Systematic Study on Individual Charge-Changing Cross-Sections of Intermediate-Energy Secondary Beams

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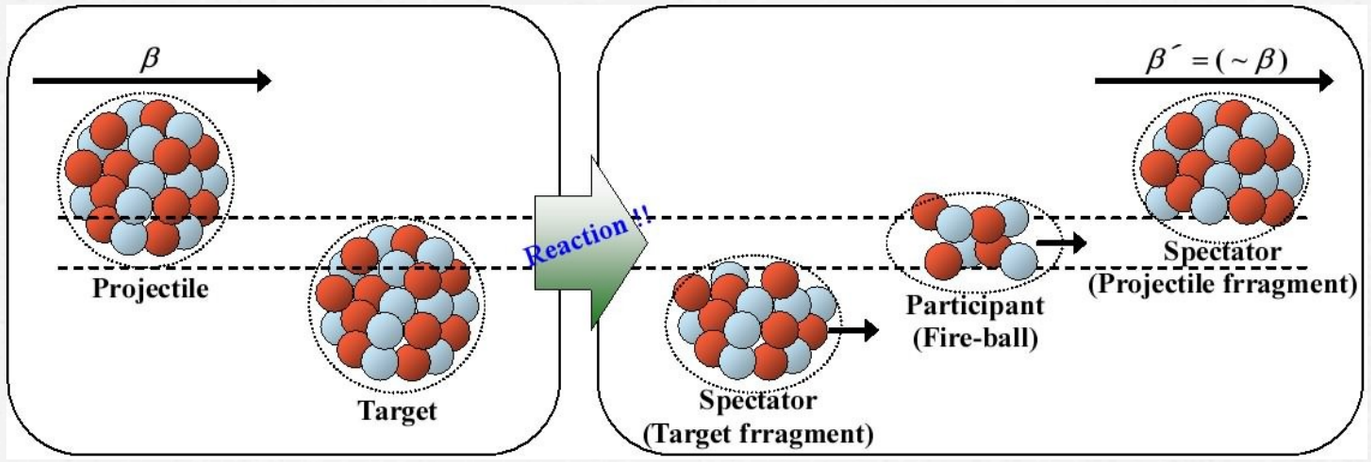
A study on fragmentations ...



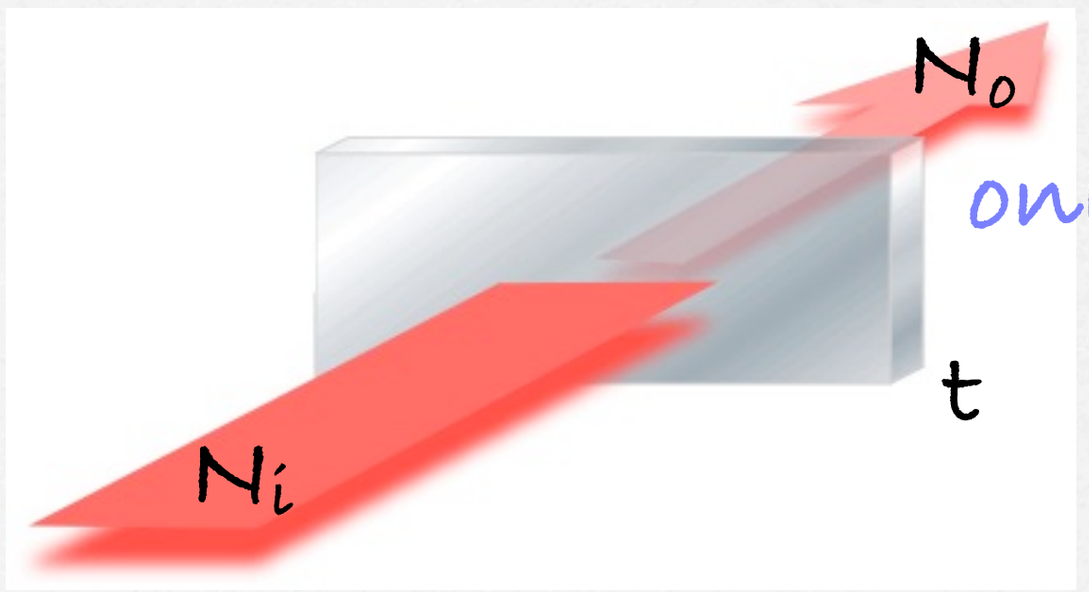
... We focus on "Charge Changing Interactions".

① what we measure ...

Total Charge-Changing Cross Sections

☑ Probability of a change of Z of the beam

Z, A



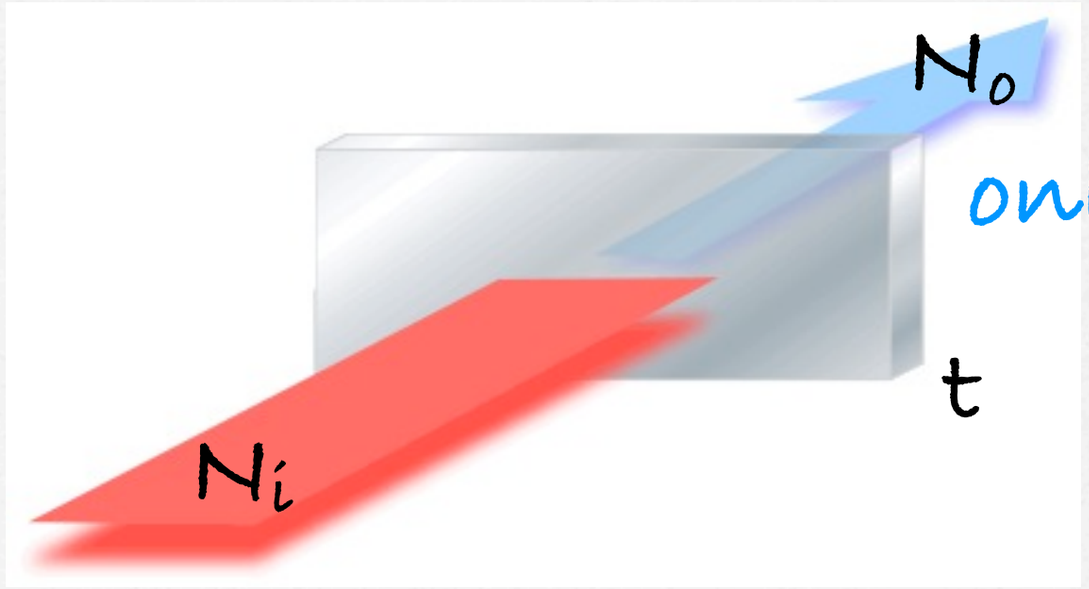
only Z identified

$$N_o = N_i e^{-\sigma_{cc} t}$$

②

Partial Charge-Changing Cross Sections
Partial Fragmentation Cross Sections

☑ Probability of productions of different Z



Z, A

only Z identified

$$\sigma_F = \frac{1}{t}\frac{N_o}{N_i}$$

Purpose of present study: reaction data

- ☑ A simple experiment; feasible!

  efficient production

- ☑ Precision data for Applications;

  reaction models, empirical formulae:

  EPAX, abrasion-ablation model

  - ▶ PHITS: radiation protection, therapy

Purpose of present study:
Nuclear Reactions and Structures

- ☑ partial fragmentations

  (only Z identified)

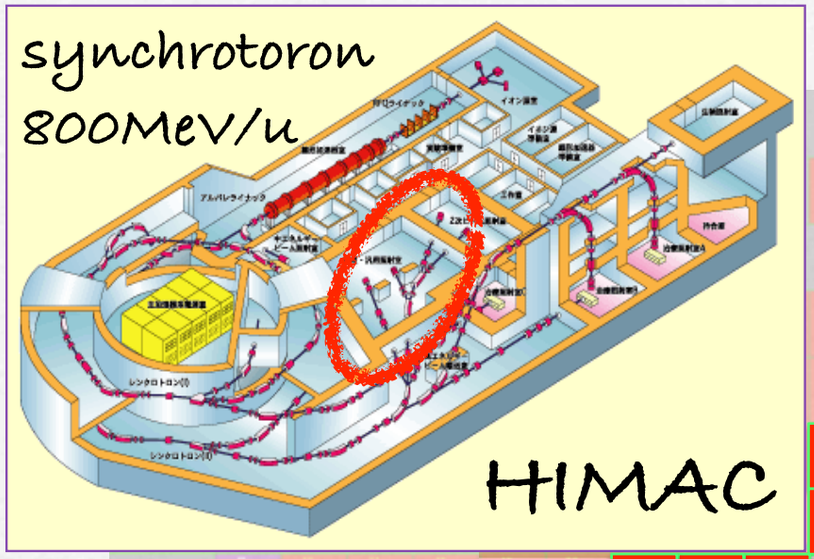
  compared with EPAX ...

  even-odd effects

- ☐ charge radii ... ? a new approach

  charge-changing interactions
  sensitive to charge radii ...

