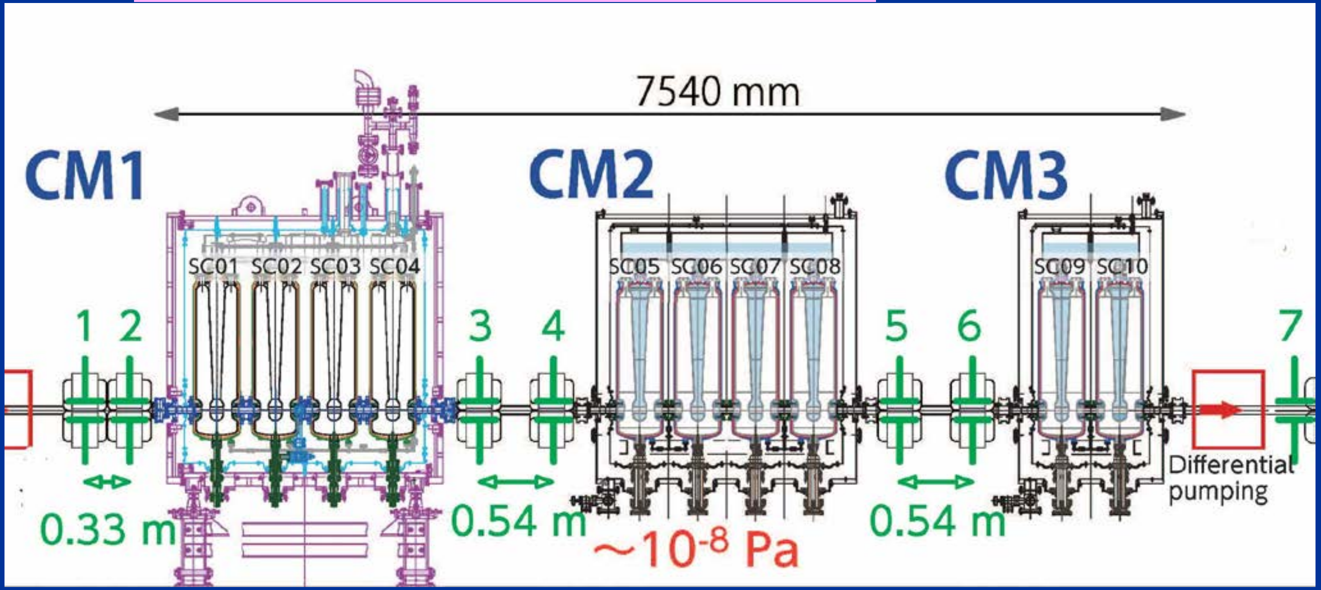
$^{248}Cm(^{51}V, xn)^{299-x}119$ channel x	Cross section (fb) 3n	4n
Ghahramany (2016)	20	100
Zhu (2016)	6	11
Adamian (2018)		12
Manjunatha (2019)	4	
Siwek-Wilczynska (2019)	3	6
Aritomo (2020)	20 at E*=20 MeV	
Lv (2021)	9.8	1.3

Courtesy to : N. Sakamoto for SRILAC
: Y. Higurashi, T. Nagatomo for SC-ECRIS
: K. Morimoto, P. Brionnet for GARIS-III
: H. Haba for Target

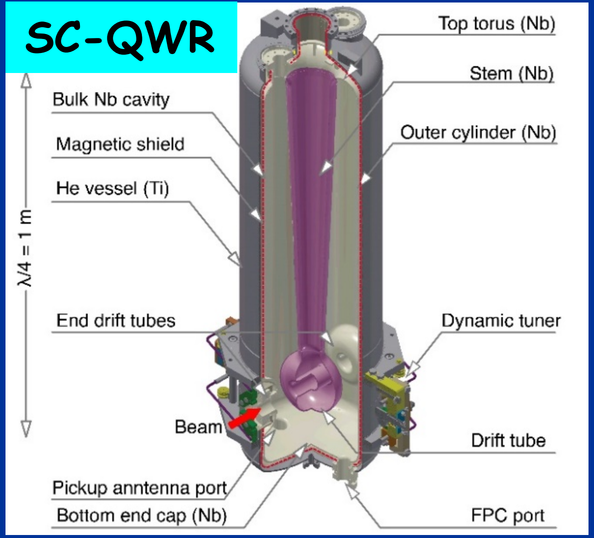
SRILAC, SC-ECRIS and GARIS-III



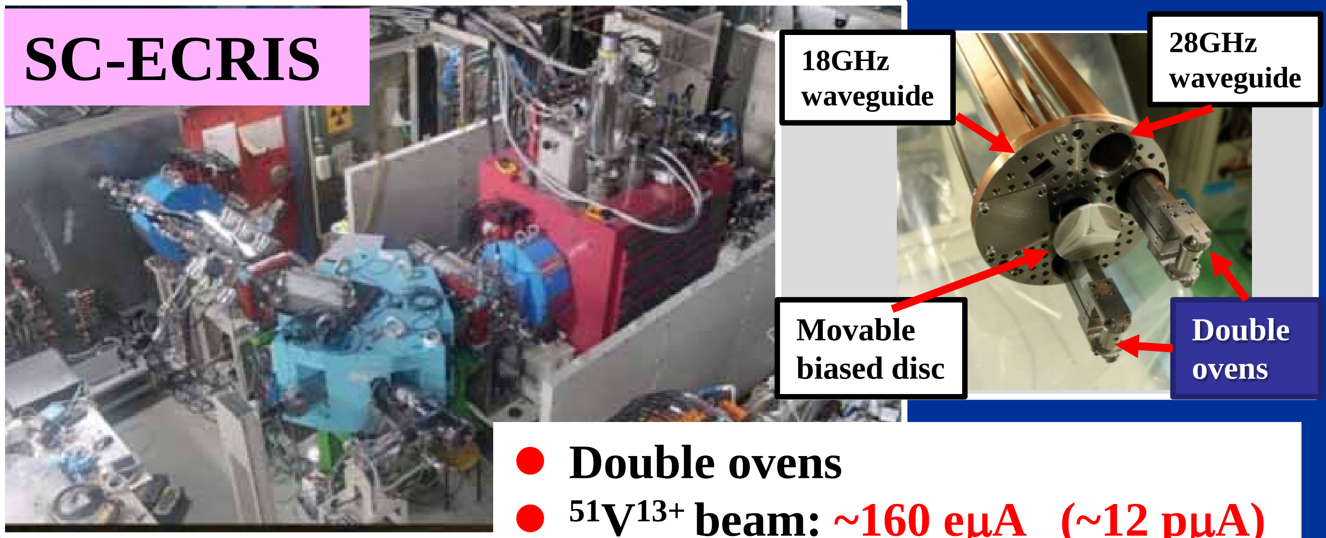
SRILAC (10 SC-QWRs)



