Reaction parameter study of the ^{51}V beam onto deformed target: $^{51}V+^{159}Tb$ reaction

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REC SEP @ SHE CHEM TASCA 23

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Plan

- Introduction: reaction mechanism and side collision using ^{51}V beam
  - Goal
  - Surrogate lighter systems
- Experimental method and setup
- Results
  - Barrier distribution
  - Excitation function

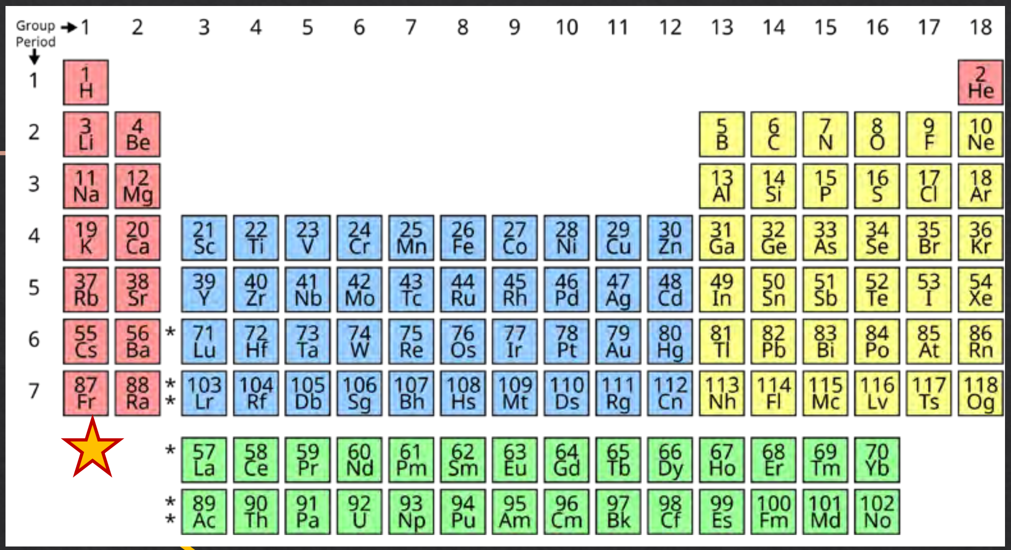
Physics Case : Synthesis of new elements

- Production of new element using ^{48}Ca is no longer possible
  - ^{50}Ti, ^{51}V and ^{54}Cr needed to expend beyond Og with fusion evaporation technic

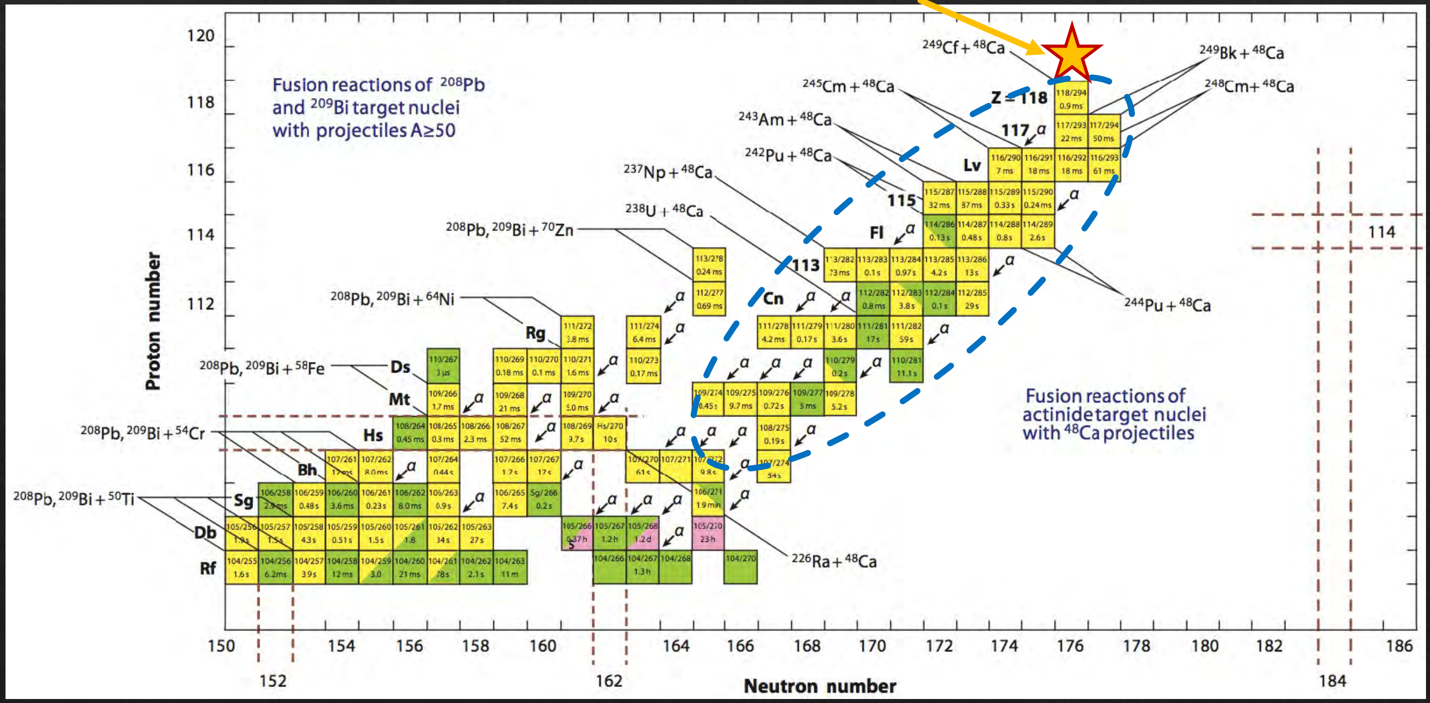
- Reaction mechanism on actinide target not study with these heavier beam

- Current search Z = 119 at RIKEN using :

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



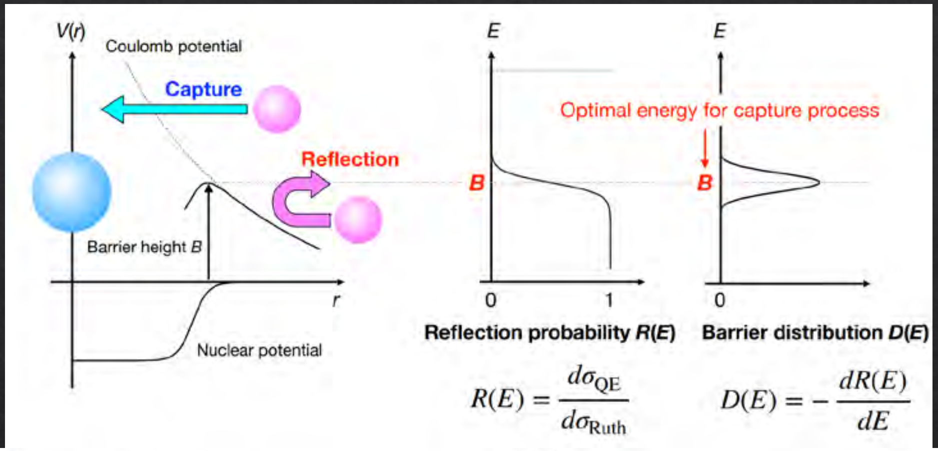
Z = 119 new element



Optimal energy for the SHE search : RIKEN approach

- Search of new element currently ongoing at RIKEN with the hot fusion evaporation of ^{51}V on ^{248}Cm using the barrier distribution measurement for the optimal beam energy selection

  M. Tanaka et al., J. Phys. Soc. Jpn. 91, 084201 (2022)



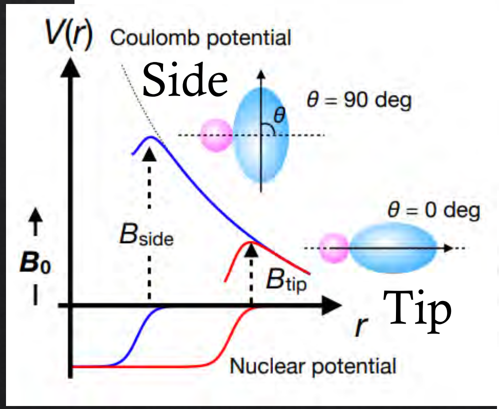
- Peak energy of barrier distribution *D(E)* is linked to the maximum cross-section of production

