

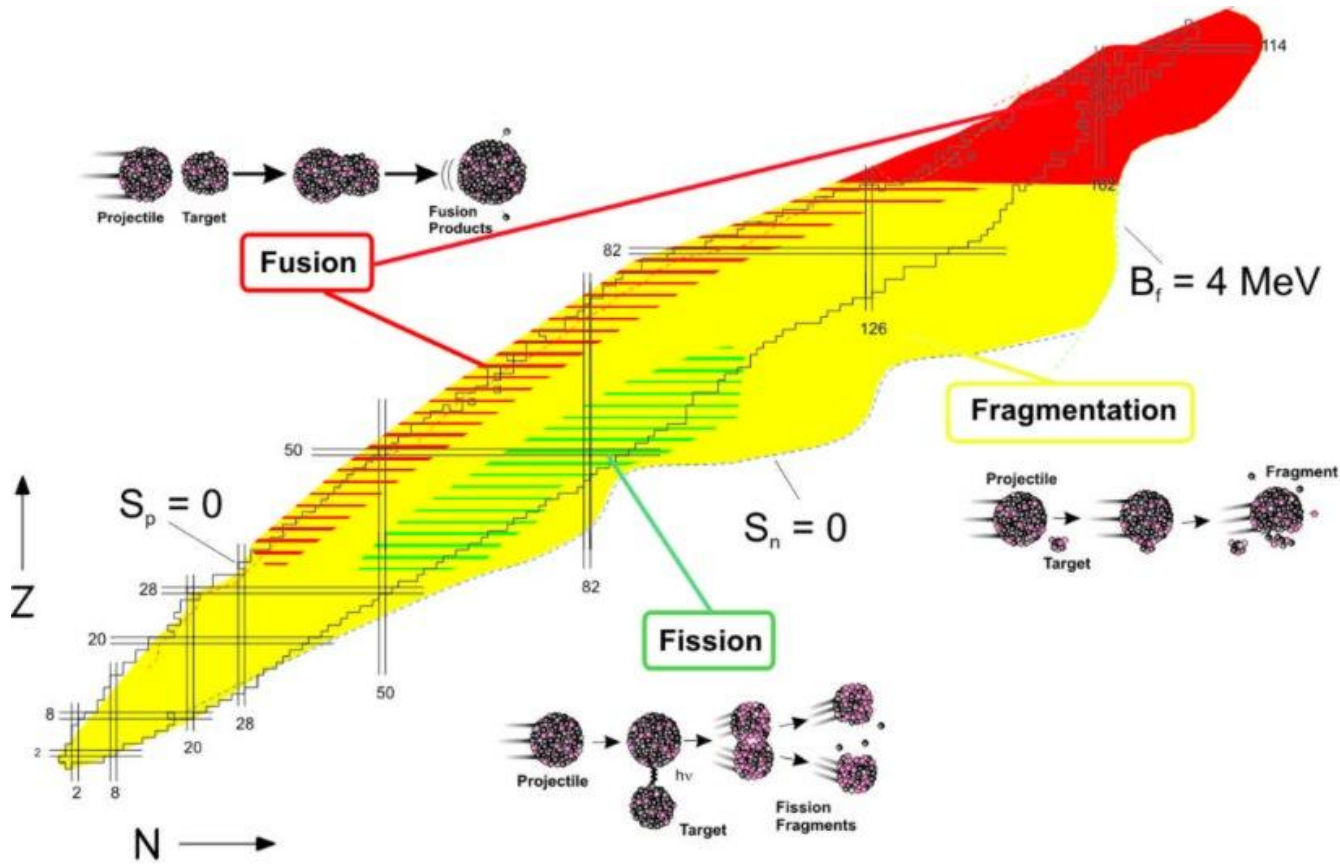
MOCADI Extension for heavy ions produced in charge-exchange reaction

