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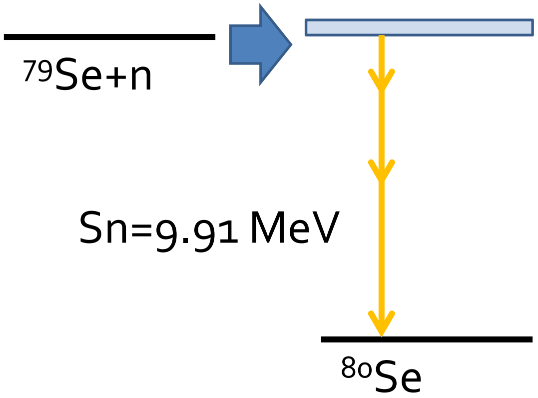
Measurement of Neutron-Induced Reactions on Radioactive Isotopes via Surrogate Reactions at RIBF

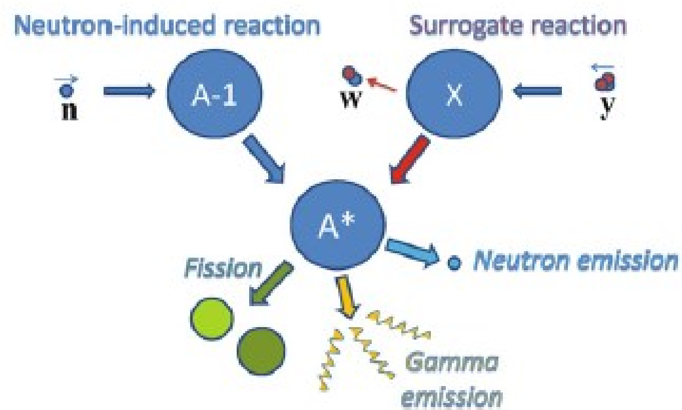
Nobu Imai
Center for Nuclear Study,
the University of Tokyo

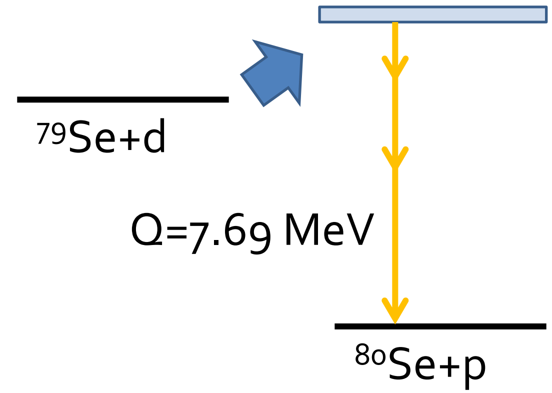
Contents

- The surrogate reaction of neutron-capture reaction rate without detecting gamma-ray
- Decelerating and focusing device OEDO in RIBF
- Three experiments of the surrogate reactions
  - ^{79}Se(n,γ)
  - ^{130}Sn (n,γ)
  - ^{56}Ni(n,p)
- Proton-fusion measurement with ^{93}Zr
- Updating plan

Surrogate reaction: (n,g) vs. (d,p)







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

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

determined by
the optical model potential

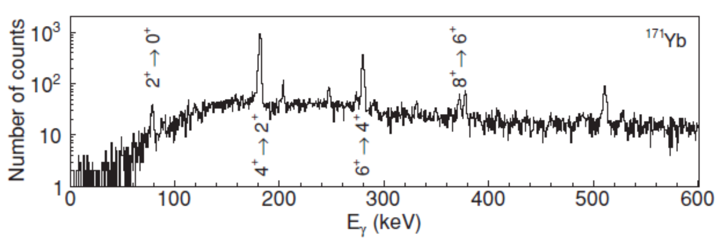
Brink-Axesl hypothesis

Surrogate reaction w/o γ-ray measurement

Typical setup for surrogate reaction exp.

= Recoil particle detectors

+ γ-ray detector array



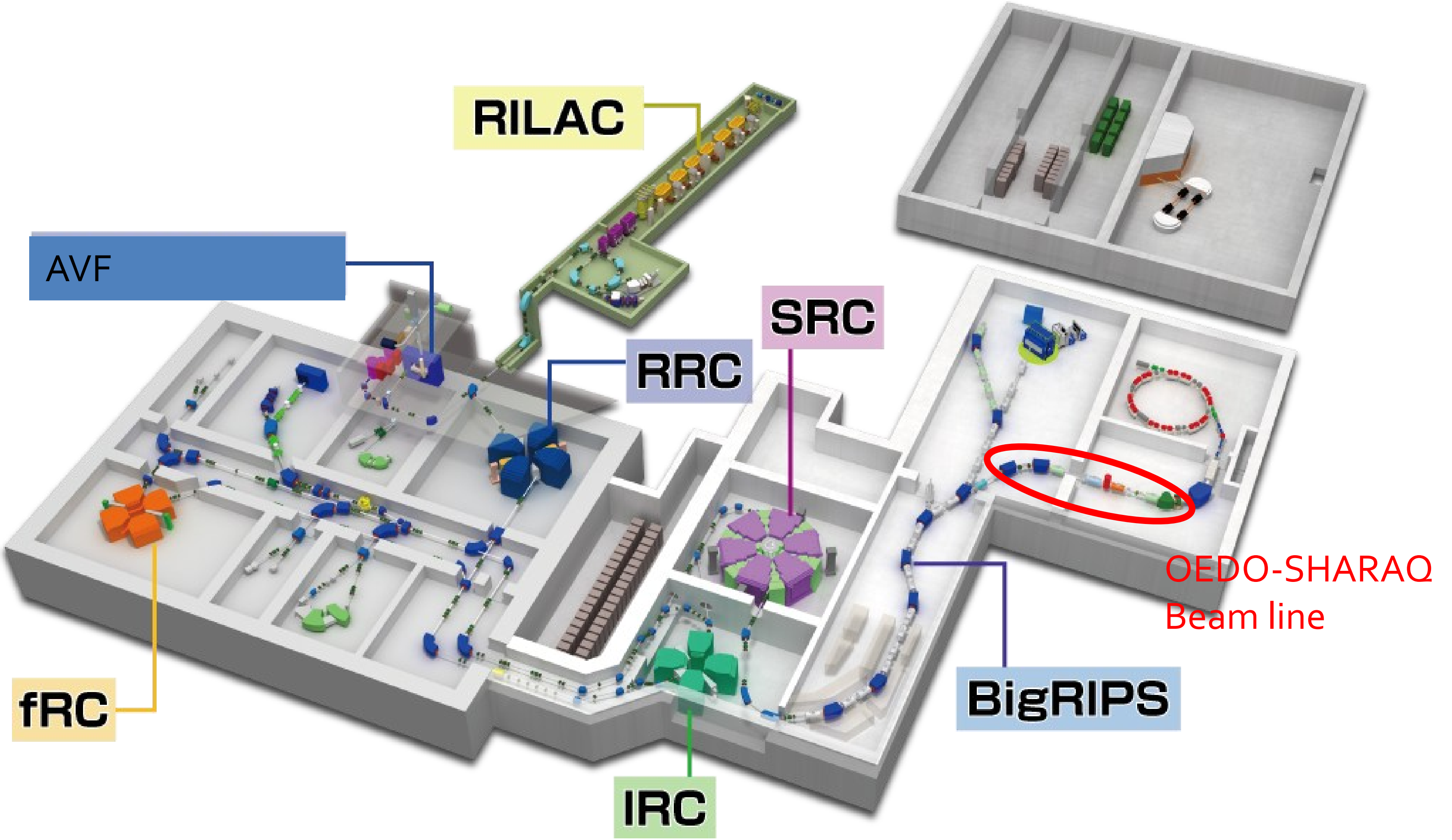
^{171}Yb(d,pγ) → ^{172}Yb(n,γ)

R. Hatarik et al.,
PRC81, 011602 (R) (2010)

Gamma emission means that the nucleus doesn't change N and Z number!

Pγ was determined by identifying the outgoing residue nucleus.

OEDO-SHARAQ beam line at RIBF



BigRIPS-OEDO beam line

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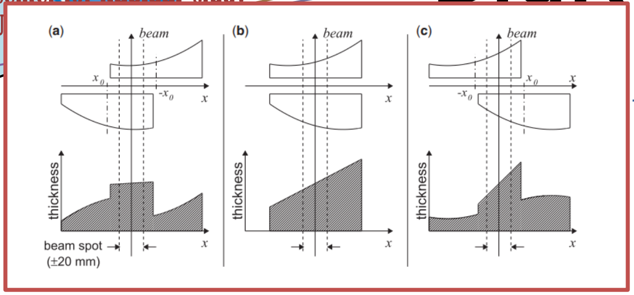
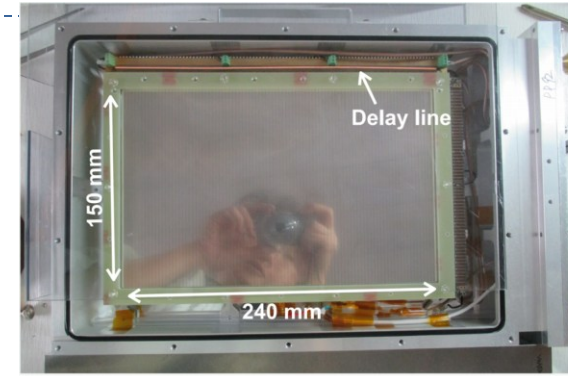
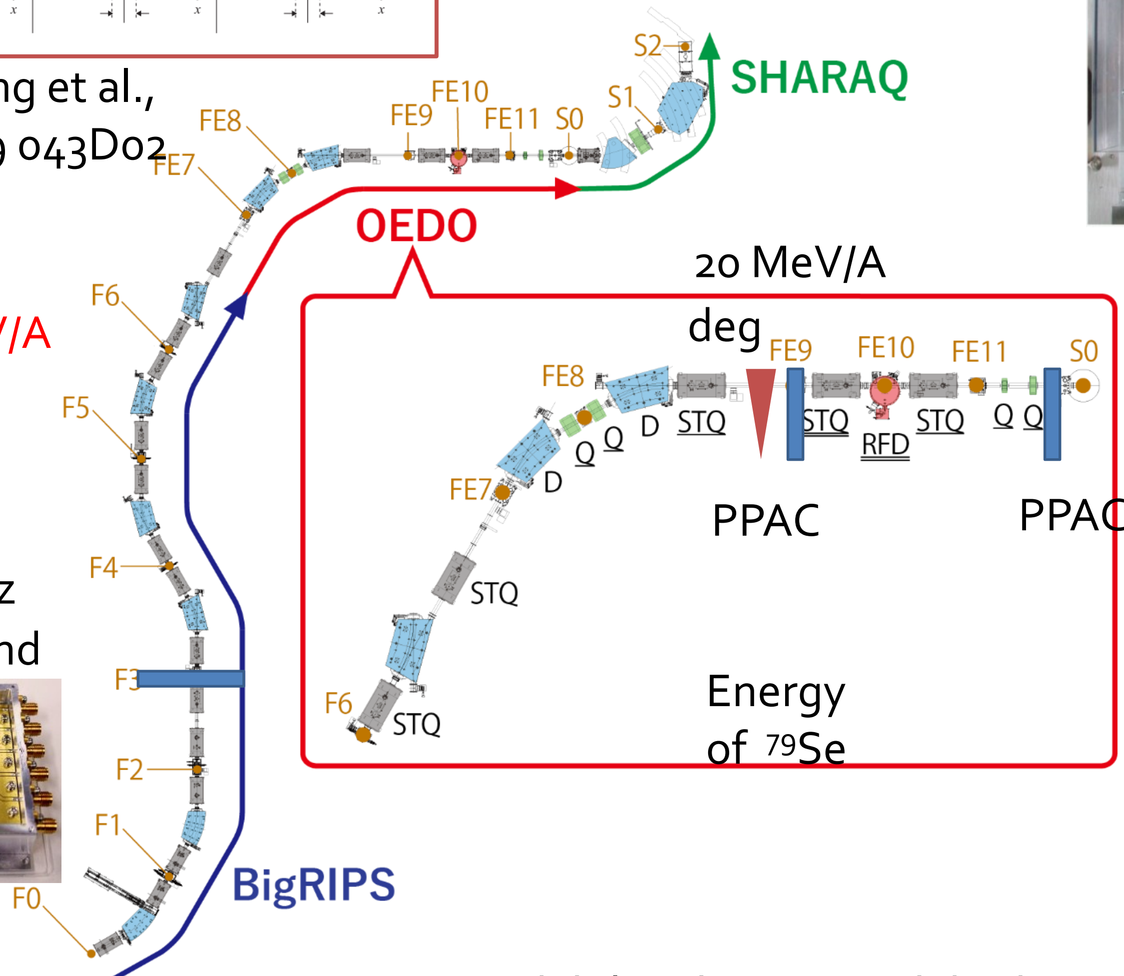