An Experiment

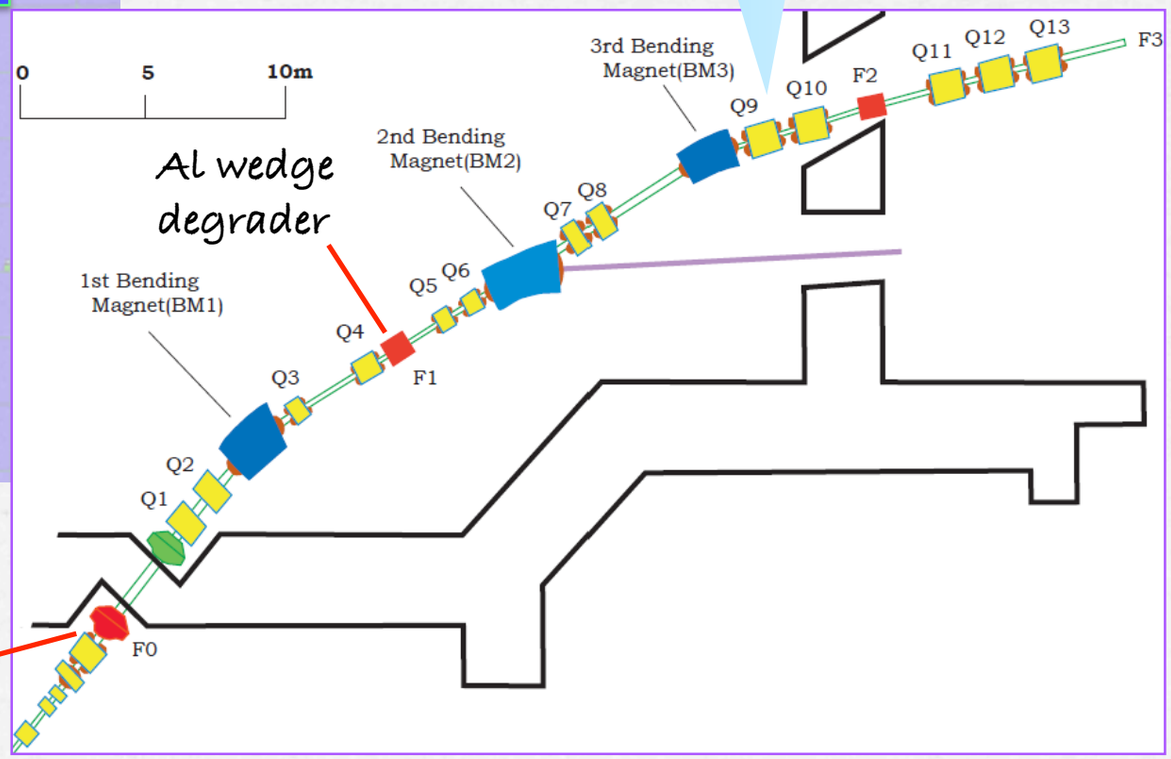


Primary: ^{56}Fe, ^{70}Ge

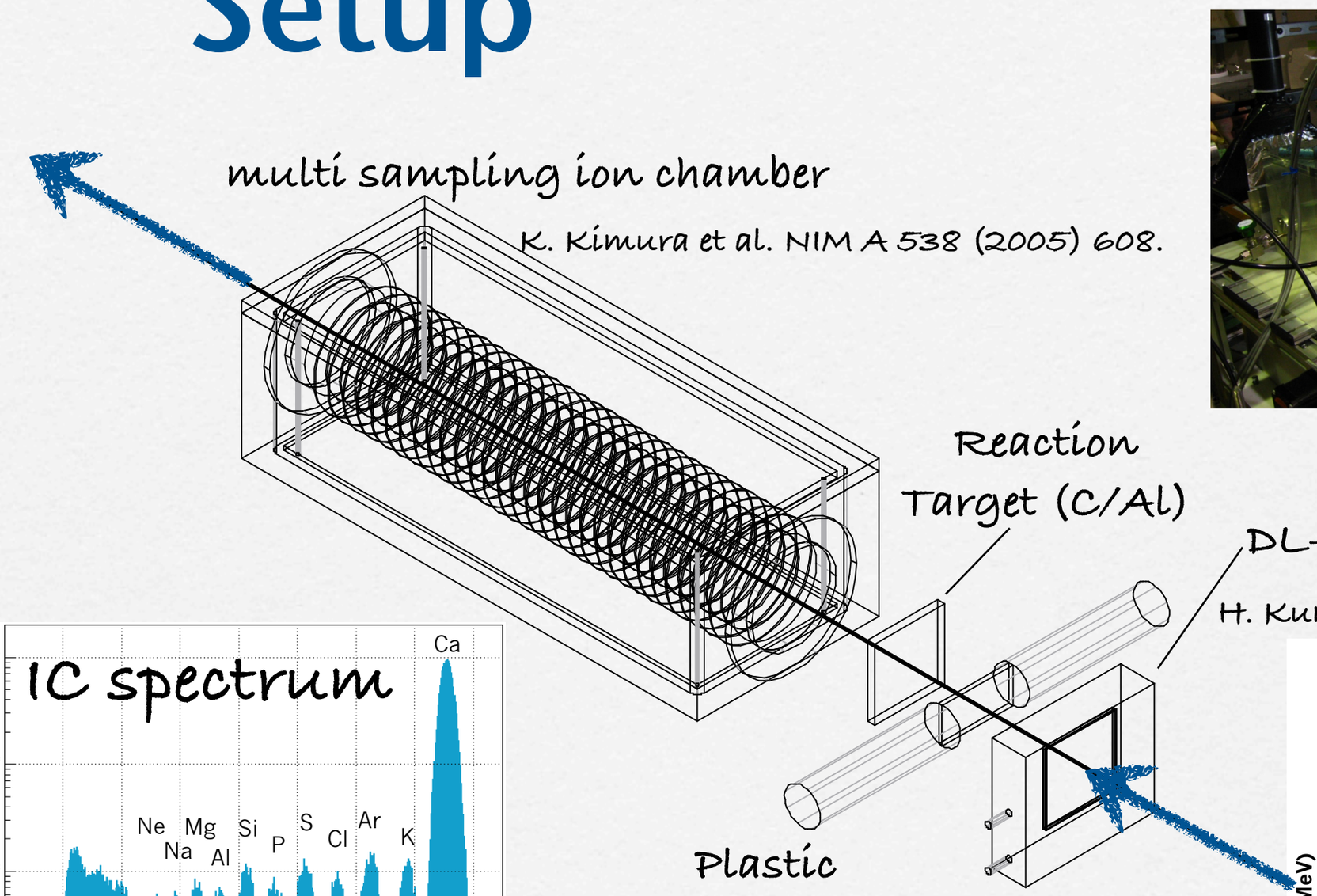
500MeV/u

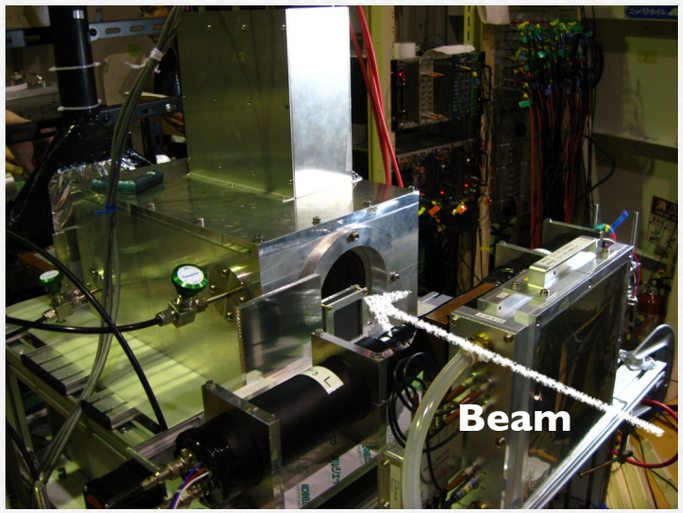
Ar - Ge: 84 nuclei

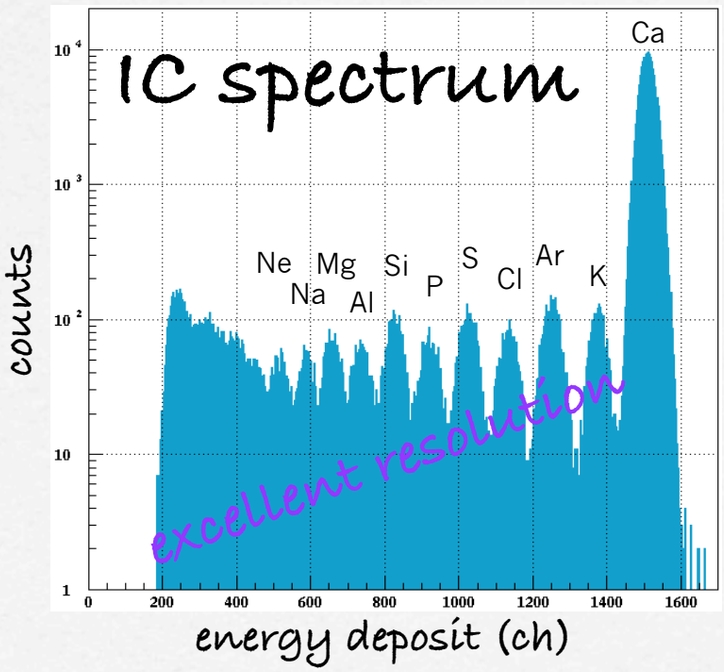
Fragment Separator

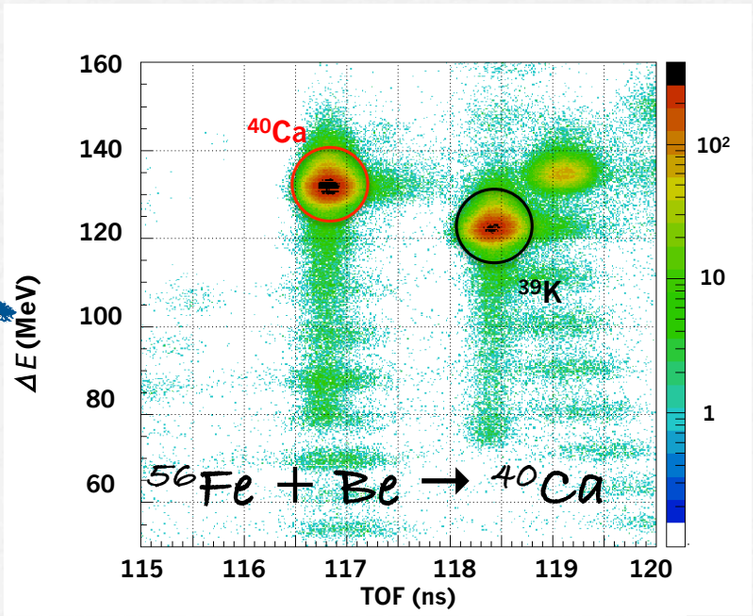


Setup


multi sampling ion chamber
K. Kimura et al. NIM A 538 (2005) 608.
Reaction
Target (C/Al)
DL-PPAC
H. Kumagai et al. NIM A 470 (2001) 562.
Plastic
Scintillator
beam from
fragment separator


