Production cross section measurements of radioactive isotopes by BigRIPS separator at RIKEN RI Beam Factory

--- RIs produced from ^{48}Ca, ^{238}U, and ^{124}Xe beam ---

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EMIS2012, Matsue, Dec 7, 2012

Outline

1. Introduction
   - Production rate and cross section
   - RI beam production at BigRIPS separator
   - Particle Identification (PID) at BigRIPS
2. Production rates and cross sections of radioactive isotopes (RIs)
   - Neutron-rich nuclei by projectile fragmentation from ^{48}Ca beam
   - Neutron-rich nuclei by in-flight fission from ^{238}U beam
   - Neutron-deficient nuclei by projectile fragmentation from ^{124}Xe beam
3. Summary

Production rate and cross section

Measurement of production cross section is important.
→ Allowing accurate estimation of RI beams.

Production rate is deduced from …

- Yield
- Beam intensity
  Deduced from the count rate of scattered particles from F0 target.
- Transmission
  Deduced from the LISE++ calculation (Monte Carlo mode).

For cross section …

- Target thickness

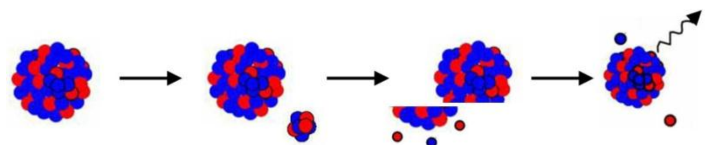
A variety of RIs have been produced at BigRIPS since the commissioning in 2007.
→ We have measured a lot of data of production rates deducing cross sections.

^{48}Ca beam : neutron-rich nuclei by projectile fragmentation
^{238}U beam : neutron-rich nuclei by in-flight fission
two mechanisms … Abrasion fission with Be target
Coulomb fission with Pb target
^{124}Xe beam : neutron-deficient nuclei (incl. ^{100}Sn) by projectile fragmentation
low-$B\rho$-side tail of the $B\rho$ distribution

Production reactions of RI beams at BigRIPS

Projectile fragmentation

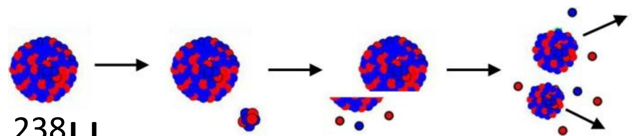
- Abrasion-ablation model



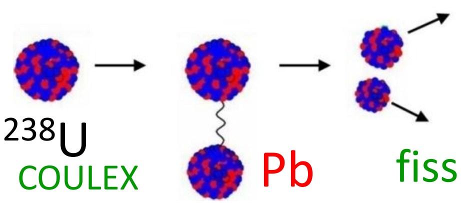
- All kinds of fragments (RI beams) lighter than projectile can be produced.

In-flight fission (of ^{238}U)

- Abrasion fission

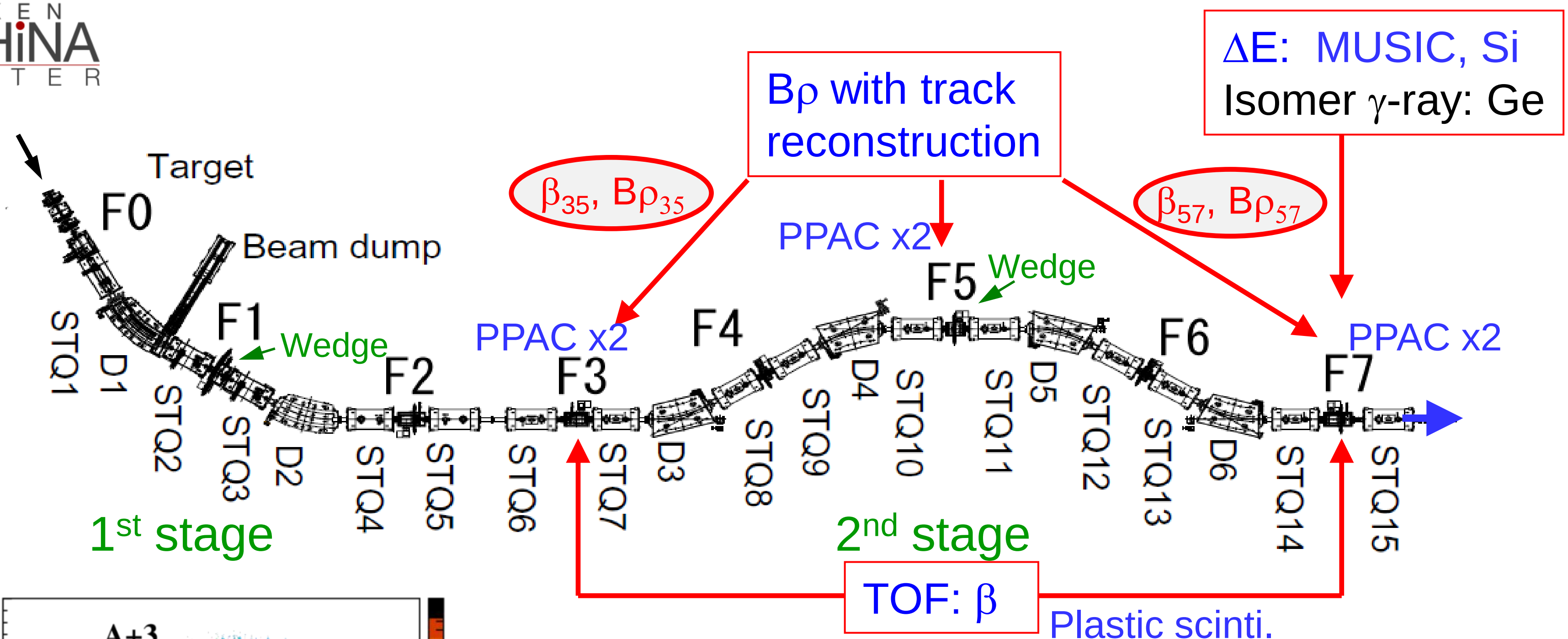


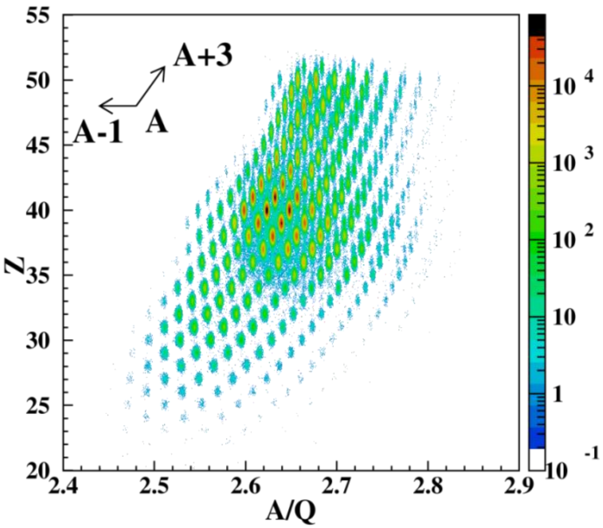
- Coulomb fission



- Very powerful for medium heavy neutron-rich isotopes.

