# Model analysis of isotope-production cross sections for proton- and deuteron-induced reactions on ^{93}Zr

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1. Introduction

- Treatment of High-Level Radioactive Waste is a crucial issue due to the long-term radiotoxicity of Long-Lived Fission Products (LLFPs).
- Nuclear transmutation has been proposed as a possible method of shortening their half-lives.
- So far, we have measured isotope-production cross sections in ^{93}Zr + p, d reactions at RIKEN RIBF[1,2] and performed systematic benchmark tests for PHITS[3].

^{238}U beam @ 345 MeV/u
^{9}Be target
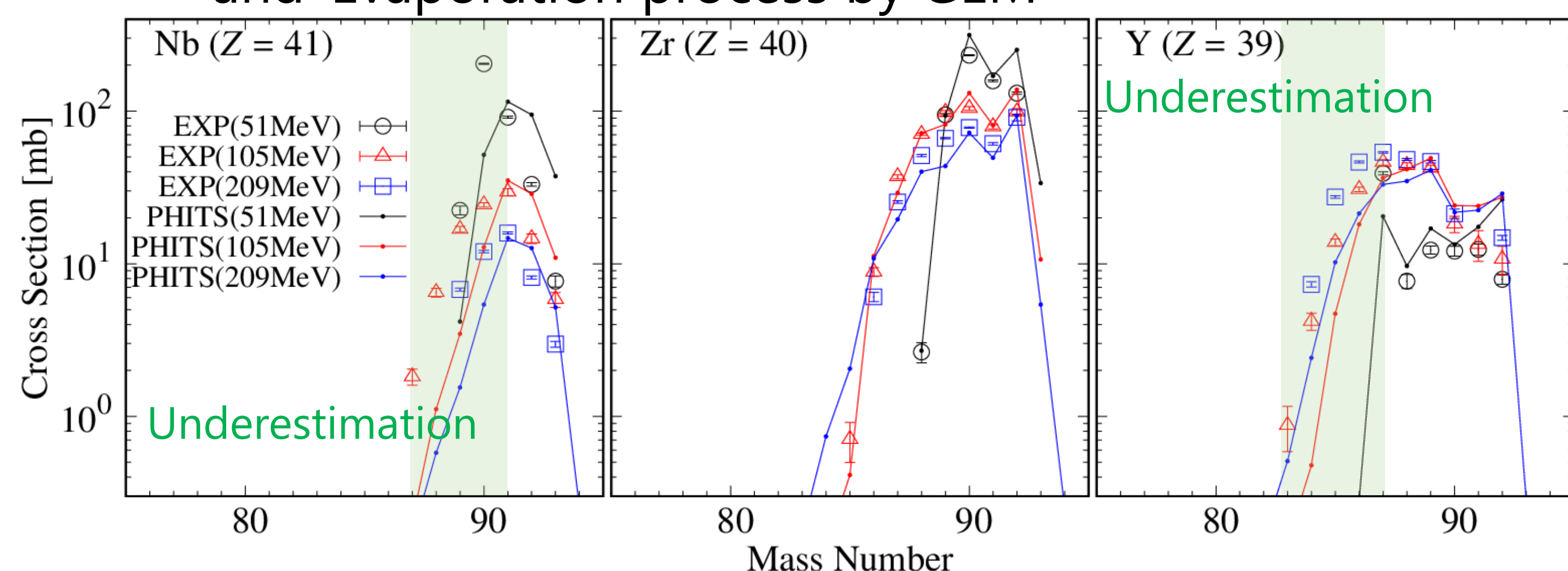^{93}Zr beam
H$_2$, D$_2$ targets
^{93}Zr
Reaction products
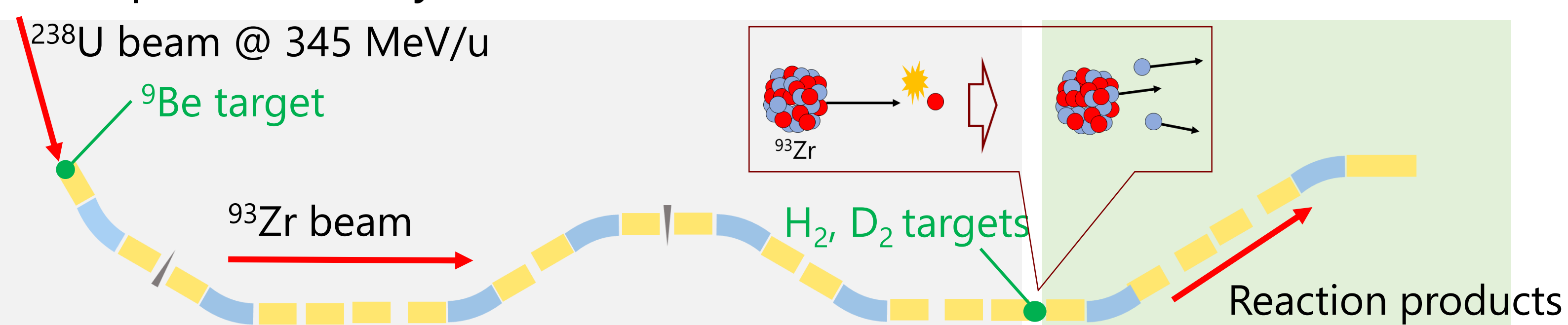
[1] S. Kawase et al., Prog. Theor. Exp. Phys. 2017, 093D03 (2017).
[2] S. Kawase et al., JAEA-Conf2018-001 2018, 111 (2018). [3] T. Sato et al., J. Nucl. Sci. Technol. 55, 684 (2018).
[4] A. Boudard et al., Phys. Rev. C 87, 014606 (2013). [5] S. Furihata, Nucl. Instrum. Meth. B 171, 251 (2000)