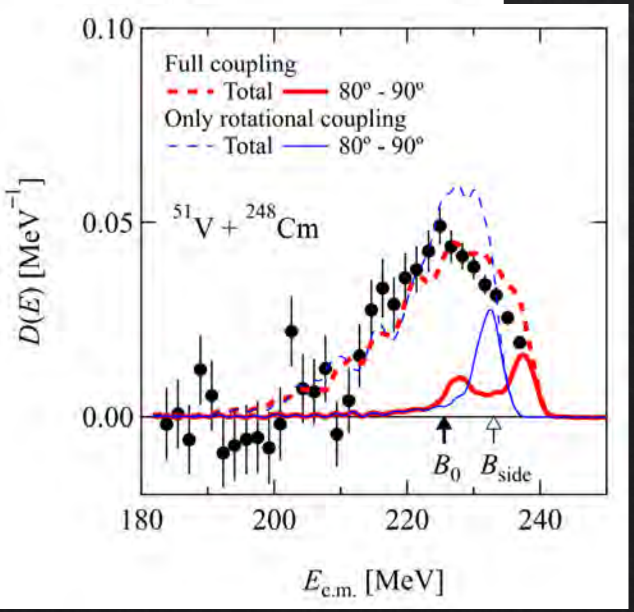
  T. Tanaka et al., J. Phys. Soc. Jpn. 87, 014201 (2018).

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

  T. Tanaka, Doctoral thesis, Kyushu University (2019).

  - Cold fusion reaction : *D(E)* and σ_{ER} are consistent
  - Hot fusion reaction : σ_{ER} > *D(E)*, due to the large prolate deformation
    - Side vs Tip configuration
    - B_{side} derived from the experimental B_0 and CCFULL calculation
    - Only studied for beam lighter than ^{48}Ca : no cross section with heavier beam known





M. Tanaka et al., J. Phys. Soc. Jpn. 91, 084201 (2022)

Surrogate reaction : test the side to tip collision effect

- Direct systematic measurement with actinide target impossible due to the very low fusion-evaporation cross section (pb to fb range)

- Systematic studies needed on deformed target : using surrogate target

  - Similar deformation parameter : study of the side collision effect

  - Surrogate reaction with deformed lanthanide targets:

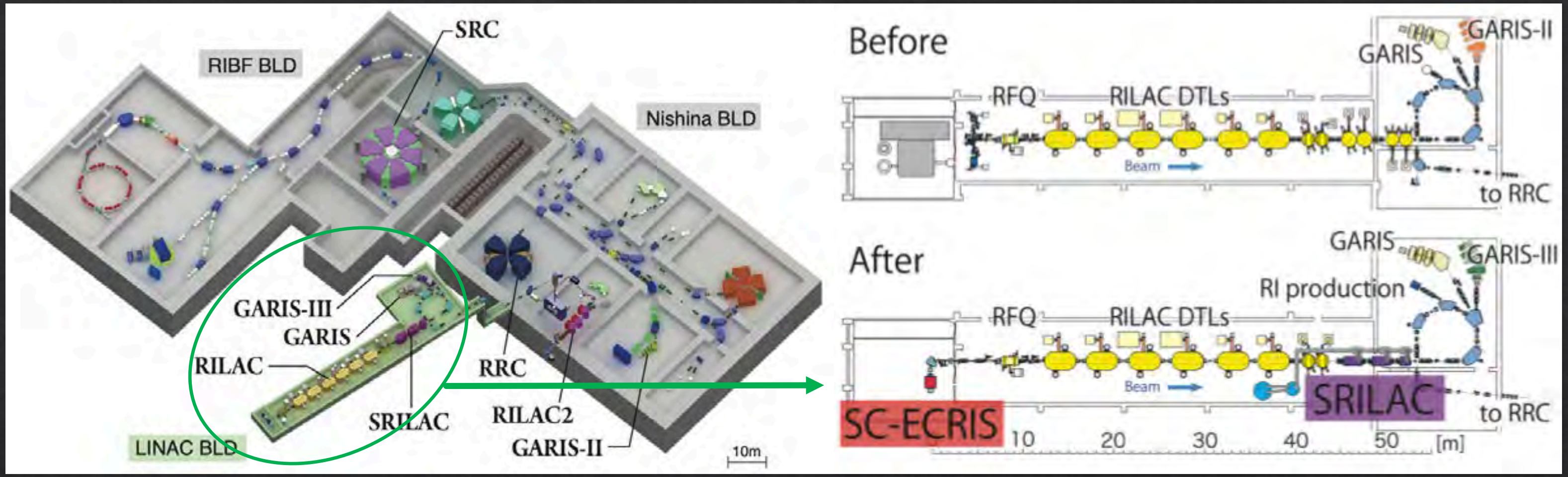
    ^{159}Tb β_2=0.271, β_4=0.066 vs ^{248}Cm β_2=0.286, β_4=0.039

  - Cross-section of production in μb range

=> First surrogate measurement using the ^{51}V+^{159}Tb system

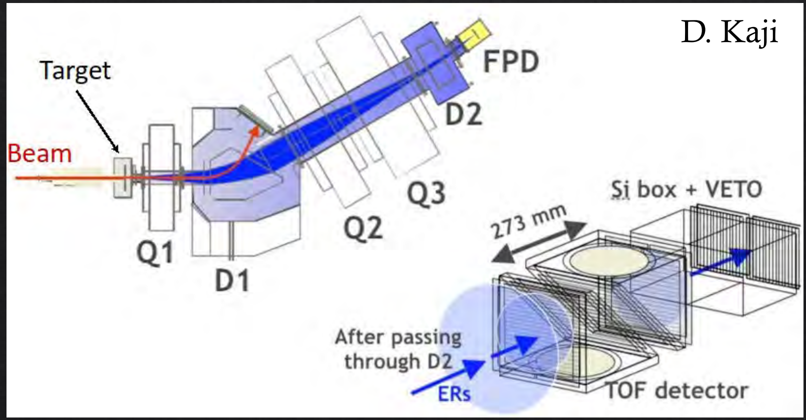
Experimental Setup

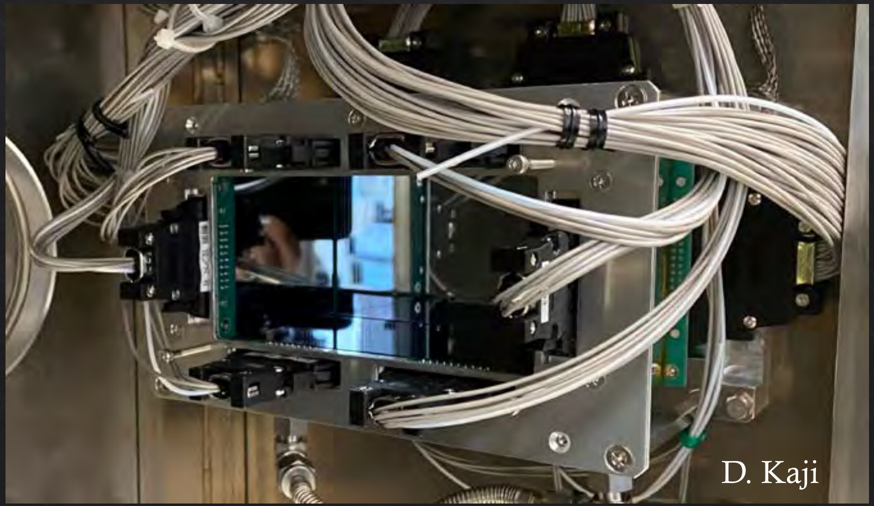
- SRILAC facility
  - SC-ECRIS ion source: 28 GHz
  - SRILAC : Supra Conducting Tank



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

- GARIS-III separator and focal plane detection (FDP)