J.W. Hwang et al.,
PTEP2019 043D02

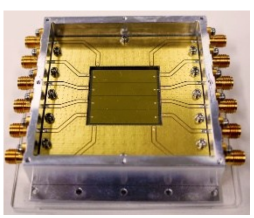


S. Hanai, S. Ota et al.,
NIMB541(2023)194-196.

170 MeV/A



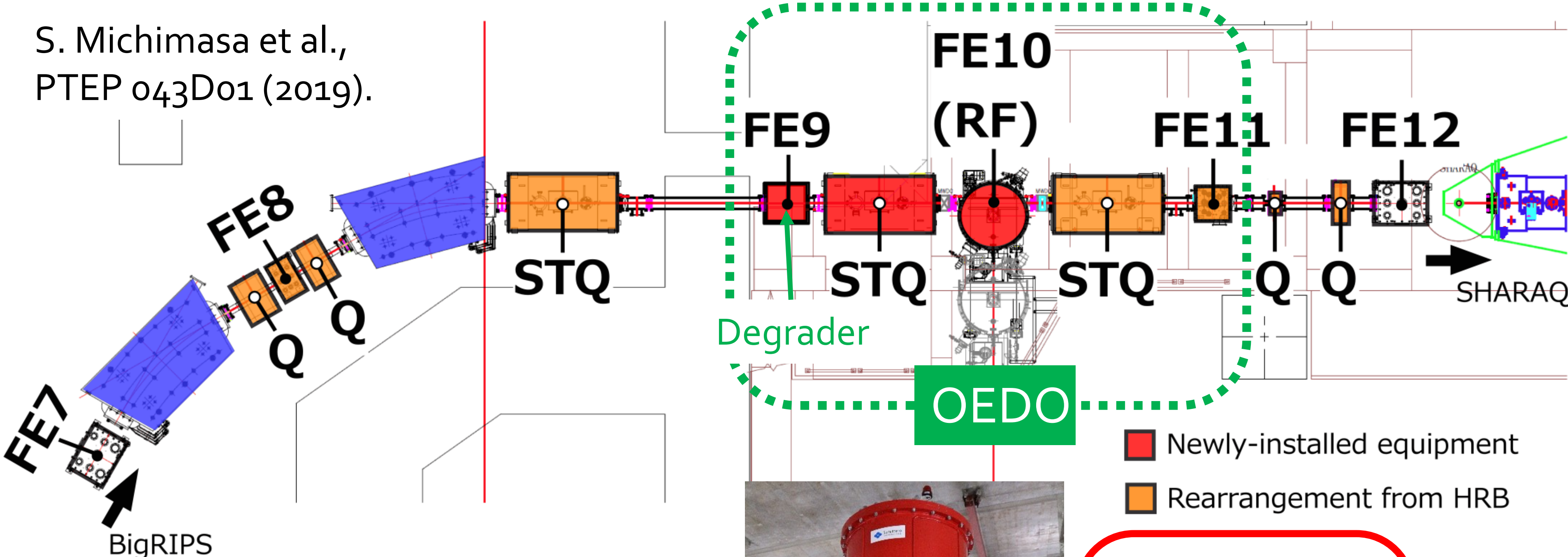
500 kHz
Diamond

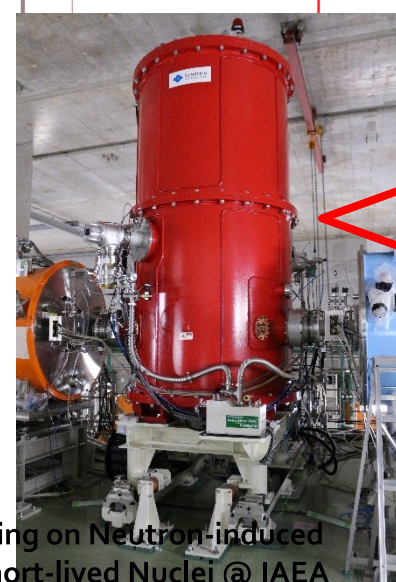


^{79}Se
Purity ~ 50%
Intensity ~ 10 kHz
@S0

Optimized Energy Degrading Optics for RI beams at RIBF

S. Michimasa et al.,
PTEP 043D01 (2019).





OEDO RFD

f_{RF} = 18.25 MHz
V_{max} = 350 kV
Gap(H) = 200 mm
L (Z) = 1200 mm
W(V) = 400 mm

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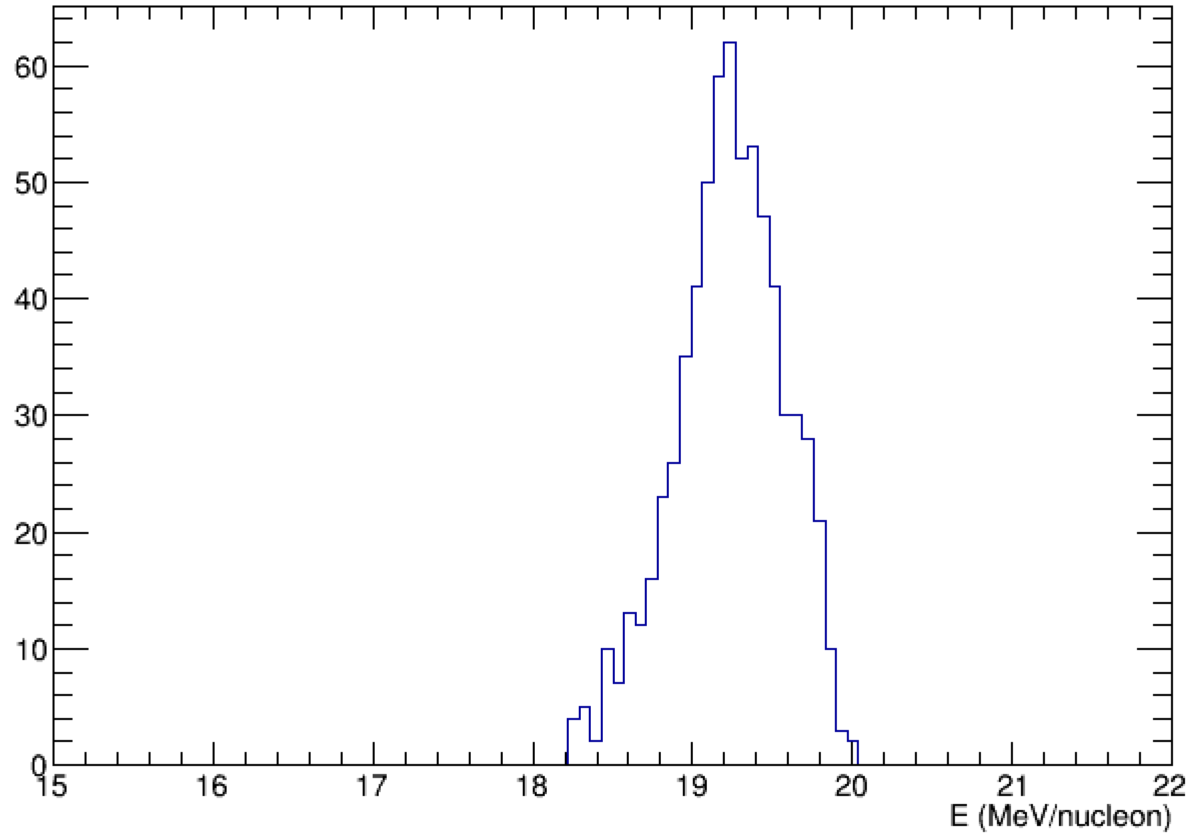
$^{79}Se(d,p)^{80}Sn$

