Particle identification at BigRIPS and its optimization in the off-line analysis

N. Fukuda et al., Nucl. Instr. Meth. B 317 (2013) 323

- TOF-$B\rho$-ΔE method
- Trajectory reconstruction for $B\rho$ determination
- Background removal (*Please see the above paper.*)
  - How to identify and remove the events whose charge state changes at F5

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Particle identification scheme at BigRIPS

TOF-$B\rho$-ΔE method

$$\frac{A}{Q} = \frac{B\rho}{\gamma\beta}\frac{c}{m_u}$$

$$Z \leftarrow \Delta E = f(Z, \beta)$$

Bethe-Bloch formula

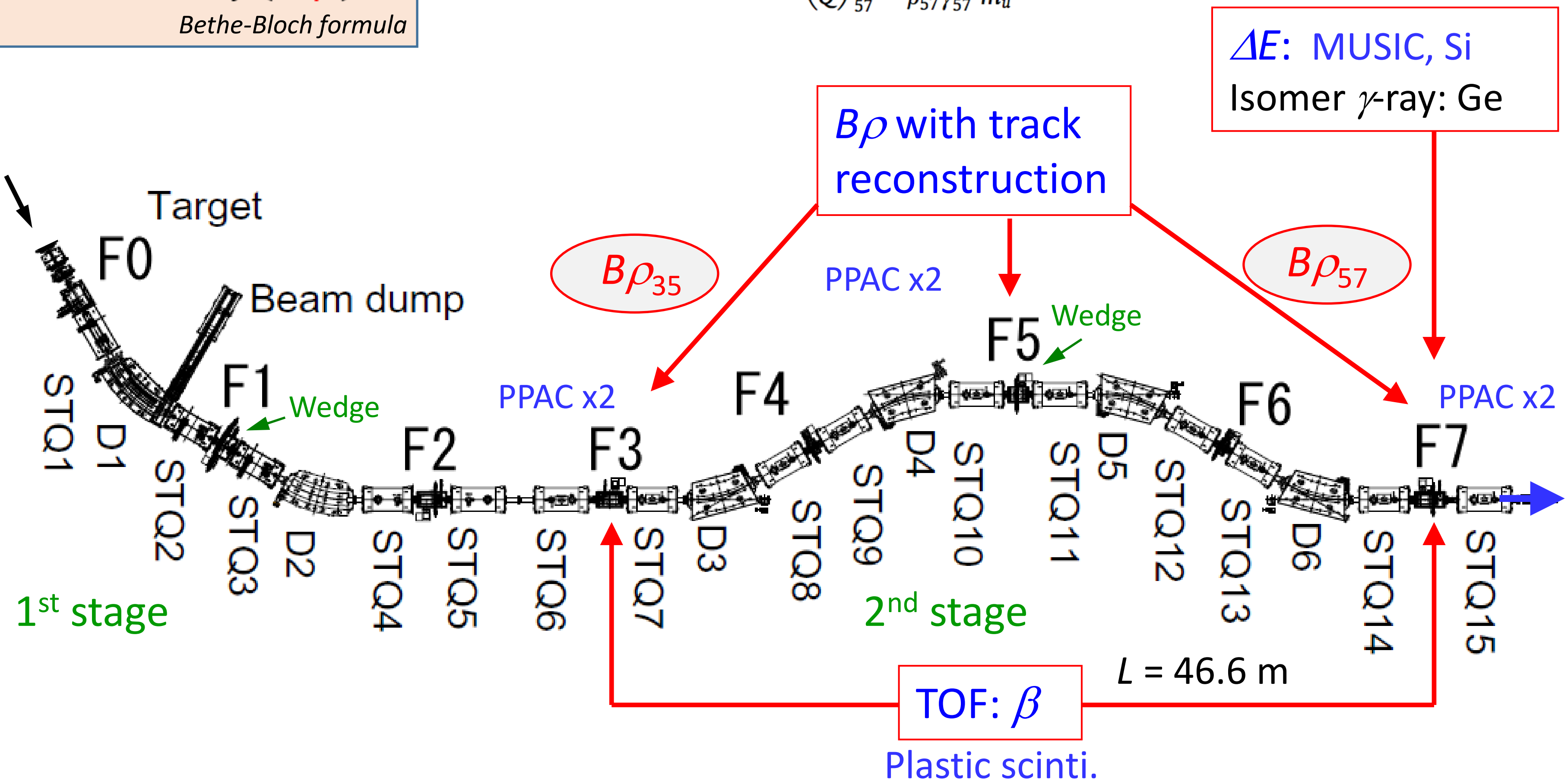
TOF: Time of flight
$B\rho$: Magnetic rigidity
ΔE: Energy loss

