Charge-changing and total interaction cross section measurements

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Collaborators

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. [*10] Radioactive Isotope Center, Niigata University , [*11] Al - Farabi Kazakh National University

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Nuclear Size and Interaction Cross Sections

Reaction Cross Section $\sigma_{tot} = \sigma_R + \sigma_{el}$

Interaction Cross Section $\sigma_I = \sigma_R + \sigma_{inel}$

σ_I or σ_R ⟷ Nuclear Size

Glauber Calculation

$$\sigma_R = \int d\boldsymbol{b}\left[1 - \exp\left(-\int d^2\boldsymbol{r}\sum_{i,j}\sigma_{NN}(E)\rho_i^P(\boldsymbol{r})\rho_j^T(\boldsymbol{r})\right)\right]$$

σ_R can be uniquely calculated by **3** quantities

ρ^P Projectile Density

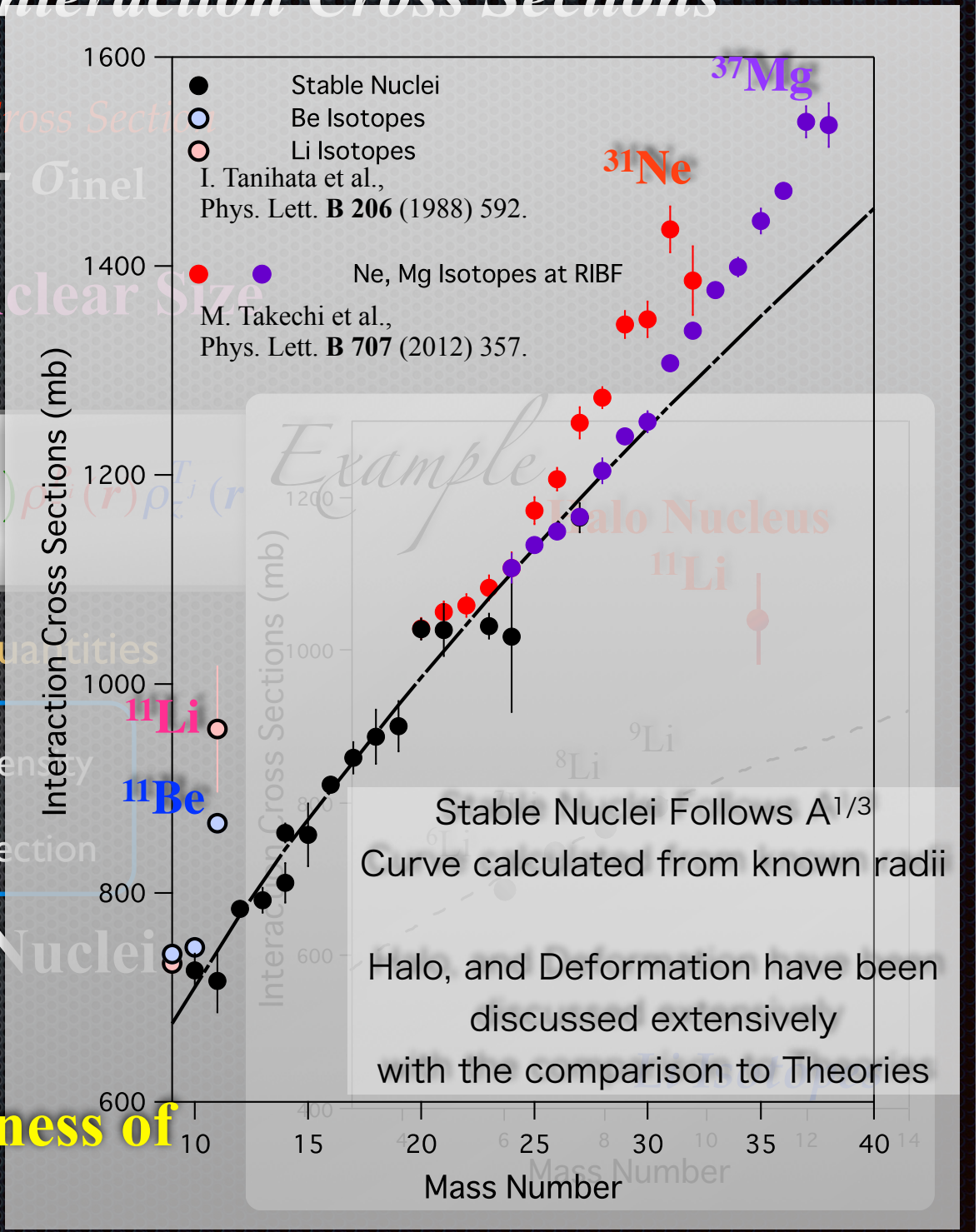
ρ^T Target Density

σ_{NN} Nucleon- Nucleon Total Cross Section

Nuclear Size of unknown Nuclei

→ Halo features

Next : Neutron Skin Thickness of Nuclei A>40



Neutron Skin and Nuclear Matter EOS

$$w(n,\delta) \approx w_0 + \frac{K_0}{18n_0^2}(n-n_0)^2 + \delta^2\left[S_0 + \frac{L}{3n_0}(n-n_0)\right]$$

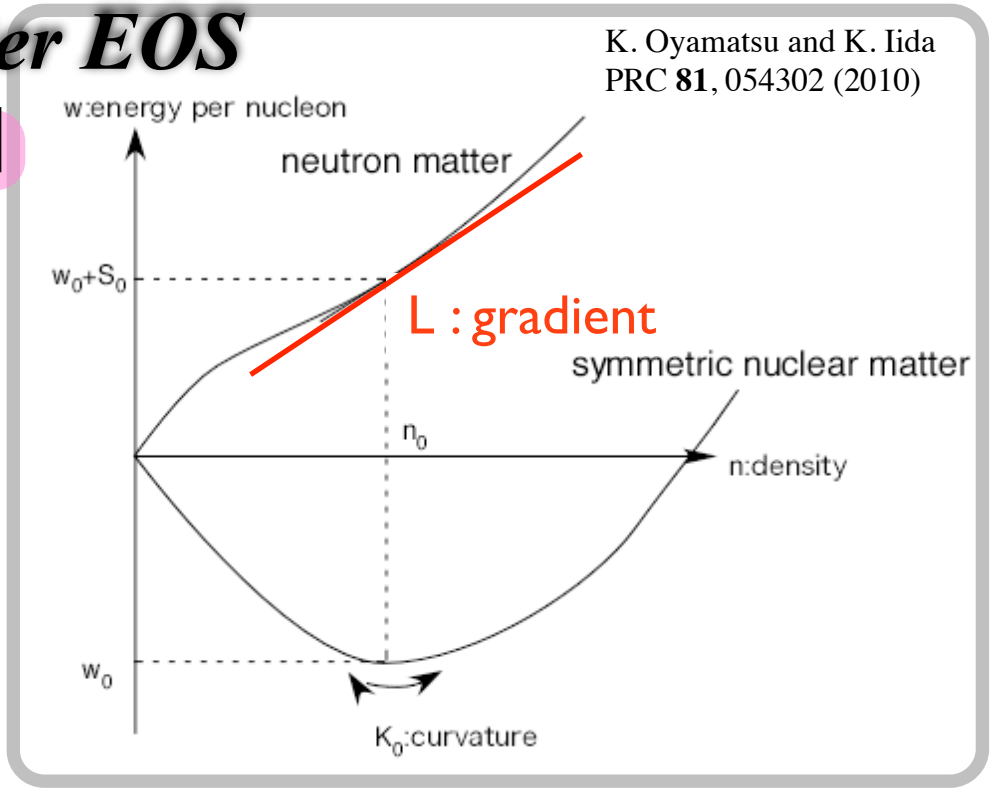
n_0 : saturation density, w_0 : saturation energy
K_0 : incompressibility, S_0 : symmetry energy at $n = n_0$

$\delta = (N - Z)/A$

L : Density derivative coefficient of symmetry energy

First Key Parameter : L

How to know L?