N. Imai (U-Tokyo)

Beam energy of ^{79}Se

Beam energy was measured event-by-event



Setup for ^{79}Se(d,p)^{80}Se in inverse kinematics

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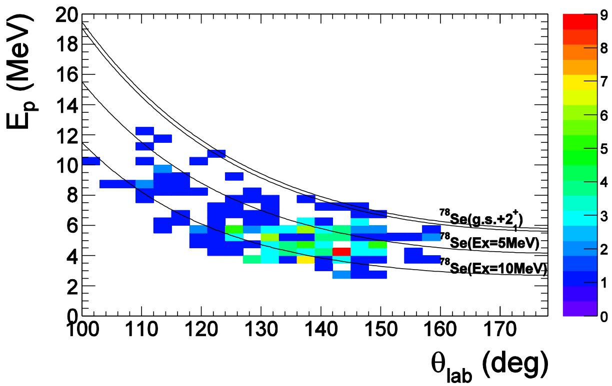
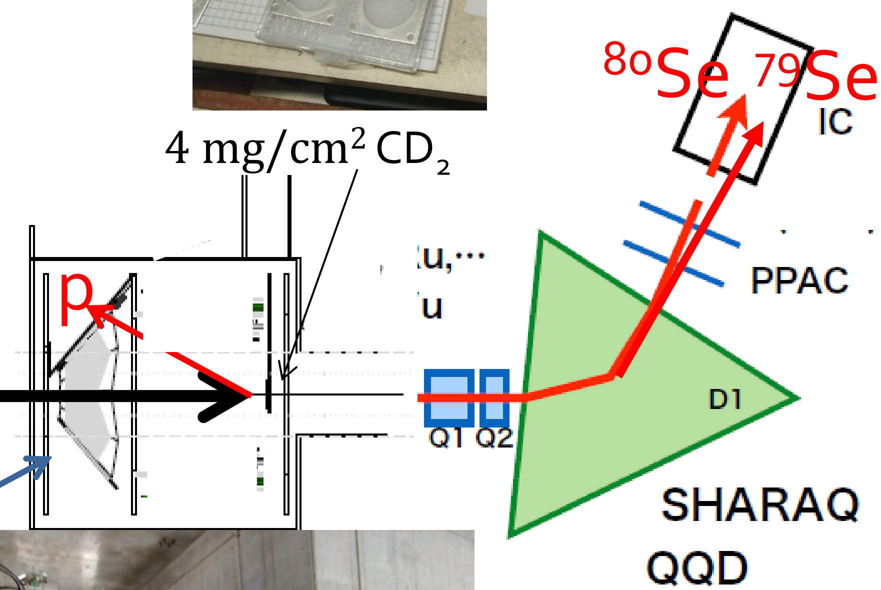
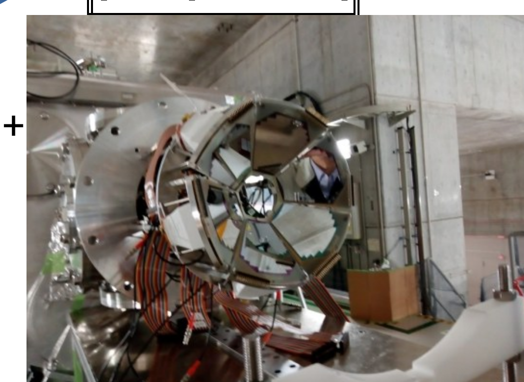
Recoil particles: TiNA, SSD-CsI (CNS/RCNP/RIKEN)
reaction products: detectors at final focal plane
target: CD_2 4 mg/cm^2
Beam int~ **10^4 pps** at on CD_2





^{79}Se, ^{77}Se
(~20 MeV/u)

6x (SSD(YY1 16ch)+CsI)



coincidence measurement of recoil particles + outgoing particles.

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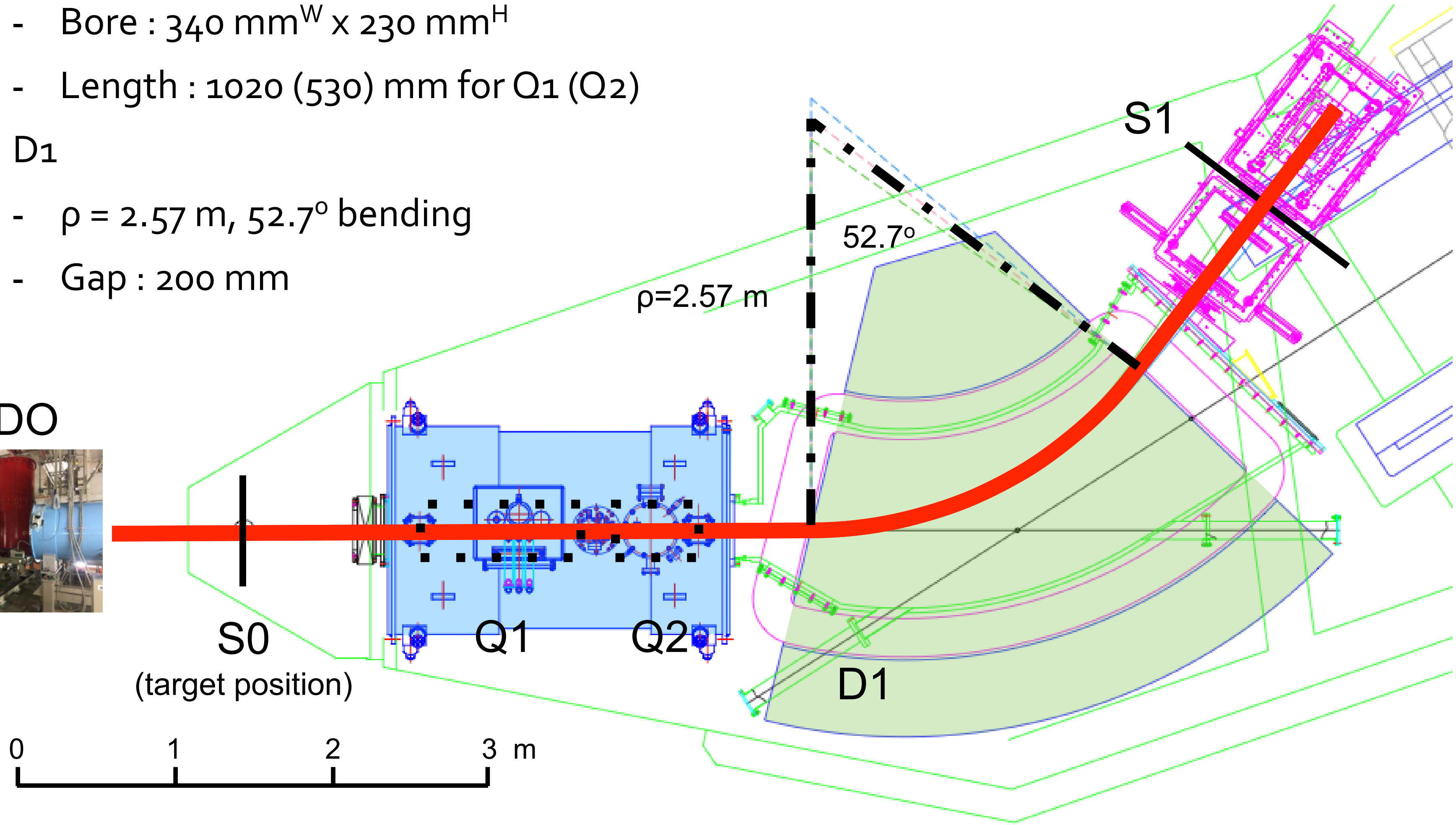
SHARAQ spectrometer

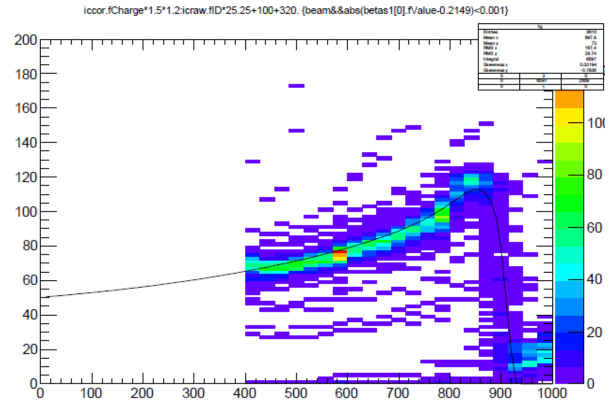
- Q-Q-D magnet configuration (First-half part of SHARAQ spectrometer)
  - Q1, Q2 (Superconducting)
    - Bore : 340 mm^{W} x 230 mm^{H}
    - Length : 1020 (530) mm for Q1 (Q2)
  - D1
    - ρ = 2.57 m, 52.7° bending
    - Gap : 200 mm

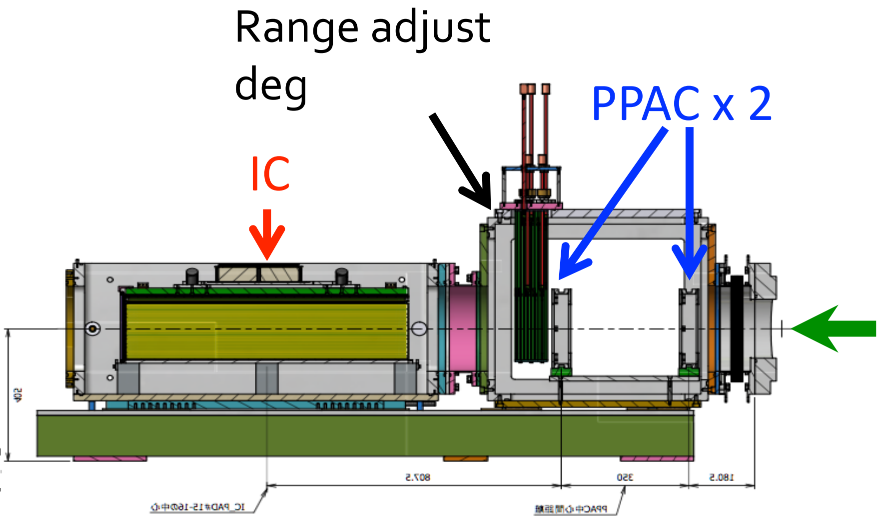
OEDO



S1 Focal plane detector

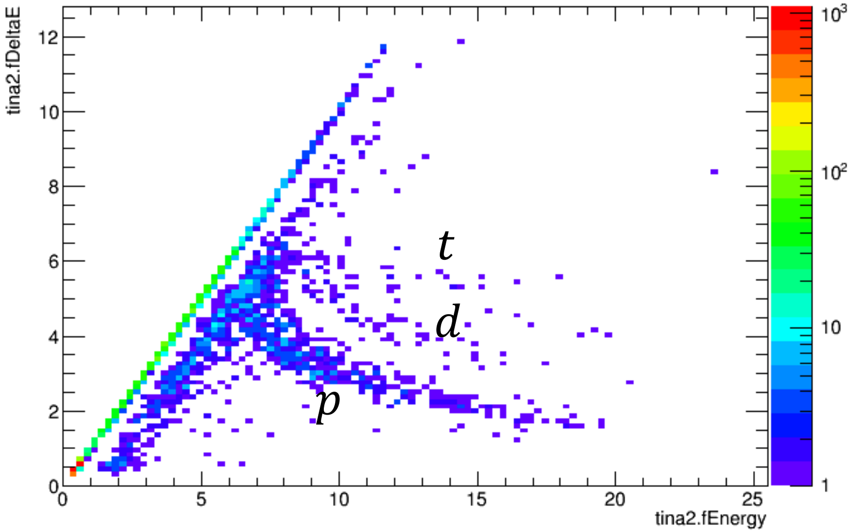
- PPAC :position, time of flight
  - Single(X-A-Y), Delay-line readout
  - 240 mm^W x 150 mm^H
- Ionization chamber : ΔE, Range
  - 30 pads
  - 280 mm^W x 150 mm^H
  - Total depth 757.5 mm
  - CF_4 110 torr
- Degrader to tune the range
- Kapton foil of 75 um



