Systematic Measurements of Interaction-Cross Sections for Nuclides around ^{136}Xe at the RIKEN RI Beam Factory

Tokyo City University M1

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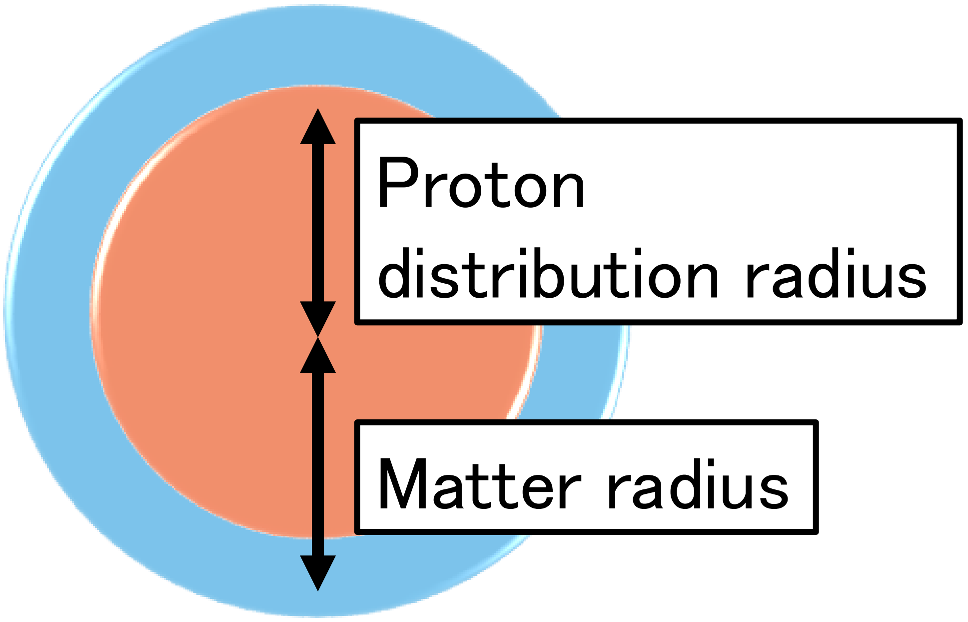
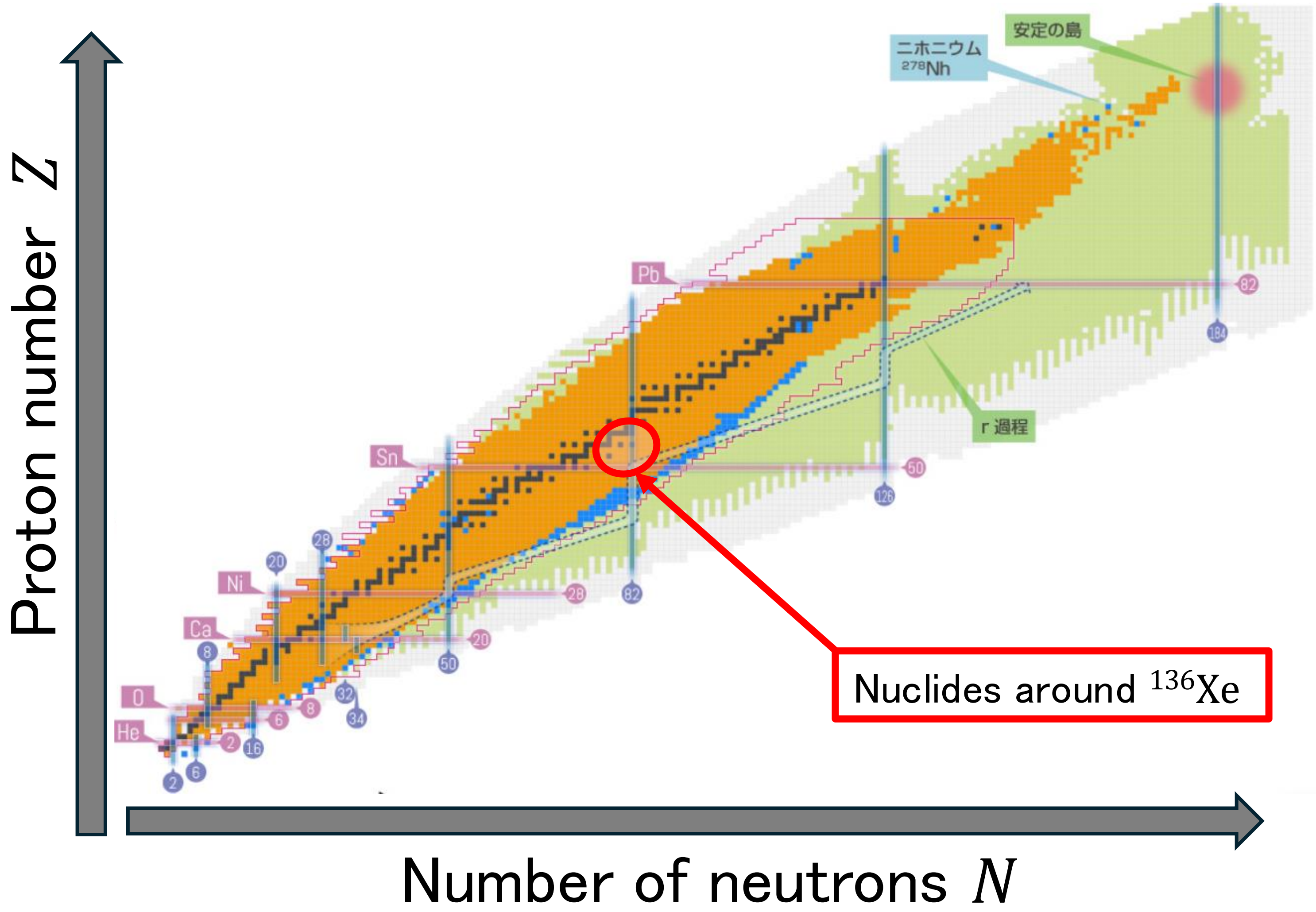
Contents

Background and Objectives

Charge radii have already been measured for many nuclei.[1]

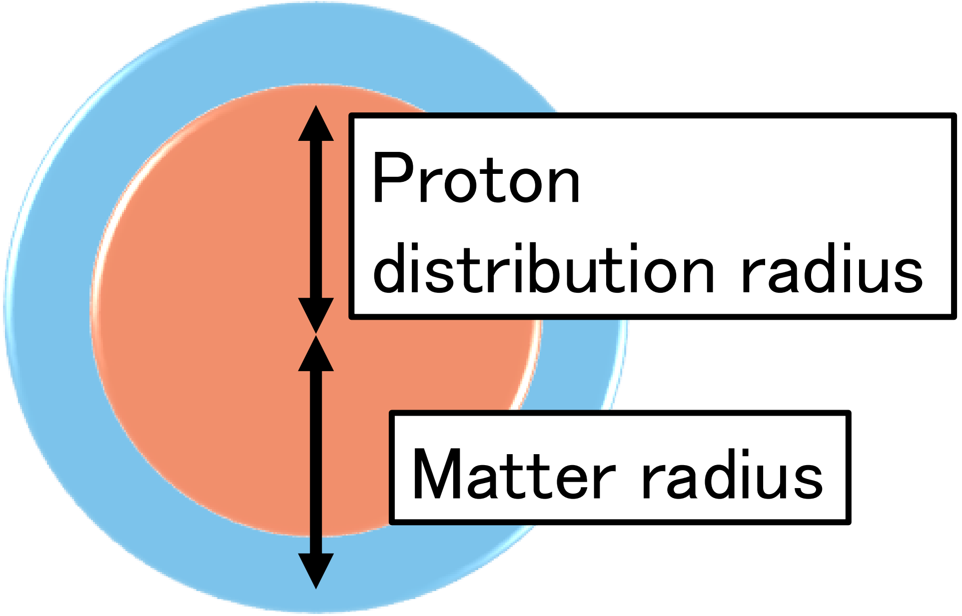


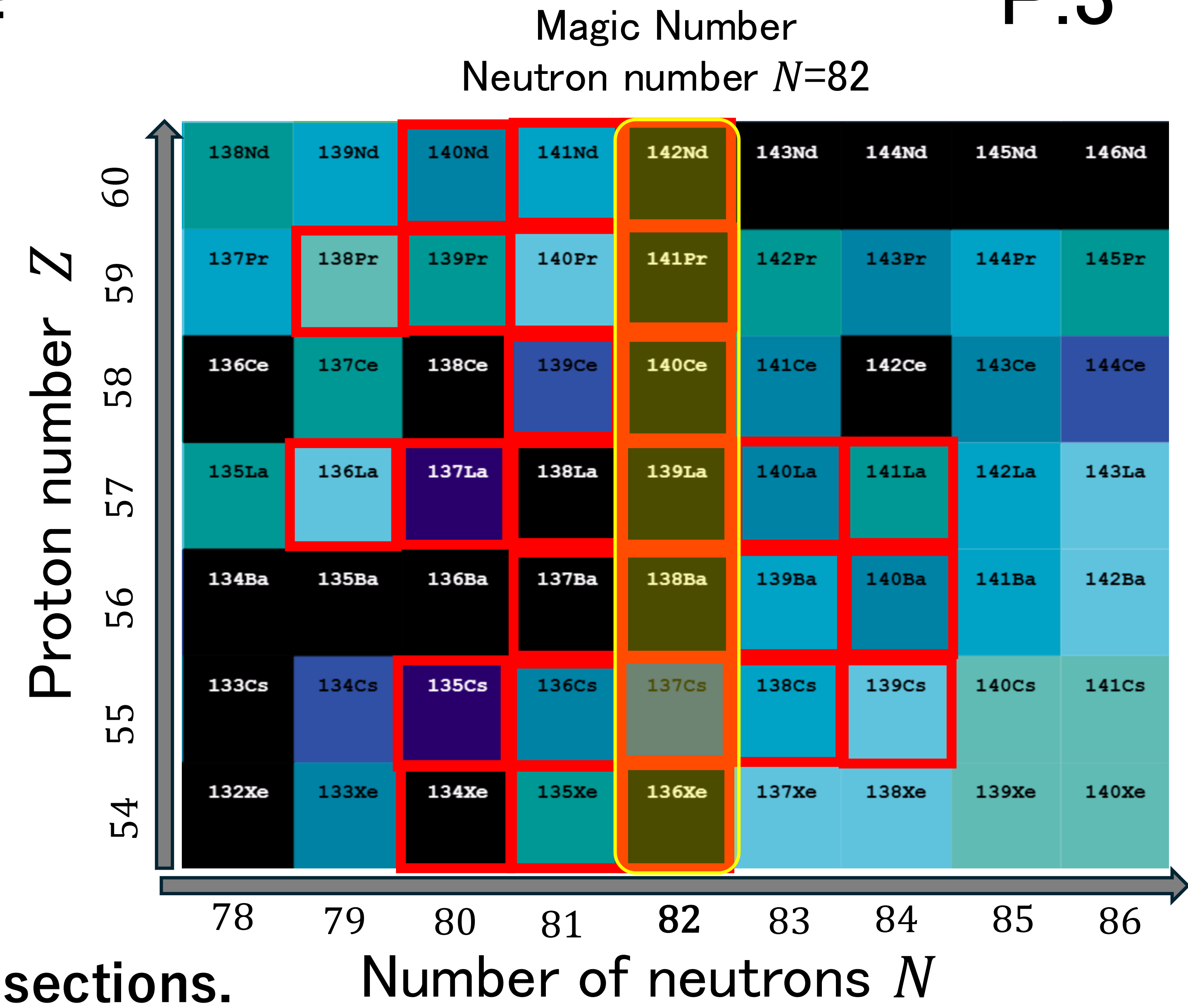


[1] I.Angeli and K. P. Marinova, At. Data and Nucl. Data Tables 99, 69–95 (2013).

Background and Objectives

Charge radii have already been measured for many nuclei.[1]





The aim of this study is to obtain matter radii from interaction cross sections.

[1] I.Angeli and K. P. Marinova, At. Data and Nucl. Data Tables 99, 69–95 (2013).

