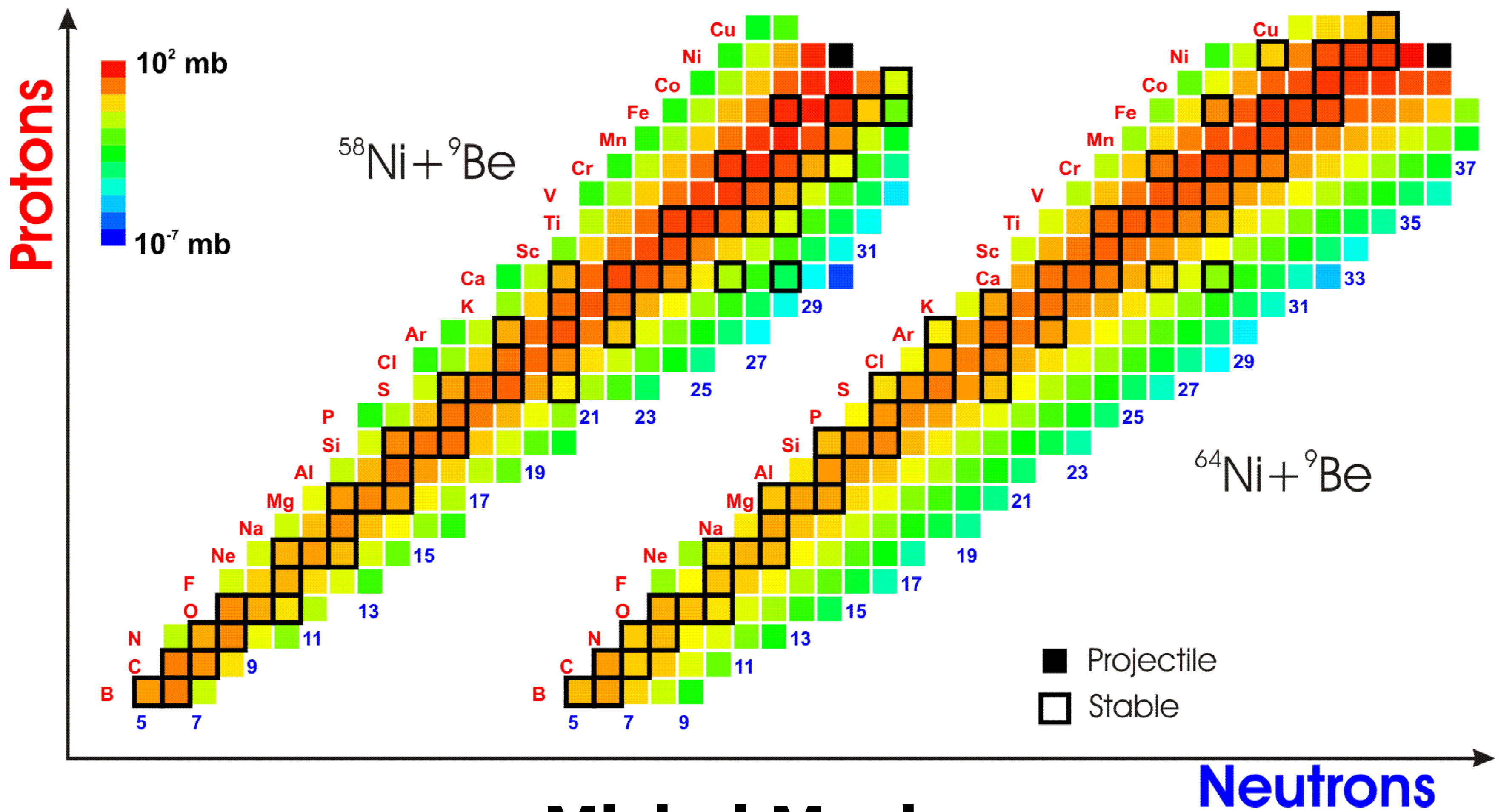
Rare Isotope Production



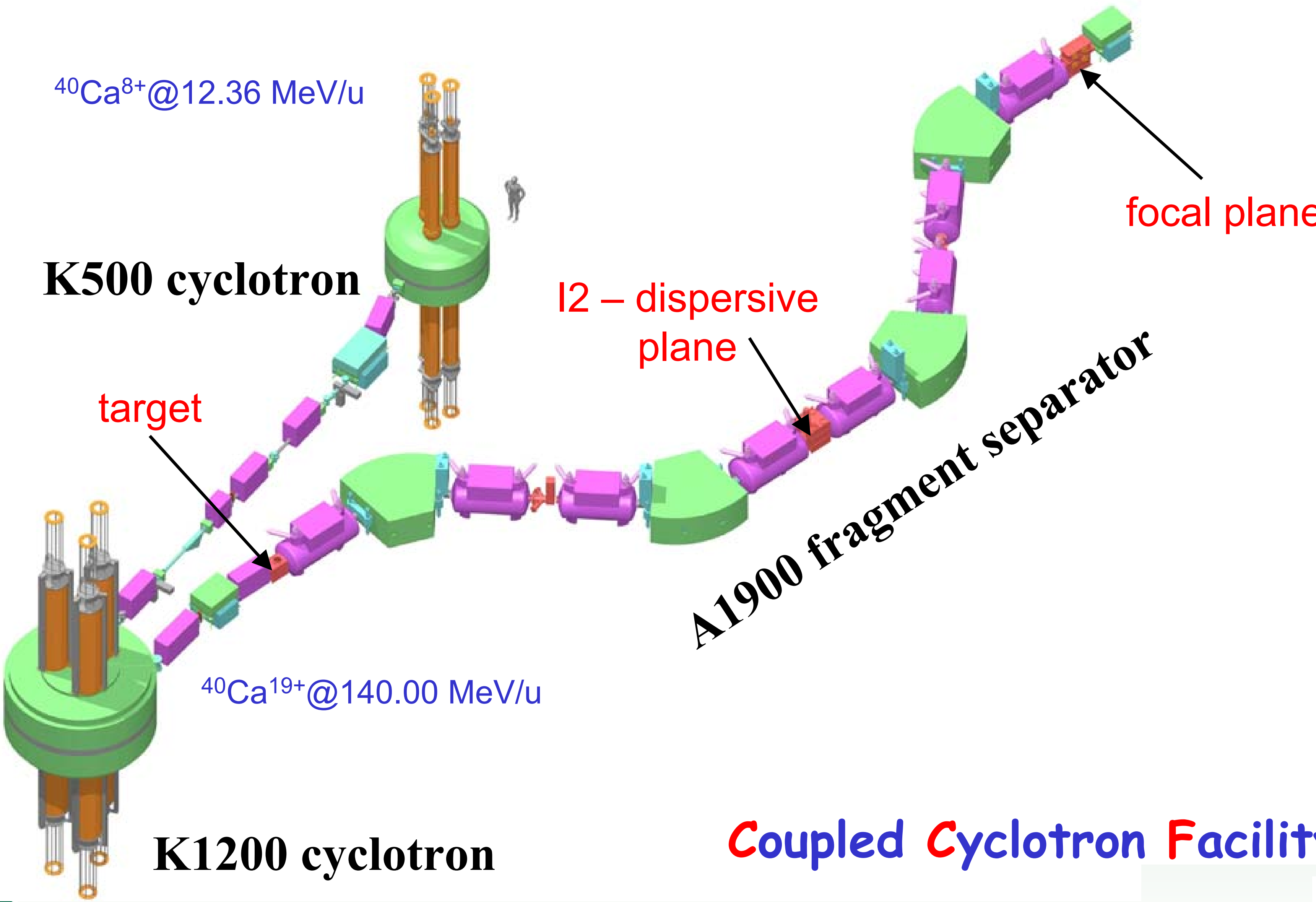
Michal Mocko

Thesis defense, MSU-NSCL

Projectile fragmentation experiments

- **Production technique for rare isotope beams**
- **Understand the fragmentation reaction mechanisms with models**
  - *How do the data compare to EPAX?*
  - *How do the data depend on target/projectile?*
  - *How do the data compare to Abrasion-Ablation models?*
  - *How can one go beyond the AA models?*
- **NSCL experiments**
  - **^{40}Ca, ^{48}Ca, ^{58}Ni, ^{64}Ni** at **140 MeV/u** (10^{6}-10^{11} pps)
  - **^{9}Be** (100 mg/cm^2) and **^{181}Ta** (220 mg/cm^2)
- **RIKEN experiment**
  - **^{86}Kr** at **64 MeV/u** (10^{6}-10^{11} pps)
  - **^{9}Be** (96 mg/cm^2) and **^{181}Ta** (153 mg/cm^2)