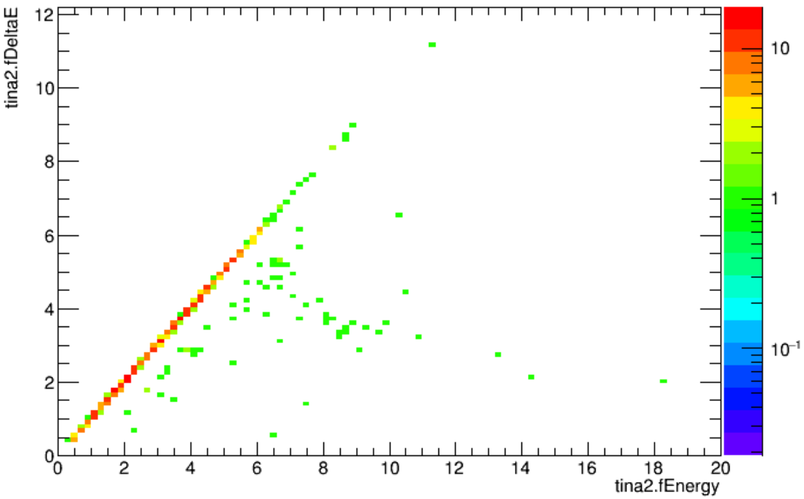


TiNA (dE-E)

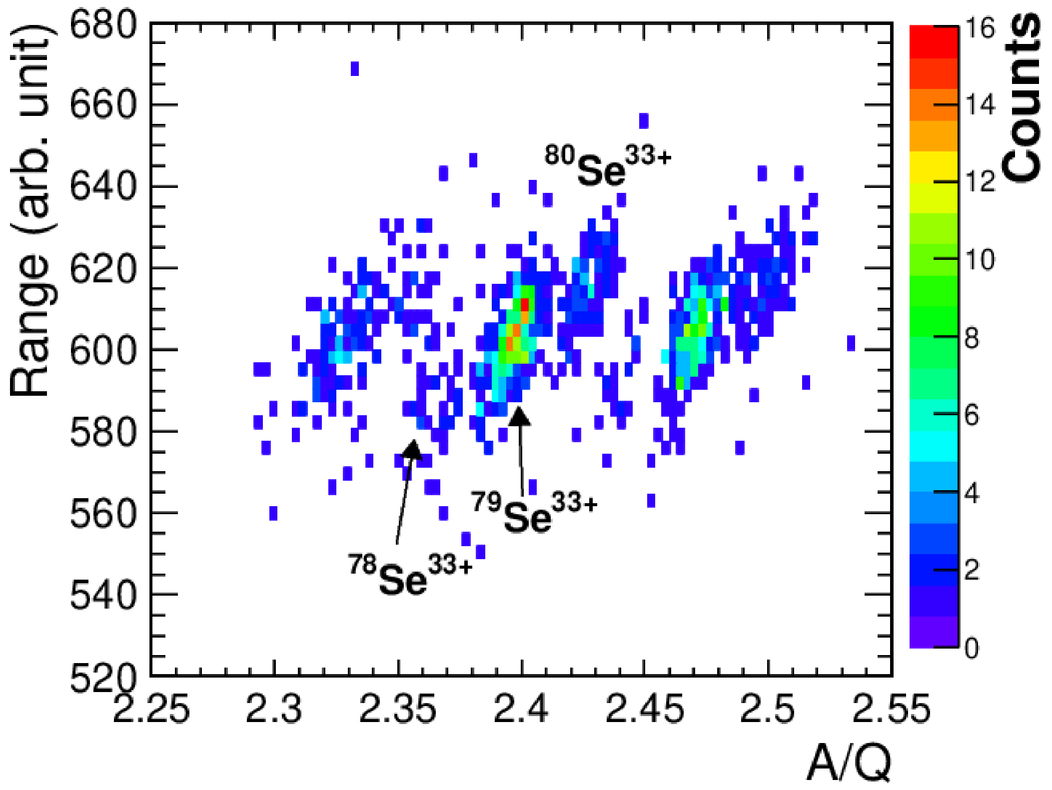
No gate



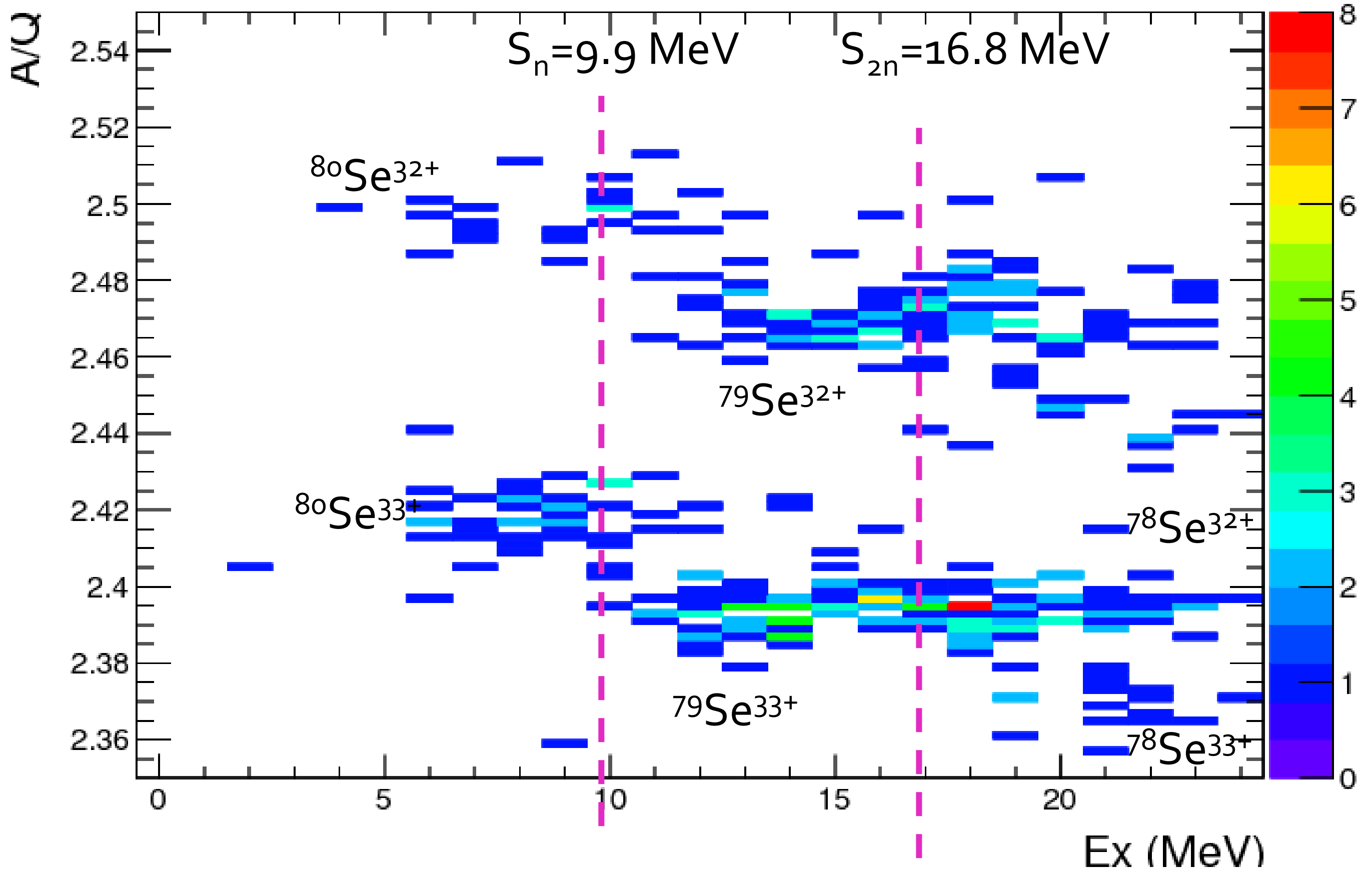
Beam, beam trajectory, ..., timing, S1



PID of outgoing residues

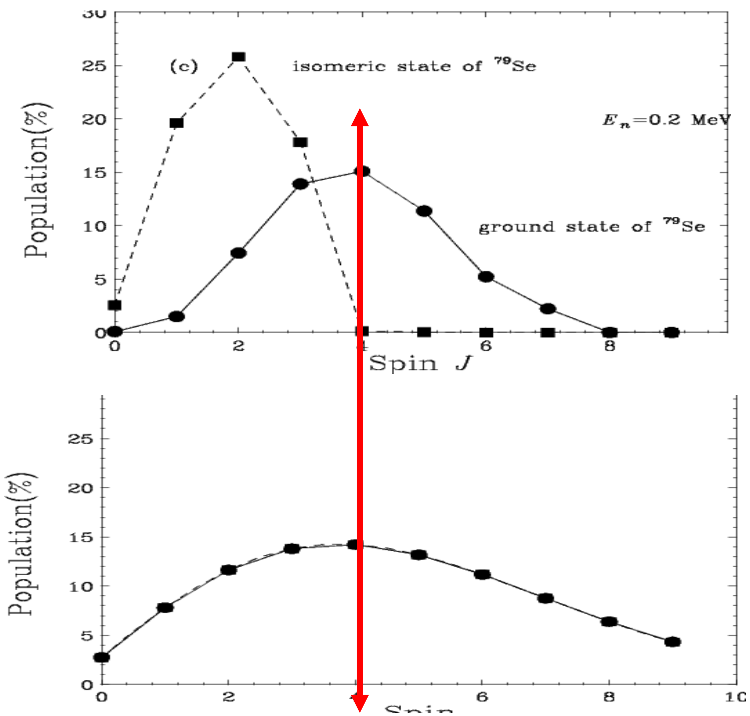


Residual nuclei vs Excitation energy



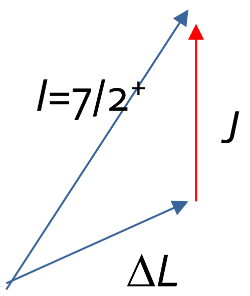
$$P_\gamma = \frac{\sum_{i=32,33} {}^{80}Se^{i+}}{\sum_{i=32,33} {}^{78}Se^{i+} + {}^{79}Se^{i+} + {}^{80}Se^{i+}}$$

Calculated spin distribution for ^{79}Se



^{79}Se g.s. $I^{\pi} = 7/2^{+}$

iso @96 keV $I^{\pi} = 1/2^{-}$



Talys spin distribution at 10 MeV
By ^{79}Se(d,p) reaction @ 40 MeV
(complete compound reaction is assumed.)