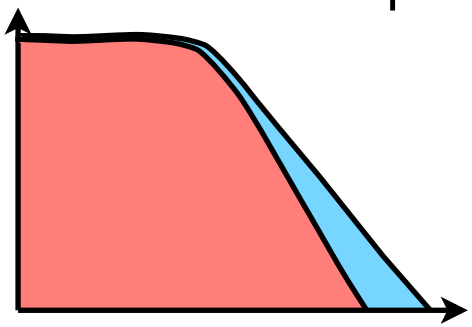


One Simple correlation between L and Neutron Skin

M. Centelles et al., PRL 102, 122502 (2009)

EOS around N≈Z $\quad w(n,\delta) \approx w_0 + \frac{K_0}{18n_0^2}(n-n_0)^2 + \delta^2\left[S_0 + \frac{L}{3n_0}(n-n_0)\right]$

Droplet Model $\quad E_B = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} - \delta(A,Z)$



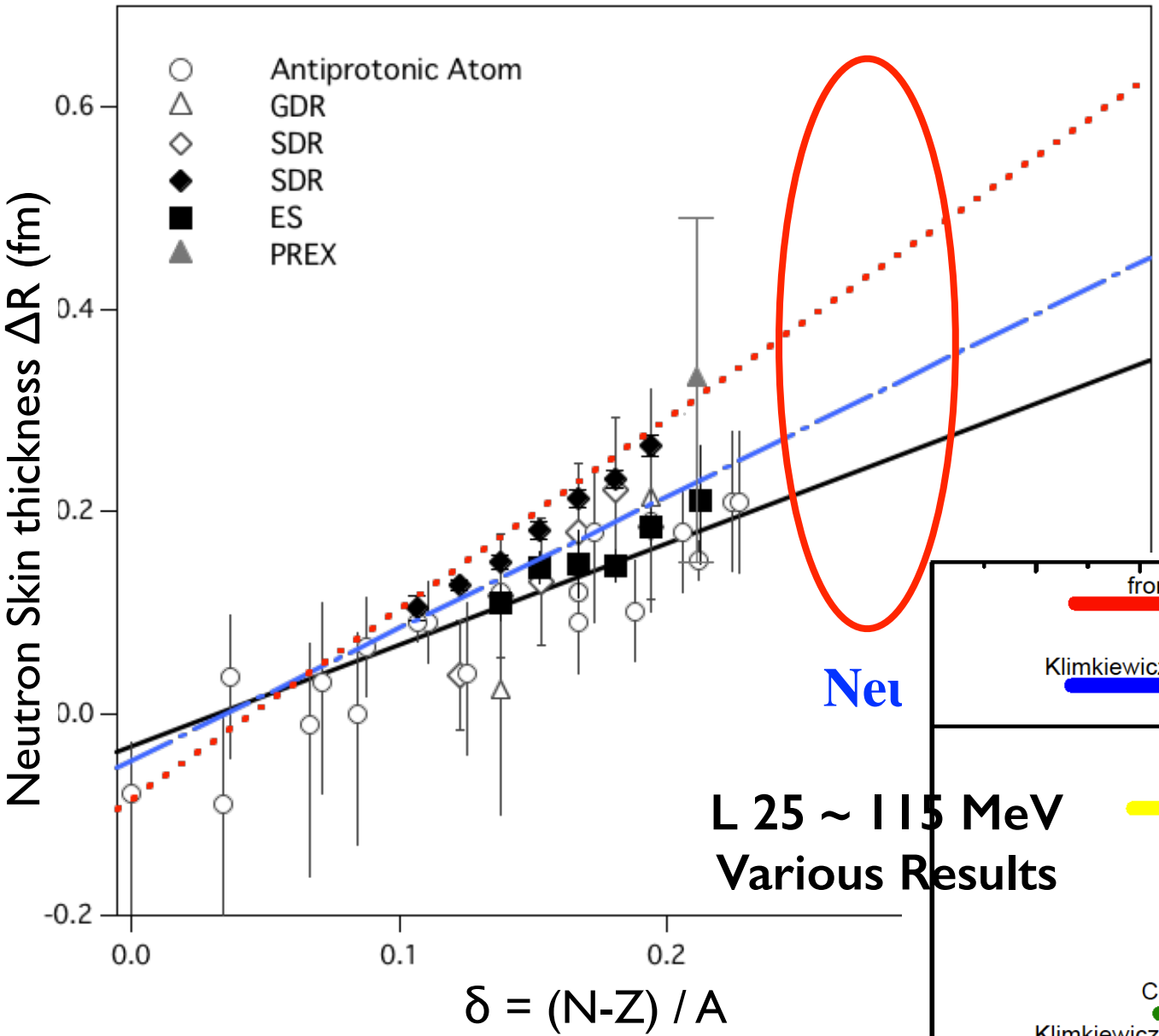
When the density of nuclear matter is around nuclear surface density ~0.1 fm^{-3}
Symmetry term a_A ≈ symmetry term of EOS

Neutron skin thickness $\Delta R \sim L \times \delta$ + *correction term*

$\delta = (N - Z)/A, \quad A > 40$

Measurement of δ dependence of ΔR → L

Existing data for Neutron Skin Thickness



Prediction from NL3 interaction
Neutron Star $R_{1.4M\odot}$ 15km
M_{max} = 2.8 M⊙

FSUGold interaction
Neutron Star $R_{1.4M\odot}$ 13km
M_{max} = 1.7 M⊙

M. Centelles et al.,
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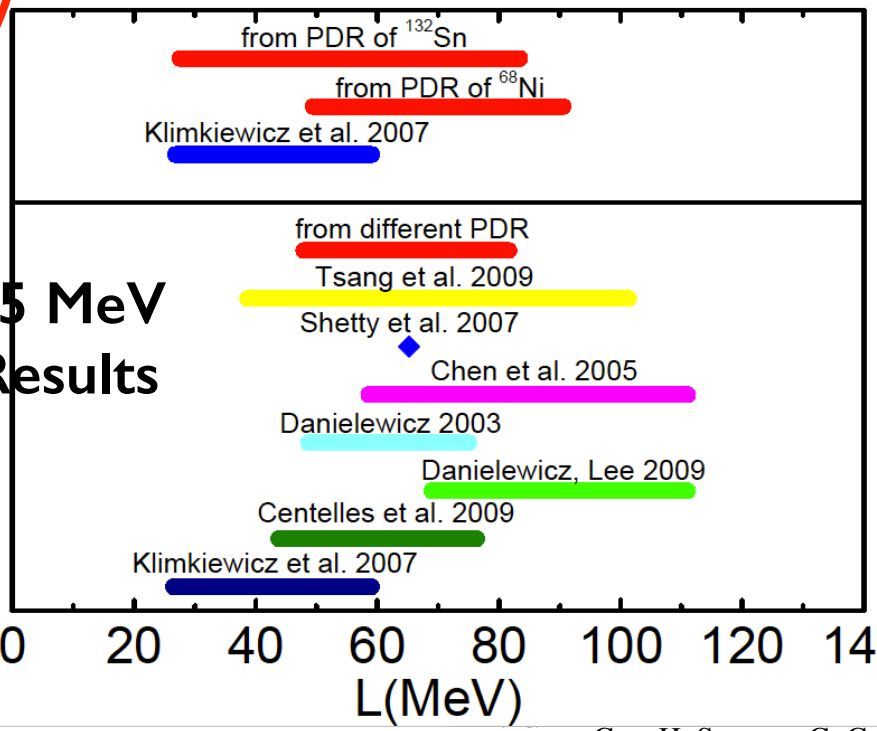
from A = 40 ~ 238

Neu



L 25 ~ 115 MeV
Various Results

Anti Protonic Atom : A. Trzcinska et al., Phys. Rev. Lett. **87** 082501 (2001).
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Skin thickness for Neutron-rich Nuclei

How to determine Neutron Skin Thickness for Exotic Nuclei?

Neutron Skin ΔR = Neutron Radius R_n - Proton Radius R_p

σ_I (Interaction cross section) → Matter Radius

σ_I ⟷ Rm

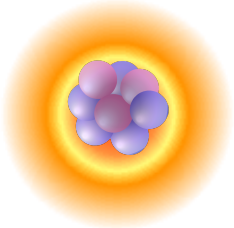
$$\sigma_R = \int db\left[1 - \exp\left(-\int d^2r \sum_{i,j} \sigma_{NN}(E)\rho_z^{P_i}(r)\rho_z^{T_j}(r-b)\right)\right]$$

To know Neutron Skin Thickness, Rp is necessary!