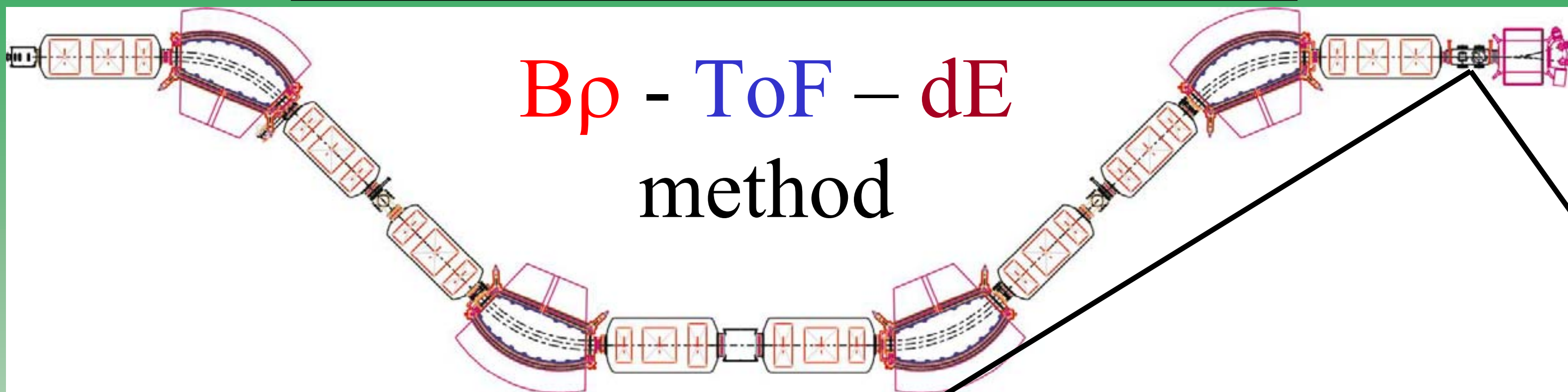
CCF @ NSCL



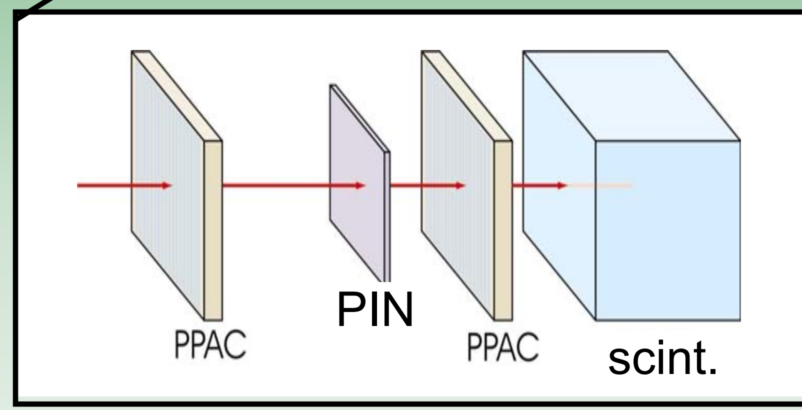
Coupled Cyclotron Facility

A1900: setup

Fragments fully stripped ➔ Z=Q



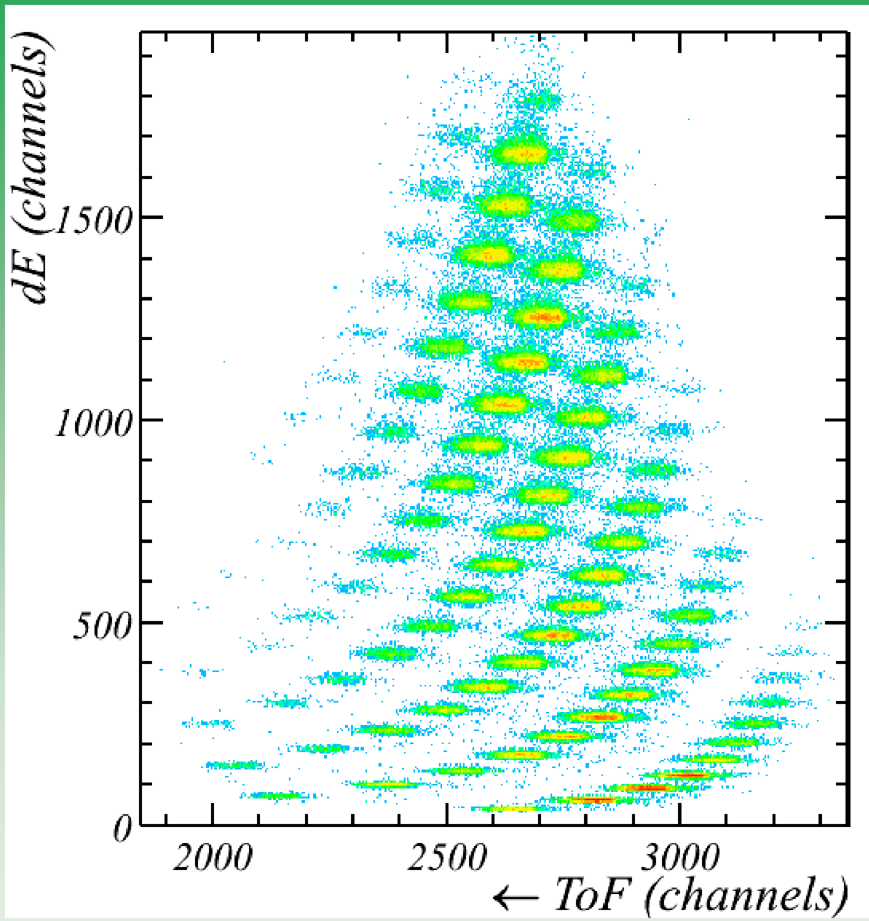
- Bρ ➔ A1900 (0.2% in dp/p)
- ToF ➔ RF ⬄ scint.
- dE ➔ PIN

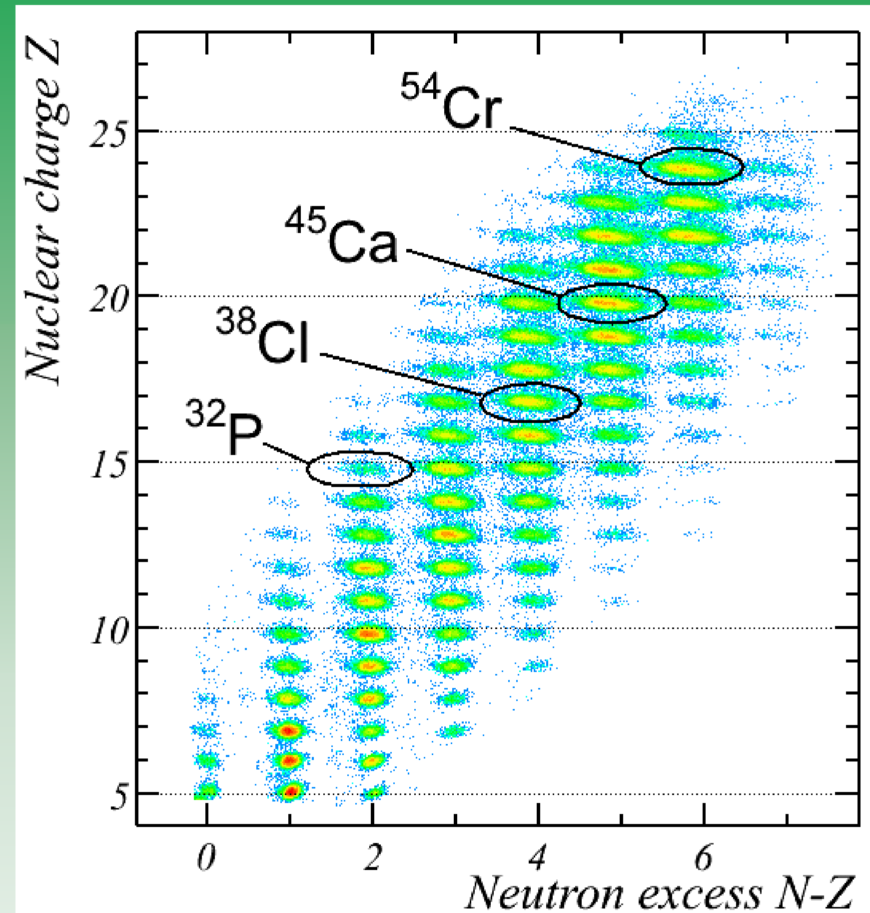


$$B\rho \approx \frac{A}{Z}\beta\gamma \qquad dE \approx \frac{Z^2}{\beta^2}$$

- **PIN:** 0.5 mm thick, 50×50 mm^2 Si
- **PPAC:** 100×100 mm^2, ***resistive readout***, Isobutane (5 Torr)
- **Scintillator:** 150×100×100 mm^3, plastic