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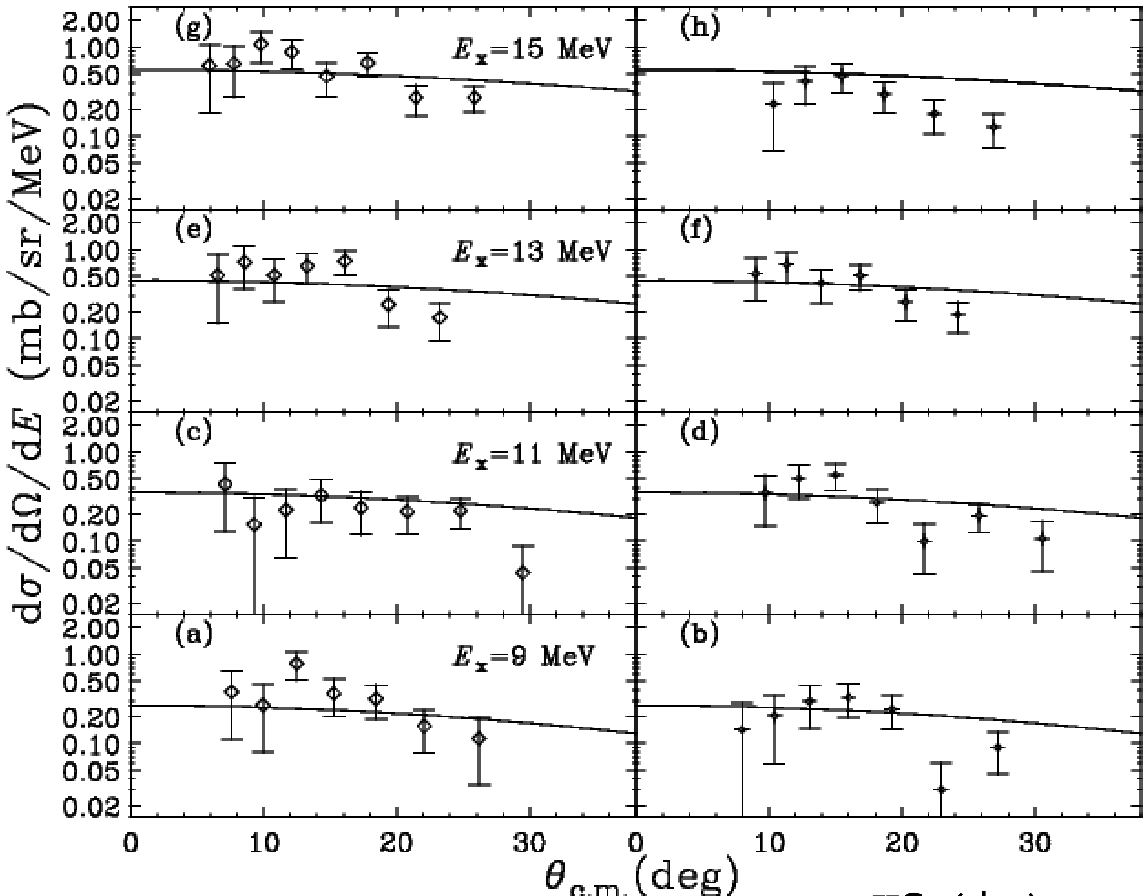
Double differential cross sections



^{79}Se(d,p) ^{77}Se(d,p)

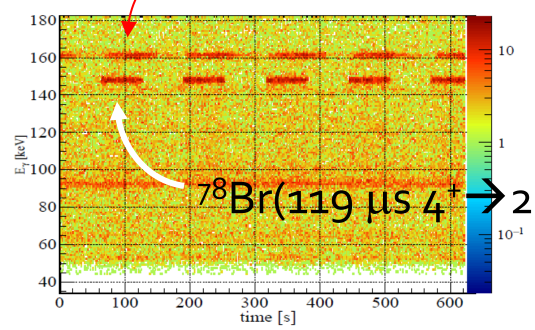
Solid line:
Pre-equilbrium curve by Calbach model (Talys 1.96)

Isomer ratio of ^{77,79}Se

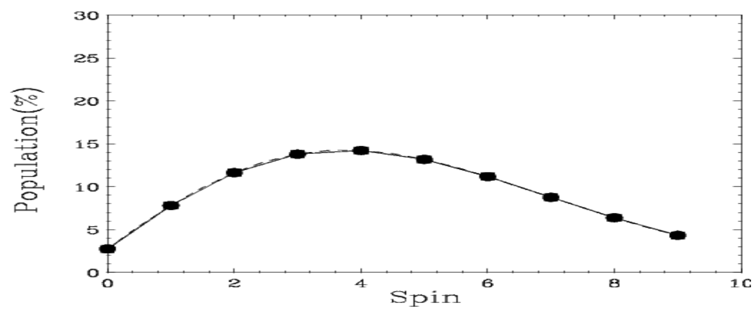
	7/2+ g.s.	½- @ 95.8 keV
^{79}Se	76 ± 7	24 ± 7%

	½- g.s.	$7/2^+$ @ 160 keV
^{77}Se	13 ± 7%	87 ± 7%

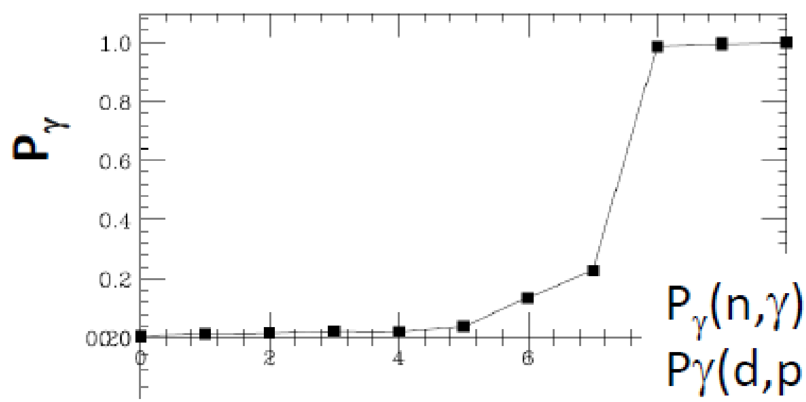
$7/2^+$ is dominant (~80%) for both beams



Theoretical P_{γ}(Ex)