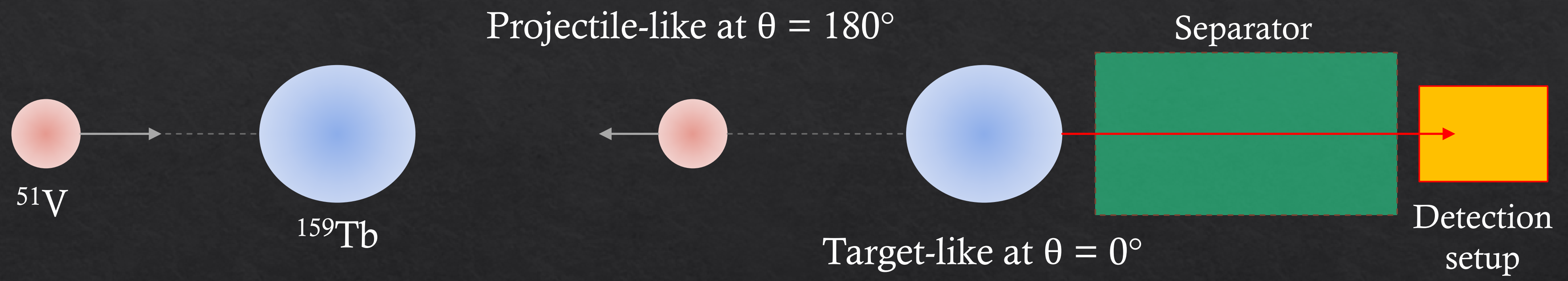




Experimental Method: Barrier distribution and excitation function

- Detection of the target-like events transported in GARIS-III separator at θ = 0°
  - Similar method as previous measurement

M. Tanaka et al., J. Phys. Soc. Jpn. 91, 084201 (2022)
T. Tanaka et al., J. Phys. Soc. Jpn. 87, 014201 (2018).
T. Tanaka et al., PRL 124, 052502 (2020).
T. Tanaka, Doctoral thesis, Kyushu University (2019)



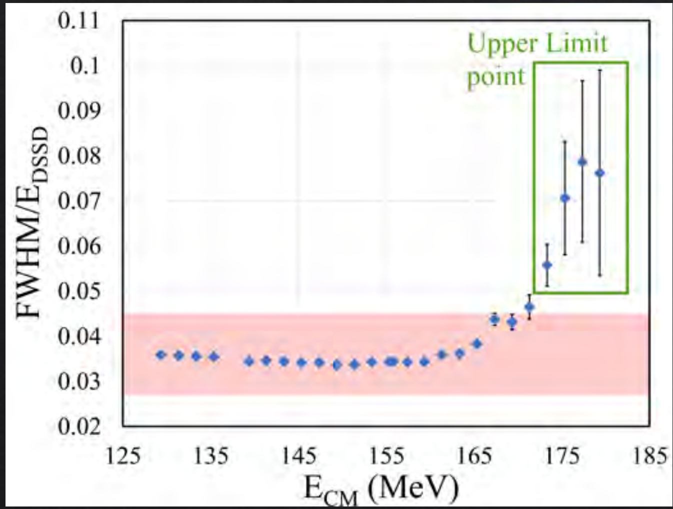
- Excitation function:
  - Transport of all the evaporation residue (*xn, pxn,* …) at the focal plane detection system
  - Production rate estimated from the total alpha spectrum

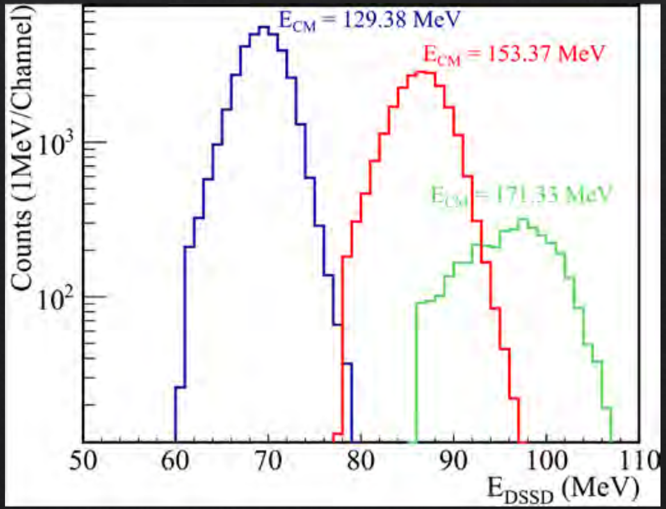
Analysis and Results

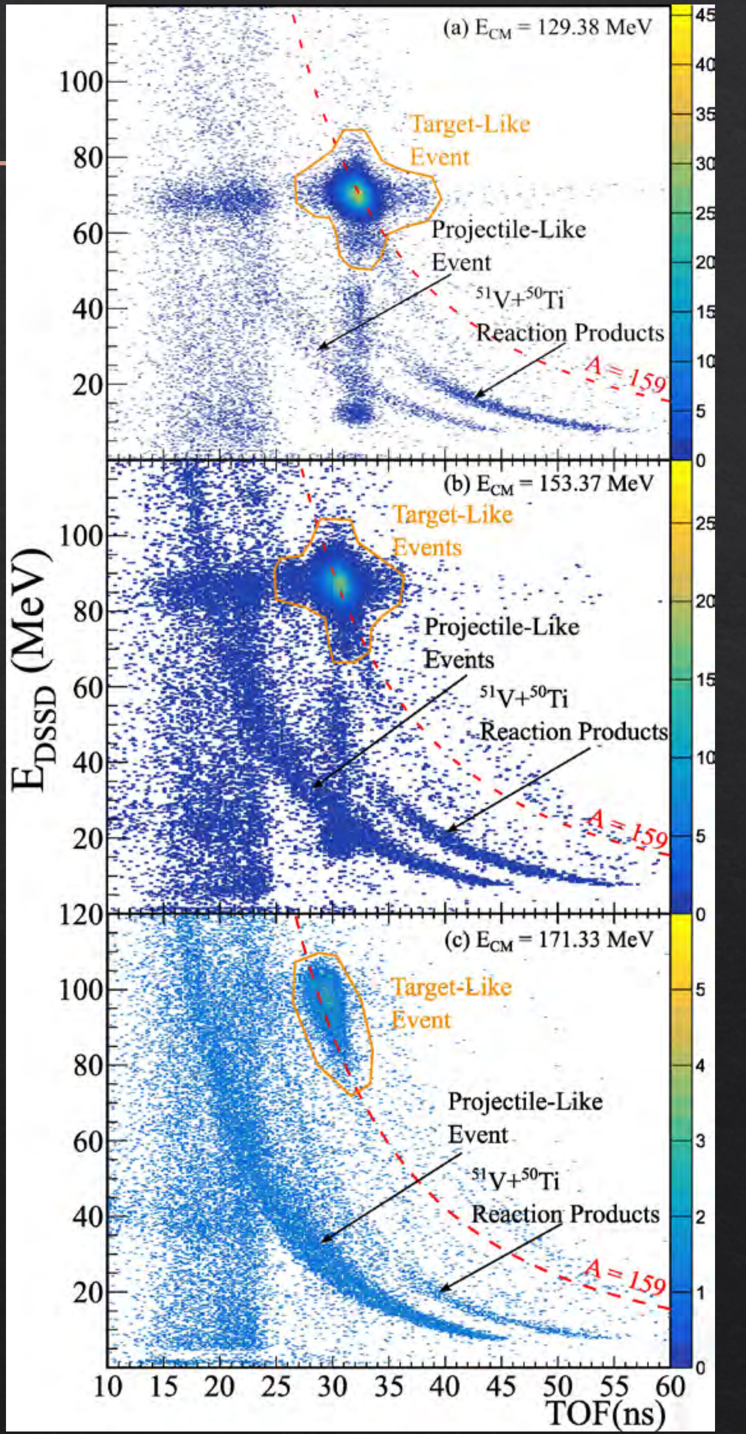
Barrier distribution : condition and identification