Particle Identification scheme at BigRIPS





TOF-$B\rho$-ΔE method with track reconstruction @ 2nd stage

- N. Fukuda : Identification and separation of RI beams by BigRIPS separator at RIKEN RI Beam Factory
- D. Kameda : Detector system for particle identification and beam diagnosis in the fragment separator BigRIPS

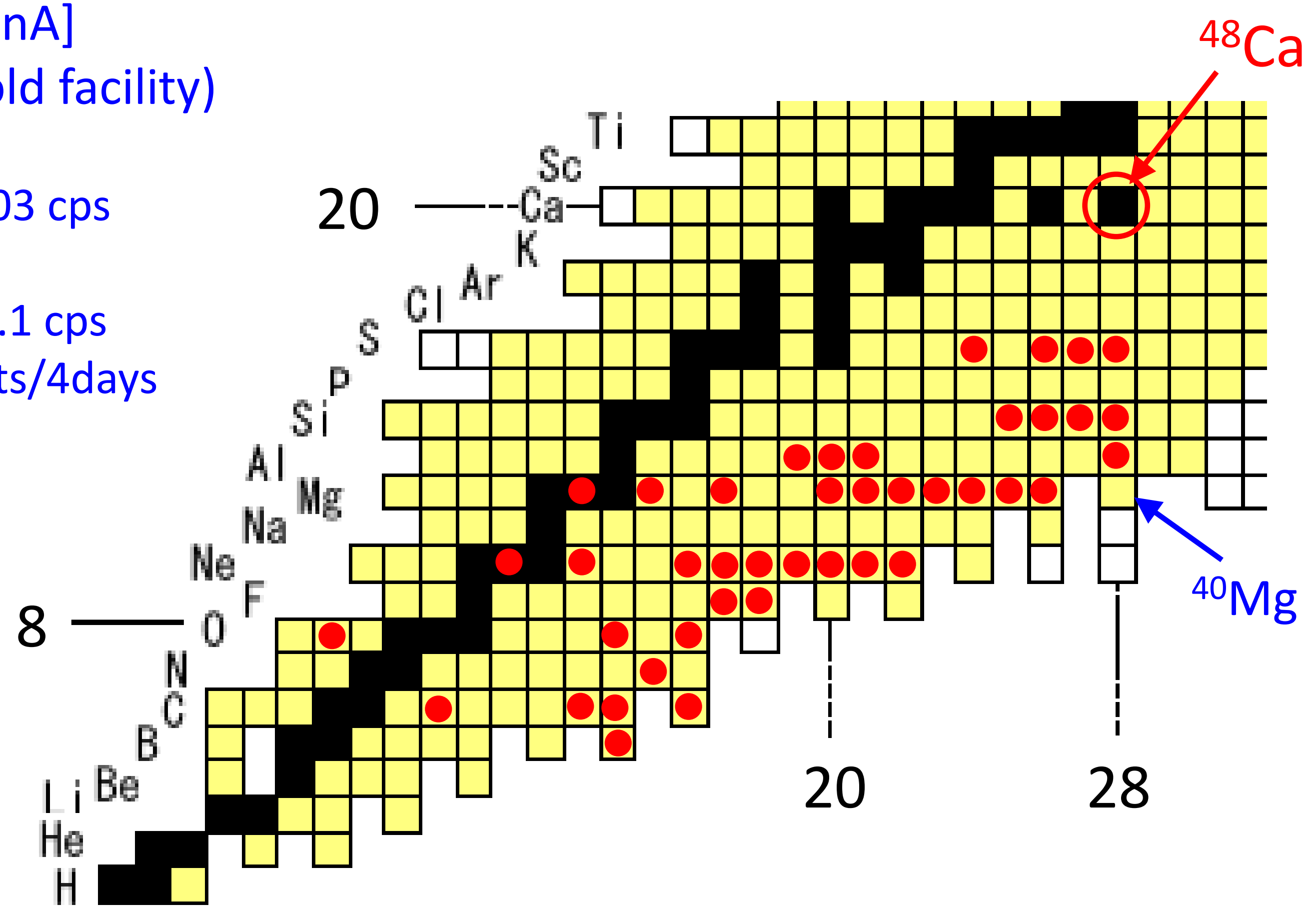
BigRIPS: T. Kubo, NIM B 204 (2003) 97, & T. Kubo et al. , IEEE Trans. Appl. Supercond. 17 (2007) 1069.