Stable Nuclei :
Electron Scattering Experiment
X-ray Measurements Muonic Atom

Unstable Nuclei :
Isotope shift Measurements

→ **Proton Radii**
Sensitive to the **Coulomb Potential** of Protons

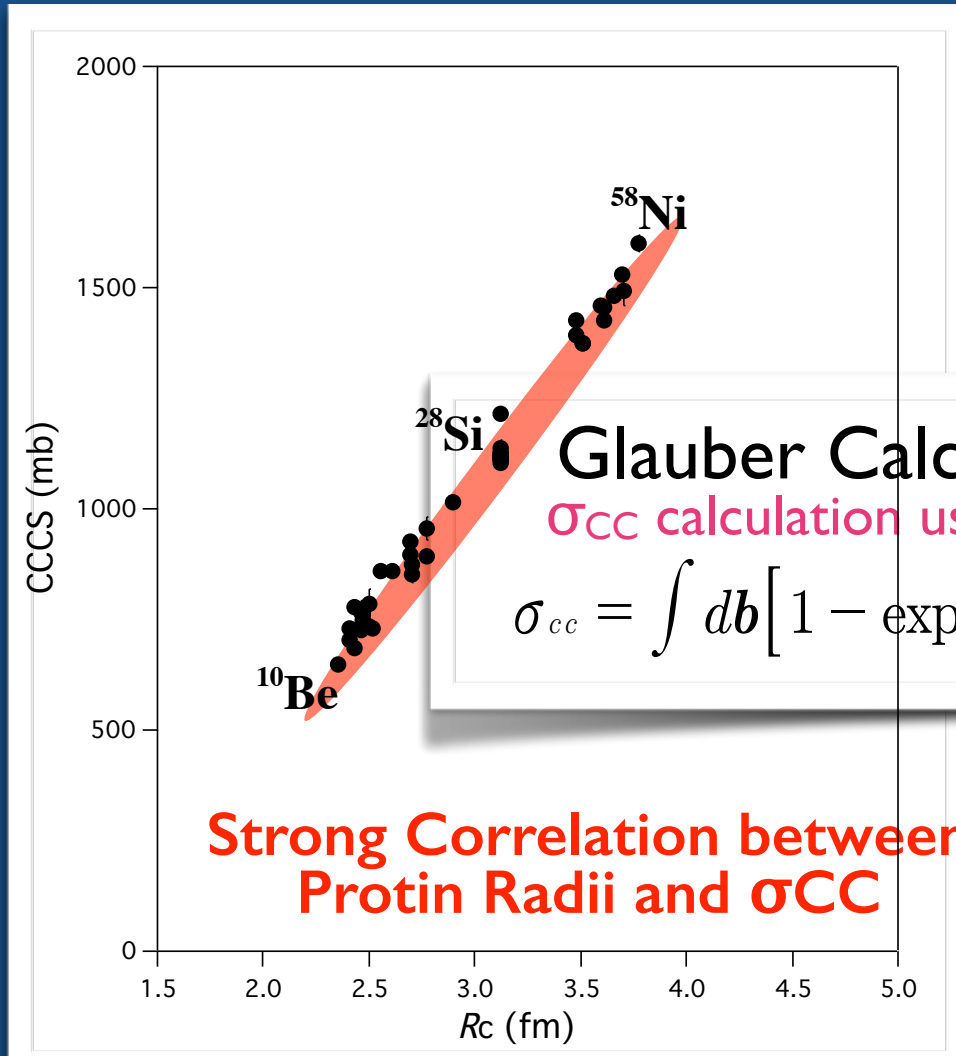


New Method :
Charge Changing Cross Section

σ_{CC} ⟷ R_p

Proton Distribution Radius Rp and σ_{CC}

Rp (Electron Scattering Data) vs σ_{CC}



Strong Correlation between Protin Radii and σCC

$\sigma_{CC} \rightarrow$ Proton Radius ?

Glauber Calculation for σ_{CC}

σ_{CC} calculation using charge distribution of nucleus

$$\sigma_{cc} = \int db\left[1 - \exp\left\{-\left(\sigma_{pp}\int \rho_{proton}^{Projectile}\,\rho_{proton}^{Target} + \sigma_{np}\int \rho_{proton}^{Projectile}\,\rho_{neutron}^{Target}\right)\right\}\right]$$

σ_{CC} ⟷ R_p

?

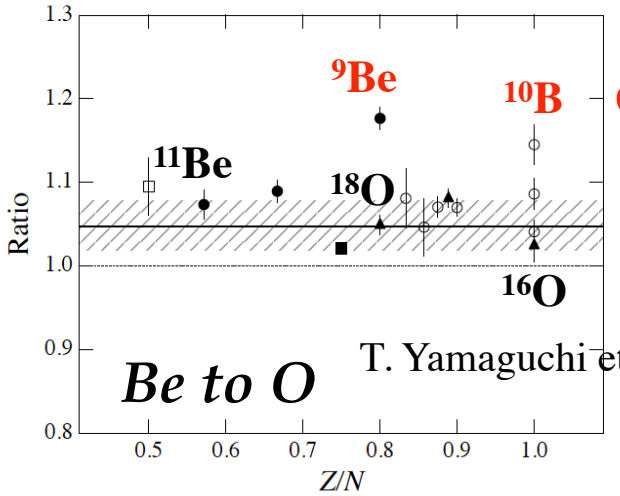
Determination of skin thickness
Charge radii from CC cross sections

Glauber Calculation for σ_{CC}

σ_{CC} calculation using charge distribution of nucleus

$$\sigma_{cc} = \int db\left[1 - \exp\left\{-\left(\sigma_{pp}\int \rho^{Projectile}_{proton}\,\rho^{Target}_{proton} + \sigma_{np}\int \rho^{Projectile}_{proton}\,\rho^{Target}_{neutron}\right)\right\}\right]$$

Determination of charge radius for ^{16}C from σ_{CC} (HIMAC)



T. Yamaguchi et al., PRL. **107**, 032502 (2011)

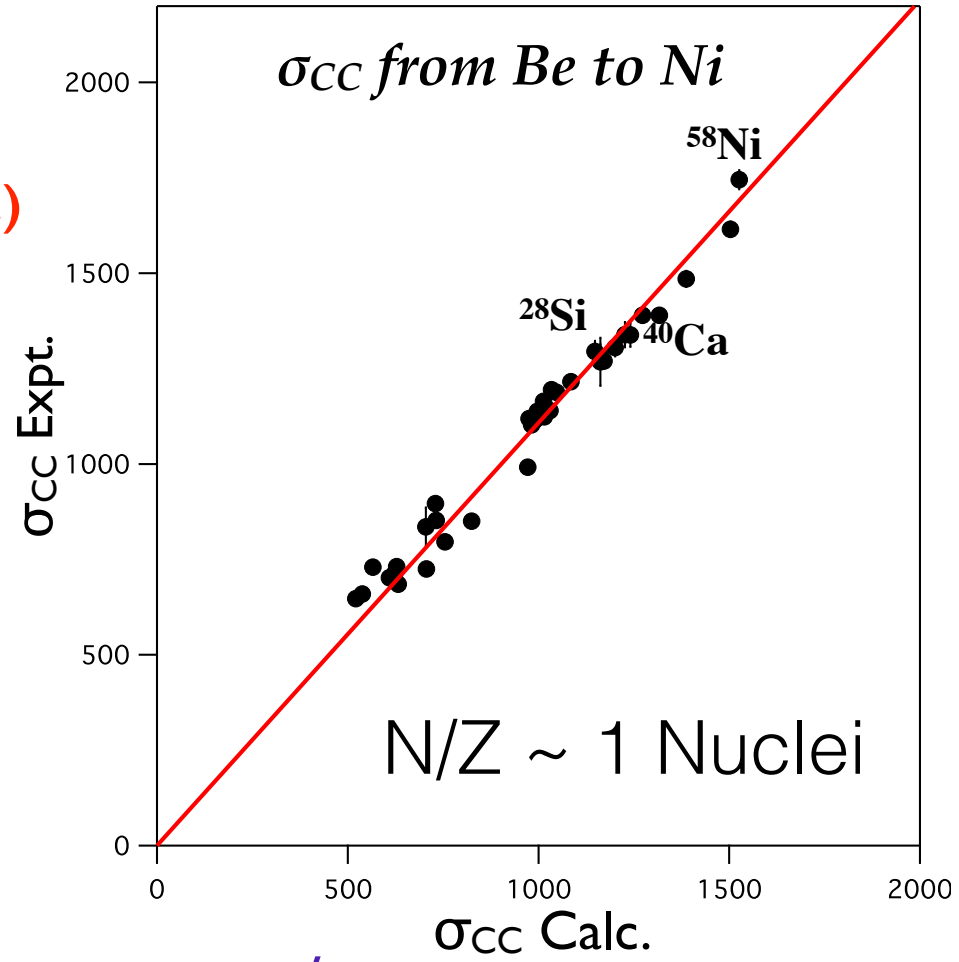
Calibration of σ_{CC}(Expt..) / σ_{CC}(Calc.) for light nuclei in wide range of Z/N (Charge Radii known)

^{9}Be, ^{10}B, Borromeans

Determination of charge radius for $^{12-19}$C from σ_{CC} (GSI) ~1 GeV/u

R. Kanungo et al., PRL **117**, (2016) 102501

How about unstable, heavier nuclei A>40 ?