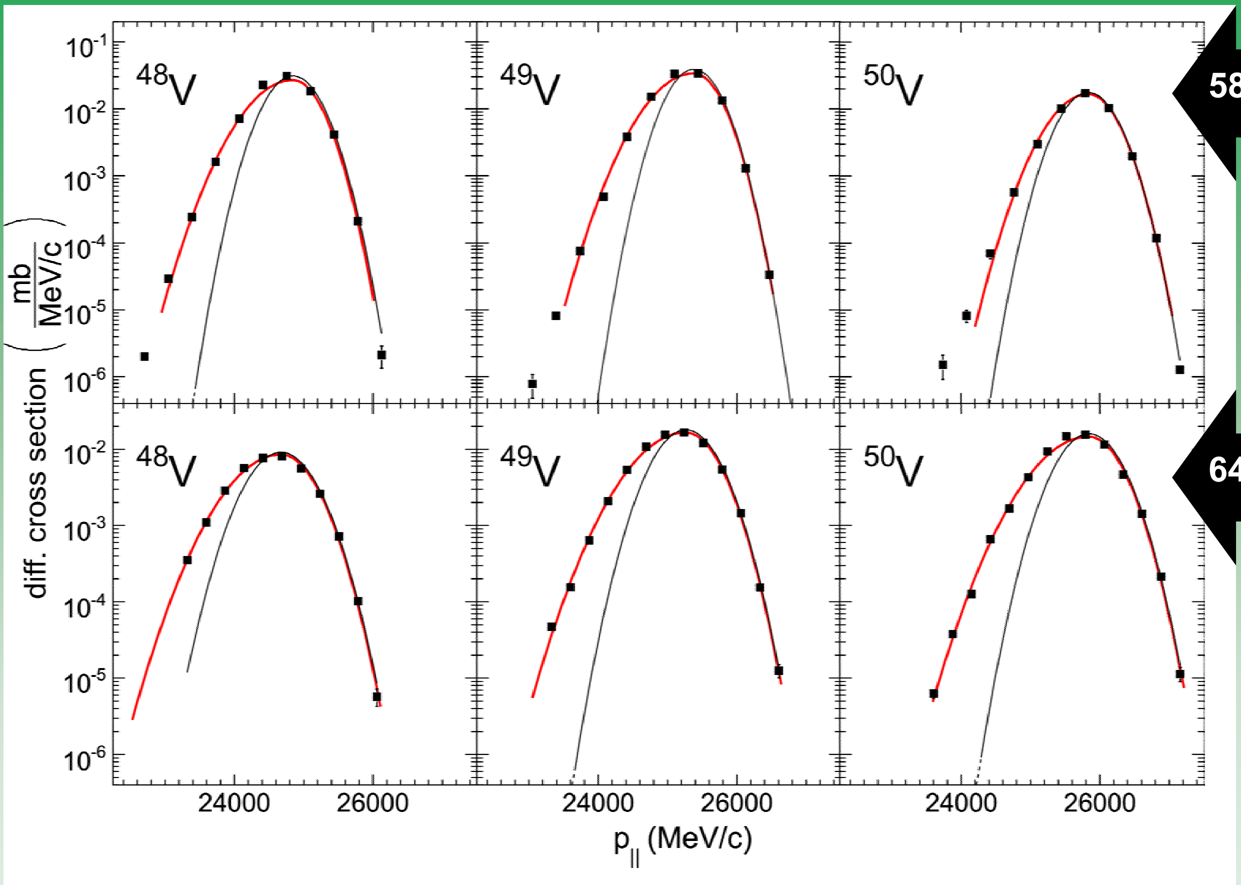
Fragment identification $^{58}Ni + ^{9}Be$





$$\frac{\mathrm{d}\sigma}{\mathrm{d}p}(A,Z) = \frac{N(A,Z)}{N_{BEAM}\, n_{TARGET}\, \tau_{LIVE}\, \Delta p} \cdot \frac{1}{\varepsilon}[mb/(MeV/c)]$$

Momentum distributions



$^{58}Ni+^{9}Be$

$^{64}Ni+^{9}Be$

- Modified gaussian function
- $p_0, \sigma_L, \sigma_R, N$
- Reproduced very well
- Final cross sections

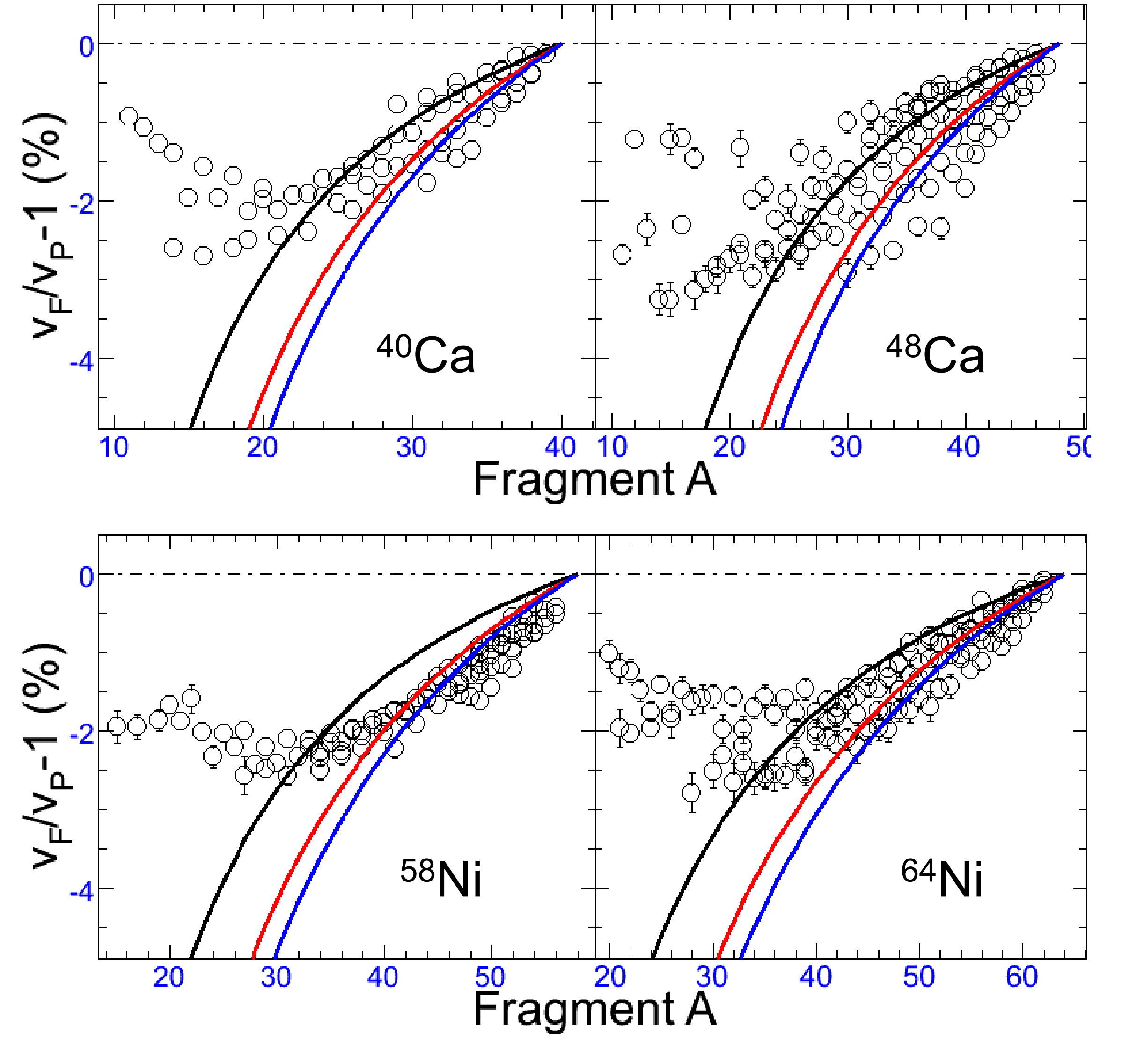
Modified gaussian

$p<p_0$	$p\geq p_0$
$N\exp\left(-\frac{(p_0-p)^2}{2\sigma_L^2}\right)$	$N\exp\left(-\frac{(p_0-p)^2}{2\sigma_R^2}\right)$

