Nuclear Reaction Data for Long-Lived Fission Products

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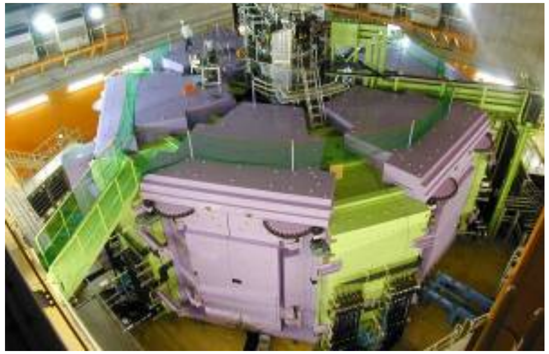
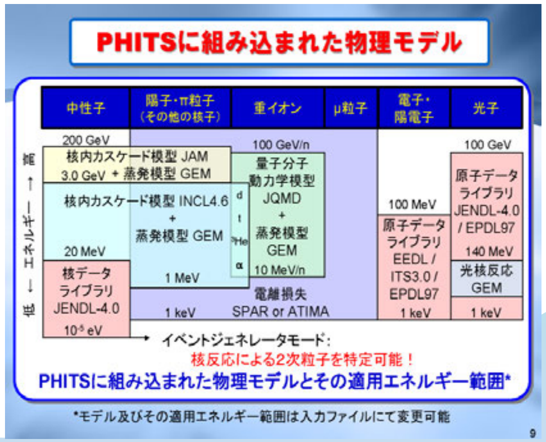
Background for new reaction data

- Nuclear reactions which transmute Long-Lived Fission Products (LLFP) to stable or short lived RI

- Recent world-best accelerators (such as RIBF, J-Parc) in Japan enable us to obtain good nuclear data by using new technology in nuclear science.
- Good simulation software and database of evaluated nuclear data in Japan

RI Beam Factory（RIBF）





Nuclear reactions for nuclear transmutation by Accelerator

- Nuclear reactions which transmute Long-Lived Fission Product (LLFP: ^{107}Pd, ^{93}Zr, ^{79}Se, ^{135}Cs, ^{126}Sn, (^{129}I, ^{99}Tc)) to stable or short lived RI

Candidates

- Neutron induced reaction
    - Neutron capture
    - Neutron knockout
- Negative muon capture reaction
- Fragmentation/Spallation reaction
- Proton/deuteron-induced fusion-like reaction

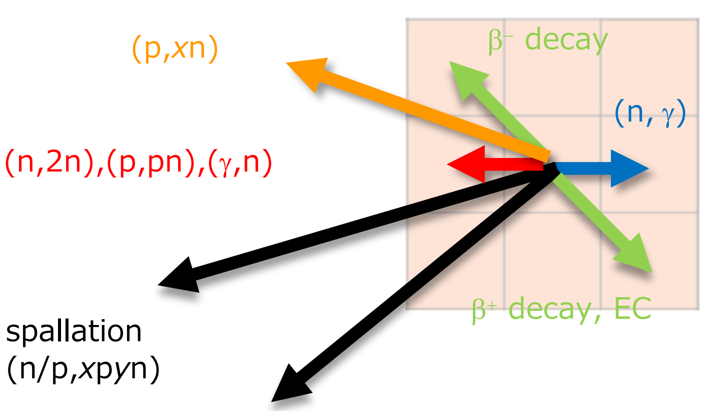
Nuclear reactions for nuclear transmutation

- Nuclear reactions which transmute Long-Lived Fission Product (LLFP) to stable or short lived RI

Candidates

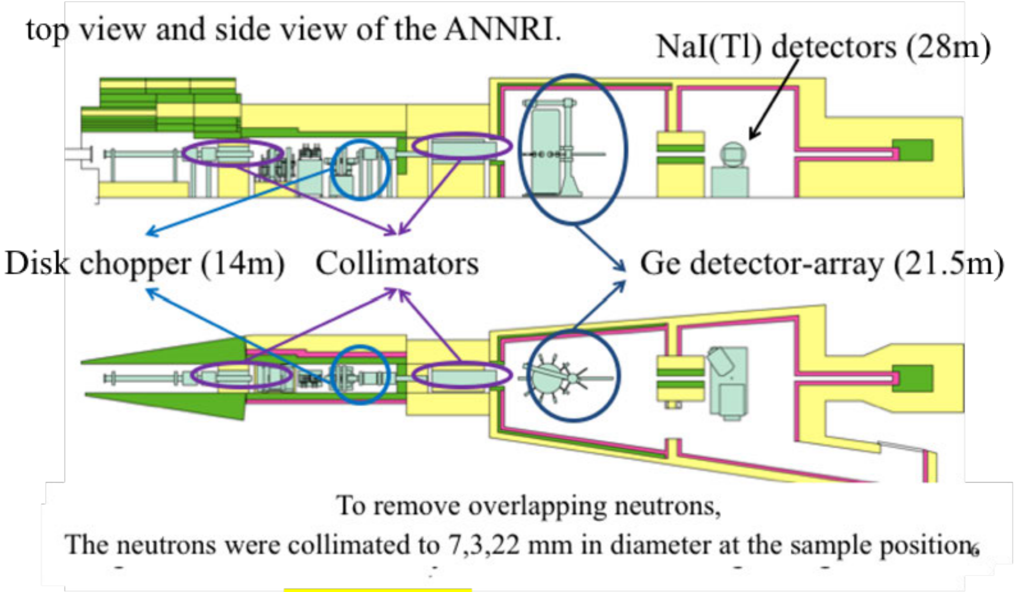
- Neutron induced reaction
  - Neutron capture (n,γ) $\quad {}^{A}Z \rightarrow {}^{A+1}Z$
  - Neutron knockout $(n,2n)$ $\quad {}^{A}Z \rightarrow {}^{A-1}Z$

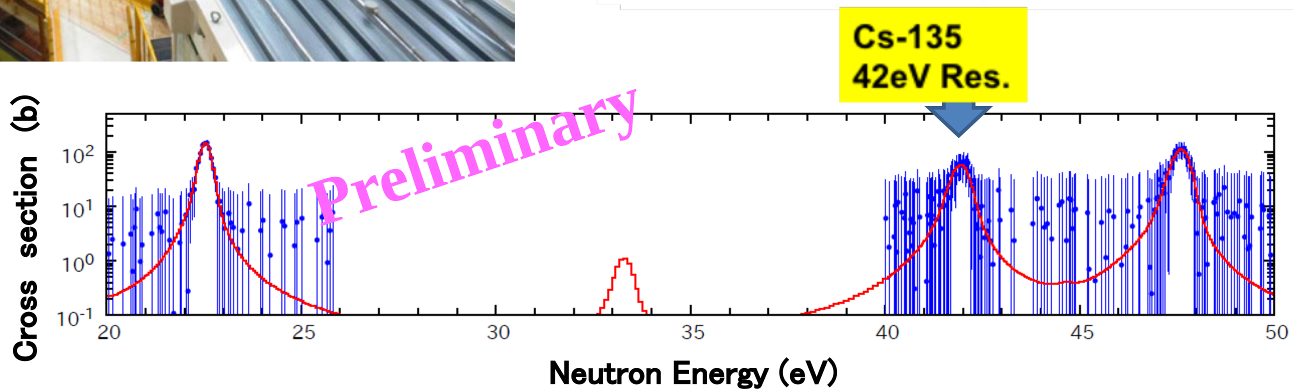
p/n induced reaction



Neutron capture cross section (Term./Res.)

ANNRI (Accurate Neutron-Nucleus Reaction measurement Instrument)
LLFP targets (^{135}Cs, (^{137}Cs))



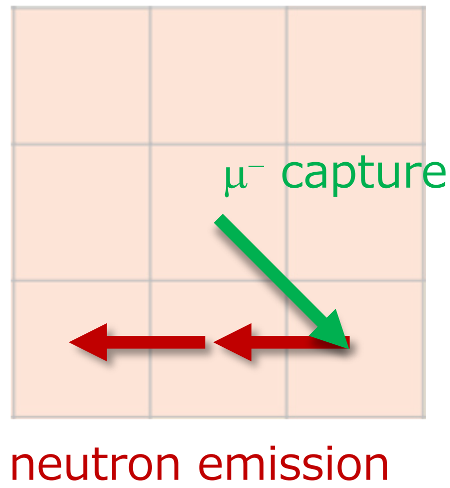


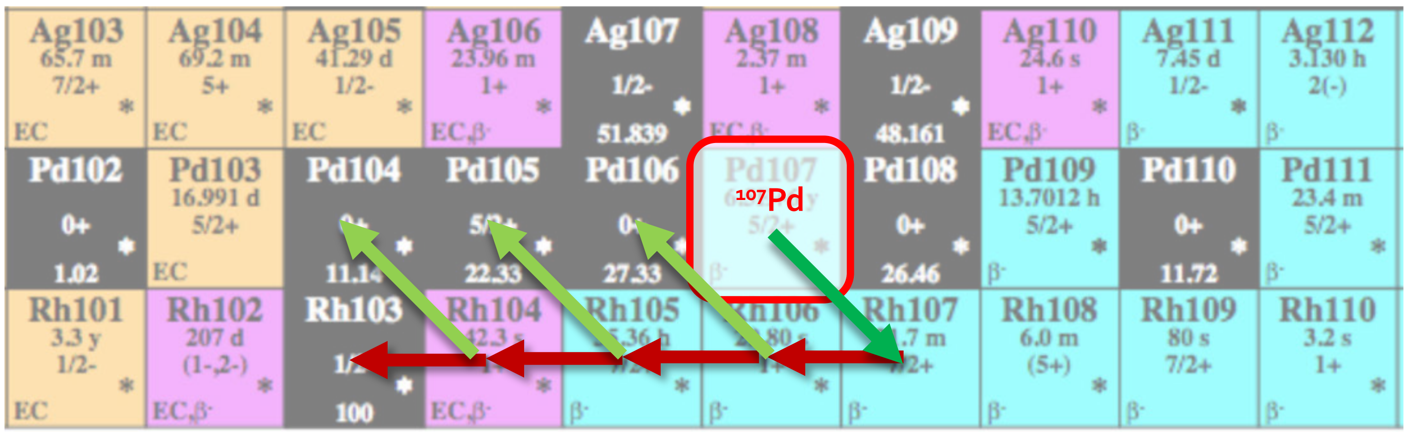
Nuclear reactions for nuclear transmutation

- Nuclear reactions which transmute Long-Lived Fission Product (LLFP) to stable or short lived RI