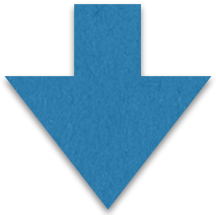
$\sigma_{CC(Expt..)}$ / $\sigma_{CC(Calc.)}$ ~ Constant

σ_{CC} Measurements

σ_{CC} Measurements for $^{40\text{-}48,\ 50}$**Ca,** $^{58\text{-}64}$**Ni,** $^{38\text{-}47}$**K,** $^{62\text{-}80}$**Cu**

Charge Radii are known
(Isotope-shift Measurements)

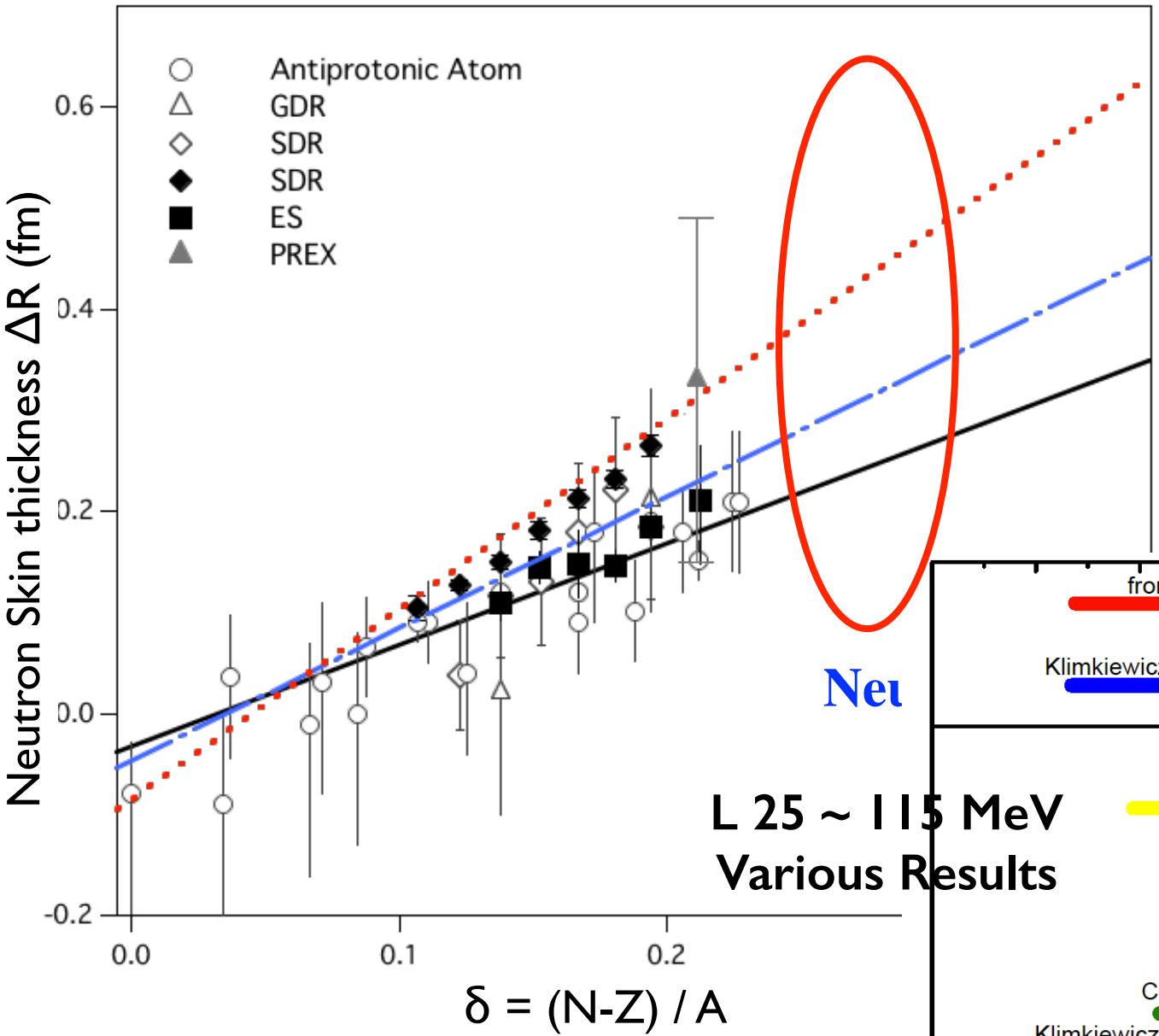
Study of σ_{CC}(Expt..) / σ_{CC}(Calc.) for A>40 nuclei in wide Z/N range



And

σ_I and σ_{CC} Measurements for $^{58\text{-}78}$**Ni**

Existing data for Neutron Skin Thickness



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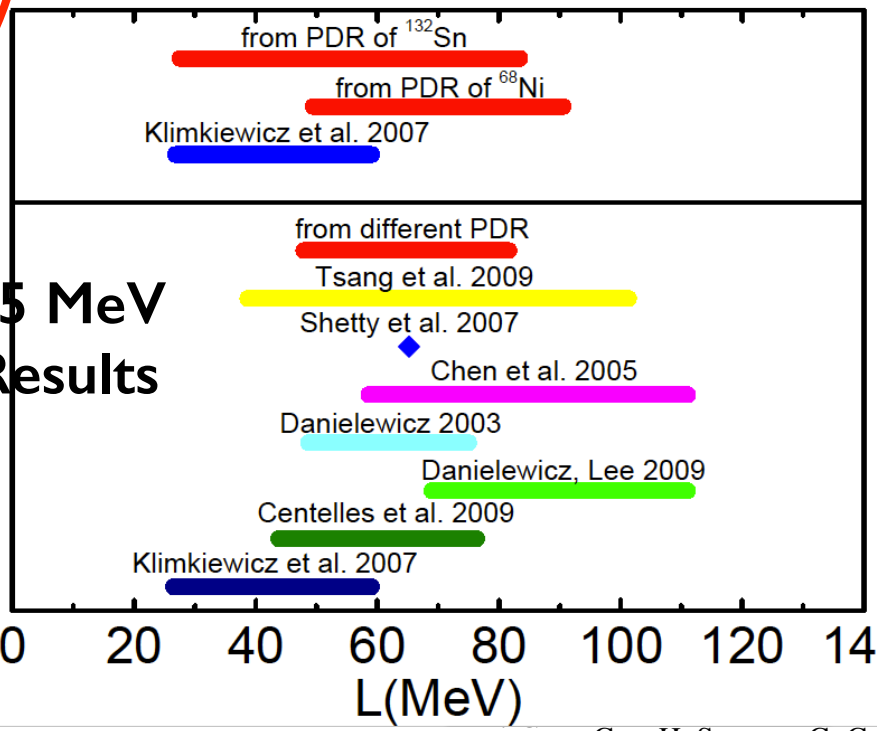

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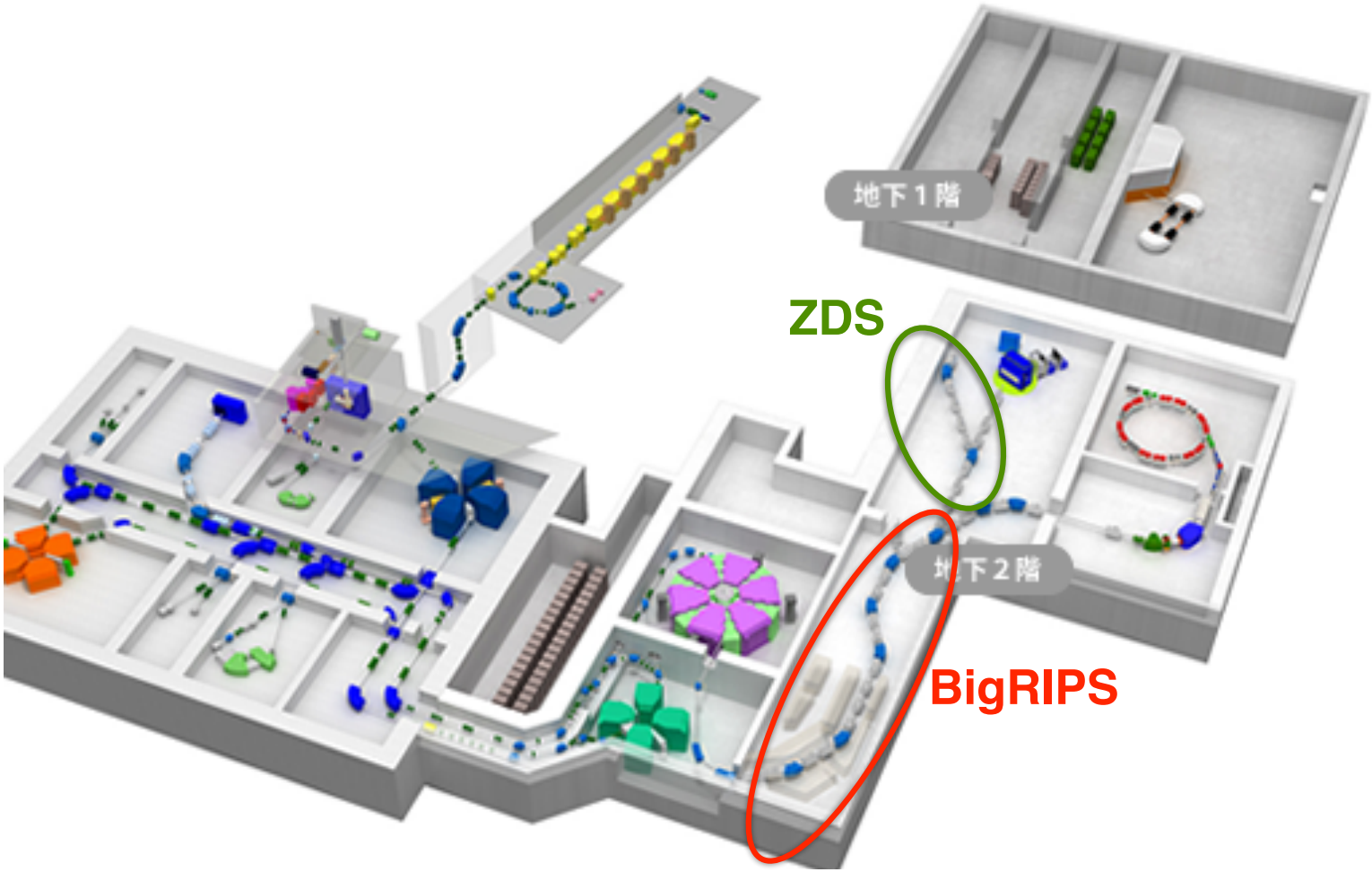
Skin thickness for Neutron-rich Nuclei

