

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  $\alpha$ -decay meas.,  $^{248}\text{Cm}$  target preparation**

## 3. $^{51}\text{V}+^{248}\text{Cm}$ : Quasi-elas. barrier distribution measurement

- **Choice of  $E_{\text{opt}}(^{51}\text{V})$**   
M. Tanaka et al., *JPSJ* 91 (2022) 084201

## 4. $^{248}\text{Cm} (^{51}\text{V}, xn)^{299-x}\text{119}$ reaction (x=3 and 4)

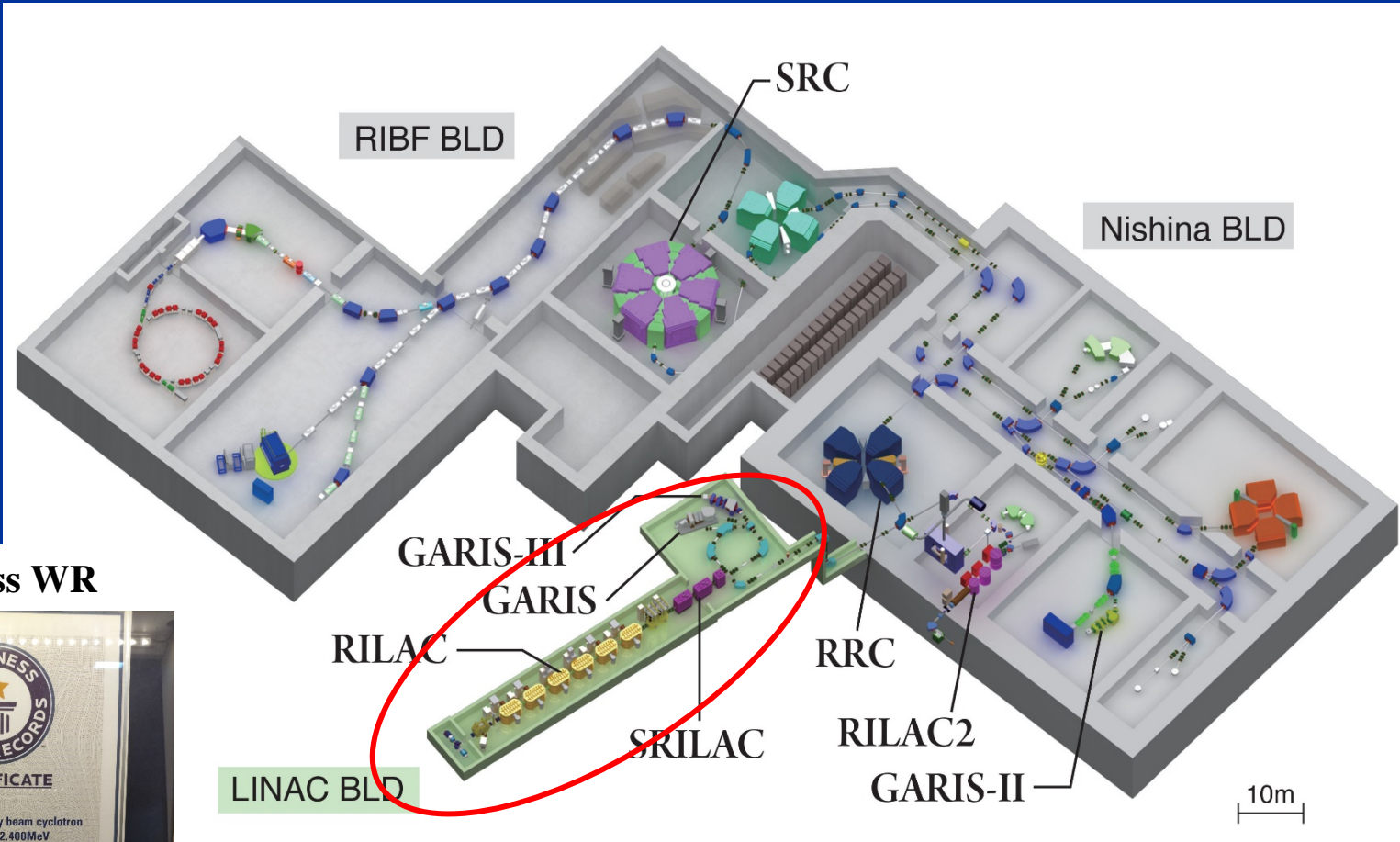
- **Present status**

## 5. $^{51}\text{V}+^{159}\text{Tb}$ 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:  $^{238}\text{U}$  345 MeV/u  
82.4 GeV ,  
~100pA

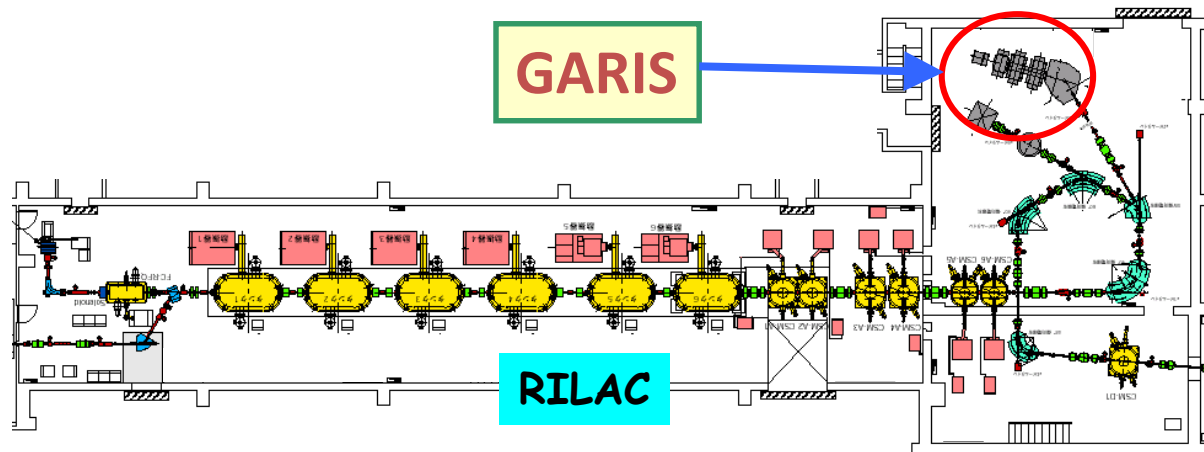
## Guinness WR



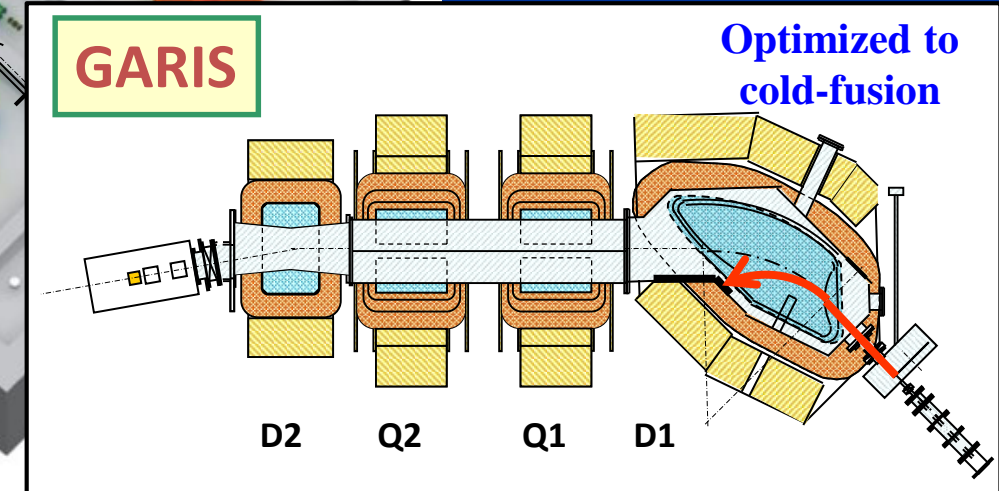
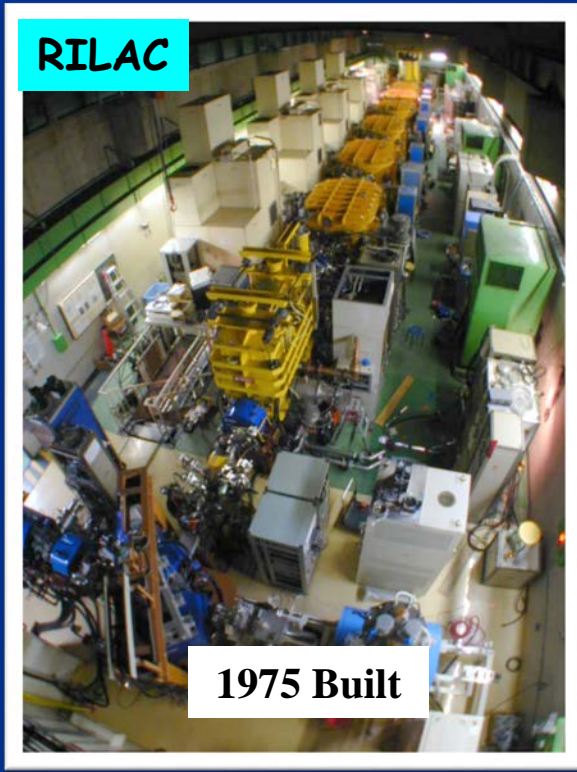
Highest beam energy cyclotron

# Discovery of nihonium

- $^{209}\text{Bi}(^{70}\text{Zn},n)^{278}113$  : 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  $\sim 22$  fb