Beam


IC spectrum
Ca
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
excellent resolution
counts
energy deposit (ch)

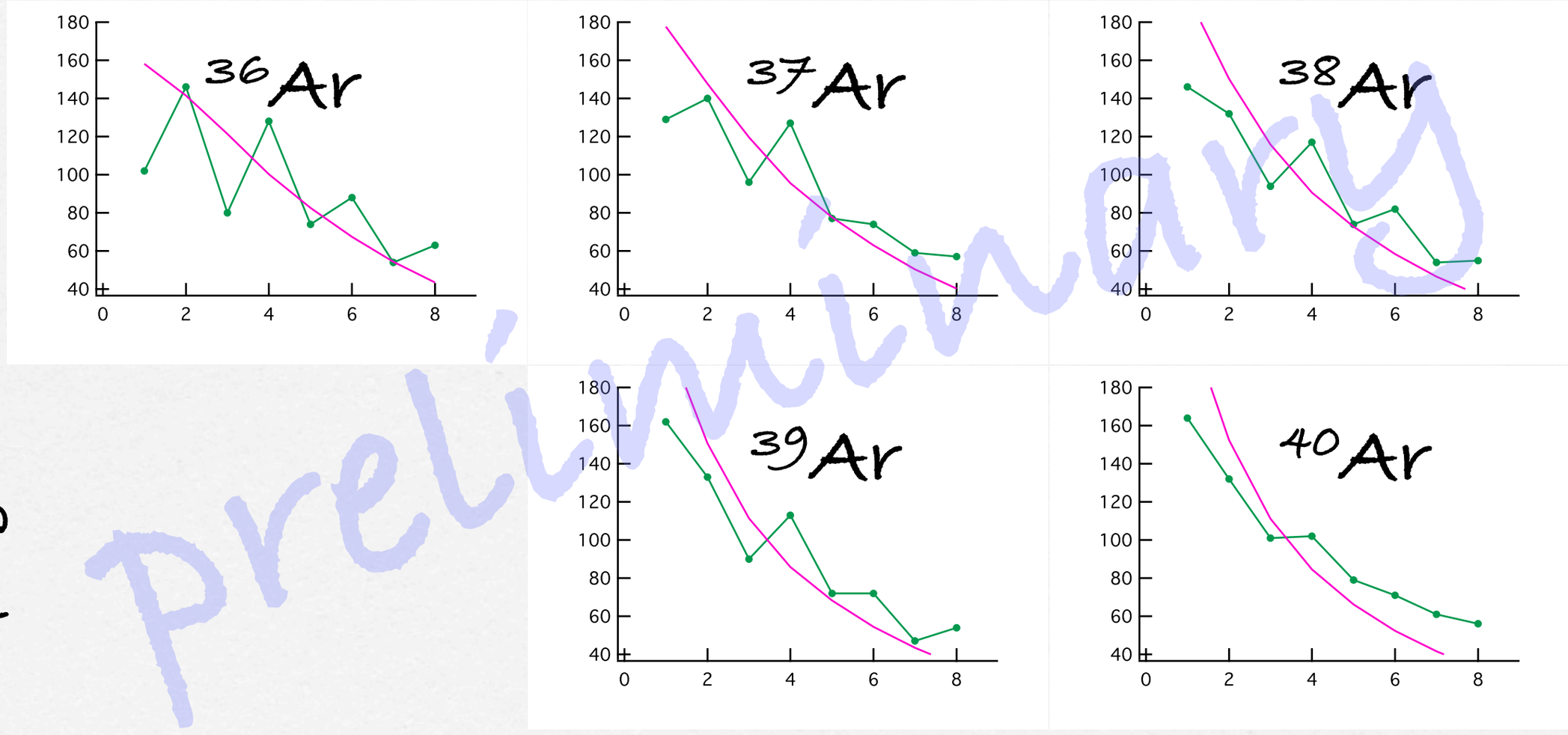

40Ca
39K
56Fe + Be → 40Ca
ΔE (MeV)
TOF (ns)