$$\mathrm{TOF} = \frac{L_{35}}{\beta_{35}c} + \frac{L_{57}}{\beta_{57}c},$$

$$\left(\frac{A}{Q}\right)_{35} = \frac{B\rho_{35}}{\beta_{35}\gamma_{35}}\frac{c}{m_u}, \quad \Rightarrow \quad \frac{\beta_{35}\gamma_{35}}{\beta_{57}\gamma_{57}} = \frac{B\rho_{35}}{B\rho_{57}}. \quad \Rightarrow \quad \beta_{35},\ \beta_{57},\ A/Q$$

$$\left(\frac{A}{Q}\right)_{57} = \frac{B\rho_{57}}{\beta_{57}\gamma_{57}}\frac{c}{m_u}.$$

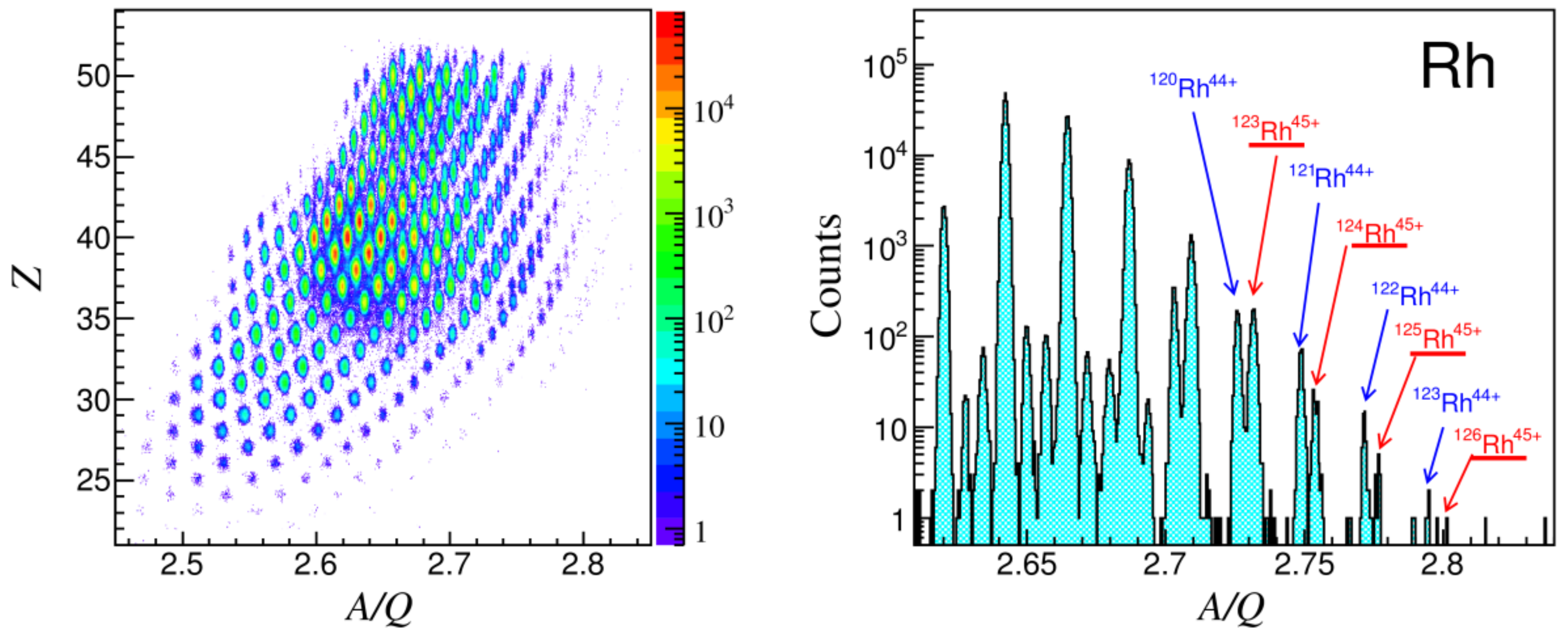
If $(A/Q)_{35} = (A/Q)_{57}$



Particle identification (PID) resolving power

TOF-$B\rho$-ΔE method with trajectory reconstruction

A/Q resolution: High enough to identify charge states of fragments