Nishina BLD



# What is next?

IUPAC Periodic Table of the Elements

1 <b>H</b> hydrogen 1.0080 ± 0.0002																	2 <b>He</b> helium 4.0026 ± 0.0001
3 <b>Li</b> lithium 6.94 ± 0.06	4 <b>Be</b> beryllium 9.0122 ± 0.0001											5 <b>B</b> boron 10.81 ± 0.02	6 <b>C</b> carbon 12.011 ± 0.002	7 <b>N</b> nitrogen 14.007 ± 0.001	8 <b>O</b> oxygen 15.999 ± 0.001	9 <b>F</b> fluorine 18.998 ± 0.001	10 <b>Ne</b> neon 20.180 ± 0.001
11 <b>Na</b> sodium 22.990 ± 0.001	12 <b>Mg</b> magnesium 24.305 ± 0.002											13 <b>Al</b> aluminium 26.982 ± 0.001	14 <b>Si</b> silicon 28.085 ± 0.001	15 <b>P</b> phosphorus 30.974 ± 0.001	16 <b>S</b> sulfur 32.06 ± 0.02	17 <b>Cl</b> chlorine 35.45 ± 0.01	18 <b>Ar</b> argon 39.95 ± 0.16
19 <b>K</b> potassium 39.098 ± 0.001	20 <b>Ca</b> calcium 40.078 ± 0.004	21 <b>Sc</b> scandium 44.956 ± 0.001	22 <b>Ti</b> titanium 47.867 ± 0.001	23 <b>V</b> vanadium 50.942 ± 0.001	24 <b>Cr</b> chromium 51.996 ± 0.001	25 <b>Mn</b> manganese 54.938 ± 0.001	26 <b>Fe</b> iron 55.845 ± 0.002	27 <b>Co</b> cobalt 58.933 ± 0.001	28 <b>Ni</b> nickel 58.693 ± 0.001	29 <b>Cu</b> copper 63.546 ± 0.003	30 <b>Zn</b> zinc 65.38 ± 0.02	31 <b>Ga</b> gallium 69.723 ± 0.001	32 <b>Ge</b> germanium 72.630 ± 0.008	33 <b>As</b> arsenic 74.922 ± 0.001	34 <b>Se</b> selenium 78.971 ± 0.008	35 <b>Br</b> bromine 79.904 ± 0.003	36 <b>Kr</b> krypton 83.798 ± 0.002
37 <b>Rb</b> rubidium 85.468 ± 0.001	38 <b>Sr</b> strontium 87.62 ± 0.01	39 <b>Y</b> yttrium 88.906 ± 0.001	40 <b>Zr</b> zirconium 91.224 ± 0.002	41 <b>Nb</b> niobium 92.906 ± 0.001	42 <b>Mo</b> molybdenum 95.95 ± 0.01	43 <b>Tc</b> technetium [97]	44 <b>Ru</b> ruthenium 101.07 ± 0.02	45 <b>Rh</b> rhodium 102.91 ± 0.01	46 <b>Pd</b> palladium 106.42 ± 0.01	47 <b>Ag</b> silver 107.87 ± 0.01	48 <b>Cd</b> cadmium 112.41 ± 0.01	49 <b>In</b> indium 114.82 ± 0.01	50 <b>Sn</b> tin 118.71 ± 0.01	51 <b>Sb</b> antimony 121.76 ± 0.01	52 <b>Te</b> tellurium 127.60 ± 0.03	53 <b>I</b> iodine 126.90 ± 0.01	54 <b>Xe</b> xenon 131.29 ± 0.01
55 <b>Cs</b> caesium 132.91 ± 0.01	56 <b>Ba</b> barium 137.33 ± 0.01	57-71 lanthanoids	72 <b>Hf</b> hafnium 178.49 ± 0.01	73 <b>Ta</b> tantalum 180.95 ± 0.01	74 <b>W</b> tungsten 183.84 ± 0.01	75 <b>Re</b> rhenium 186.21 ± 0.01	76 <b>Os</b> osmium 190.23 ± 0.03	77 <b>Ir</b> iridium 192.22 ± 0.01	78 <b>Pt</b> platinum 195.08 ± 0.02	79 <b>Au</b> gold 196.97 ± 0.01	80 <b>Hg</b> mercury 200.59 ± 0.01	81 <b>Tl</b> thallium 204.38 ± 0.01	82 <b>Pb</b> lead 207.2 ± 1.1	83 <b>Bi</b> bismuth 208.98 ± 0.01	84 <b>Po</b> polonium [209]	85 <b>At</b> astatine [210]	86 <b>Rn</b> radon [222]
87 <b>Fr</b> francium [223]	88 <b>Ra</b> radium [226]	89-103 actinoids	104 <b>Rf</b> rutherfordium [261]	105 <b>Db</b> dubnium [268]	106 <b>Sg</b> seaborgium [269]	107 <b>Bh</b> bohrium [270]	108 <b>Hs</b> hassium [289]	109 <b>Mt</b> meitnerium [277]	110 <b>Ds</b> darmstadtium [281]	111 <b>Rg</b> roentgenium [282]	112 <b>Cn</b> copernicium [285]	113 <b>Nh</b> nihonium [286]	114 <b>Fl</b> flerovium [290]	115 <b>Mc</b> moscovium [290]	116 <b>Lv</b> livermorium [293]	117 <b>Ts</b> tennessine [294]	118 <b>Og</b> oganesson [294]

119



INTERNATIONAL UNION OF  
PURE AND APPLIED CHEMISTRY

57 <b>La</b> lanthanum 138.91 ± 0.01	58 <b>Ce</b> cerium 140.12 ± 0.01	59 <b>Pr</b> praseodymium 140.91 ± 0.01	60 <b>Nd</b> neodymium 144.24 ± 0.01	61 <b>Pm</b> promethium [145]	62 <b>Sm</b> samarium 150.36 ± 0.02	63 <b>Eu</b> europium 151.96 ± 0.01	64 <b>Gd</b> gadolinium 157.25 ± 0.03	65 <b>Tb</b> terbium 158.93 ± 0.01	66 <b>Dy</b> dysprosium 162.50 ± 0.01	67 <b>Ho</b> holmium 164.93 ± 0.01	68 <b>Er</b> erbium 167.26 ± 0.01	69 <b>Tm</b> thulium 168.93 ± 0.01	70 <b>Yb</b> ytterbium 173.05 ± 0.02	71 <b>Lu</b> lutetium 174.97 ± 0.01
89 <b>Ac</b> actinium [227]	90 <b>Th</b> thorium 232.04 ± 0.01	91 <b>Pa</b> protactinium 231.04 ± 0.01	92 <b>U</b> uranium 238.03 ± 0.01	93 <b>Np</b> neptunium [237]	94 <b>Pu</b> plutonium [244]	95 <b>Am</b> americium [243]	96 <b>Cm</b> curium [247]	97 <b>Bk</b> berkelium [247]	98 <b>Cf</b> californium [251]	99 <b>Es</b> einsteinium [252]	100 <b>Fm</b> fermium [257]	101 <b>Md</b> mendelevium [258]	102 <b>No</b> nobelium [259]	103 <b>Lr</b> lawrencium [262]

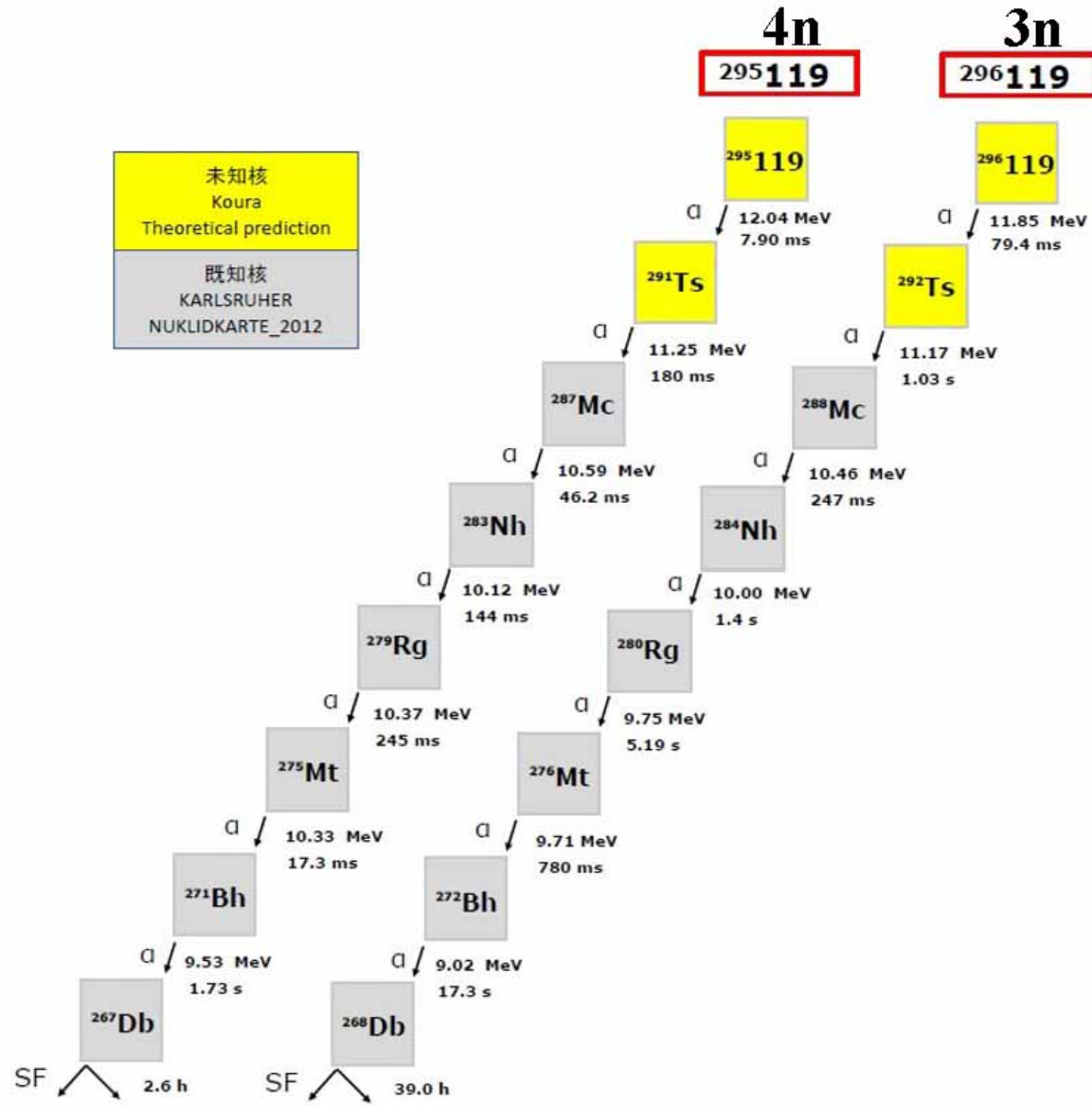
For notes and updates to this table, see [www.iupac.org](http://www.iupac.org). This version is dated 4 May 2022.  
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## 2. SHE Project (2016)

- **Goal: Discover new SHE Z=119**
- $^{248}\text{Cm}(^{51}\text{V}, xn)^{299-x}119$  by **hot** fusion reaction
- **Expected cross section  $\leq 10$  fb ( $10^{-38}$  cm<sup>2</sup>)**  
(heuristic guess!)

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

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



➤ 7 generations  
(successive  $\alpha$  emissions)