Candidates

- Negative muon capture reaction
  - Populate highly excited state
    followed by neutron(s) emission

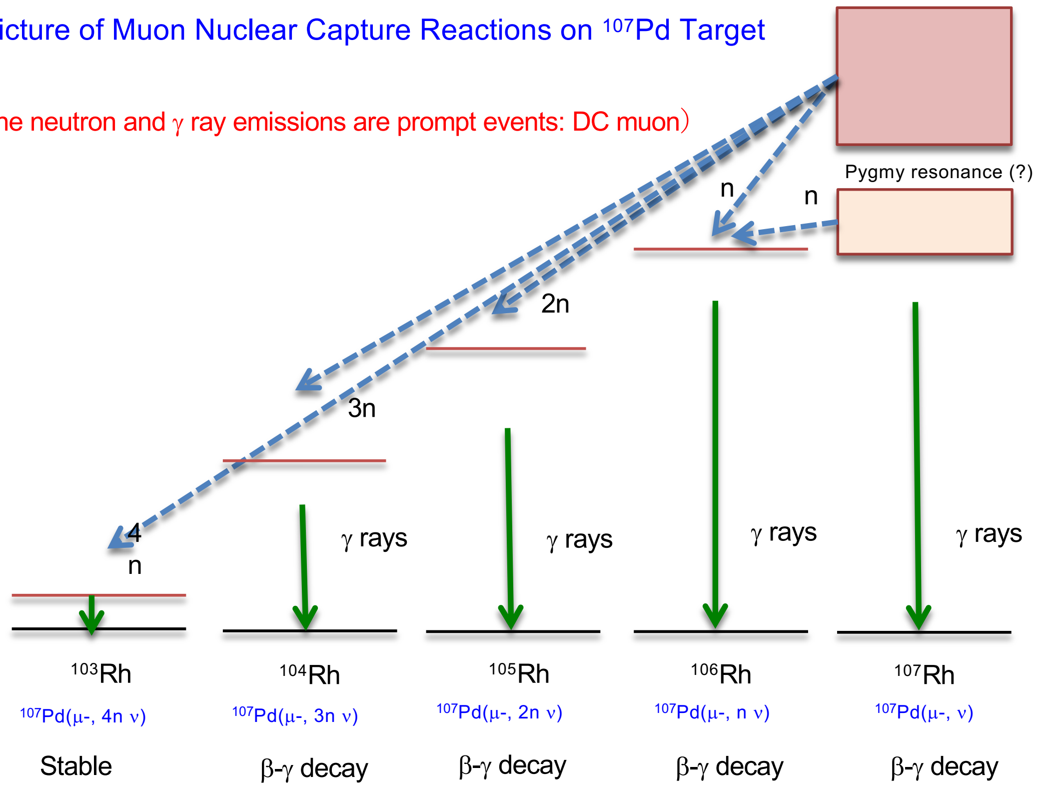




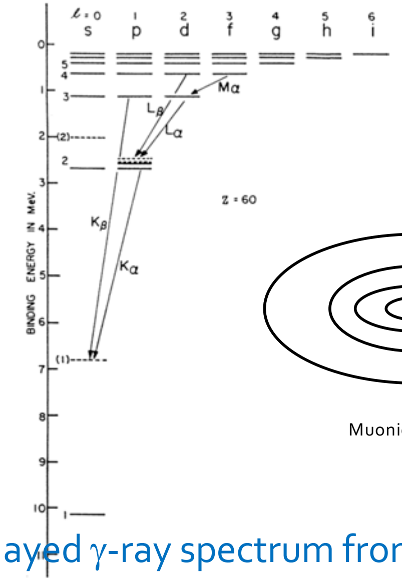
Muon capture (@RCNP, J-PARC, RAL)

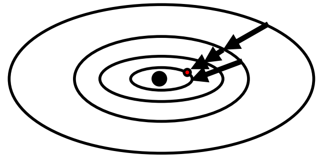
A picture of Muon Nuclear Capture Reactions on ^{107}Pd Target

（The neutron and γ ray emissions are prompt events: DC muon）



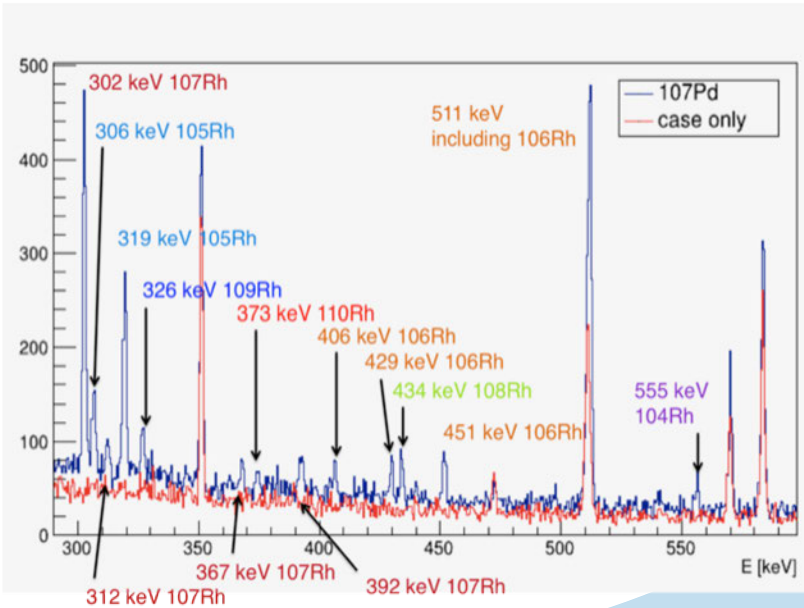
（The β^- decay and the associated γ ray emissions are delayed events. : pulsed muon.）





Muonic atom

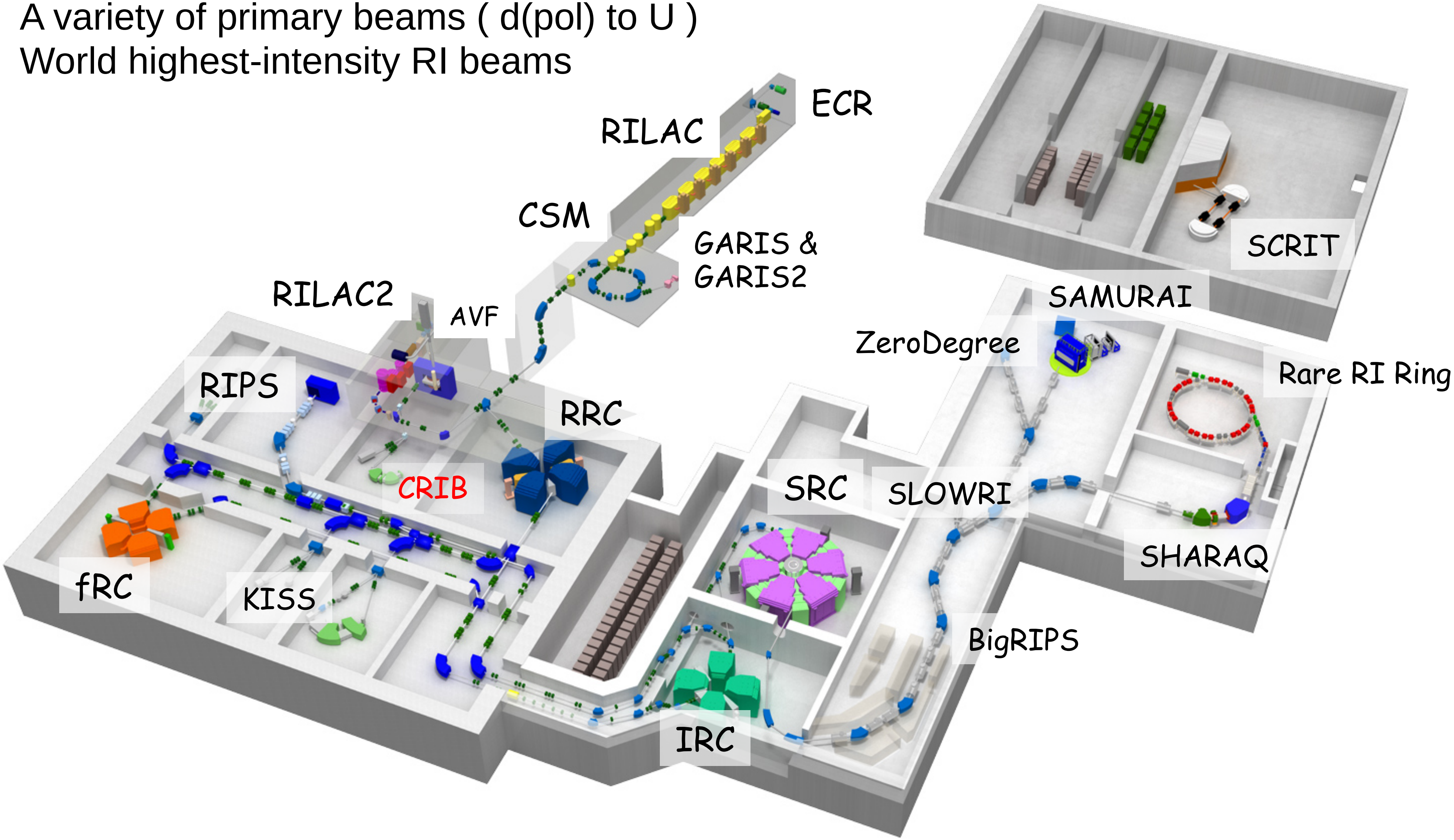
Delayed γ-ray spectrum from μ^--^{107}Pd