partial charge changing cross sections

partial fragmentation cross sections

Results ..... fragmentations
Ar on C

partial fragmentation cross section



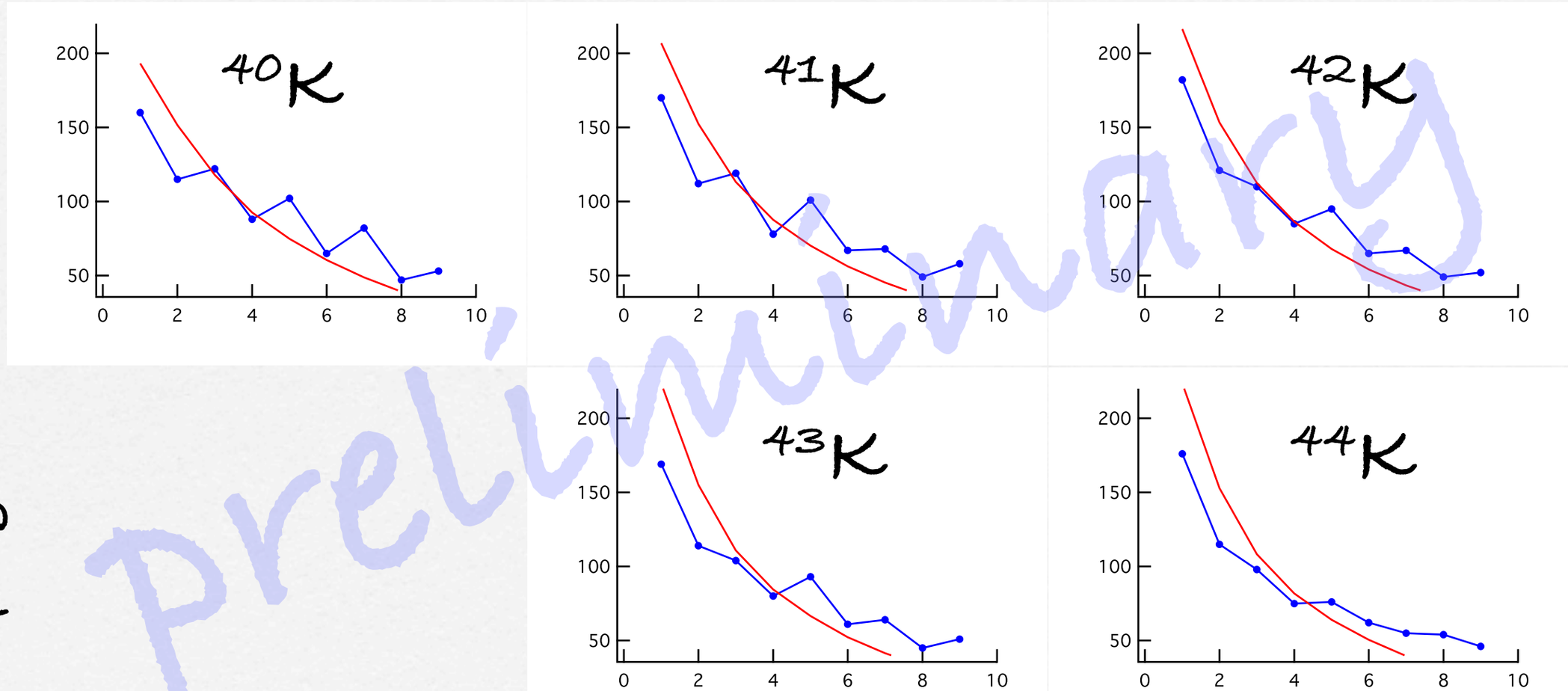
ΔZ

error < several mb

– EPAX

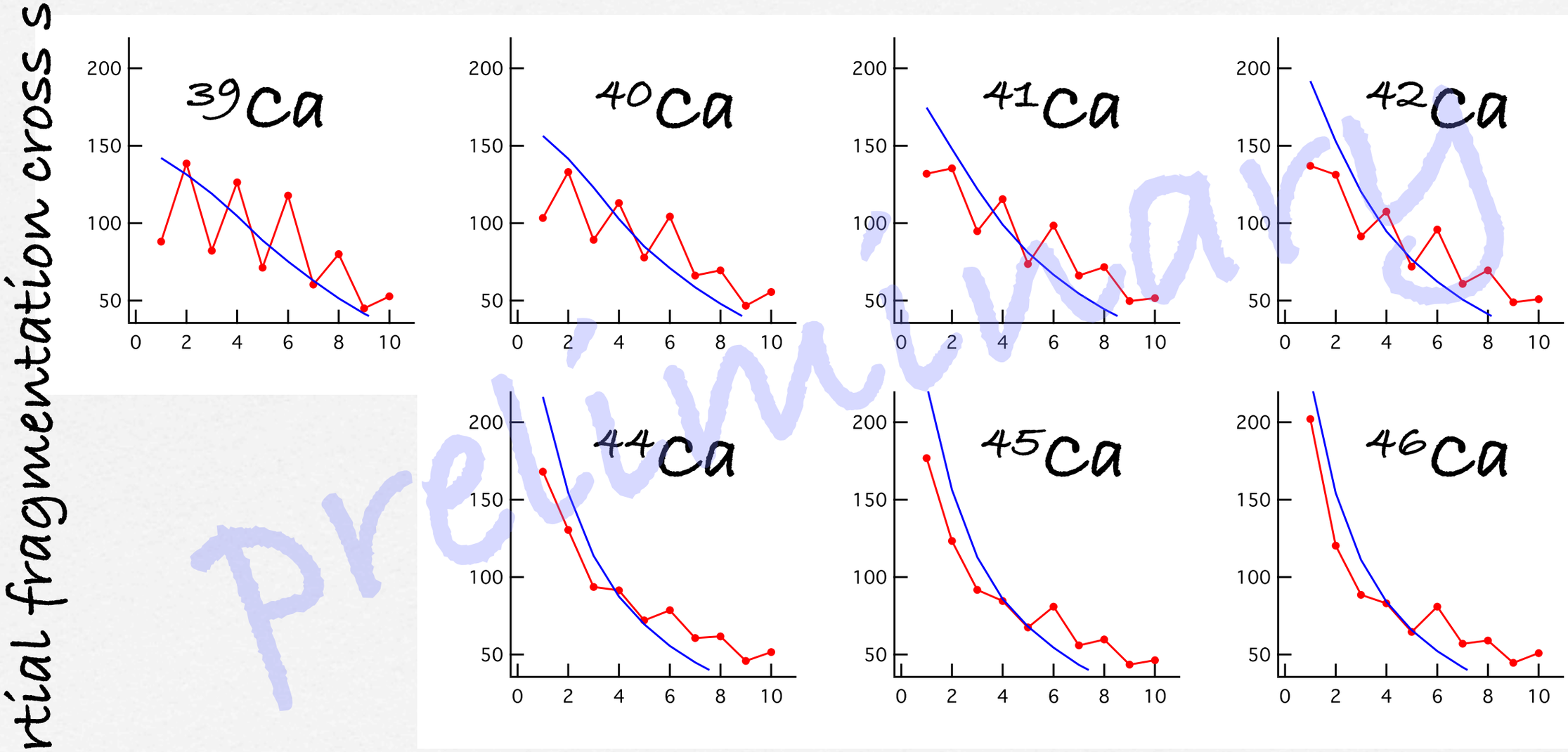
Results ...
K on C

partial fragmentation cross section

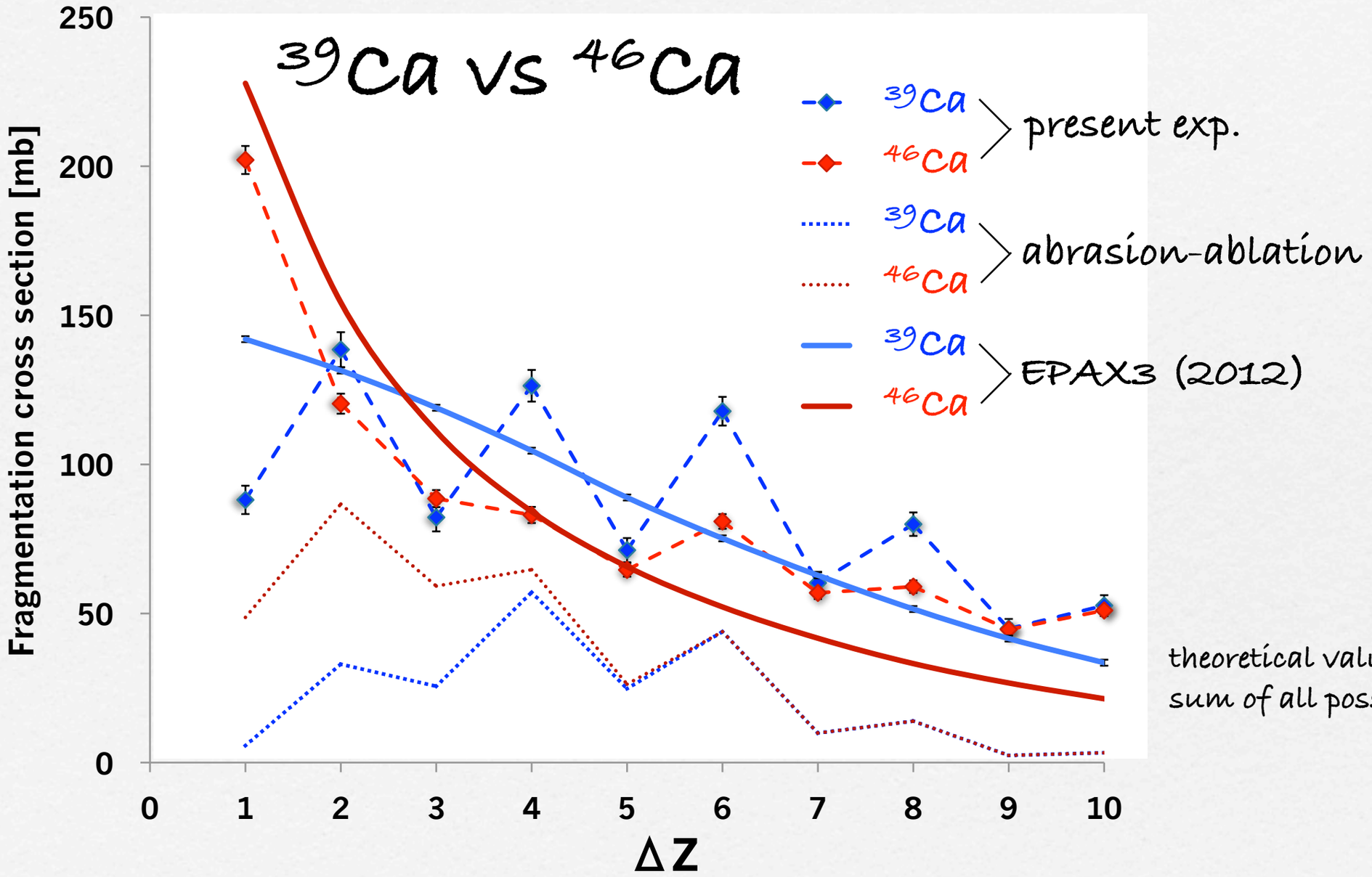


ΔZ

Results ...
Ca on C



Comparison with Models



theoretical values:
sum of all possible states

EPAX3: magnitude ○, even-odd ×

abrasion-ablation: magnitude ×, even-odd ○

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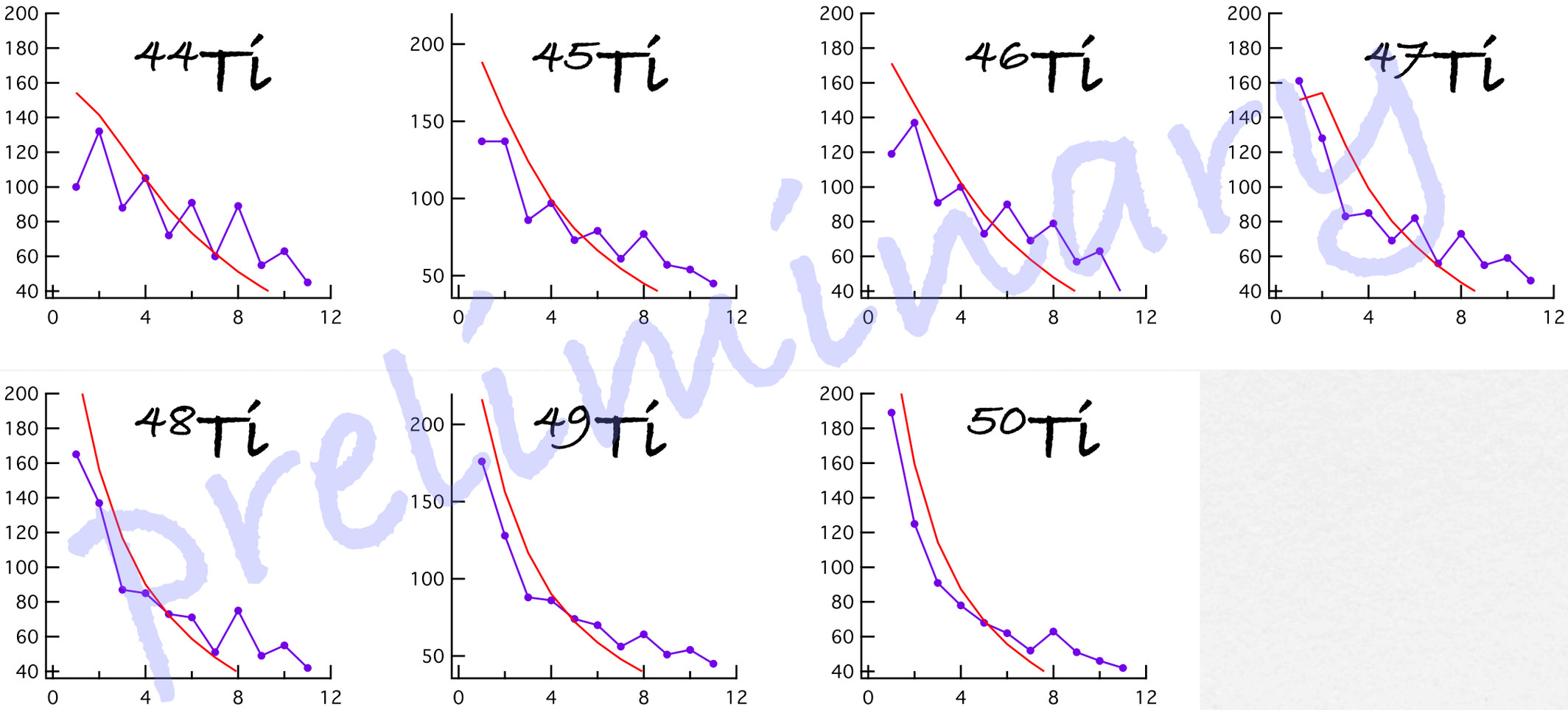
Results ...
Ti on C