SRILAC cryomodules

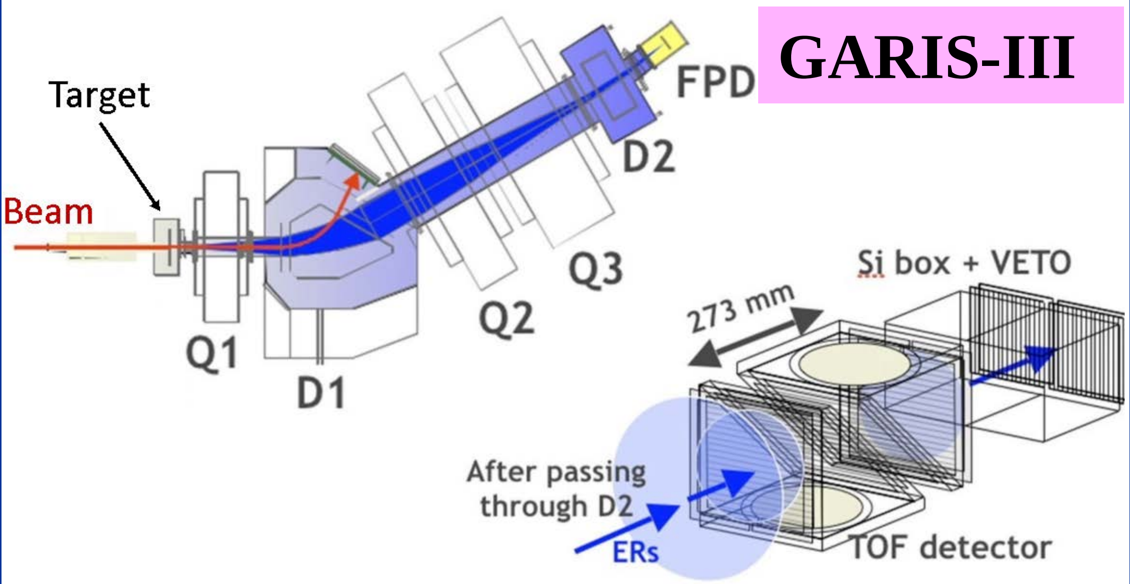


SC-ECRIS



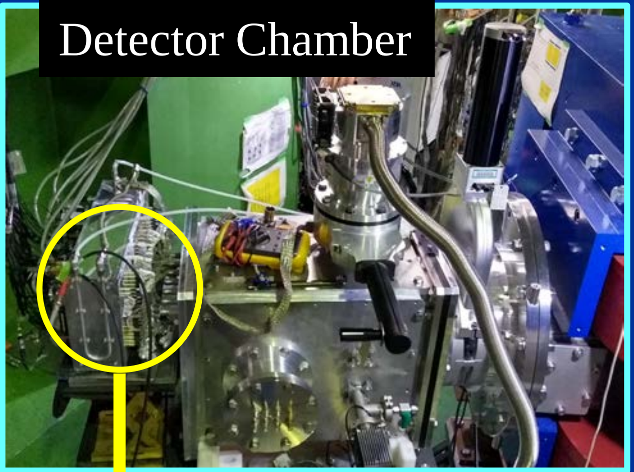
- Double ovens
- $^{51}V^{13+}$ beam: ~160 eμA (~12 pμA)
- Continuous running ~30 days

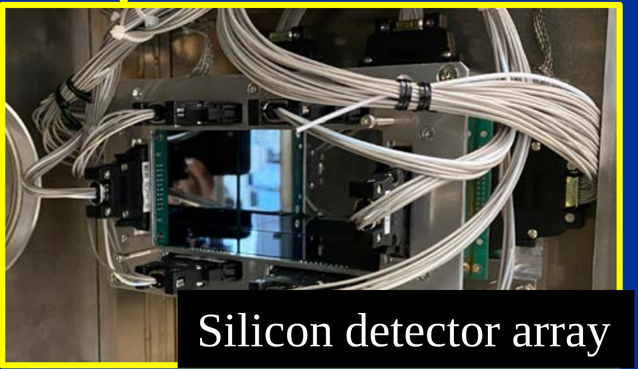
GARIS-III

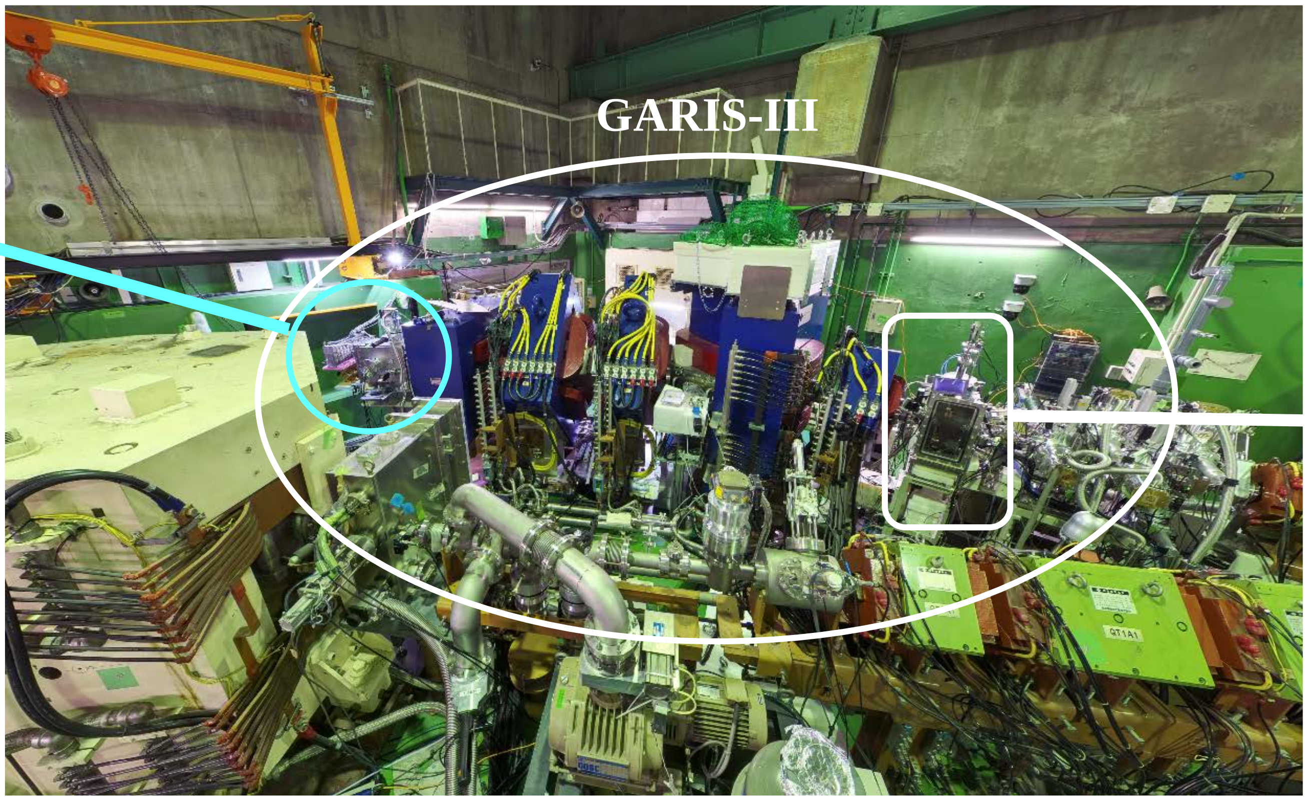


D. Kaji et al., NIM B 317, 311 (2013)

Photo of experimental room







Target chamber

SHE Project described in:

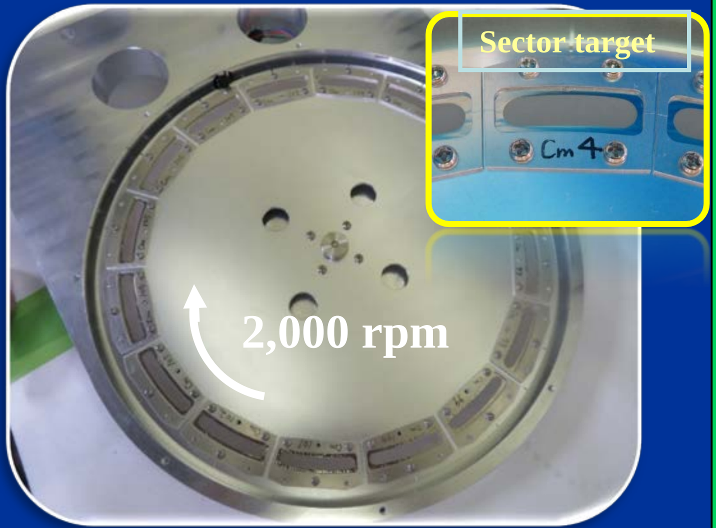
H. Sakai et al., Eur. Phys. J. A (2022) 58 :238

Target preparation

- $^{248}Cm_2O_3$ (~0.5 mg/cm^2)+ backing foil(1~3 μm)
- Fabricate by molecular plating method
- Backing material: C, Be, Ti, Mo…

- Severe envr. ~10 W /1pμA (ΔE=10 MeV) >500 °C, evaporate in a instant.
  → rotating wheel (15-30 cmϕ, 2,000 rpm)
- Testing various backing materials
- ^{248}Cm materials supplied by ORNL (DOE)

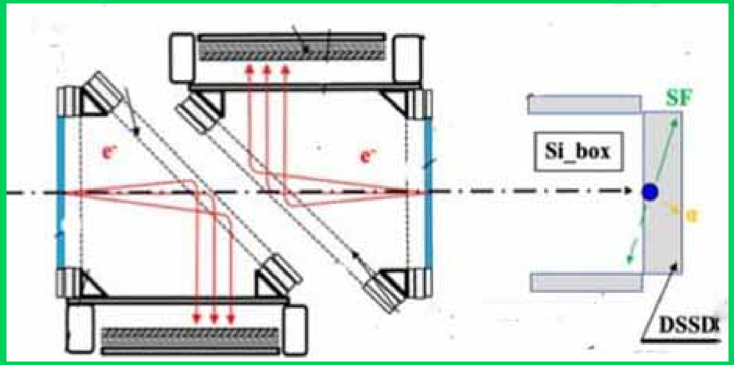

Cell for electrodeposition

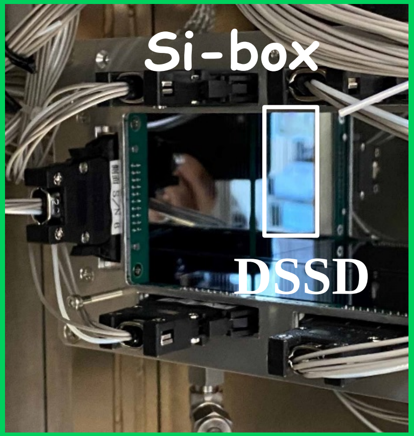


Accidental events

- Pixel of DSSD: 1×2 mm^2
- In-planted residue undergoes successive α decays (10ms-10s)