Measurement Principle

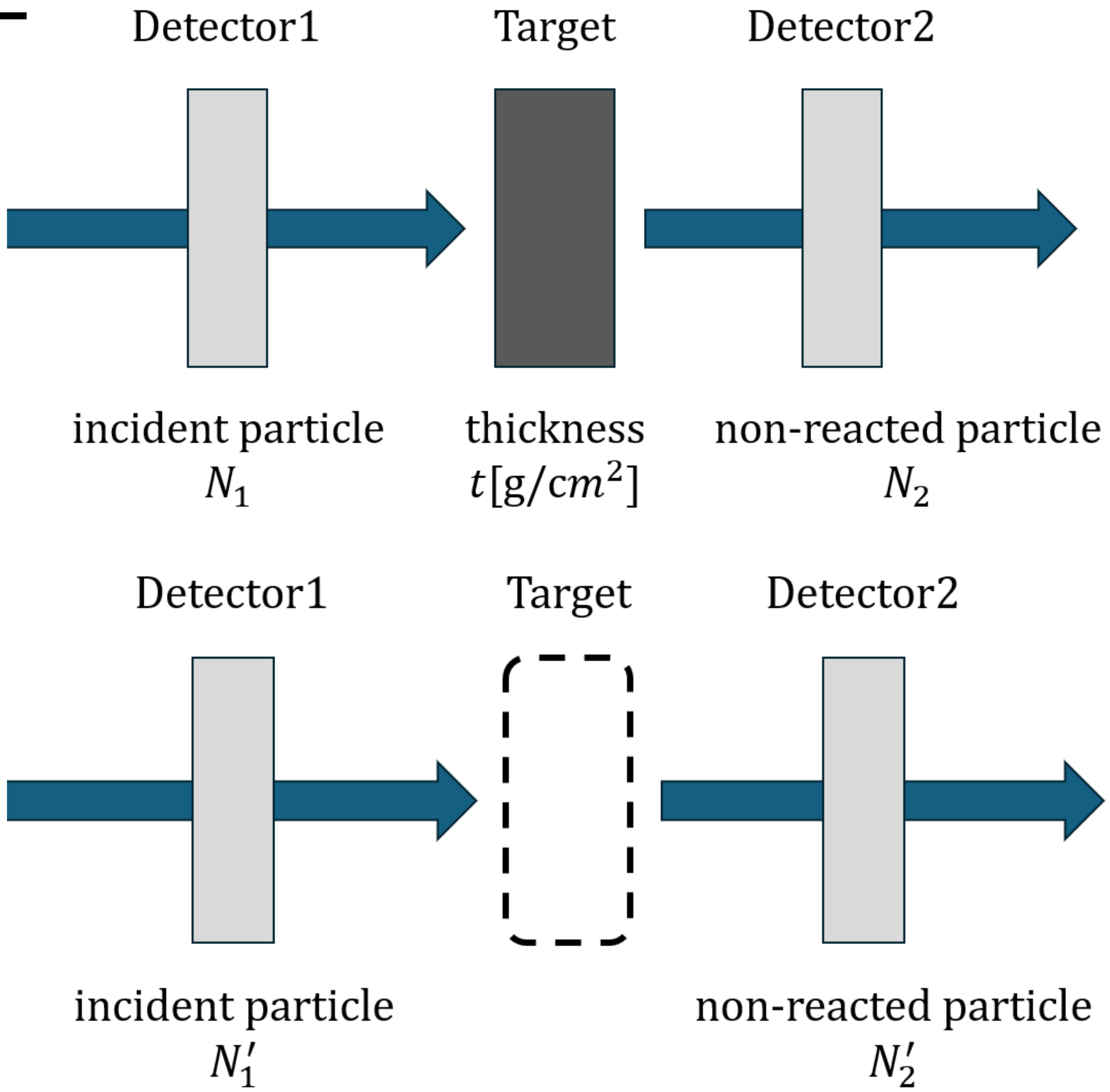
Transmission Method

$$N_t = \frac{\rho N_A}{A} x$$

$$\left.\begin{array}{l} R_{\mathrm{in}} = \dfrac{N_2}{N_1} \\[2ex] R_{\mathrm{out}} = \dfrac{N_2'}{N_1'} \end{array}\right\} \text{Transmission}$$

interaction cross sections σ_{I}

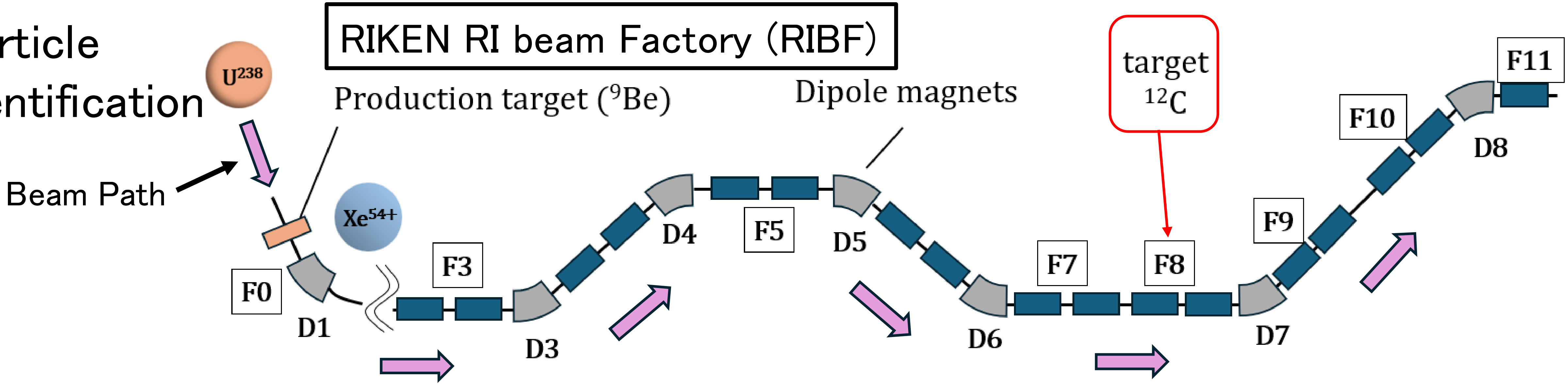
$$\sigma_{\mathrm{I}} = -\frac{1}{N_t} \ln\left(\frac{R_{\mathrm{in}}}{R_{\mathrm{out}}}\right)$$



Measurement Principle

$B\rho - \mathrm{TOF} - \Delta E$ *Method*

Particle Identification



Mass-to-charge ratio A/Q

Magnetic Rigidity

$$B\rho = \frac{mv}{q} = \frac{mc\beta\gamma}{q} = \frac{Am_u c\beta\gamma}{Qe}$$

m_u : Atomic mass unit

γ : Lorentz factor

Particle velocity

$$\beta = \frac{L}{c \cdot TOF} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$\boxed{\frac{A}{Q} \propto \frac{B\rho}{\beta\gamma}}$$

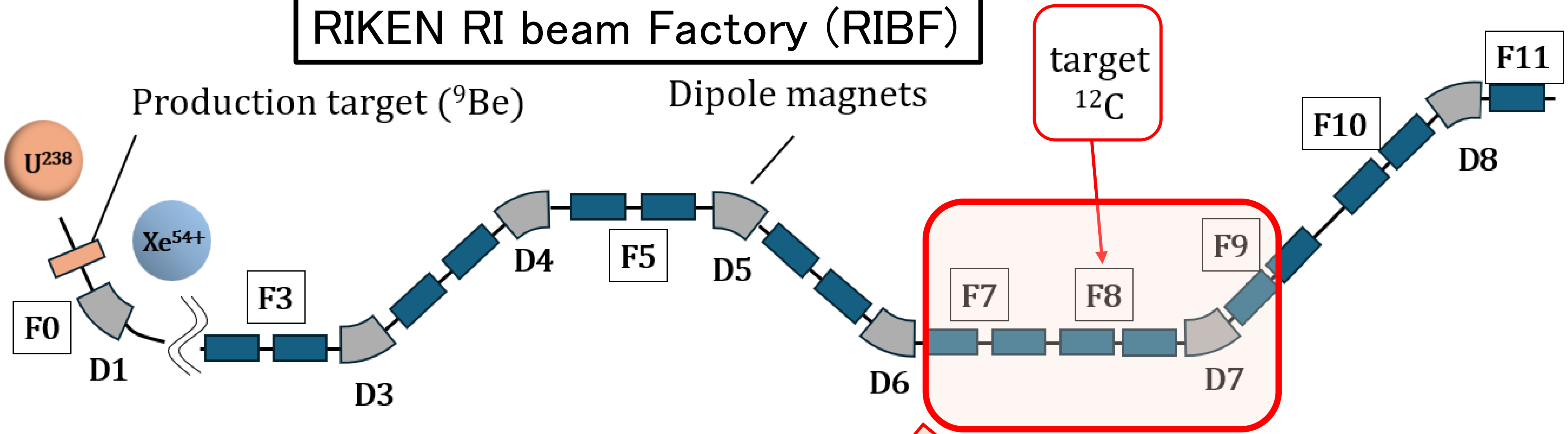
Energy loss, ΔE

From the Bethe-Bloch equation

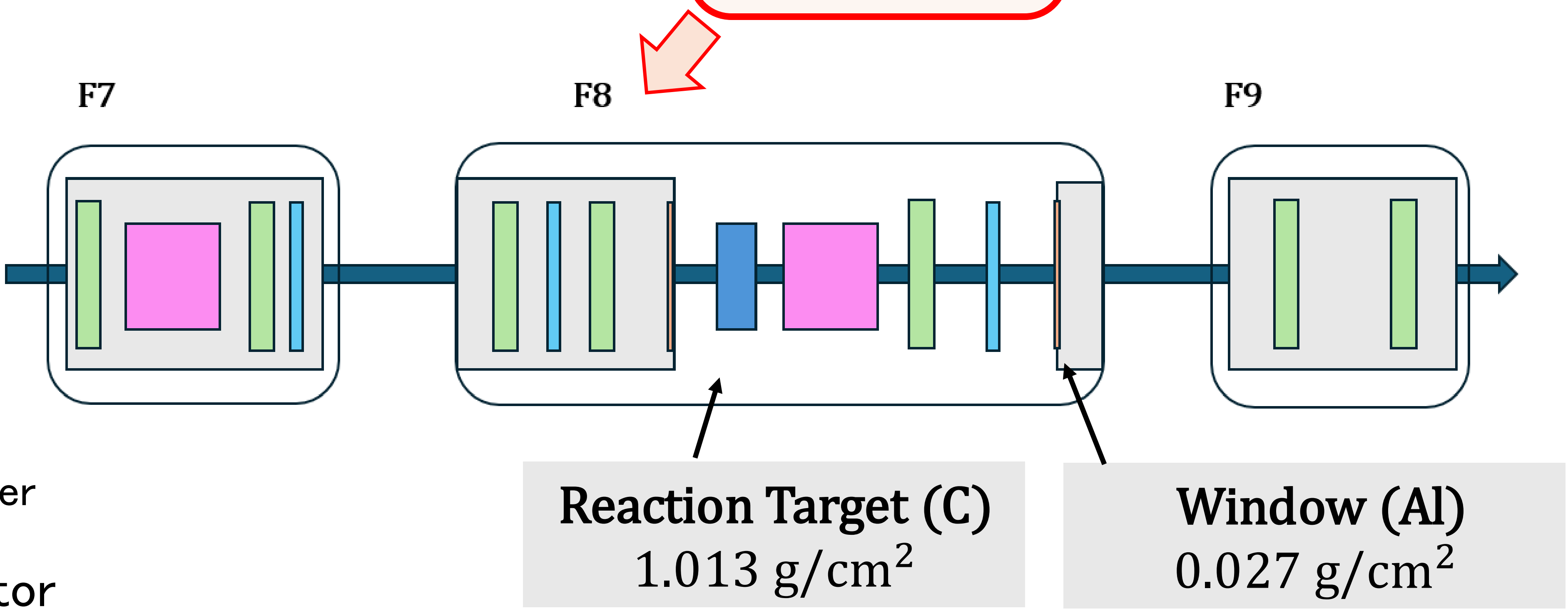
$$\Delta E \propto \frac{Z^2}{\beta^2}$$

Experiment

RIKEN RI beam Factory (RIBF)