Gaussian

$$N\exp\left(-\frac{(p_0-p)^2}{2\sigma^2}\right)$$

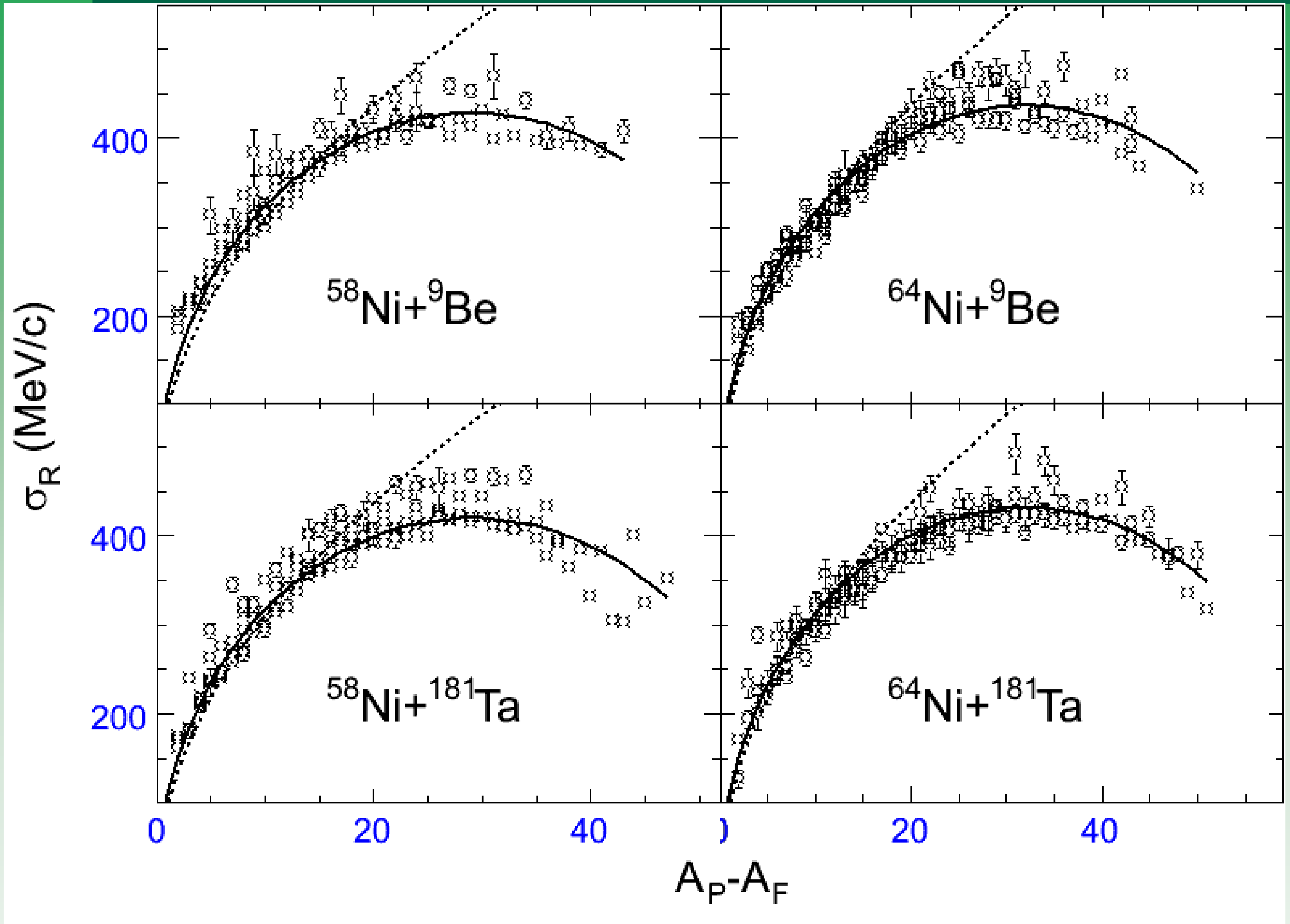
Fragment velocities: parameterization



Borrel
Kaufman
Morrissey

- Defined as maximum of the distribution (p_0)
- Similar predictions close to the projectile
- Deviate significantly for light fragments

Width of momentum distributions



- High momentum side (σ_R)
- "pure" fragmentation

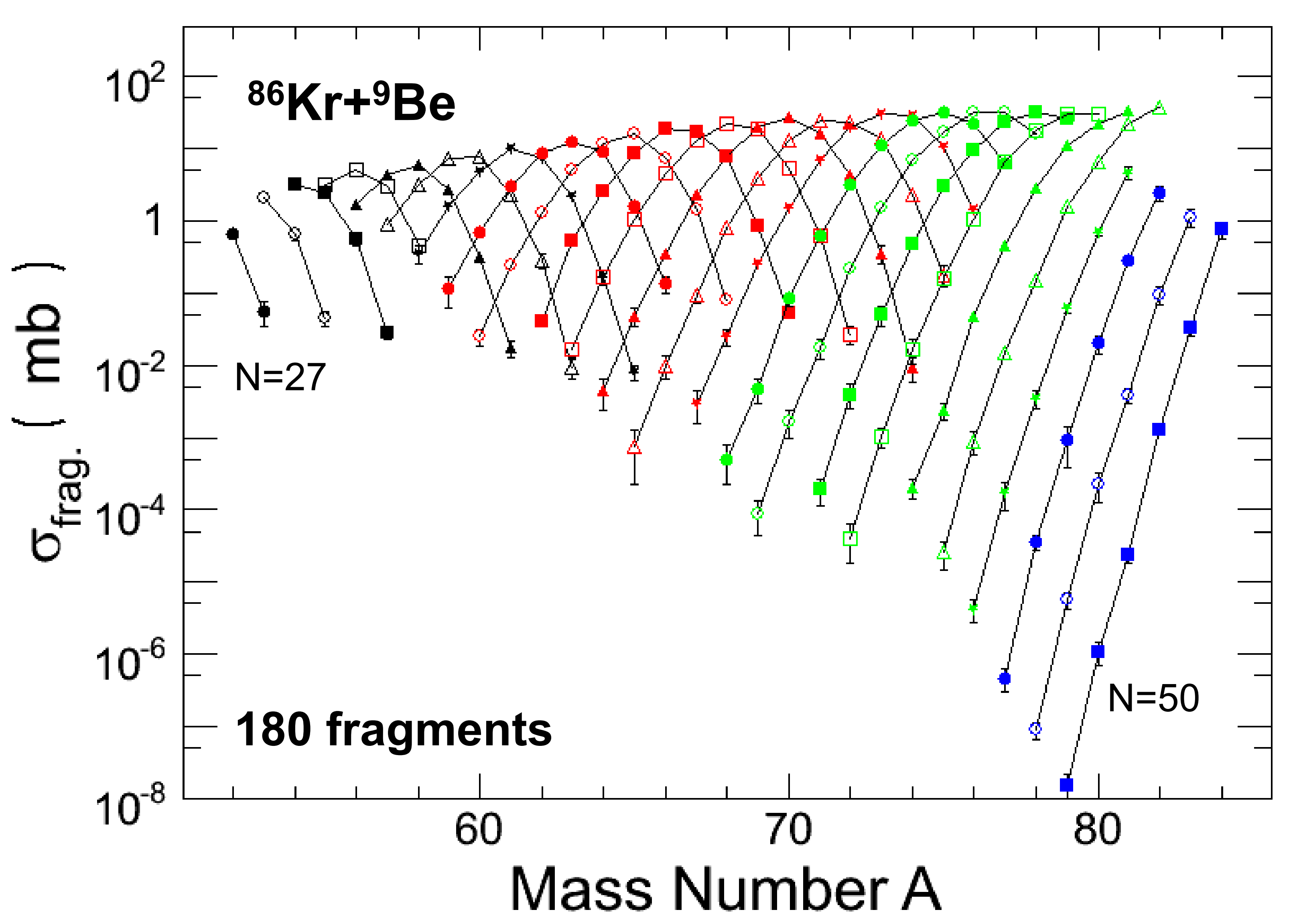
Goldhaber (fit) $\sigma_R = \sigma_0 \sqrt{\frac{A_F(A_P - A_F)}{A_P - 1}}$

Morrissey $\sigma_R = 85\sqrt{A_P - A_F}$

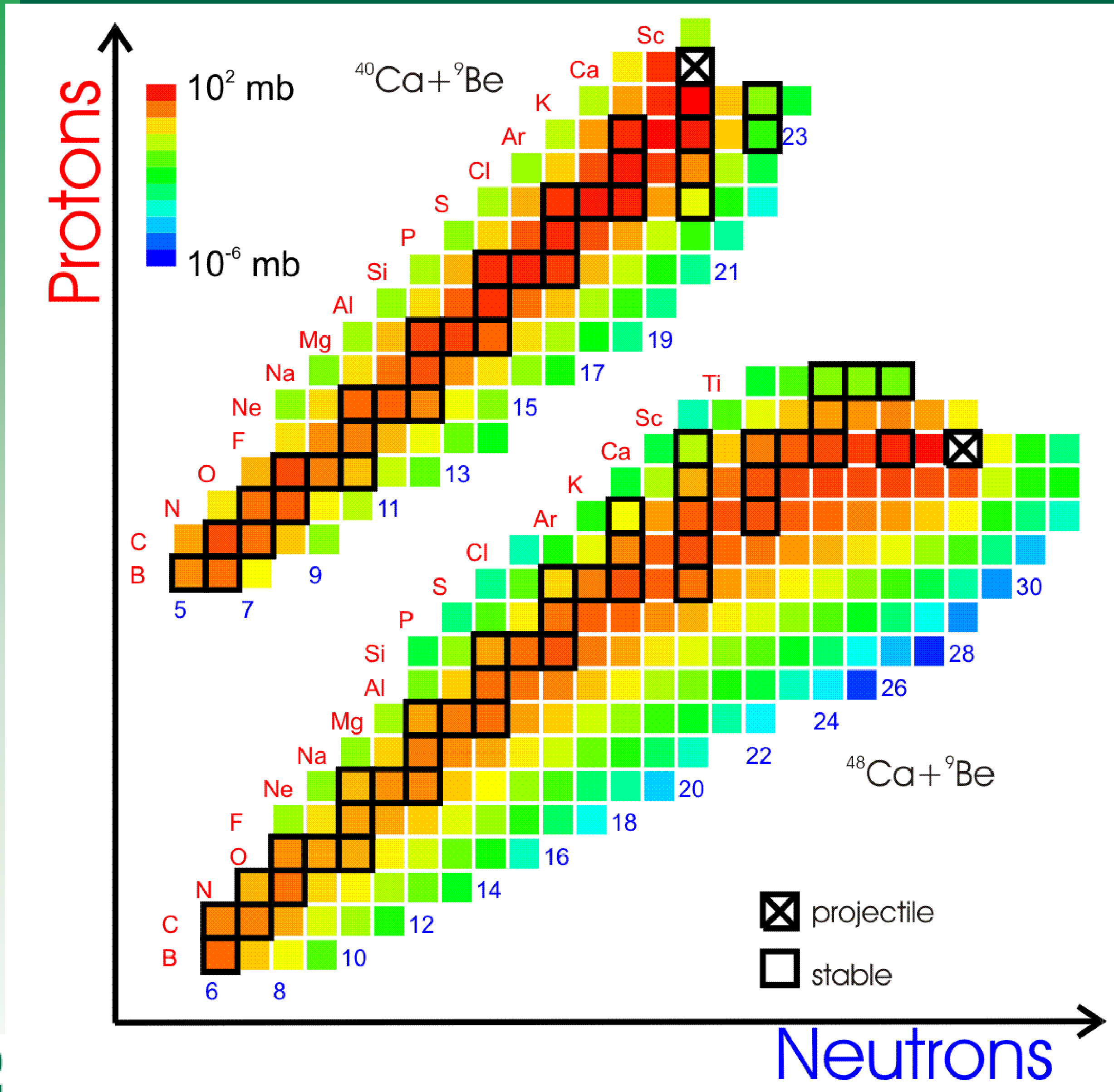
σ_0 = 84-97 MeV/c

$\sigma_0 \approx$ 120 MeV/c

Quality of data



Measured cross sections



System	# CS
^{40}Ca+^{9}Be	100(11)
^{40}Ca+^{181}Ta	101(15)
^{48}Ca+^{9}Be	176(26)
^{48}Ca+^{181}Ta	167(32)
^{58}Ni+^{9}Be	184(12)
^{58}Ni+^{181}Ta	179(10)
^{64}Ni+^{9}Be	240(3)
^{64}Ni+^{181}Ta	232(2)
^{86}Kr+^{9}Be	180(0)
^{86}Kr+^{181}Ta	70(0)