➤ 5- $\alpha$ -decay chain known

# SHE Project (2016)

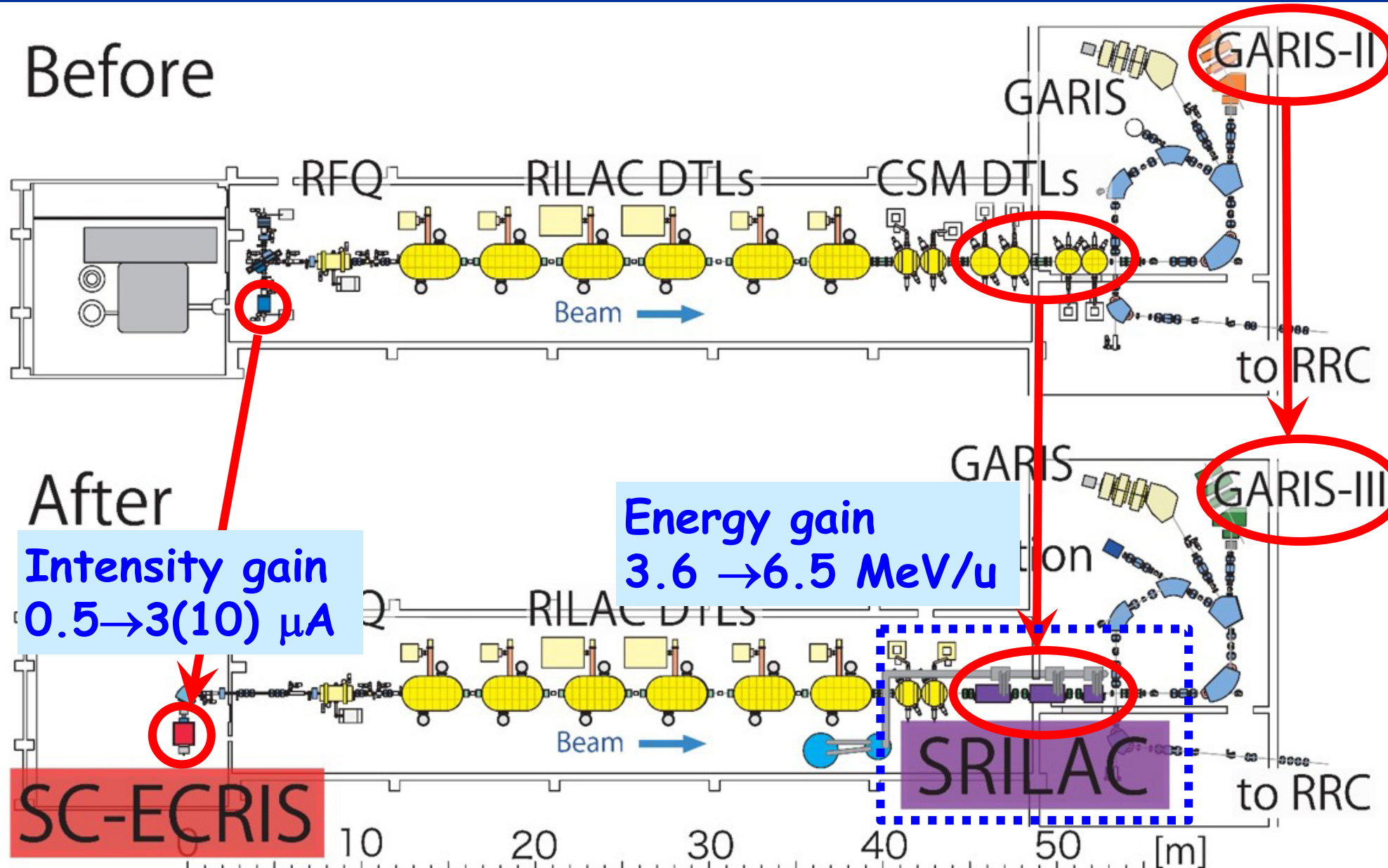
- **Goal: Synthesis new SHE Z=119**
- $^{248}\text{Cm}(^{51}\text{V}, xn)^{299-x}119$  by **hot** fusion reaction
- Expected cross section  $\leq 10$  fb ( $10^{-38}$  cm<sup>2</sup>)
- **SRILAC**: ~6 MeV/u  $^{51}\text{V}$  beam (**RILAC 5.5 MeV/u**)
- **SC-ECRIS**: High-intensity beam
- $^{248}\text{Cm}_2\text{O}_3$  material: **Collaboration with ORNL**
- **GARIS-III**: Spectrometer + Focal plane det.  
Electronics etc.

$^{248}\text{Cm}(^{51}\text{V}, xn)^{299-x}119$ 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

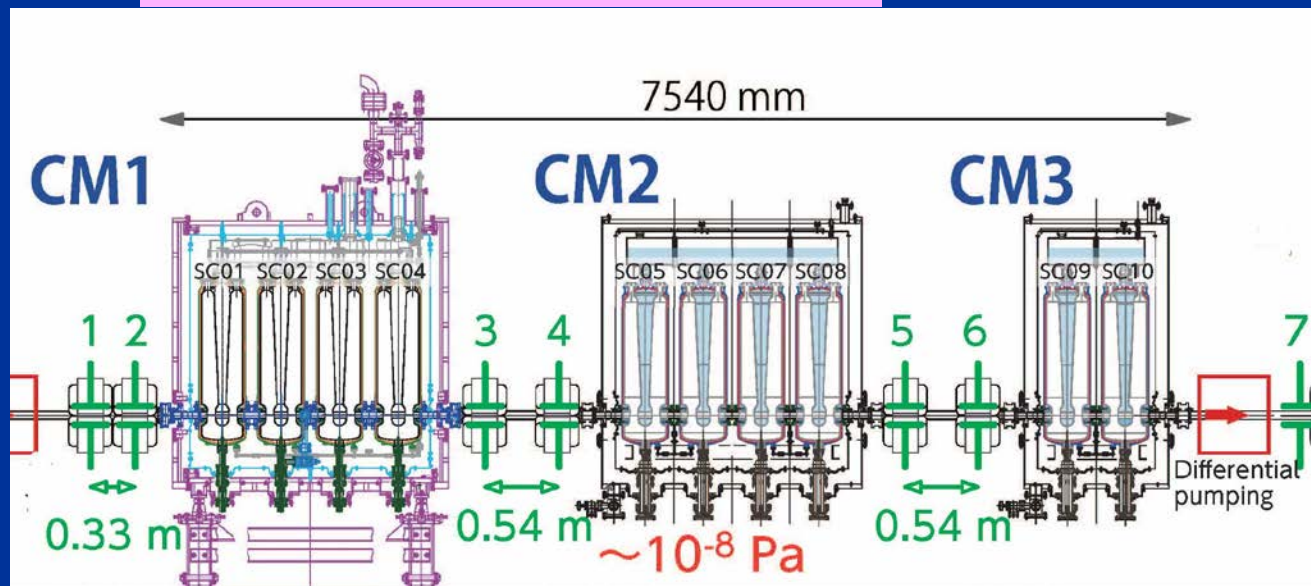
Courtesy to : **N. Sakamoto** for **SRILAC**  
: **Y. Higurashi, T. Nagatomo** for **SC-ECRIS**  
: **K. Morimoto, P. Brionnet** for **GARIS-III**  
: **H. Haba** for **Target**



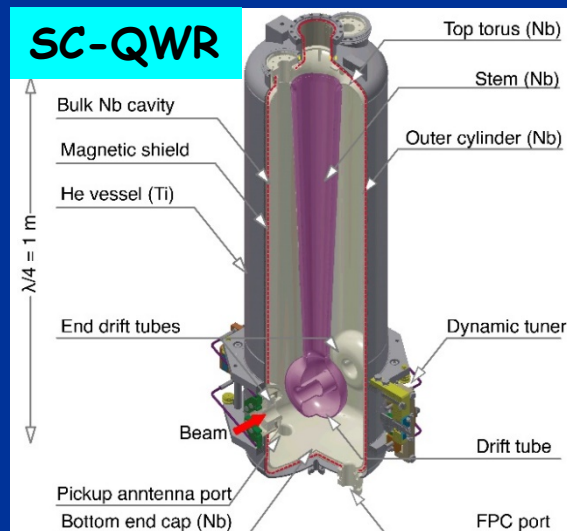
# SRILAC, SC-ECRIS and GARIS-III



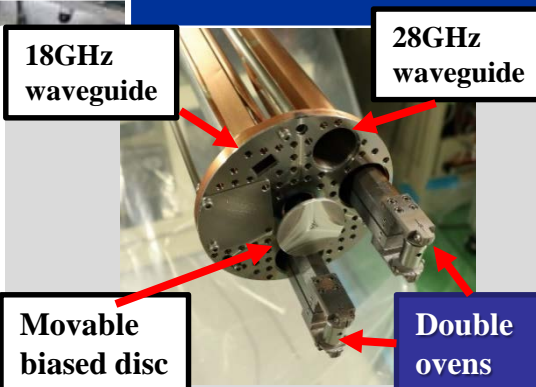
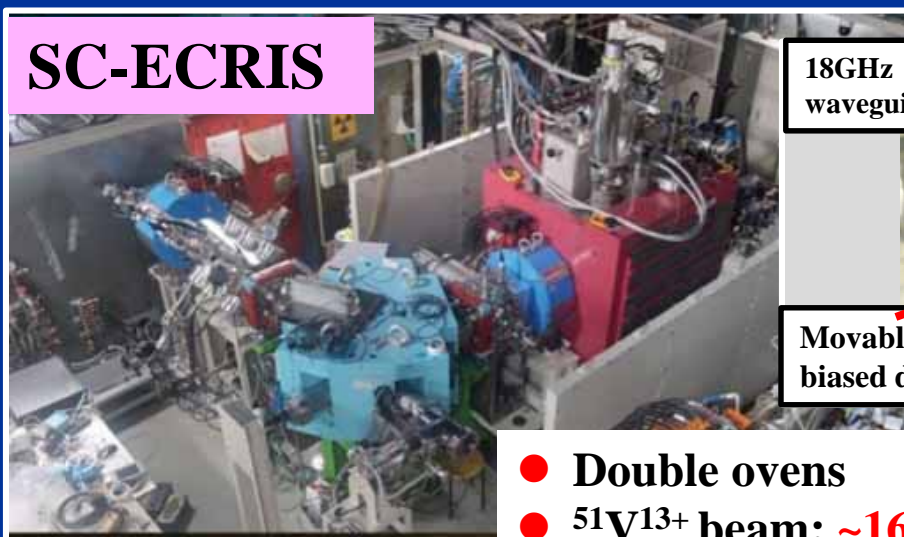
# SRILAC (10 SC-QWRs)