PHITS calculations underestimate cross sections in neutron-deficient region of odd-Z isotopes.
Two-step process:
Intranuclear Cascade (INC) process by INCL4.6[4], and Evaporation process by GEM[5]

Nb ($Z = 41$), Zr ($Z = 40$), Y ($Z = 39$)
EXP(51MeV), EXP(105MeV), EXP(209MeV)
PHITS(51MeV), PHITS(105MeV), PHITS(209MeV)
Underestimation

Purpose:
To clarify the cause of the underestimation seen in PHITS calculations of ^{93}Zr + p reactions.
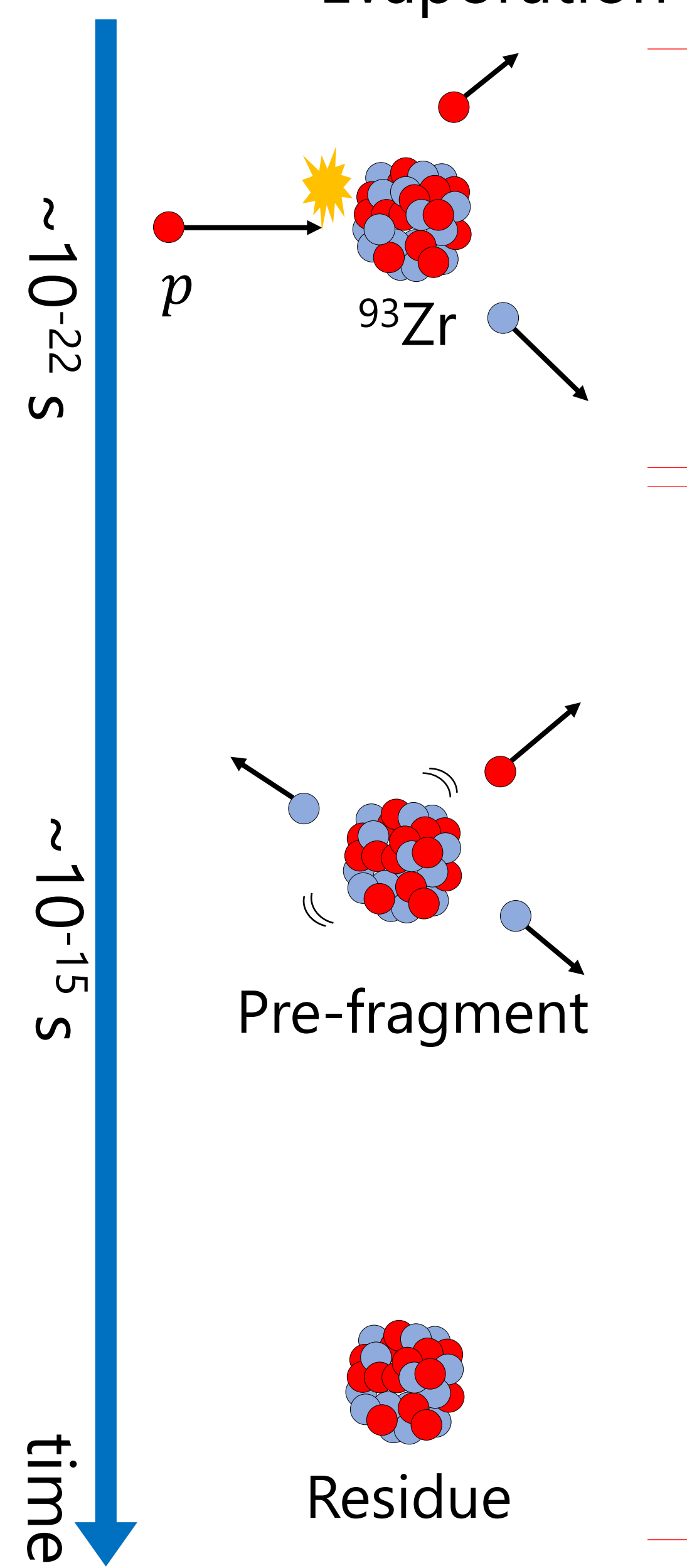
2. Method

INCL++/ABLA07[6,7] calculation reproduces the odd-Z isotopes.

Nb ($Z = 41$), Zr ($Z = 40$), Y ($Z = 39$)
EXP p
PHITS
INCL4.6/GEM
INCL++/GEM
INCL++/ABLA07
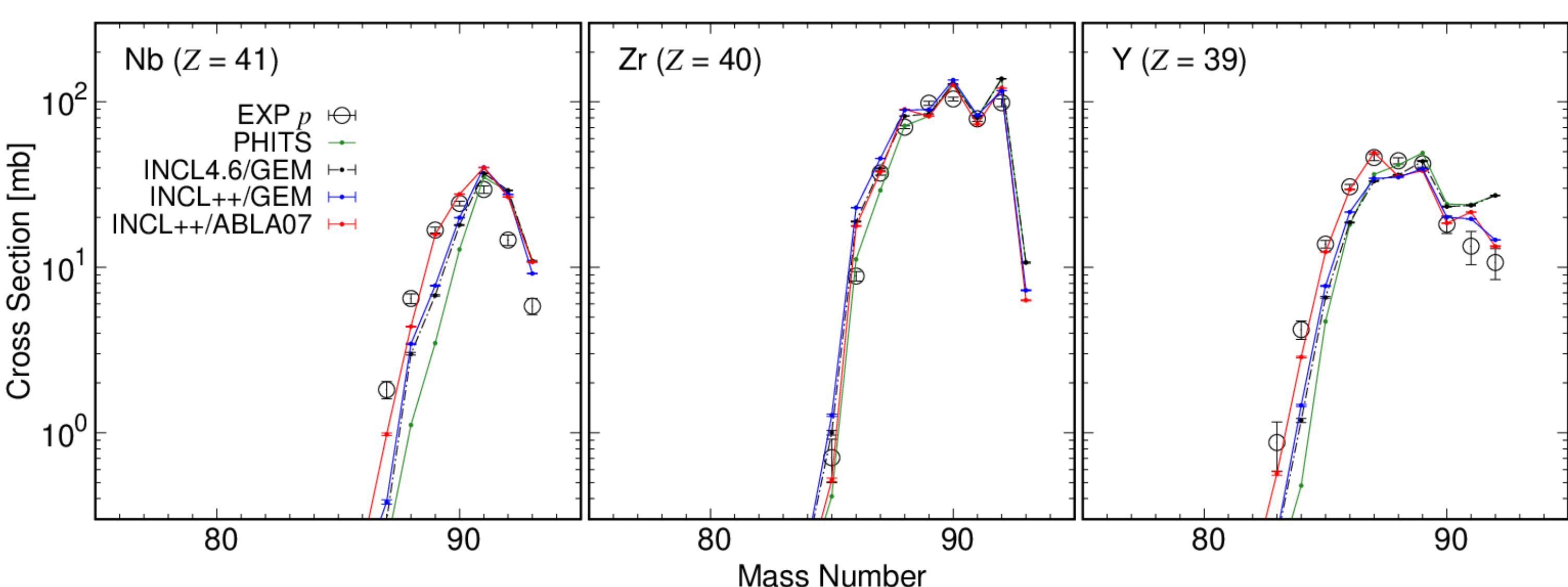
→ The cause was investigated by comparing calculations by INCL++/ABLA07 and INCL++/GEM for ^{93}Zr + p @ 105 MeV.