BigRIPS F7~F9

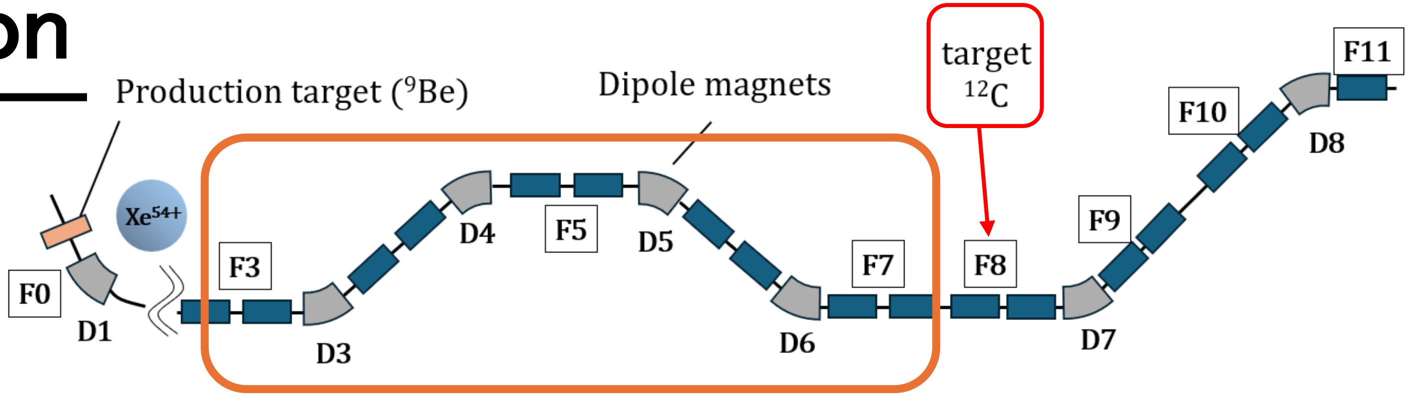


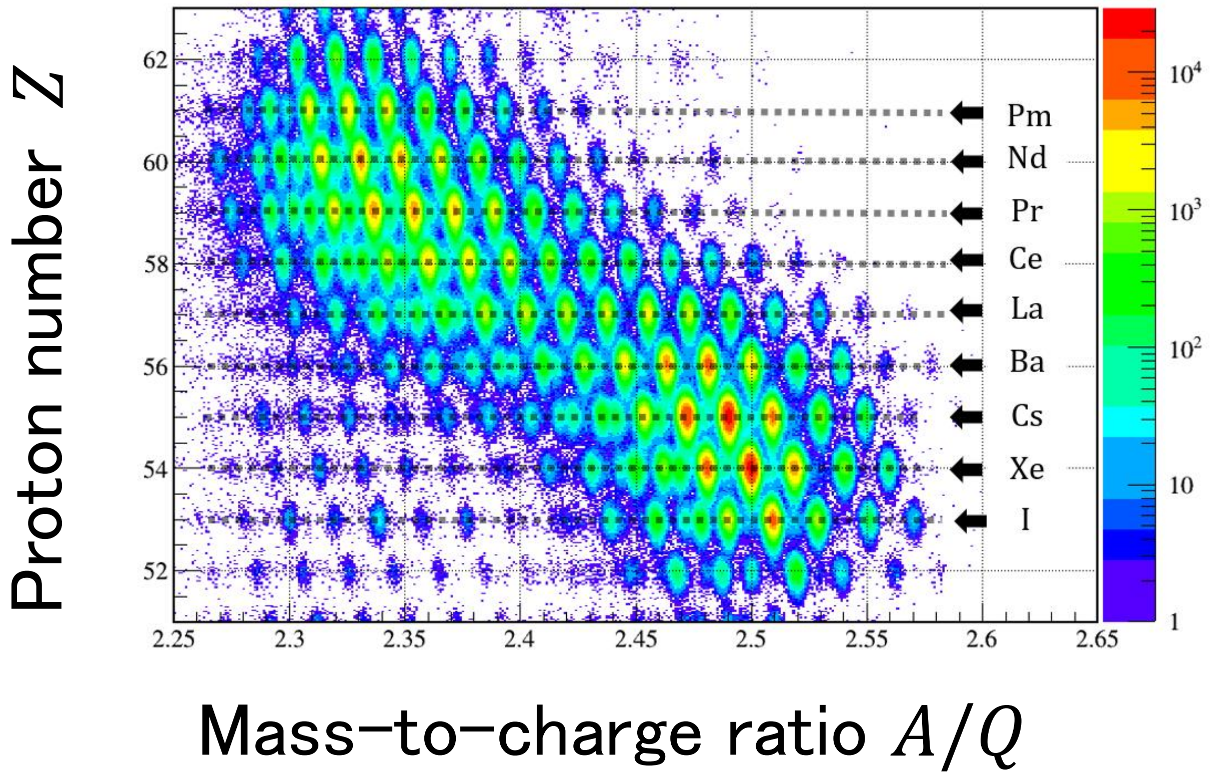
Detector

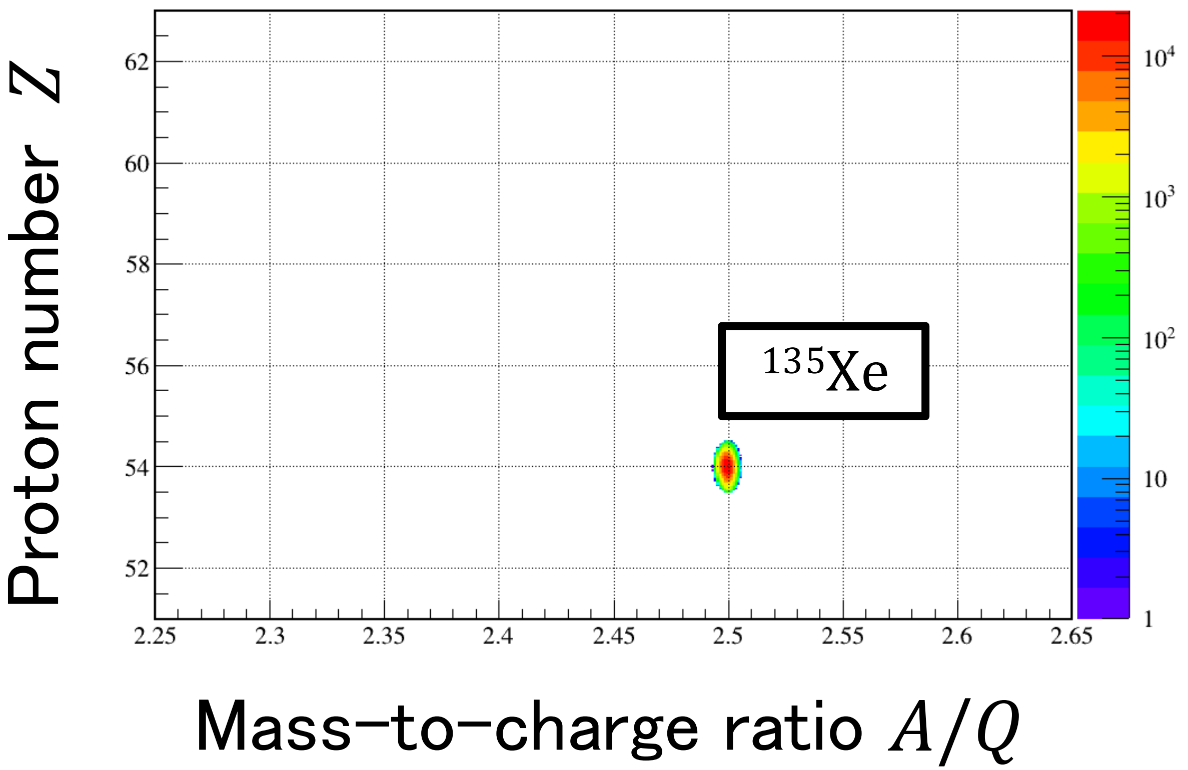
- PPAC
- Ionization Chamber
- Plastic Scintillator

Results and Discussion

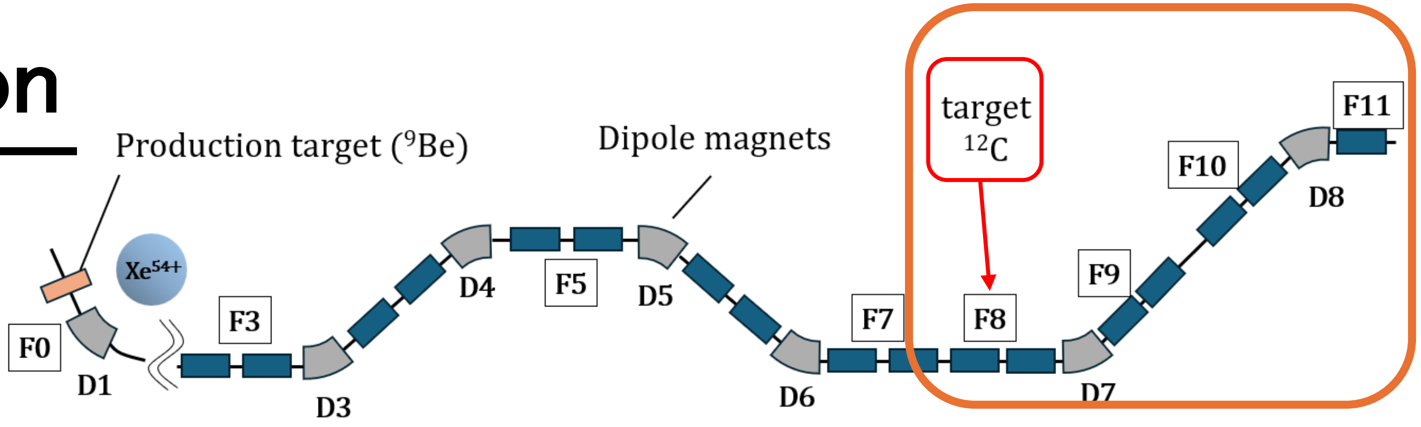
Upstream:
Particle Identification (PI) Plot



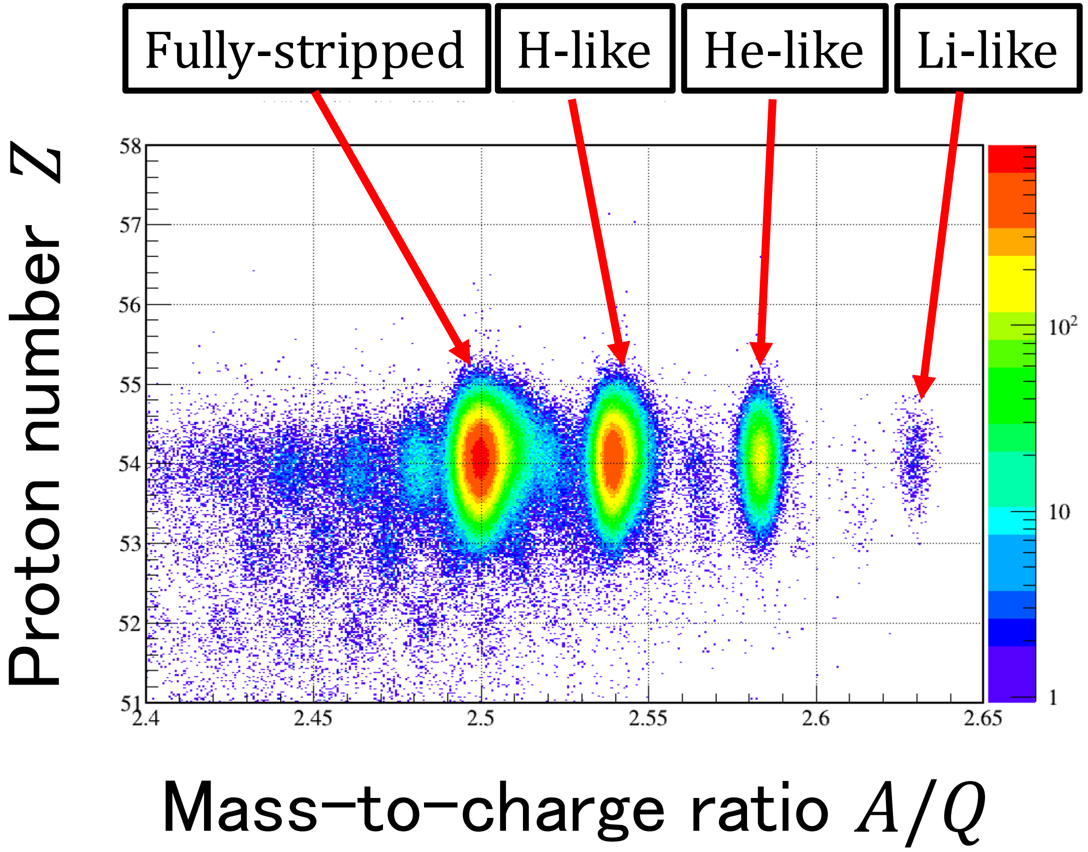


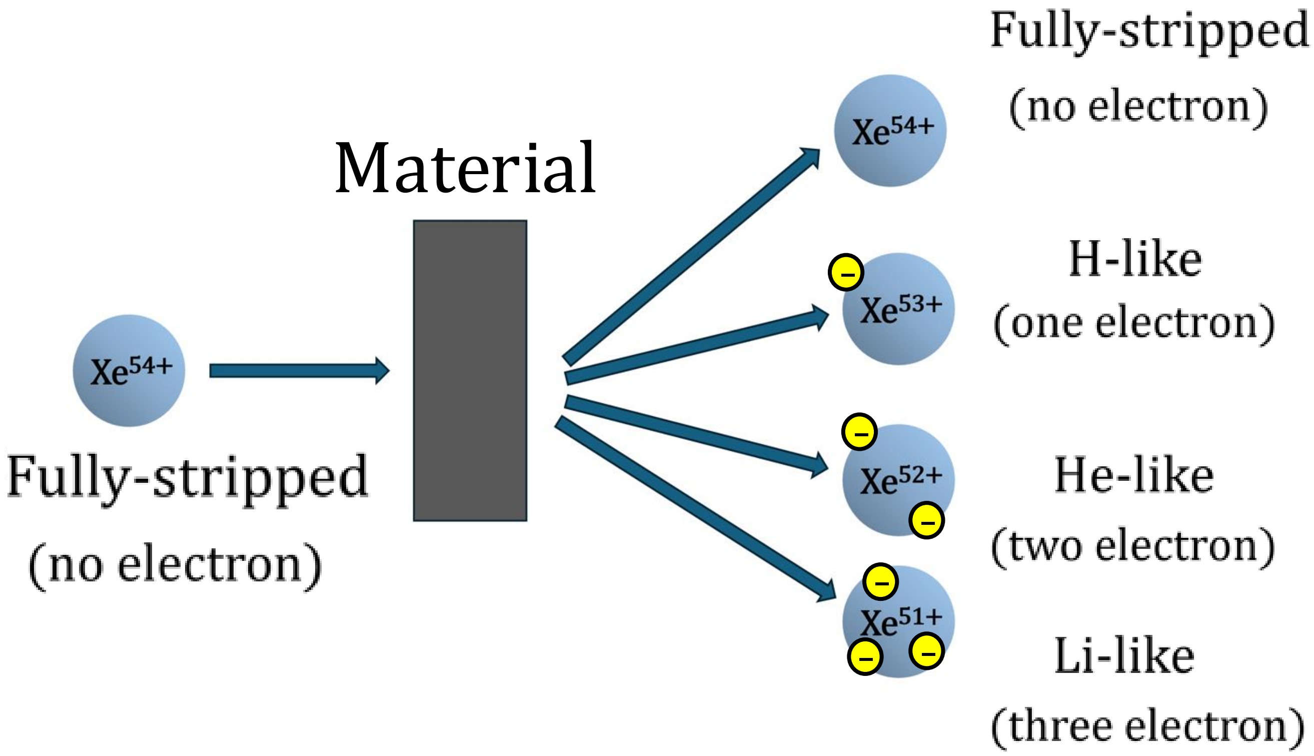


Results and Discussion



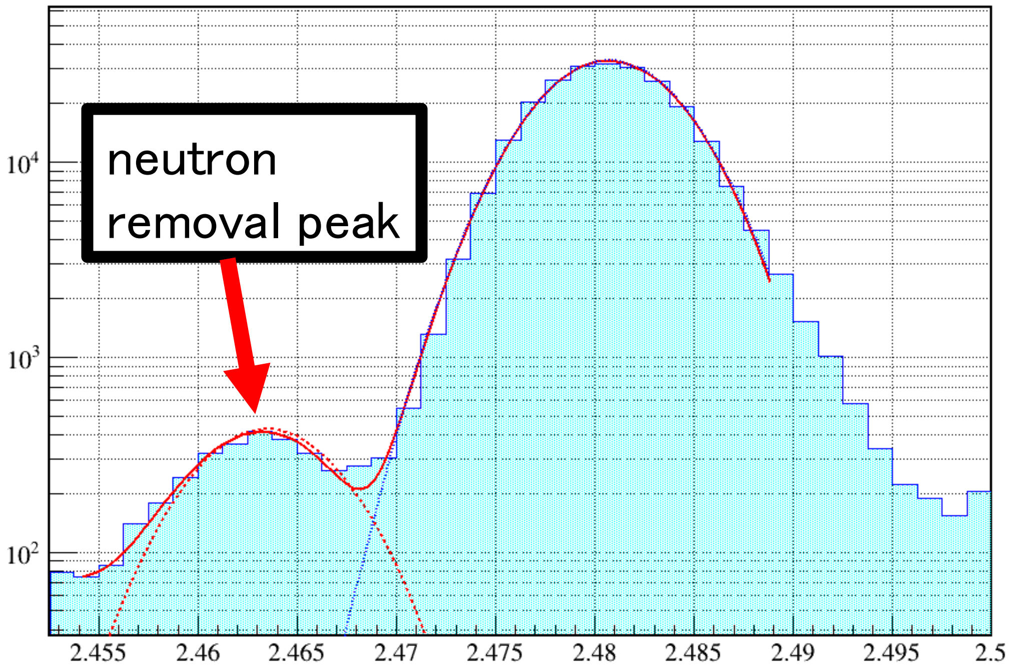
Downstream:
Particle Identification (PI) Plot