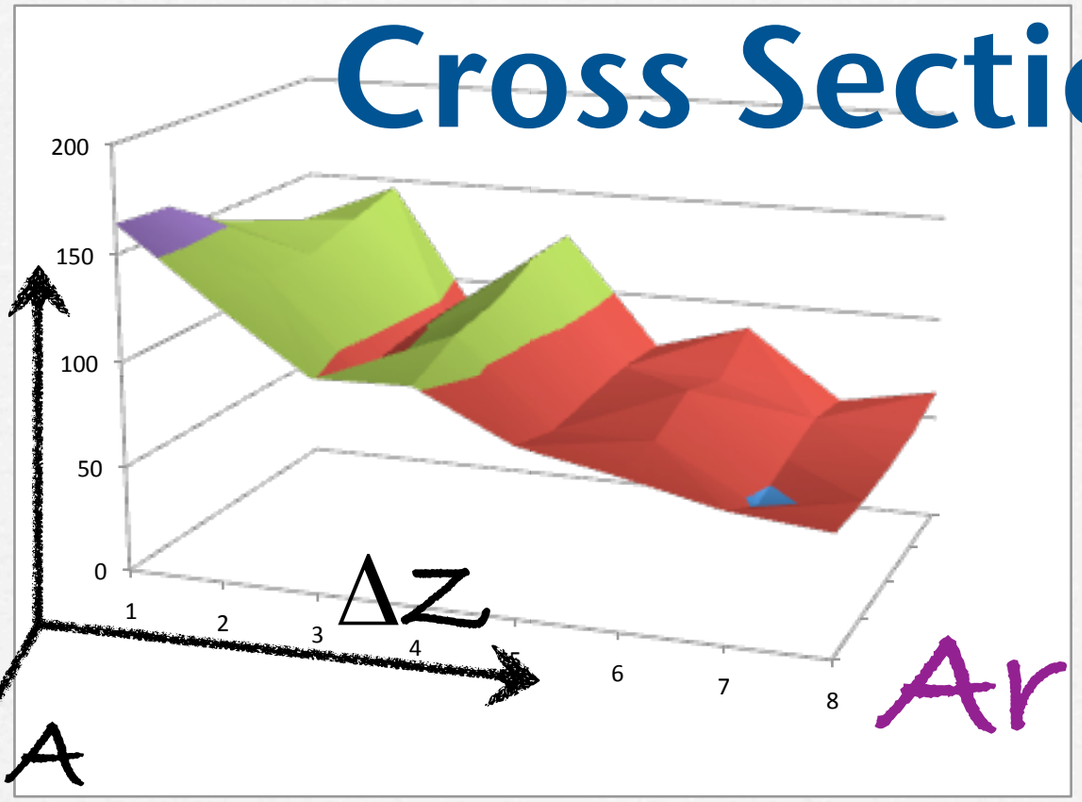
partial fragmentation cross section



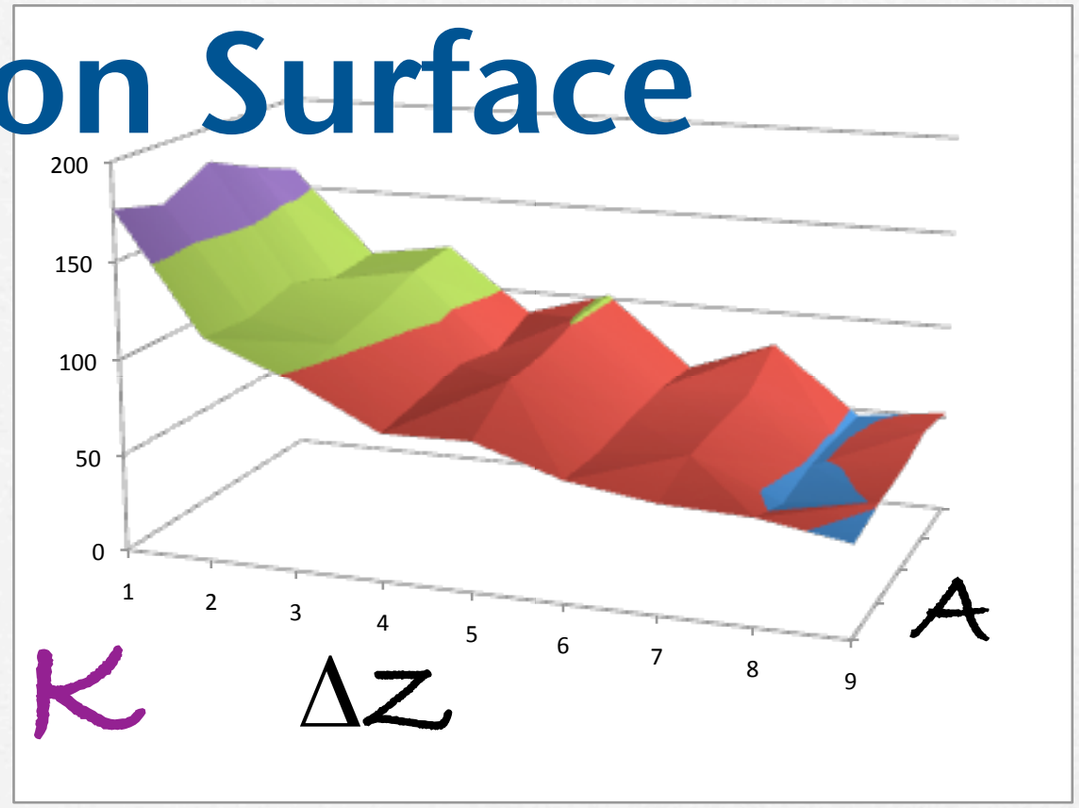
Δz

Cross Section Surface

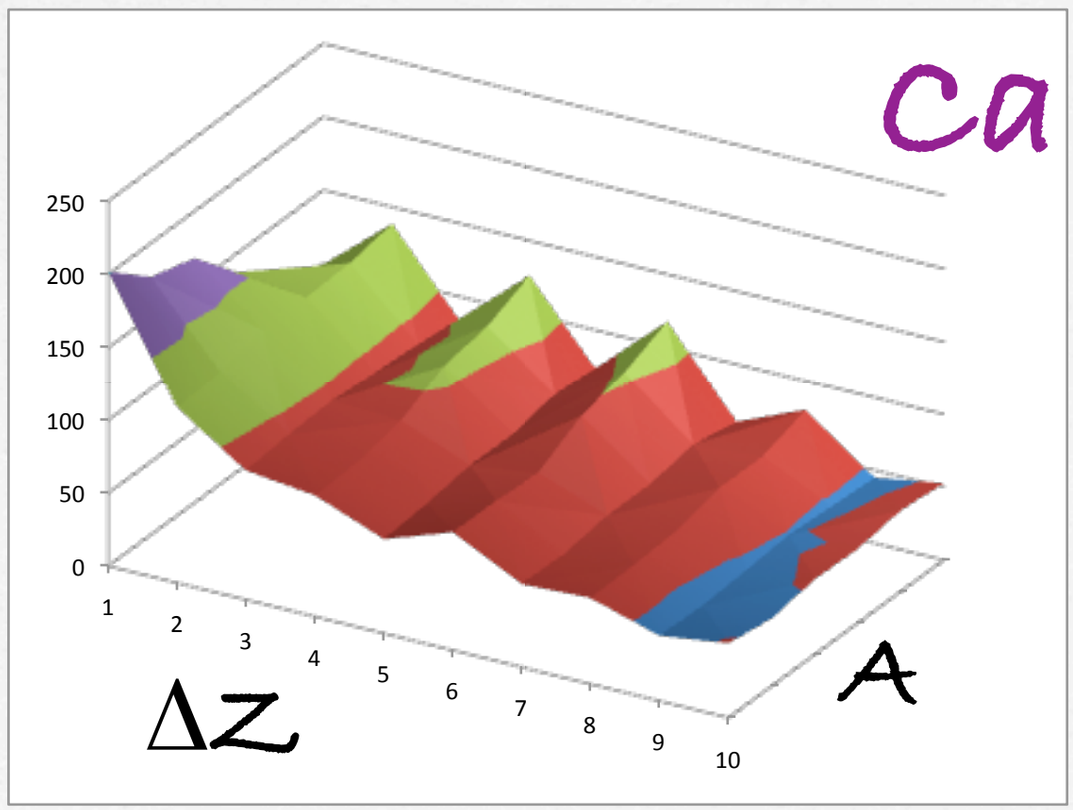
fragmentation cross section (mb)