Neutron-rich nuclei by projectile fragmentation from ^{48}Ca beam

Yields of neutron-rich RI beams using a ^{48}Ca beam at 345 MeV/u

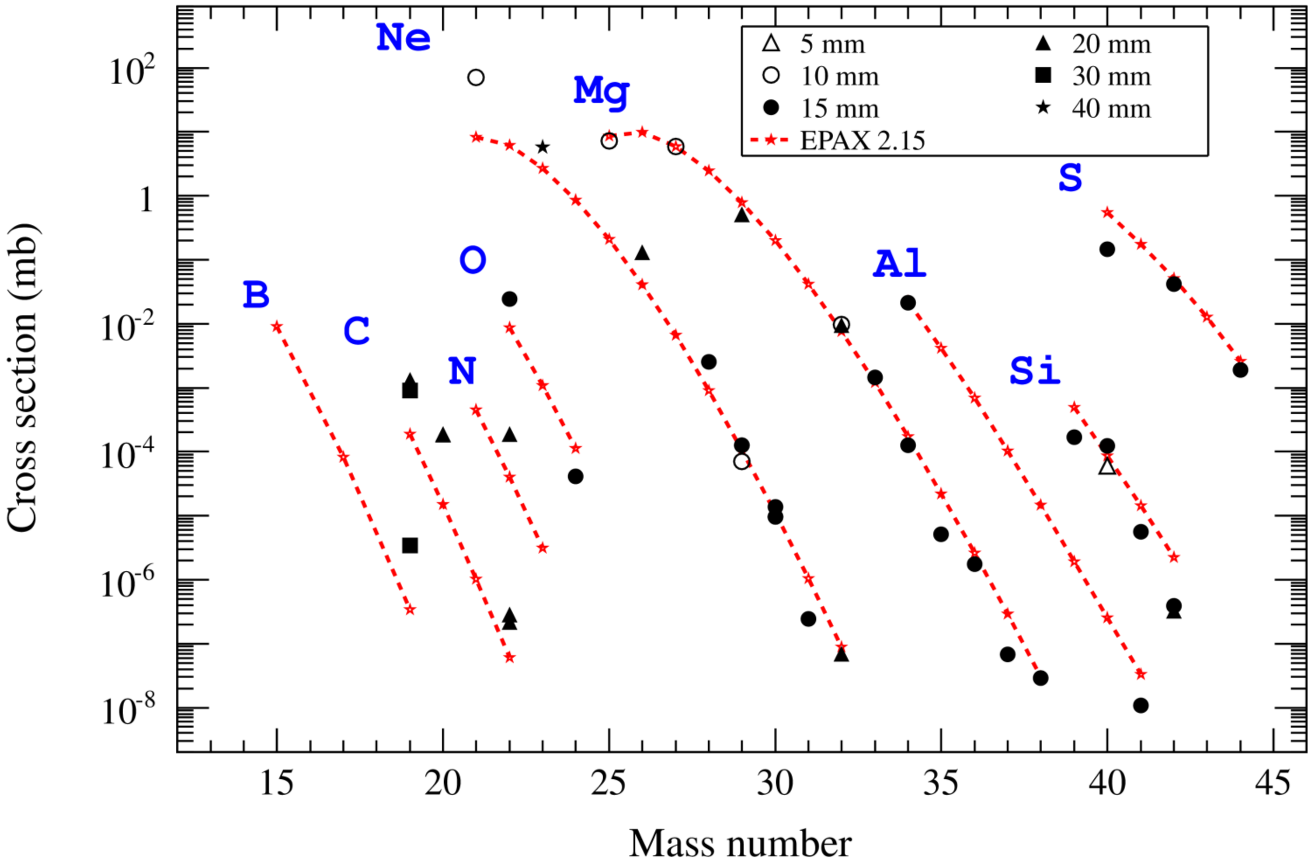
Yields [cps/100 pnA]

	BigRIPS	RIPS (old facility)
^{19}B	55 cps	
^{22}C	5 cps	0.003 cps
^{22}N	4000 cps	
^{30}Ne	550 cps	0.1 cps
^{31}Ne	13 cps	10 counts/4days
^{32}Ne	4 cps	
^{38}Mg	2 cps	
^{41}Al	0.5 cps	
^{42}Si	24 cps	



Recent ^{48}Ca-beam Intensity : ~400 pnA (May 2012)

Measured production cross sections comparison with EPAX 2.15 (^{48}Ca 345 MeV/u + Be)



Be target thickness

^{19}C	20 mm, 30 mm
^{29}Ne	10 mm, 15 mm
^{32}Mg	10 mm, 20 mm
^{40}Si	5 mm, 15 mm
^{42}Si	15 mm, 20 mm

- Fairly good agreement between the production cross section from the experimental results and the LISE++ calculation with EPAX 2.15.

Neutron-rich nuclei by in-flight fission from ^{238}U beam

Various setting for in-flight fission of ^{238}U at 345 MeV/u

					setting 1	2	3
Target	Be 7 mm			Pb 1.5 mm	Be 5.1 mm	Be 2.9 mm	Pb 0.95 mm + Al 0.3 mm
***Bρ* (Tm)**	7.2	7.4	7.6	7.0	7.902	7.990	7.706
Δp/p	±1%	±1%	±2%	±0.1%	±3%	±3%	±3%
Degrader	None	None	None	None	F1: 1.29 mm	F1: 2.18 mm	F1: 2.56 mm F5: 1.8 mm
F2 slit (mm)	±30	±30	±30	±50	±13.5	±15.5	±15 mm

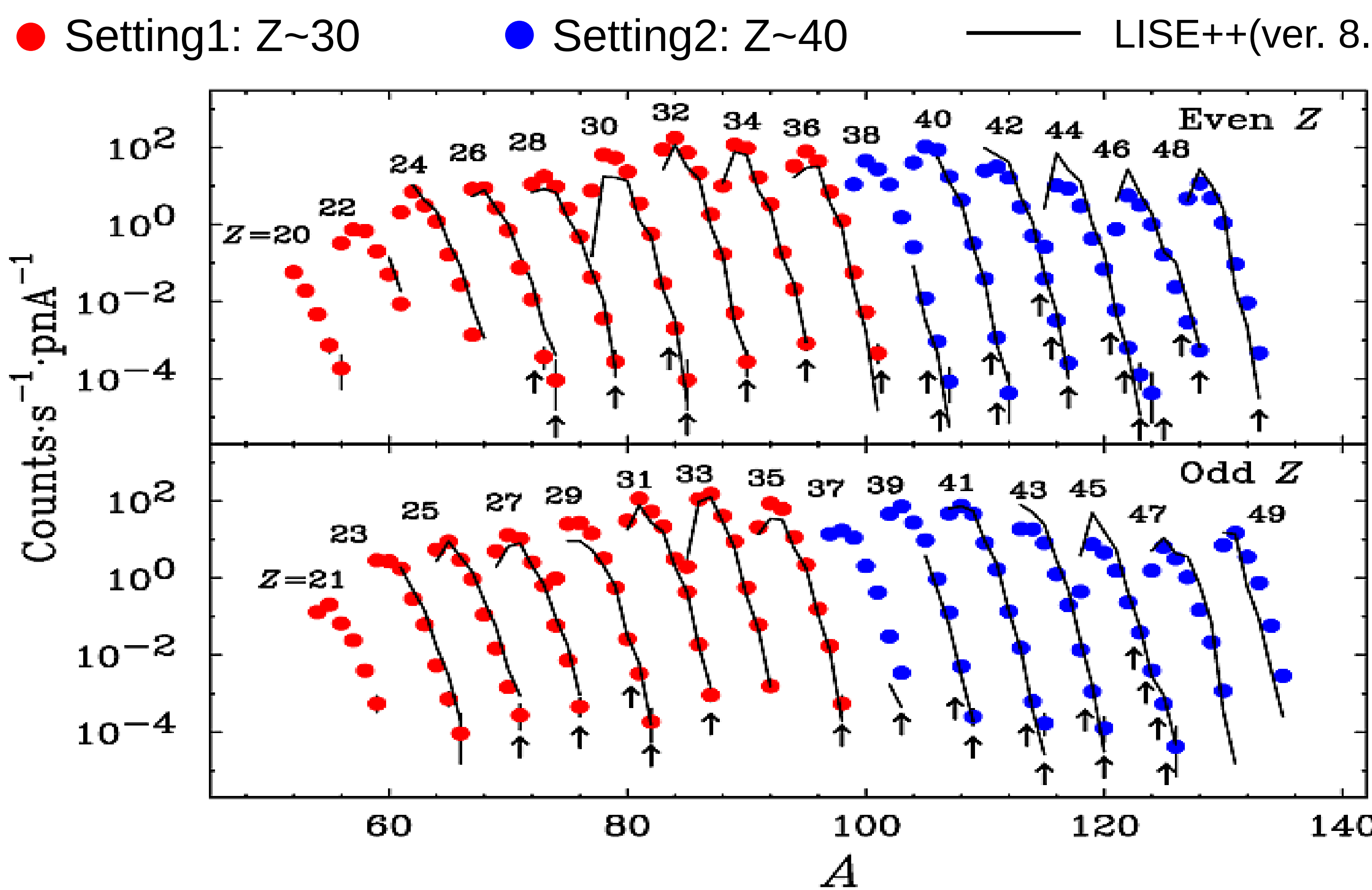
	4	5					
Target	Be 4.00 mm	Be 4.93 mm	W 0.7 mm	Be 4.93 mm		W 0.7 mm	
***Bρ* (Tm)**	7.306	6.950	6.950	6.950	7.300	6.950	7.300
Δp/p	−2%/+3%	−2%/+3%	−2%/+3%	±0.1%	±0.1%	±0.1%	±0.1%
Degrader	F1: 1.27 mm F5: 1.40 mm	F1: 1.27 mm F5: 1.40 mm	F1: 1.27 mm F5: 1.40 mm	None	None	None	None
F2 slit (mm)	−3 /+15	−4 /+15	−4/+15	±120	±120	±120	±120
F7 slit (mm)	−5 /+25	±15	±15	±120	±120	±120	±120