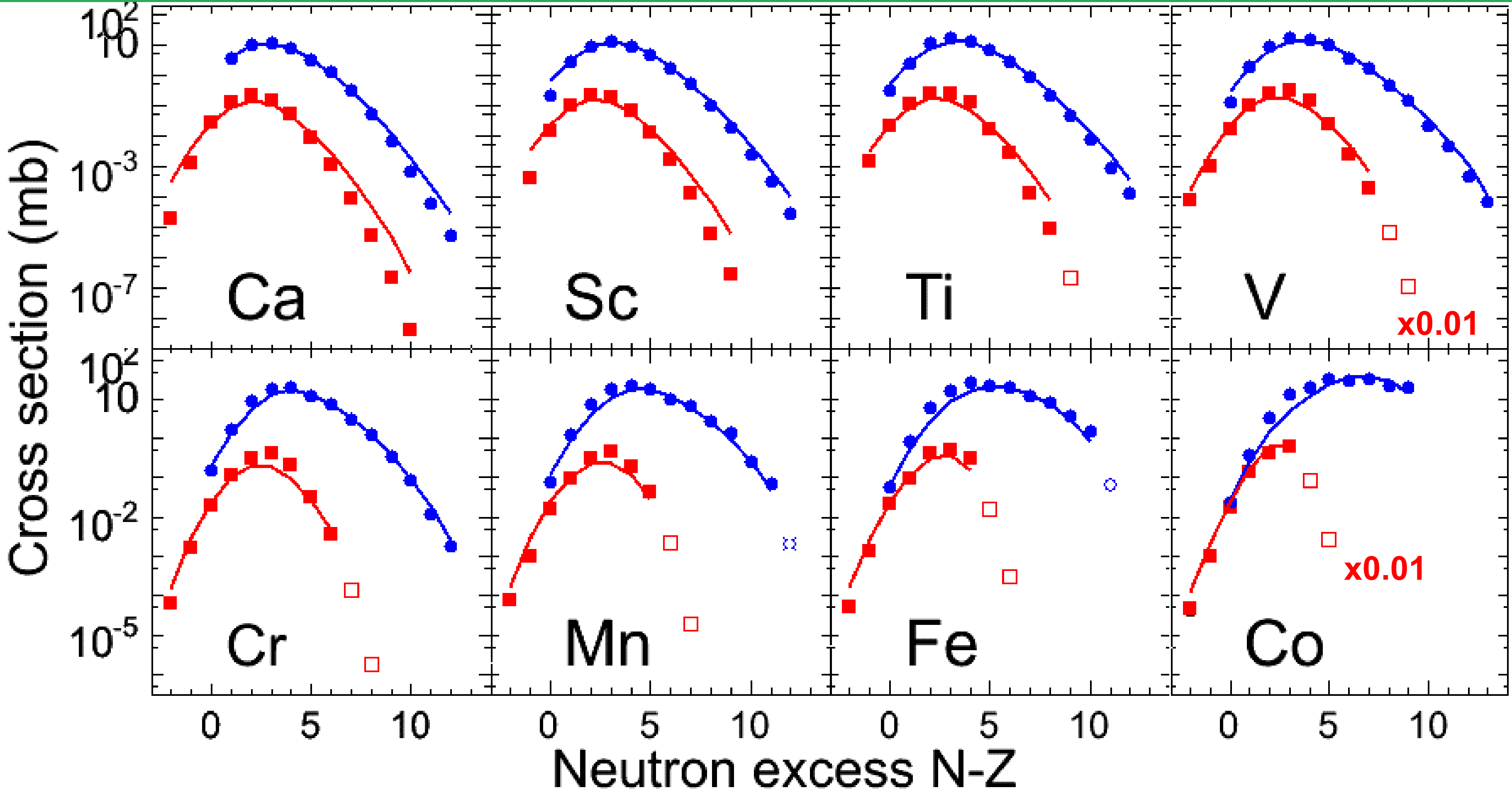
Total: 1740

Fragmentation models

Models used to characterize the data:

1. **EPAX:** **parameterization of the existing fragmentation data with little physics but important for experimental rate estimations.**
2. **Abrasion/Ablation model:** two stage model with simplified assumptions.
3. **Dynamical models:** ultimate model. It incorporates the "full" physical picture of nuclear collisions.

Data vs. EPAX (Ni+Be)

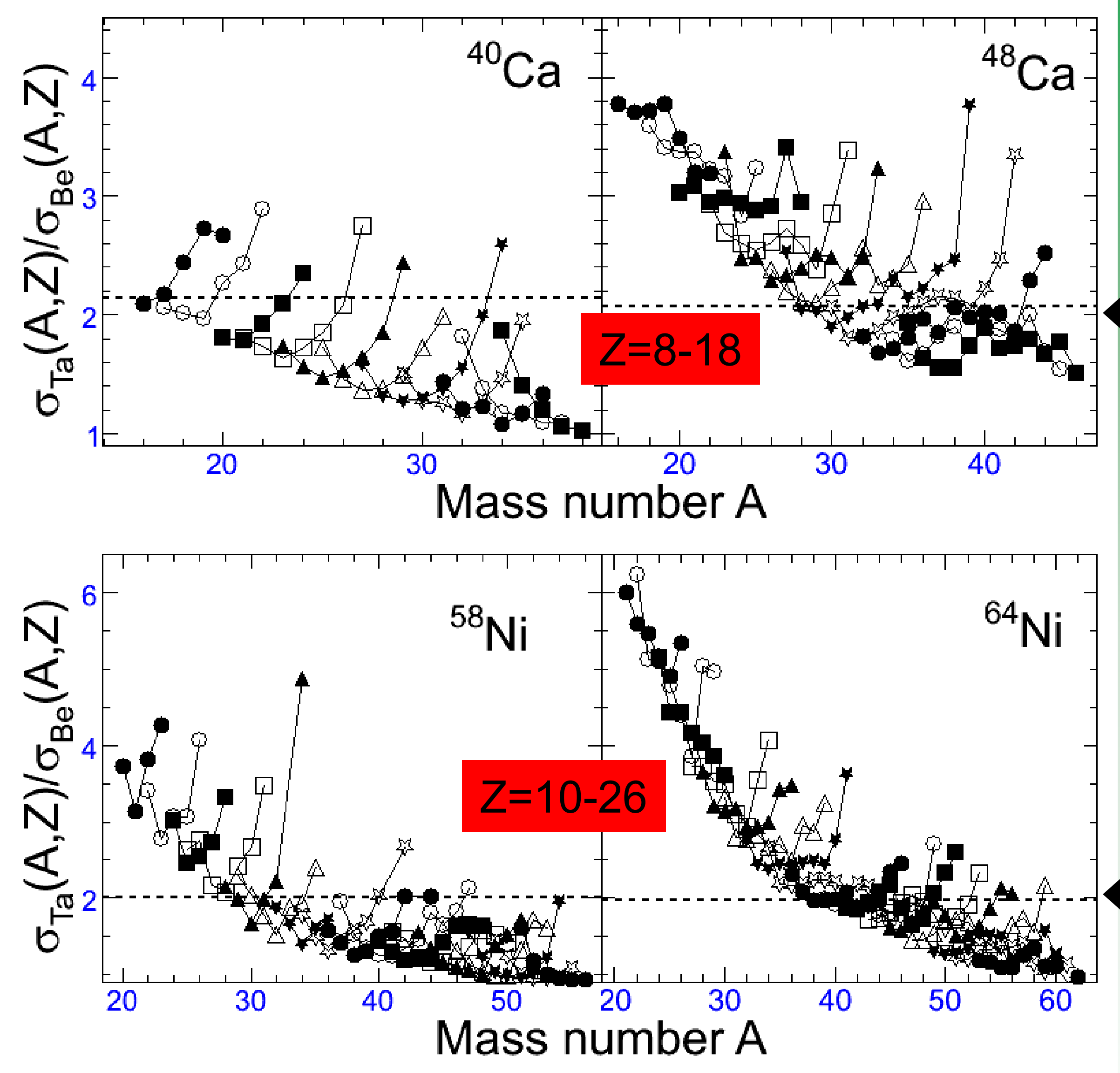


$^{58}Ni+^{9}Be$
$^{64}Ni+^{9}Be$

EPAX: overall good agreement, deviations near maxima (projectile-like) and tails of the distributions