- Condition :
  - $^{51}V^{13+}$ beam : 196 MeV < E_{lab} < 260 MeV (2 MeV steps)
  - Intensity : 1.54 pnA
  - Target : ^{159}Tb metallic : 298±10 µg.cm^{-2} onto 2.8 µm Ti backing

- Target-like selection : TOF-E telescope information
  - Separated from the identified background
  - Contamination of deep inelastic events at high beam energy (c)



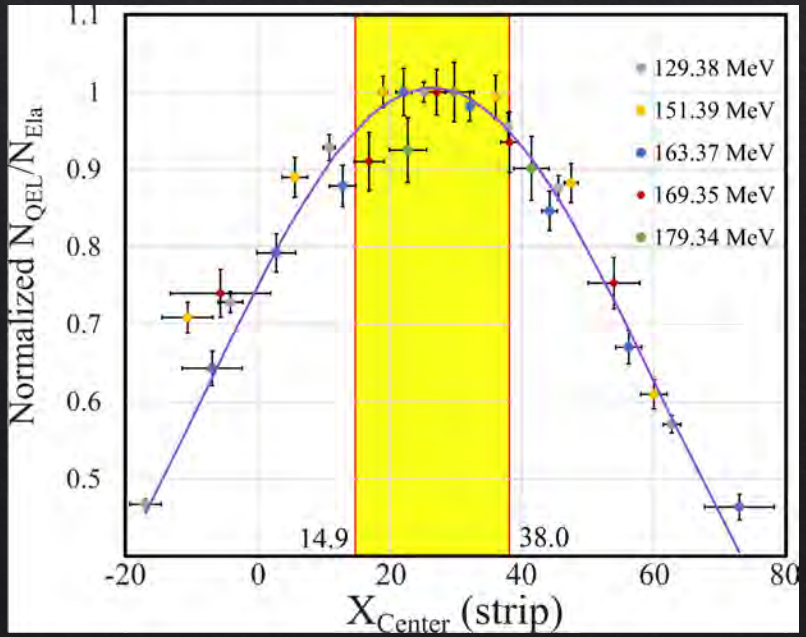


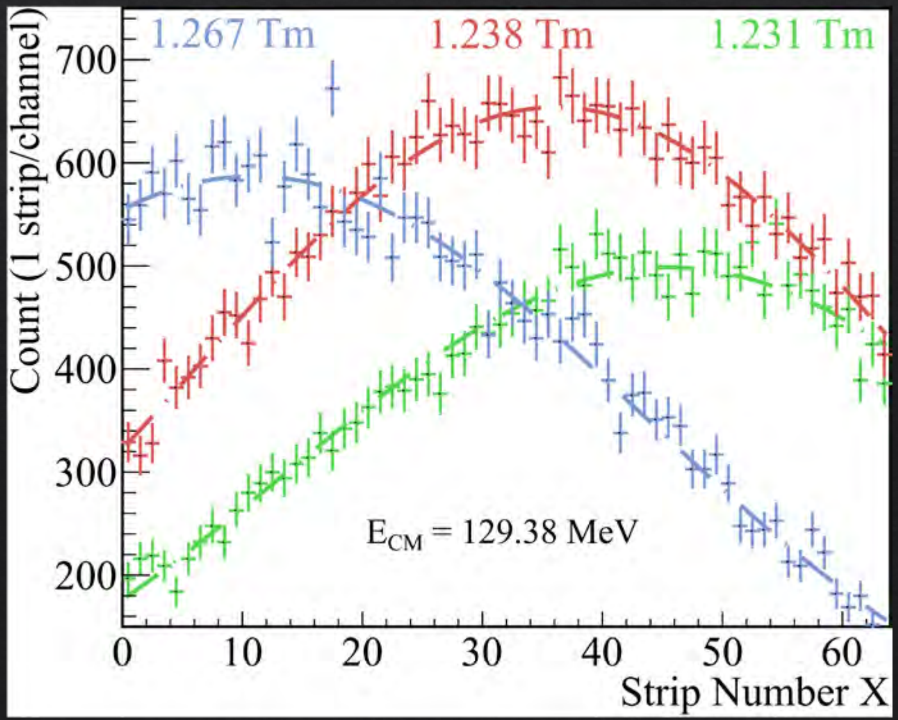


Barrier distribution : Correction factor

- Transmission dependence at the focal plane
  - Typical implantation profile on the dispersive axis (X-axis) : ~ 76.5 strip
    - Small variation will impact the transmission
    - Need correction/adjustment
- Adjustment of the Bρ setting to keep it centered :

Yellow highlight (> 95% relative transmission)





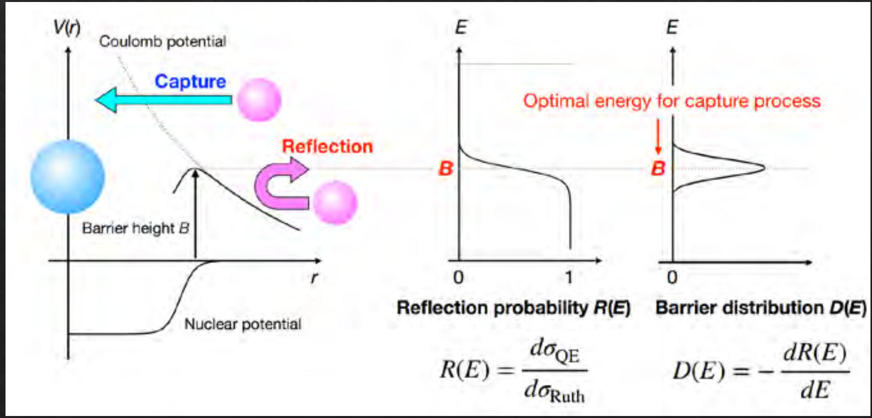
Experimental Results : barrier distribution measurement

- Reflection probability *R(E)* :

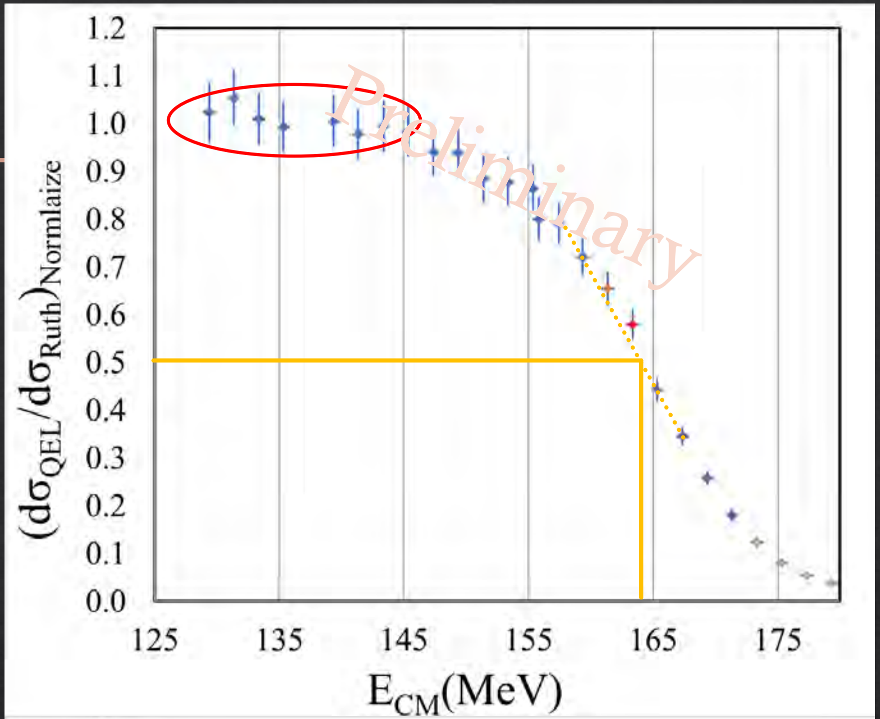
$$R(E) = \frac{d\sigma_{QE}}{d\sigma_{Ruth}} \equiv C.\frac{N_{QE}[^{159}\mathrm{Tb}]}{N_{Ruth}[^{51}\mathrm{V}]}$$