Calculations:
- No. of events: 1.0×10^7
- INC Process: INCL++ version 6.28
- Evaporation Process: GEM or ABLA07

$\sim 10^{-22}$ s

p
^{93}Zr

INC Process: INCL++
A, Z, and excitation energy (E_x) distributions of pre-fragments in INCL++/GEM and INCL++/ABLA07 calculations are completely the same.

Evaporation Process: GEM or ABLA07
For each event, we recorded
- A, Z, and E_x for pre-fragment ($A_{\rm pre}, Z_{\rm pre}$),
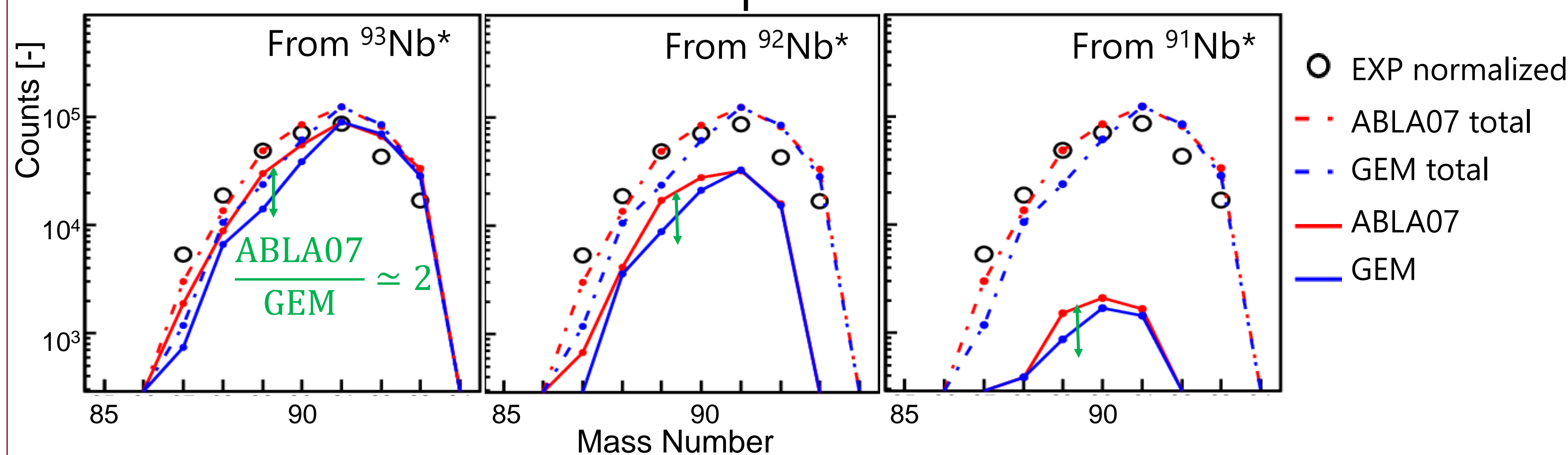- A, Z, and kinetic energy ($E_{\rm kin}$) for residual nuclei and for emission particles ($A_{\rm res}, Z_{\rm res}$).