Analysis Results

After the target



Mass-to-charge ratio A/Q

Estimation of Contamination from Neutron Removal

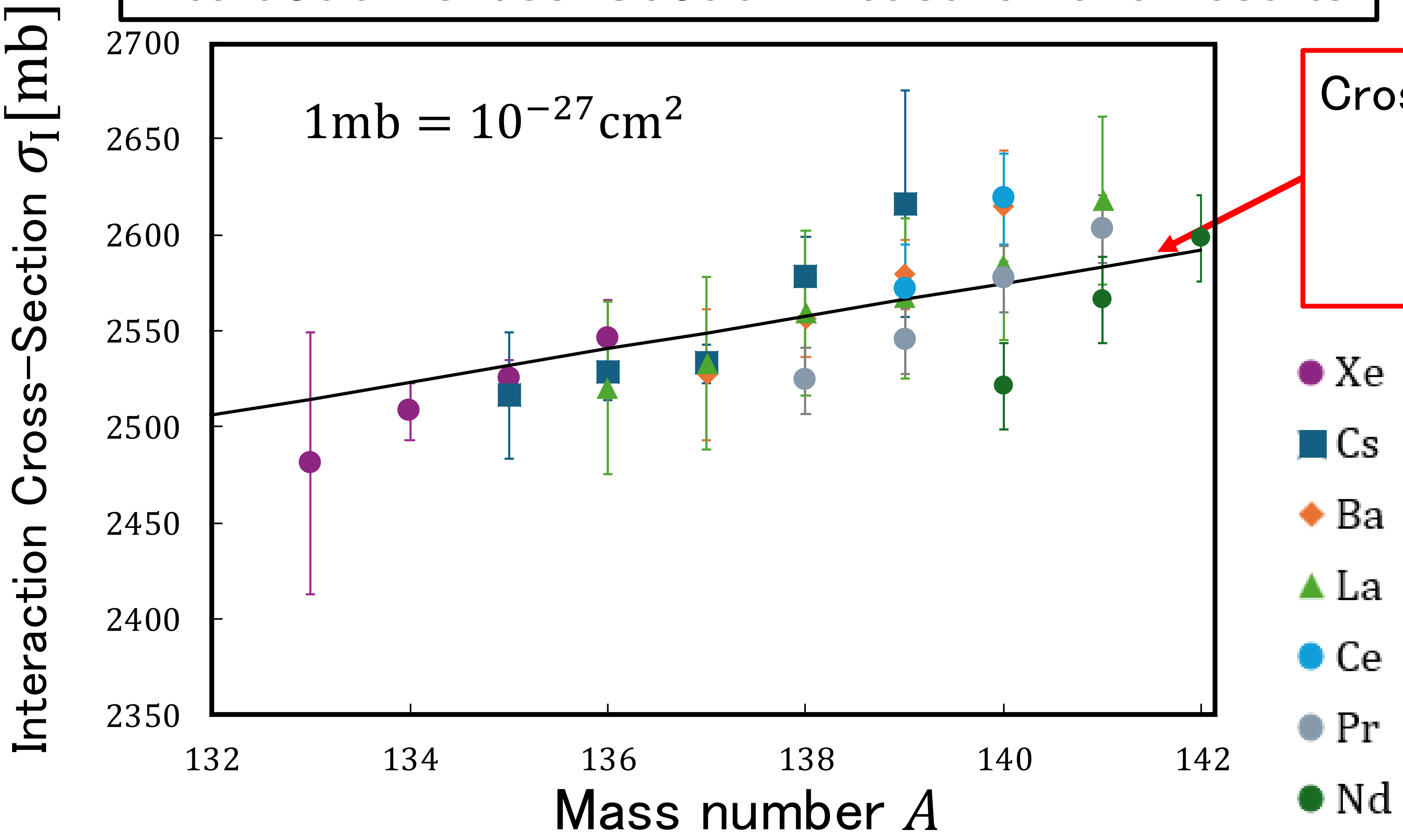
$$N_{[a,b]} = A\sigma\sqrt{\frac{\pi}{2}}\left[erf\left(\frac{b-\mu}{\sqrt{2}\sigma}\right) - erf\left(\frac{a-\mu}{\sqrt{2}\sigma}\right)\right]$$

- $N_{[a,b]}$: Neutron removal contamination in the range [a,b]
- A : Amplitude
- σ : Standard deviation
- μ : Mean of the Gaussian distribution

Exclude neutron removal events for an accurate evaluation of N_2 .

Results and Discussion

Interaction Cross–Section Measurement Results



Cross–Sections in Geometry

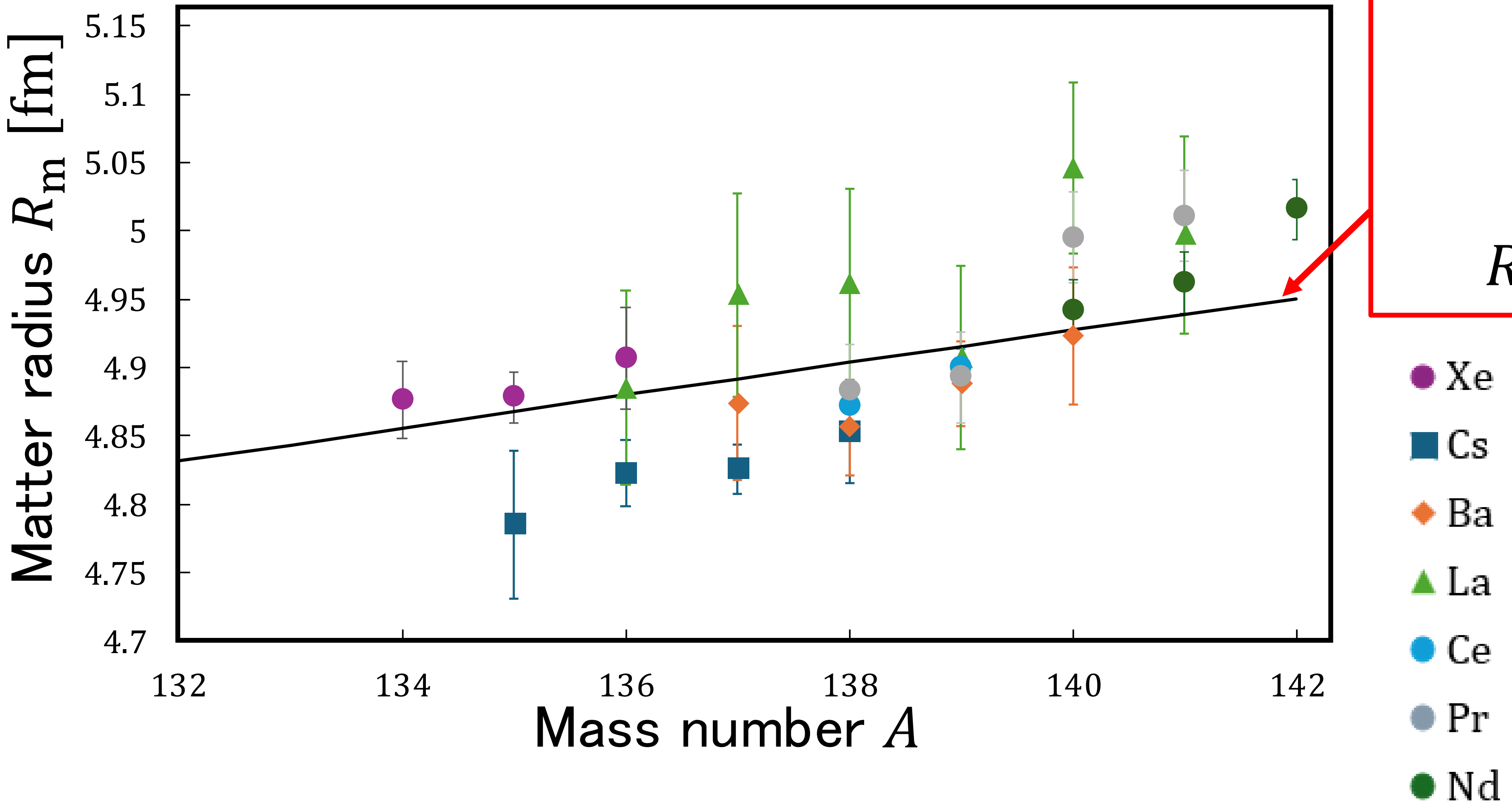
$$\sigma_\mathrm{G} = \pi(R_\mathrm{P} + R_\mathrm{T})^2$$

$$R_\mathrm{P} \simeq r_0\ A^{\frac{1}{3}}$$

The interaction cross section σ_I tends to increase with mass number.

Results and Discussion

Matter radius Results



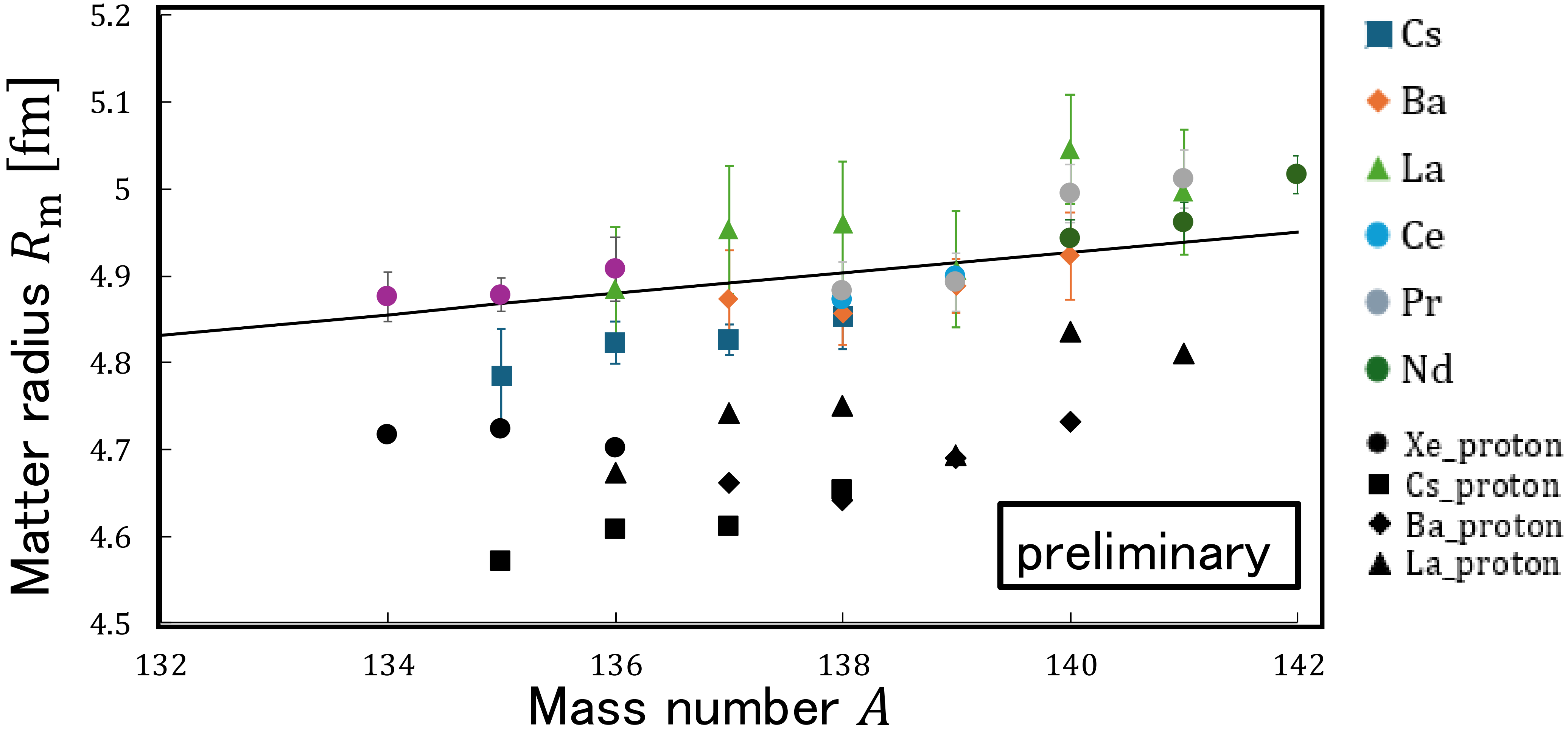
Expected RMS radius from the uniform sphere model

$$R = \sqrt{\langle r^2 \rangle}$$

$$R_{\mathrm{m}} = \sqrt{3/5}\, r_0 A^{\frac{1}{3}}$$

Results and Discussion

Matter radius Results



Matter radius > Proton distribution radius ➡ The neutron distribution extends beyond the proton distribution.