Experiment at RIBF

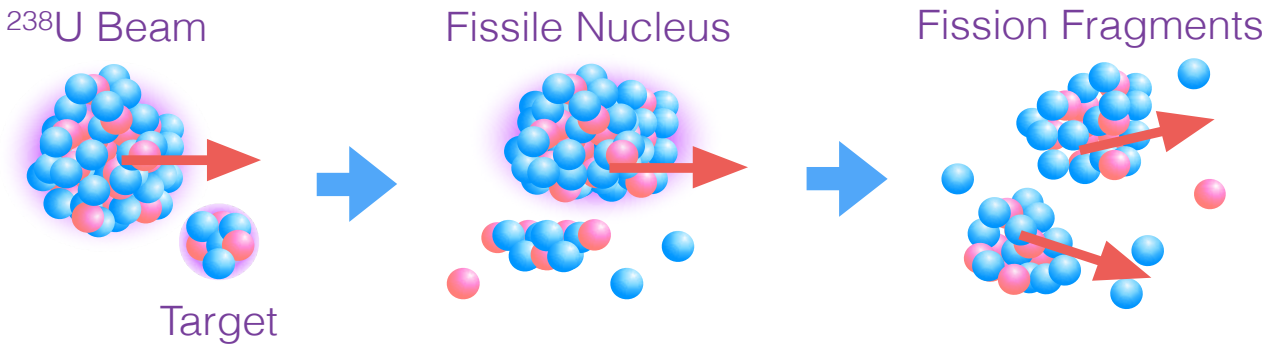
RIBF ZDS F11, two MUSICs from GSI

Experiment at RIBF

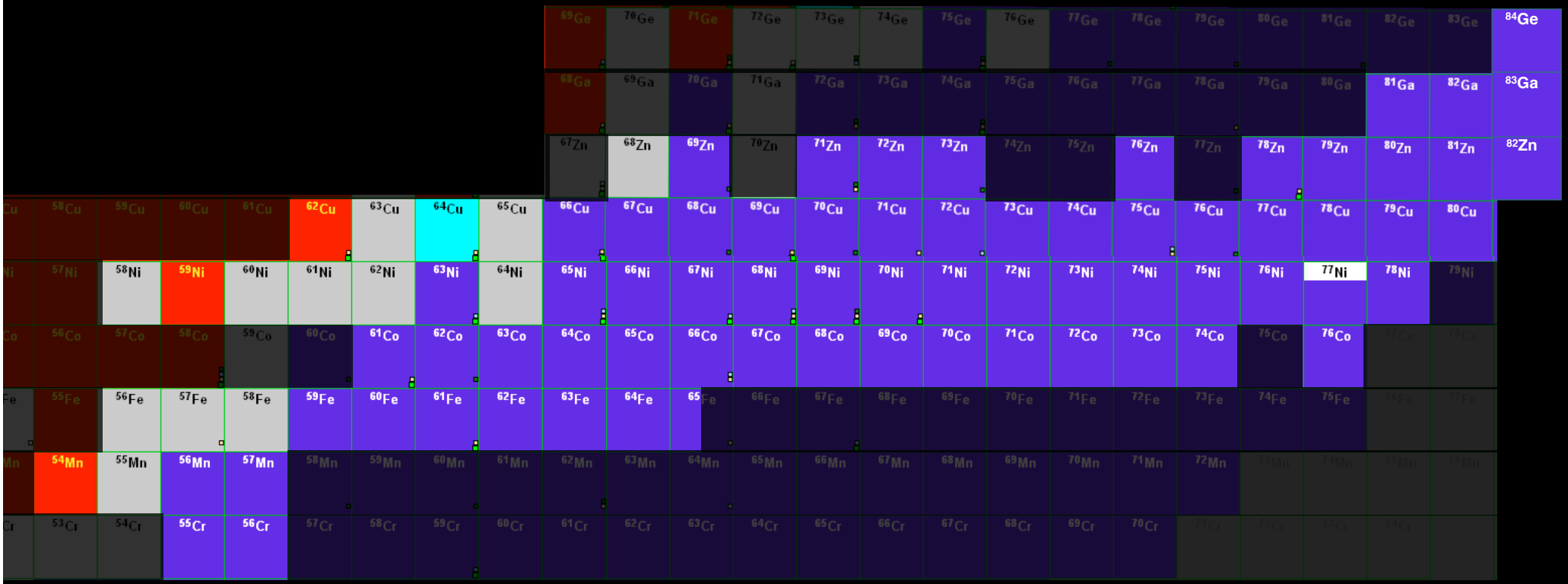


^{238}U Beam
345 MeV/u 30 pnA

Abrasion Fission
on Be Target



Produced Beam around Ni Region ^{238}U on Be Abrasion Fission



^{84}Ge $^{81\text{-}83}$Ga $^{68\text{-}82}$Zn $^{62\text{-}80}$Cu

$^{58\text{-}78}$Ni

$^{61\text{-}76}$Co $^{56\text{-}65}$Fe $^{54\text{-}57}$Mn $^{55\text{-}56}$Cr

Produced Beam around Ca Region

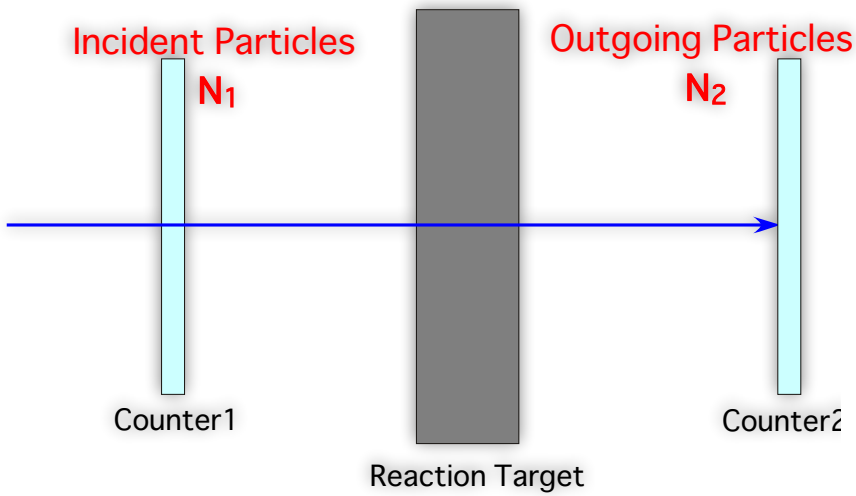
$^{40\text{-}50}$Ca $^{41\text{-}48}$K $^{39\text{-}46}$Sc etc. …

σ_{CC} Measurements for $^{40\text{-}48,\ 50}$**Ca,** $^{58\text{-}64}$**Ni,** $^{38\text{-}47}$**K,** $^{62\text{-}80}$**Cu**

Charge Radii are known
(Isotope-shift Measurements)