projectile= 0 mode

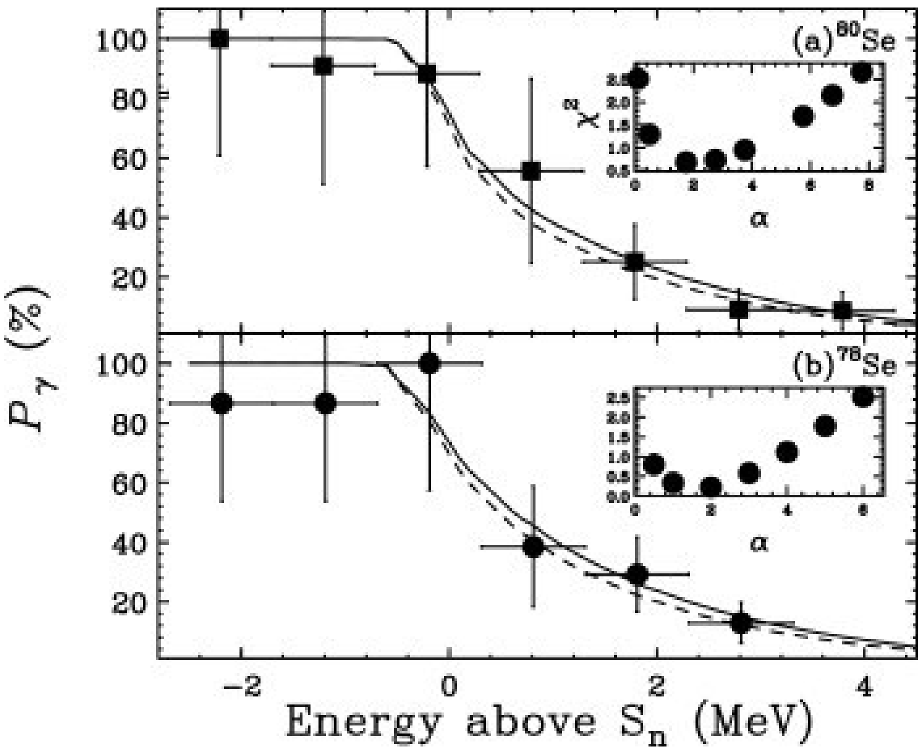


$P_{\gamma}(n,\gamma)$ =17%

$P\gamma(d,p)$=16%

P_γ in $^{77,79}Se(d,p)$ reaction

$$P_\gamma(E) = \sum G_{decay}(J^\pi, E) F^{dp}(J^\pi, E)$$



TENDL2019 recommendation
Normalization $\Gamma_\gamma \equiv \alpha = 1.75$

Best fitting: $\alpha = 1.6^{+4.1}_{-1.2}$

TENDL2019 recommendation
α=1.00
Best fitting: $\alpha = 1.6^{+3.5}_{-1.3}$

^{79}Se(n,γ) cross section

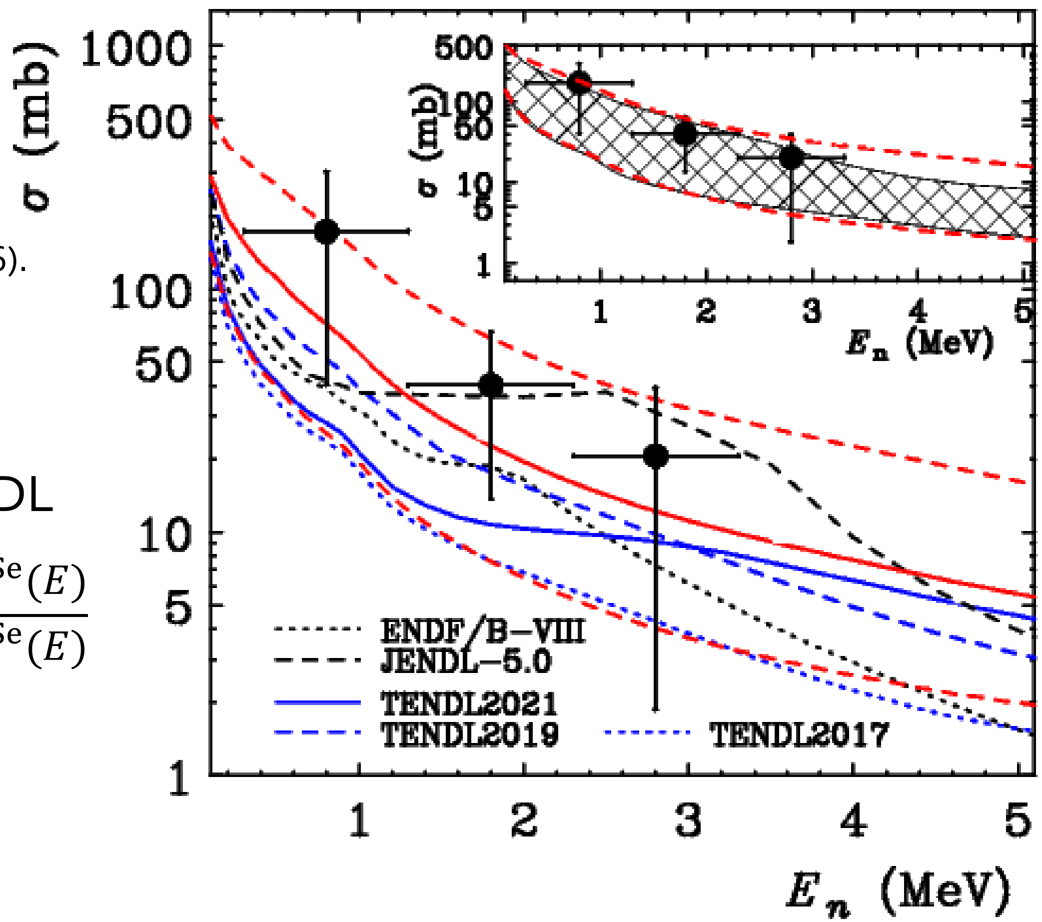
- Hatched region (inset):
  ^{79}Se(n,γ) by ^{80}Se(γ,γ')

  A. Makinaga, Phys. Rev. C 94, 044304 (2016).

- Points:
  surrogate ratio method
  ^{77}Se*(7/2$^+$)(n,γ) taken from TENDL

$$\sigma^{(n,\gamma)}_{^{79}\mathrm{Se}}(E) = \sigma^{(n,\gamma)}_{^{77}\mathrm{Se}}(E) \times \frac{\sigma^{CN}(^{80}\mathrm{Se})}{\sigma^{CN}(^{78}\mathrm{Se})} \times \frac{P_\gamma^{^{80}\mathrm{Se}}(E)}{P_\gamma^{^{78}\mathrm{Se}}(E)}$$

- Red line:
  normalized Γ_γ



N. Imai et al., PLB850, 138470 (2024).

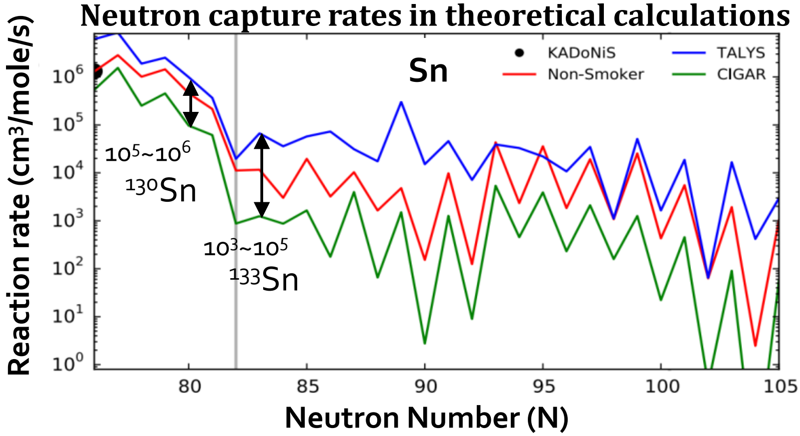
$^{130}Sn(d,p)^{131}Sn$

S. Bae (IRIS RAON/ U-Tokyo), N. Imai (U-Tokyo)

Neutron capture rates around ^{132}Sn

- **N = 82 waiting point:**
  - Second peak of *r*-process elemental abundances
  - Bottle-neck toward the third abundance peak

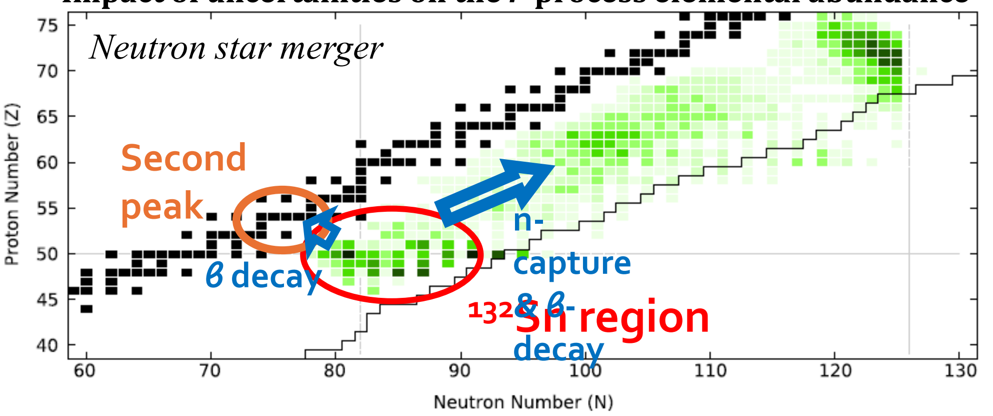
Neutron capture rates in theoretical calculations



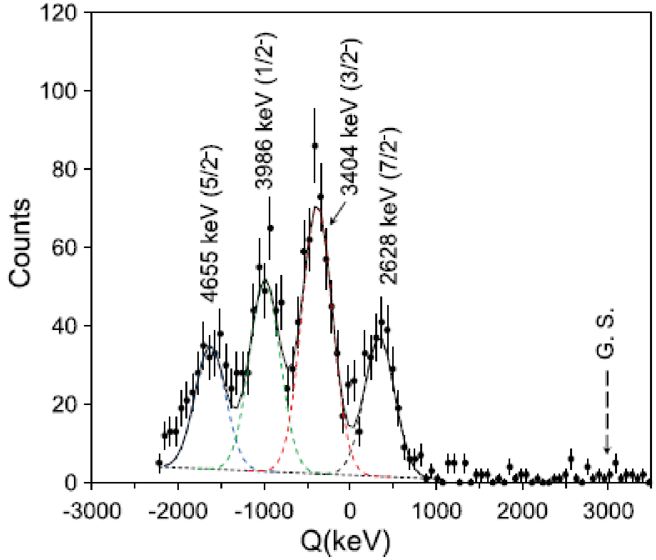
Prog. Part. Nucl. Phys. 86, 86-126 (2016)

- **A few orders of theoretical deviations** in neutron capture rates of Sn

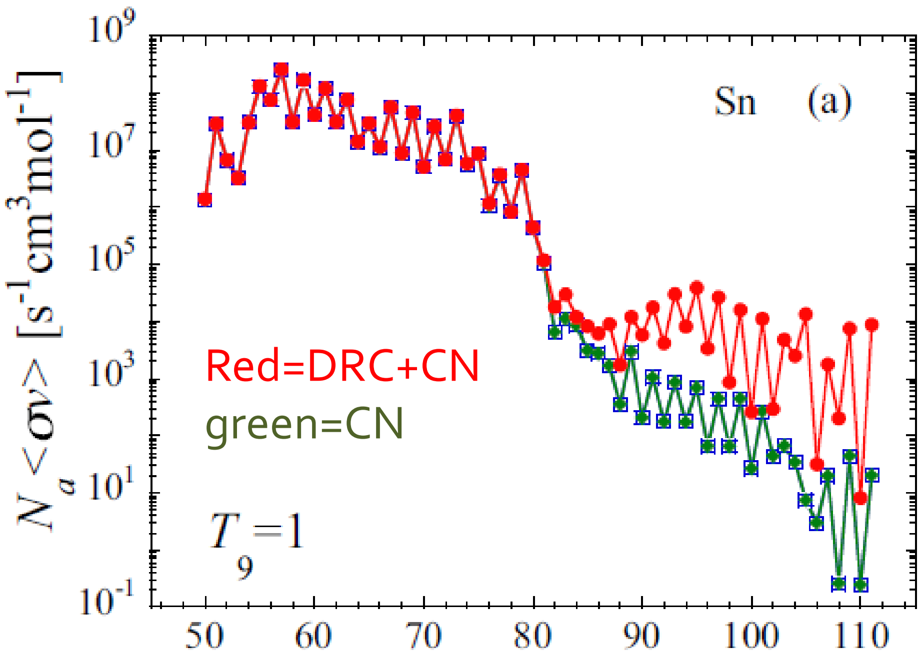
Impact of uncertainties on the *r*-process elemental abundance



Neutron capture reaction on ^{130}Sn



d(^{130}Sn,p)@4.8 MeV/nucleon



R.L. Kozov et al., PRL109 172501 (‘12)