^{238}U(345 MeV/u) + Be 2.9 mm

$B\rho$ 01 = 7.990 Tm, F1 deg Al 2.18mm

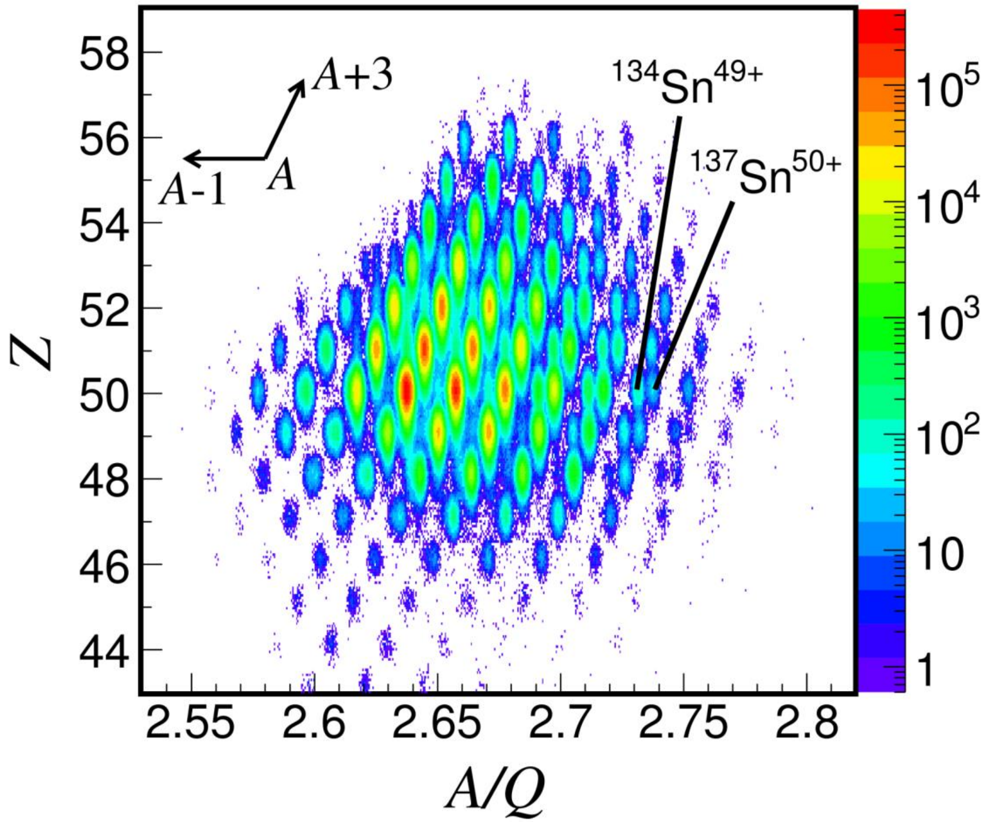
r.m.s. *A/Q* resolution: 0.034 %

6.1σ separation

Identification of 45 New Neutron-Rich Isotopes
by In-Flight fission of a 238U Beam at 345 MeV/nucleon
T. Ohnishi et al., J. Phys. Soc. Jpn **79** (2010) 073201

Example:
PID for fission fragments produced by in-flight fission of ^{238}U beam

^{238}U 345 MeV/u + Pb 0.95 mm (+Al 0.3 mm)
$B\rho$ = 7.706 Tm, F1 deg. Al 2.56 mm, F5 deg. Al 1.8 mm



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Trajectory reconstruction for $B\rho$ determination