Tomoyasu Miyashita

Tohoku University

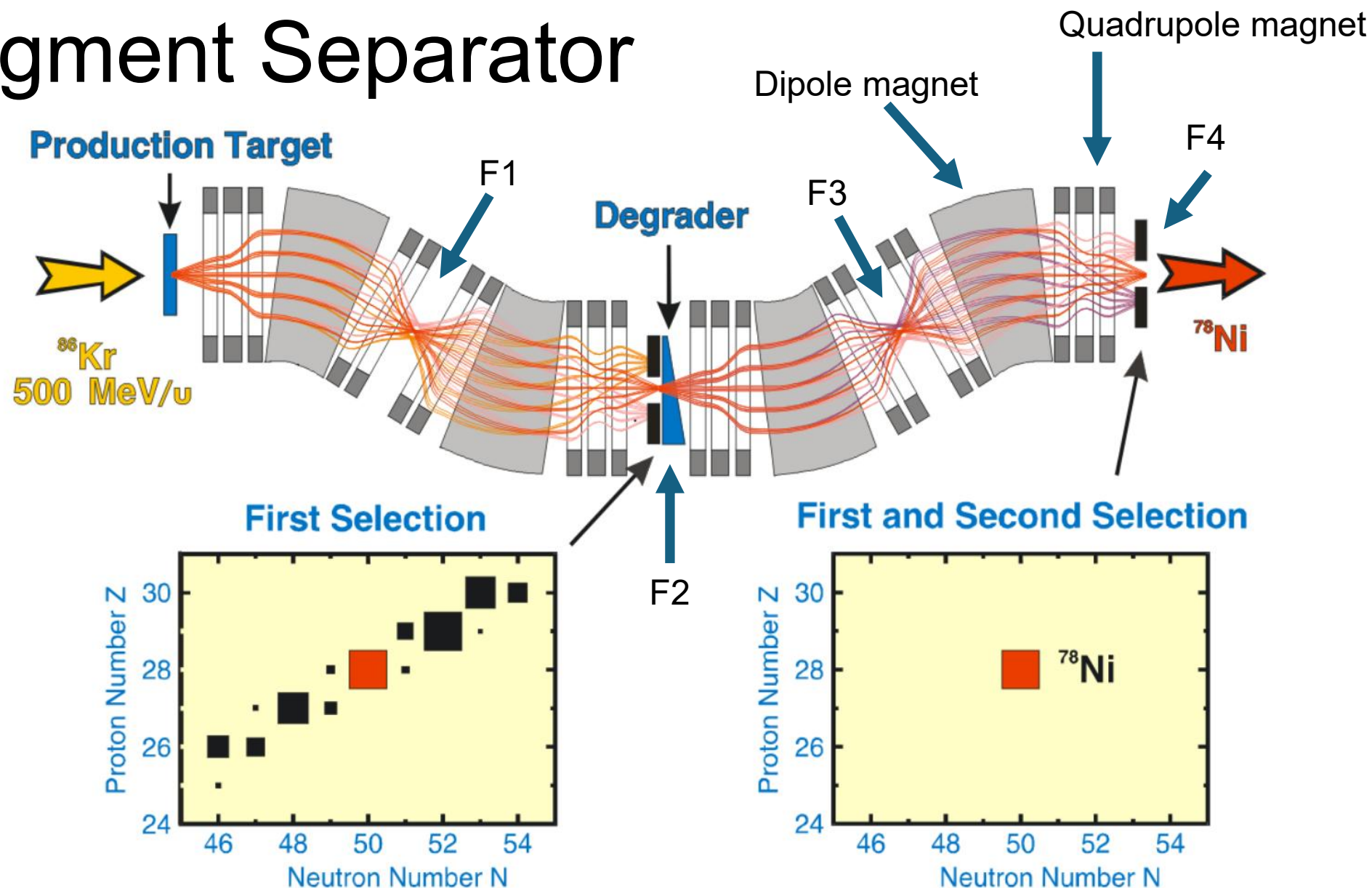
14 September 2026

Study of Unstable Nuclides

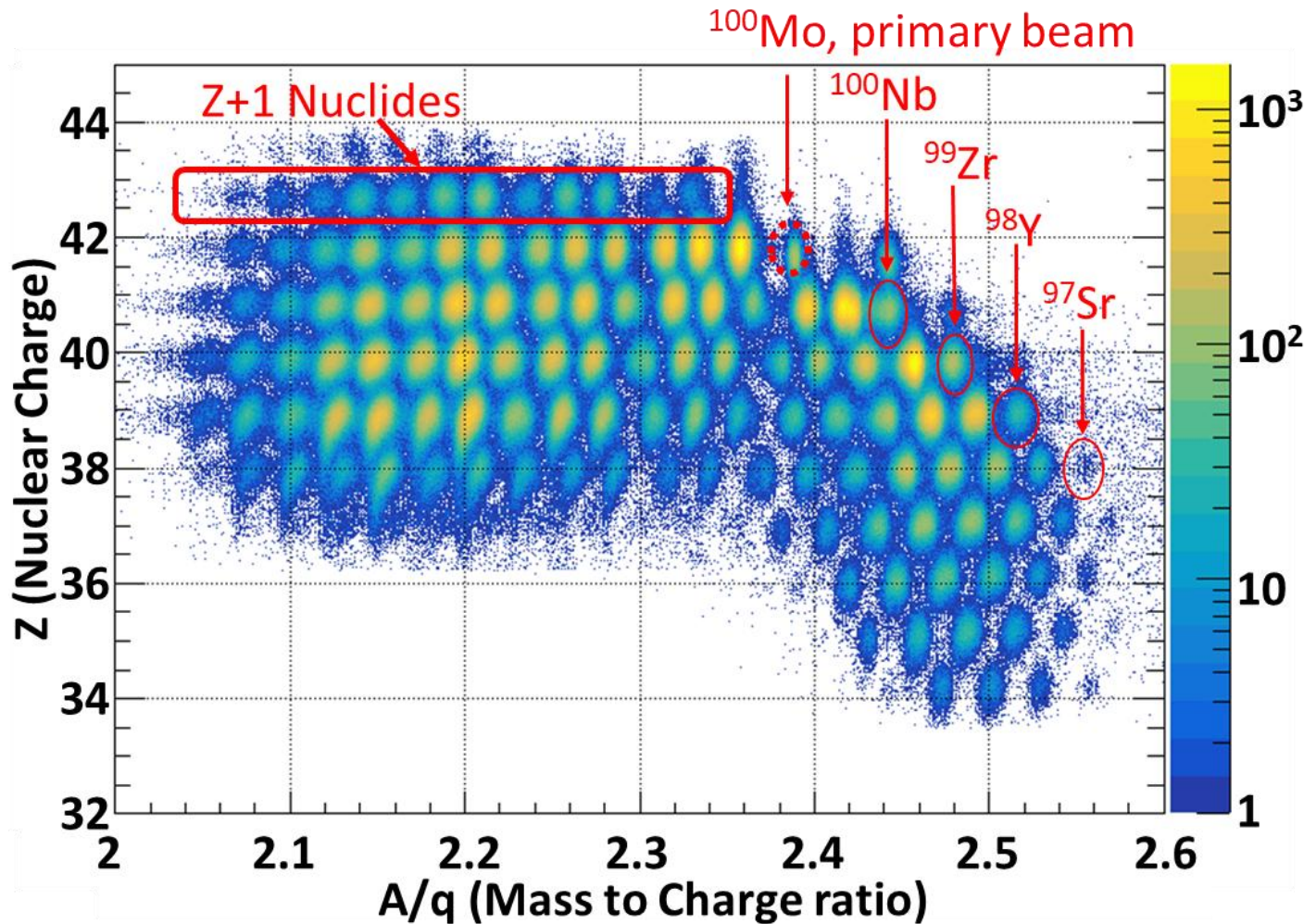


- Explore the properties of nuclei far from stability
- Extend our understanding of nuclear structure
- Understand the origin of the elements in the Universe