Target dependence

$$R_{tgt} = \frac{\sigma_{Ta}(A,Z)}{\sigma_{Be}(A,Z)}$$

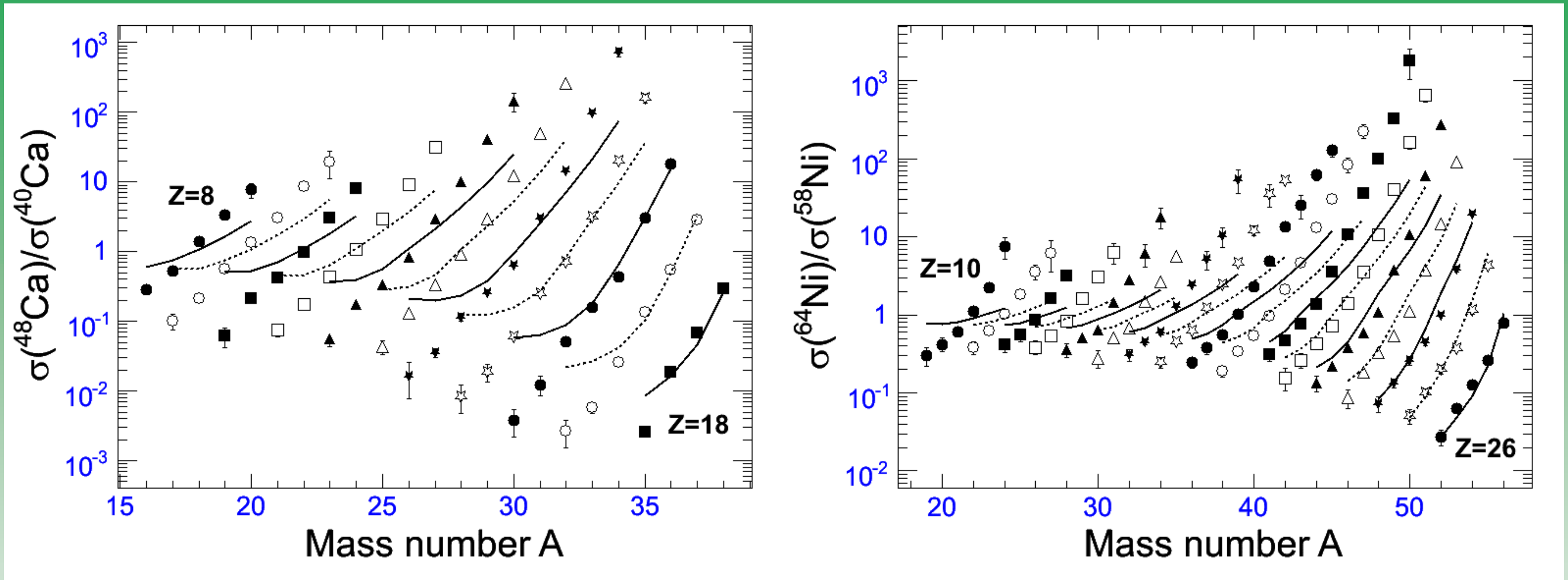


EPAX

EPAX

- Enhancement for n-rich and p-rich fragments
- Projectile/target isospin equilibration
- Not significant for production purposes

Projectile dependence



$$R_{proj} = \frac{\sigma_{48}(A,Z)}{\sigma_{40}(A,Z)} = \frac{\sigma_{64}(A,Z)}{\sigma_{58}(A,Z)}$$

- Shown for reactions on ^{9}Be target
- Much larger effect than target ratios
- Lines = ratios by EPAX

Fragmentation models

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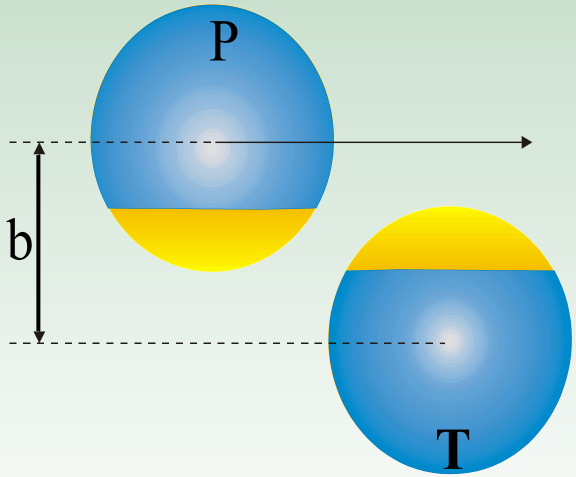
Abrasion-Ablation model

- Frequently employed fragmentation model
  - **Approximates reaction by two steps:**

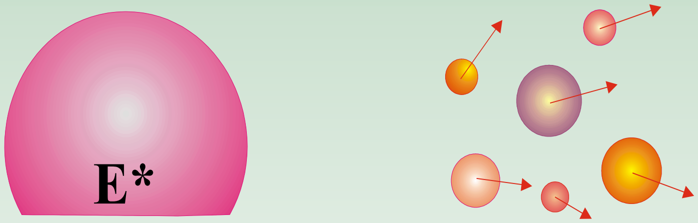
➢ Abrasion ➔ geometrical overlap

➢ Ablation ➔ excitation function integration

Abrasion (Shear-off)



Ablation (Evaporation)

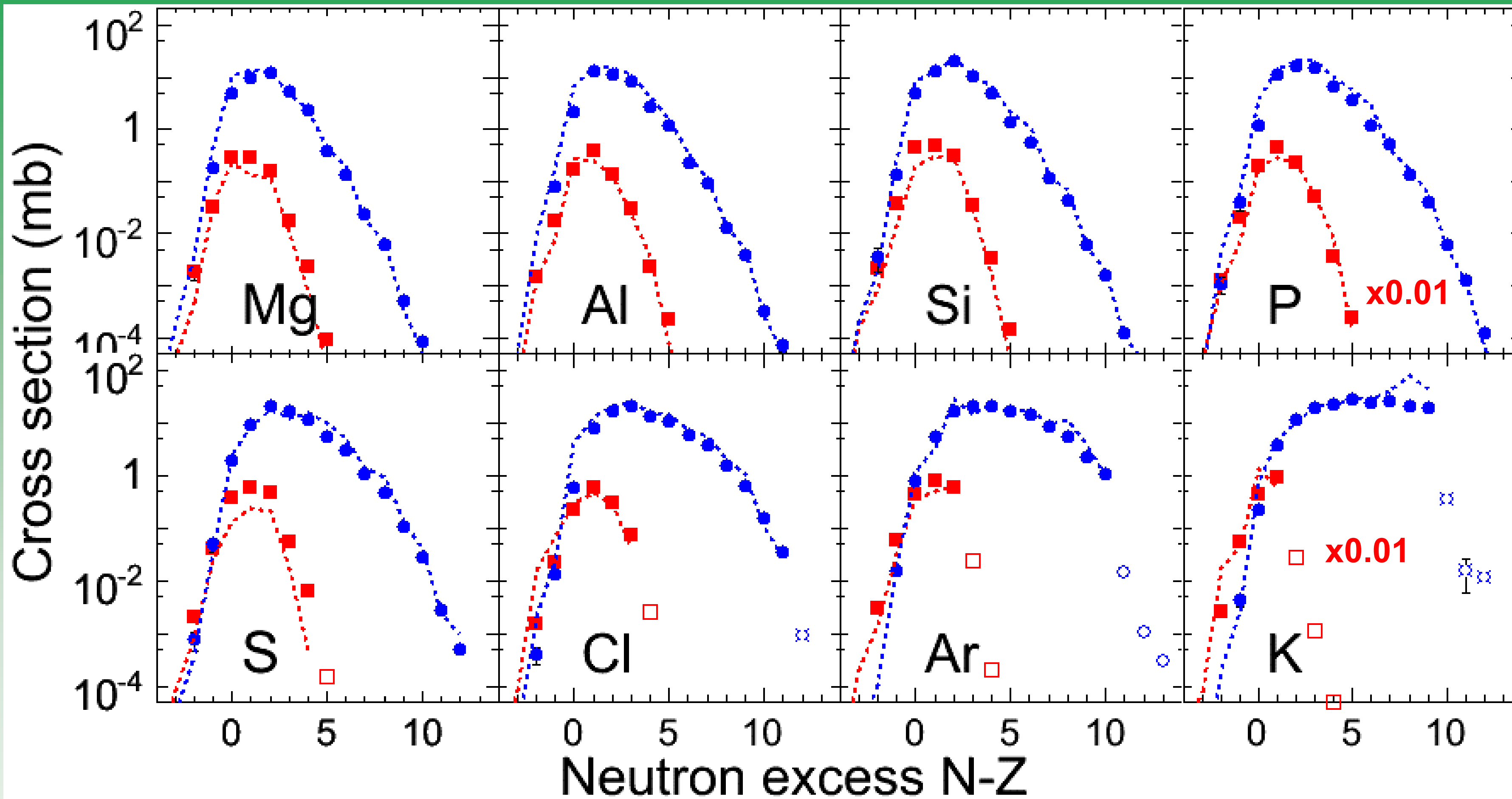


$E^* \sim K\,\Delta A$ (ΔA = removed nucleons)

<u>$K = 13.3^{\#}, 27^{*}$ MeV</u>

#(Gaimard *et al.*, NPA 531 (1991) 709)
*(Schmidt *et al.*, NPA 710 (2002) 157)

AA LISE++ (Ca+Be)