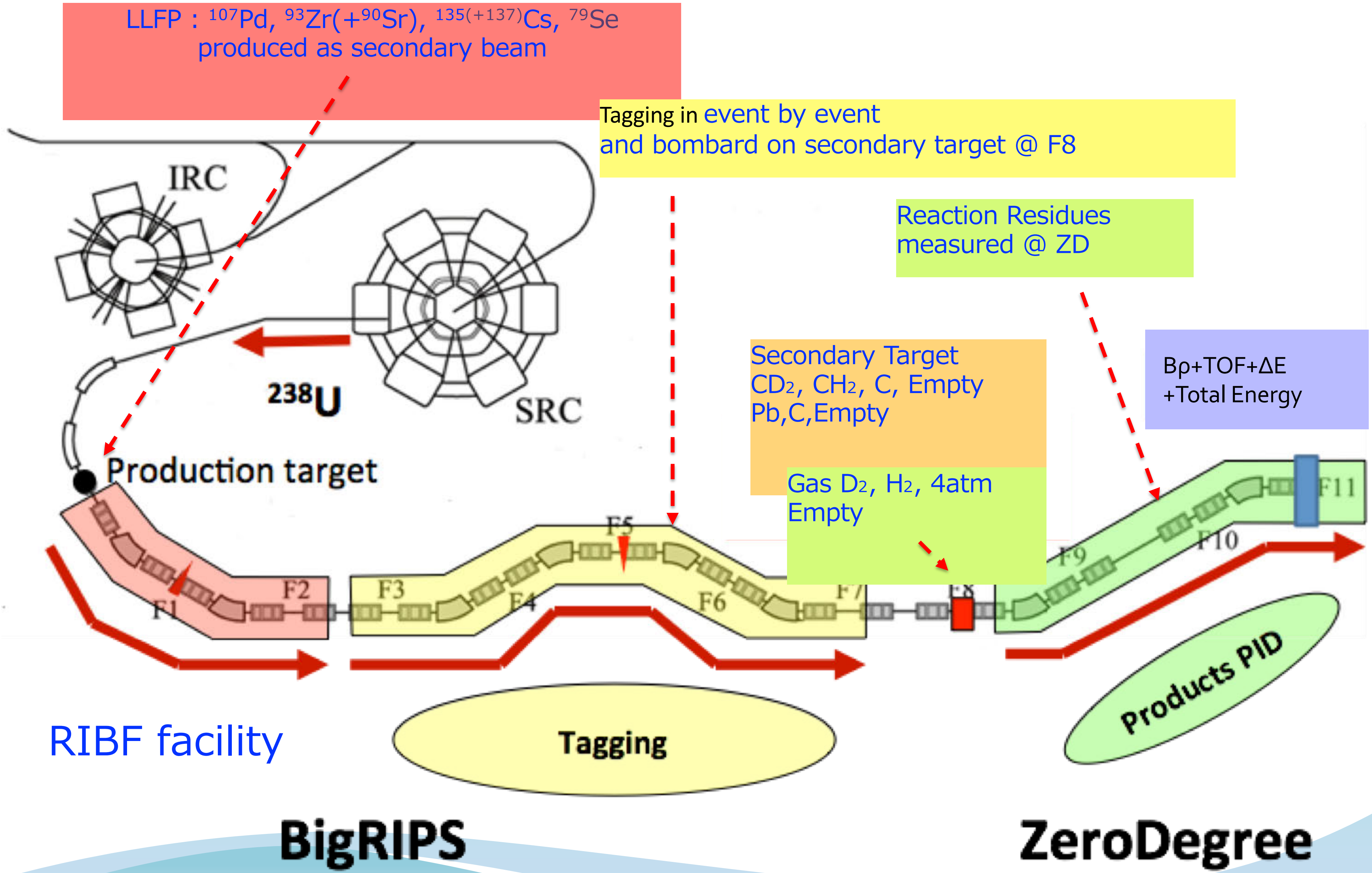
@J-PARC MUSE facility

RI Beam Factory at RIKEN

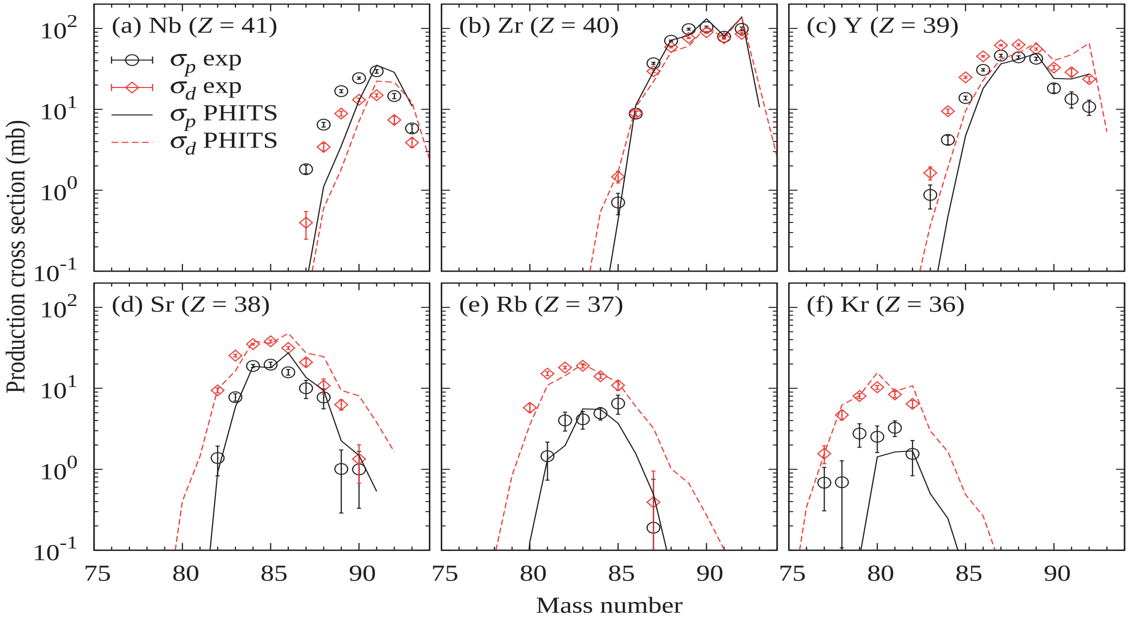
3 injectors + cascade of 4 cyclotrons
 ⇒ several to 345 MeV/nucleon
A variety of primary beams (d(pol) to U)
World highest-intensity RI beams