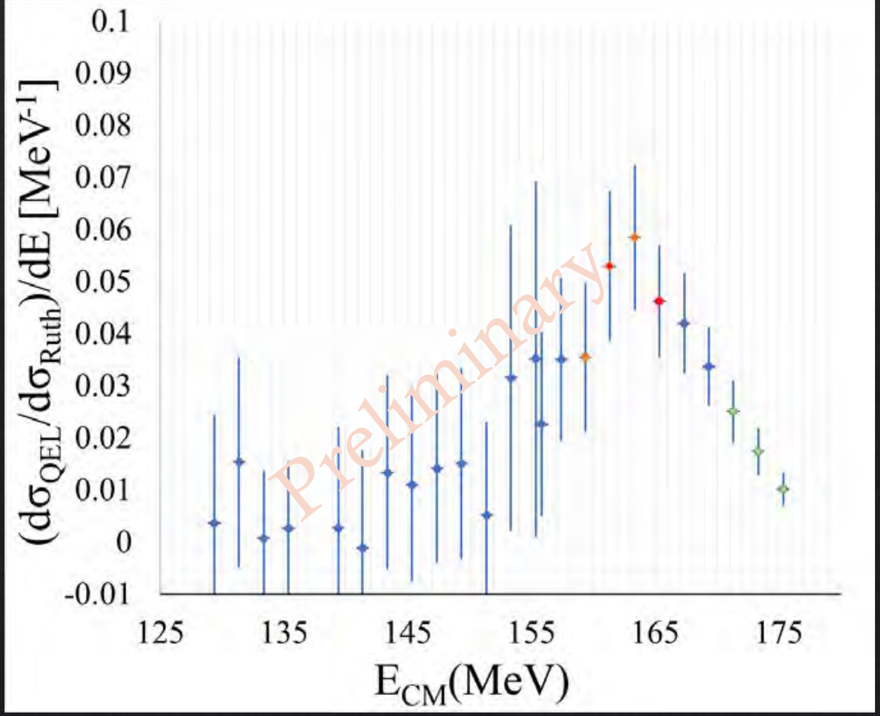
- QE barrier distribution *D(E)* :

$$D(E(i)) = \frac{R(E(i+1)) - R(E(i-1))}{E(i+1) - E(i-1)}$$



- Average barrier height : **B_0 = 164.12 ± 0.31 MeV**





Couple Channel Calculation (CCFULL)

- Couple Channel Calculation using CCFULL code

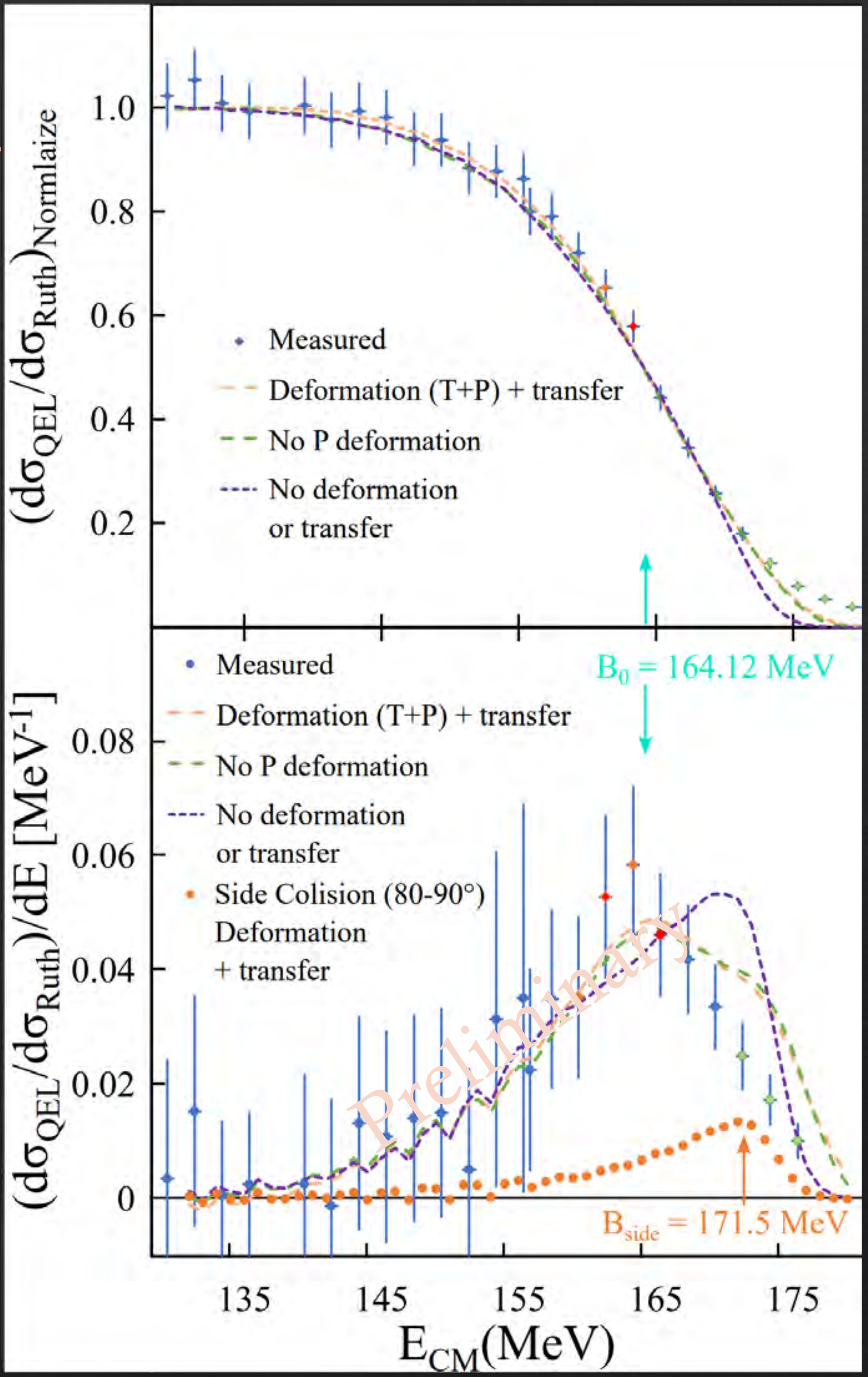
  K. Hagino et al., Comput. Phys. Commun **123**, 143 (1999)

- Optimization of the parameter to fit the experimental measurement :

Optical potential		
Real part		
V_0 = 68 MeV	r_0 = 1.176 fm	a_0 = 0.689 fm
Imaginary part		
V_w = 45 MeV	r_w = 1.05 fm	a_w = 0.689 fm
Excitation of the ^{51}V (Quadrupole vibrational coupling)		
β_2 = 0.11	E_{1ph} = 0.320 MeV	N_{ph} = 1
Excitation of the ^{159}Tb		
Quadrupole vibrational coupling		
β_2 = 0.271	E_{1ph} = 0.058 MeV	N_{ph} = 1
Rotational coupling		
β_2 = 0.271	β_4 = 0.066	β_6 = -0.007
Coupling of neutron-transfer reaction		
F_{tr} = 0.05	Q = -0.821 MeV	

- Derivation of the side collision energy B_{side} ($80° < \theta < 90°$)