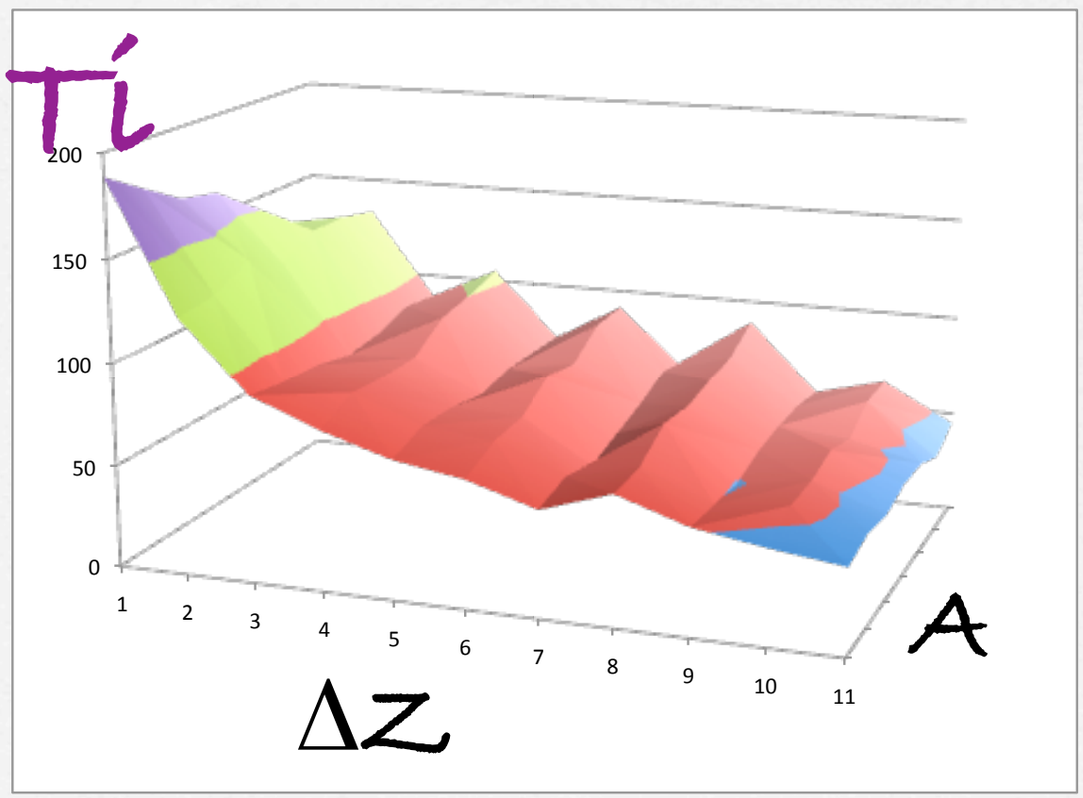


ArK



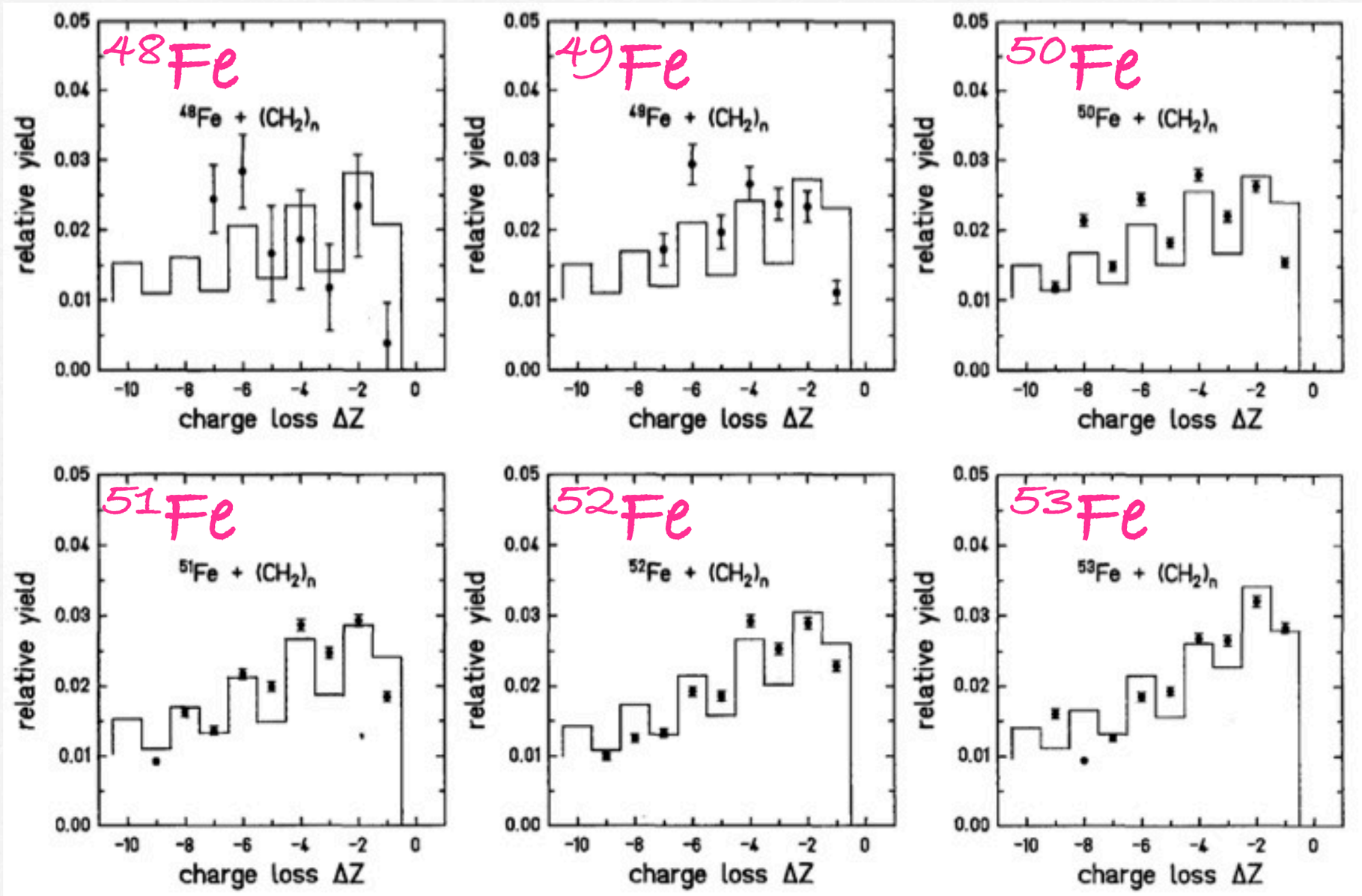
caTí





Previous study @GSI

neutron-deficient



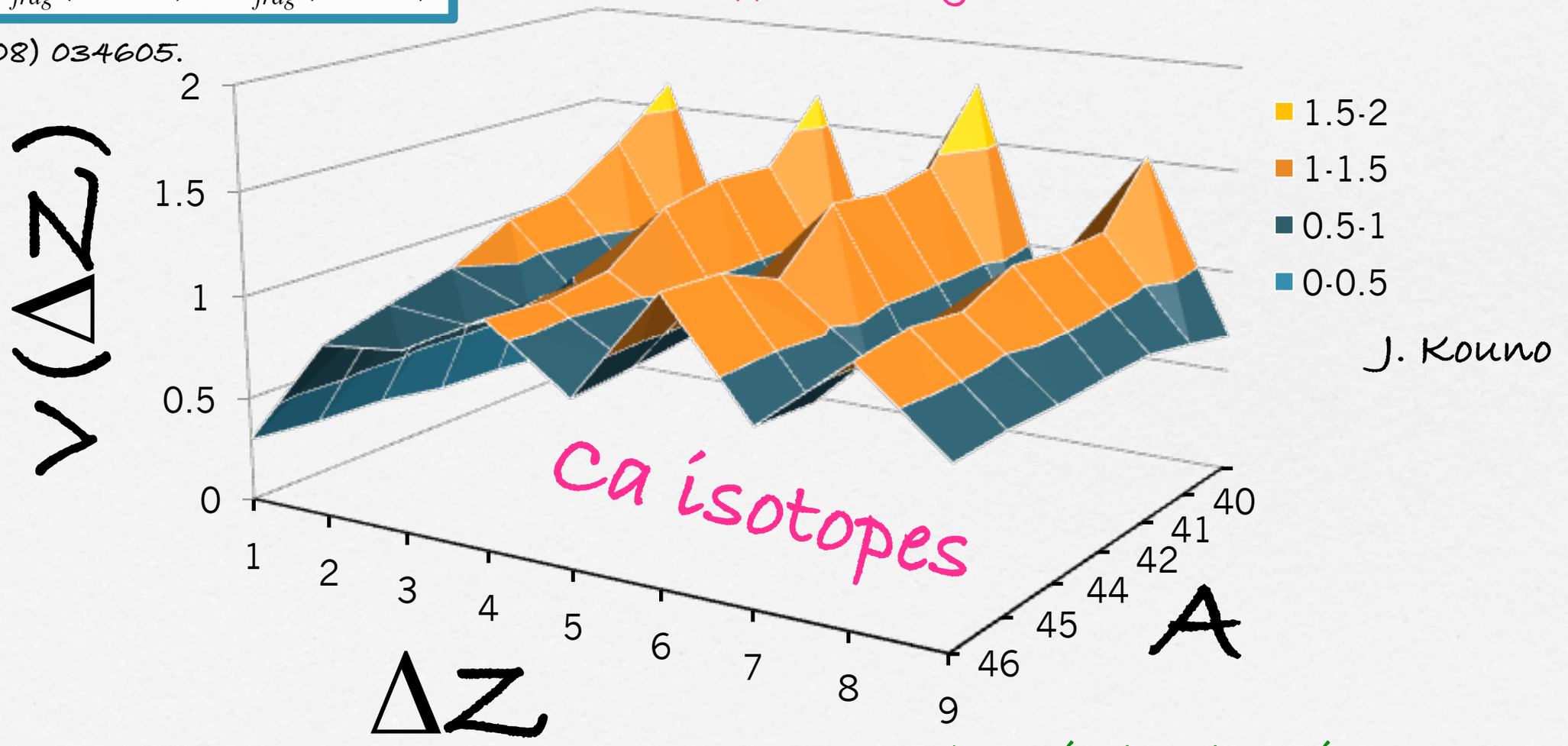
B. Blank et al., Z. Phys. A 352 (1995) 77.