$\sim 10^{-15}$ s

Pre-fragment

Residue

time

Event	$A_{\rm pre}$	$Z_{\rm pre}$	E_x[MeV]	$A_{\rm res}$	$Z_{\rm res}$	$E_{\rm kin}$[MeV]
1	92	39	12.08	1	0	3.84
1	-	-	-	91	39	0.04
2	93	40	71.54	1	0	3.14
2	-	-	-	1	0	4.93
2	-	-	-	1	1	6.65
2	-	-	-	87	39	0.14

Data of pre-fragment and residue were stored in ROOT file, and Event-by-Event analysis was performed for each event.

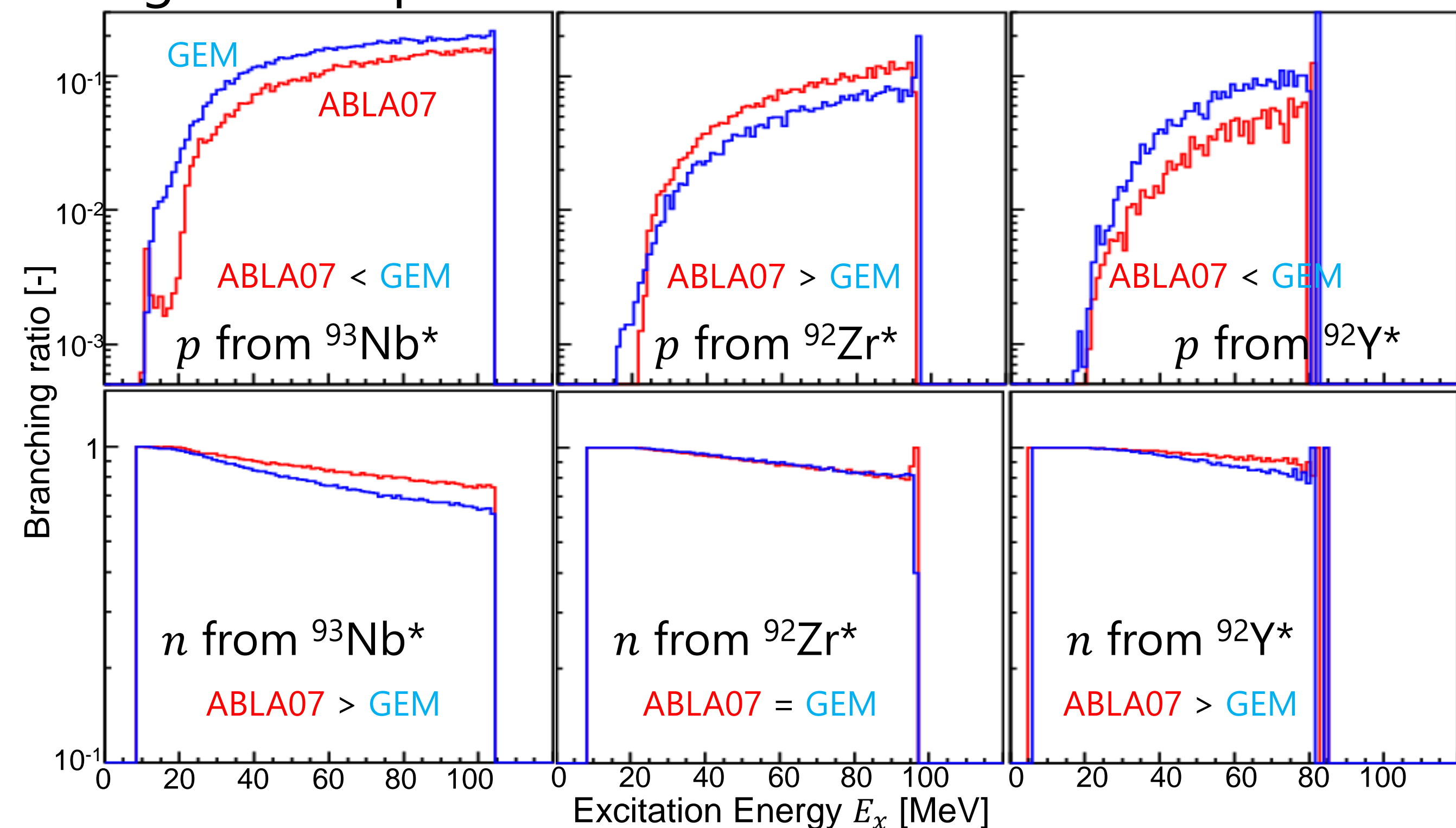[6] D. Mancusi et al., Phys. Rev. C 90, 054602 (2014).   [7] A. Kelic et al., arXiv 0906 4193 (2009).