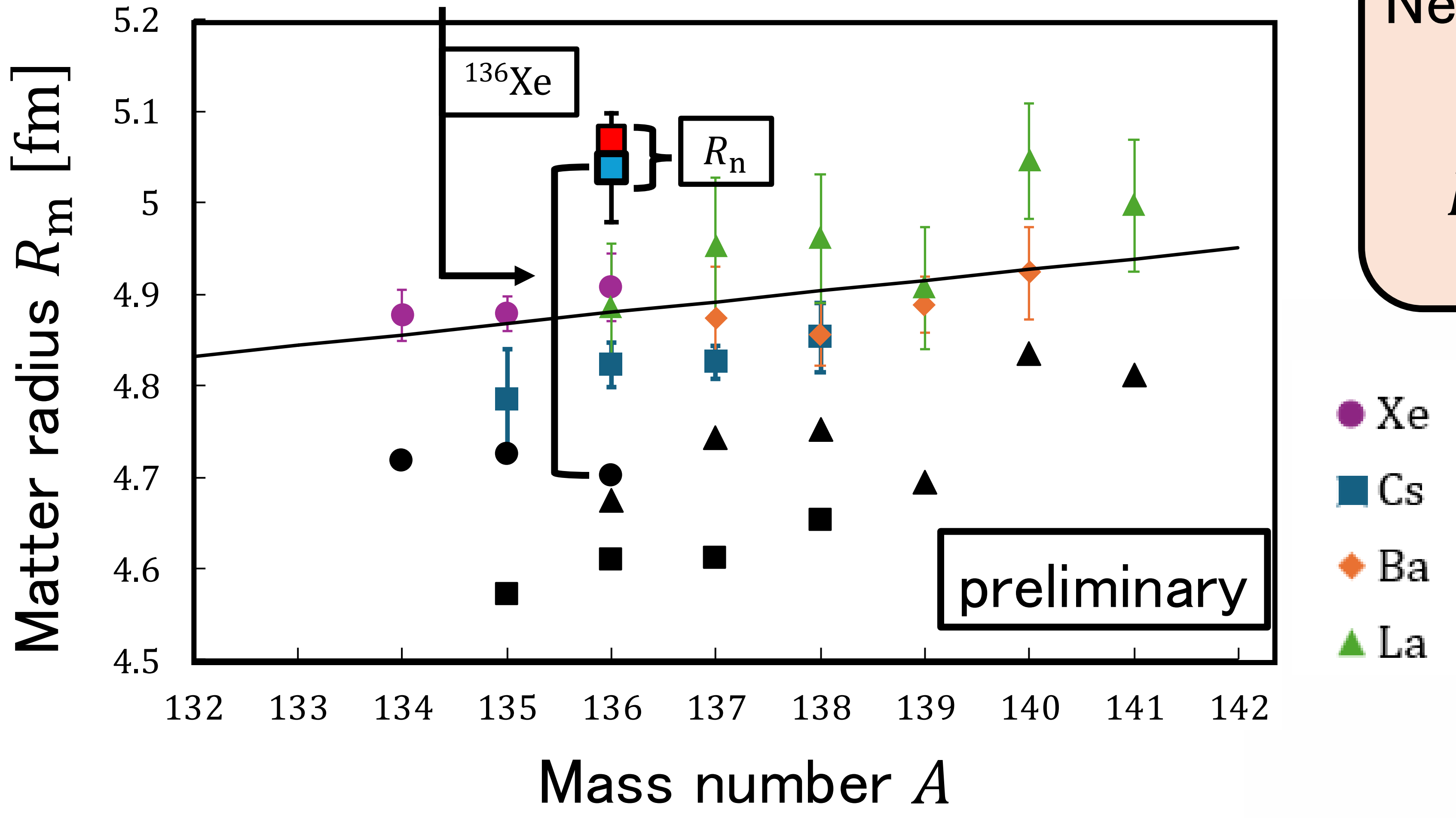
Results and Discussion

Matter radius Results

Comparison with previous studies

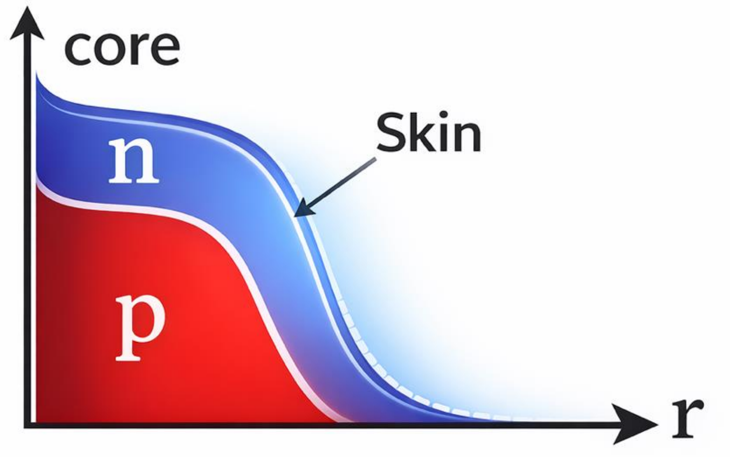
Neutron skin thickness
(0.28 ± 0.06) fm

■ Theoretical values from previous study[2]
■ Experimental values



Neutron distribution radius

$$R_\mathrm{n} = \sqrt{\frac{AR_\mathrm{m}^2 - ZR_\mathrm{p}^2}{N}}$$



[2] S. Yoshida et al., "Neutron distribution radii from magnetic rigidity of secondary beams," arXiv:2411.13622 [nucl-th] (2024).

Summary and Future Prospects

Measurement of Interaction Cross Sections and Matter Radii for Isotopes of Z=54–60 (Xe, Cs, Ba, La, Ce, Pr, Nd)

- Comparison of the obtained interaction cross sections with geometric cross sections

➡ The results show a trend consistent with the mass-number dependence of the geometric cross section.

- Derivation of matter radii

➡ Matter radii increase with mass number, consistent with the RMS radii expected from the uniform sphere model.

- Comparison with previous studies

➡ The obtained matter radii are larger than the proton distribution radii for all nuclides.

Future Prospects

- Study of the effects of nuclear structure on interaction cross sections around N=82.

Collaborators and Affiliations

D. Nishimura[1], S. Endo[1], Y. He[1], C. Inoue[1], K. Matsuyama[1] , F. Sato[1], T. Moriguchi[2], T. Tanaka[3], M. Fukutome[4], S. Ishitani[5], R. Taguchi[5], G. Takayama[5], A. Yano[2], K. Adachi[4], H. Baba[6], M. Fukuda[5], N. Fukuda[6], Y. Ichinohe[6], R. Kageyama[1], Y. Kikuchi[7], N. Kobayashi[8], H. Kobayashi[2], K. Kusaka[6], S. Michimasa[6], M. Mihara[5], M. Mikawa[2], M. Mitsui[2], D. Nagae[7], S. Nishizawa[7], M. Ohtake[6], T. Ohtsubo[4], A. Ozawa[2], C. Santonastaso[6], R. Sasamori[4], T. Shimamura,[4], Y. Shimizu[6], T. Suzuki[7], H. Suzuki[6], H. Takeda, S. Takeshige[9], K. Tezuka[4], Y. Togano[6], K. Watanabe[7], Y. Wei[7], T. Yamaguchi[7], Y. Yanagisawa[6], I. Yasuda[7], K. Yasuda[5], M. Yoshimoto[6]

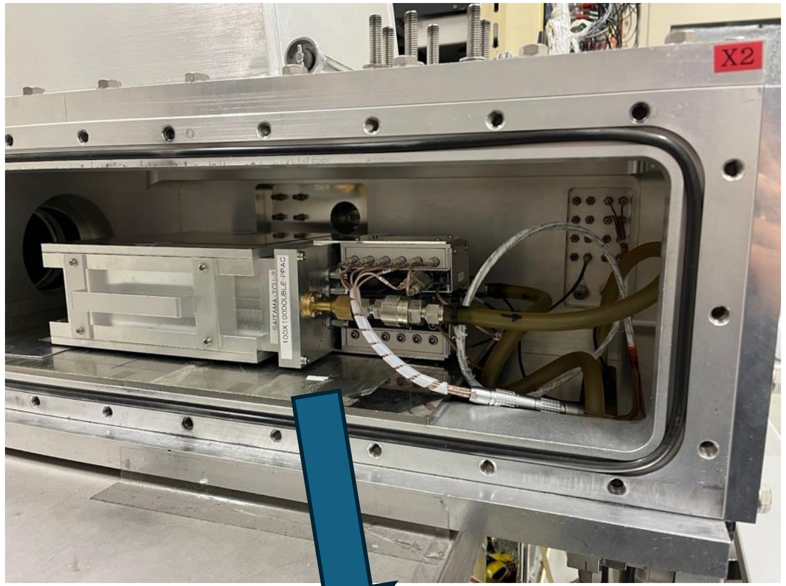
Affiliations

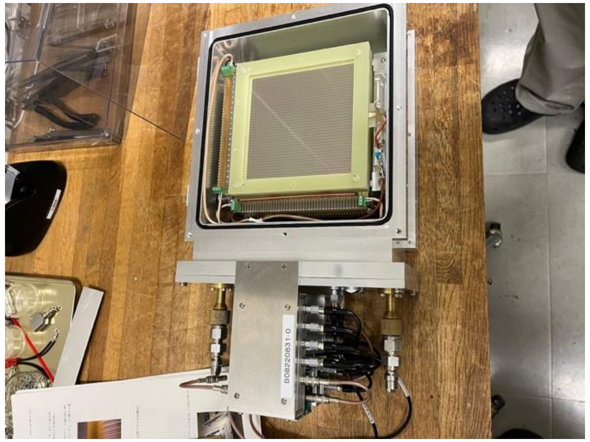
1. Tokyo City University 2. University of Tsukuba 3. Kyushu University
4. Niigata University 5. Osaka University 6. RIKEN Nishina Center
7. Saitama University 8. Rikkyo University 9. RCNP, The University of Osaka