Fragment Separator



$^{100}\text{Mo} + ^9\text{Be}$ reaction at 500 MeV/u



Nuclides containing

one more proton
→ $Z + 1$ nuclides

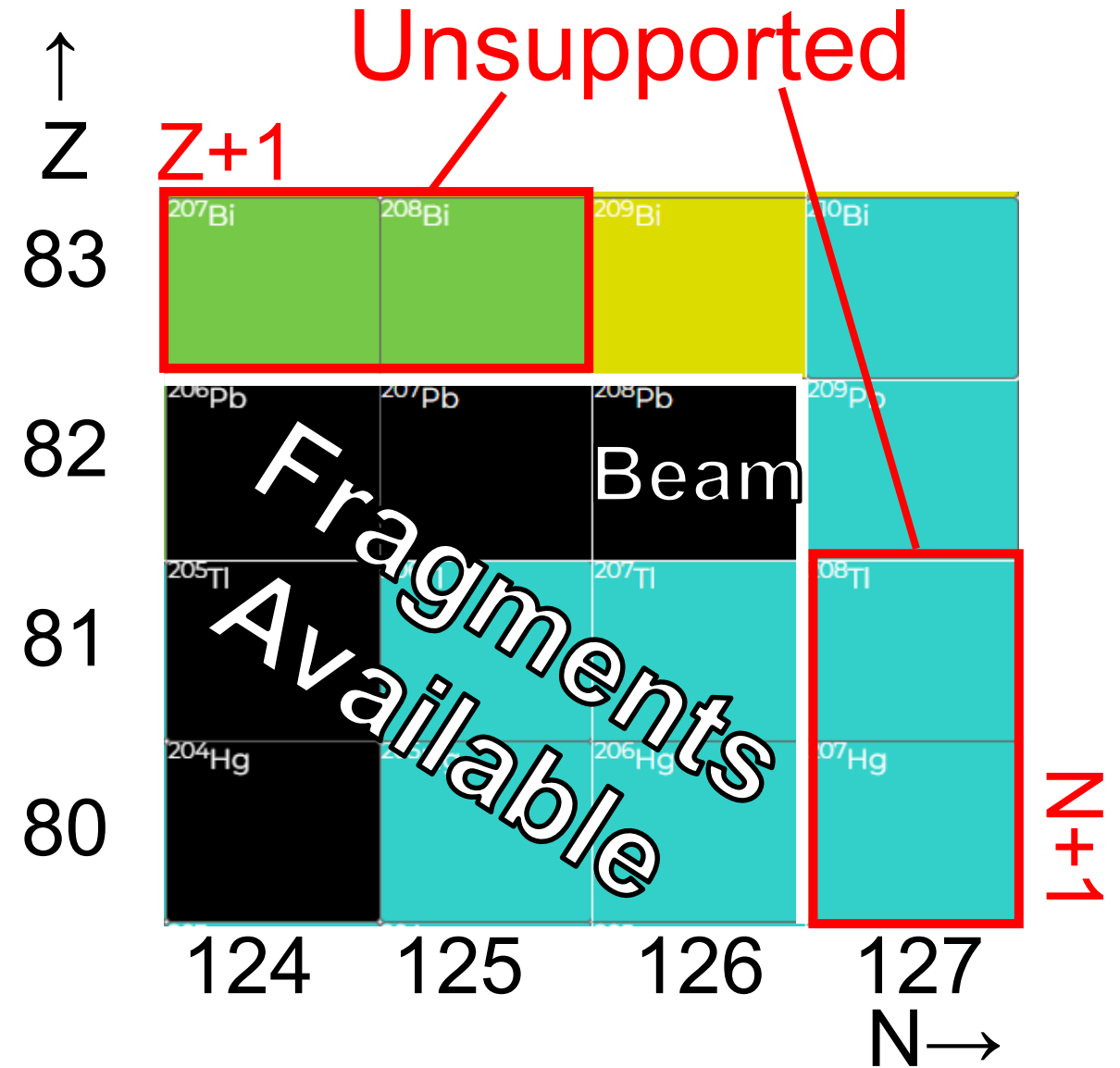
one more neutron
→ $N + 1$ nuclides

MOCADI

- Monte-Carlo code for simulating particle transport through ion-optical systems
- Includes nuclear reaction models
 - Projectile fragmentation, fission, fusion-evaporation reaction, and two-body kinematics
- Atomic interactions for
 - energy loss and straggling