σ_I and σ_{CC} Measurements for $^{58\text{-}78}$**Ni** and nuclides nearby

Measurements : Transmission Method



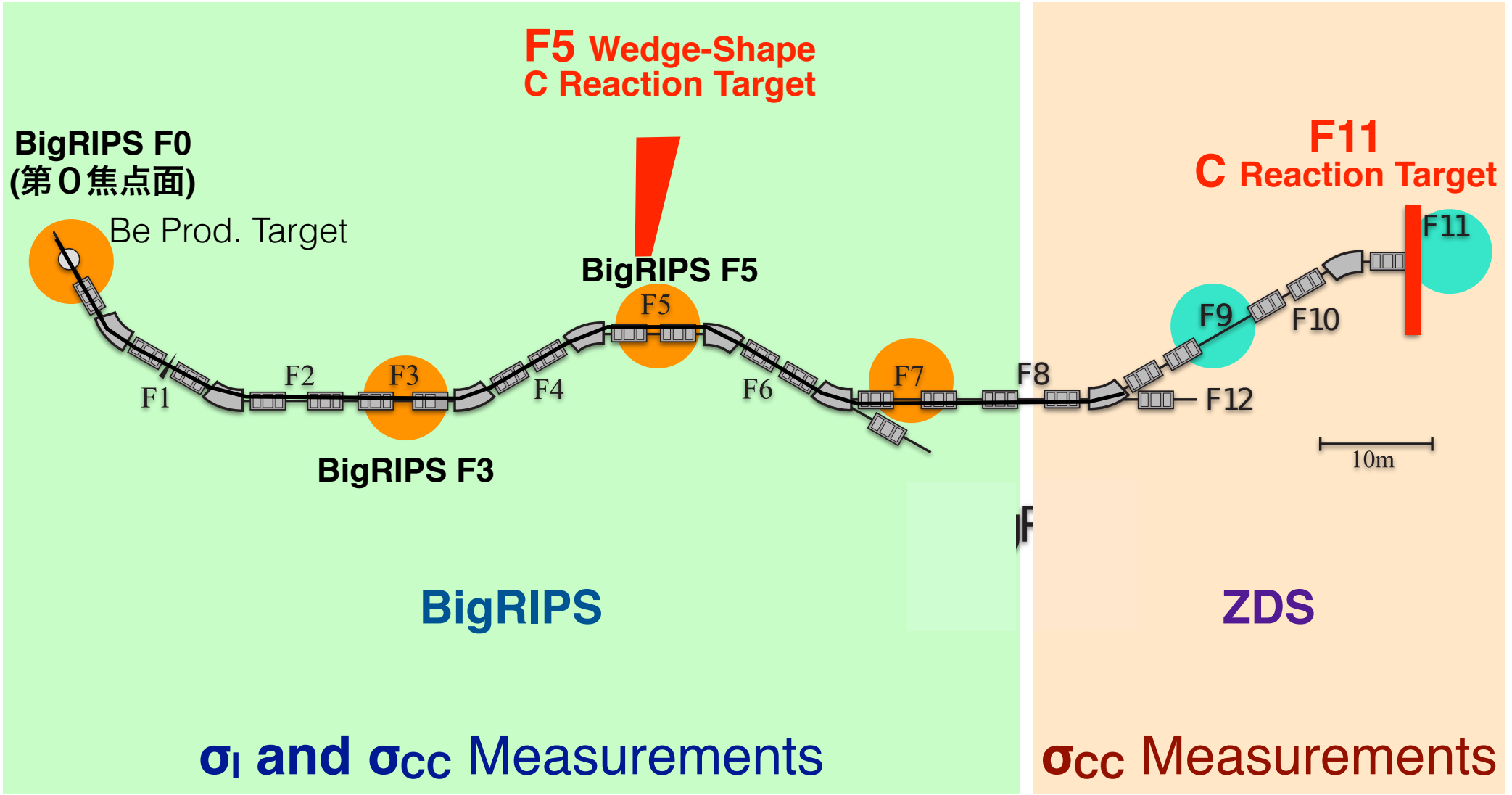
$$\sigma_{\text{I or CC}} = -\frac{1}{t}\ln\left(\frac{N_2}{N_1}\right)$$

N_1 : Incident particle

σ_I N_2 : Without changing Z and A

σ_{CC} N_2 : Without changing Z

Experimental Setup



σ_I and σ_{CC} Measurements
at **260 MeV/u**

σ_{CC} Measurements
at **170 MeV/u**

σ_{CC} at two different energies and σI
measured simultaneously

F5 Target Measurement

BigRIPS F0 - F5

BigRIPS F0
(第０焦点面)

Be Prod. Target

Reaction Target

PPAC F5PL

Slit

BigRIPS F5

F1 F2 F3 F4 F5 F6 F7 F8 F9 F10 F11 F12

10m

BigRIPS F3

IC

$$\sigma_{\mathrm{I\ or\ CC}} = -\frac{1}{t}\ln\left(\frac{N_2}{N_1}\right)$$

N_1 : Incident particle

F0 - F5 : Counting N_1

σ_I and σ_{CC} Measurements
at **260 MeV/u**

Identification : *ΔE - Bρ - TOF* Method

Magnetic Rigidity (Bρ) : F5 PPAC

Energy Loss : Ion Chamber at F3 (F3IC)

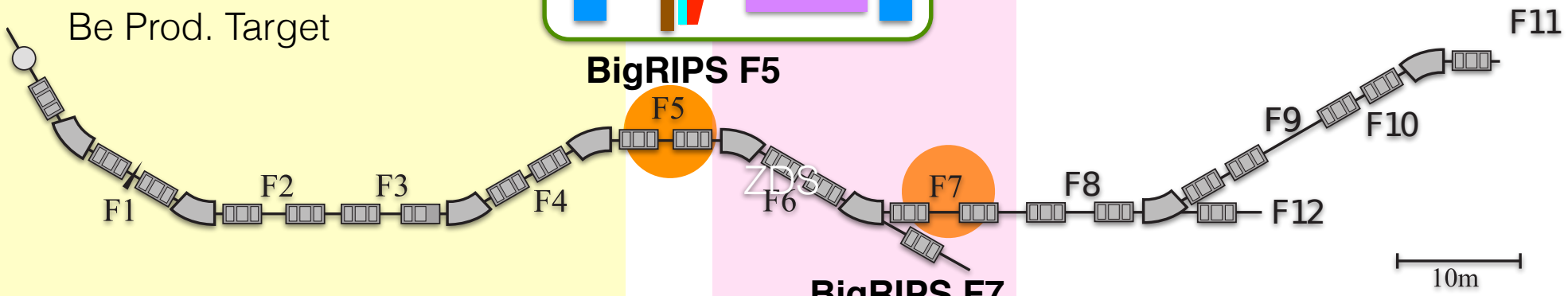
Time of Flight of F3 - F5 : F3PL, F5PL

F5 Target Measurement

BigRIPS F0 - F5

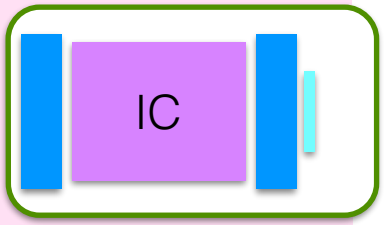
BigRIPS F0
(第０焦点面)

Be Prod. Target



BigRIPS F5

BigRIPS F7



BigRIPS F5 - F7

$$\sigma_{\mathrm{I\ or\ CC}} = -\frac{1}{t}\ln\left(\frac{N_2}{N_1}\right)$$

σ_I N_2 : Without changing Z and A

σ_{CC} N_2 : Without changing Z

σ_I and σ_{CC} Measurements
at **260 MeV/u**

F5 - F7 : Counting N_2

Identification : *ΔE - Bρ - TOF* Method

Magnetic Rigidity (Bρ) ：F5 PPAC

Energy Loss：Ion Chamber at F5 and F7 (F5IC, F7IC)