Backup slides

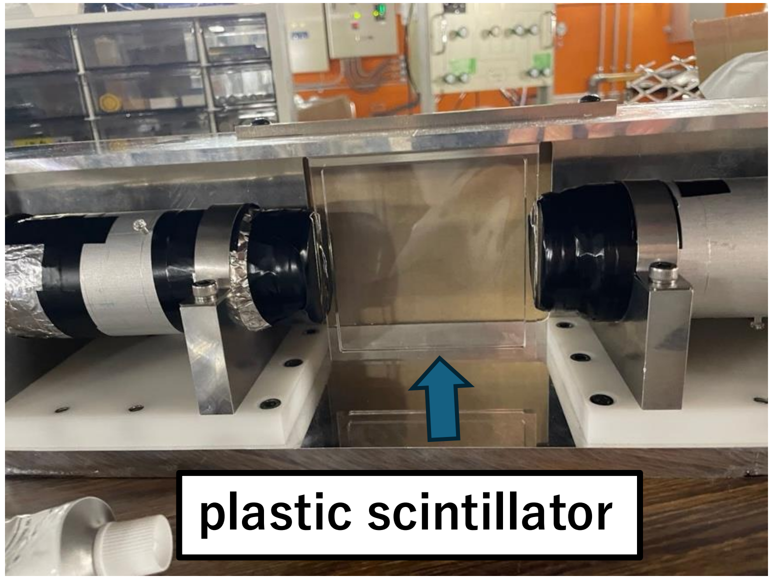
Detector List

PPAC

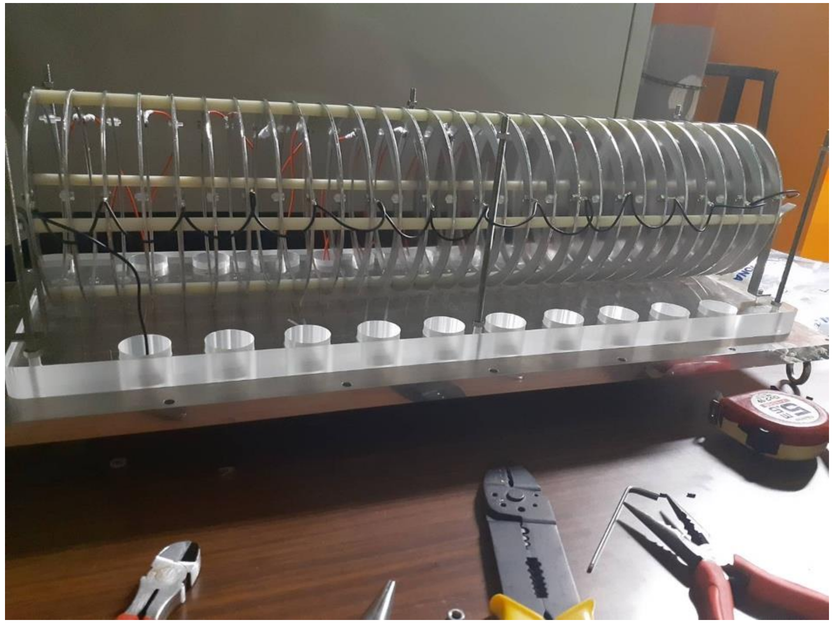


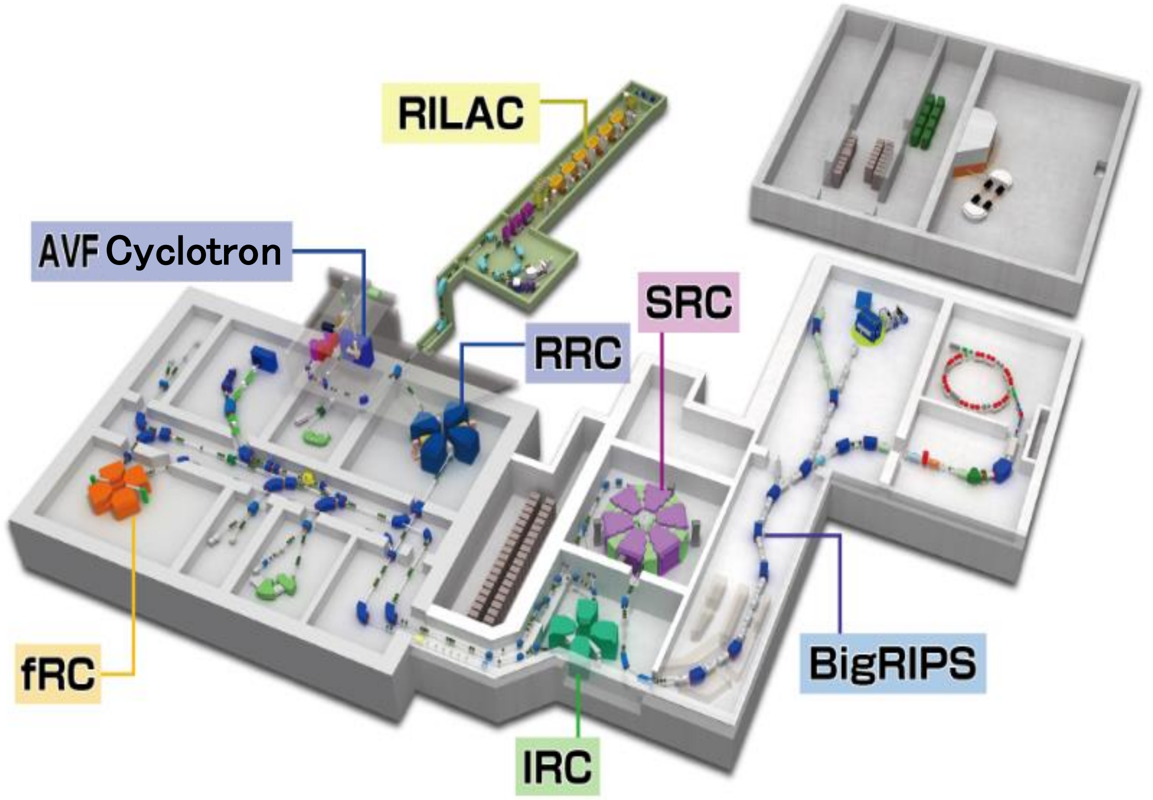


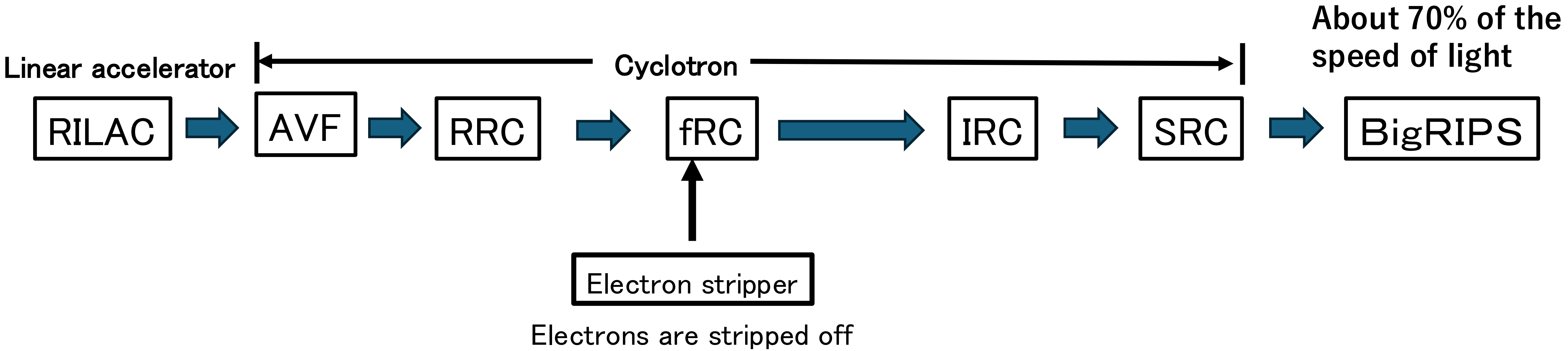
plastic scintillator



ion chambers




RILAC
AVF Cyclotron
SRC
RRC
fRC
BigRIPS
IRC


About 70% of the speed of light
Linear accelerator
Cyclotron
RILAC
AVF
RRC
fRC
IRC
SRC
BigRIPS
Electron stripper
Electrons are stripped off

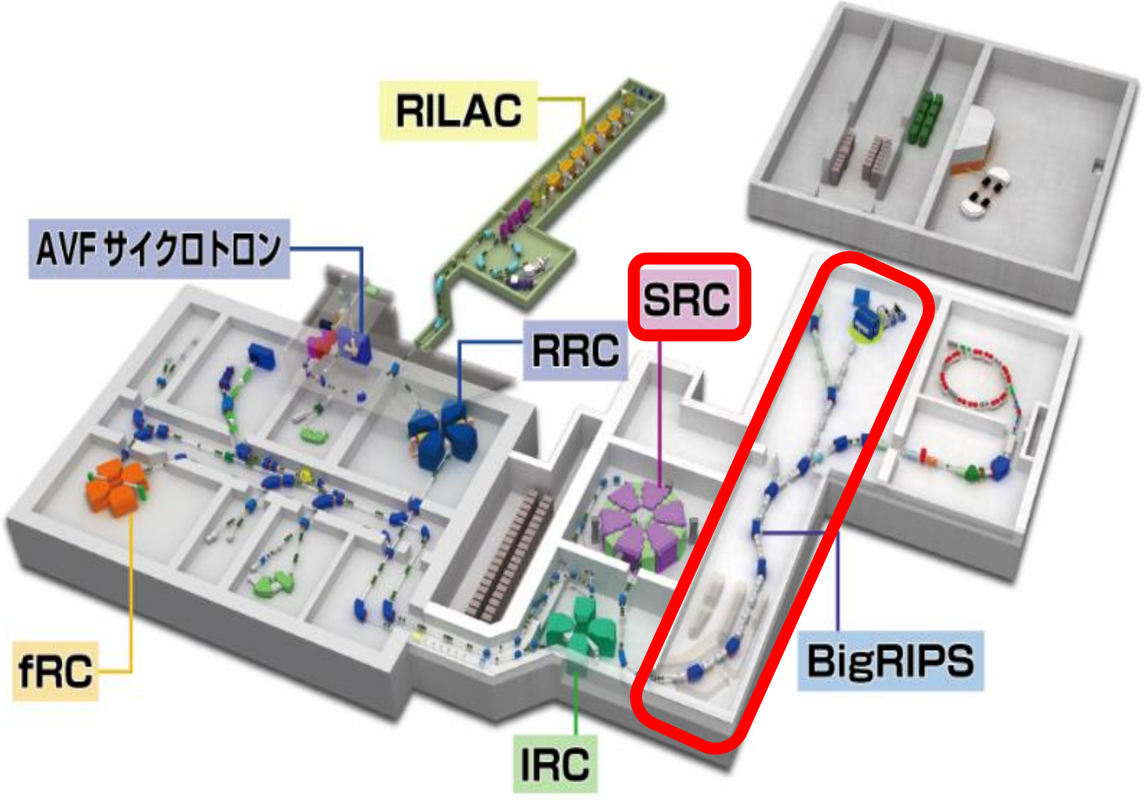
About the Experiment

RIKEN RI Beam Factory (RIBF)

The primary beam (^{238}U) is accelerated to about 70% of the speed of light by the Superconducting Ring Cyclotron (SRC).

Incident

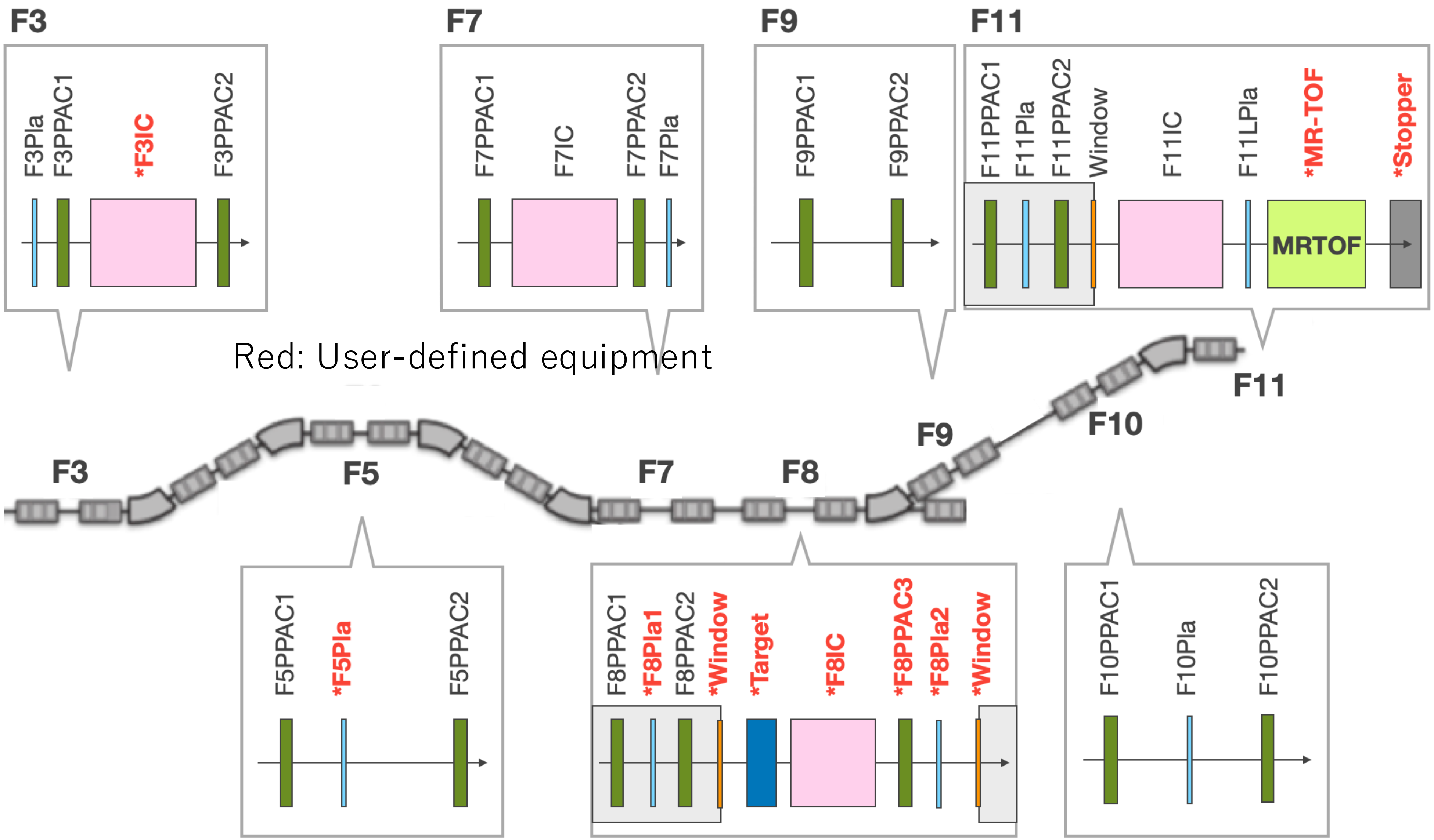
RI beams are produced, separated, and identified by the BigRIPS separator.