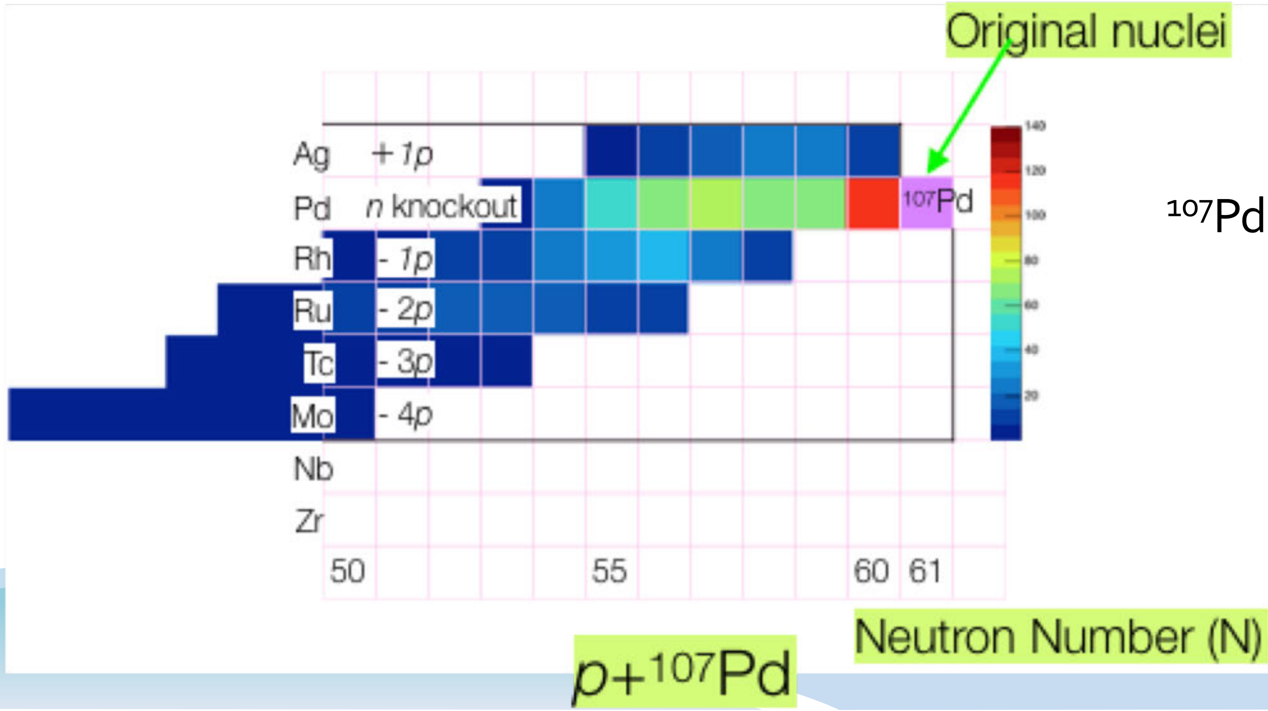
Experiment in Inverse Kinematics



Fragmentation/Spallation reaction



^{93}Zr@100MeV/u



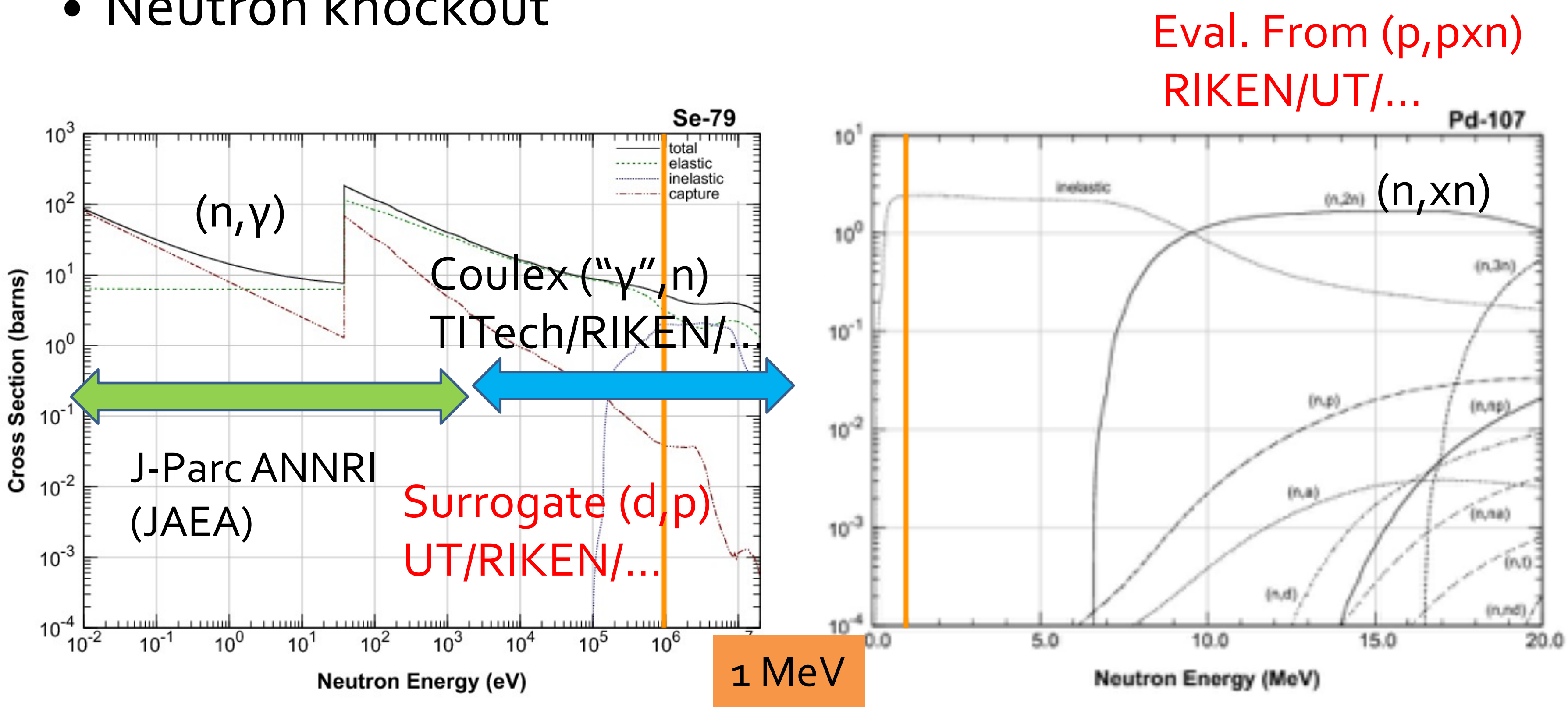
^{107}Pd@200MeV/u

Reaction data with LLFPs by RIBF-ImPACT

Experiments	Beam lines	Settings	Purpose	Energy [MeV/u]
Pre-ImPACT	BigRIPS+ZeroDegree	^{137}Cs	Fragmentation/ spallation	190
		^{90}Sr		
ImPACT in 2015 spring	BigRIPS+ZeroDegree	^{107}Pd	Fragmentation/ Spallation/Coulomb	100/200
		^{93}Zr/^{90}Sr		
		^{135}Cs		
ImPACT in 2015 autumn	BigRIPS+SAMURAI	^{93,94}Zr	Exclusive measurements	100/200
		^{79,80}Se		100/200
ImPACT in 2016 autumn	BigRIPS+ZeroDegree	^{107}Pd	Spallation	50
		^{93}Zr	Spallation	50
		^{126,127}Sn	Spallation/Coulomb	100/200
ImPACT in 2017 autumn	BigRIPS+OEDO/SHARAQ	^{107}Pd	p/d induced reaction	24/30
		^{93}Zr		30
		^{79,77}Se	(d,p) for (n,γ) surrogate	20

Neutron induced reaction

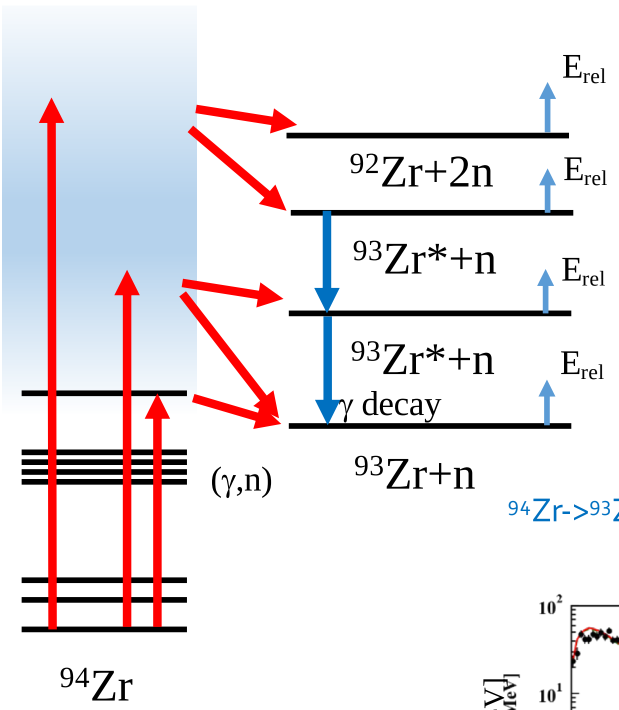
- Neutron capture
  - Direct measurements for thermal to resonance region
  - Surrogate reactions (d,p), ("γ",n) for higher energy
- Neutron knockout



Evaluated Data from JENDL4

Coulomb dissociation [("γ",n) reaction]

(Beam of fission fragments) + (Pb targets)

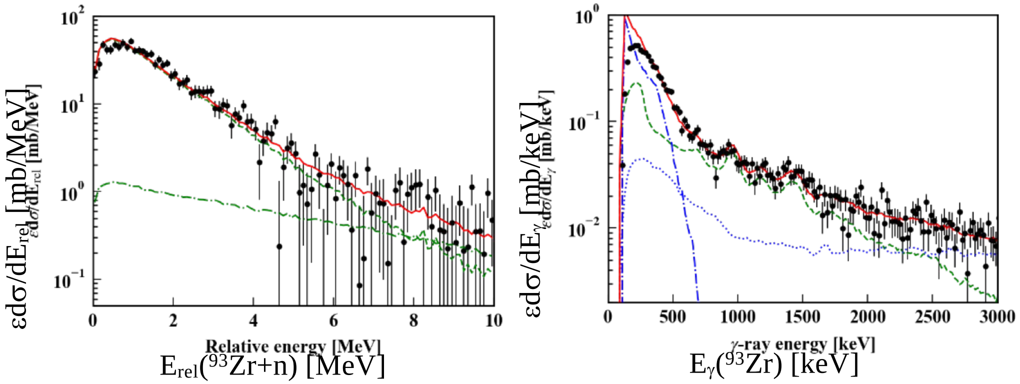


Coulex cross sections

Nucleus	present	systematics	Berman	Cb-TDHFB	HFB+QRPA
^{94}Zr	403 ± 26 ± 31	388 ± 1	317 ± 1	380	462
^{93}Zr	374 ± 29 ± 30	424 ± 1	-	402	475