## SRILAC cryomodules

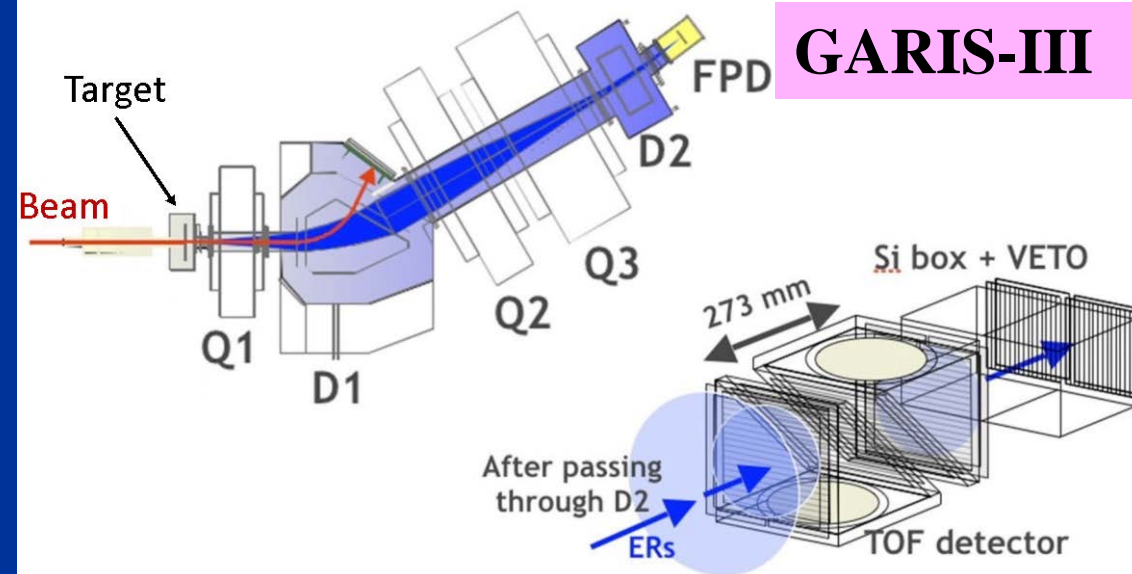


## SC-ECRIS



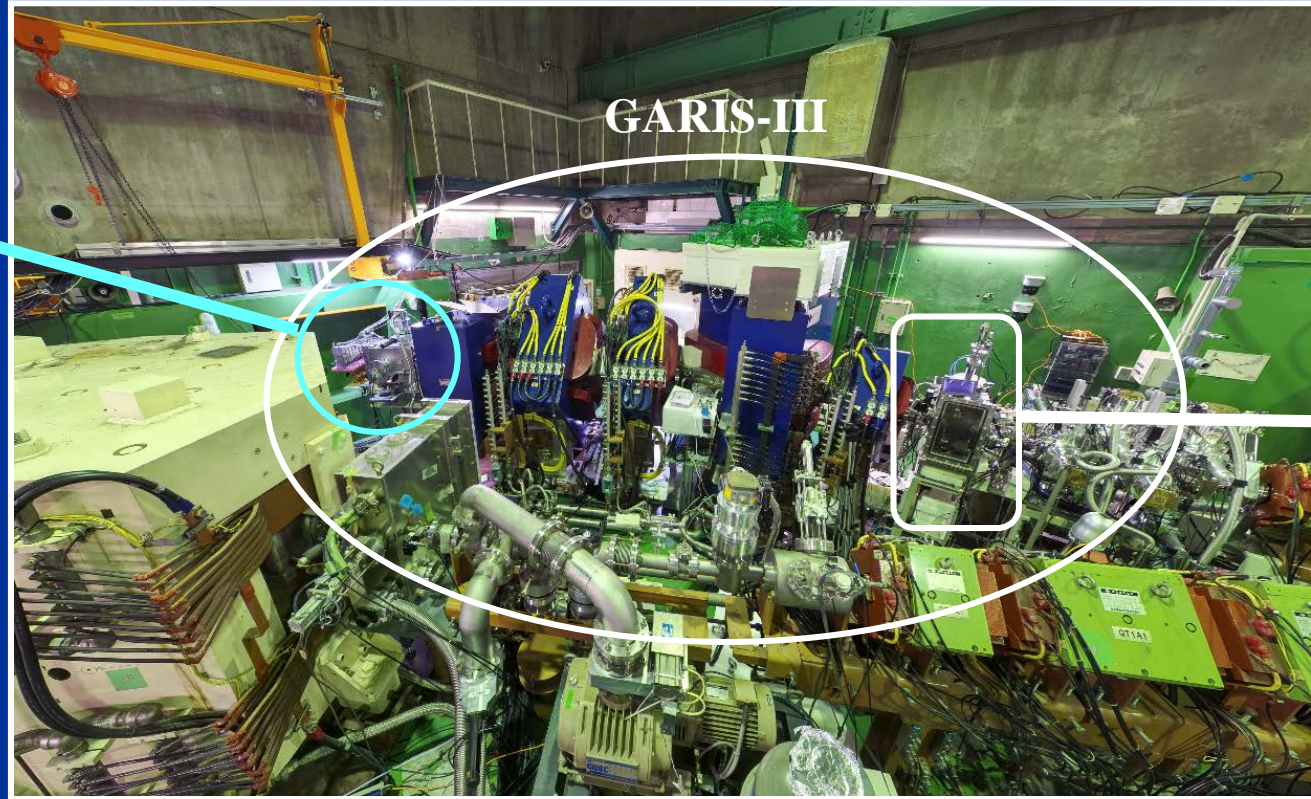
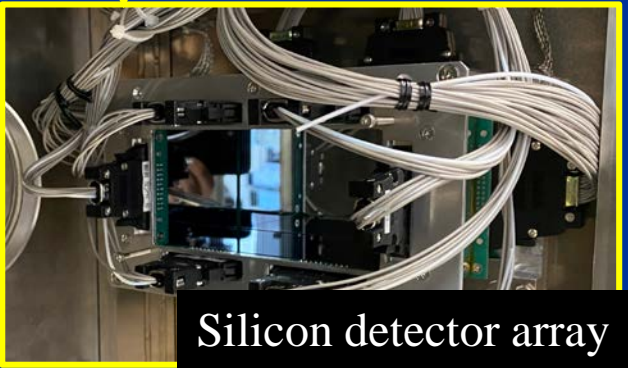
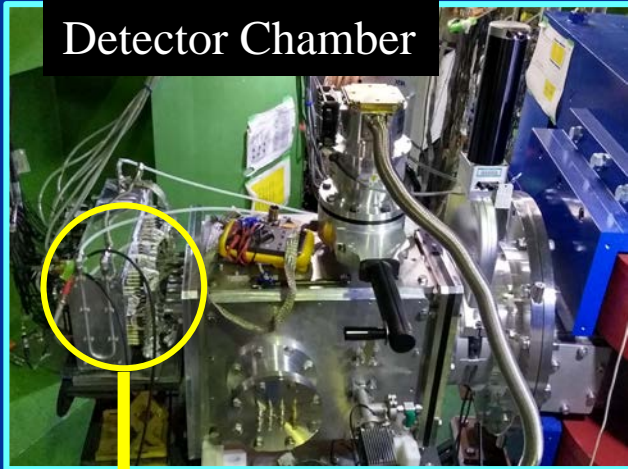
- Double ovens
- $^{51}\text{V}^{13+}$  beam:  $\sim 160 \mu\text{A}$  ( $\sim 12 \text{ p}\mu\text{A}$ )
- Continuous running  $\sim 30$  days

## GARIS-III



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

# Photo of experimental room



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

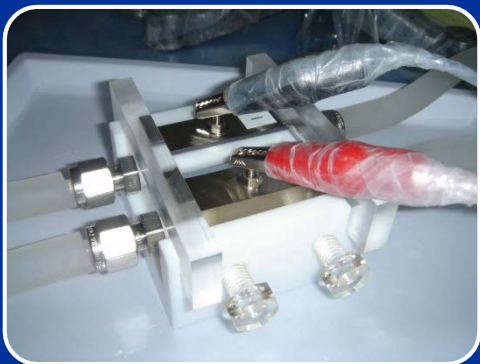
# Target preparation

- $^{248}\text{Cm}_2\text{O}_3$  ( $\sim 0.5 \text{ mg/cm}^2$ ) + backing foil ( $1\sim 3 \mu\text{m}$ )
- Fabricate by molecular plating method
- Backing material: C, Be, Ti, Mo...

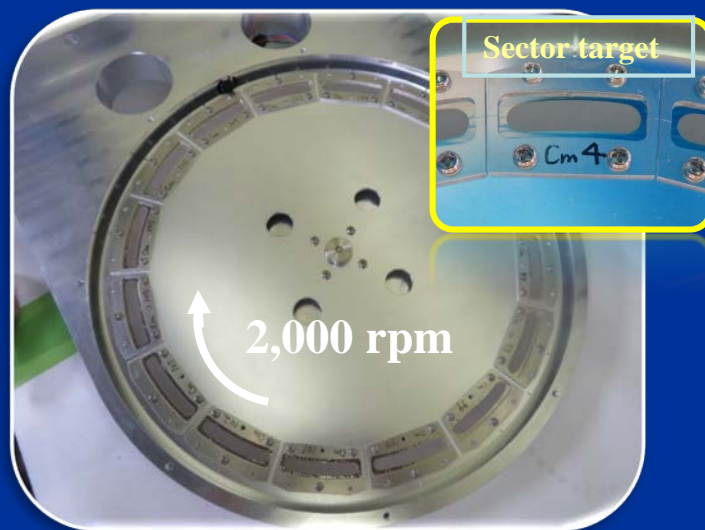
- Severe envr.  $\sim 10 \text{ W / } 1\text{p}\mu\text{A}$  ( $\Delta E = 10 \text{ MeV}$ )  
 $> 500 \text{ }^\circ\text{C}$ , evaporate in a instant.

→ rotating wheel ( $15\text{-}30 \text{ cm}\phi$ ,  $2,000 \text{ rpm}$ )

- Testing various backing materials
- $^{248}\text{Cm}$  materials supplied by ORNL (DOE)



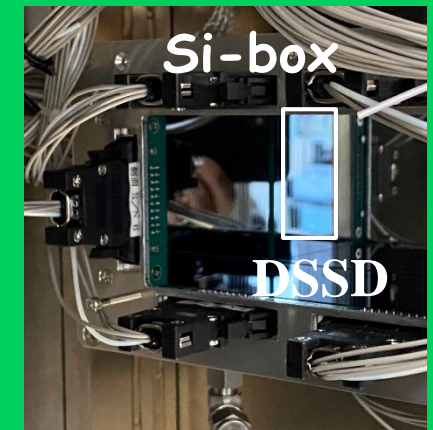
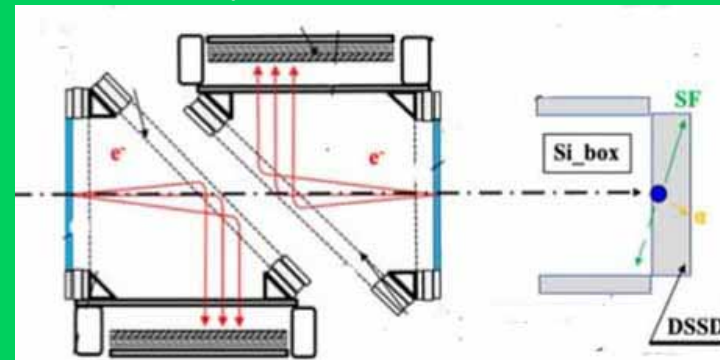
Cell for electrodeposition



# Accidental events

- Pixel of DSSD:  $1 \times 2 \text{ mm}^2$
- In-planted residue undergoes successive  $\alpha$  decays ( $10\text{ms}\text{-}10\text{s}$ )

## Focal plane detectors



- $\alpha$  particle-like accidental events
- Estimated as  $6.9 \times 10^{-4}/\text{s}$  at a beam intensity of  $2 \text{ p}\mu\text{A}$  for  $2 \times 4 \text{ mm}^2$  pixel size

Achieved a pretty quiet environment  
→ reliable assignment

### 3. Quasi-elastic barrier distribution measurement

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

- 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  $^{51}\text{V}+^{248}\text{Cm}$  Reaction with Quasielastic Barrier Distribution Measurement”
- Determine the optimal bombarding energy of  $E_{\text{opt}}(^{51}\text{V})$  beam
$$P_{\text{ER}} = P_{\text{CAP}}(E_{\text{opt}}) \times P_{\text{CN}} \times P_{\text{surv}}$$
- $P_{\text{CAP}}(E_{\text{opt}})$  : Coulomb barrier ( $B_0$ ) penetration prob.
- $B_0$  may be inferred by (quasi-)elastic scat. measurement