Focal plane detectors





- α particle-like accidental events
- Estimated as 6.9×10^{-4}/s at a beam intensity of 2 pμA for 2×4 mm^2 pixel size

Achieved a pretty quiet environment → reliable assignment

3. Quasi-elastic barrier distribution measurement

Choice of $E_{opt}(^{51}V)$

- SRILAC+GARIS-III started in 2018

- QE barrier distribution measurement by Masaomi Tanaka
  - Published in J. Phys. Soc. Jpn. 91 (2022) 084201

    "Probing Optimal Reaction Energy for Synthesis of Element 119 from 51V+248Cm Reaction with Quasielastic Barrier Distribution Measurement"

- Determine the optimal bombarding energy of $E_{opt}(^{51}V)$ beam

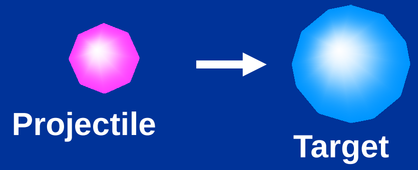
$$P_{ER} = P_{CAP}(E_{opt}) \times P_{CN} \times P_{surv}$$

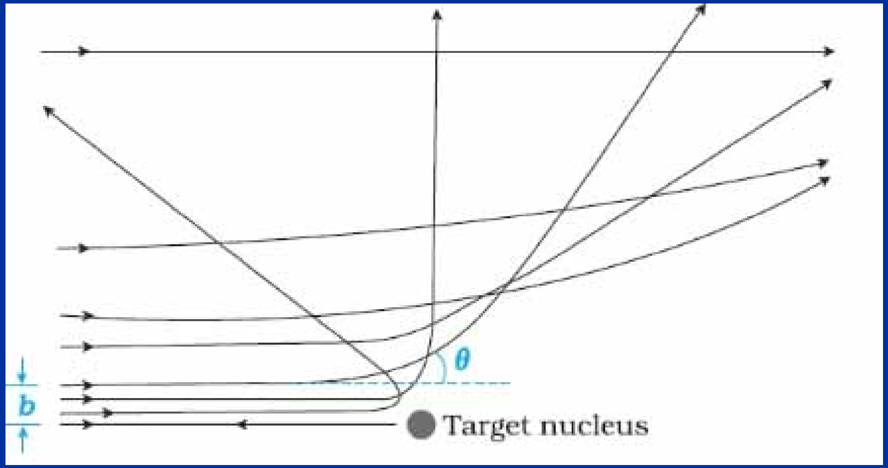
- $P_{CAP}(E_{opt})$: Coulomb barrier (B_0) penetration prob.

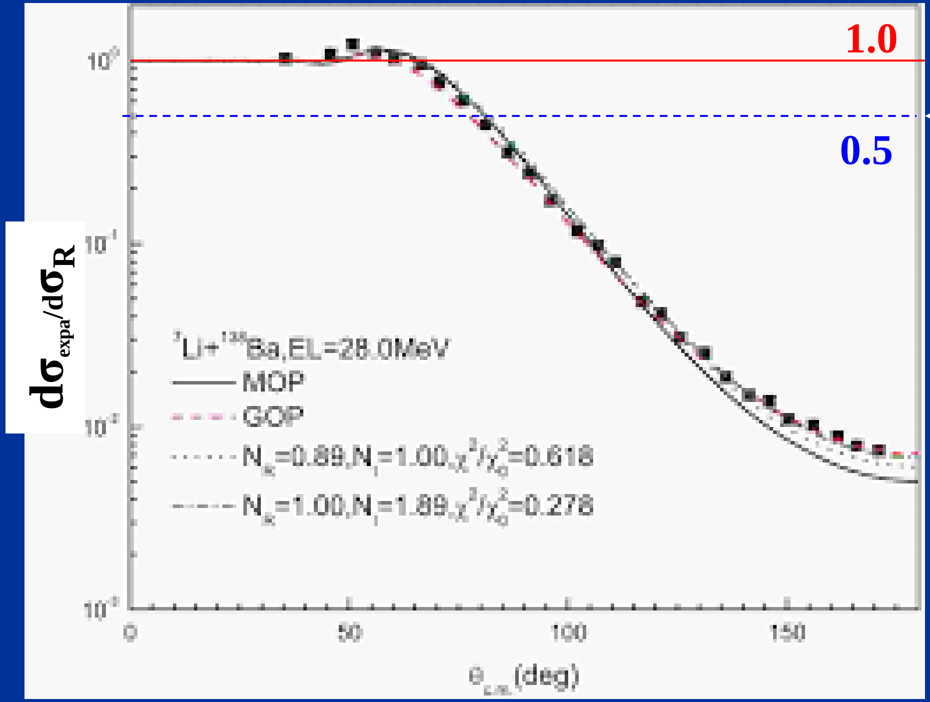
- B_0 may be inferred by (quasi-)elastic scat. measurement

Principle of QE barrier measurement

- Rutherford scattering
  - $\theta \leftrightarrow b$ (impact para.) : rotate detector for θ
  - Rutherford ratio $d\sigma_{exp}/d\sigma_R=1$ for pure Coulomb
  - $R_{min} \leq r_b + r_T \rightarrow$ nuclear force starts working
  - then, $d\sigma_{exp}/d\sigma_R \geq 1$ due to absorption (iW pot.)







Deduce Coulomb barrier height

- RIKEN:
  - E_{beam} change instead of θ change
  - But detector set at θ=180° (recoil of tgt)
  - Direct measure of QE barrier at $L \sim 0$.

(Most important component of ER production)

Experimental setup QE barrier measurement

Target

$^{248}Cm_2O_3$ (483 ug/cm^2) on Ti backing (1.31 mg/cm^2)

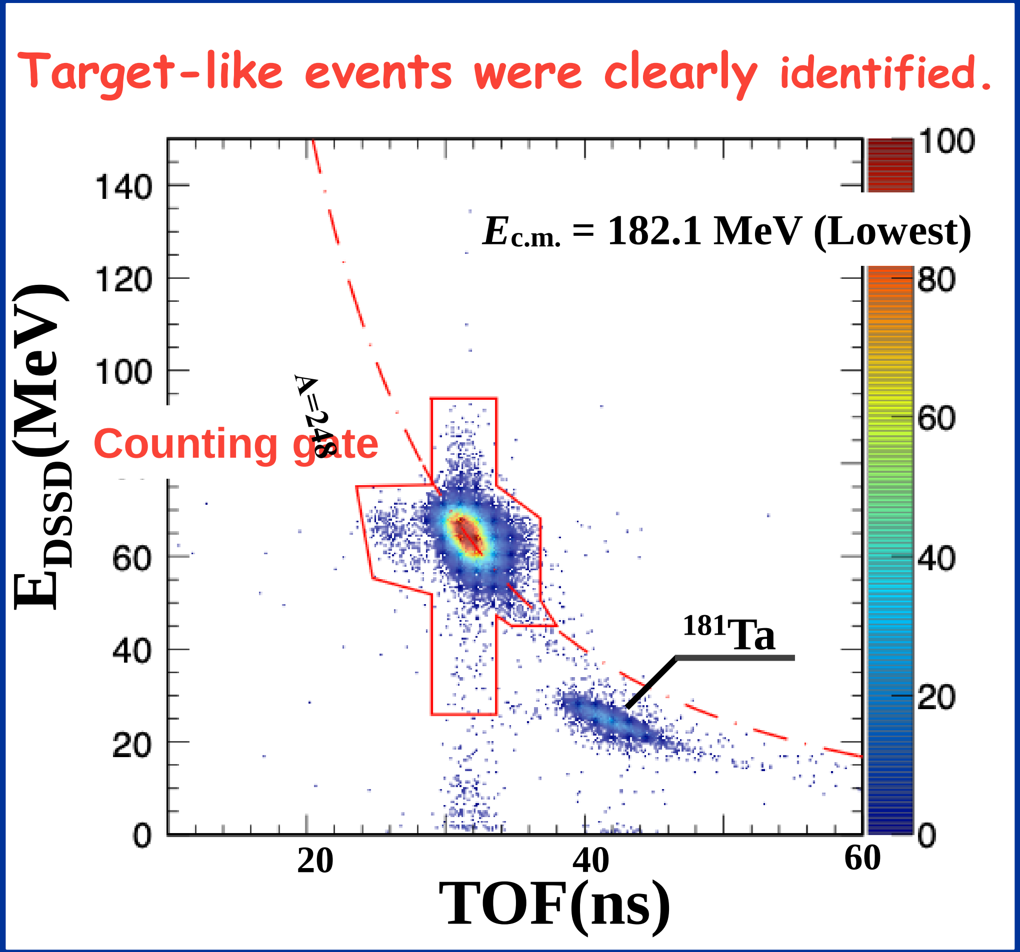
Gas-filled recoil ion separator GARIS-III