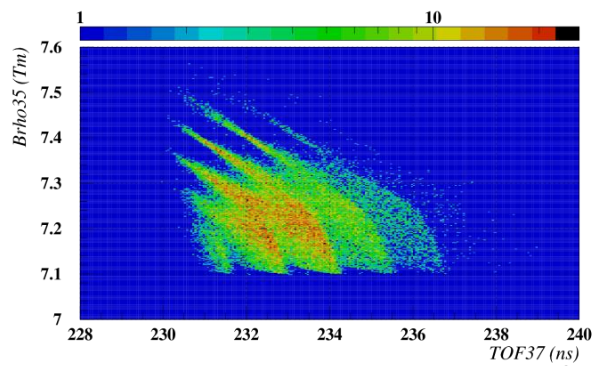
by using the position and angle measured at the focuses (such as F5x, F5a, F3x) and the experimentally determined transfer matrices as follows:

$$F5x = (x|x)F3x + (x|a)F3a + (x|\delta)\delta$$

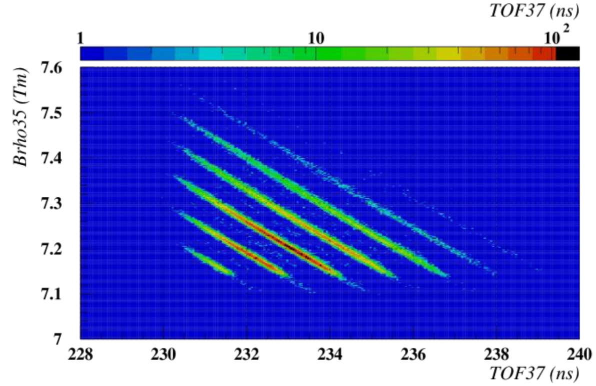
$$F5a = (a|x)F3x + (a|a)F3a + (a|\delta)\delta$$

$$B\rho = B\rho_0(1+\delta)$$

Measured F5x, F5a, F3x
→ deduce δ, F3a



Without track reconstruction
(from the position at dispersive focus)



With track reconstruction

For Z = 50 isotopes produced by in-flight fission of a ^{238}U beam at 345 MeV/u.

Trajectory reconstruction

F3—F5 case

$$\begin{cases} x_5 = \underline{(x|x)x_3 + (x|a)a_3 + (x|\delta)\delta_{35}} \\ \quad +(x|xx)x_3^2 + (x|xa)x_3a_3 + (x|x\delta)x_3\delta_{35} + (x|aa)a_3^2 + (x|a\delta)a_3\delta_{35} \\ \quad +(x|\delta\delta)\delta_{35}^2 + (x|yy)y_3^2 + (x|yb)y_3b_3 + (x|bb)b_3^2 \\ a_5 = \underline{(a|x)x_3 + (a|a)a_3 + (a|\delta)\delta_{35}} \\ \quad +(a|xx)x_3^2 + (a|xa)x_3a_3 + (a|x\delta)x_3\delta_{35} + (a|aa)a_3^2 + (a|a\delta)a_3\delta_{35} \\ \quad +(a|\delta\delta)\delta_{35}^2 + (a|yy)y_3^2 + (a|yb)y_3b_3 + (a|bb)b_3^2 \end{cases}$$