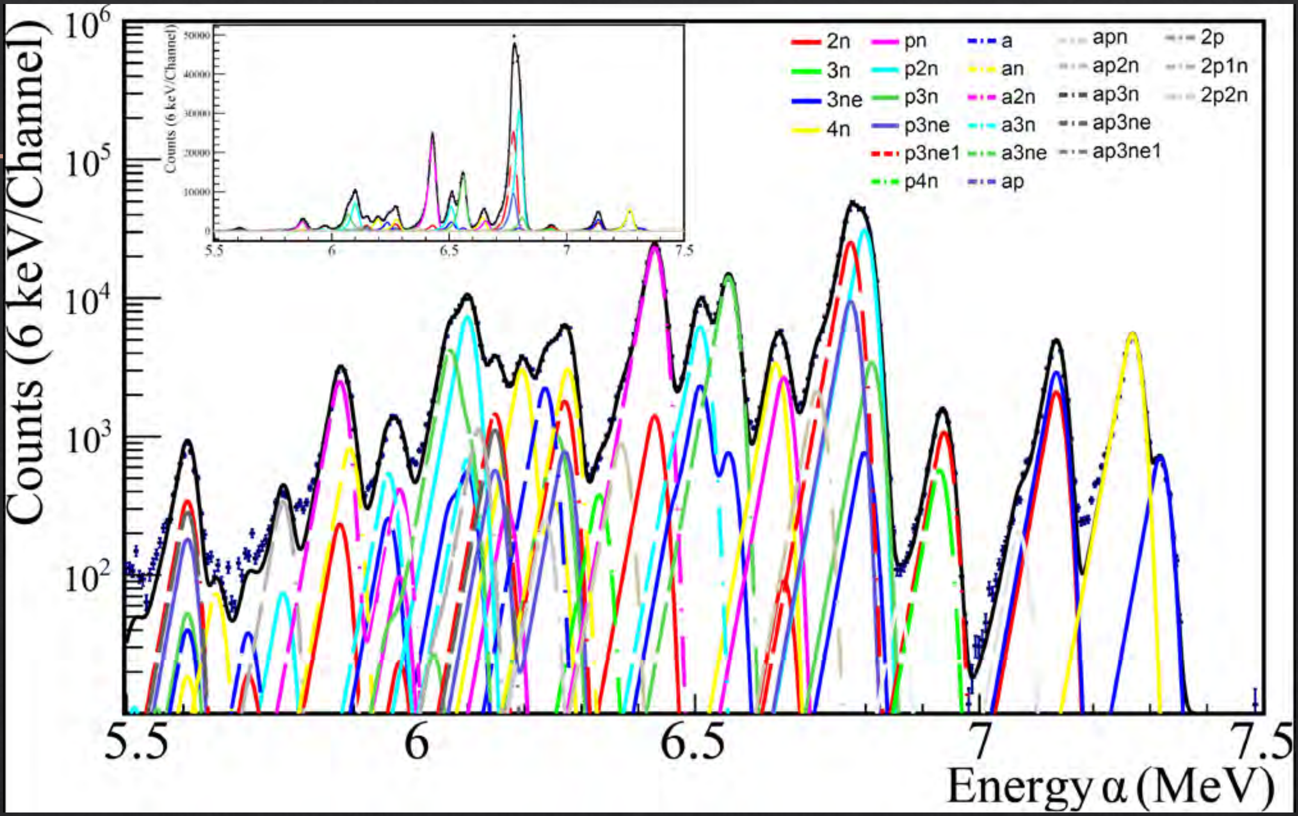
B_{side} = 171.5 ± 0.5 MeV

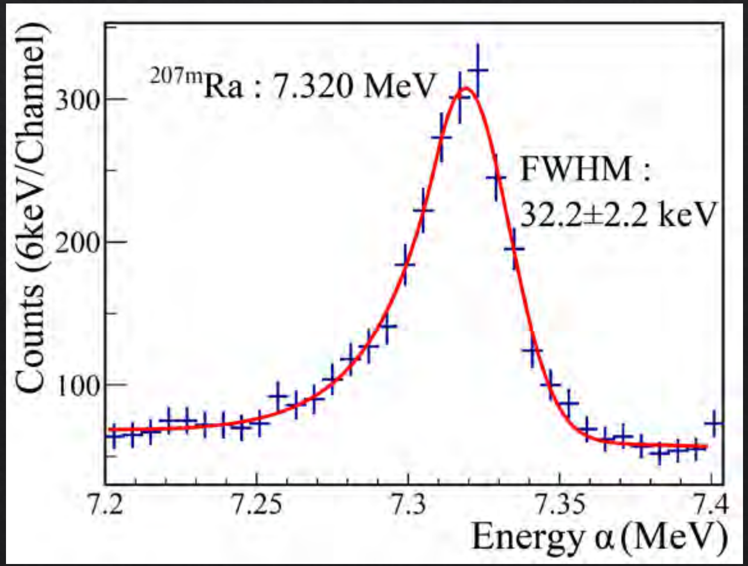


Excitation function : Production rates

- Estimation of the production rate based on the total α-spectrum:
  - Anti-correlation with ToF signal (TDC and QDC information) to define the α-spectrum
  - 24h accumulation per energy point
  - No timing information applied
  - Fit of the overall spectrum based on the know branching ratio and α-energies
  - Skew-gaussian function used for the DSSD response : optimized on the 7.320MeV α-decay of the ^{207m}Ra

C. John Bland, Appl. Radiat. Isot. 49 (9–11) (1998) 1228–1229



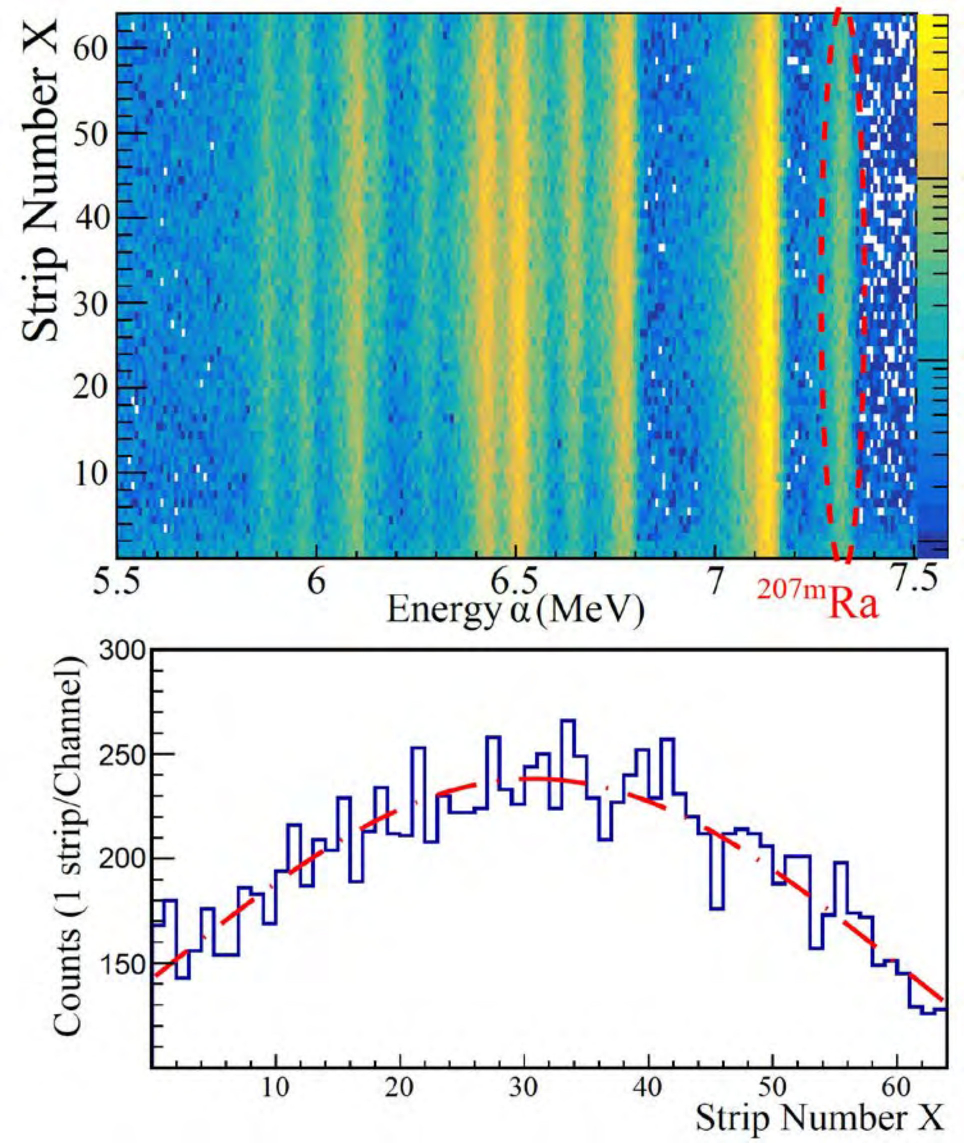


Excitation function : Transmission correction

- Transmission dependence per exit channel : Wide variety of evaporation residue transported at the same time
  - Bρ dependence need to be corrected for each considered exit channel
  - Bρ value of each exit channel for each energy point estimated