Purpose of Project

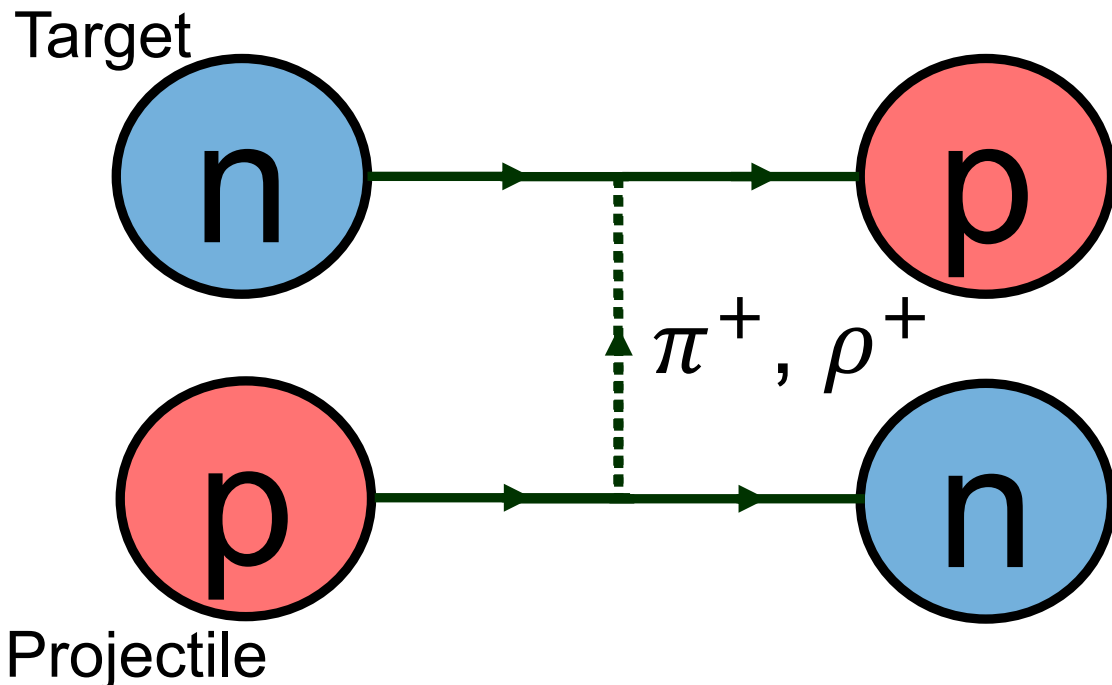
- Current MOCADI does not support Z+1 and N+1 fragments.
- The goal of the project is to
 - Enable the simulation of Z+1 and N+1 nuclei with mass loss
 - Implement their production mechanisms in practical way
 - Achieve a reasonable reproduction of experimental data



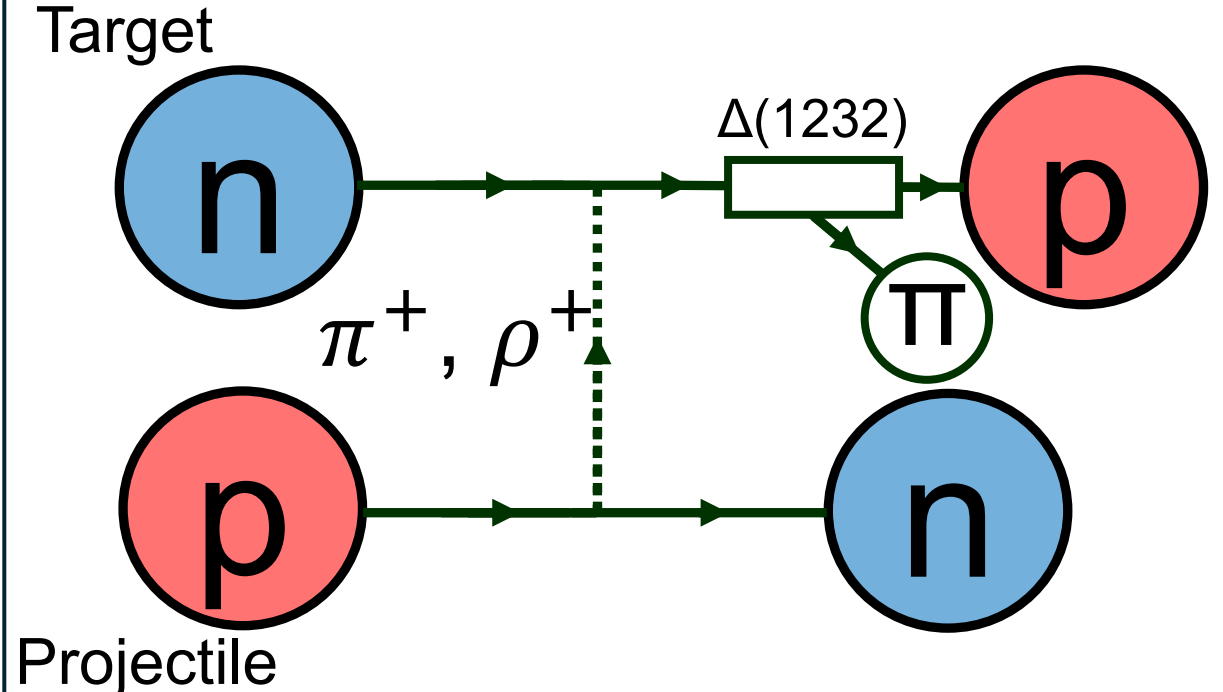
Reaction Mechanisms for Z+1, N+1 Production

- Z+1, N+1 fragments are mainly produced through two mechanisms:

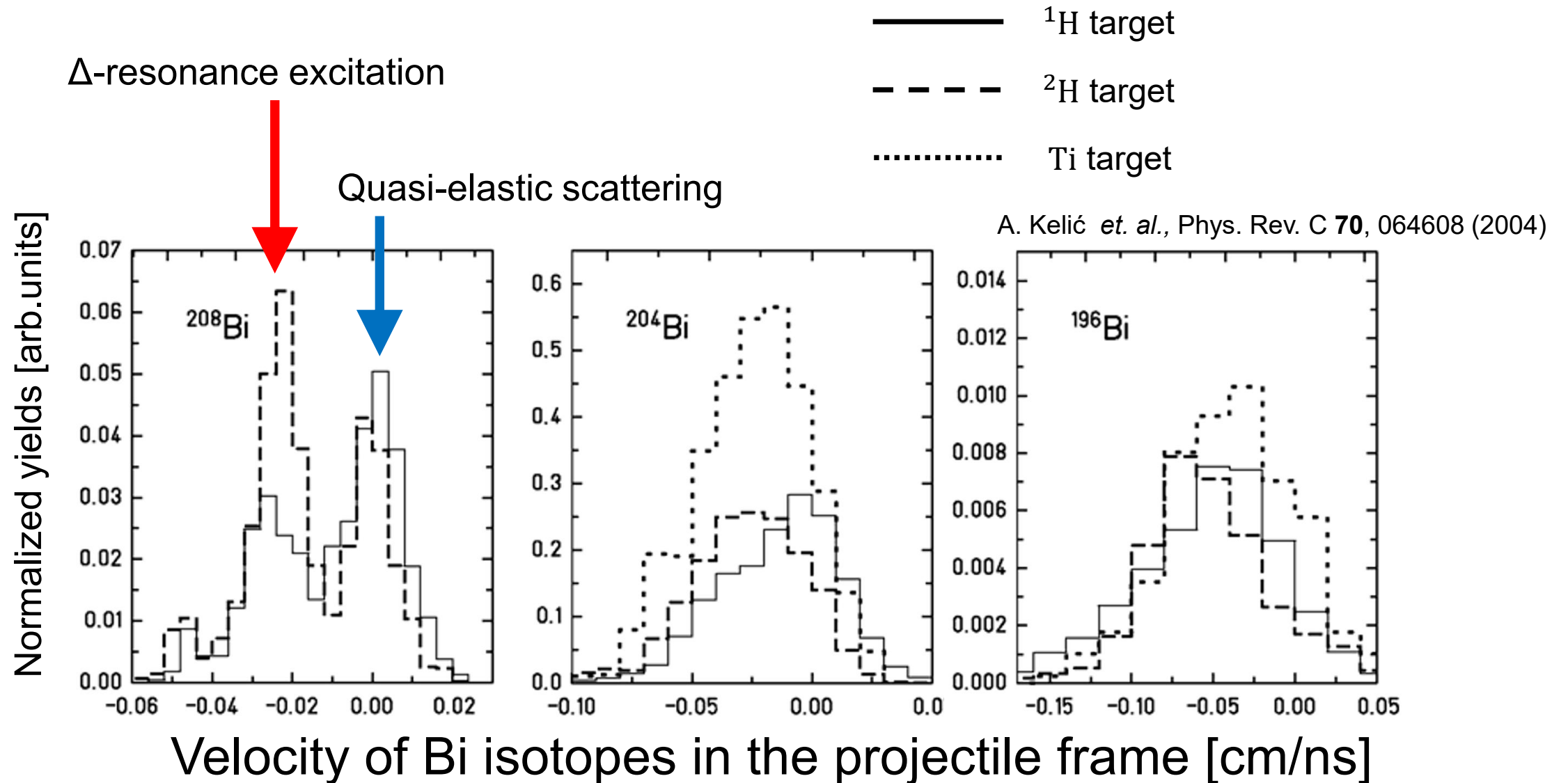
-Quasi-elastic scattering



$\Delta(1232)$ -resonance excitation



$^{208}\text{Pb} + ^1\text{H}$, $^{208}\text{Pb} + ^2\text{H}$ reactions at 1000 MeV/u

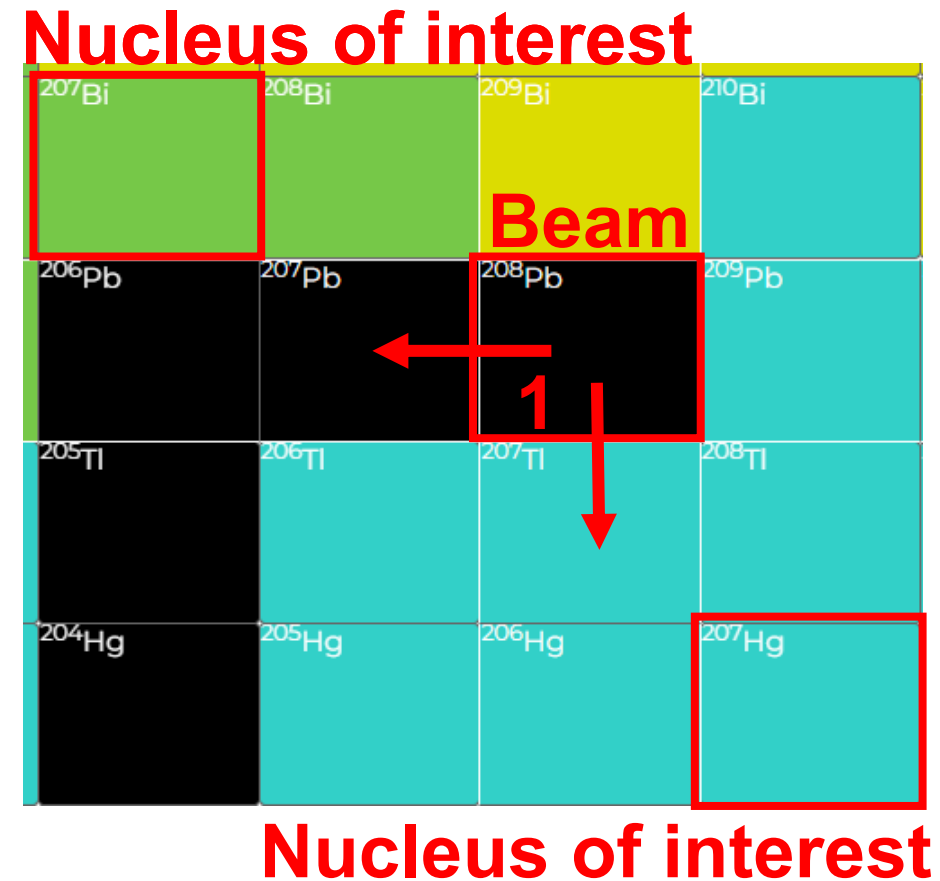


Model for Production of $Z + 1$ and $N + 1$ Nuclides

Assumption: production of $Z + 1$ and $N + 1$ nuclides can be approximated in two steps.