Detect target-like events recoiled at $\theta_{lab}=0°$ ($\theta_{cm}=180°$)
→ L~0 (s-wave, most important of ER production)

Reflection probability *R(E)*

$$R(E) = \frac{d\sigma_{QE}}{d\sigma_{Ruth}}$$

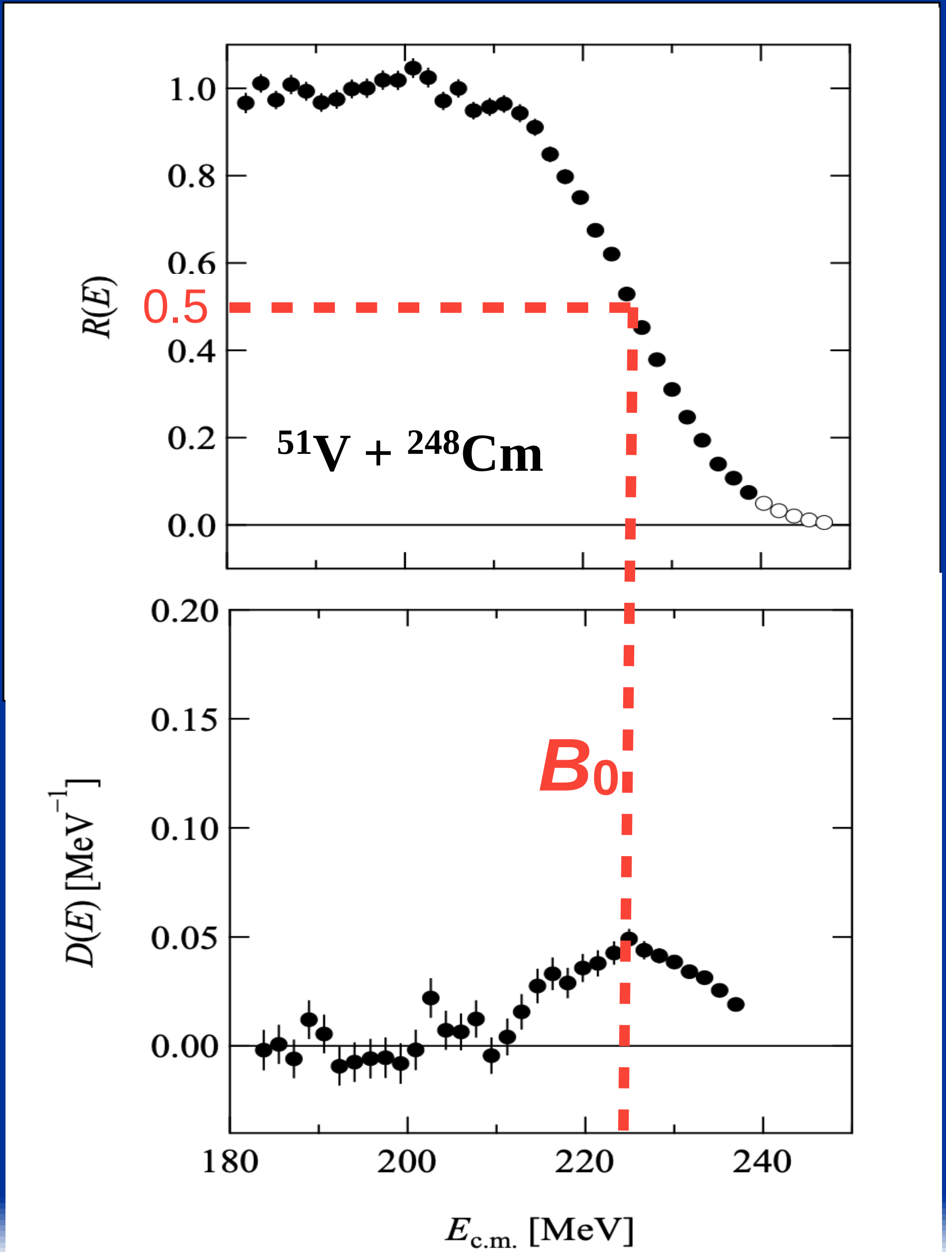
R(E) = 0.5 → σ (capture) = σ (reflection)



Result: Average Coulomb barrier height B_0 of $^{51}V+^{248}Cm$

$$R(E) = \frac{d\sigma_{QE}}{d\sigma_{Ruth}}$$

$$D(E) = -\frac{dR(E)}{dE}$$



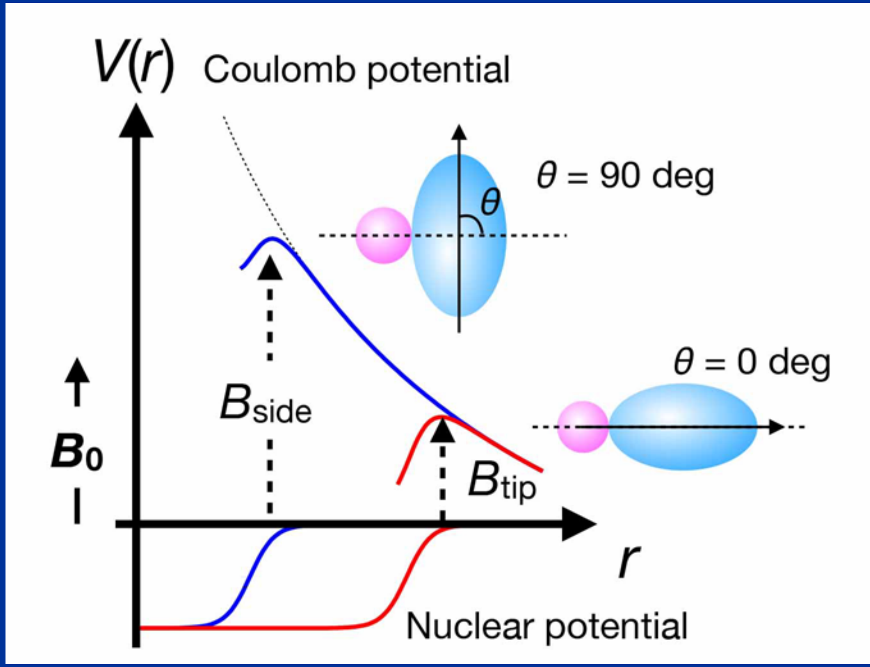
B_0 = 225.6 ± 0.2 MeV

- **Need to consider for:**
  - Side-collision (B_{side})
  - $\Delta E_{opt}(\sigma_{EV})$ ~ +1.8 MeV
- **Adopted ^{51}V beam energy**
  E_{opt}(adopted)= 234.8 MeV
- **Final beam energy**
  - Energy loss of target+backing