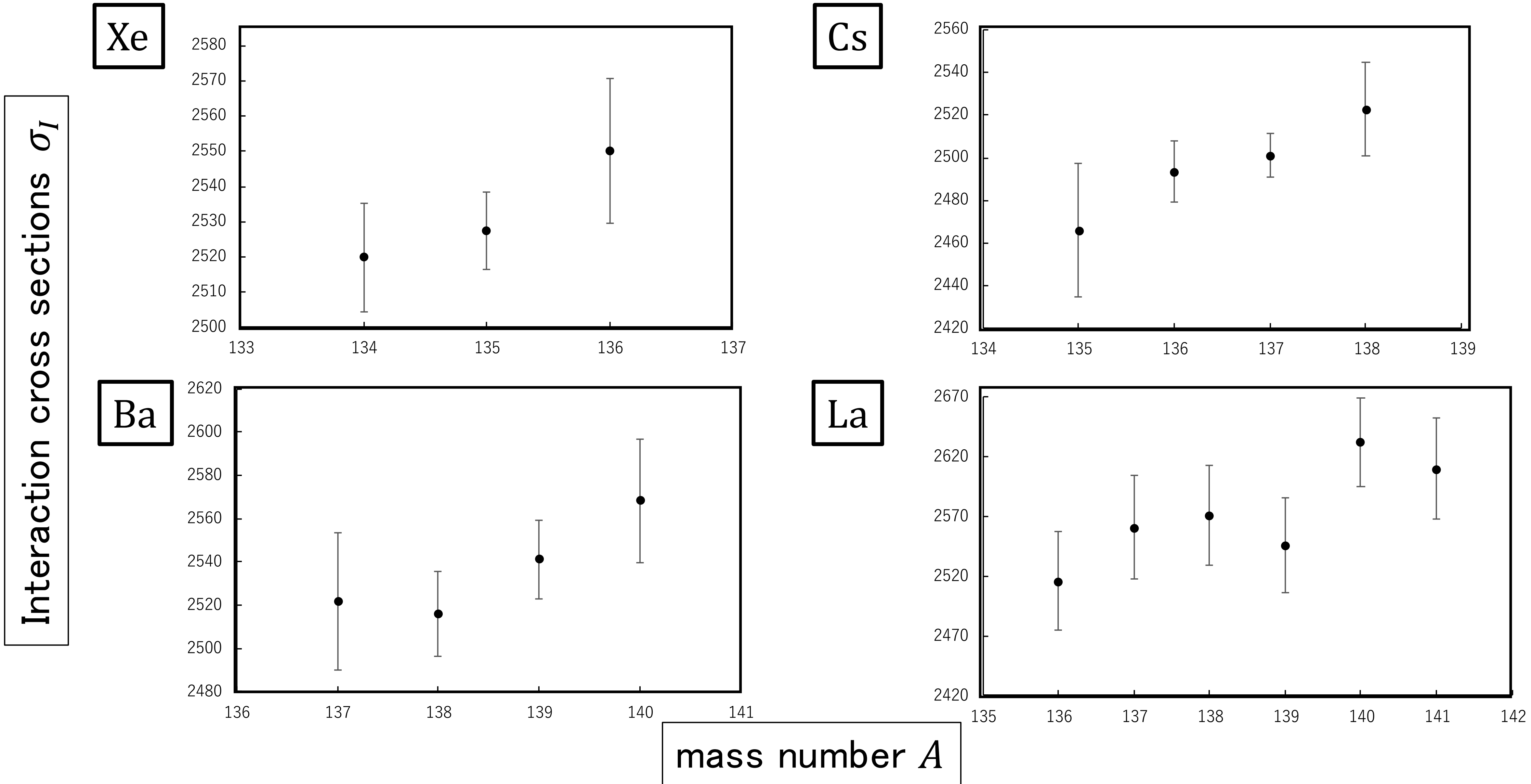
About 126m long from F0 to F11

Source: RIKEN

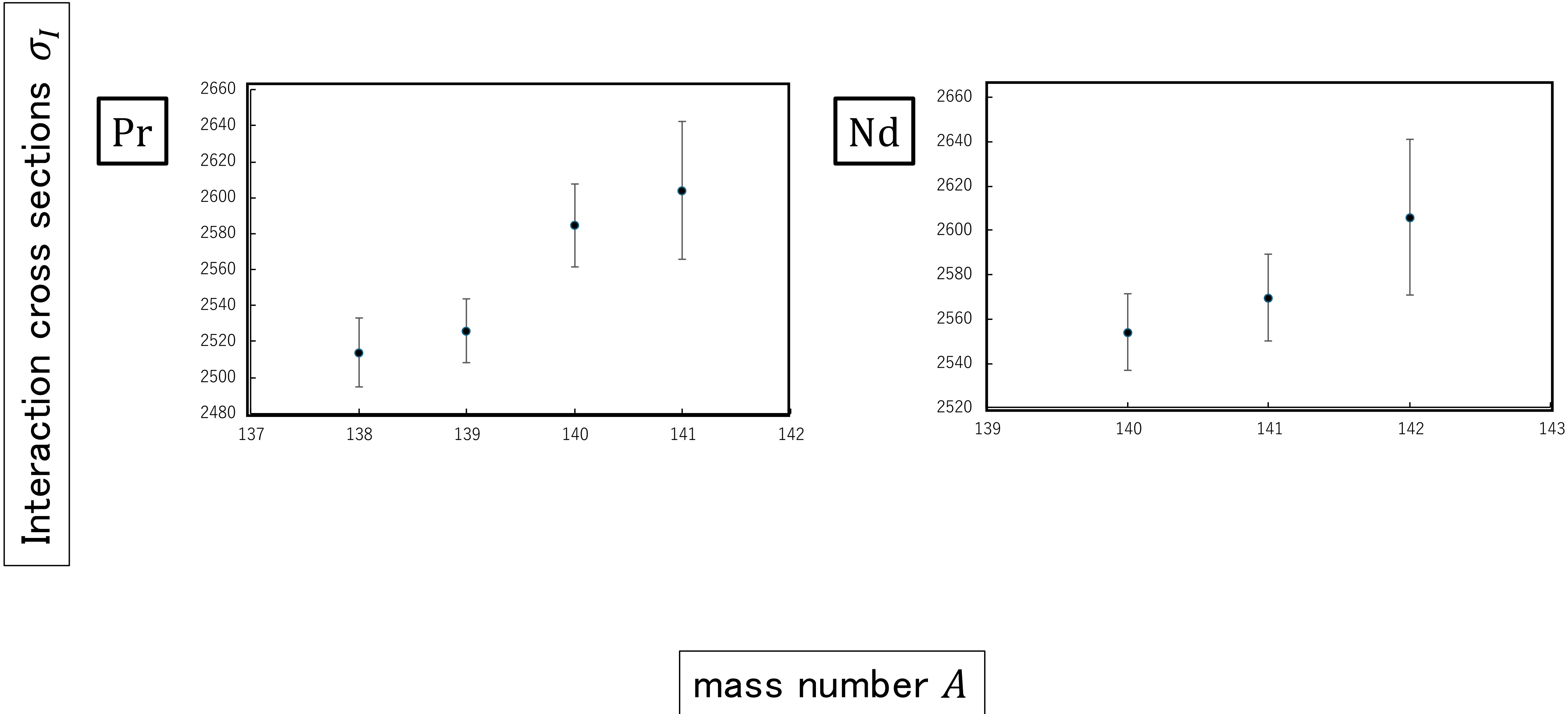
Red: User-defined equipment



Interaction cross sections for each nuclide



Interaction cross sections for each nuclide



Interaction cross sections

The following differential equation describes
the number of particles N passing through the target.

$$\frac{dN}{dx} = -\sigma_I \left(\frac{\rho N_A}{A}\right) N$$

Solving this equation gives

$$N_t[1/\mathrm{cm}^2] = \frac{\rho N_A}{A} x$$

$$N_2 = N_1 \exp(-\sigma_I N_t)$$

The interaction cross section is

$$\sigma_I = -\frac{1}{N_t} \ln\left(\frac{N_2}{N_1}\right)$$

Solving this equation gives

$$\sigma_\mathrm{I} = \frac{1}{N_t} \sqrt{\left(\frac{1 - R_\mathrm{in}}{N_1^\mathrm{in} R_\mathrm{in}} + \frac{1 - R_\mathrm{out}}{N_1^\mathrm{out} R_\mathrm{out}}\right)}$$

Derivation of the Matter Radius

Measured Interaction Cross Section

↓

Assuming a Fermi-type Nuclear Density Distribution

↓

The Glauber calculation uses this distribution to obtain the matter radius.

Nucleon Density (Fermi Distribution)

$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r - r_0}{c}\right)}$$

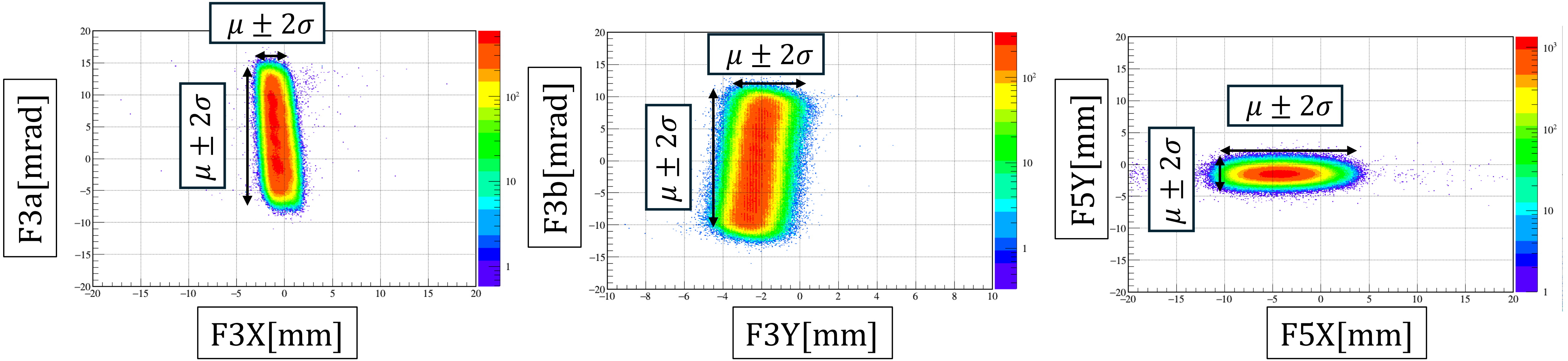
- r : Distance from the Nuclear Center
- ρ_0 : Central Density
- r_0 : Nuclear Radius where $\rho(r) = \frac{\rho_0}{2}$
- c : Surface Diffuseness （$c = 0.56$）

r_0 was chosen to reproduce the measured interaction cross section.

Transmission

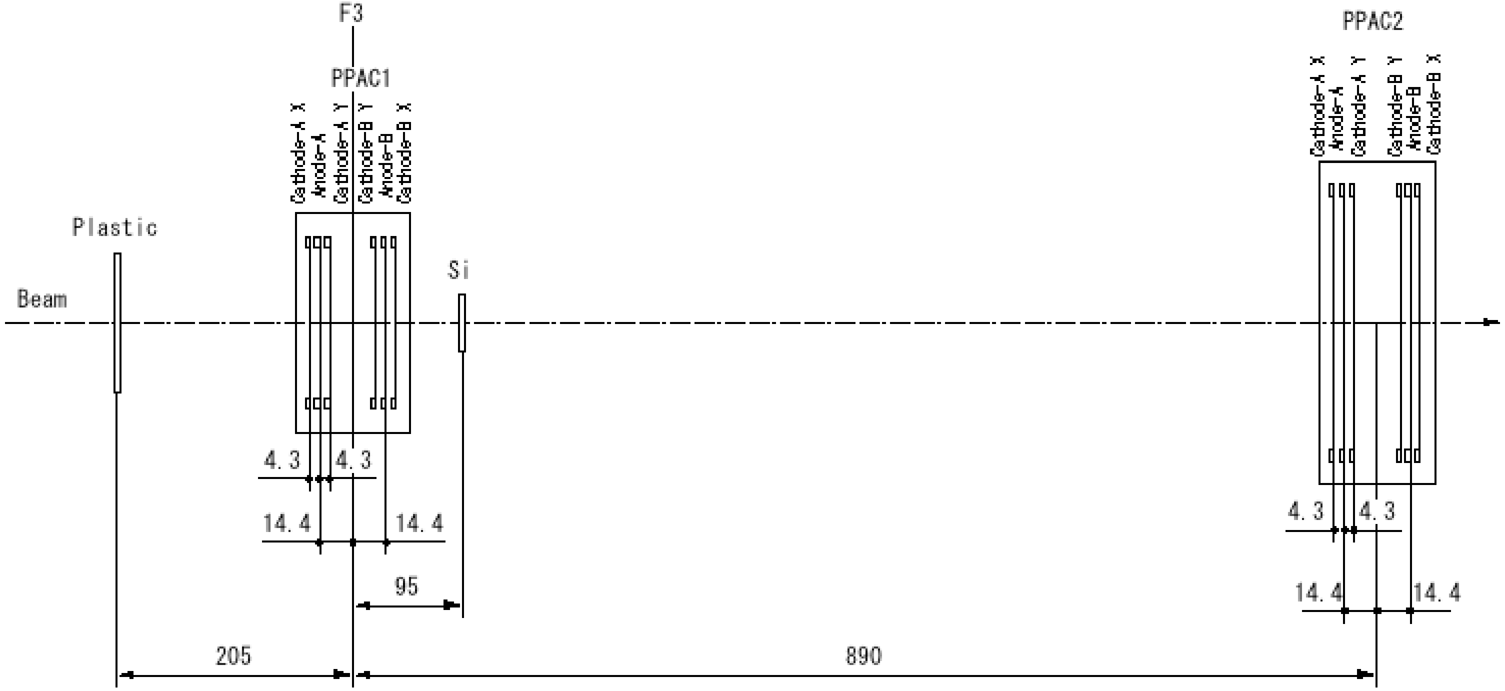
Transmission: Selection of stably transported beam components

$$\text{Transmission} = \frac{\text{Number of non-reacted particles}}{\text{Number of incoming particles}}$$



emittance cut

F3



F3

F3X：Horizontal beam position

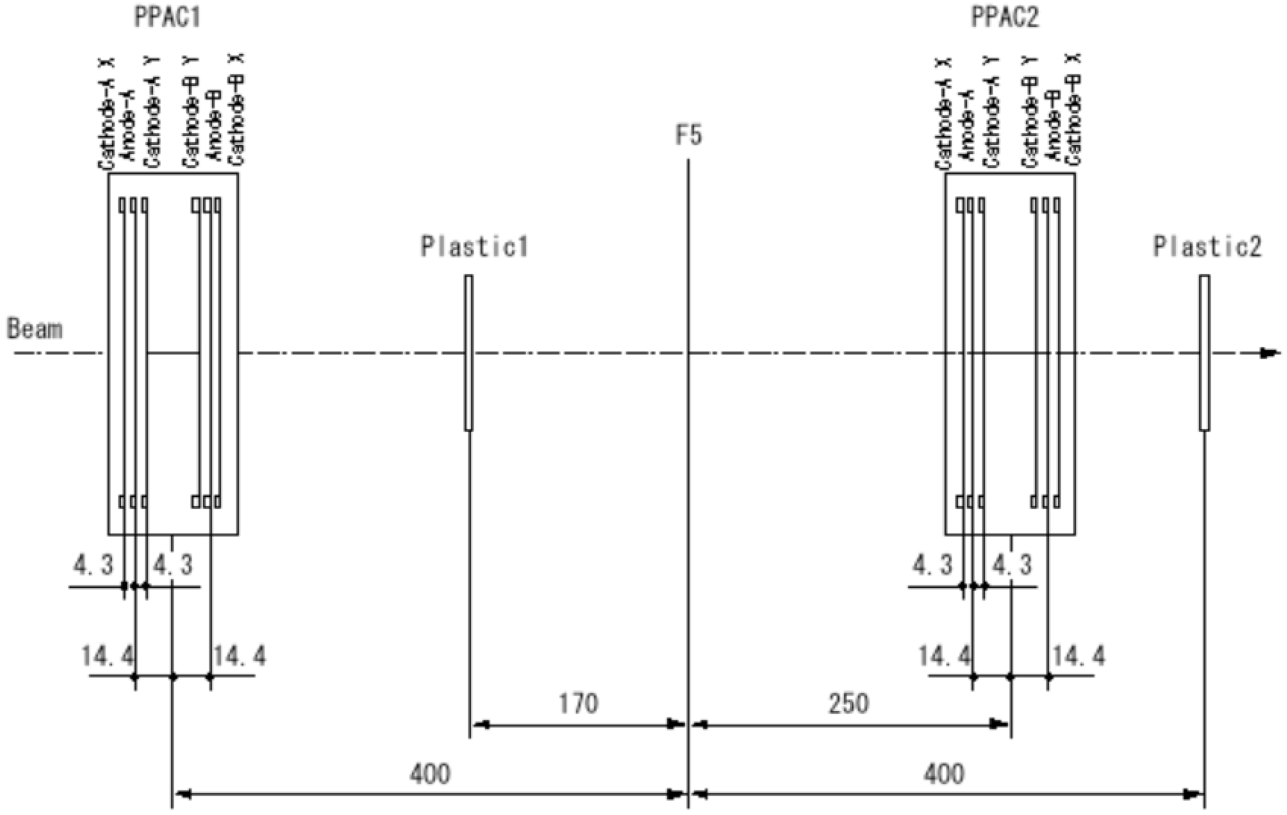
F3Y：Vertical beam position

F3a：Horizontal beam angle

F3b：Vertical beam angle

emittance cut

F5



F5

F5X : Horizontal beam position

F5Y : Vertical beam position

Expected RMS radius from the uniform sphere model

$$\boxed{R_{\mathrm{m}} = \sqrt{\langle r^2 \rangle}}$$

$$\langle r^2 \rangle = \frac{\int r^3 \rho(\vec{r})\, d^3 r}{\int \rho(\vec{r})\, d^3 r}$$