First step

- A precursor nucleus is formed through projectile fragmentation.
- Mass number of precursor = Mass number of nucleus of interest
- The central momentum and momentum spread of the precursor are determined

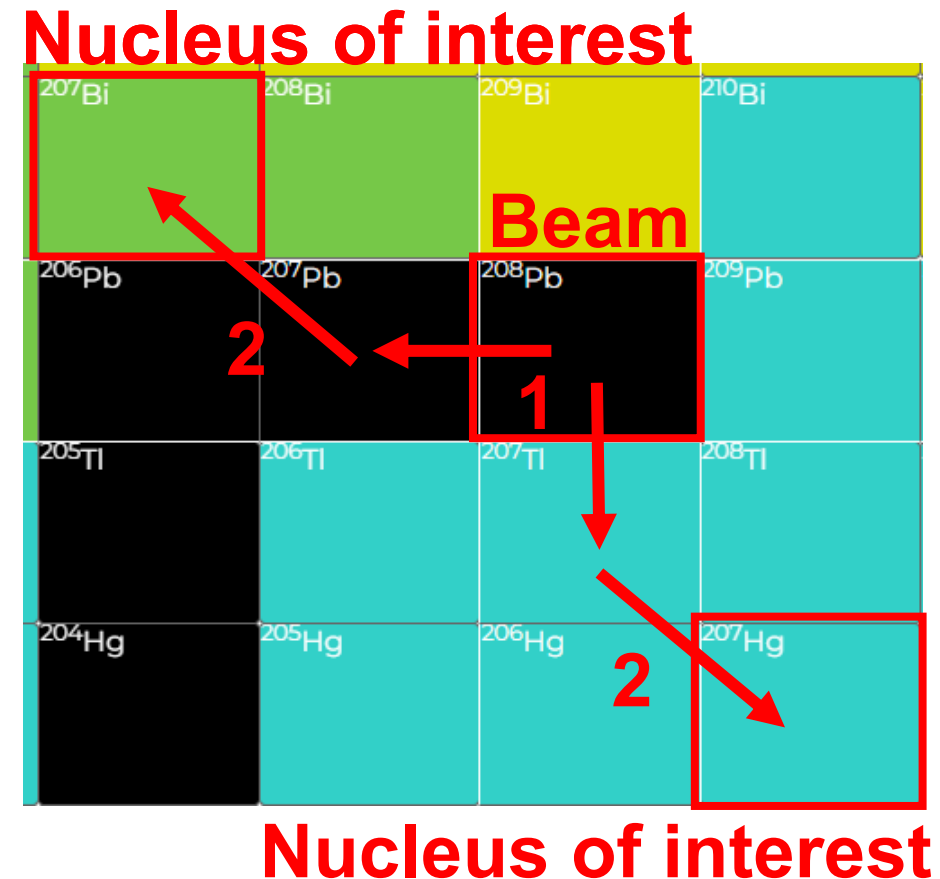


Model for Production of $Z + 1$ and $N + 1$ Nuclides

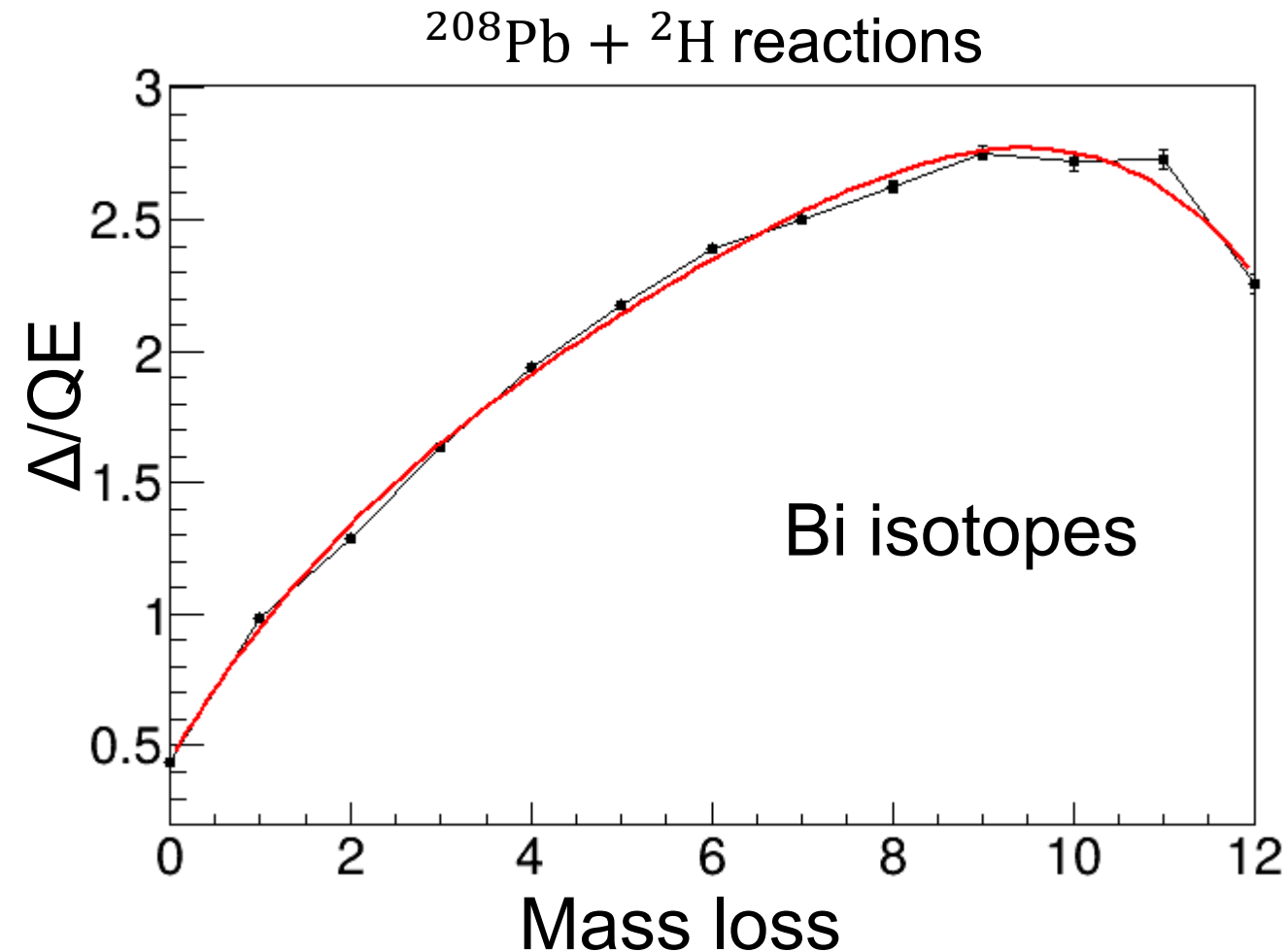
Assumption: production of $Z + 1$ and $N + 1$ nuclides can be approximated in two steps.