Even-odd effects in the partial fragmentation cross sections

$$V(\Delta Z) = \frac{2\sigma_{frag}(\Delta Z)}{\sigma_{frag}(\Delta Z+1)+\sigma_{frag}(\Delta Z-1)}$$

PRC 77 (2008) 034605.

even-odd effect clearly observed at "stable" nuclei!



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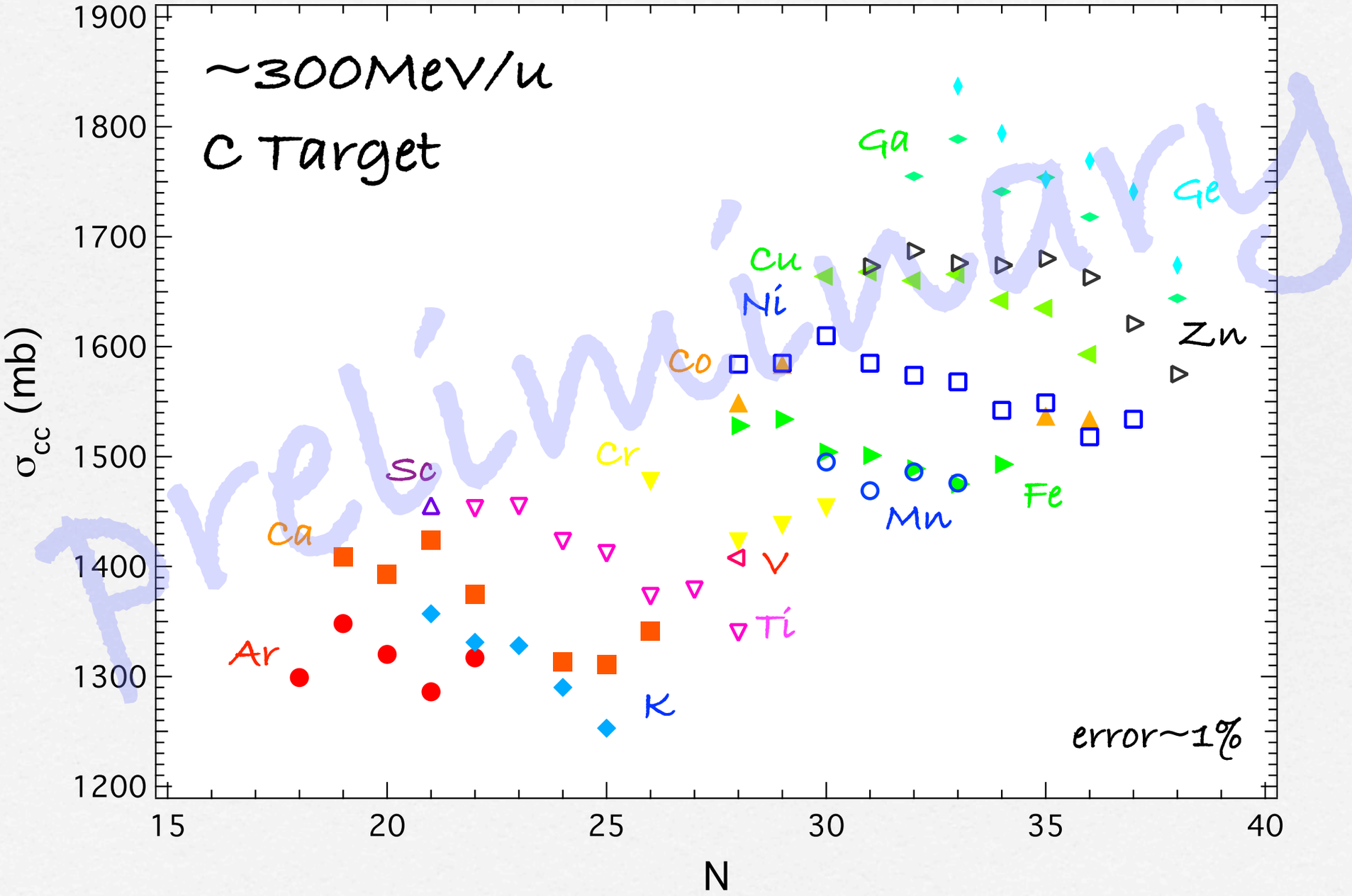
theoretical explanation ...

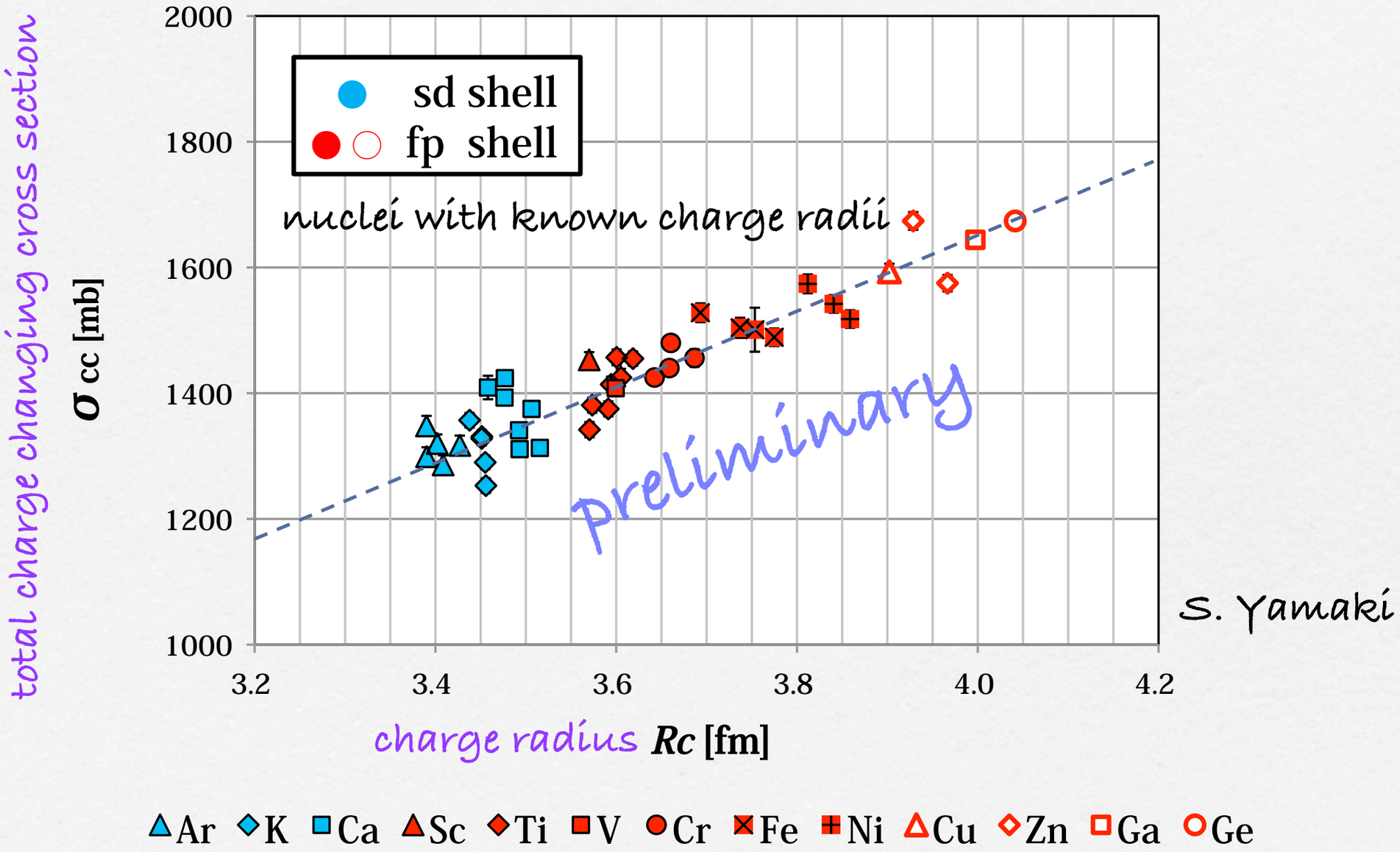
lowest particle separation energy

total charge changing cross sections

Results ...
Total Charge-Changing Cross-Sections



Correlation of Cross Sections and Charge Radii



A Modification of Glauber Model

How to calculate charge radii ...

total reaction cross section

$$\sigma_R = 2\pi \int b[1 - T(b)]db, \; T(b) = \exp\left[-\sigma_{NN} \int \rho_m^{targ} \rho_m^{proj}\right]$$

optical-limit approx.

analogy ?

charge changing cross section

$$\sigma_{cc} = 2\pi \int b[1 - T^p(b)]\mathcal{E}(E)db,$$

$$T^p(b) = \exp\left[-\left(\sigma_{pp} \int \rho_p^{targ} \rho_p^{proj} + \sigma_{np} \int \rho_n^{targ} \rho_p^{proj}\right)\right]$$

use proton density only!