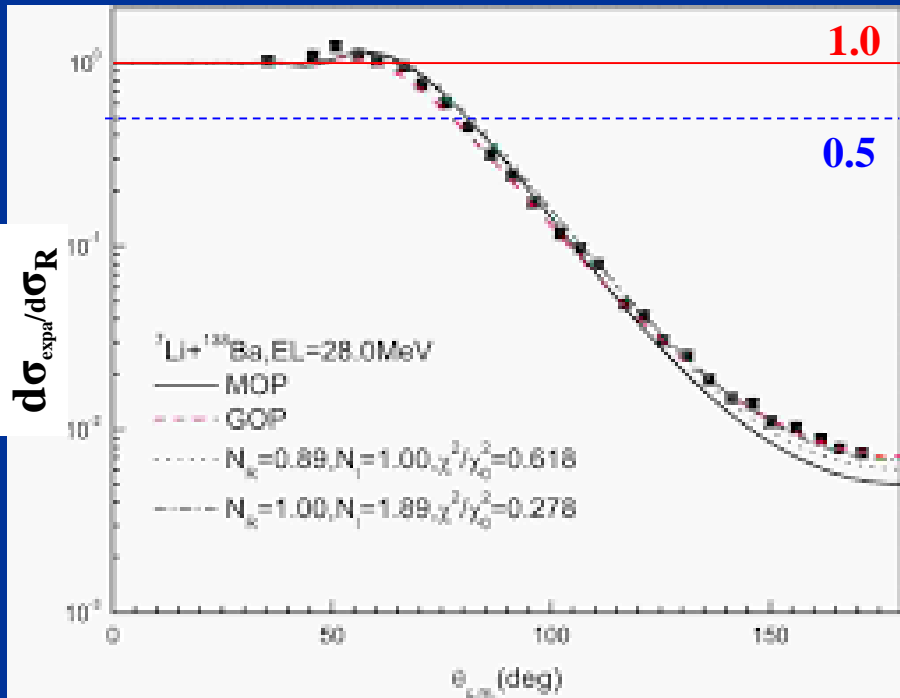
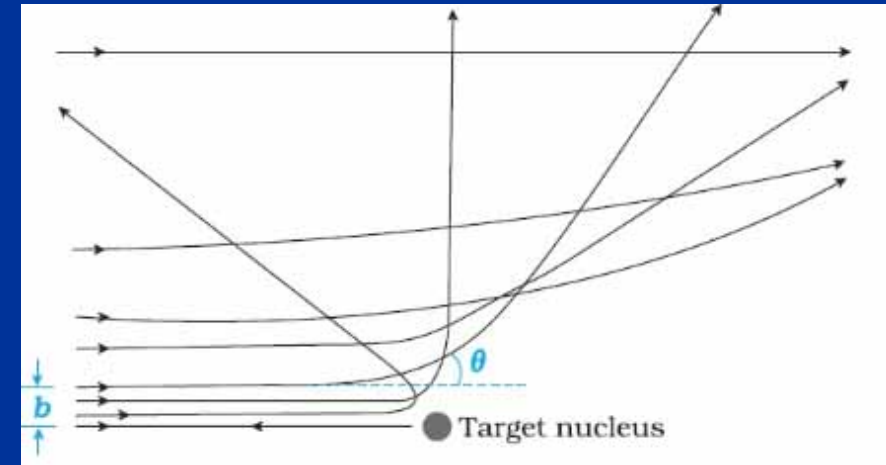
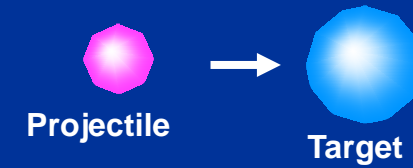


Masaomi Tanaka

# Principle of QE barrier measurement

## ● Rutherford scattering

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



Deduce Coulomb barrier height

## ● RIKEN:

- $E_{\text{beam}}$  change instead of  $\theta$  change
  - But detector set at  $\theta=180^\circ$  (recoil of tgt)
  - Direct measure of QE barrier **at  $L \sim 0$** .
- (Most important component of ER production)

# Experimental setup QE barrier measurement

## Target

$^{248}\text{Cm}_2\text{O}_3$  (483  $\mu\text{g}/\text{cm}^2$ ) on Ti backing (1.31  $\text{mg}/\text{cm}^2$ )

## Gas-filled recoil ion separator GARIS-III

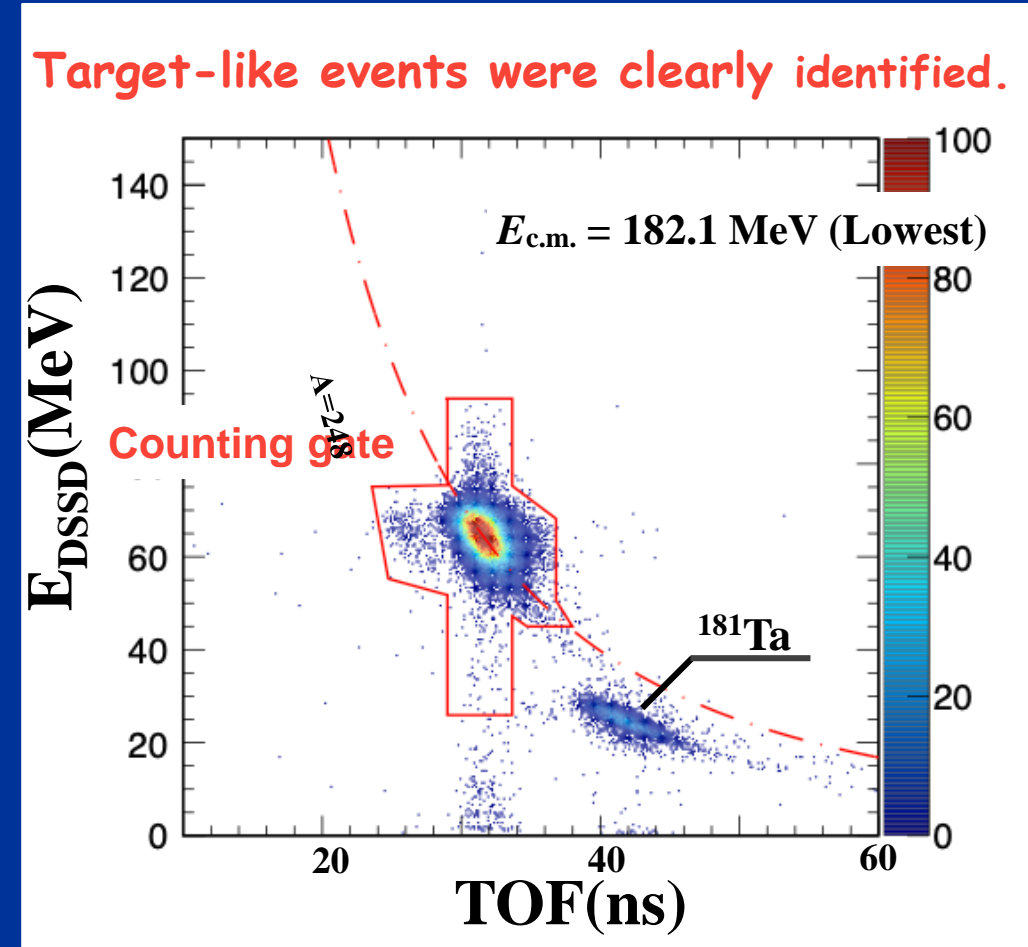
Detect target-like events recoiled at  $\theta_{\text{lab}}=0^\circ$  ( $\theta_{\text{cm}}=180^\circ$ )

→  $L\sim 0$  (s-wave, most important of ER production)

## Reflection probability $R(E)$

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

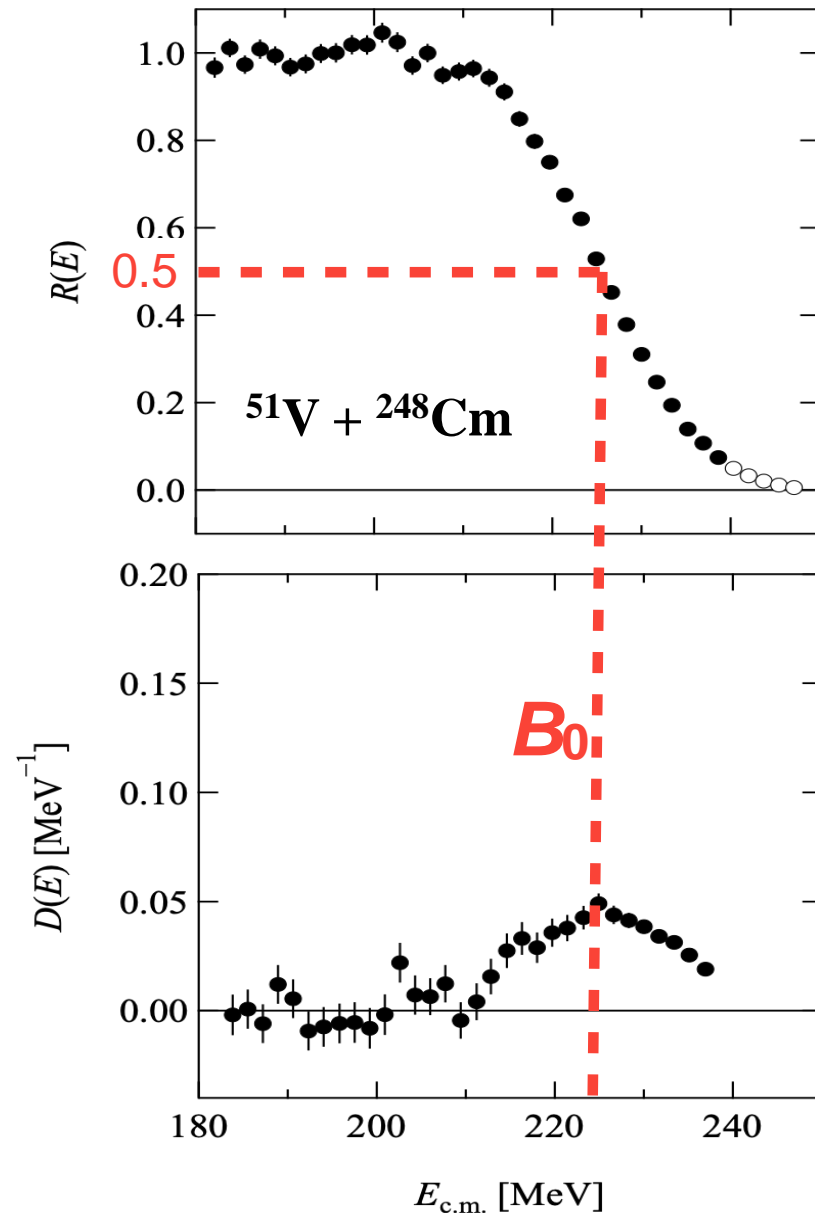
$$R(E) = 0.5 \rightarrow \sigma(\text{capture}) = \sigma(\text{reflection})$$



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

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

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



$$B_0 = 225.6 \pm 0.2 \text{ MeV}$$

## ● Need to consider for:

- Side-collision ( $B_{\text{side}}$ )
- $\Delta E_{\text{opt}}(\sigma_{\text{EV}}) \sim +1.8 \text{ MeV}$