Y. Xu, S. Goriely et al., PRC90, 024604 (‘14)

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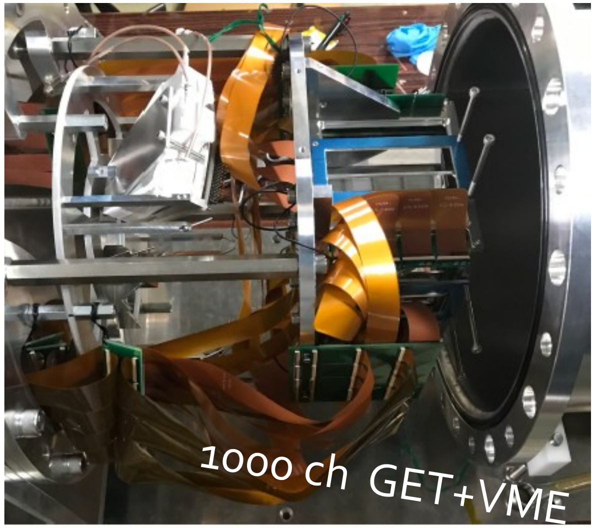
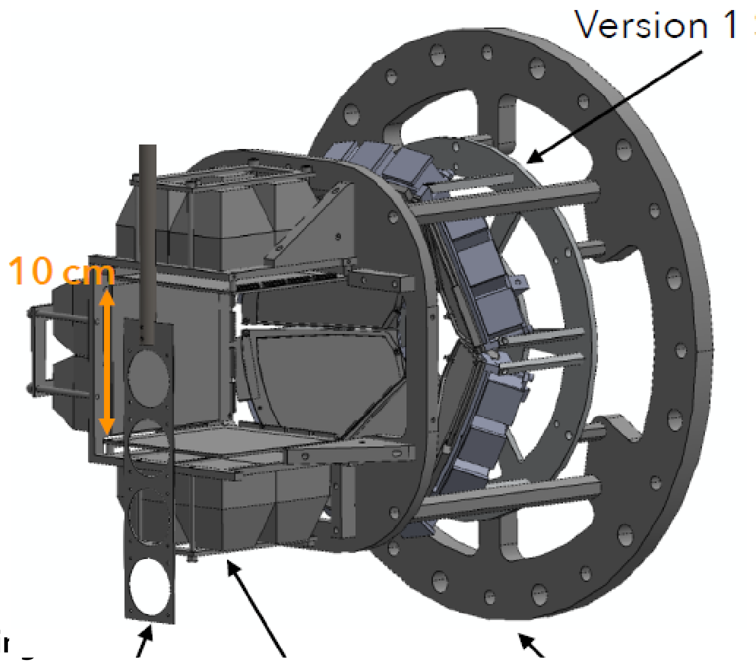
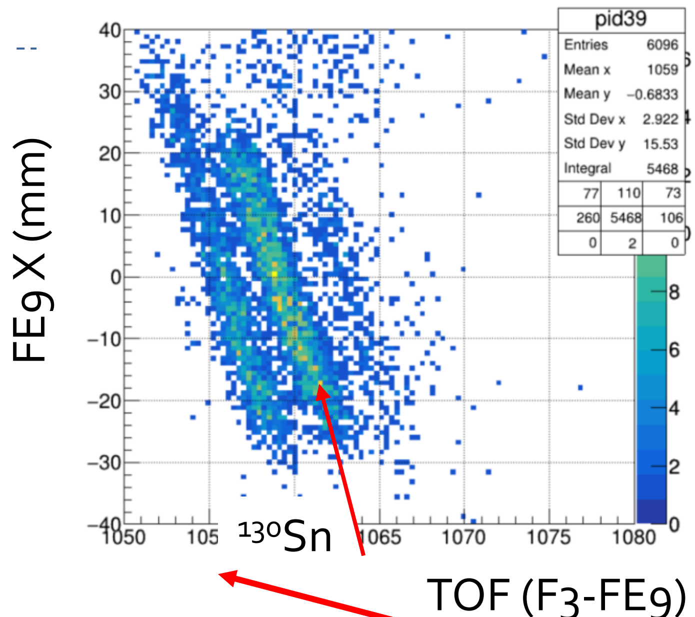
Three Improvements

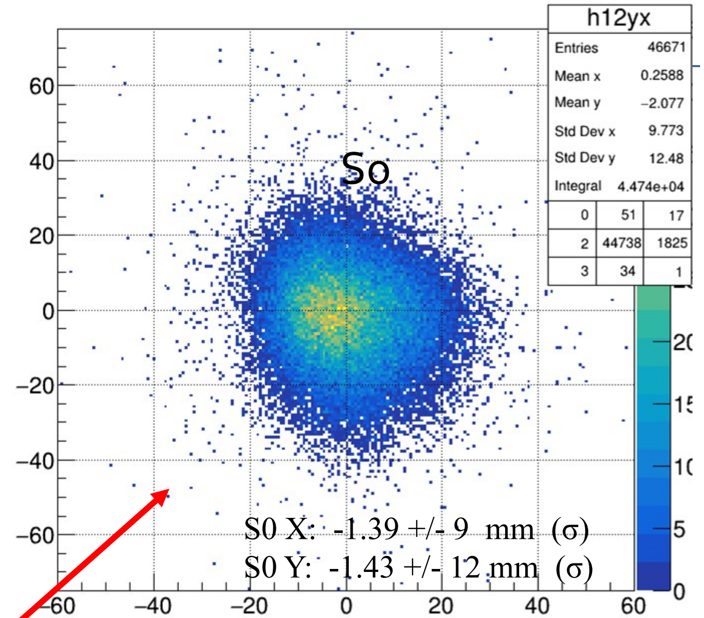
- Transmission 20% → 80%
- Target thickness was reduced to be 200 $\mu g/cm^2$
- Finer angular resolution of recoil particle detector