$^{48}Ca+^{9}Be$
$^{40}Ca+^{9}Be$

.... AA Lise++

E*(^{48}Ca) = **11** MeV/ΔA
E*(^{40}Ca) = **11** MeV/ΔA

E*(^{58}Ni) = E*(^{64}Ni) = **13** MeV/ΔA
E*(^{86}Kr) = 19 MeV/ΔA

Fragmentation models

Models used to characterize the data:

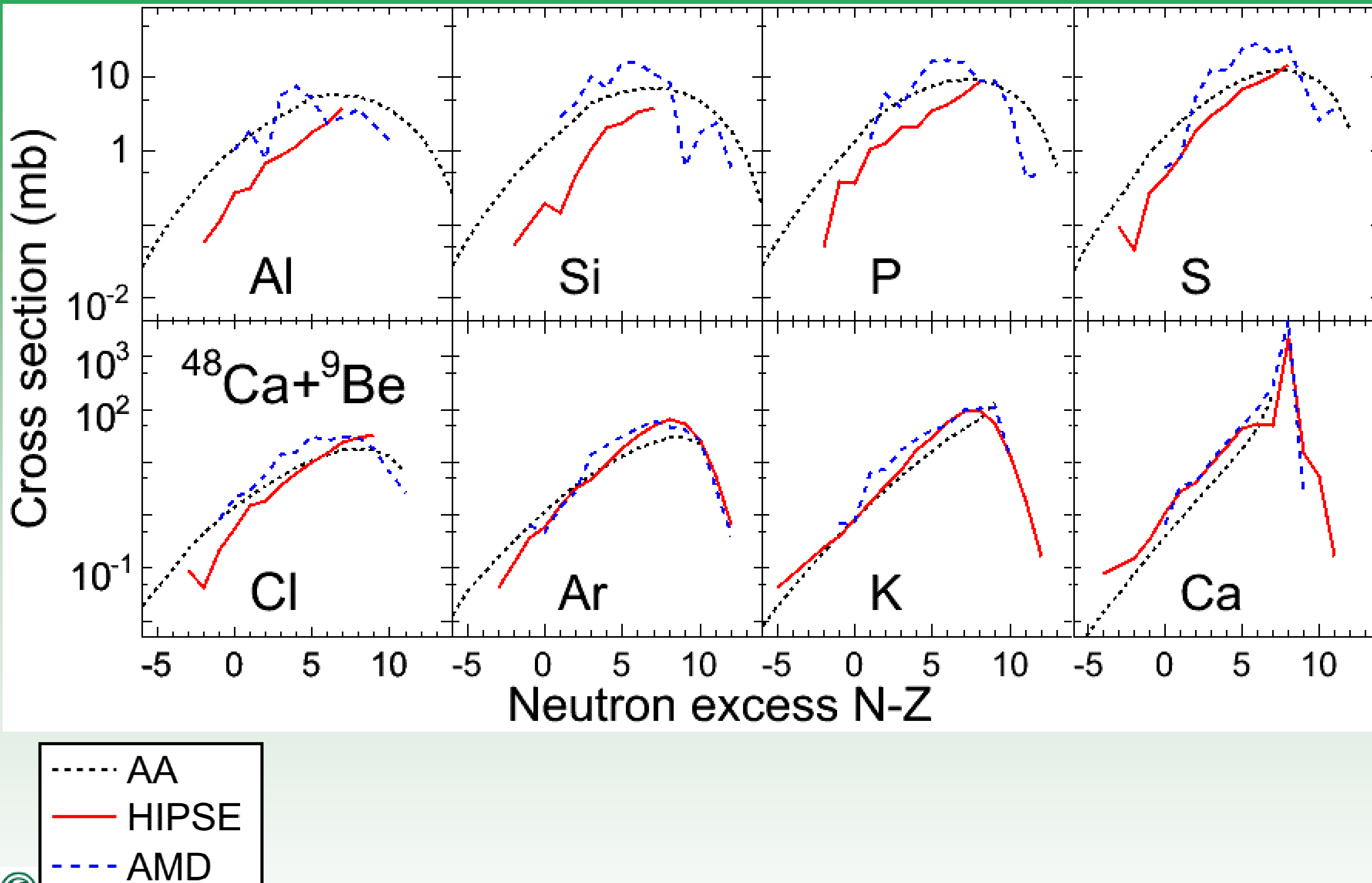
1. <u>**EPAX:**</u> parameterization of the existing fragmentation data with little physics but important for experimental rate estimations.
2. <u>**Abrasion/Ablation model:**</u> two stage model with simplified assumptions.
3. <u>**Dynamical models:**</u> **ultimate model. It incorporates the "full" physical picture of nuclear collisions.**

Dynamical models

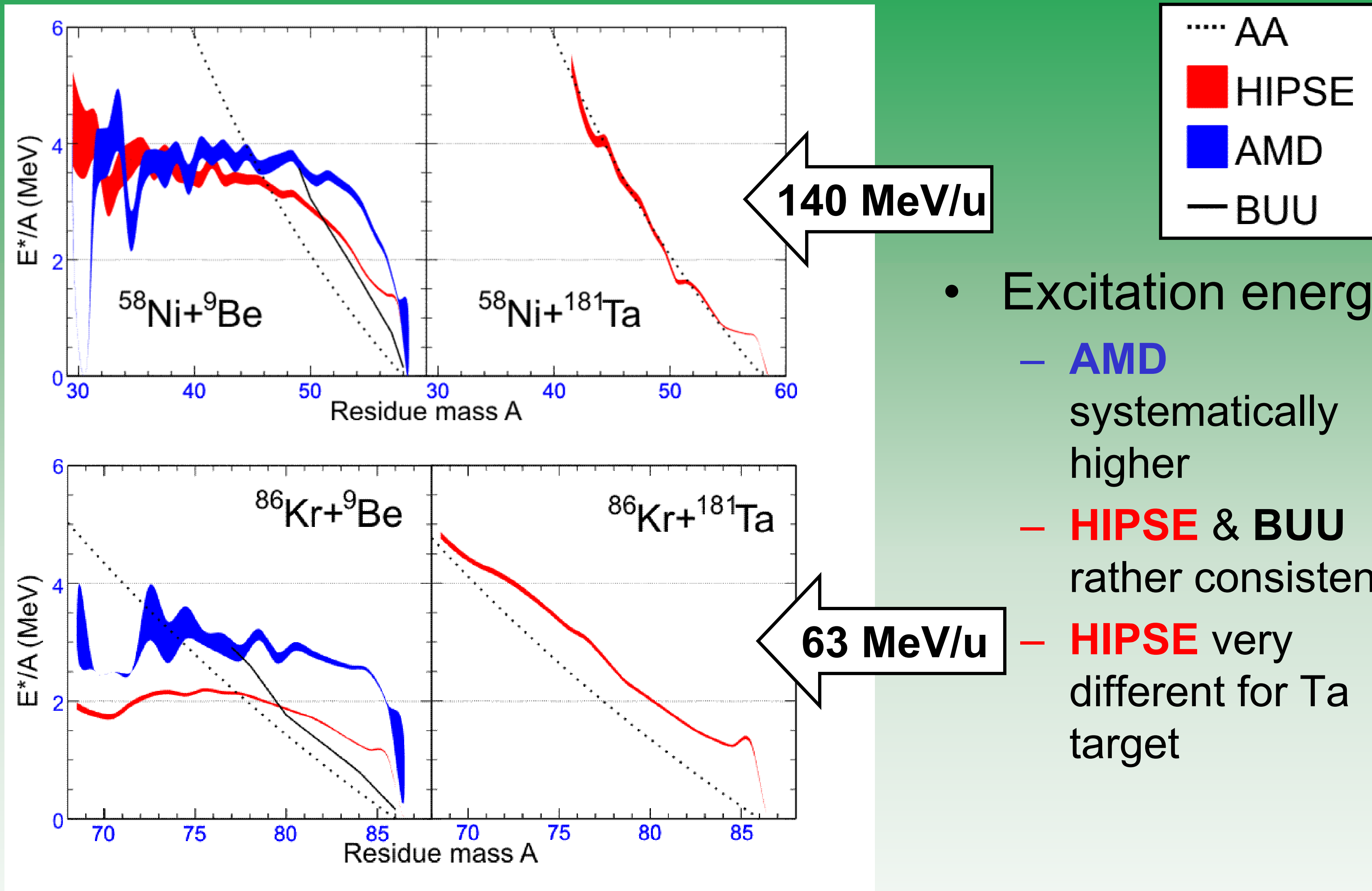
- **Heavy Ion Phase Space Exploration (HIPSE)** (**D. Lacroix** *et al.*, PRC 69, 054604, 2004)
  - **Clusters defined at t=0 in complete phase space (x,y,z,p_x,p_y,p_z)**
  - **Total excitation energy from the energy balance**
  - **Divided among fragments with A_f as weight**
- **Boltzmann-Uehling-Uhlenbech (BUU)** (**P. Danielewicz**, Nucl. Phys. **A673** (2000), 375)
  - **Transport model that solves the equation of motion for nucleons**
  - **Residue properties from integration over density**
  - **Excitation energy from the total energy minus the calculated ground state**
- **Antisymetrized Molecular Dynamics (AMD)** (**A. Ono** and H. Horiuchi, Prog. Part. Nucl. Phys. **53** (2004) 501-581)
  - **The most sophisticated *dynamical model* to simulate collisions between heavy nuclei**
  - **Residues defined in (x,y,z) space at *t=150 fm/c***
  - **Excitation energy calculated from the kinetic energies of nucleons within a prefragment and experimental masses**