Yield measurements for in-flight fission of ^{238}U at 345 MeV/u

Setting	1	2	4	5	3
Region	Z ~ 30	Z ~ 40	Z ~ 60	Z ~ 65	Z ~ 50
Production mechanism	Abrasion fission				Coulomb fission + Abrasion fission
Target	Be 5.1 mm	Be 2.9 mm	Be 4.00 mm	Be 4.93 mm	Pb 0.95 mm + Al 0.3 mm
Bρ (Tm)	7.902	7.990	7.306	6.950	7.706
Δp/p	±3%	±3%	−2%/+3%	-2%/+3%	±3%
Degrader	F1: 1.29 mm	F1: 2.18 mm	F1: 1.27 mm F5: 1.40 mm	F1: 1.27 mm F5: 1.40 mm	F1: 2.56 mm F5: 1.8 mm
F2 slit (mm)	±13.5	±15.5	−3 / +15	±15	±15 mm
F7 slit (mm)			−5 / +25	±15	

Production rates of the fragments in setting-1 & 2 and comparison with LISE++ predictions by AF model

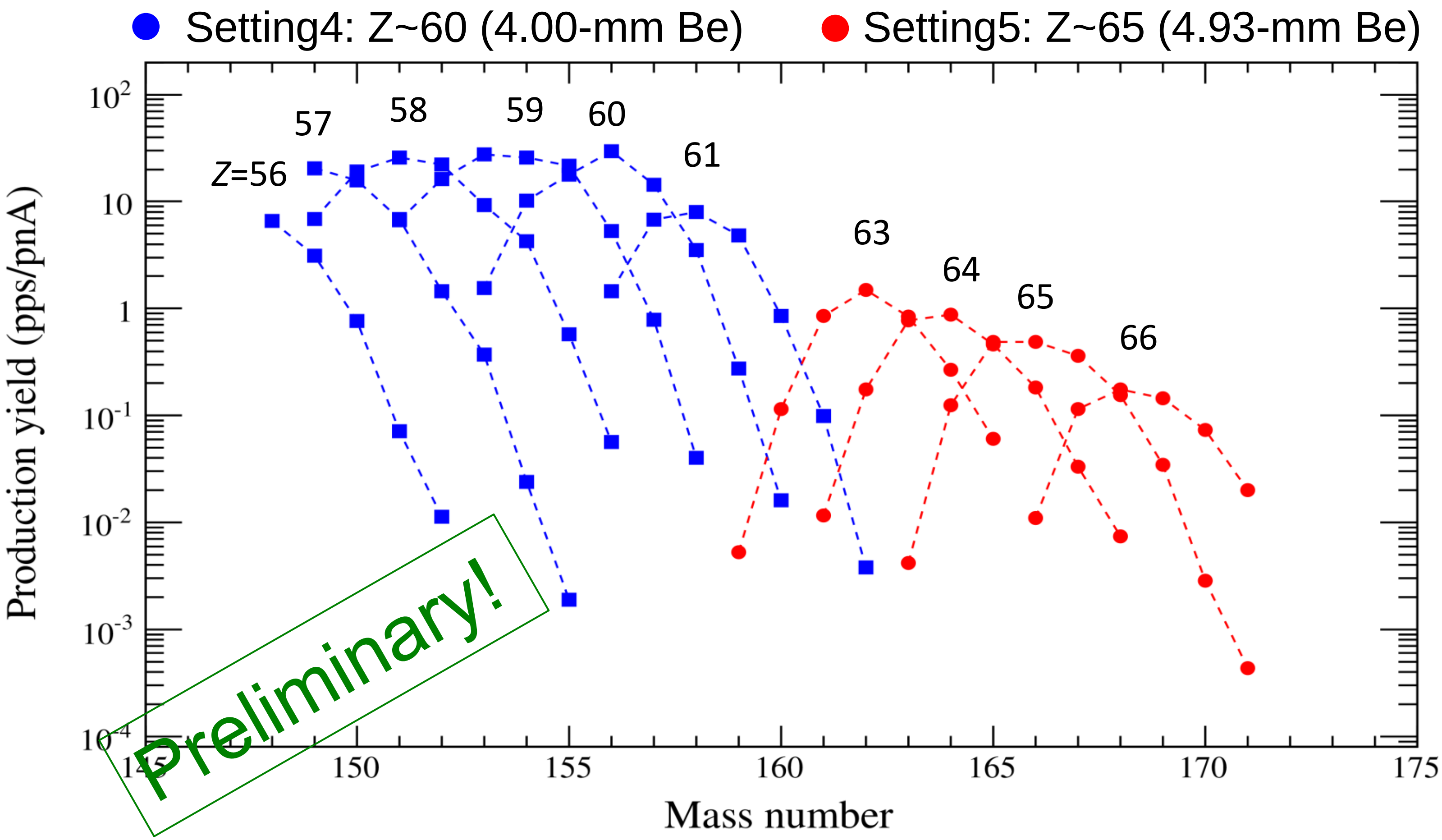
$^{238}U^{86+}$ 345MeV/u + Be   Abrasion fission



- Fairly good agreement with LISE++ calculation with Abrasion fission model around the region of Z = 25 ~ 50.

Production rates of the fragments in setting-4 & 5

$^{238}U^{86+}$ 345MeV/u + Be   Abrasion fission + Projectile fragmentation



- Yields are measured for the region of *Z* ~ 60.