First-order matrix elements

First-order matrix elements

$$B\rho = B\rho_0(1+\delta)$$

$B\rho_0$: Central $B\rho$ value

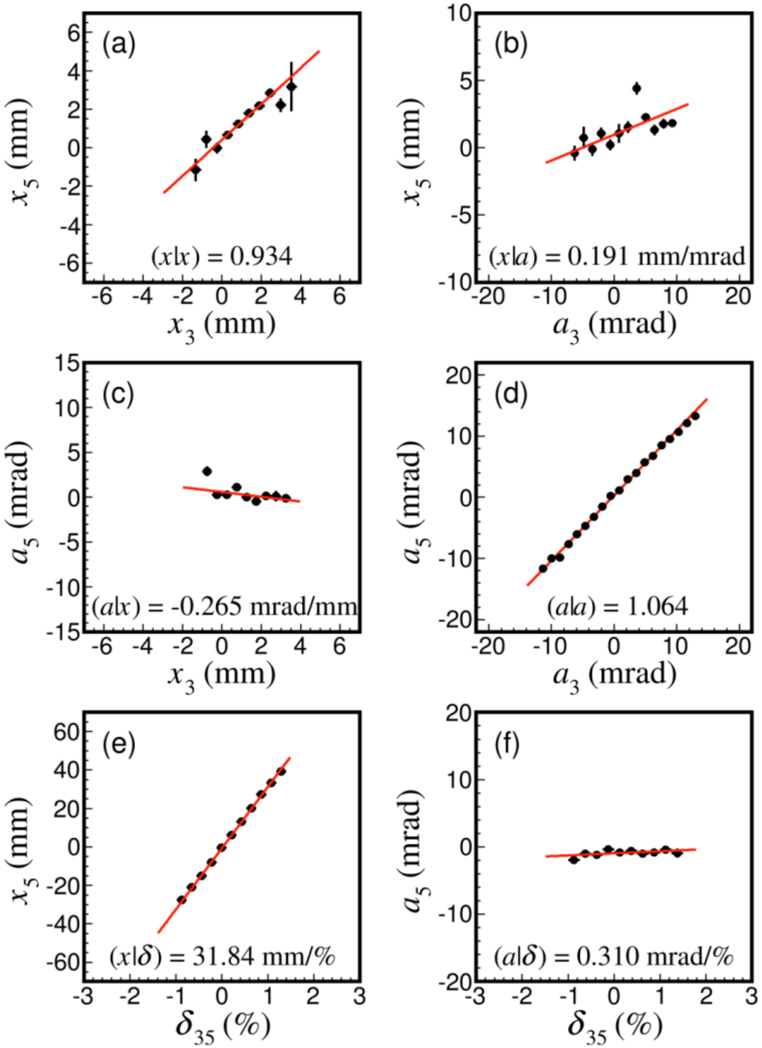
Magnetic field measured by NMR probes
The central trajectory radii deduced from the magnetic field-map data.

- First-order matrix elements: Derived directly from the measurement
- Higher-order matrix elements: Determined by the empirical method

Next

Determination of first-order transfer matrix elements

$^{143}I^{53+}$ selected



$$\begin{cases} x_5 = (x|x)x_3 + (x|a)a_3 + (x|\delta)\delta_{35} \\ a_5 = (a|x)x_3 + (a|a)a_3 + (a|\delta)\delta_{35} \end{cases}$$

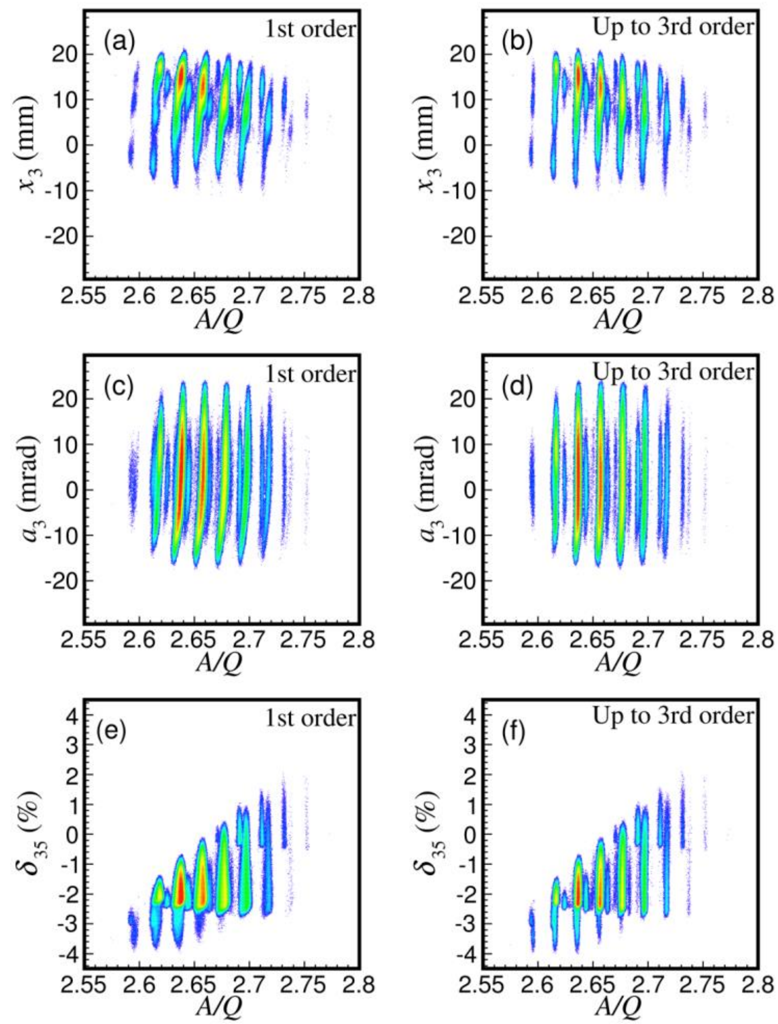
Matrix elements	Experimentally derived	Calculated using COSY INFINITY
$(x\|x)$	0.934 ± 0.094	0.927
$(a\|x)$	-0.265 ± 0.138	-0.020
$(x\|a)$	0.191 ± 0.039	-0.005
$(a\|a)$	1.064 ± 0.009	1.079
$(x\|\delta)$	31.84 ± 0.090	31.67
$(a\|\delta)$	0.310 ± 0.209	0.015
Determinant	1.044 ± 0.01	1