## ● Adopted $^{51}\text{V}$ beam energy

$$E_{\text{opt}}(\text{adopted}) = 234.8 \text{ MeV}$$

## ● Final beam energy

- Energy loss of target+backing

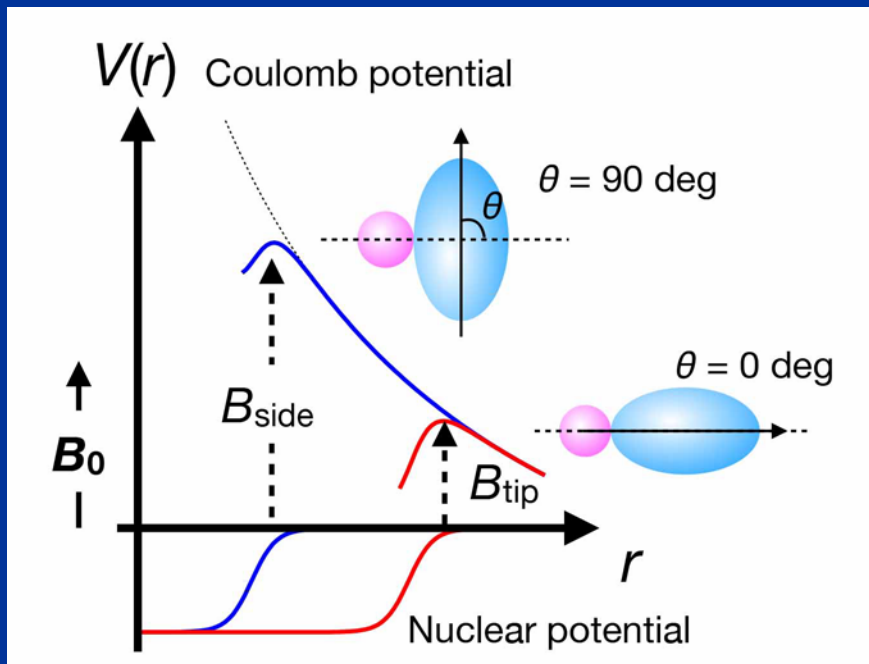


# Side-collision

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

## Side collision in hot-fusion reaction

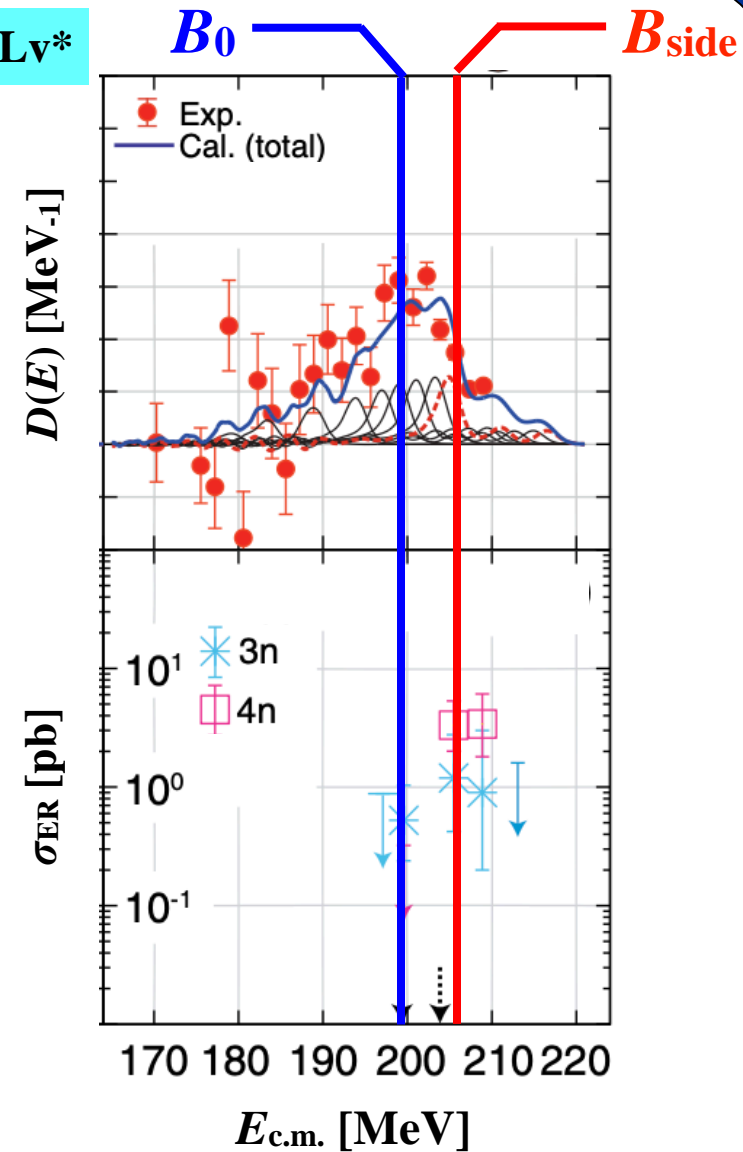
Actinide target (large prolate deformation)  
 → Side collision is favorable for CN&ER formation.



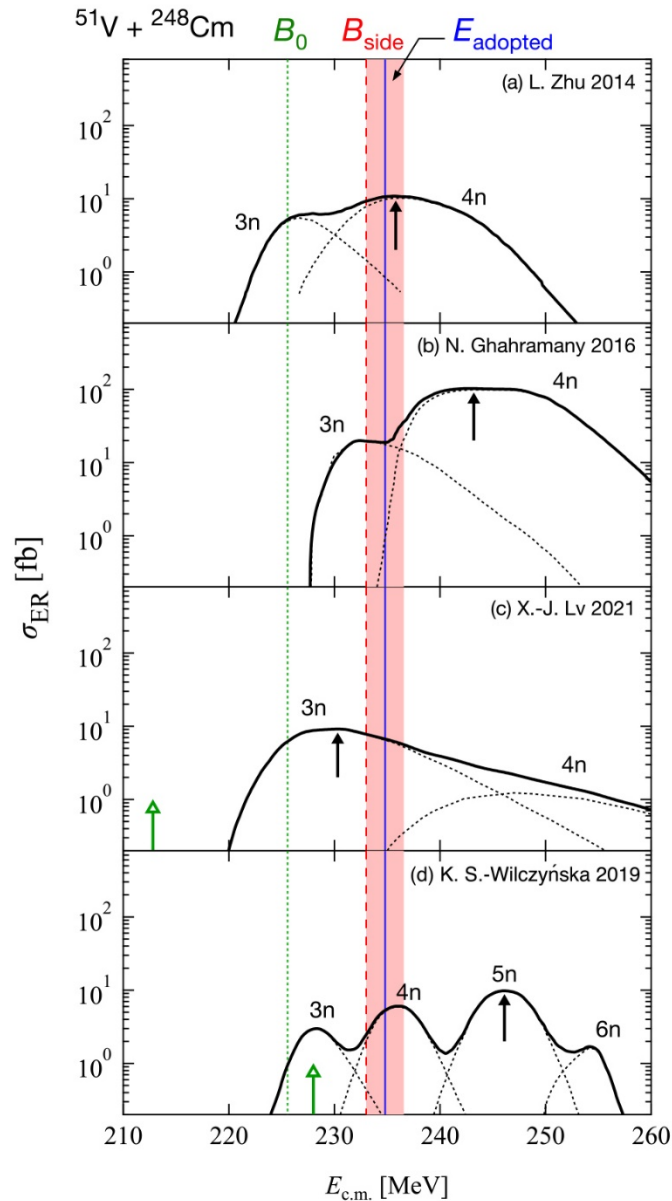
$B_{\text{side}}$  is estimated with CC calculation  
 → Model dependent



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



# 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).

$^{248}\text{Cm}(^{51}\text{V}, xn)^{299-x}119$ 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

**$E_{\text{beam}}(\text{adopted}) = 234.8$  MeV**

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

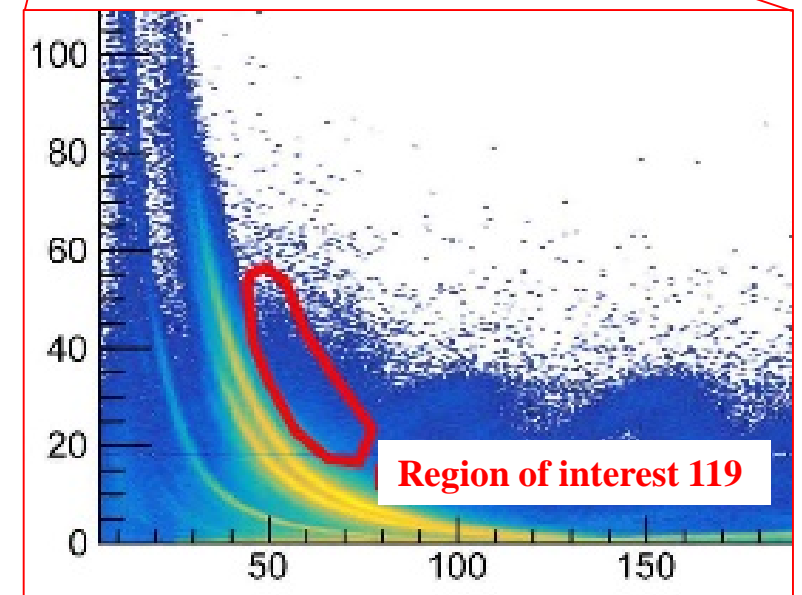
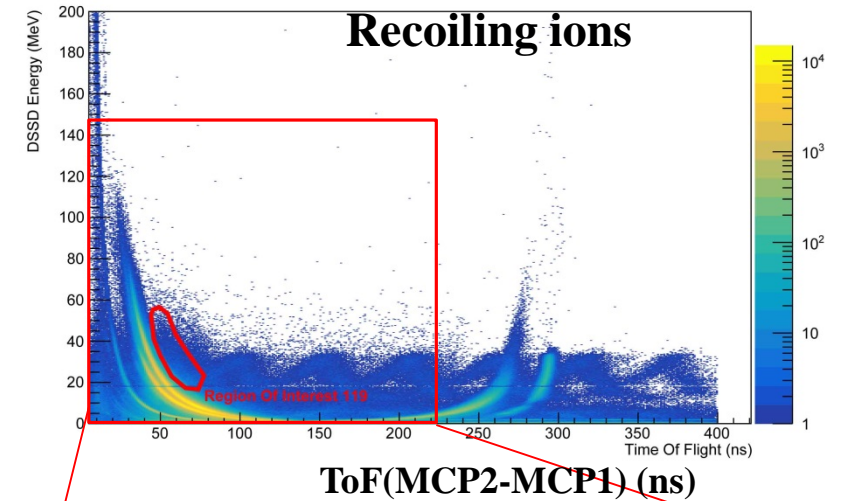
### 3. Present status