Kinematics of fragments: angular and momentum distributions for ^{168}Gd (Z=64)

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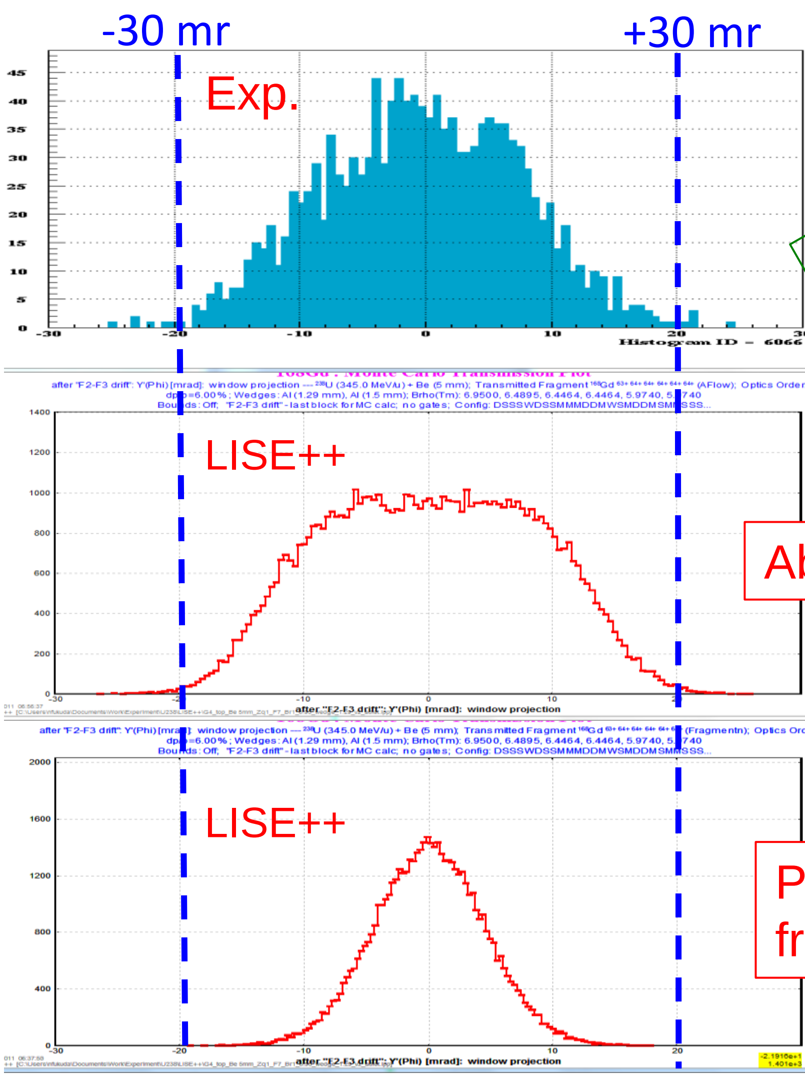
Y-angle(ϕ) at F3

Wide spreads: consistent with fission!

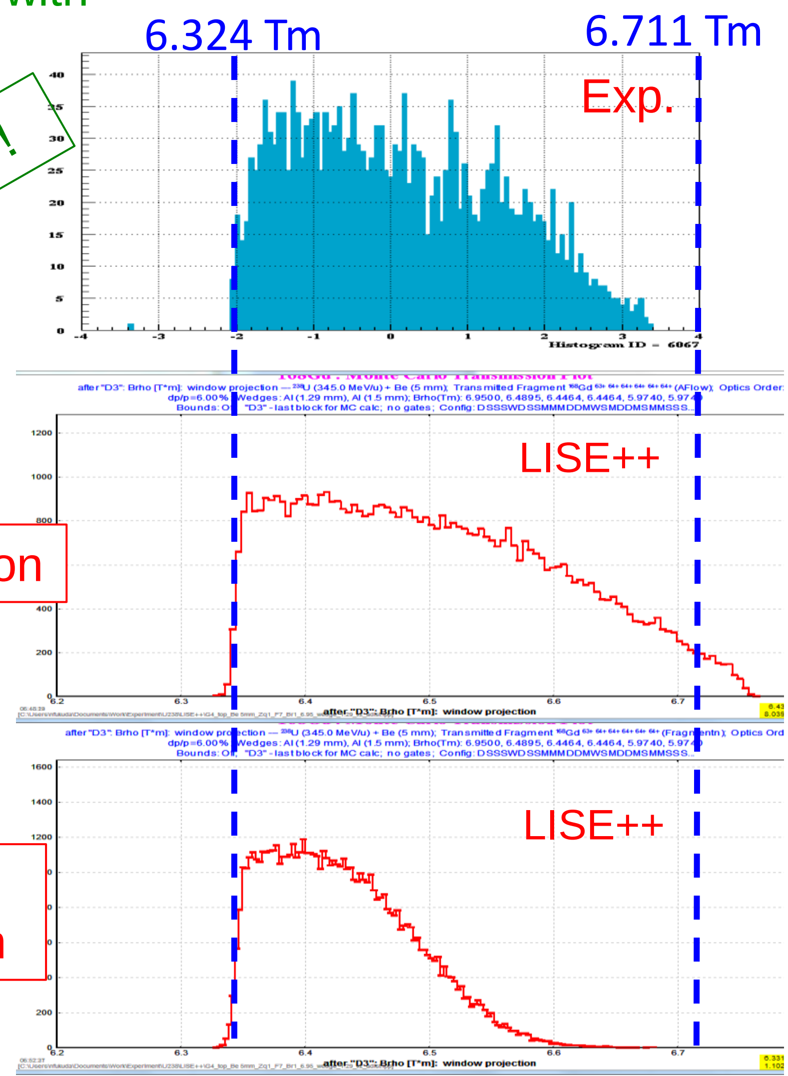
$B\rho$ distribution



Preliminary!