^{94}Zr->^{93}Zr+n relative energy spectrum

Fitting results with the response functions

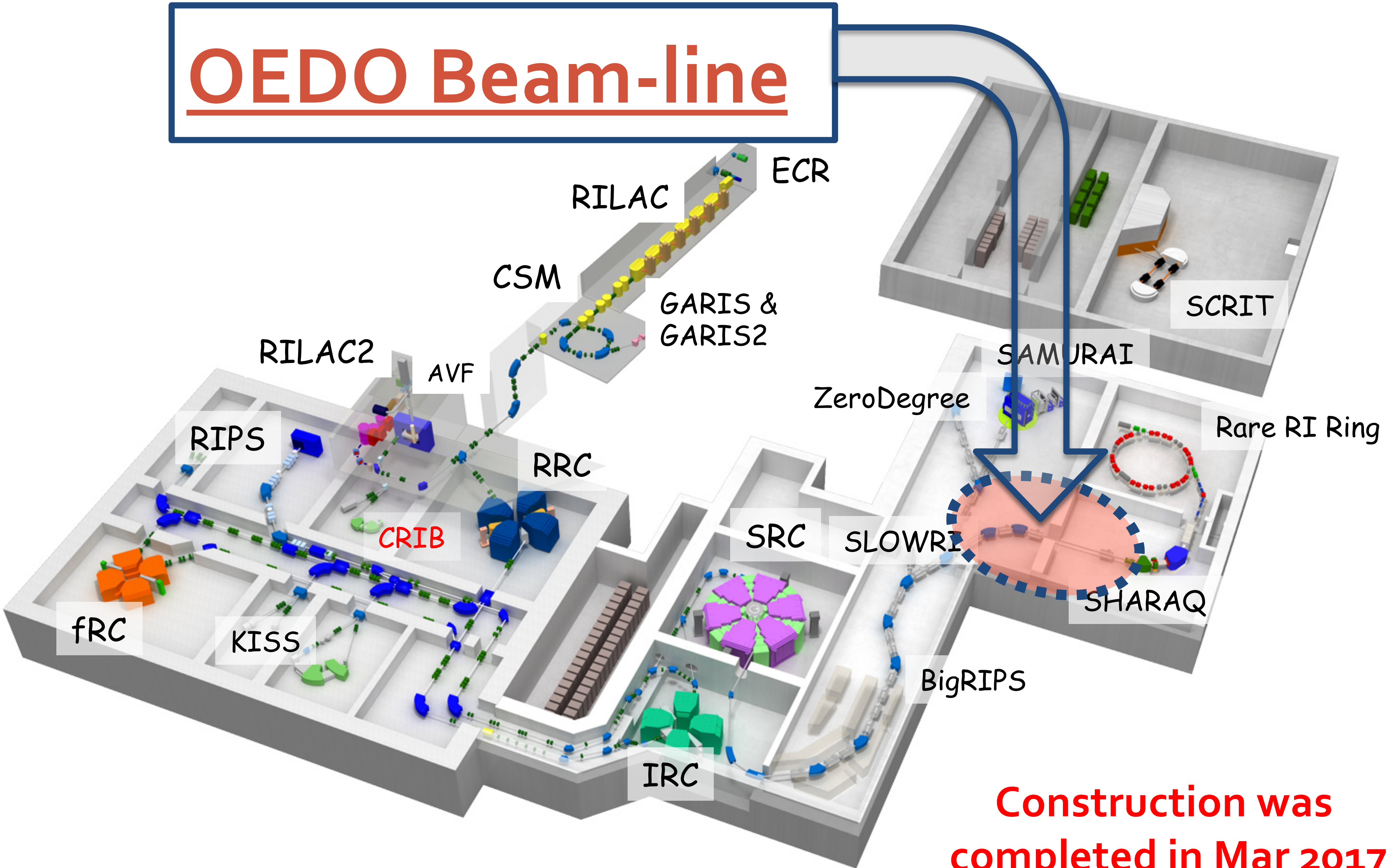


Fitting relative energy spectrum assuming response function using TALYS code

Level density: Back-shifted Fermi Gas model

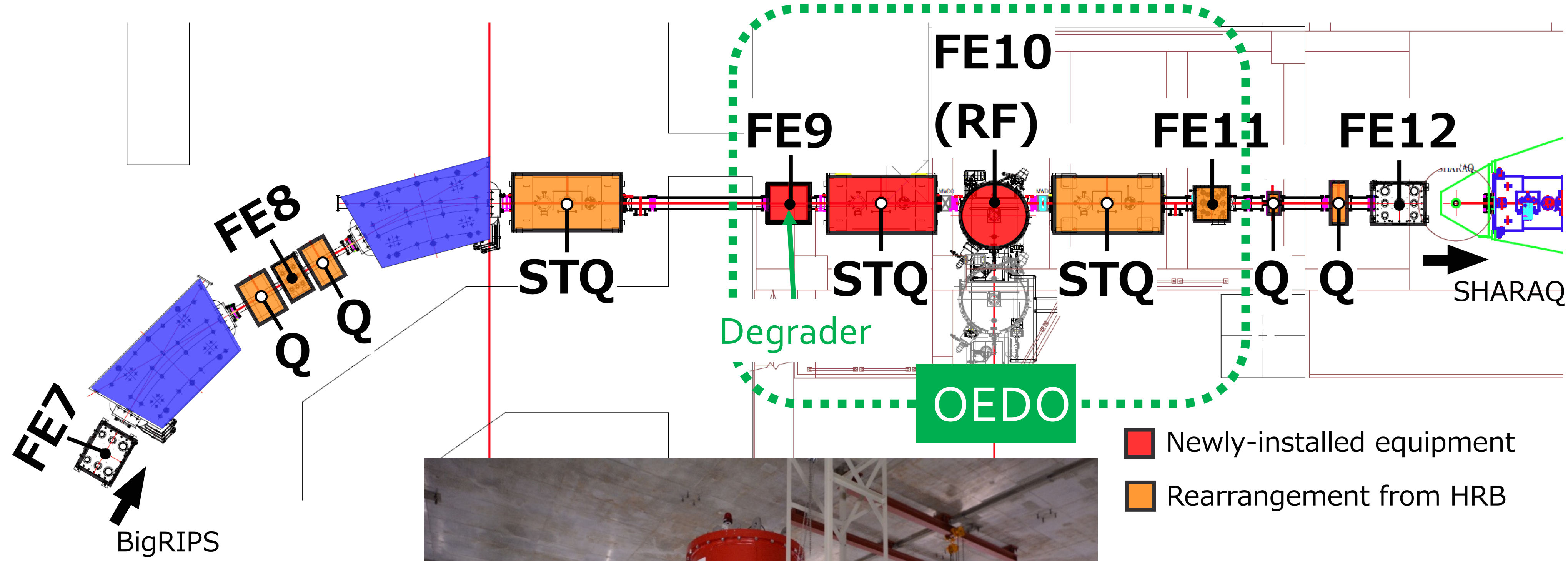
σ_γ: previous result by Berman

Low-energy beam below 50 MeV/u



Construction was completed in Mar 2017

OEDO Beamline



OEDO RFD

f_{RF} = 18.25 MHz
V_{max} = 400 kV
Gap(H) = 200 mm
L (Z) = 1200 mm
W(V) = 400 mm

Installed in Mar. 2017.

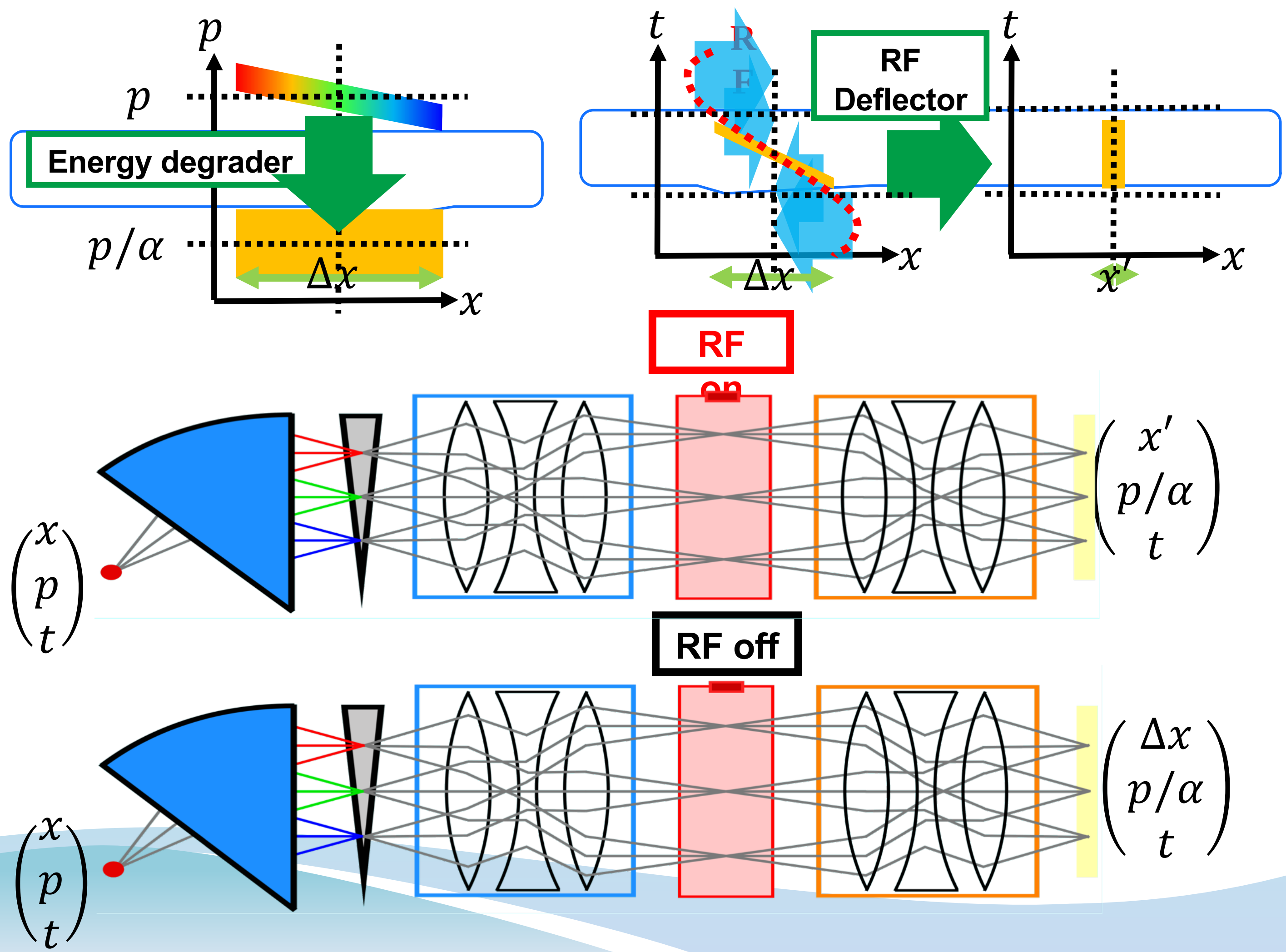
STQ

Bore Radius: 120 mm
Max. gradient: 14.1 T/m
Combination:
500- 800 -500 mm
Total length: 2700 mm

Low-energy nuclear reaction data for LLFP

- Surrogate reactions (d,p)
- Evaluation of (n,xn) from proton/deuteron induced knockout
- Proton/deuteron-induced fusion-like reaction

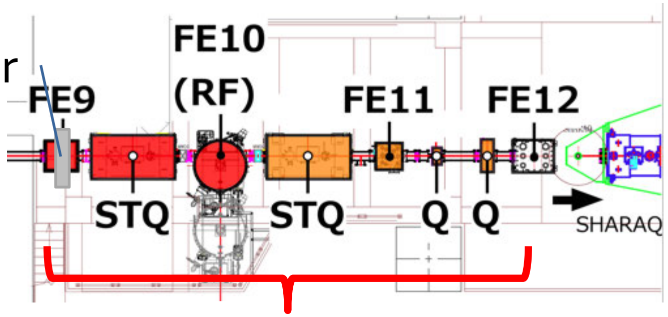
- New energy-degrading system at RIBF



Energy compaction by mono-energetic degrader

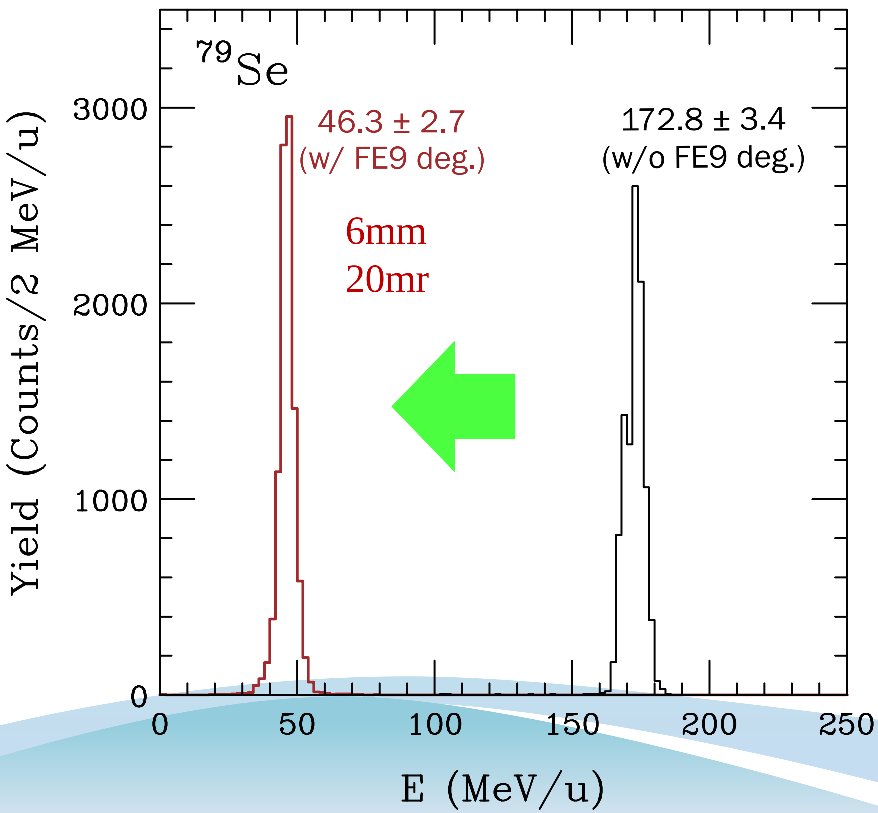
Degrader

^{107}Pd, ^{79}Se
(BigRIPS)