Second step

- The fragmentation is followed by a charge-exchange reaction.
- Charge-exchange reaction has contributions from :
 - Quasi-elastic process
 - Inelastic process involving the $\Delta(1232)$ resonance.
- The inelastic process is modeled as 293 MeV excitation of the target nucleus.
- The relative probabilities of the two processes are parameterized.



Ratio between Quasi-Elastic and Δ -Resonance



INCL++ simulation



Estimation of Δ/QE



Input to MOCADI

Comparison with Experimental Data

Case 1: Velocity Distribution

$^{208}\text{Pb} + ^2\text{H}$ at 1000 MeV/u

A. Kelić *et. al.*, Phys. Rev. C **70**, 064608 (2004)

- Bi isotopes
- Longitudinal velocity distributions
- Mean velocity vs. mass loss
- Only reaction properties

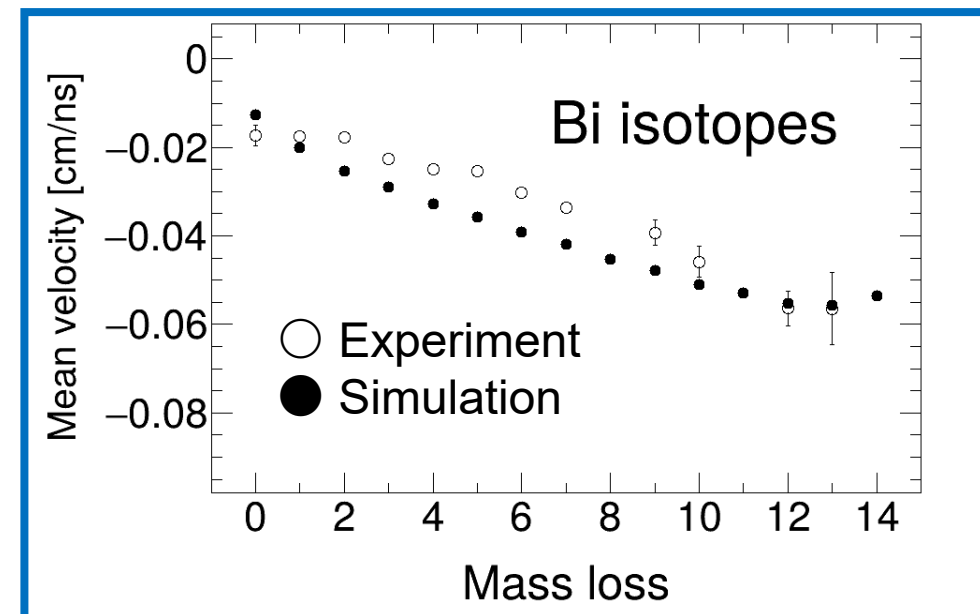
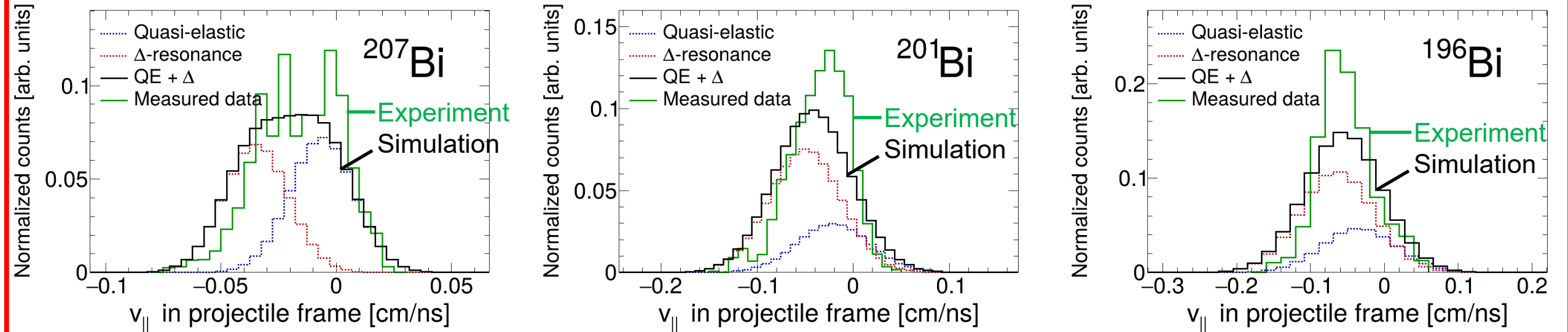
Case 2: Horizontal position at F2