Decay: GEMINI (**R. J. Charity** *et al.*, Nucl. Phys. A**483,** (2004) 371)

Primary fragments: comparison

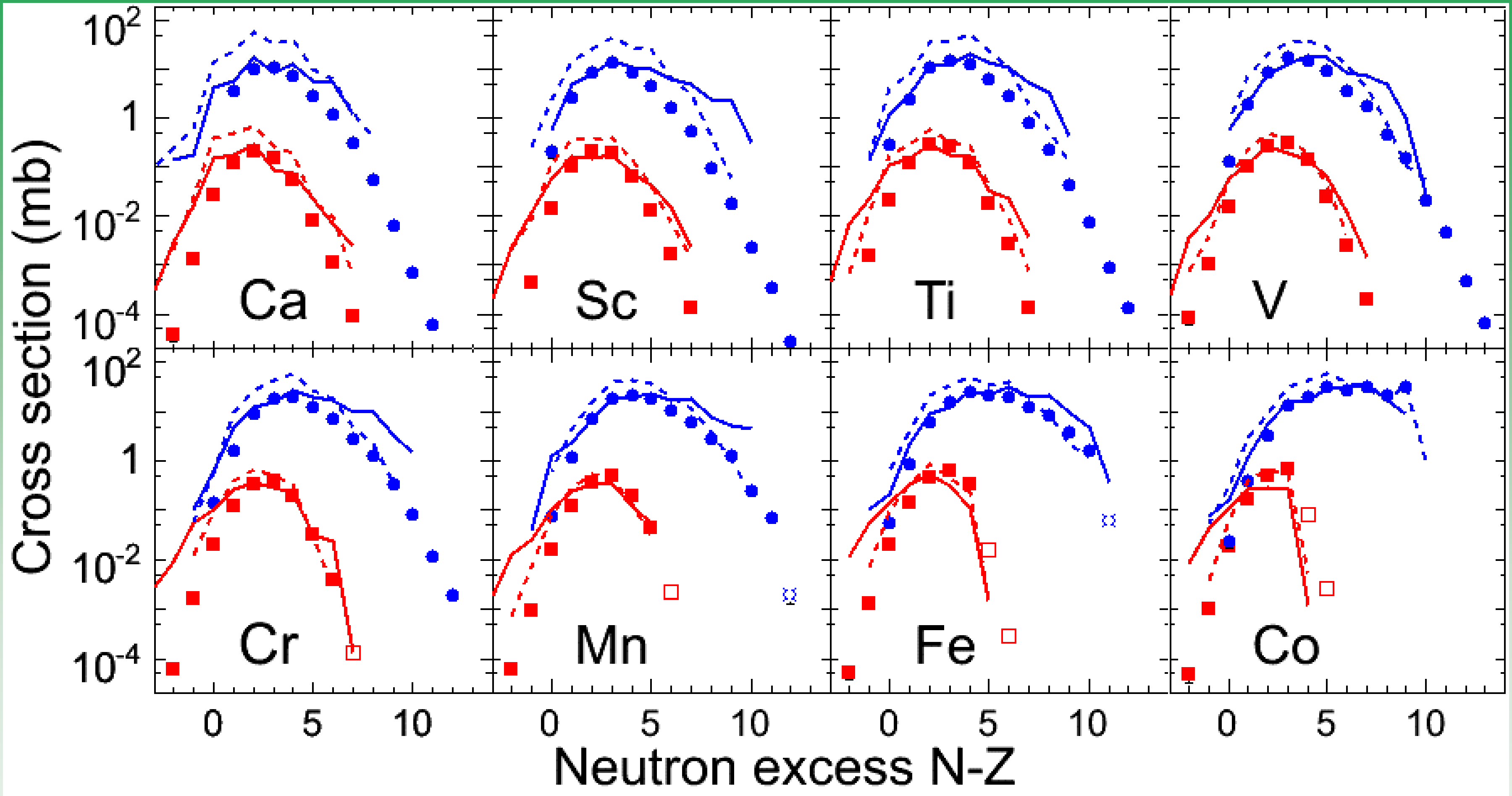


Excitation energy: comparison



- Excitation energy
  - **AMD** systematically higher
  - **HIPSE** & **BUU** rather consistent
  - **HIPSE** very different for Ta target

Final states: Ni+Be systems

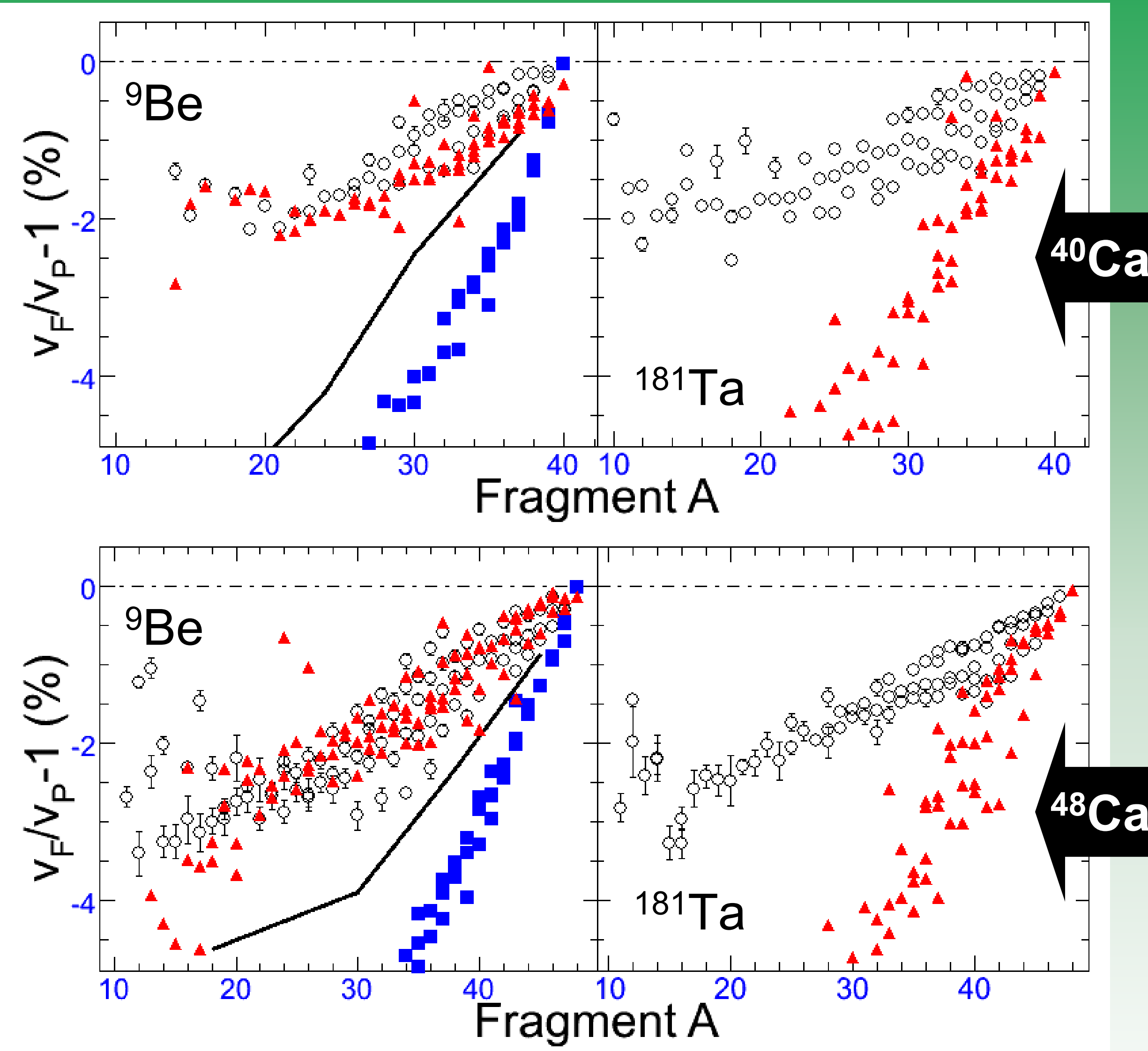


^{64}Ni+^{9}Be
^{58}Ni+^{9}Be

—— HIPSE + GEMINI
- - - AMD + GEMINI

Level density parameter **a=A/10**

Fragment velocities: comparison



BUU
HIPSE
AMD
+GEMINI

- Velocity deviations with respect to the projectile
- Be data reproduced by **HIPSE** calculation
- **AMD** and **BUU** high stopping
- **HIPSE** suggests very different trend for Ta target systems

Summary

- Systematic fragmentation data with (^{40,48}Ca, ^{58,64}Ni) + (Be, Ta) & ^{86}Kr+(Be, Ta) ➔**1740** measured cross sections (momentum distributions)
- EPAX2 reproduces the experimental data rather well while discrepancies are observed
- Abrasion-Ablation model in LISE++
  - **Small sensitivity to excitation energy**
  - **Very good description of experimental data**
- Reaction mechanisms investigated with dynamical models (AMD, HIPSE, BUU)
  - **Final distributions governed by the statistical decay.**
  - **Cross sections not very sensitive to E* determination.**
  - **Kinematics observables such as velocity distributions may provide insights to the fragmentation reaction mechanisms.**
- Evaporation codes
  - **Essential to understand details (level density)**

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