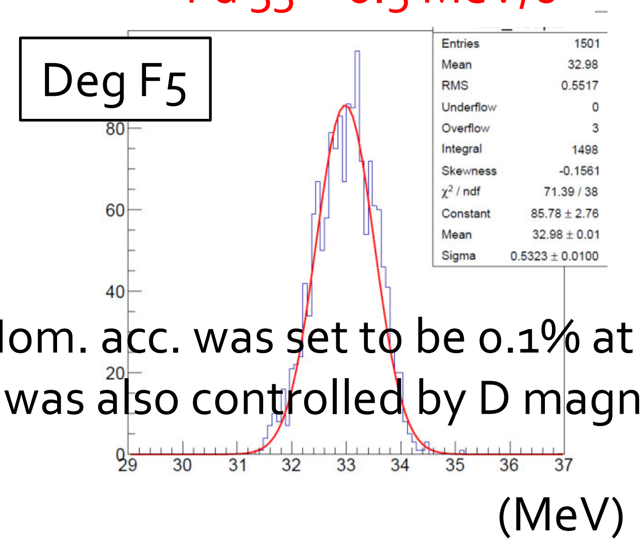


^{107}Pd, ^{79}Se
(SHARAQ)

Energy measurement from TOF

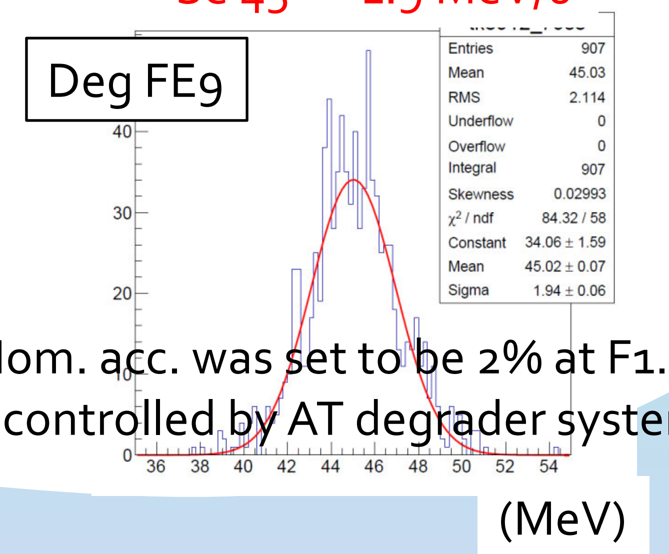


^{107}Pd 33 ± 0.5 MeV/u



Mom. acc. was set to be 0.1% at F1.
E was also controlled by D magnets.

^{79}Se 45 ± 1.9 MeV/u



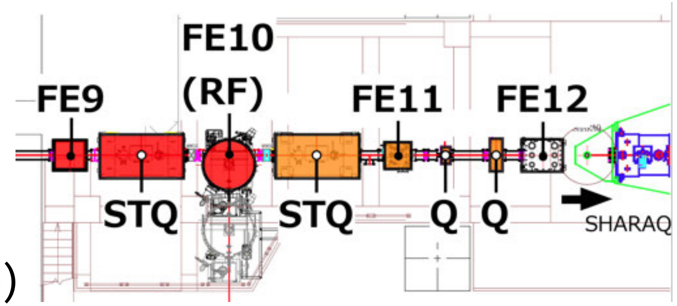
Mom. acc. was set to be 2% at F1.
E controlled by AT degrader system.

Beam focusing

^{79}Se at 170MeV/u

^{107}Pd at 170MeV/u

(BigRIPS production)



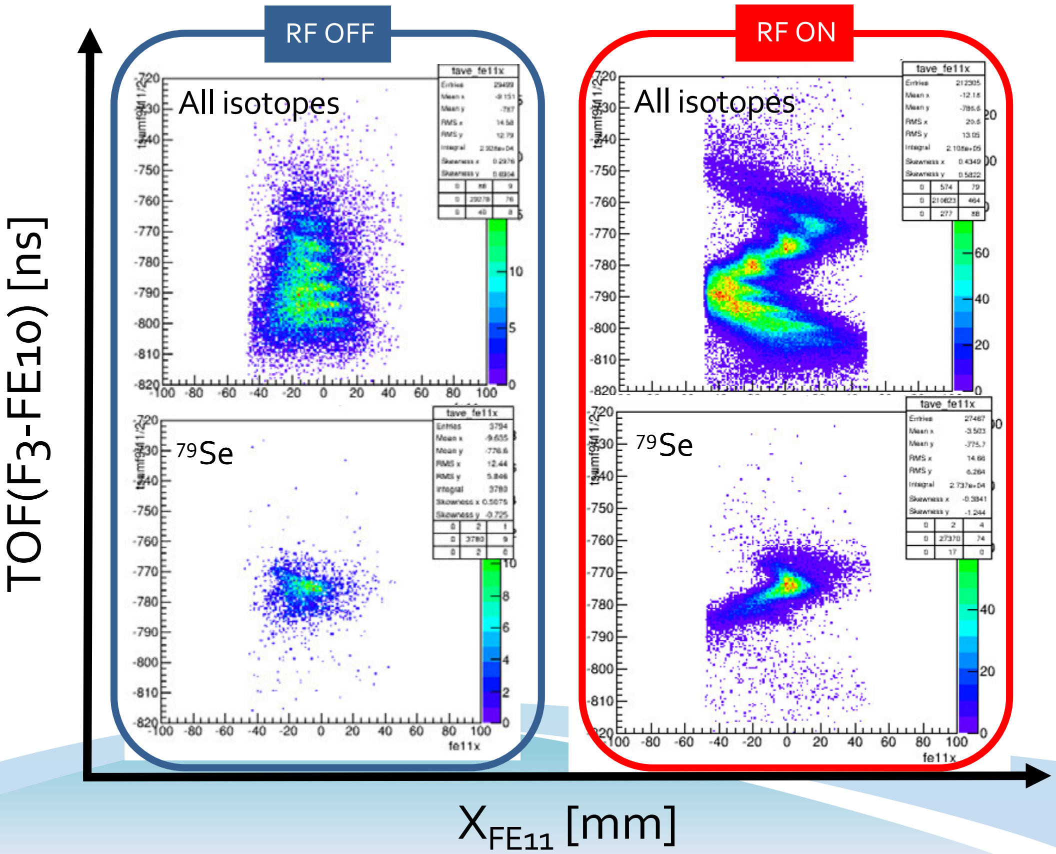
RF HV: 250kV
Phase: 80 deg.

^{79}Se at 45MeV/u

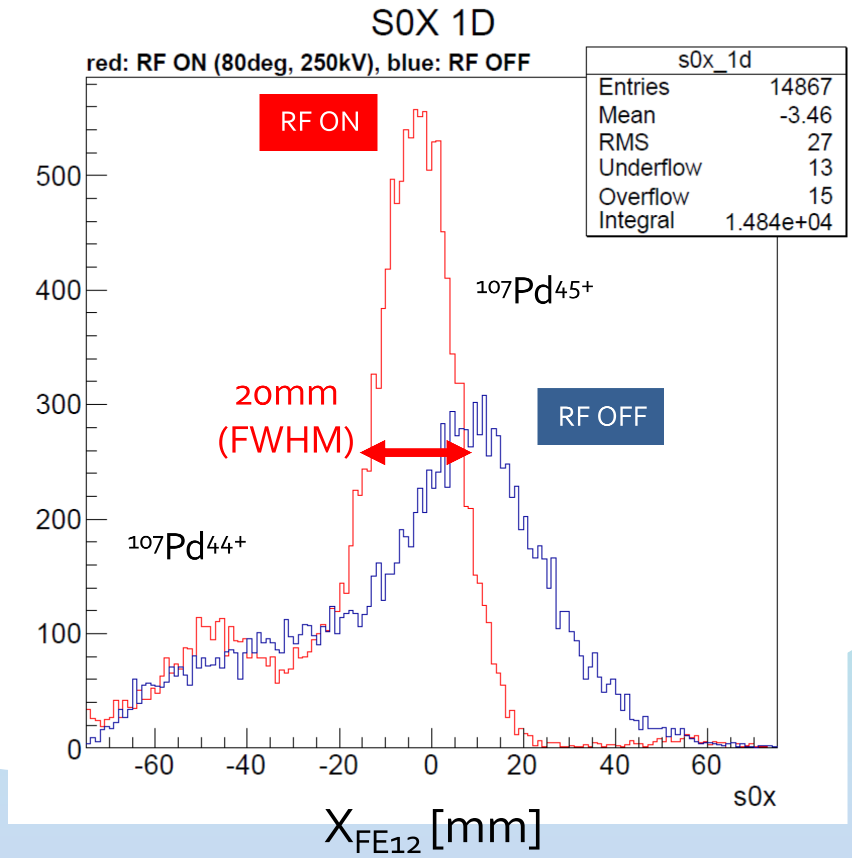
^{107}Pd at 33MeV/u

(FE12)

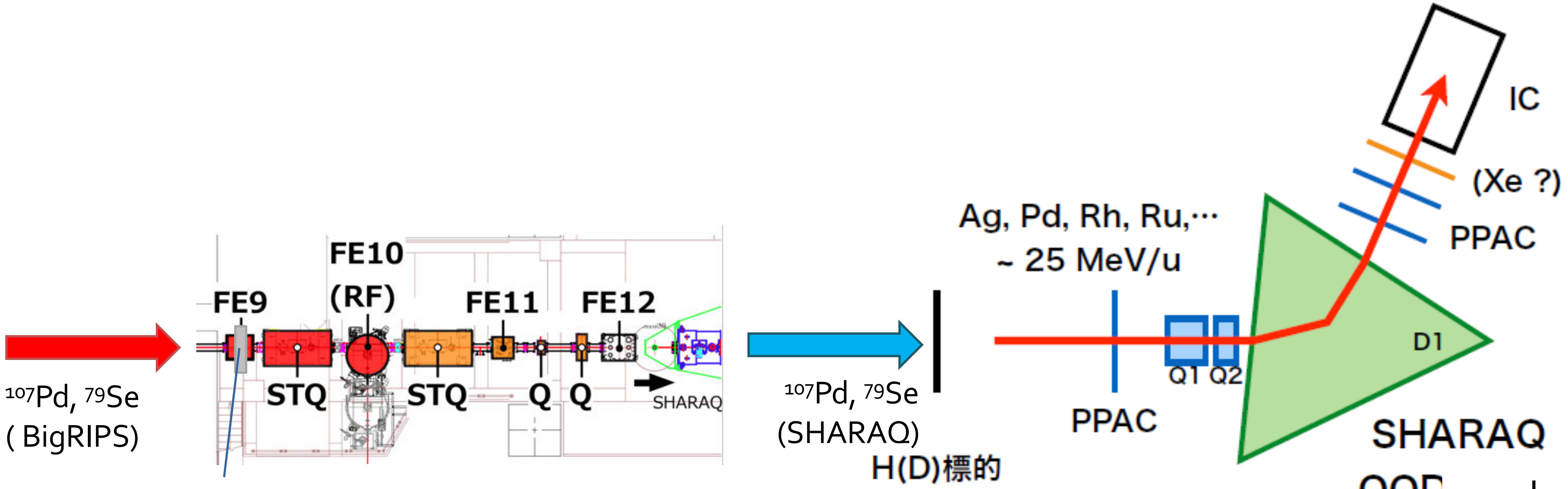
Effects of RF Deflector



Focusing (FE12)