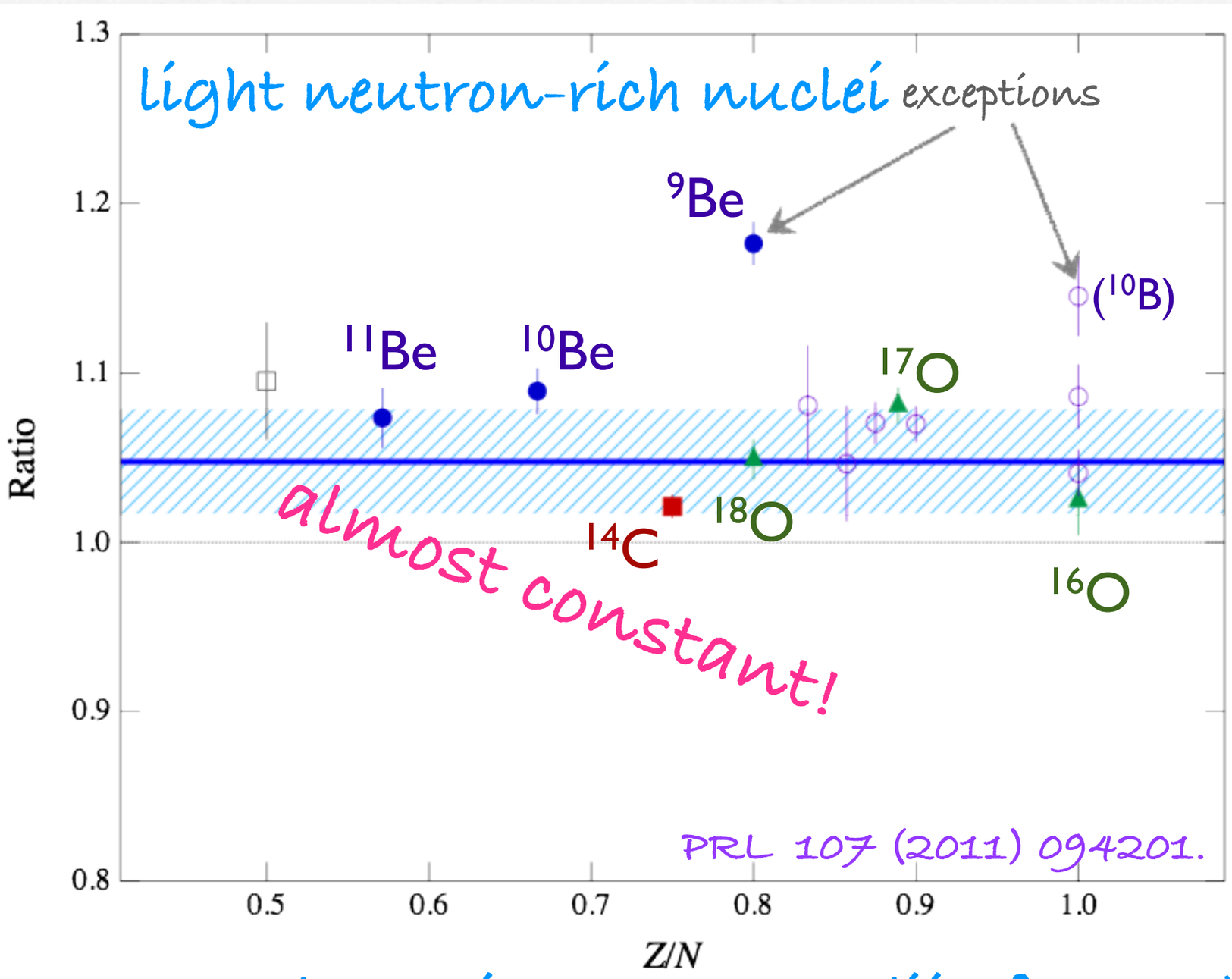
energy dependent correction factor : $\mathcal{E}(E)$

incl. higher order effects.

Scaling of Charge Changing Interactions

total charge changing cross section

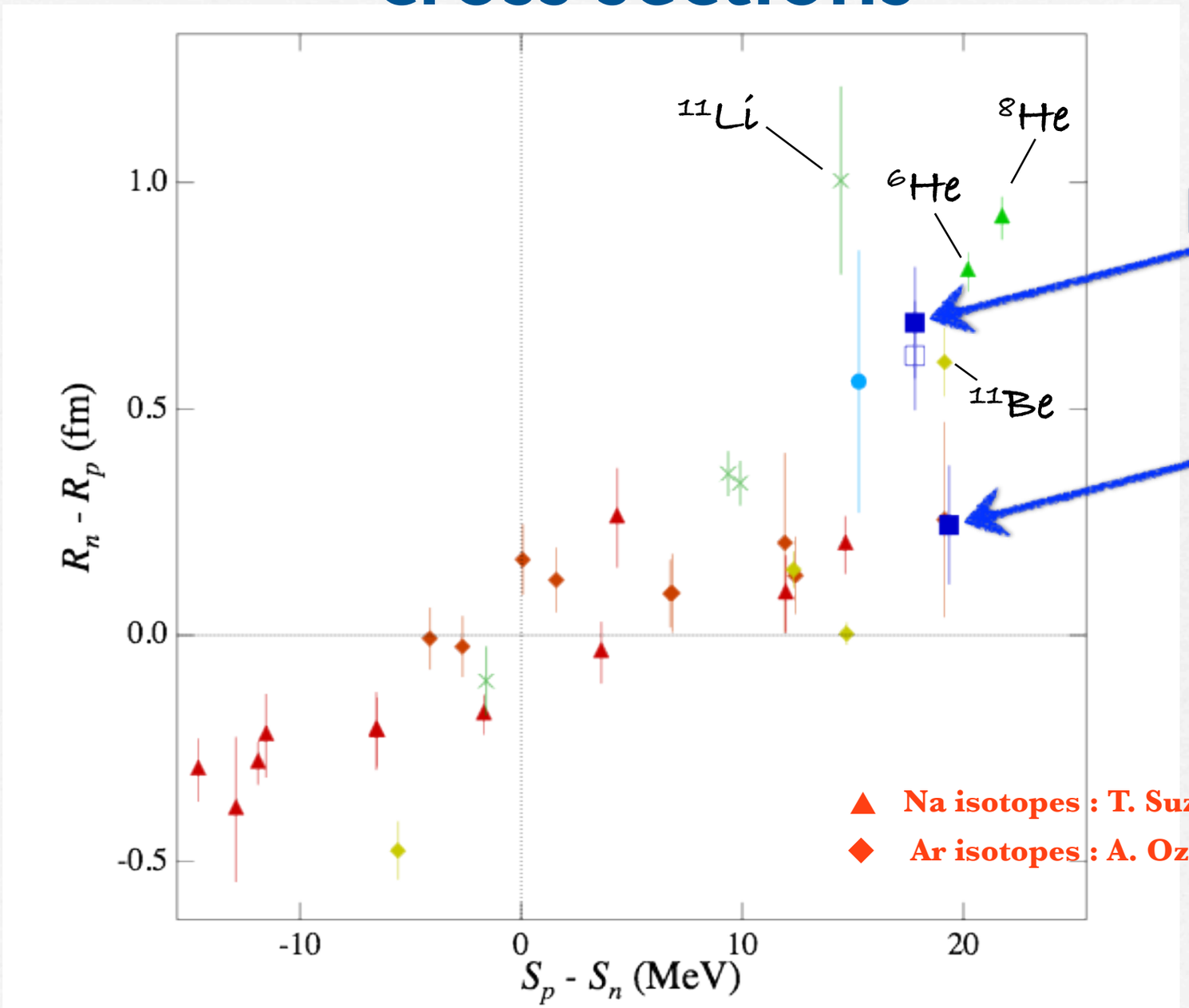
exp./calc.



☑ a new way to determine charge radii of unstable nuclei

Neutron Skin from charge-changing cross sections

Neutron Skin



PRL 107 (2011) 094201.

▲ Na isotopes : T. Suzuki et al., PRL 75(95)3241.

◆ Ar isotopes : A. Ozawa et al., NPA 709(02)60.

Separation Energy difference

Summary

- Total and partial Charge-Changing Cross-Sections of various secondary beams were systematically precisely measured at the intermediate energies.
- The fragmentation cross sections compared with the models.
- The even-odd effect was clearly observed for a wide range on nuclear chart.
- The total charge changing cross sections are sensitive to the charge radii. ... a new tool !

Collaborators

- Saitama

  T. Yamaguchi, N. Ichihashi, J. Kouno, K. Sato, S. Yamaki, T. Suzuki,

  H. Furuki, N. Inaba, S. Miyazawa, I. Nishizuka, F. Suzaki, S. Suzuki, S. Yasumoto

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- Tsukuba

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- NIRS

  A. Kitagawa, S. Sato

- Kochi

  S. Momota

- TUS

  D. Nishimura

Thank you for attention!