Side-collision

Side collision in hot-fusion reaction

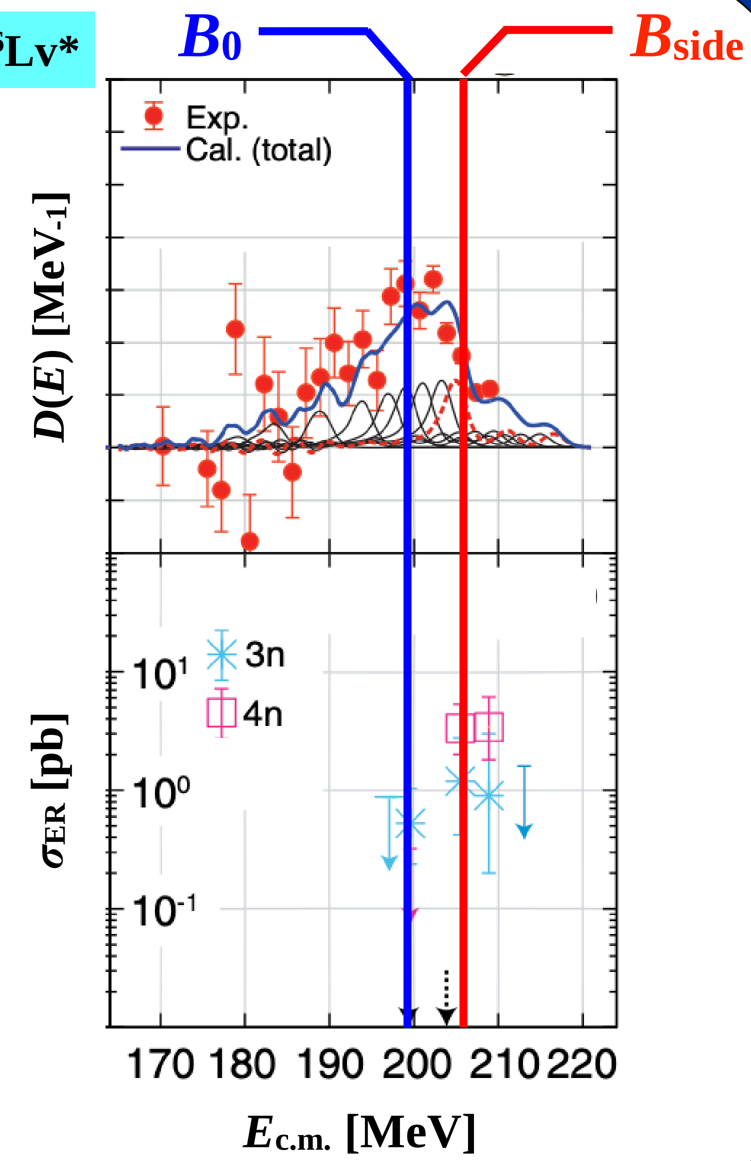
Actinide target (large prolate deformation)
→ Side collision is favorable for CN&ER formation.



B_{side} is estimated with CC calculation
→ Model dependent

T. Tanaka eta al., PRL 124, 052502 (2020).

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



$^{51}V + ^{248}Cm$

B_{side} = 233.0 MeV (B_0 + 7.4 MeV)

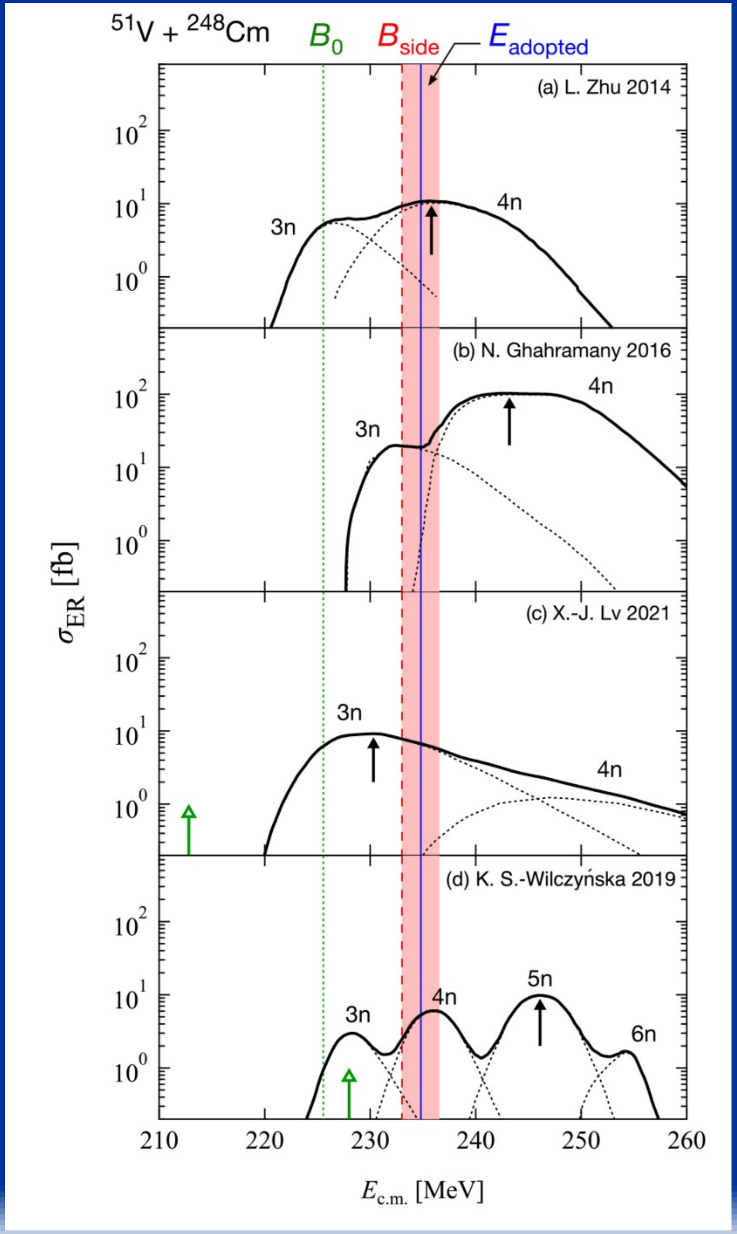
Comparison to theoretical models

L. Zhu et al.,
*PRC **89**, 024615 (2014).*

N. Ghahramany et al.,
*Eur. Phys. J. A **52**, 287 (2016).*

X.-J. Lv et al.,
*PRC **103**, 064616 (2021).*

K. Swiek-Wilczyńska et al.,
*PRC **99**, 054603 (2019).*



^{248}Cm(^{51}V,xn)$^{299-x}$119	Cross section (fb)	
channel x	$3n$	$4n$
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Manjunatha (2019)	4	
Siwek-Wilczynska (2019)	3	6
Aritomo (2020)	20 at E*=20 MeV	
Lv (2021)	9.8	1.3

E_{beam}(adopted)= 234.8 MeV

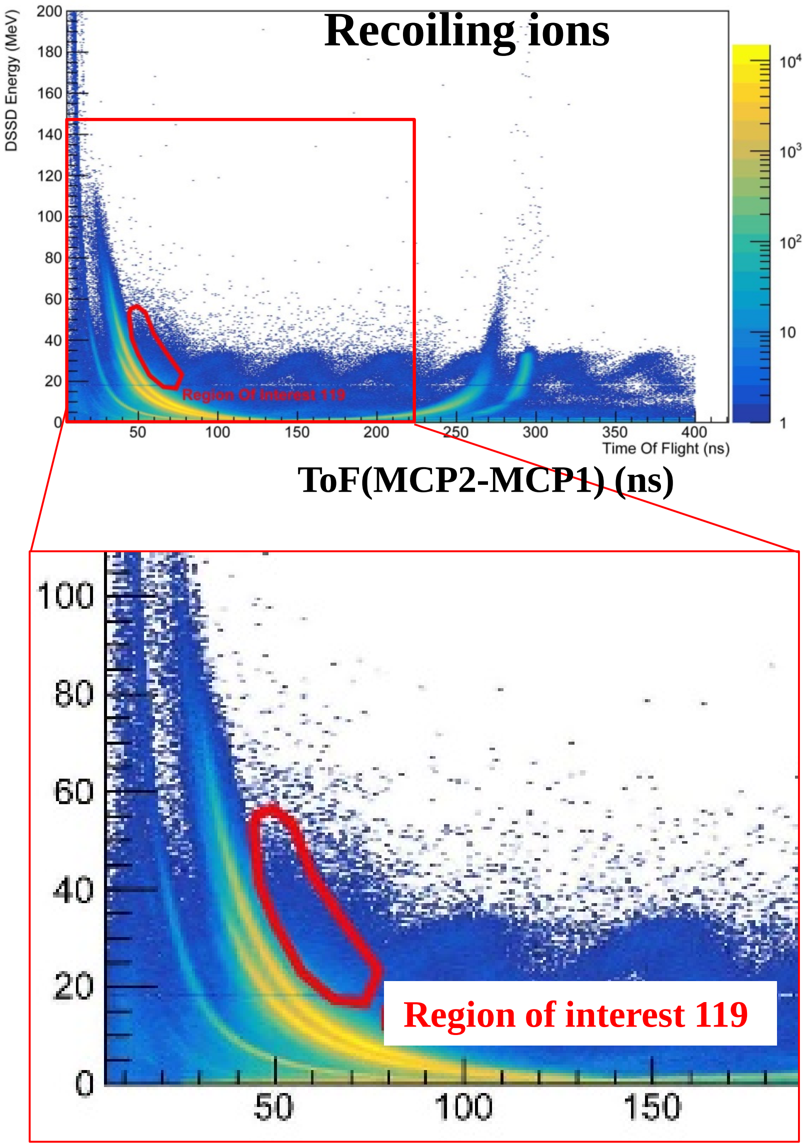
(E_{ex}[^{299}119*] = 40.3 MeV)