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

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



### Online spectra



# Snapshots



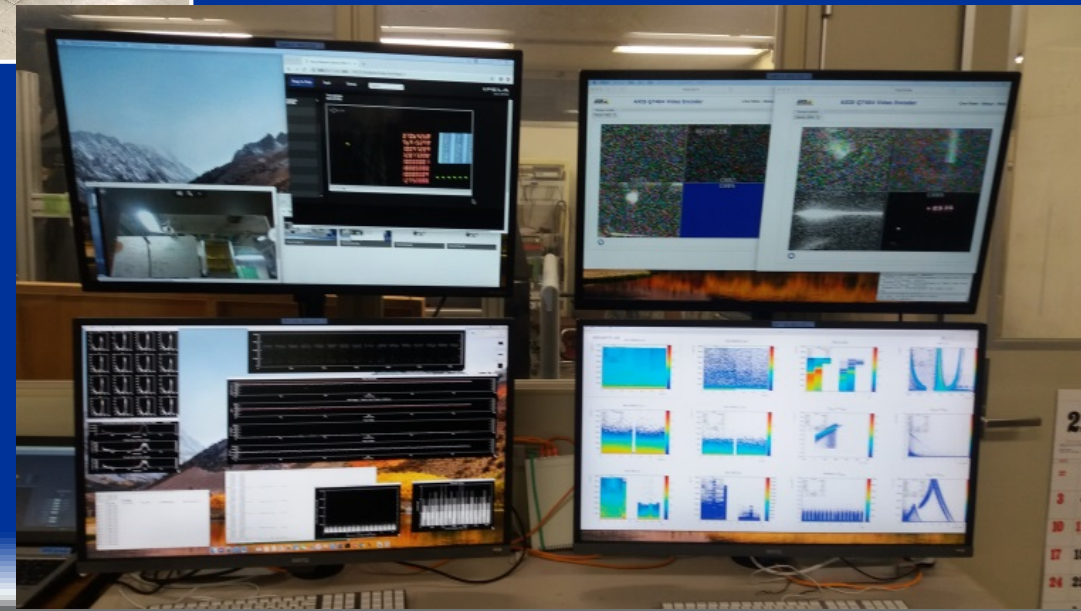
Pierre Brionnet



GARIS-II

Morimoto

Morita

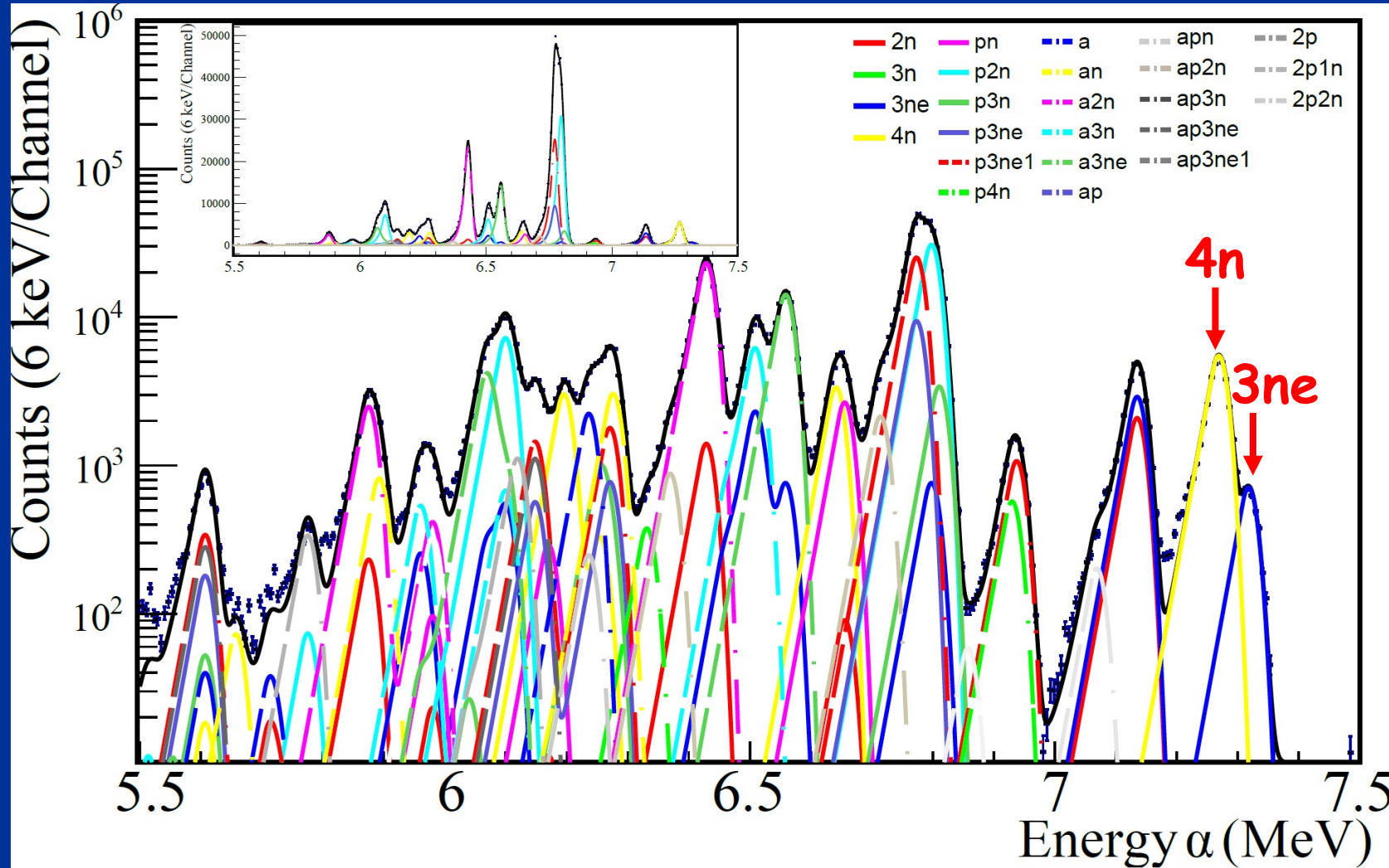


## 5. $^{51}\text{V} + ^{159}\text{Tb} \rightarrow ^{210}\text{Ra}^* (N = 122)$ reaction

- Study on fusion reaction mechanisms
  - Deformation effect (tip and side collisions)
  - Using  $^{159}\text{Tb}$  ( $\beta \approx 0.3$ , large X-sec)
- Excitation function on fusion residues measured
  - Barrier distribution
  - xn, pxn and  $\alpha$ xn channels identified by characteristic  $E_\alpha$
- Detailed analysis: Pierre Brionnet (paper in preparation)

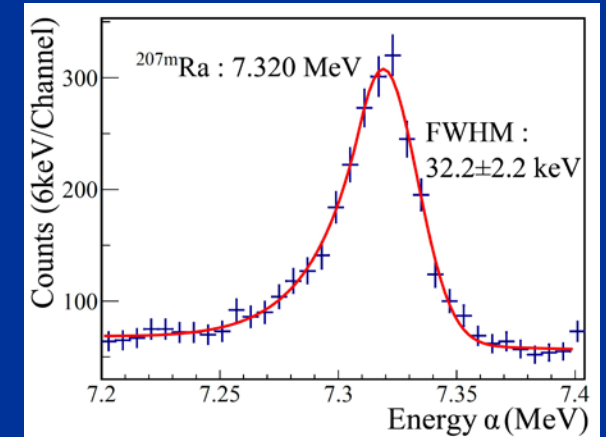


# $^{51}\text{V} + ^{159}\text{Tb}$ fusion cross sections



- Estimate production-rates based on the total  $\alpha$ -spectrum

- Anti-correlation with ToF signal (TDC and QDC information) to define  $\alpha$ -spectrum
- No timing information applied
- Fit of the overall spectrum based on the known branching ratios and  $\alpha$ -energies



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

## Barrier distribution

➤  $B_0 = 164 \text{ MeV}$

## Excitation function for nx-, pxn-, $\alpha$ xn-channels

➤ Most comprehensive measurement ever

➤ Seems NO side collision effect ???

➤ Why ?

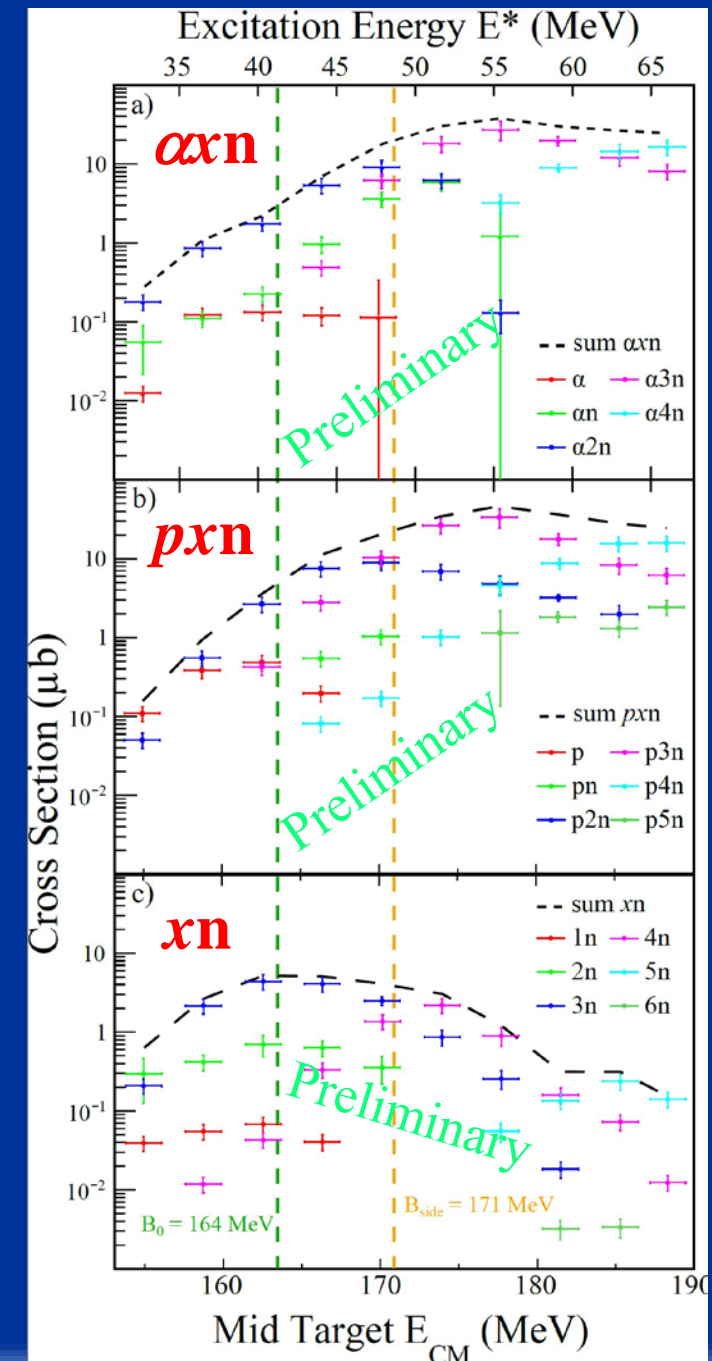
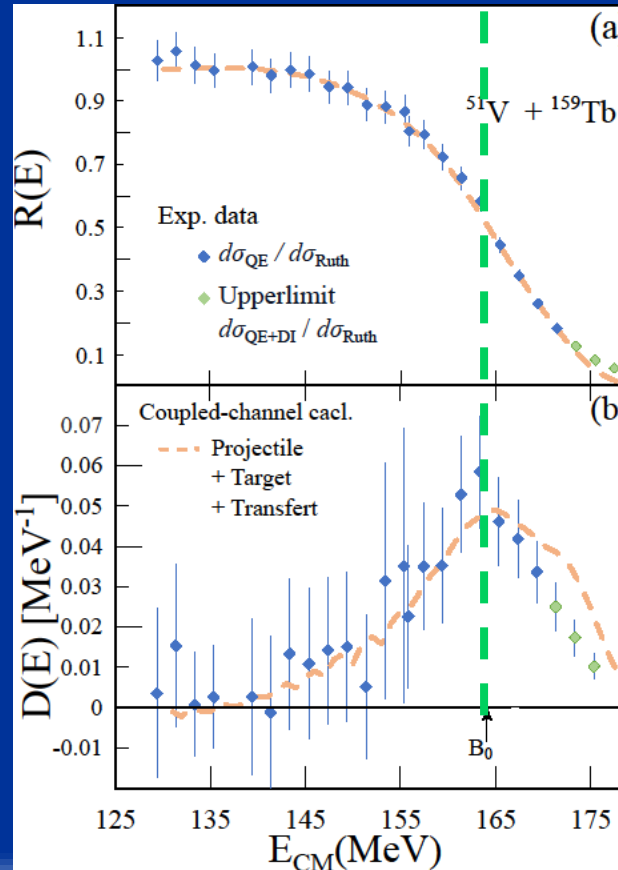
➤ Maximum X-sec ( $\pm 25\%$  stat. error)