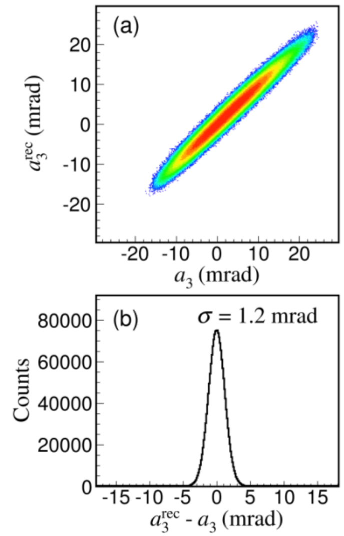
0.12% shift in δ_{35} for a_3 = 20 mrad

Determination of the first-order matrix is carried out in the ONLINE analysis.

Determination of higher-order transfer matrix elements (Advanced)

1st order | **Up to 3rd order**



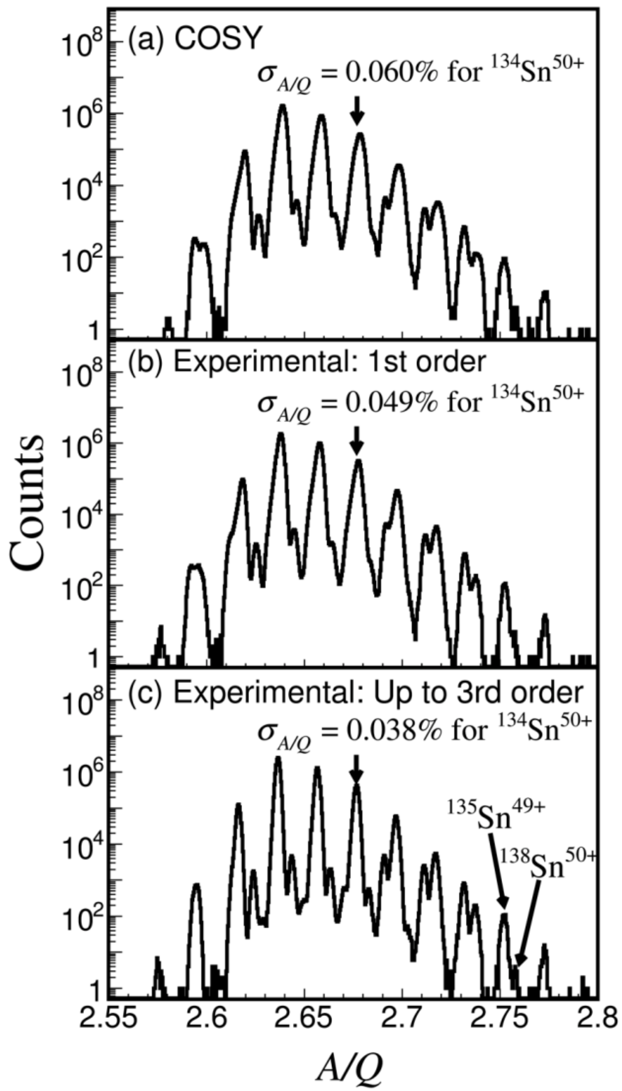


Verification of trajectory reconstruction

Matrix elements	Empirically derived
$(x\|xa)$	0.008
$(x\|x\delta)$	-0.065
$(x\|a\delta)$	-0.051
$(x\|bb)$	0.003
$(x\|aaa)$	0.00009
$(a\|xa)$	0.0027
$(a\|x\delta)$	-0.011
$(a\|aa)$	-0.0058
$(a\|a\delta)$	0.0065
$(a\|aa\delta)$	-0.0018