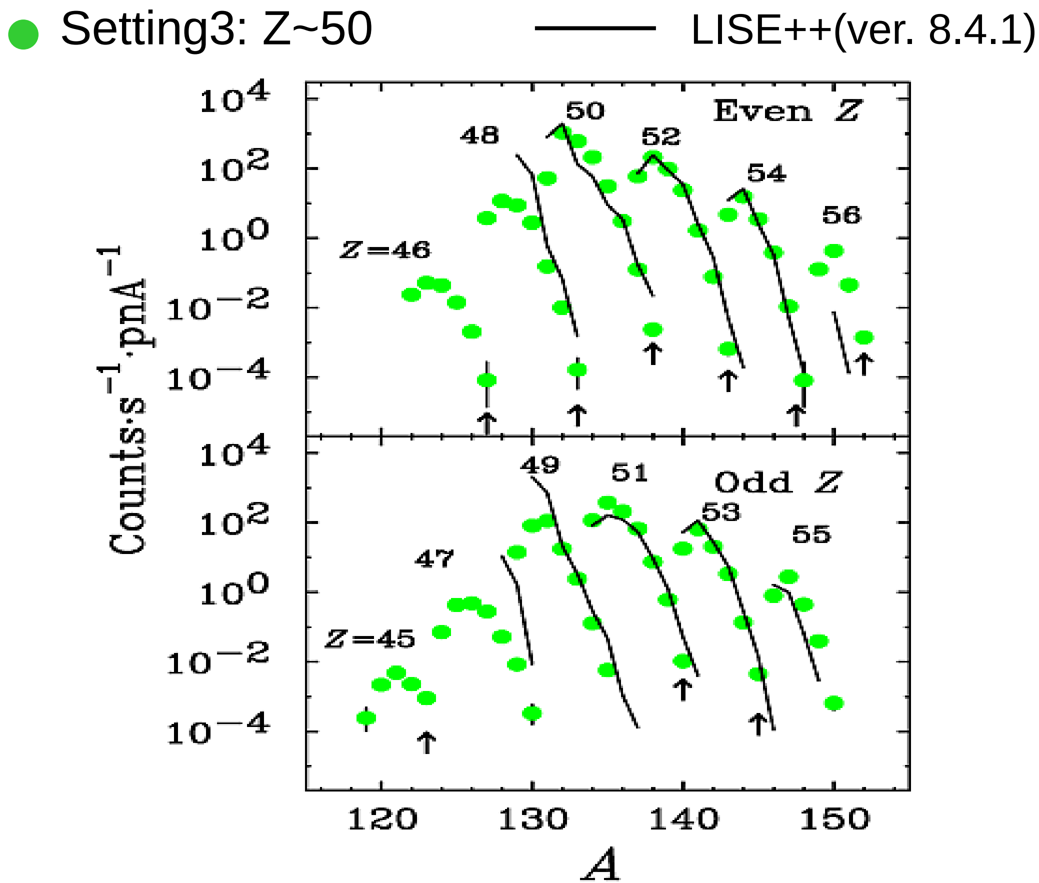
Abrasion-fission

Projectile fragmentation



Production rates of setting-3 fragments and comparison with LISE++ predictions by CF+AF model

$^{238}U^{86+}$ 345MeV/u + Pb   *Z* ~ 50   Coulomb fission + AF

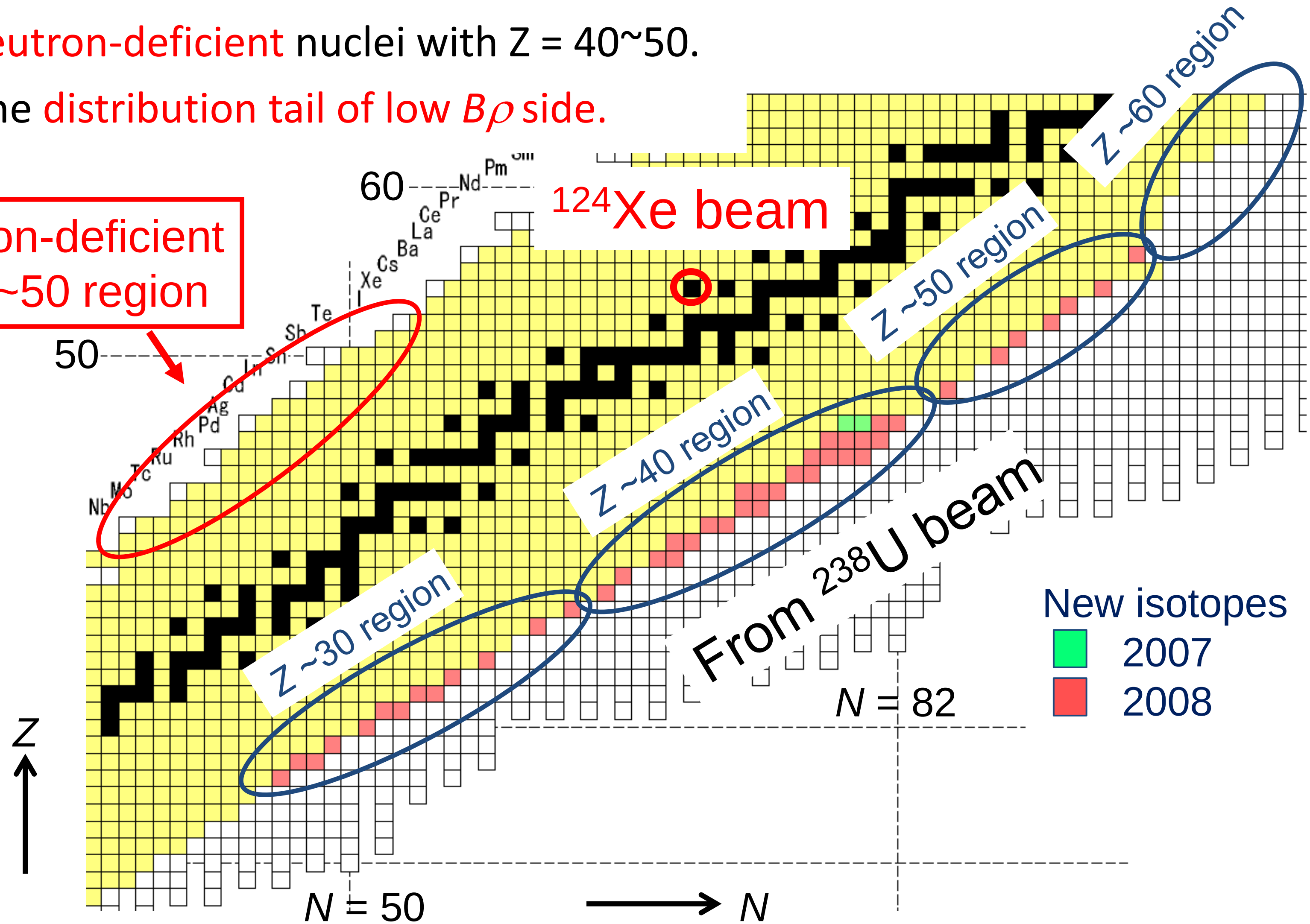


- Fairly good agreement with LISE++ calculation with "Coulomb fission + Abrasion fission" models around the region of *Z* ~ 50.

Neutron-deficient nuclei by projectile fragmentation from ^{124}Xe beam

Production of neutron-deficient RI beams using a $^{124}Xe^{52+}$ beam at 345 MeV/u

- The first Xe-beam experiment in RIBF in Nov. 2011.
- Produced neutron-deficient nuclei with Z = 40~50.
- Measured the distribution tail of low $B\rho$ side.