3. Present status

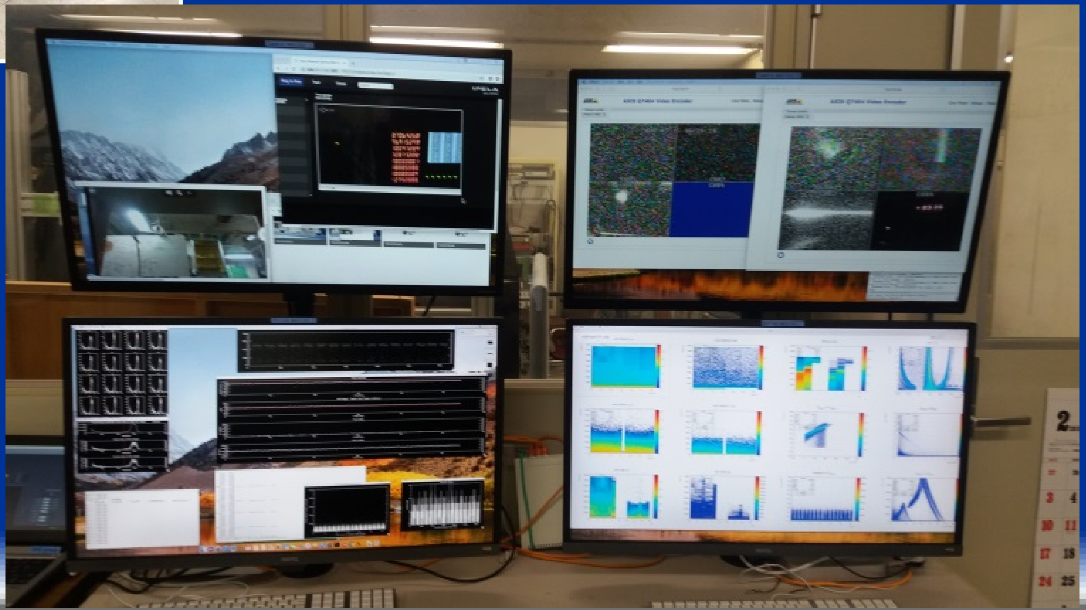
- $^{248}Cm(^{51}V, xn)\,^{299-x}119$ started in 2020
- Measurement is going on.

SRILAC can provide 3 pμA ^{51}V beam.
(Development of ^{248}Cm target+backing
that accepts high intensity beam is underway.)

Online spectra



Snapshots



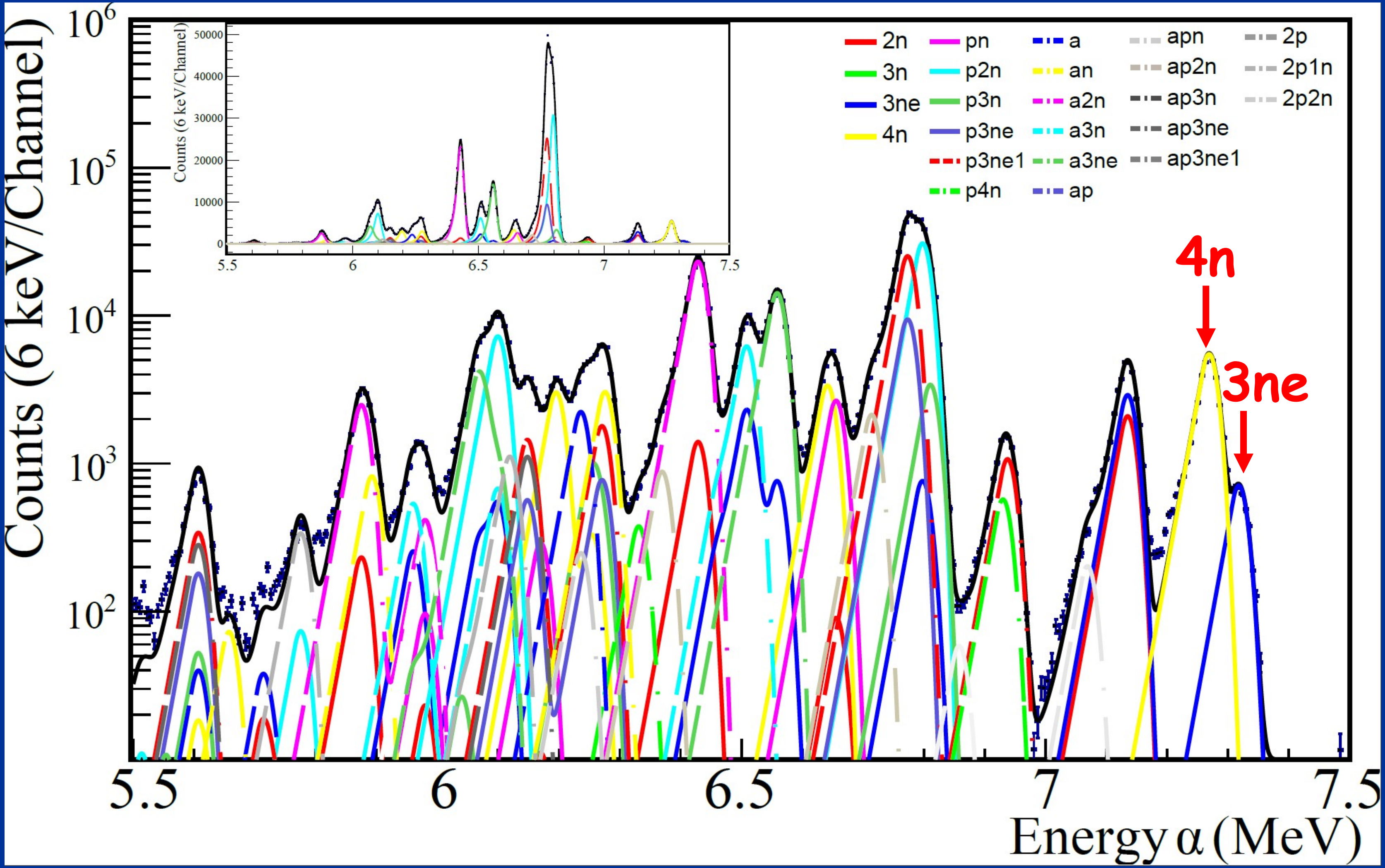
5. $^{51}V + ^{159}Tb \rightarrow ^{210}Ra^*$ (N = 122) reaction

- **Study on fusion reaction mechanisms**
  - **Deformation effect (tip and side collisions)**
  - **Using ^{159}Tb ($\beta \approx 0.3$, large X-sec)**

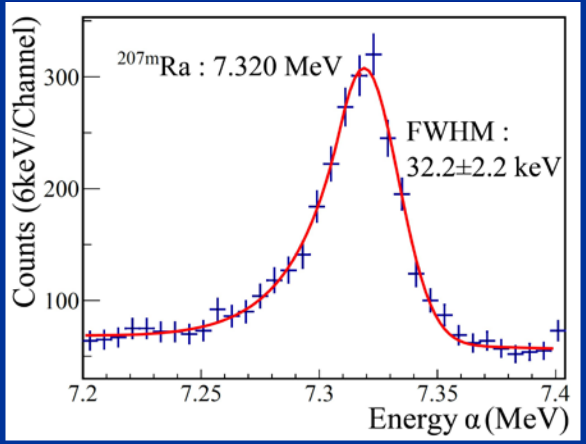
- **Excitation function on fusion residues measured**
  - **Barrier distribution**
  - **xn, pxn and αxn channels identified by characteristic E_α**

- **Detailed analysis: Pierre Brionnet (paper in preparation)**

$^{51}V+^{159}Tb$ fusion cross sections



- **Estimate production-rates based on the total α-spectrum**
  - Anti-correlation with ToF signal (TDC and QDC information) to define α-spectrum
  - No timing information applied
  - Fit of the overall spectrum based on the known branching ratios and α-energies



Results ($^{51}V + ^{159}Tb \rightarrow ^{210}Ra^*$ (N = 122))