Improvement in A/Q resolution

Sn isotopes



^{238}U 345 MeV/u + Pb 0.95 mm (+Al 0.3 mm)
$B\rho$ = 7.706 Tm, F1 deg. Al 2.56 mm, F5 deg. Al 1.8 mm

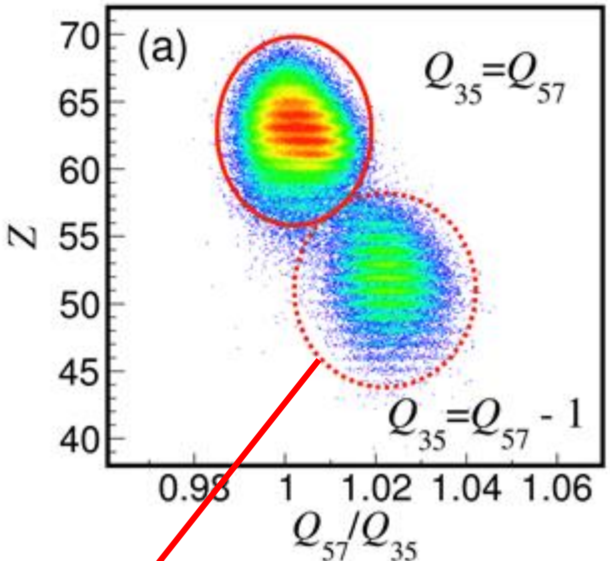
COSY
$\boldsymbol{\sigma}$ **= 0.060%**

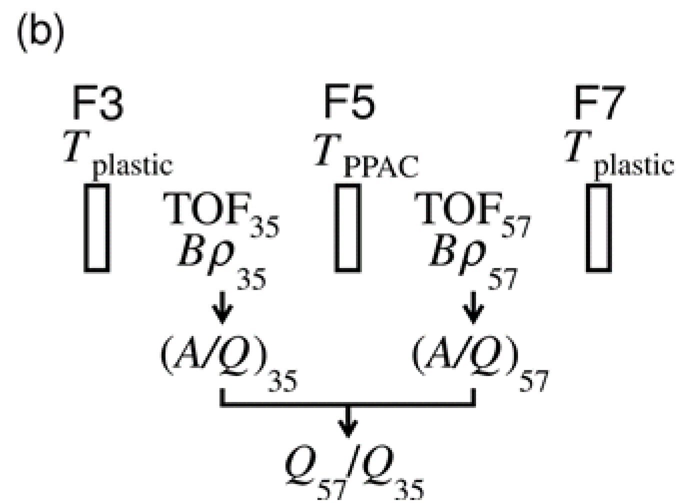
Experimental: 1st order
$\boldsymbol{\sigma}$ **= 0.049%**

Experimental: 3rd order
$\boldsymbol{\sigma}$ **= 0.038%** **Excellent tail separation**

Identification of charge-state change at F5: Method-I

^{238}U 345 MeV/u + Be 4.9 mm
Tuned for ^{168}Gd



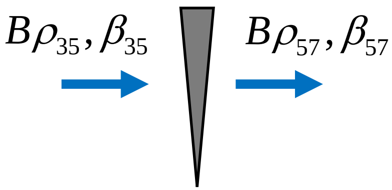


Timing resolution of PPAC is about 900 ps(σ)

These isotopes lose one electron at F5

Identification of charge-state change at F5: Method-II

$\Delta E_{\mathrm{F5deg}}$: F5 degrader での energy loss



If A and Q do not change

$$\Delta E_{\mathrm{deg}} = (\gamma_{35} - 1)Am_{\mathrm{u}} - (\gamma_{57} - 1)Am_{\mathrm{u}}$$
$$= cQ\left(\frac{B\rho_{35}}{\beta_{35}} - \frac{B\rho_{57}}{\beta_{57}}\right),$$