For a spherical object

$$d^3 r = 4\pi r^2\, dr$$

Numerator $\displaystyle \int_0^R r^2 \cdot 4\pi r^2 dr = \int_0^R 4\pi r^4 dr$

$$\int_0^R 4\pi r^4 dr = 4\pi \cdot \frac{1}{5} R^5$$

Denominator $\displaystyle \int_0^R 4\pi r^2 dr$

$$\int_0^R 4\pi r^2 dr = 4\pi \cdot \frac{1}{3} R^3$$

$$R_{\mathrm{rms}} = \sqrt{\frac{3}{5}} R \qquad R = r_0 A^{\frac{1}{3}}$$

Proton distribution radius

$$\langle r^2\rangle_{\mathrm{ch}} = \langle r^2\rangle_{\mathrm{P}} + \left\langle R_{\mathrm{P}}^2\right\rangle + \frac{N}{Z}\left\langle R_{\mathrm{N}}^2\right\rangle + \frac{3\hbar^2}{4m^2pc^2} \quad \cdots (1)$$

$$\langle r^2\rangle_{\mathrm{P}} = \langle r^2\rangle_{\mathrm{ch}} - \left\langle R_{\mathrm{P}}^2\right\rangle - \frac{N}{Z}\left\langle R_{\mathrm{N}}^2\right\rangle - \frac{3\hbar^2}{4m^2pc^2} \quad \cdots (2)$$

$$r_p = \sqrt{\langle r^2\rangle_{\mathrm{P}}} \quad \cdots (3)$$

- $\langle r^2\rangle_{\mathrm{P}}$ ：Point-proton distribution radius
- $\langle r^2\rangle_{\mathrm{ch}}$ ：Squared charge radius
- $\left\langle R_{\mathrm{P}}^2\right\rangle$ ：Squared proton charge radius
- $\left\langle R_{\mathrm{N}}^2\right\rangle$ ：Squared neutron charge radius
- $\frac{3\hbar^2}{4m^2pc^2}$ ：Foldy term (relativistic correction)

Neutron distribution radius

$$\boxed{\Delta r_{\mathrm{np}} = R_{\mathrm{n}} - R_{\mathrm{p}}}$$

$$R_{\mathrm{m}} = \frac{Z}{A} R_{\mathrm{p}}^2 + \frac{N}{A} R_{\mathrm{n}}^2$$

$$R_{\mathrm{n}} = \sqrt{\frac{A R_{\mathrm{m}}^2 - Z R_{\mathrm{p}}^2}{N}}$$

R_{m} : Matter radius [fm]

R_{p} : Proton distribution radius [fm]

R_{n} : Neutron distribution radius [fm]

$\sigma_{\mathrm{R_m}}$: Statistical uncertainty of the matter radius [fm]

$\sigma_{\mathrm{R_p}}$: Statistical uncertainty of the proton distribution radius [fm]

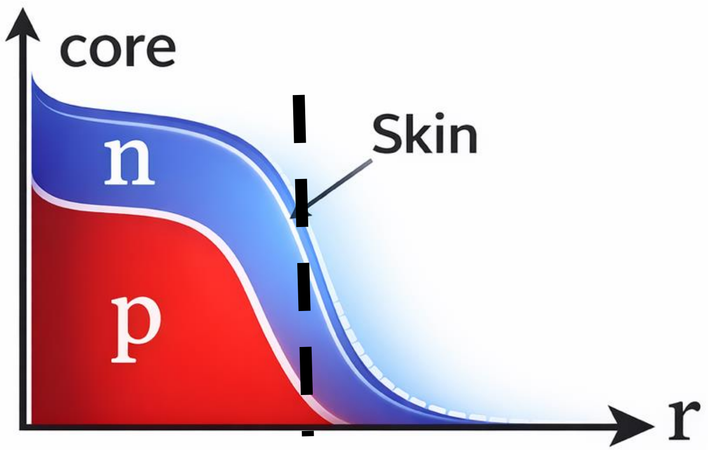
Uncertainty of the neutron distribution radius

$$\sigma_{R_{\mathrm{n}}} = \sqrt{\left(\frac{A R_{\mathrm{rms}}}{N R_{\mathrm{n}}} \sigma_{\mathrm{R_{rms}}}\right)^2 + \left(\frac{Z R_{\mathrm{p}}}{N R_{\mathrm{n}}} \sigma_{R_{\mathrm{p}}}\right)^2}$$

Neutron distribution radius

Neutron distribution radius

$$R_{\mathrm{n}} = \sqrt{\frac{AR_{\mathrm{m}}^2 - ZR_{\mathrm{p}}^2}{N}}$$



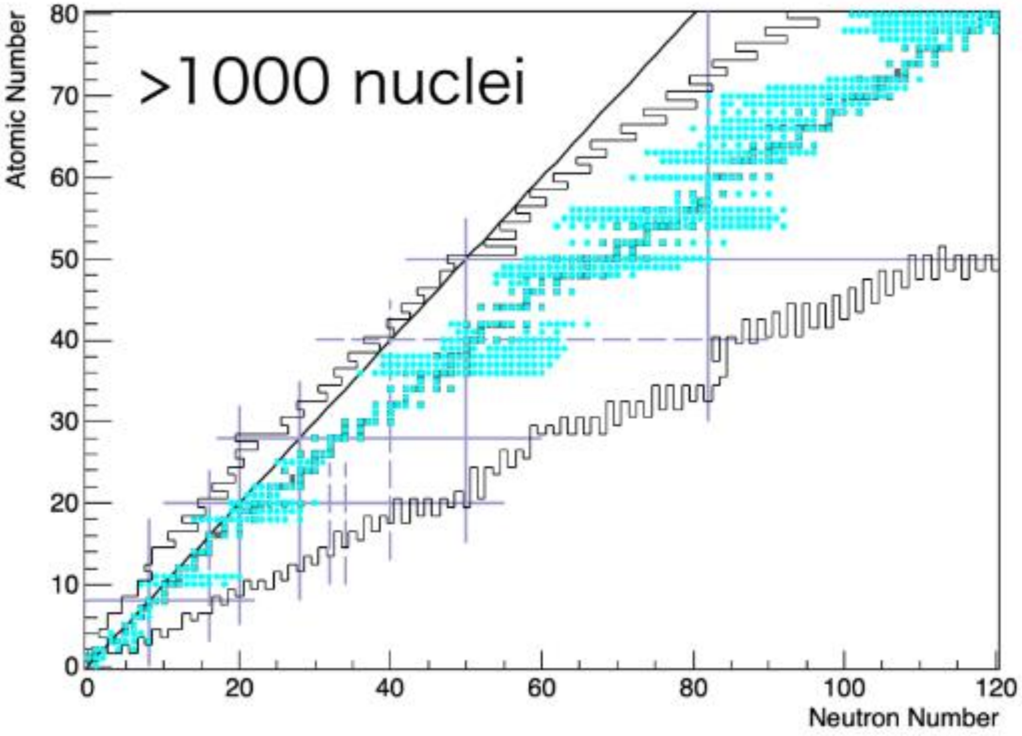
$$r_0 = \sqrt{\frac{3}{5}}R = 0.77R$$

$$R_{\mathrm{n}} = \sqrt{\langle r^2 \rangle}$$

The neutron distribution radius
does not represent a specific boundary.

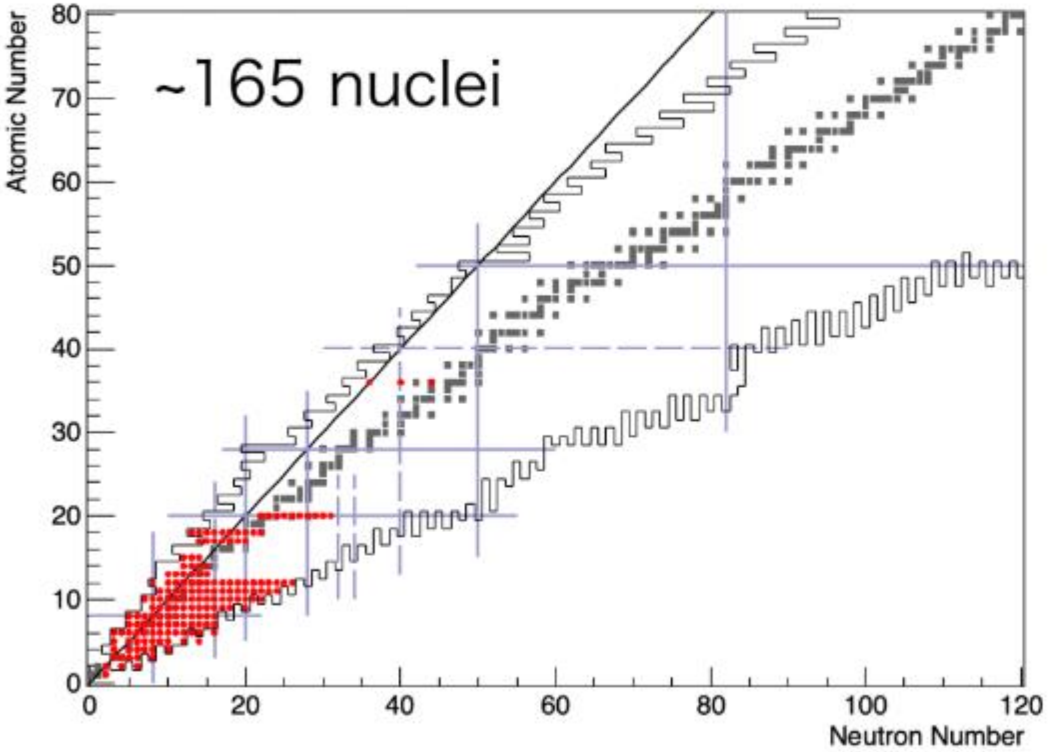
It is the weighted average distance of the neutron distribution from the nuclear center.

No large difference from the uniform sphere model



measured **charge radii**

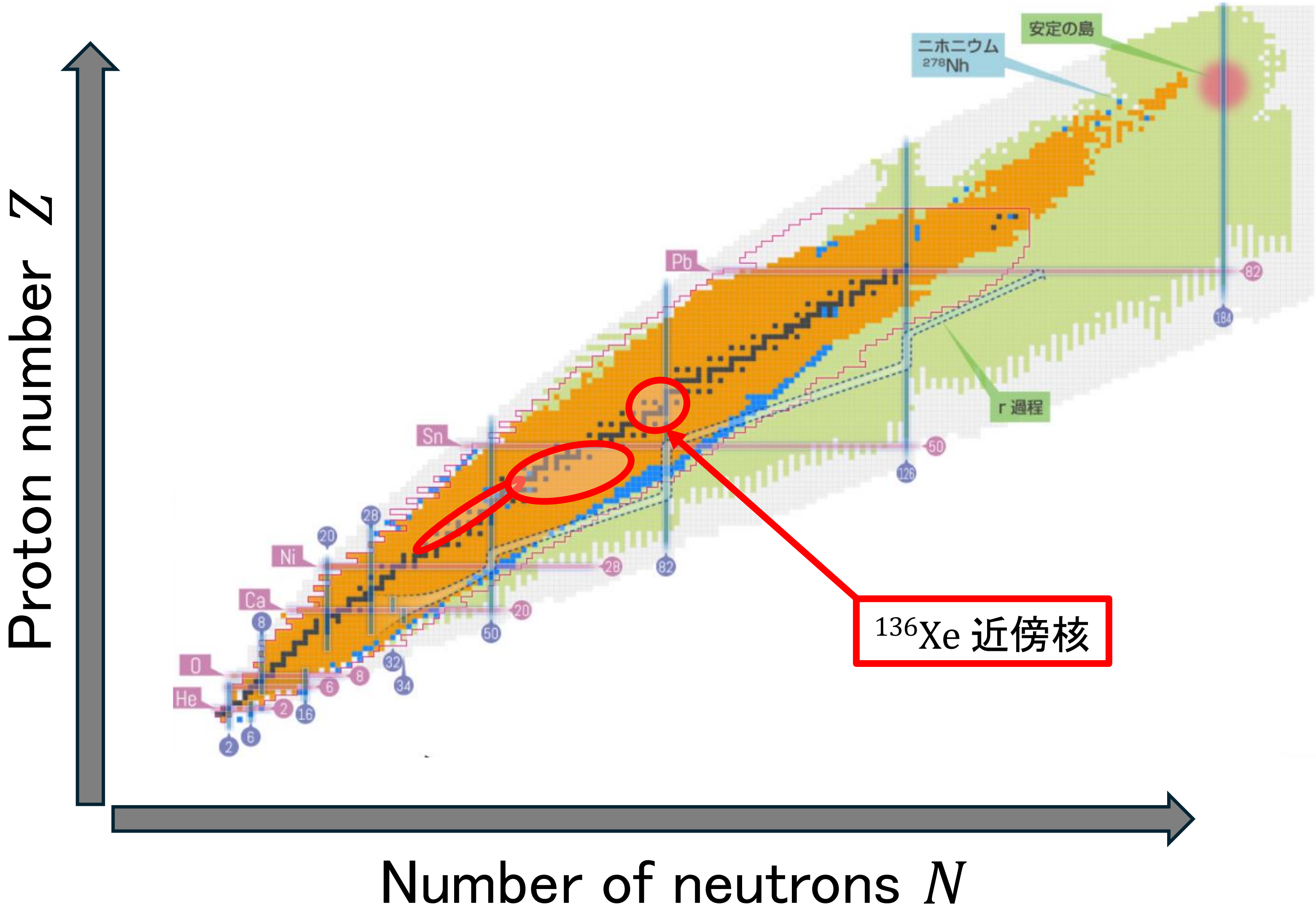
I. Angeli et al., At. Data and Nucl. Data Tables, 99, (2013) 69.
T. Li et al., At. Data and Nucl. Data Tables, 140, (2021) 101440.



measured **σ_I at 200M-1GeV**

L.Y.Li et al., At. Data and Nucl. Data Tables, 166, (2025) 101747.

Full measurement range of this experiment



Source: RIKEN

Future Work

Extend the measurements to nuclides around the magic number N=82 and study changes in interaction cross sections due to nuclear structure effects.

Nuclear Structure Effects

- Shell structure (shell effects)
- Nuclear deformation (spherical, ellipsoidal, etc.)
- Neutron skin / halo structure
- Non-uniform density distributions and other nuclear structures