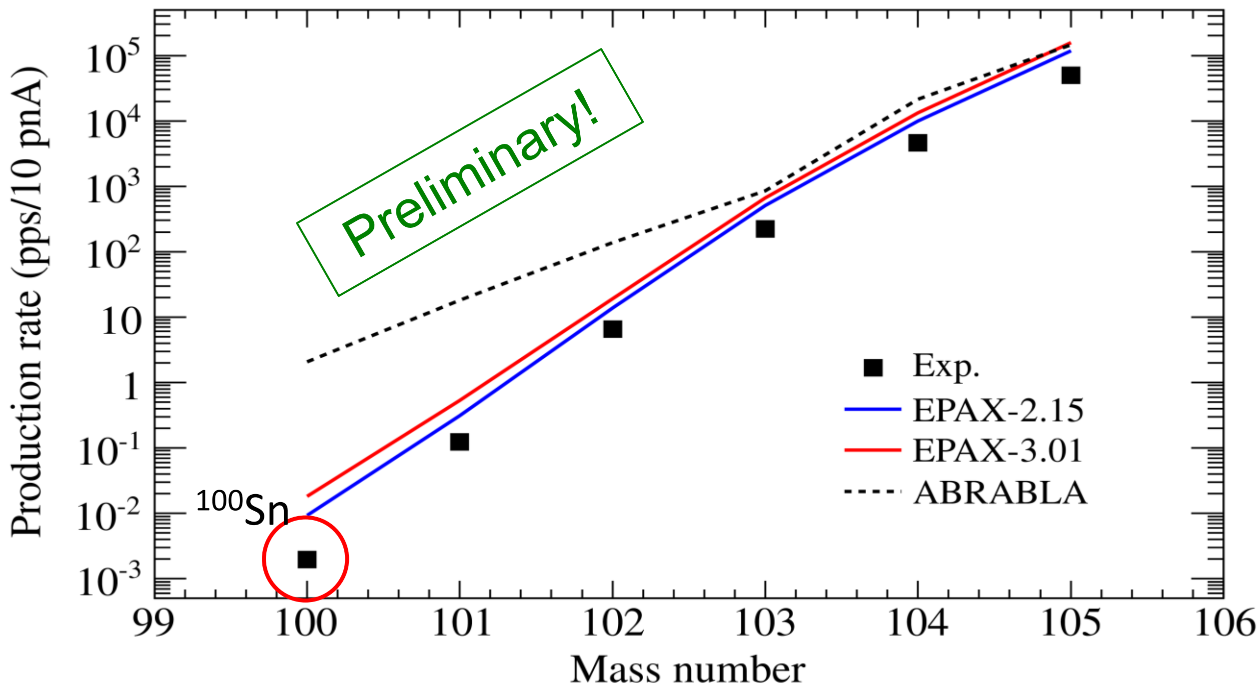


Production rate of neutron-deficient Sn isotopes from a ^{124}Xe beam at 345 MeV/u

^{124}Xe 345 MeV/u + Be 4 mm   Δp/p = +/-2%

Production rate [cps/10 pnA]

^{100}Sn	0.002 cps
^{101}Sn	0.12 cps
^{102}Sn	6.5 cps
^{103}Sn	220 cps
^{104}Sn	4600 cps
^{105}Sn	50000 cps

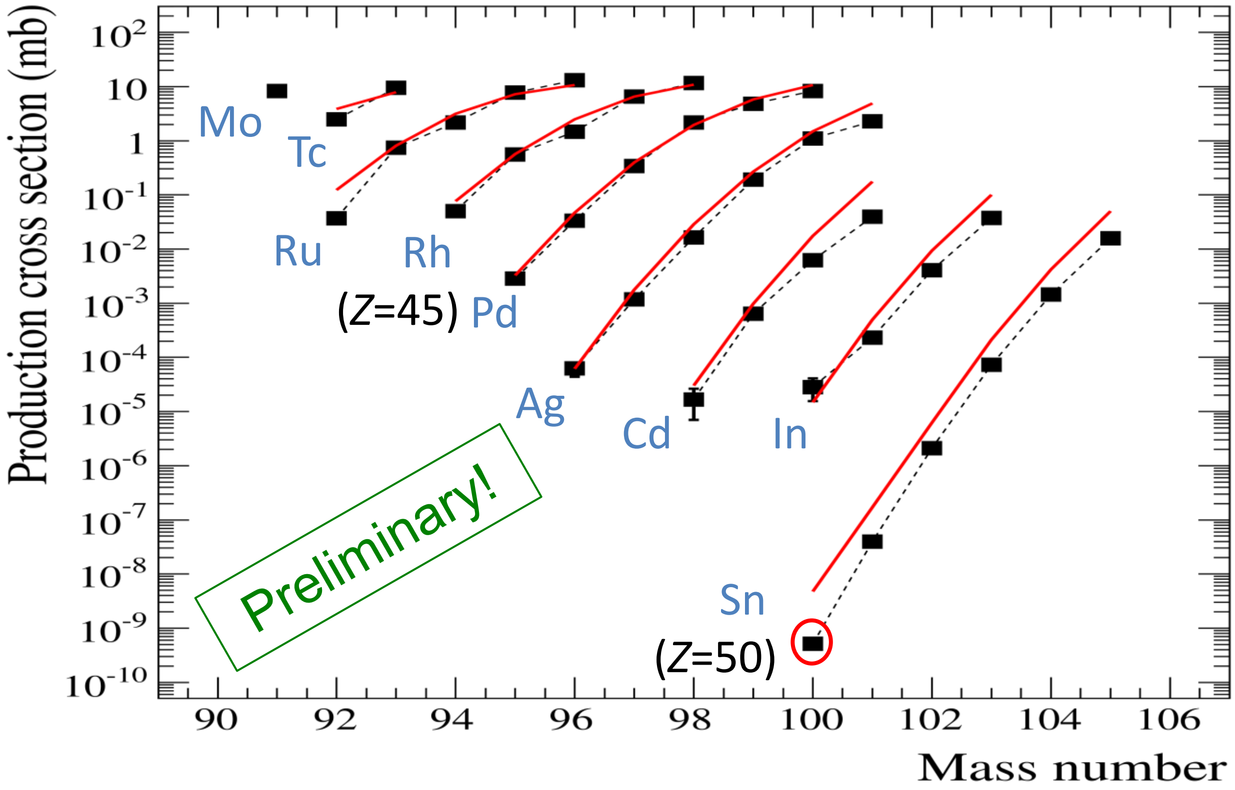


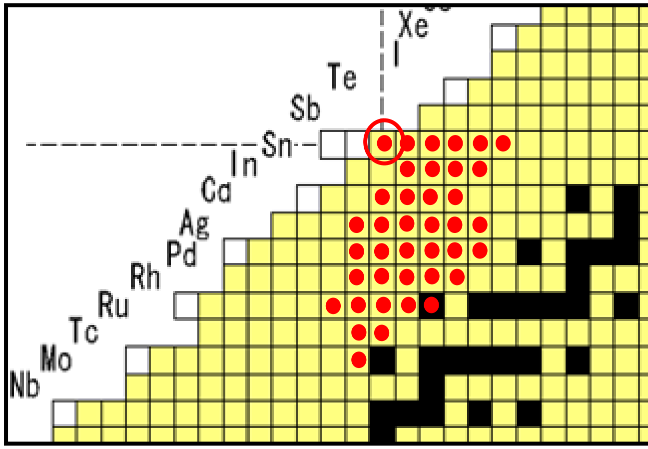
- Production rate of ^{100}Sn is ~ 1/10 of LISE++ calculation with EPAX 3.01