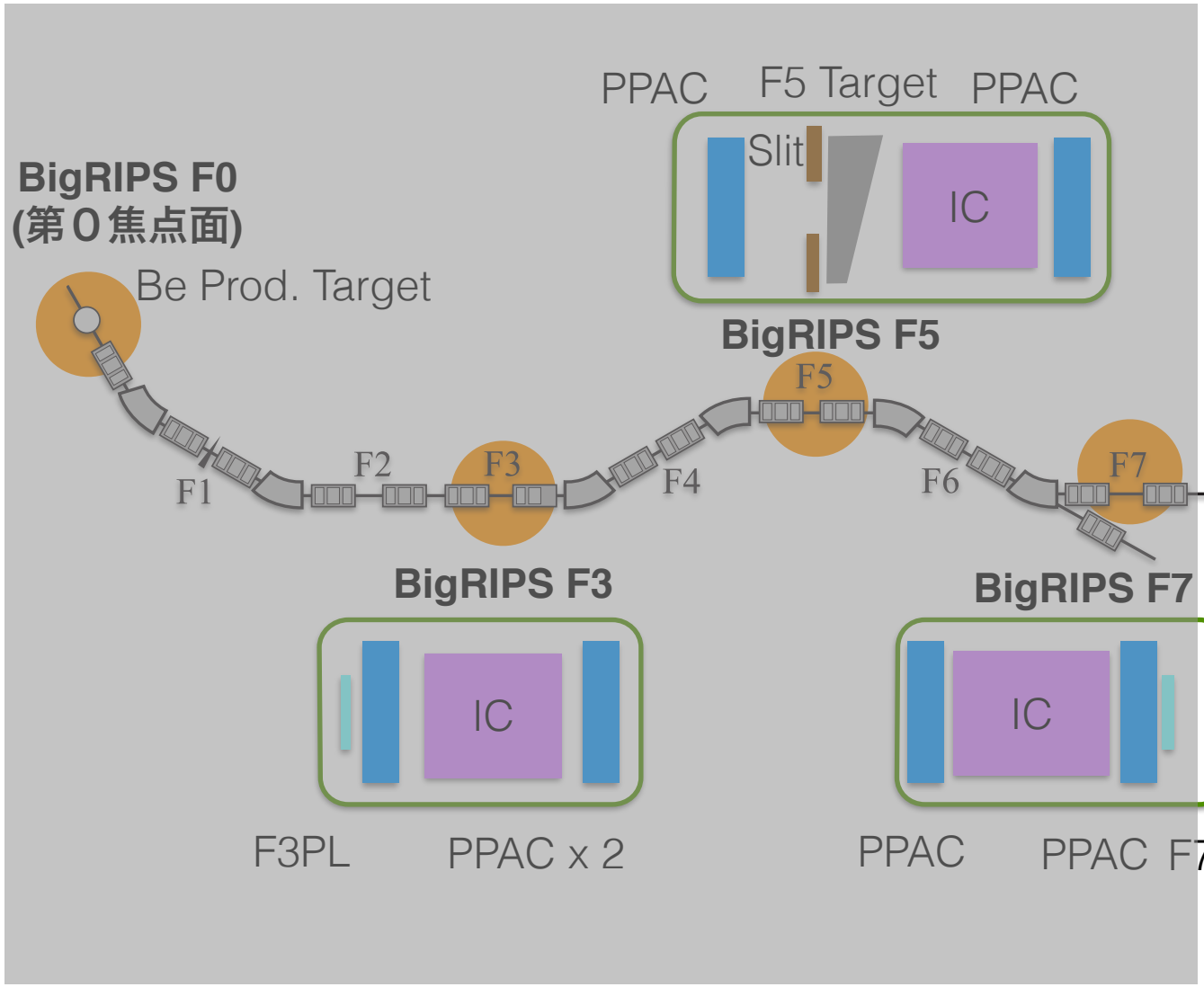
Time of Flight of F5 - F7：F5PL, F7PL

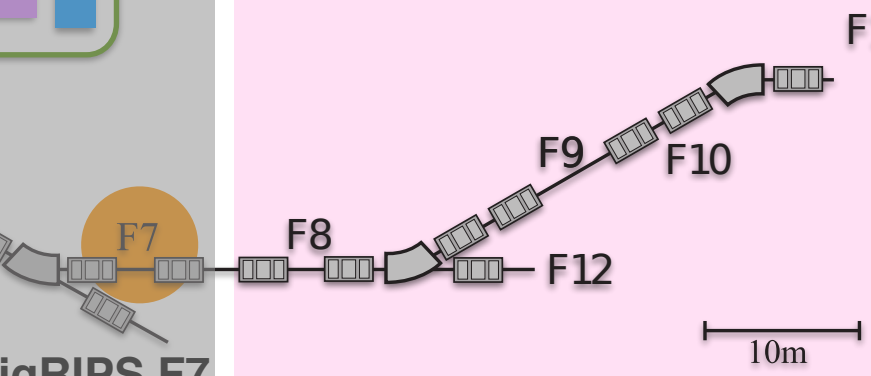
F11 Target Measurement

$$\sigma_{CC} = -\frac{1}{t}\ln\left(\frac{N_2}{N_1}\right)$$

N_1 : Incident particle

N_2 : Without changing Z





σ_{CC} Measurements at 170 MeV/u

F11 Target Measurement

F7 - F11 : Counting N_1

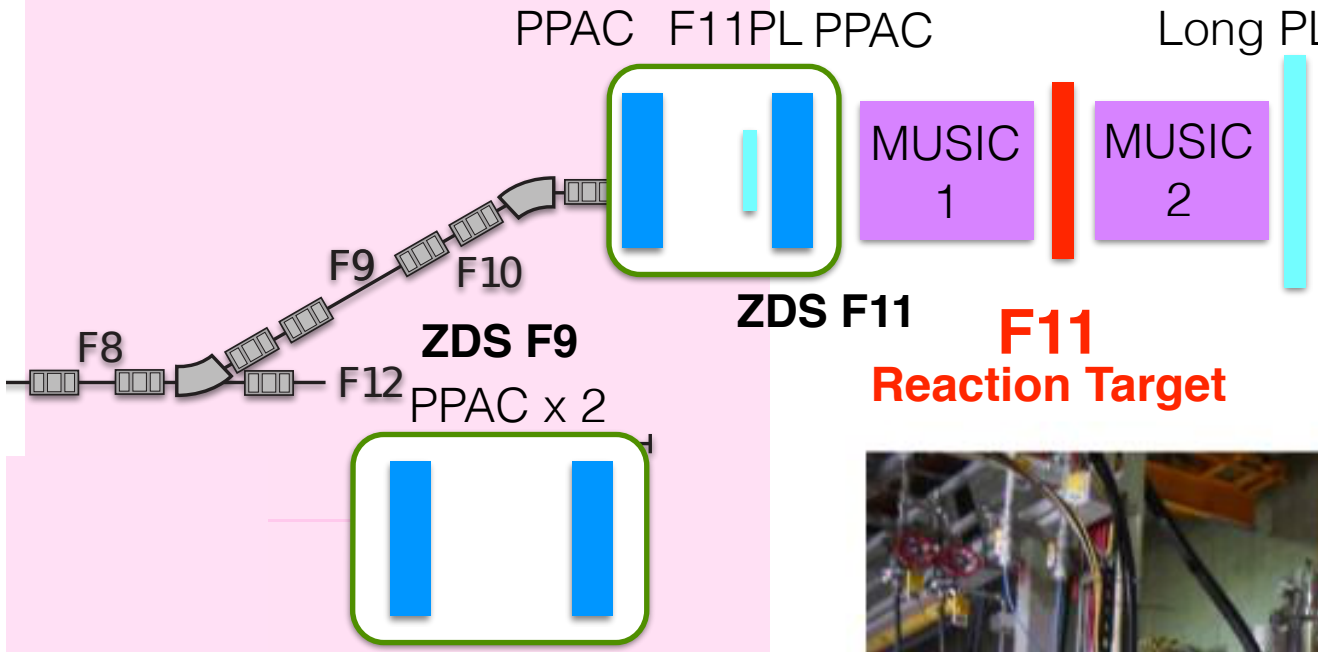
Identification : *ΔE - Bρ - TOF* Method

Bρ : F9 PPAC
ΔE : MUSIC 1