3. Results and Discussion

Residue distributions from Nb pre-fragments

From ^{93}Nb*, From ^{92}Nb*, From ^{91}Nb*
EXP normalized
ABLA07 total
GEM total
ABLA07
GEM
$\frac{\rm ABLA07}{\rm GEM} \simeq 2$

ABLA07 has twice larger yields in neutron-deficient region. This tendency is the same among the all Nb isotopes.

Branching ratio of proton and neutron

GEM, ABLA07
ABLA07 < GEM, p from ^{93}Nb*
ABLA07 > GEM, p from ^{92}Zr*
ABLA07 < GEM, p from ^{92}Y*
ABLA07 > GEM, n from ^{93}Nb*
ABLA07 = GEM, n from ^{92}Zr*
ABLA07 > GEM, n from ^{92}Y*

GEM has larger p-emission branching ratio than ABLA07 in odd-Z.
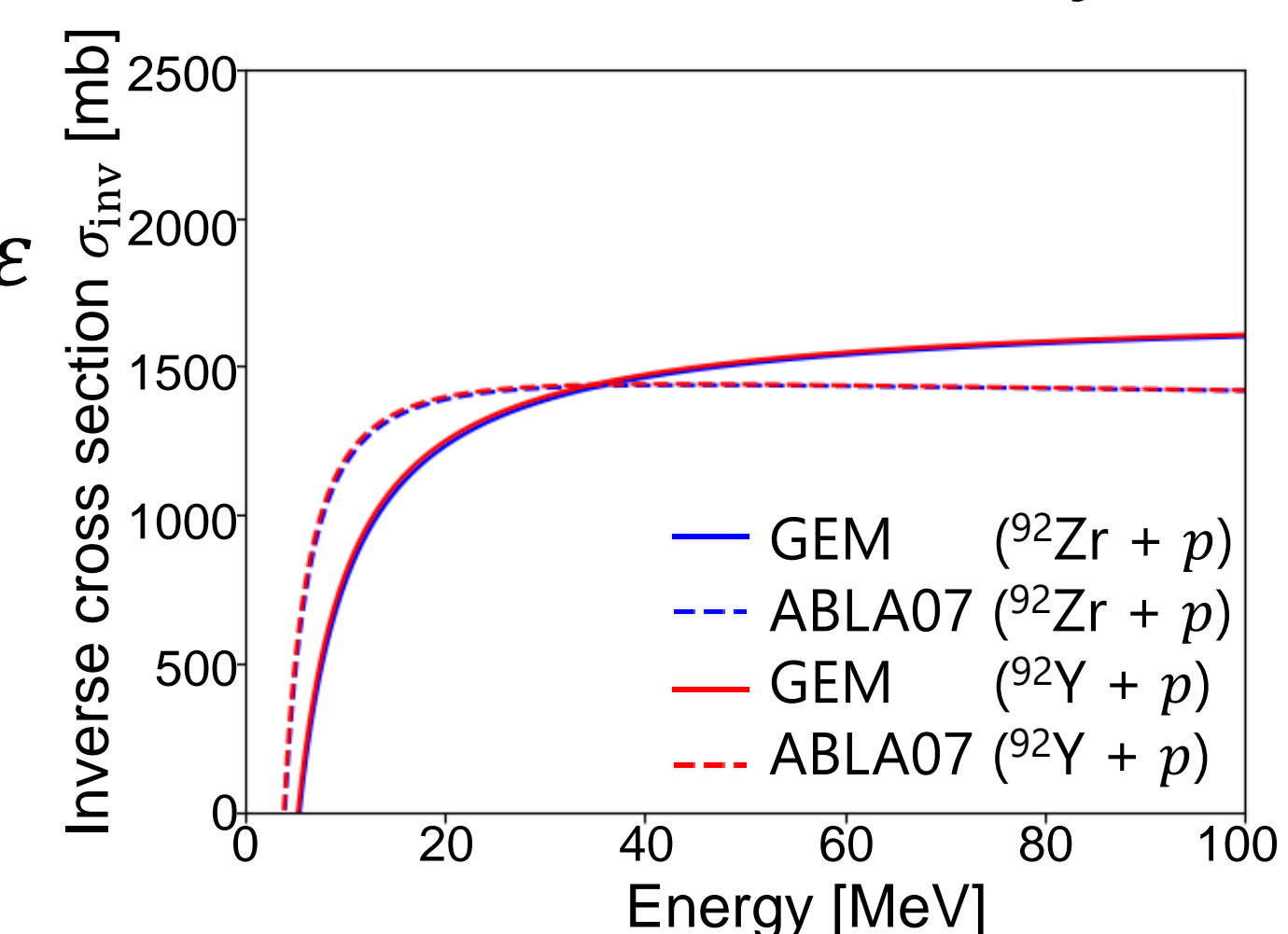→ Underestimation was observed in odd-Z isotopes

In ABLA07 and GEM, decay width of particle j emission (Γ_j) is calculated from inverse cross section (σ_{inv}) and level density (ρ):

$$\Gamma_j \propto \int_V^{E_x-Q} \sigma_{\rm inv}(\varepsilon) \frac{\rho_{\rm fin}(E_x - Q - \varepsilon)}{\rho_{\rm init}(E_x)} d\varepsilon$$

V: Coulomb barrier
ε: Kinetic energy of emission particle

Both or either $\sigma_{\rm inv}$ or ρ can be the cause of the underestimation.

GEM (^{92}Zr + p)
ABLA07 (^{92}Zr + p)
GEM (^{92}Y + p)
ABLA07 (^{92}Y + p)

σ_{inv} has no dependence on even-odd of pre-fragment.
→ Level densities ($\rho_{\rm fin}, \rho_{\rm init}$) must be reconsidered to resolve the underestimation.

4. Summary and Future Perspectives

- Cause of underestimation in odd-Z isotope was investigated.
- GEM shows larger p-emission branching ratio than ABLA07.

- From the comparison of inverse cross sections, modification of level density in GEM has a possibility to improve the underestimation.
- In the future, modification of pairing correction in GEM is expected.