$^{100}\text{Mo} + ^9\text{Be}$ at 500 MeV/u

S. K. Singh, private communication (2026)

- ^{99}Zr
- Horizontal position distribution at F2
- Including material effects

Case 1: Comparison of Velocity Distribution



Velocity distribution

- Overall shapes are in reasonable agreement.
- Widths can be tuned by applying scaling factor.

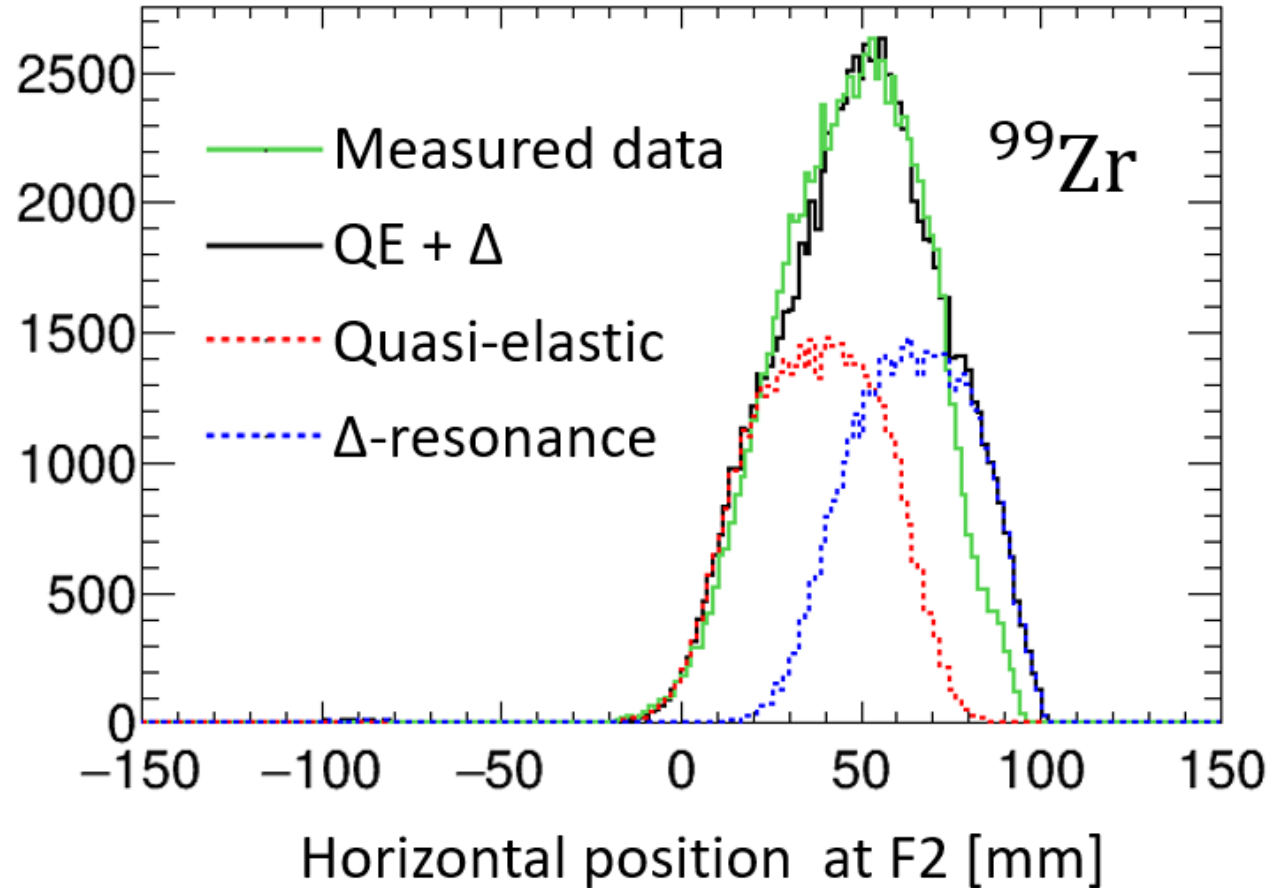


Mean velocity

- Overall dependence is in good agreement.
- The discrepancies could be due to the relative probabilities of Δ and QE.

Case 2: Comparison of Horizontal Position at F2

100Mo + 9Be at 500 MeV/u



- Compared horizontal position at F2
 - Reproduced distributions observed in the experiment
 - Both QE and Δ processes are necessary to reproduce the distribution

Summary

- We updated MOCADI to enable simulations of $Z + 1$ and $N + 1$ nuclides.
- We implemented the production of $Z + 1$ and $N + 1$ nuclides with mass loss assuming a simplified two-step model:
 - Fragmentation process followed by charge-exchange reaction
- Approximate reproduction of the main features of the experimental distributions are achieved using the updated MOCADI.
- Slight discrepancies still remained in the velocity distributions, which can be refined by tuning parameters in MOCADI.
- Further developments will include the target N/Z and projectile-energy dependences of Δ/QE , a more realistic treatment of Δ formation, and an extension to $Z + 2$ nuclides.