$$\Delta E_{\mathrm{deg}} \propto Z^2/\beta_{35}^2 d$$

Bethe-Bloch formula

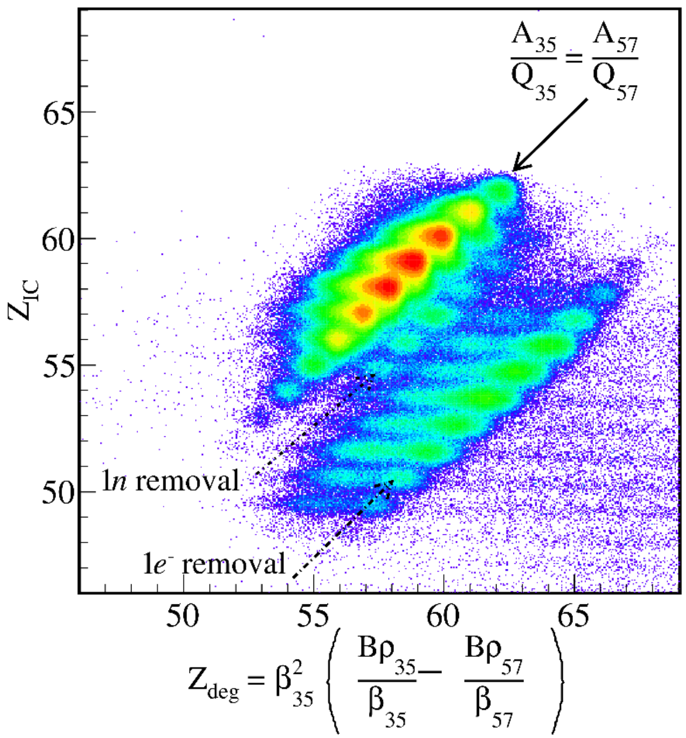
d: degrade thickness

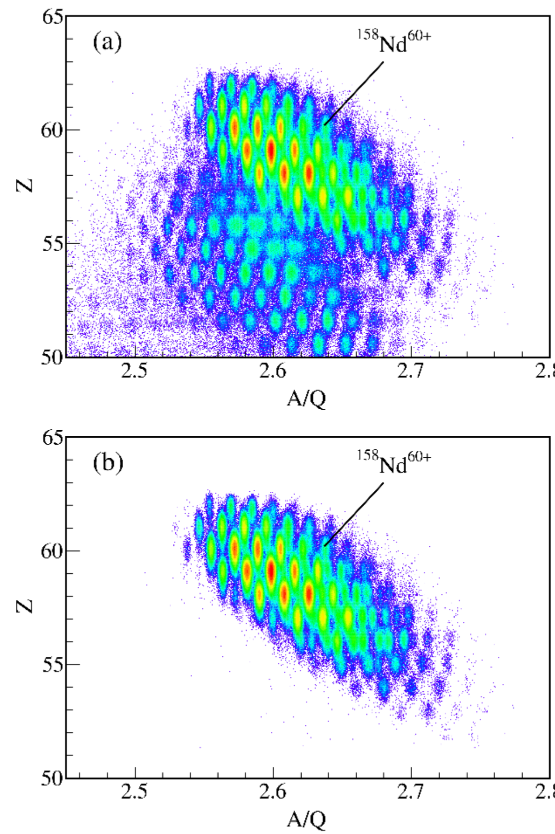
$$Q_{35} = Q_{57} = Z,$$

$$\boxed{Z \propto \beta_{35}^2 \left(\frac{B\rho_{35}}{\beta_{35}} - \frac{B\rho_{57}}{\beta_{57}}\right)\frac{1}{d}}$$

^{238}U 345 MeV/u + Be 5 mm

Tuned for ^{158}Nd





Summary

- Trajectory reconstruction (COSY 1st-order matrix) + No slew correction
  → $\sigma_{A/Q}$ ~ 0.06—0.08%

⇩

- Trajectory reconstruction (Experimental 1st-order matrix) + No slew correction
  → $\sigma_{A/Q}$ ~ 0.05%

⇩

Sufficient for most cases

- Trajectory reconstruction (Experimental 3rd-order matrix) + No slew correction
  → $\sigma_{A/Q}$ ~ 0.04%

⇩ Iteration

- Trajectory reconstruction (Experimental 3rd-order matrix) + slew correction
  → $\sigma_{A/Q}$ ~ 0.035%

Trajectory reconstruction with the experimental 1st-order transfer matrix

+

Removal the events whose charge state changes at F5