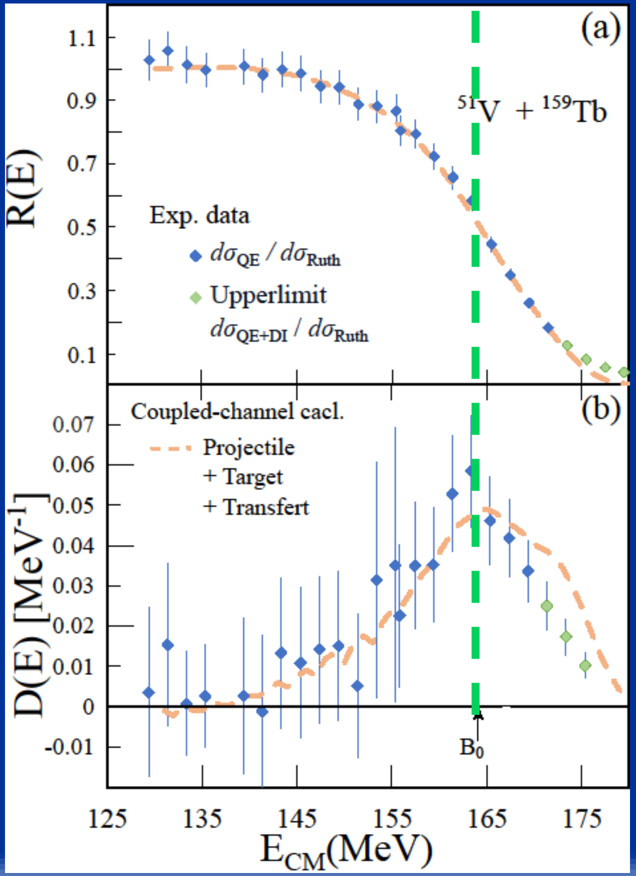
- **Barrier distribution**
  - B_0=164 MeV

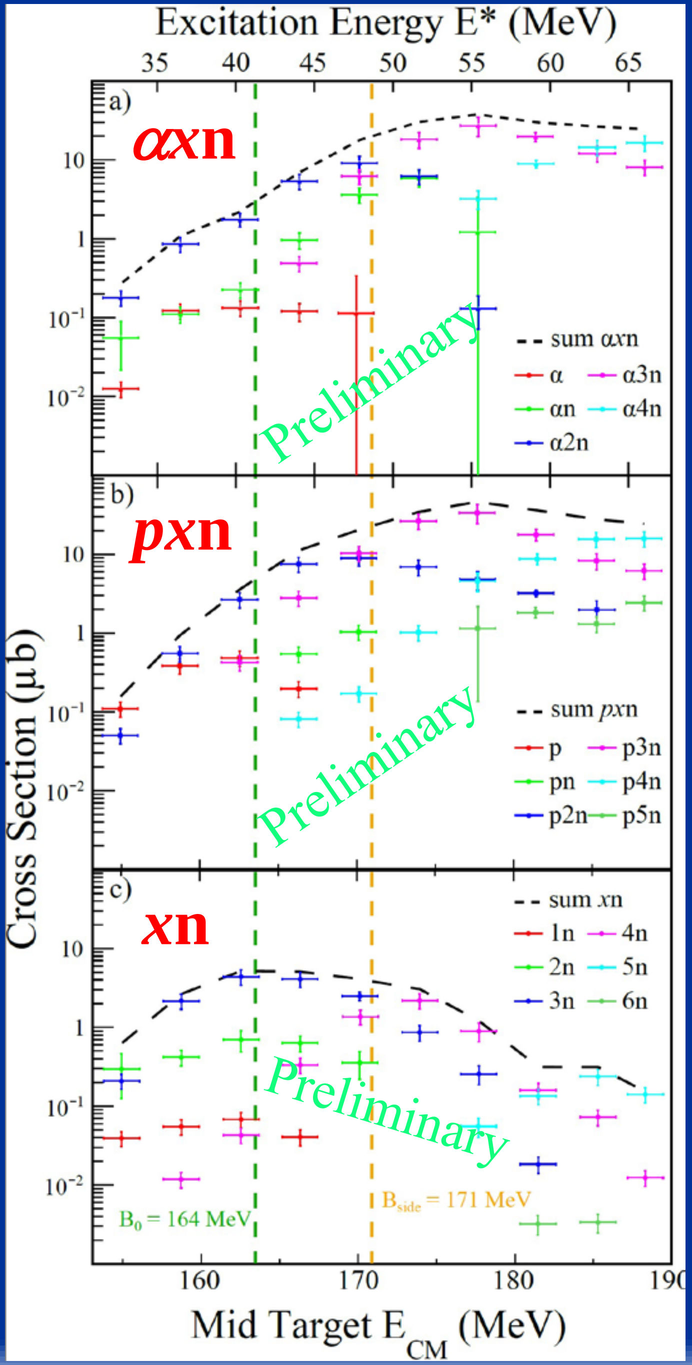
- **Excitation function for nx-, pxn-, αxn-channels**
  - Most comprehensive measurement ever
  - Seems NO side collision effect ???
  - Why ?
  - Maximum X-sec (±25% stat. error)

    σ(p3n): 33 μb at E* = 56 MeV

    σ(α3n) : 27 μb at E* = 56 MeV

    σ(3n): 4.4 at E* = 40 MeV
  - σ(p3n) and σ(α3n) >> σ(3n)





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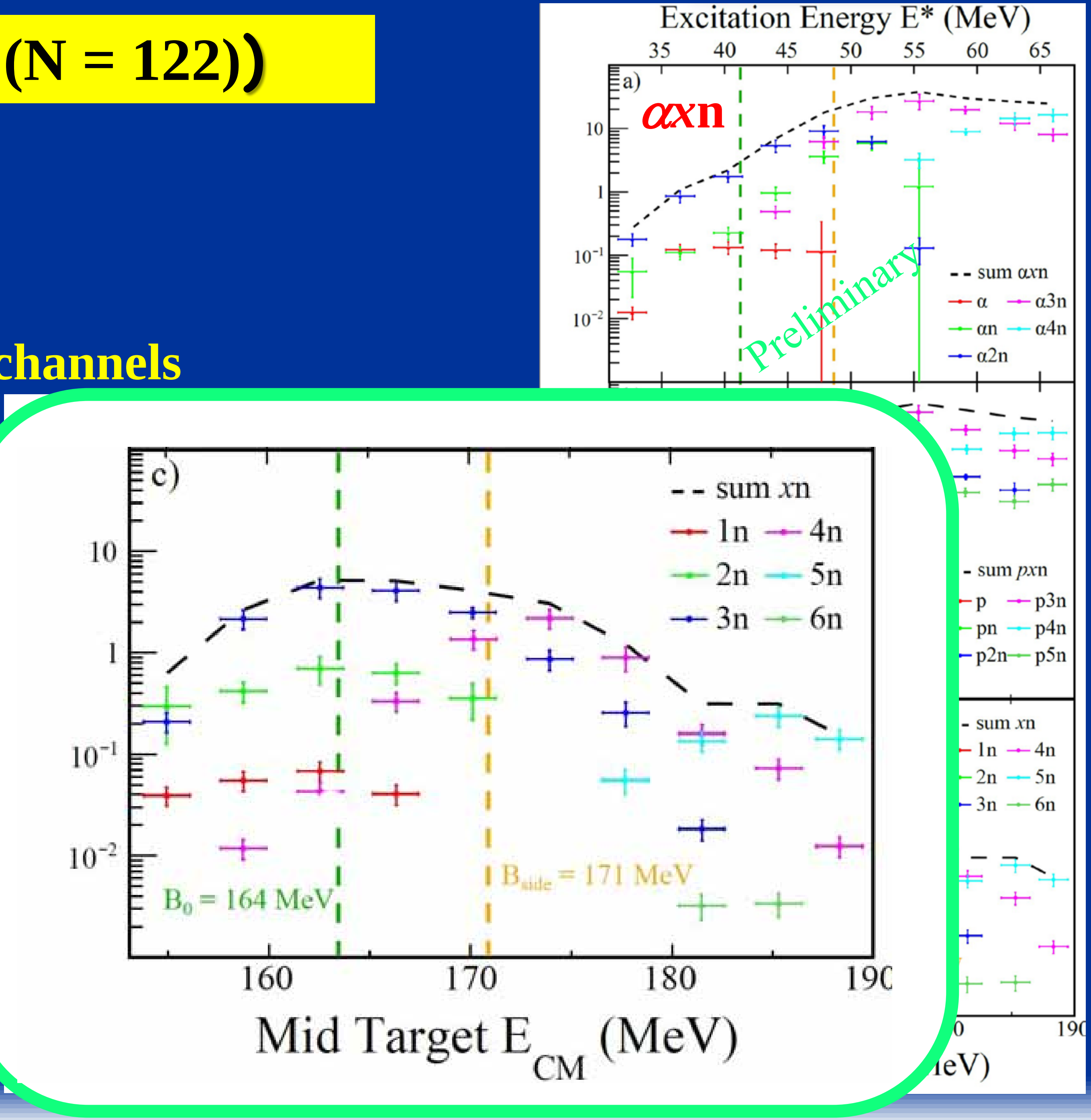


Can we understand xn-channel suppression ?