    K.E. Gregorich et al., Phys. Rev. C, 72 (2005), Article 014605
  - One exit channel kept centered at each energy point for reference
  - Deviation from the reference based on the know dispersion of GARIS-III (19.8 mm/%) and the implantation characteristic at each energy (width and energy)

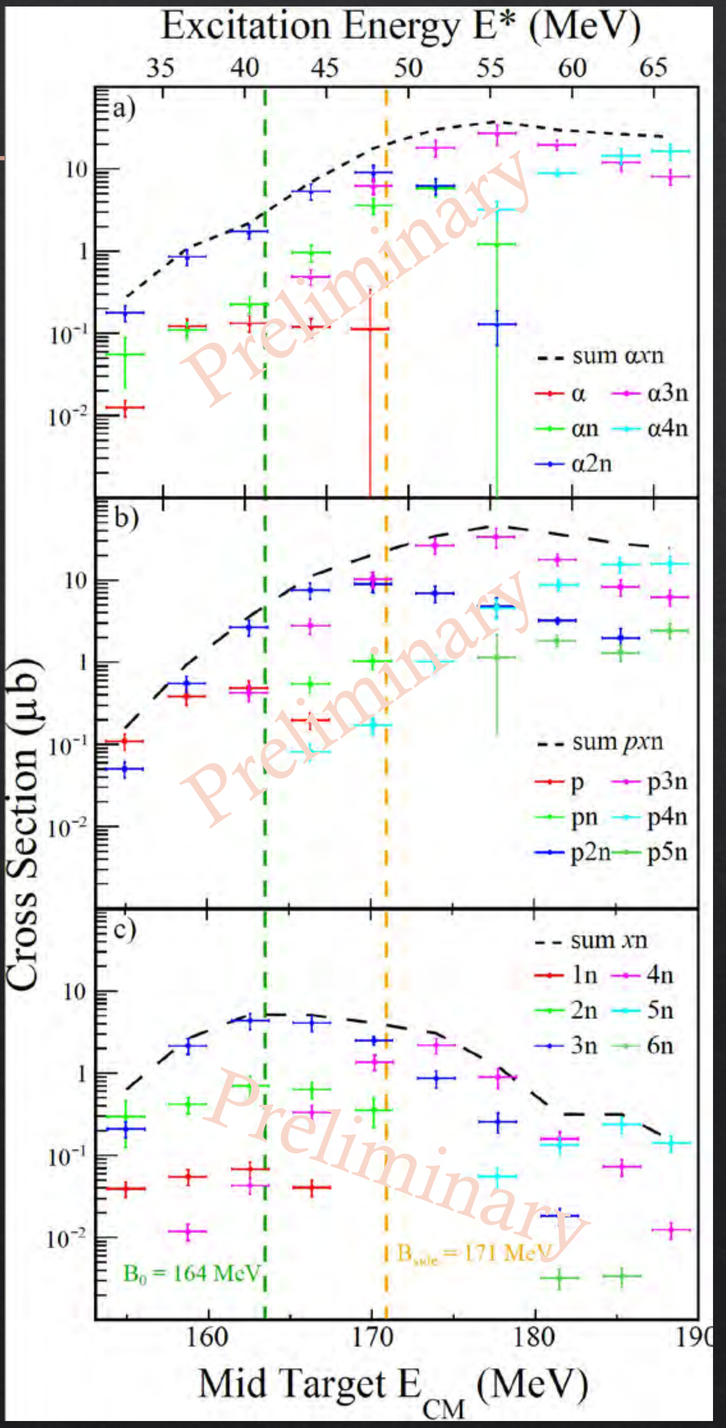
=> Individual transmission per reaction channel



Excitation function : condition and results

- Experimental condition :
  - $^{51}V^{13+}$ beam : 205 MeV < E_{lab} < 250 MeV (5 MeV steps)
  - Intensity : [152-345] pnA
  - Target : ^{159}Tb metallic : 363.8±16.3 µg.cm^{-2} onto 2.8 µm Ti backing
  - Nominal transmission : 75 ± 15 % D. Kaji et al., Proc. Radiochim. Acta 1 (2011) 105
  - α detection efficiency : 55 % (DSSD only)

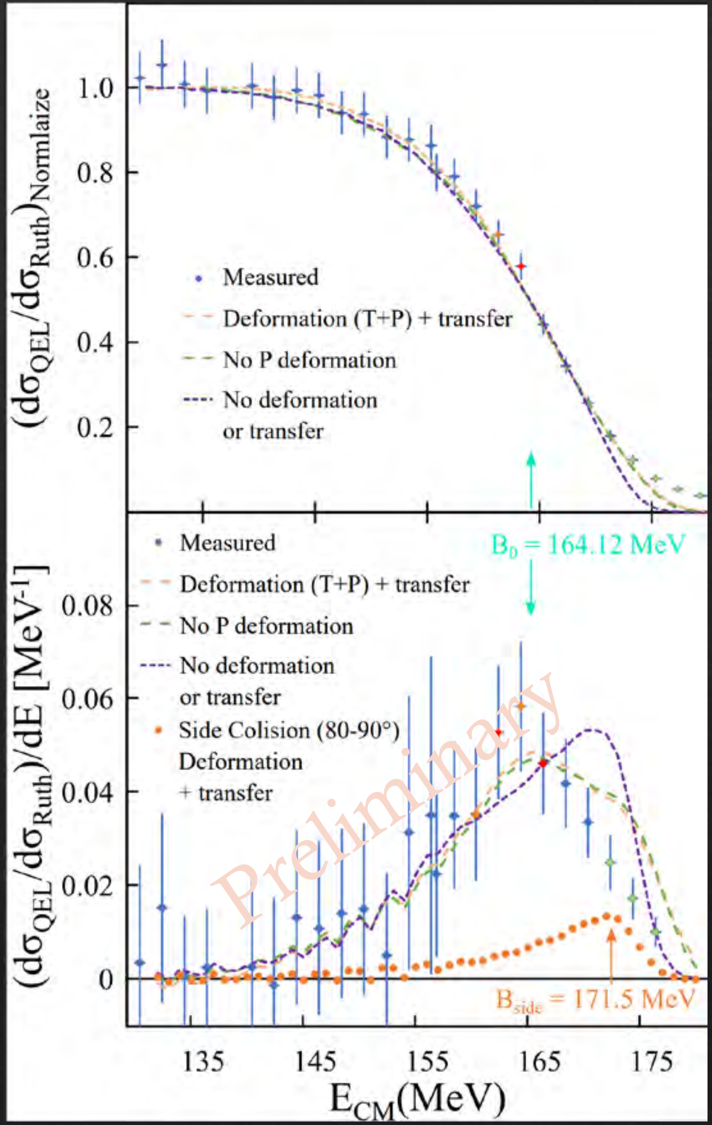
- Maximum cross-sections:
  - p3n : **33.1 ± 8.9 µb** at E* = 55.5 ± 1.1 MeV
  - α3n : **27.1 ± 7.3 µb** at E* = 55.5 ± 1.1 MeV
  - 3n : **4.38 ± 0.95 µb** at E* = 40.3 ± 1.1 MeV