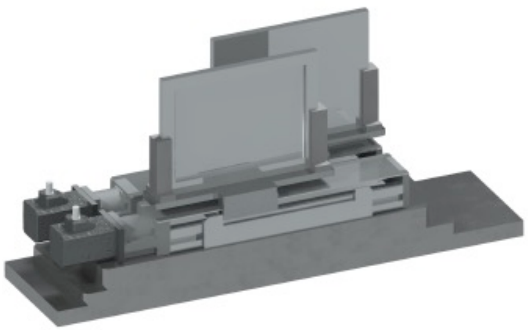
Setup of experiments at low energy

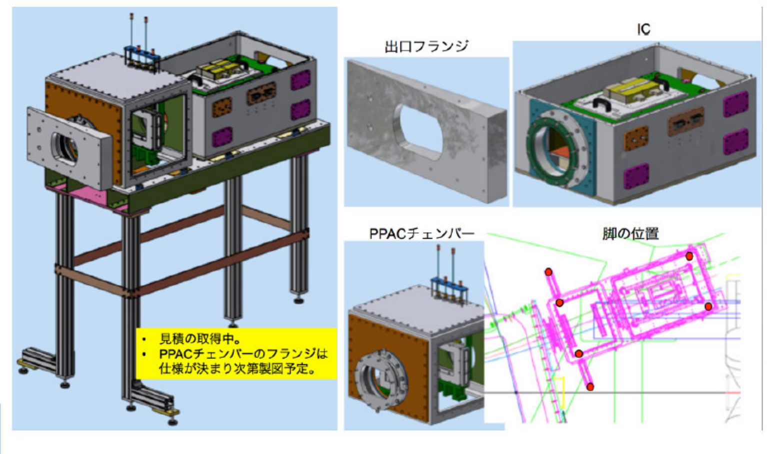


Degrader

~10 mg/cm2

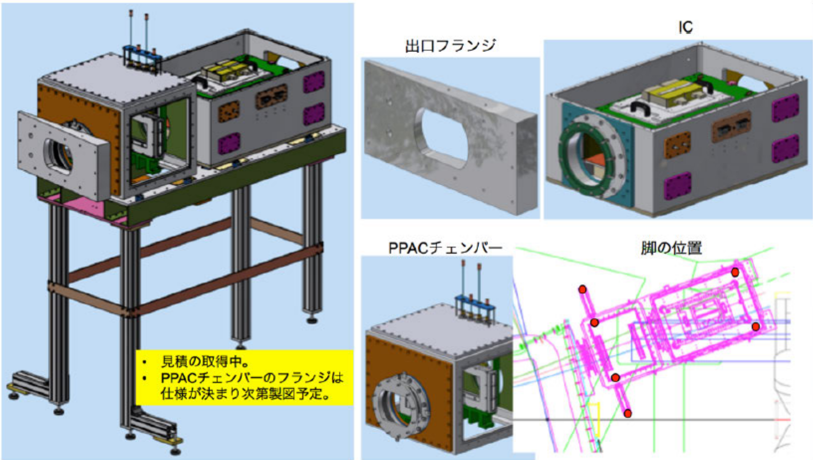
PI of the outgoing particles; TOF-dE-Range

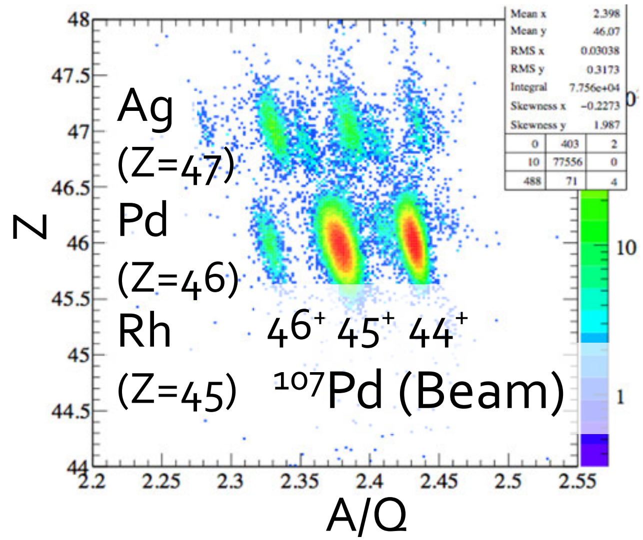


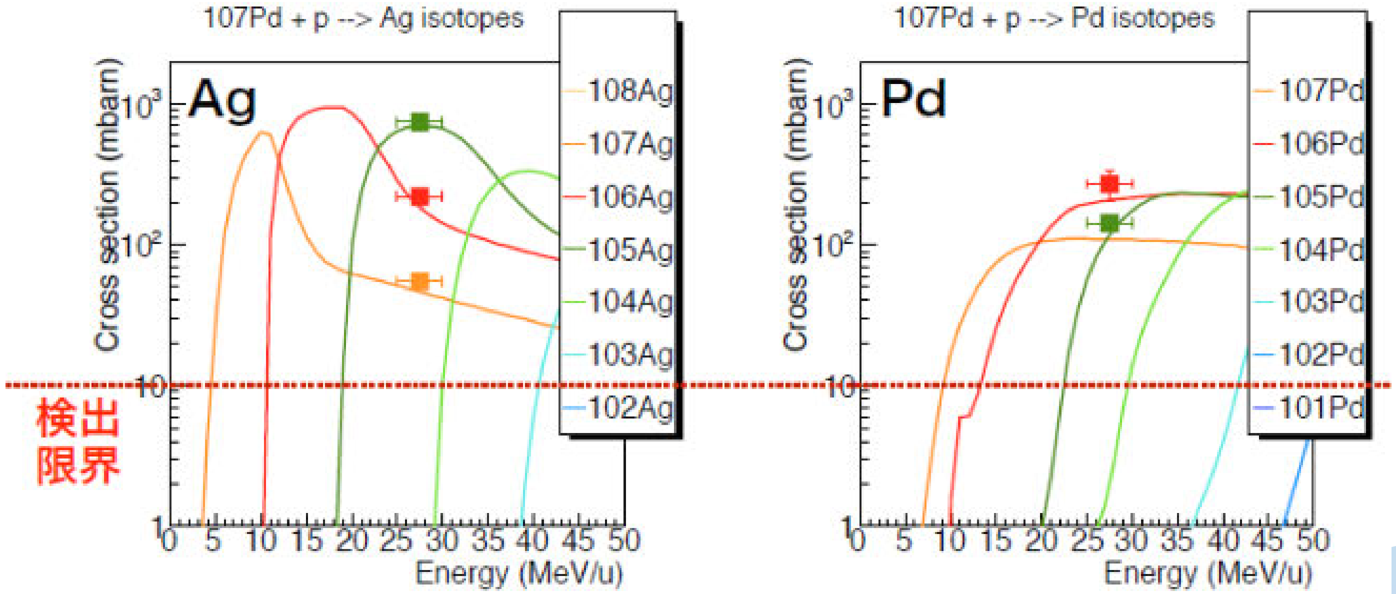


^{93}Zr, ^{107}Pd p/d induced reaction

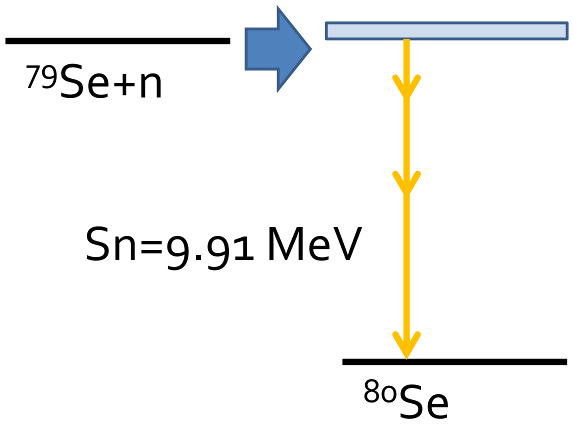
M. Dozono

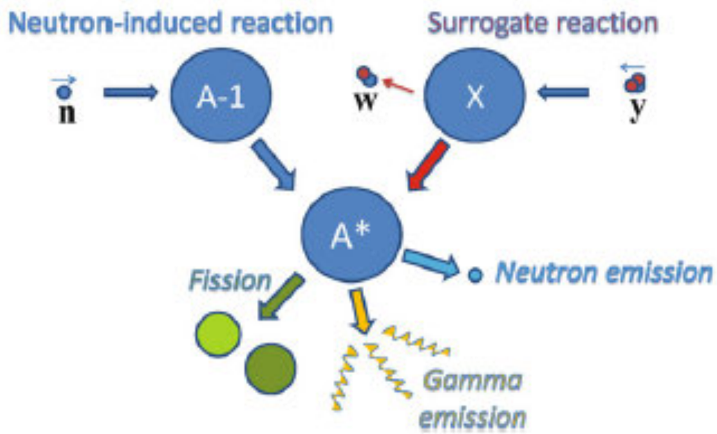


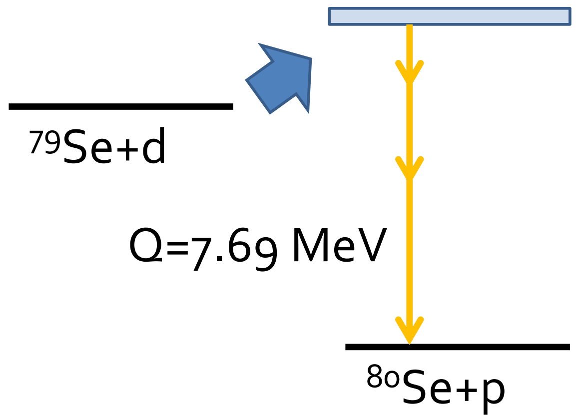




(n,γ) vs. (d,p)