$\sigma(\text{p}3\text{n})$ :  $33 \mu\text{b}$  at  $E^* = 56 \text{ MeV}$

$\sigma(\alpha 3\text{n})$ :  $27 \mu\text{b}$  at  $E^* = 56 \text{ MeV}$

$\sigma(3\text{n})$ :  $4.4$  at  $E^* = 40 \text{ MeV}$

➤  $\sigma(\text{p}3\text{n})$  and  $\sigma(\alpha 3\text{n}) \gg \sigma(3\text{n})$



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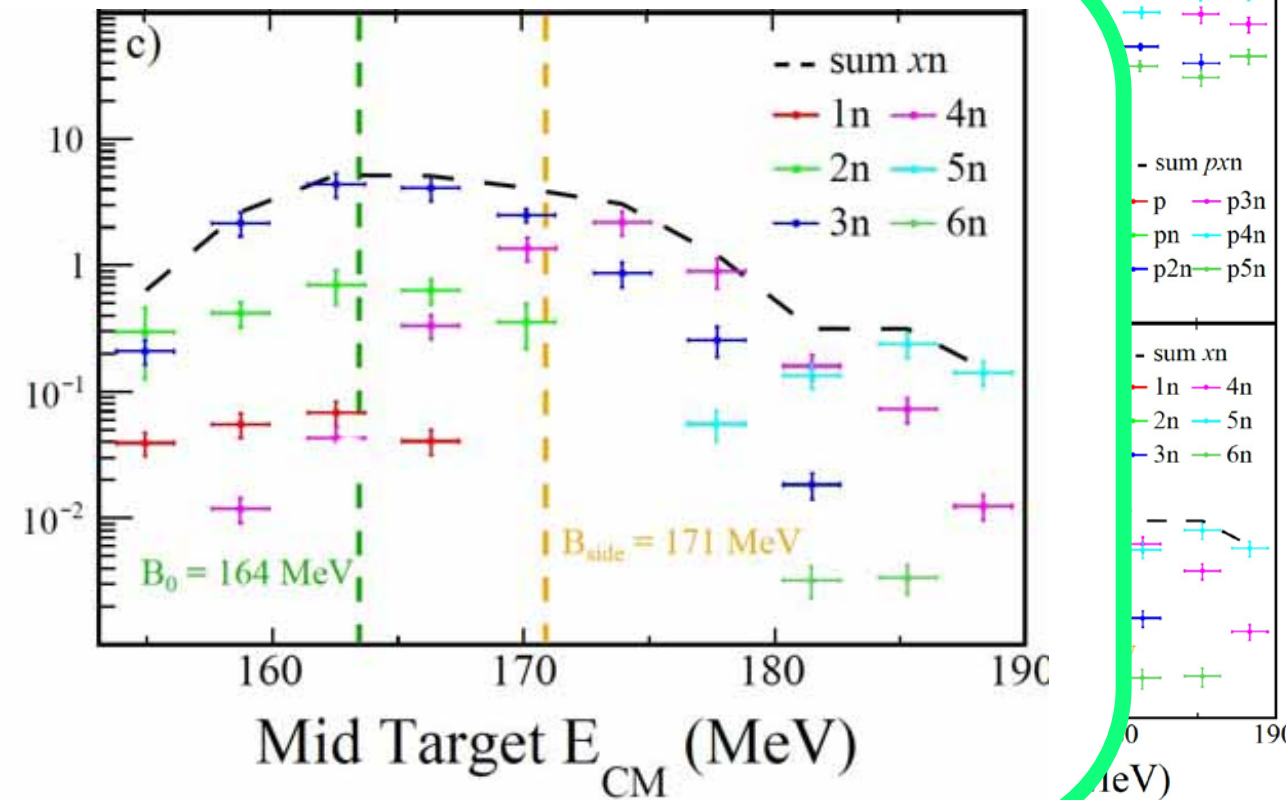
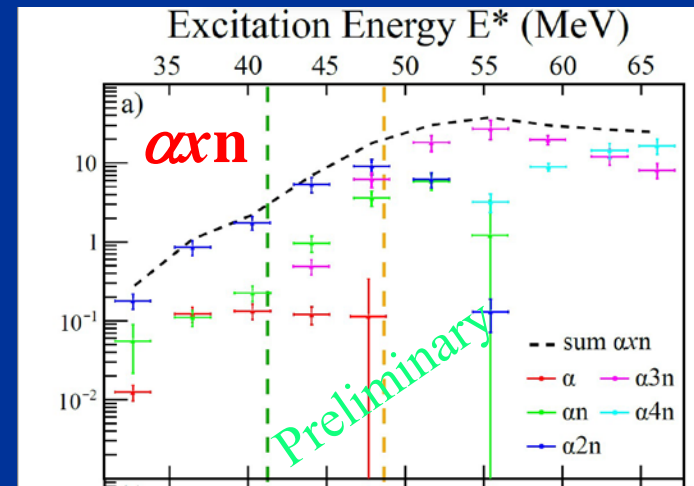
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# Can we understand xn-channel suppression ?

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

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

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

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

- In case of  $^{210}\text{Ra}^*$

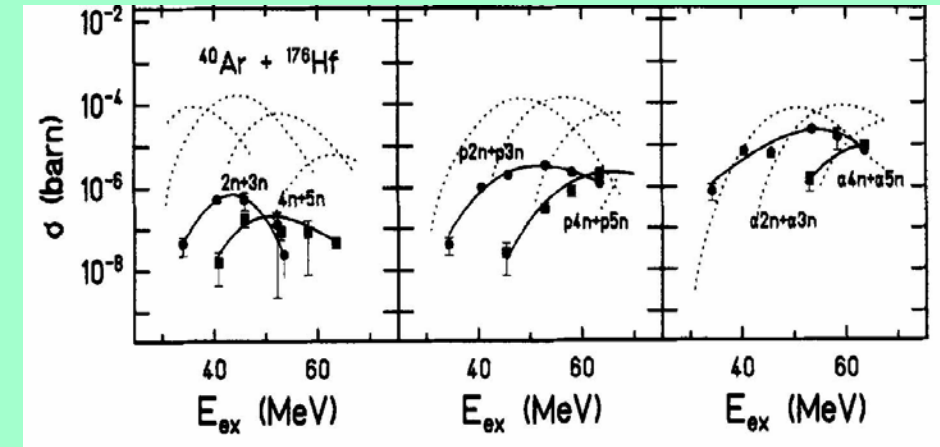
$$\Gamma_n : \Gamma_p : \Gamma_\alpha : \Gamma_f = 1 : 0.04 : 0.04 : (0.1 - 1)$$

$\Gamma_n$  dominate,  $\Gamma_f$  significant effect

- $0^{\text{th}}$  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

- xn suppression is general phenom.?  
➤ Maybe 'YES' for Lanthanoid trng

Vermeulen: Z. Phys. A318(1984)157



## ● Parameters for decay-width estimation

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

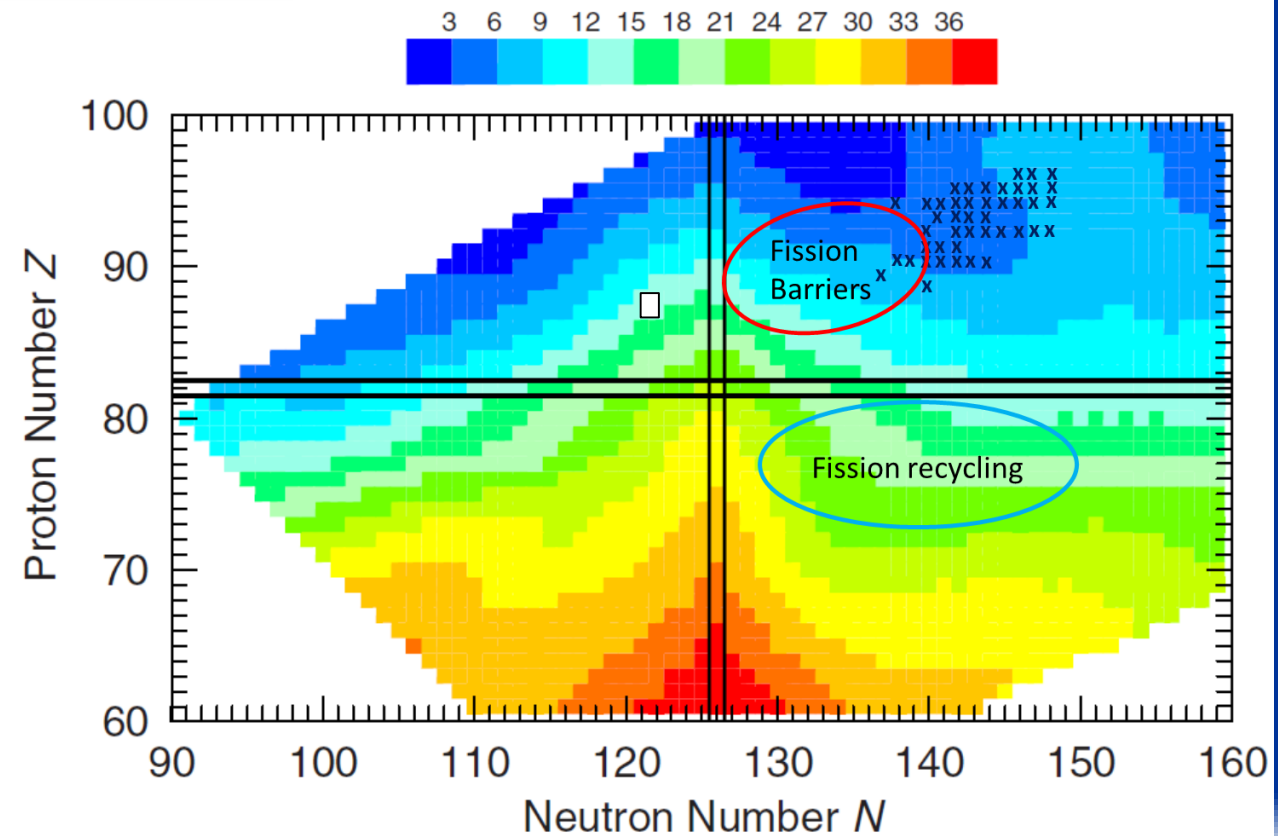
$$B_n = 9.5 \text{ MeV} \quad B_p = 3.1 \text{ MeV} \quad Q_\alpha = 7.2 \text{ MeV}$$

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

$$E_{\text{ex}}^* = 42.9 \text{ MeV} \rightarrow T \sim 1.3 \text{ MeV} \quad (E_{\text{ex}}^* = aT^2, \quad a = \frac{A}{15})$$

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

Calculated Fission-Barrier Height (MeV)



# 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  $^{51}\text{V}$  beams
- **Average Coulomb barrier height  $B_0$  of  $^{51}\text{V}+^{248}\text{Cm}$** 
  - M. Tanaka et al., JPSJ, 91, 084201 (2022).  $B_0 = 225.6$  MeV
- **Search of Z=119 by  $^{248}\text{Cm}(^{51}\text{V}, xn)^{299-x}119$  since 2020**
  - Measurement is going on.
- **Reaction mechanism study of  $^{51}\text{V}+^{159}\text{Tb}$** 
  - No side collision effect ?
  - Suppression of xn channel ?