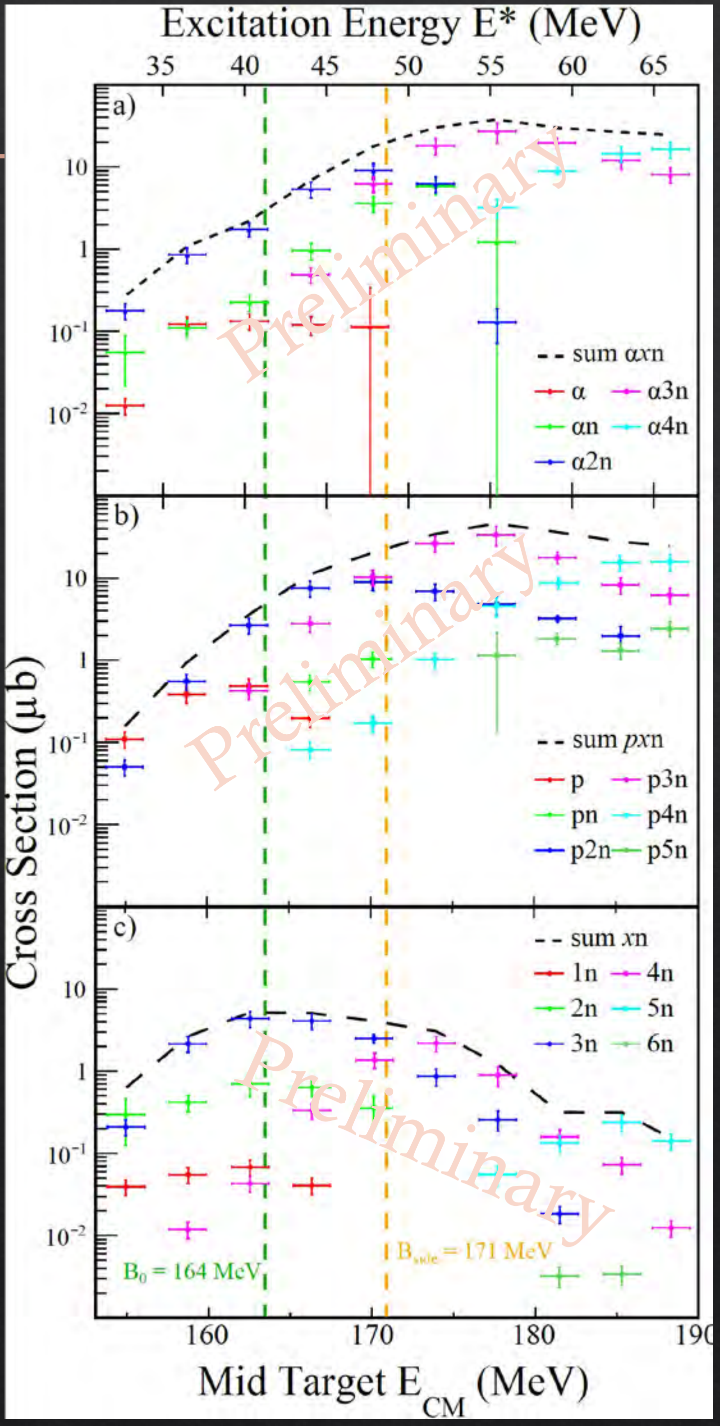


Preliminary Results/interpretation

Preliminary discussion/interpretation : barrier distribution

- Deformation needed to fit the measurement of the barrier distribution
- Maximum of the *xn* exit channel consistent to B_0 and not B_{side}
  - No side effect observed ?
- In discussion with Hagino-san for CCFULL interpretation

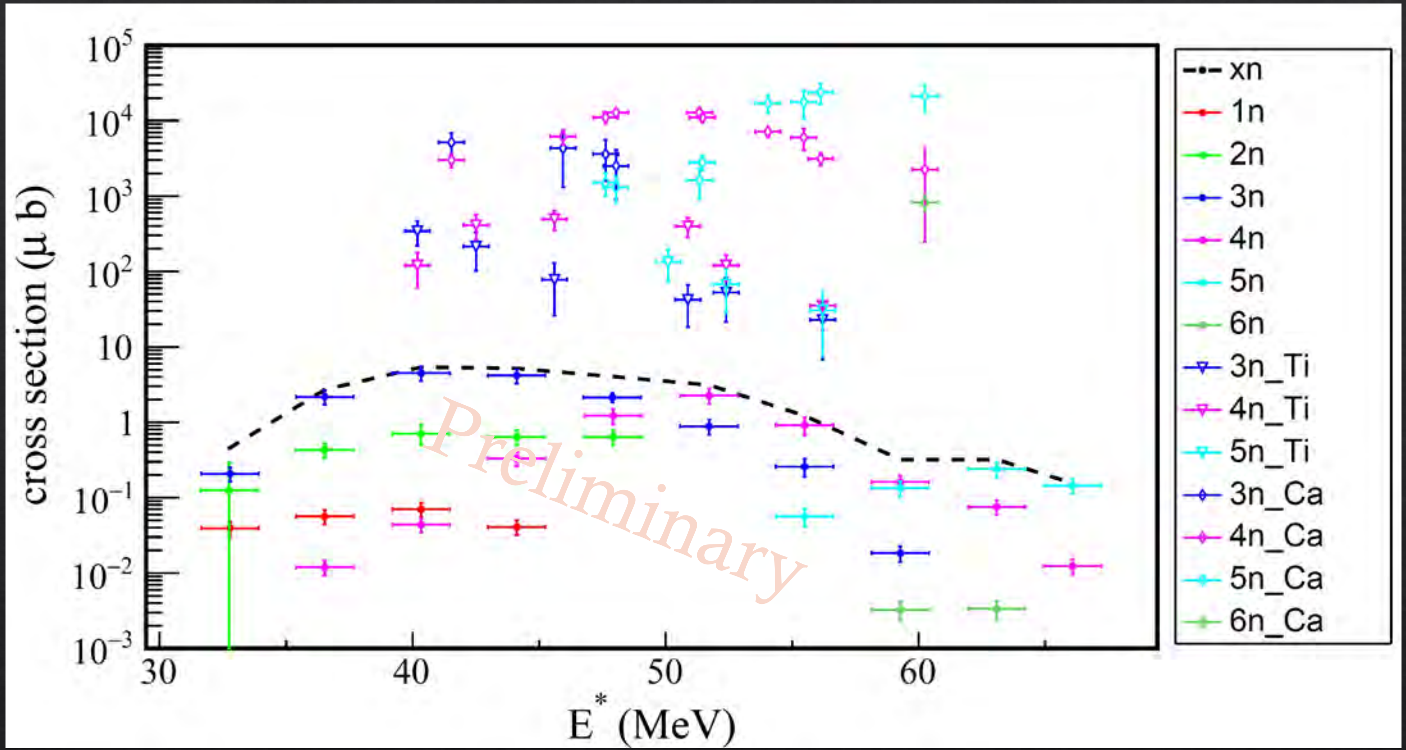




Preliminary discussion/interpretation : Cross-section of production

- Systematic decrease from Ca and Ti reaction on same target

D.A. Mayorov et al., PHYSICAL REVIEW C **90**, 024602 (2014)
D.A. Mayorov et al., PHYSICAL REVIEW C **92**, 054601 (2015)



- Ratio *pxn* to *xn* inverted compared to SHE mass region: higher fission barrier seems to enhance charged particle emission
- The ratio *pxn* to *xn* not always inverted in this mass region
  - ^{50}Ti + ^{159}Tb not inverted
  - ^{40}Ar + ^{174}Yb not inverted
  - ^{44}Ca + ^{159}Tb/^{162}Dy equal
  - ^{40}Ar + ^{171}Yb inverted
- In discussion with M. Kowal and T. Caps (Warsaw, Poland) for the cross-section discussion and theoretical estimation

Recap

- Barrier distribution measurement performed
  - Deformation strongly impact the fit to the data
  - Maximum of the *xn* consistent with B_0 and not B_{side}
  - Interpretation and discussion ongoing

- Detail excitation function for *xn*, *pxn* and *αxn* produced with high statistics
  - *pxn* and *αxn* higher than *xn* in production rate
    - Not unusual in this mass region because of the higher fission barrier
    - Theoretical input and discussion on going

- Publication in preparation

Collaborator

- RIKEN Nishina Center : K. Morimoto, D. Kaji, S. Kimura, H. Haba, H. Sakai
- Wako Nuclear Science Center (WNSC), IPNS, KEK : T. Niwase
- Department of Physics, Kyushu University: T. Fukatsu, Y. Michimoto, S. Sakaguchi, Y. Yamanouchi
- DNE team, IPHC : M. Forge
- For the nSHE collaboration