- **Decay widths (Compound nucleus)** $O(0^{th})$

$$\frac{\Gamma_p}{\Gamma_n} \approx exp\left(\frac{B_n - B_p - V_c^p)}{T}\right)$$

$$\frac{\Gamma_\alpha}{\Gamma_n} \approx exp\left(\frac{B_n + Q_\alpha - V_c^\alpha)}{T}\right)$$

$$\frac{\Gamma_n}{\Gamma_f} \propto exp\left(\frac{B_f - B_n}{T}\right)$$

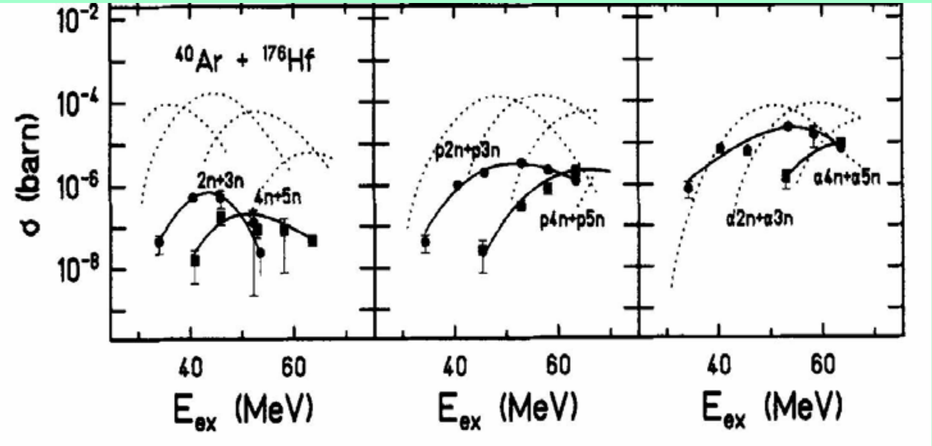
- **In case of ^{210}Ra***

$$\Gamma_n : \Gamma_p : \Gamma_\alpha : \Gamma_f = 1 : 0.04 : 0.04 : (0.1-1)$$

Γ_n dominate, Γ_f significant effect

- **xn suppression is general phenom.?**
  - **Maybe 'YES' for Lanthanoide trg**

Vermeulen: Z. Phys. A318(1984)157



- **0th order estimate: xn-channel dominates. On the contrary, it is suppressed.**
- **It is interesting how the xn-channel suppression can be explained by compound-decay model.**
- **Discussion with M. Kowal and T. Caps (Warsaw, Poland) is going on**

Parameters for decay-width estimation

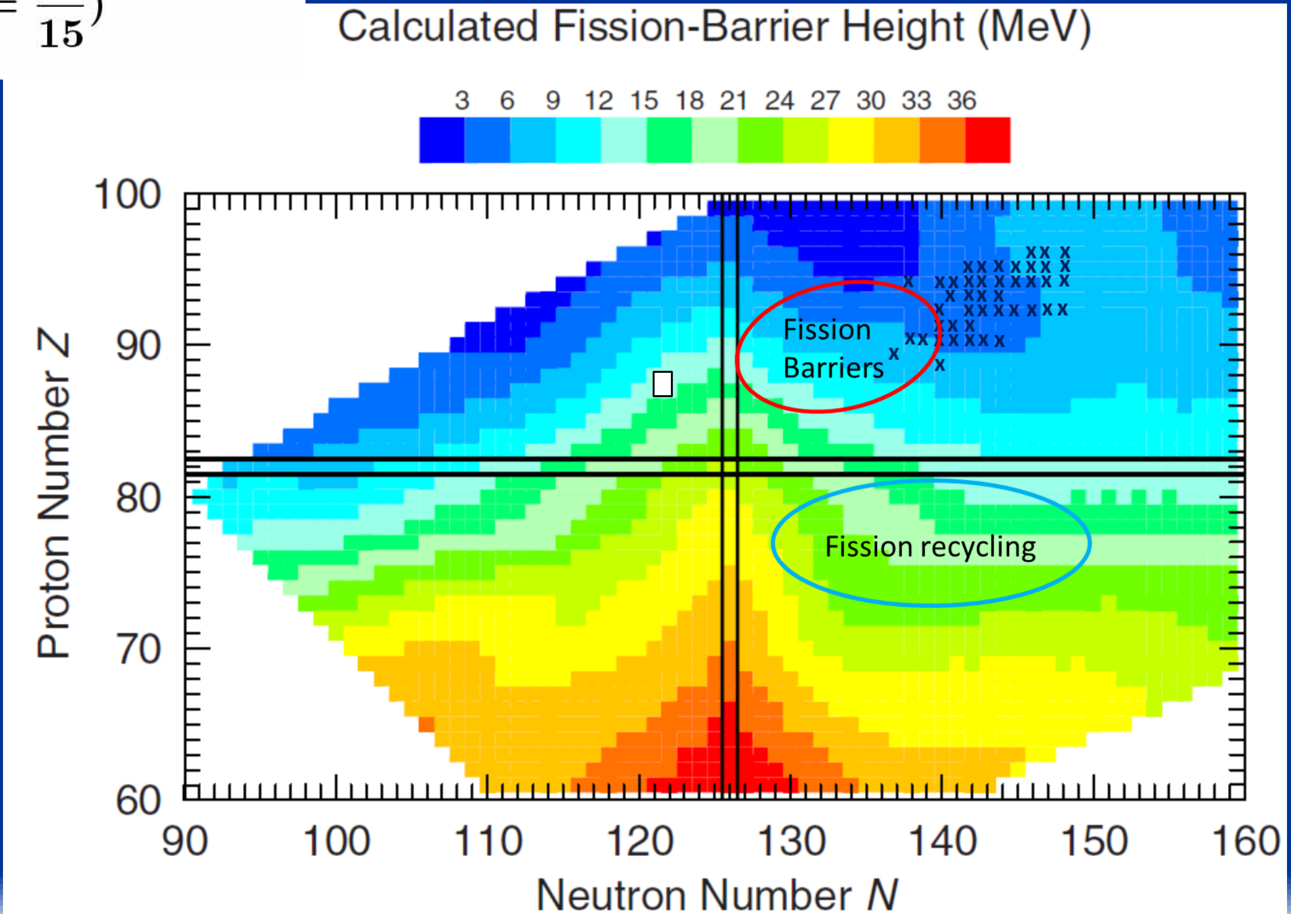
$$^{51}\mathrm{V}+^{159}\mathrm{Tb}\rightarrow^{210}\mathrm{Ra}^{*} \qquad E_{\mathrm{cm}}(^{51}\mathrm{V})=165\ \mathrm{MeV}$$

$$B_n = 9.5\ \mathrm{MeV} \qquad B_p = 3.1\ \mathrm{MeV} \qquad Q_\alpha = 7.2\ \mathrm{MeV}$$

$$B_f = 7.5(4\mathrm{n})-9.5(3\mathrm{n})\ \mathrm{MeV} \quad (\mathrm{Folden:J.Phys.420(2013)012007})$$

$$E^{*}_{\mathrm{ex}} = 42.9\ \mathrm{MeV}\rightarrow \mathrm{T}\sim 1.3\ \mathrm{MeV} \quad (E^{*}_{\mathrm{ex}}=a\mathrm{T}^2,\quad a=\frac{A}{15})$$

B. Back1, EPJ Web of Conf 232, 03002 (2020)



nSHE Research Group Collaboration

RIKEN, ORNL, UTK, Kyushu U., IPHC, Niigata U., RCNP, Saitama U., Tohoku U., JAEA, Yamagata U., IMP, ANU

(Managing board member's institutes)

May 31 2019
nSHE Research Group Collaboration meeting at ORNL/UTK Knoxville

Summary

- **SHE project (2016-2019) at RNC**
  - **SRILAC, SC-ECRIS, GARIS-III constructed and commissioned**
  - **Able to provide strong ^{51}V beams**

- **Average Coulomb barrier height B_0 of $^{51}V+^{248}Cm$**
  - **M. Tanaka et al., JPSJ, 91, 084201 (2022). B_0 = 225.6 MeV**

- **Search of Z=119 by $^{248}Cm(^{51}V, xn)\,^{299-x}119$ since 2020**
  - **Measurement is going on.**

- **Reaction mechanism study of $^{51}V+^{159}Tb$**
  - **No side collision effect ?**
  - **Suppression of xn channel ?**