Recent ^{124}Xe-beam Intensity : ~30 pnA (Jun 2012)

cf) ^{100}Sn (optimized setting) … Yield : 0.0022(7) cps/30 pnA, Purity : 0.0016%

Measured production cross sections comparison with EPAX 3.01 (^{124}Xe 345 MeV/u + Be)

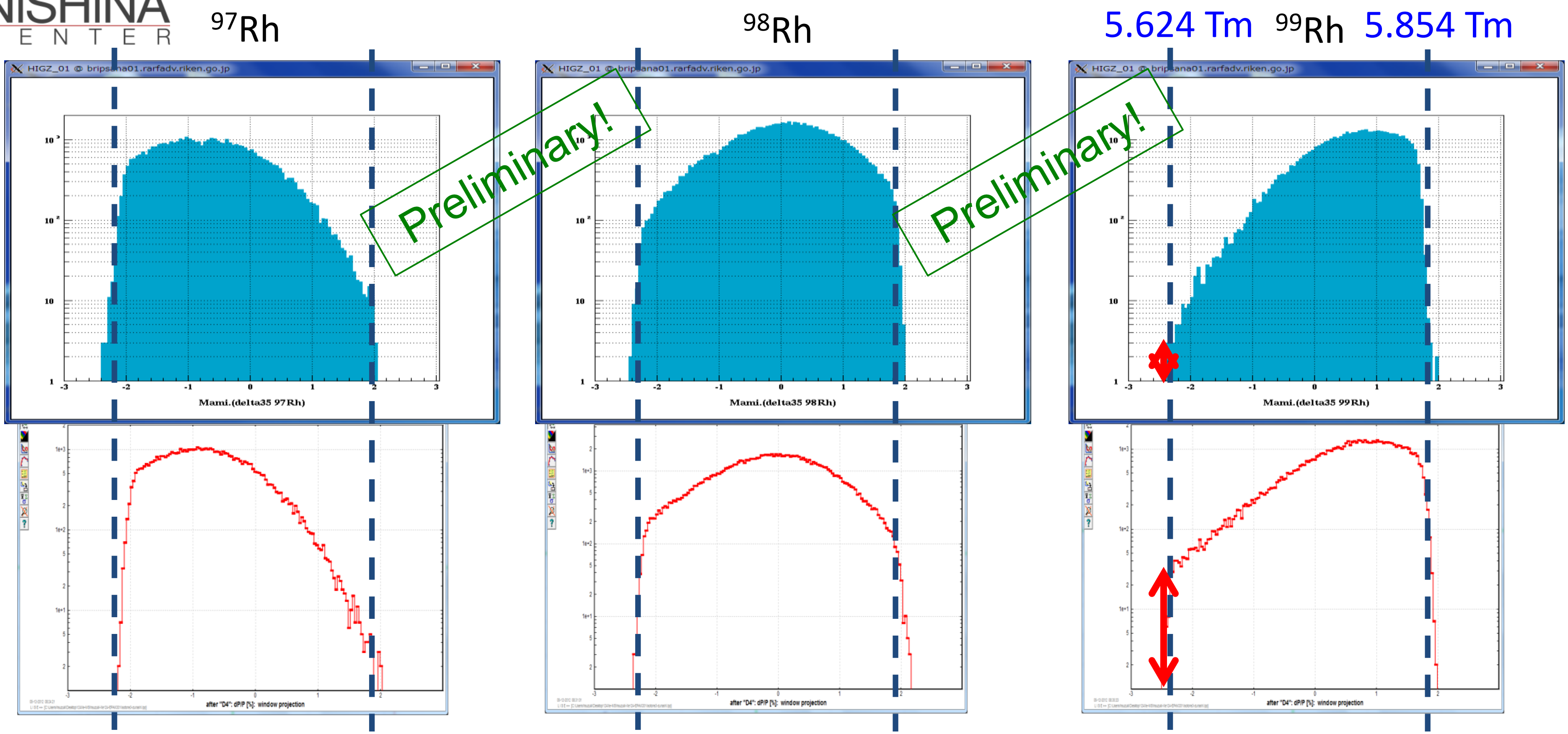




- Fairly good agreement between the experimental results and the LISE++ calculation with EPAX 3.01 at close to the stable region.
- However, in more neutron-deficient region, the experimental cross section is smaller than EPAX 3.01 (in the case of ^{100}Sn: 1/10).

Tail distribution of low $B\rho$ side

Bρ distribution



- ^{97}Rh: high $B\rho$ side is seen.
  → $B\rho$ distribution agrees with LISE++ calculation.
- ^{99}Rh: low $B\rho$ side is seen (low-$B\rho$-side tail).
  → the tails are smaller than the LISE++ calculation.

Summary

- Production cross sections (production rates, yields) of various RIs are measured using with BigRIPS separator at RIKEN RI Beam Factory.
- These cross section data are available at
  http://www.nishina.riken.jp/RIBF/BigRIPS/intensity.html
- Neutron-rich RIs are produced by fragmentation from ^{48}Ca beam at 345 MeV/u.
  - Fairly good agreement with EPAX2.15 parameterization in LISE++ calculation.
- Neutron-rich RIs are produced by In-flight fission from ^{238}U beam at 345 MeV/u.
  - Production yields are obtained with Be and Pb targets.
  - Fairly good agreement with LISE++ calculation using the Abrasion-fission model for Z~30,40 region.
  - We measured the yield of the nuclei around the region of Z~60.
  - Fairly good agreement with LISE++ calculation using the Coulomb-fission & Abrasion-fission model for Z~50 region.
- Neutron-deficient RIs are produced by fragmentation from ^{124}Xe beam at 345 MeV/u.
  - Fairly good agreement with EPAX 3.01 parameterization around stable region.
  - In more deficient region, the yield is less than the EPAX parameterization.
  - The low $B\rho$ tails falls faster than the LISE++ calculation.