TOF F7PL, F11PL

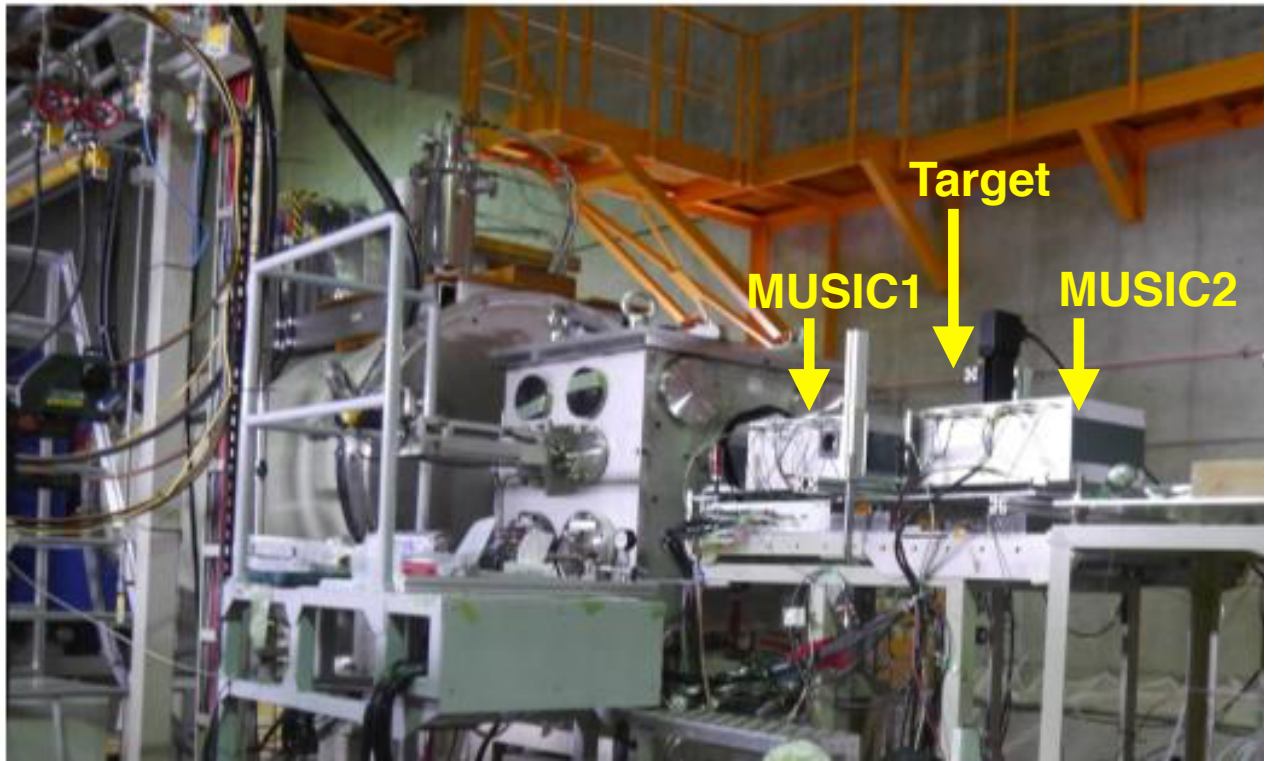
$$\sigma_{CC} = -\frac{1}{t}\ln\left(\frac{N_2}{N_1}\right)$$

N_1 : Incident particle

N_2 : Without changing Z

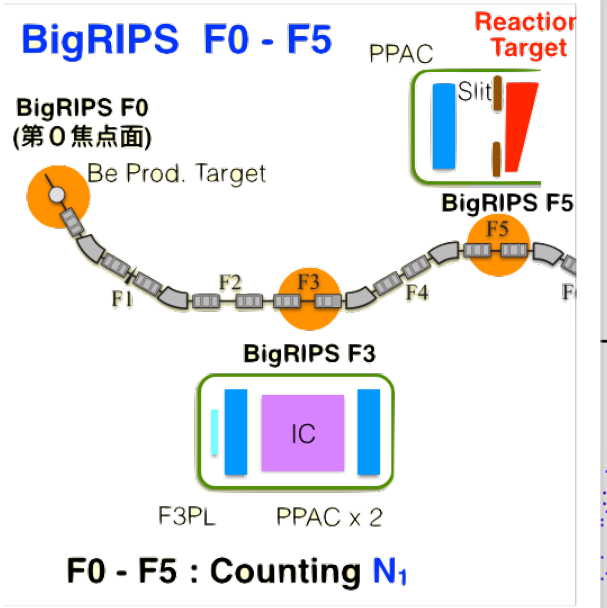


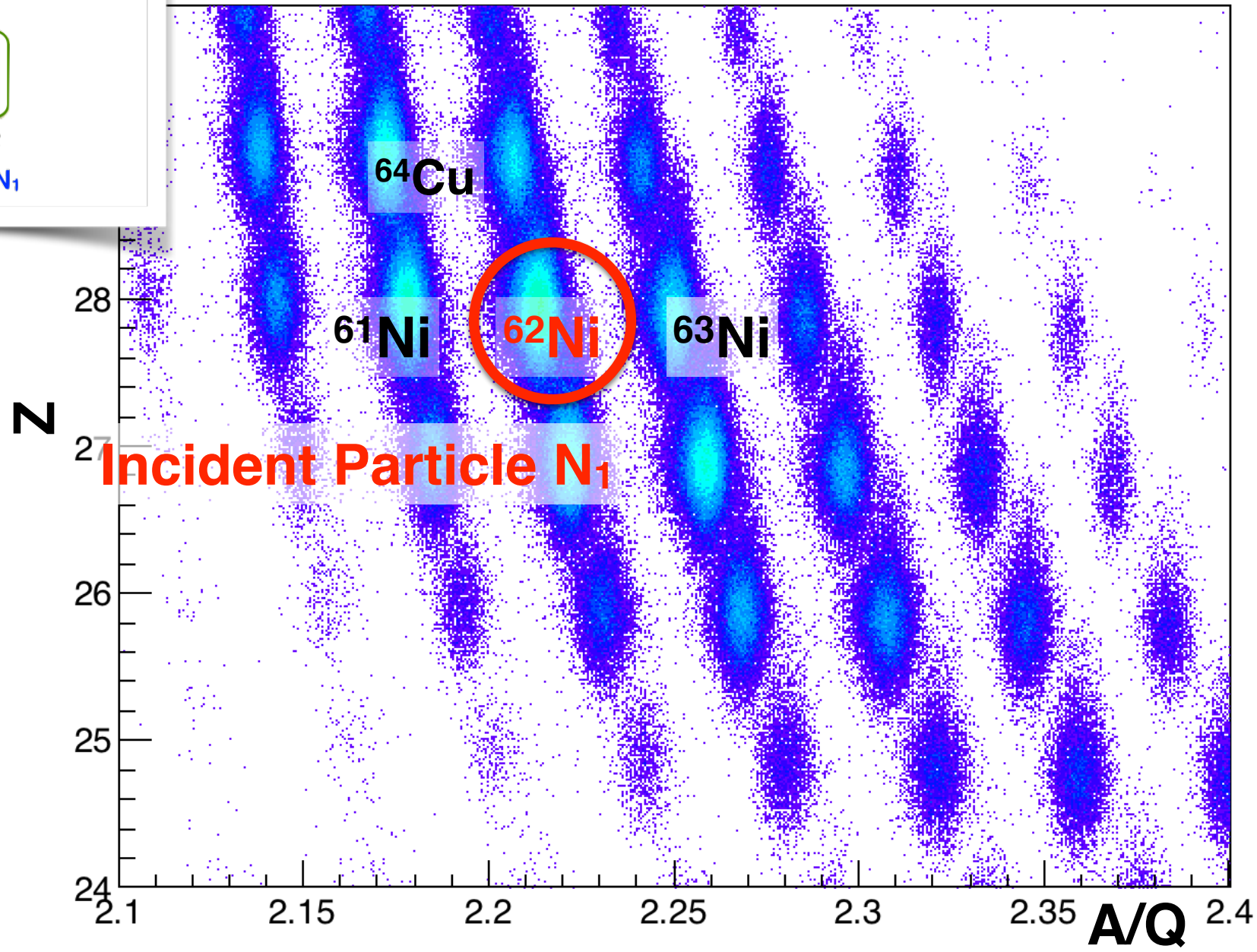
MUSIC2 : Counting N_2

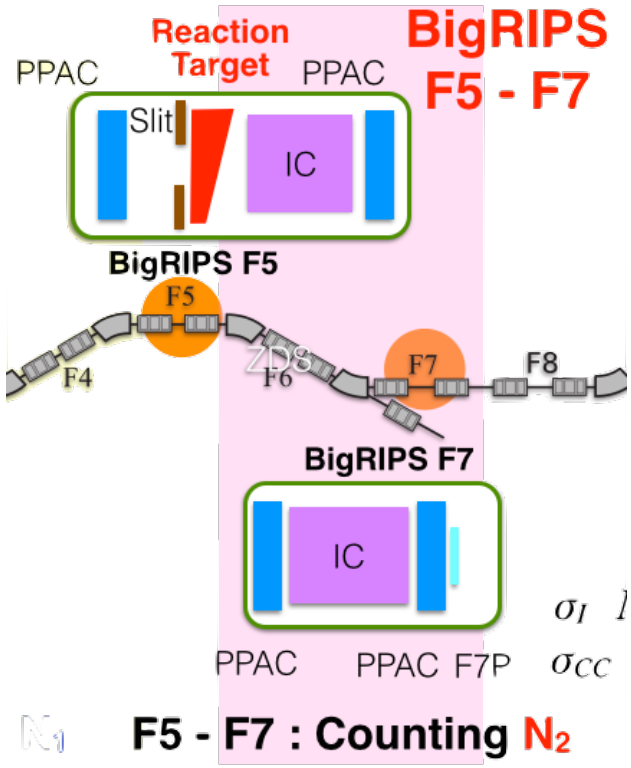


σ_{CC} Measurements at 170 MeV/u

Particle Identification
Incident Beam on F5 Target







Particle Identification after the Reaction Target