G. Boutoux et al., PLB 712, (2012) 319-325.

$$\sigma_{^{79}\mathrm{Se}(n,\gamma)^{80}\mathrm{Se}}(E_n) = \boxed{\sigma^{CN}_{^{80}\mathrm{Se}}(E_n)}\, P^{decay}_{^{80}Se^{*}\to\gamma+^{79}Se}(E^{*})$$

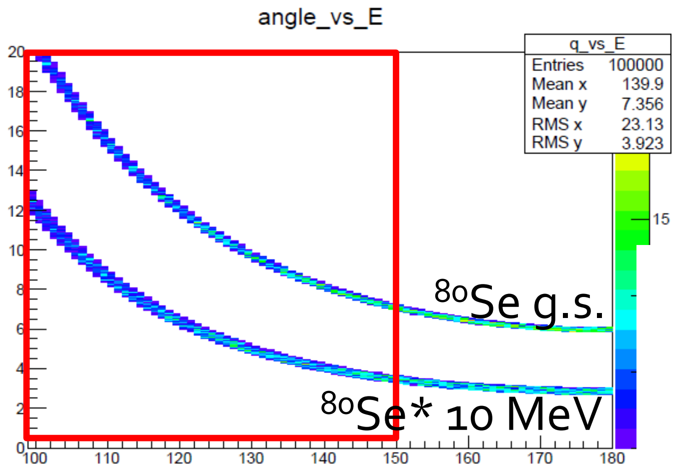
determined by
the optical model potential

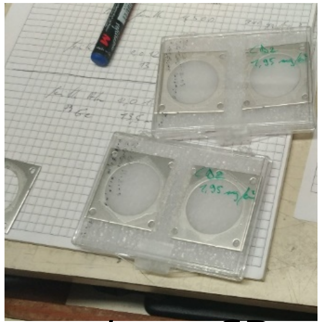
determined by
(d,p)

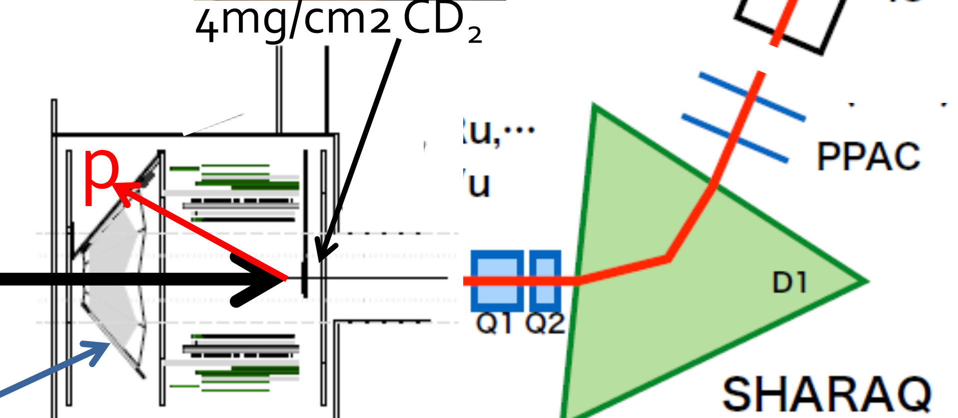
Weisskopf-Ewing approximation
V. Weisskopf, DH. Ewing, Phys. Rev. 57, 472('40)

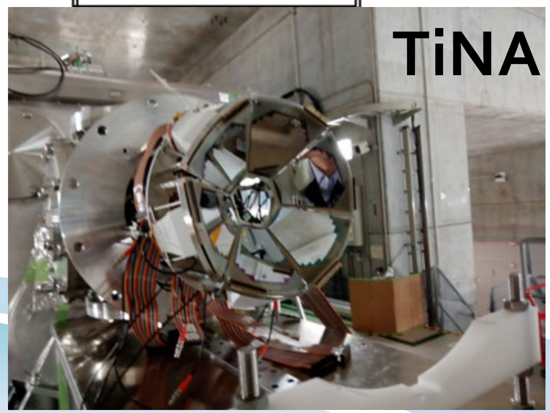
Experimental Setup at OEDO

Recoil particles: TiNA, SSD-CsI (CNS/RCNP/RIKEN)
reaction products: detectors at final focal plane
target: CD_2 4mg/cm^2
Beam int~ 10^4 pps at on CD_2



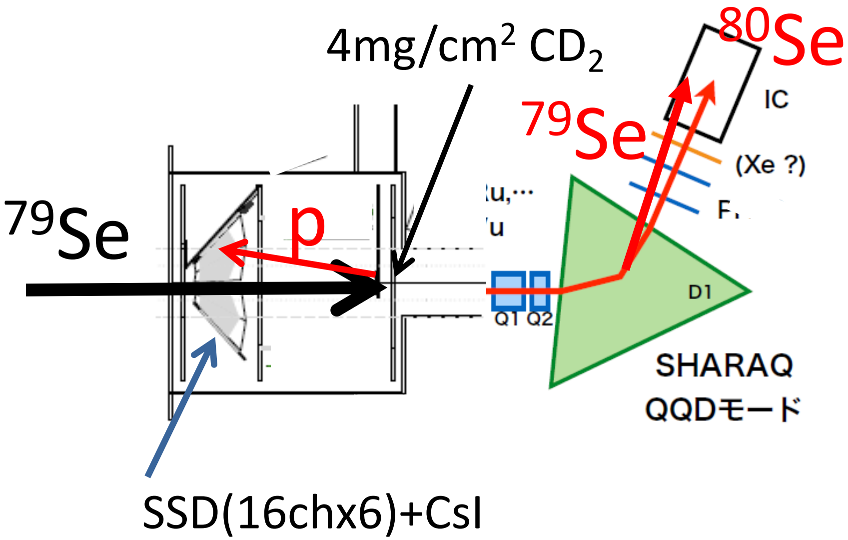




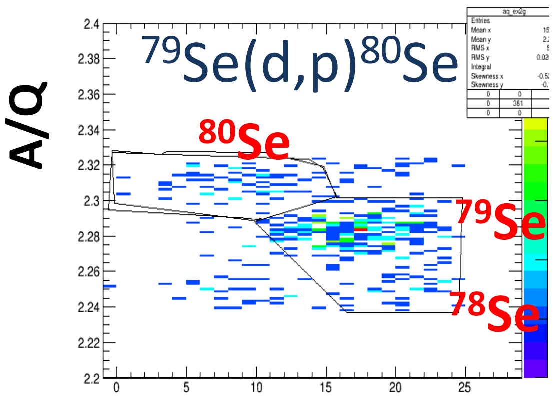


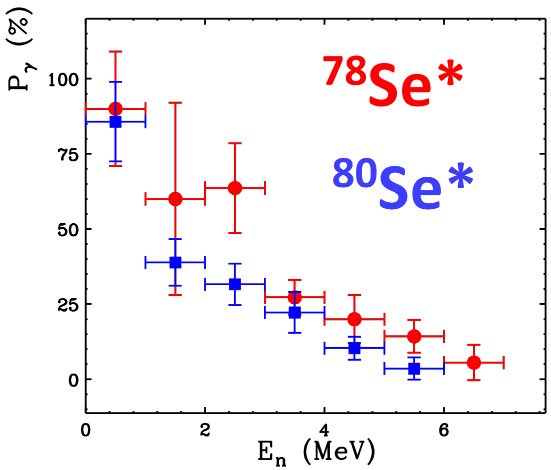
coincidence measurement of
recoil particles + outgoing particles.

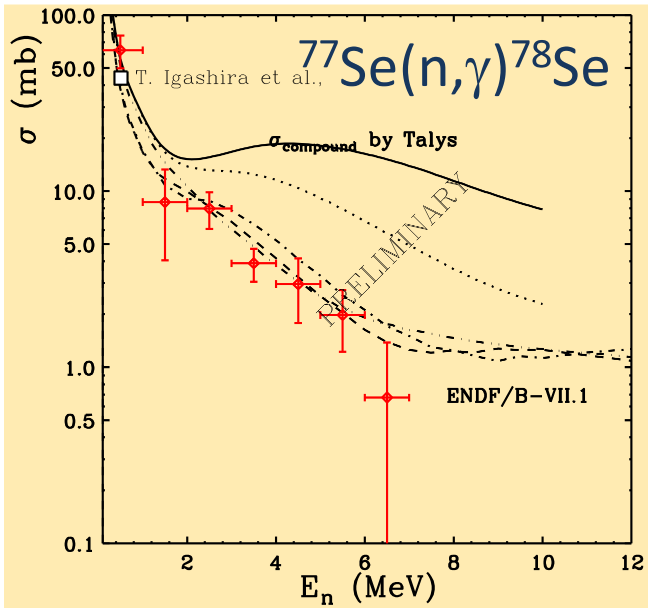
Surrogate for ^{79}Se(n,γ) w/o measuring γ rays

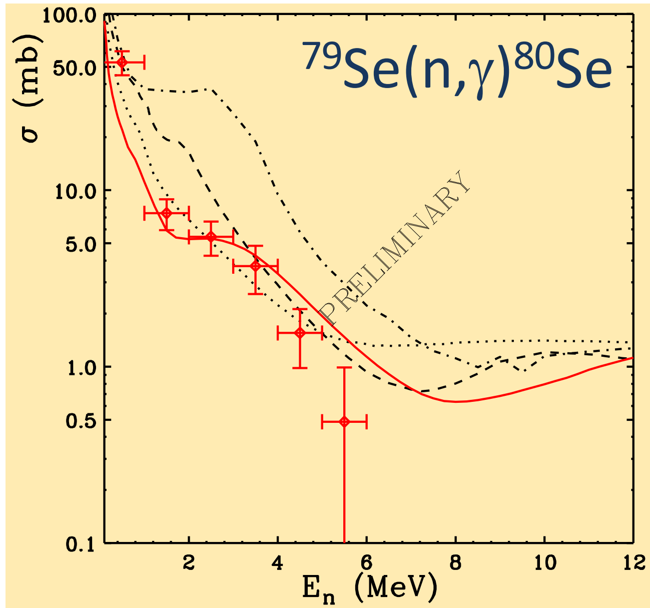


coincidence meas. of
recoil particles
& outgoing particles.









Summary

- Nuclear reactions which transmute Long-Lived Fission Product (LLFP) to stable or short lived RI are measured
- Fragmentation/Spallation reactions on p/d were measured at 200, 100, 50 MeV/u @ BigRIPS+ZDS/SAMURAI
- Proton/deuteron-induced fusion-like reaction
- Lower energy LLFP beam is now ready at OEDO beamline
- ^{77,79}Se(d,p) were measured successfully with a newly developed recoil particle tracker TiNA.