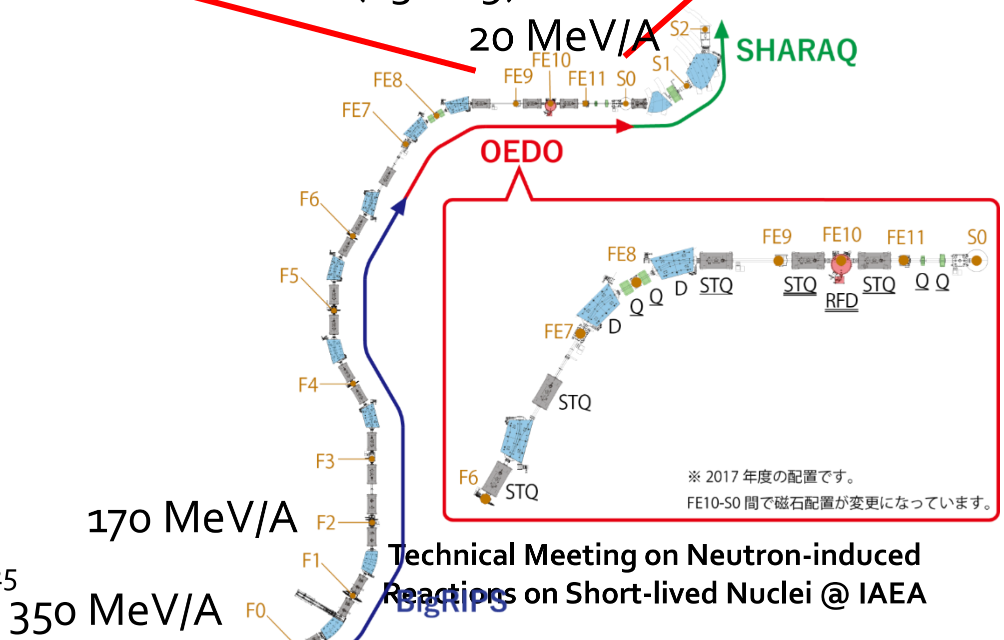




^{130}Sn beam at FE9 and S0

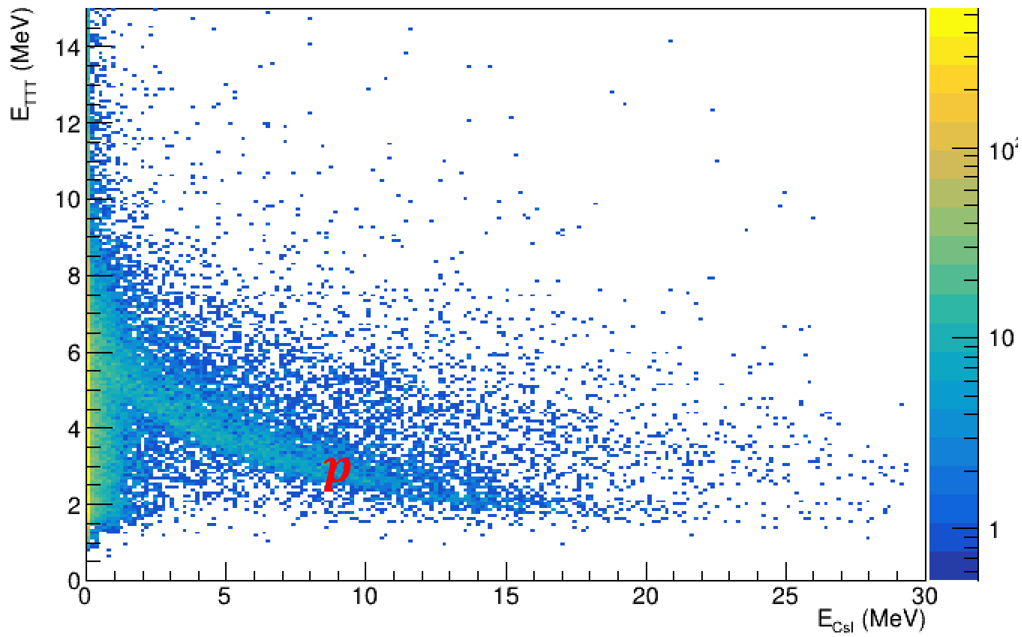






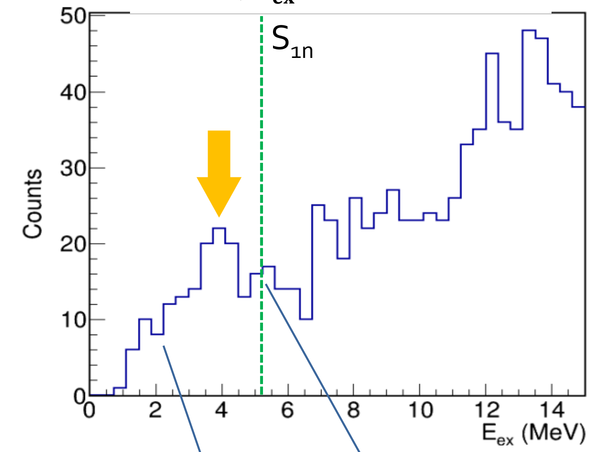
165 kHz
50% purity
@S0

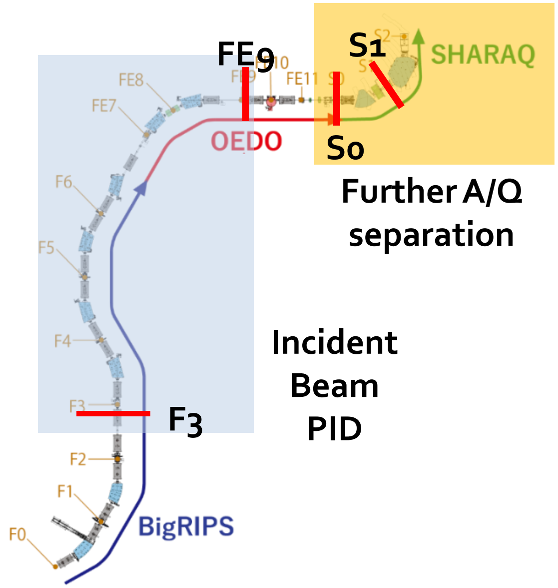
TTT-CsI(Tl) @TiNA2

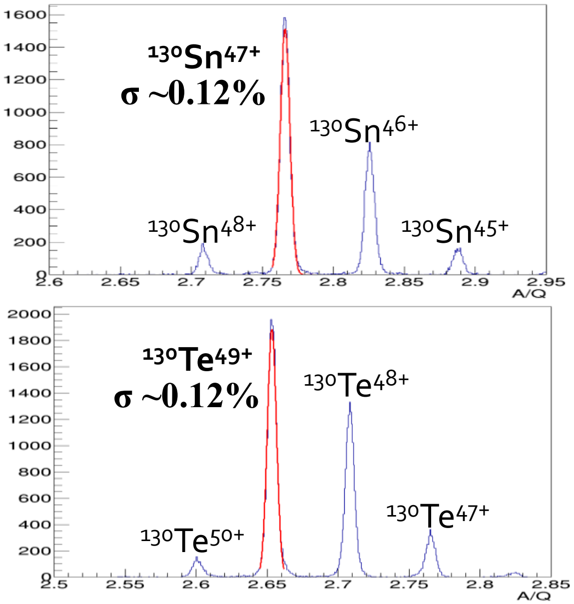


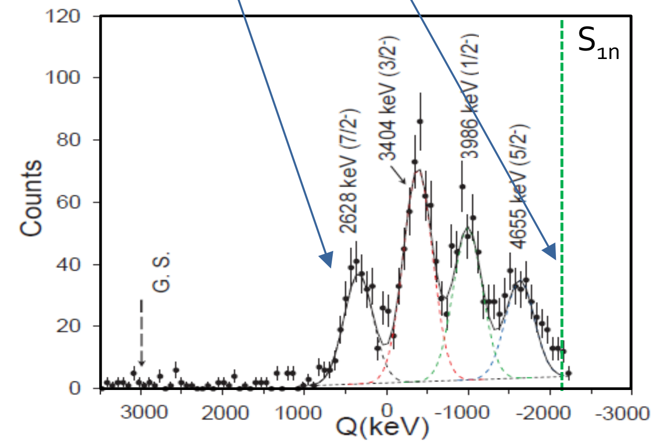
Experimental results

- A/Q resolution σ ~0.12% for Li-like ions
  => **ΔA/Q (A = 131 to 130) = ~6σ**
- **Missing mass spectrum of bound state is consistent E_{ex} = 3-4 MeV**







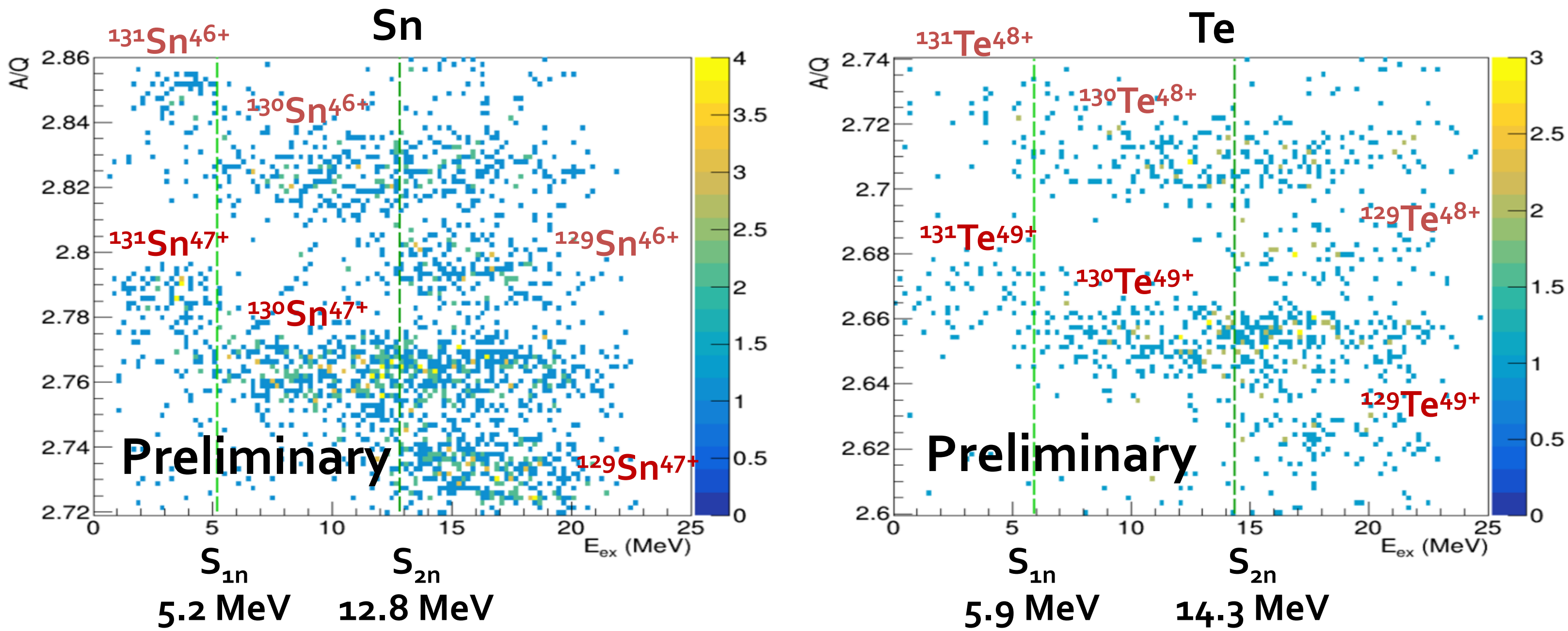


Q-value spectrum of ^{130}Sn(d,p), 4.8 MeV/u
Phys. Rev. Lett. 109, 172501 (2012)

A/Q vs Ex for ^{131}Sn and ^{131}Te

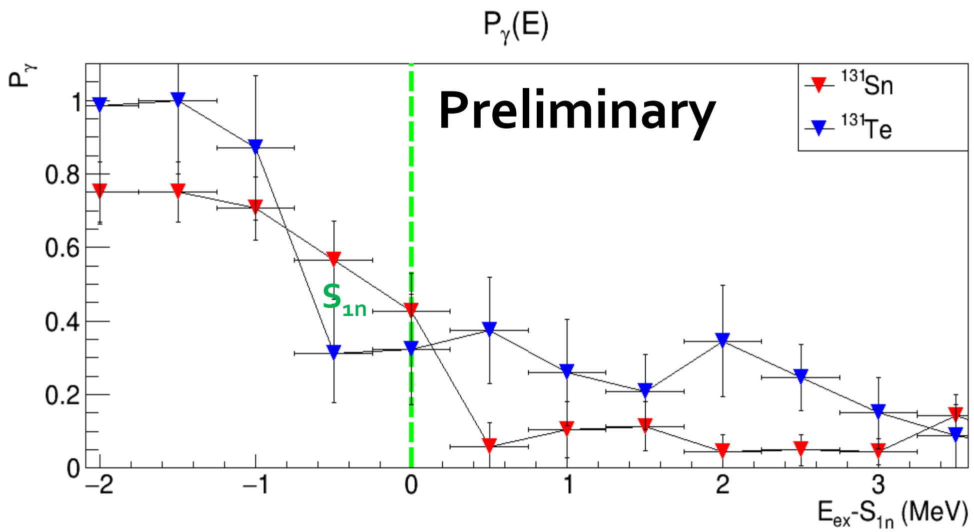
- **Clear mass number changes at S_{1n} and S_{2n}**
- Mainly, **Li-like (Q = Z−3)** and **Be-like (Q = Z−4)** isotopes are identified.
- $P_\gamma(E)$ distribution was obtained by isotopic ratios around S_{1n}.

$$P_\gamma(E) = \frac{(A = 131)}{(A = 130) + (A = 131)}$$

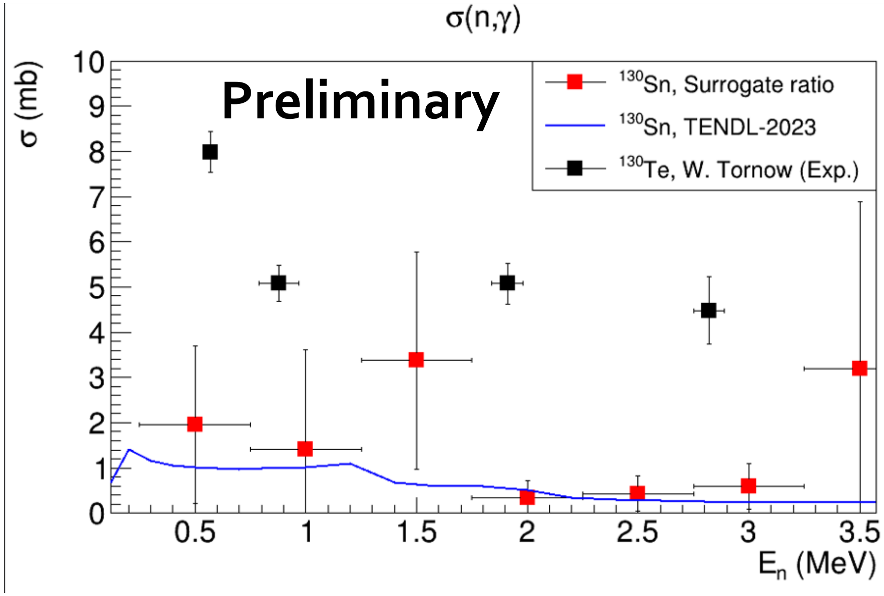


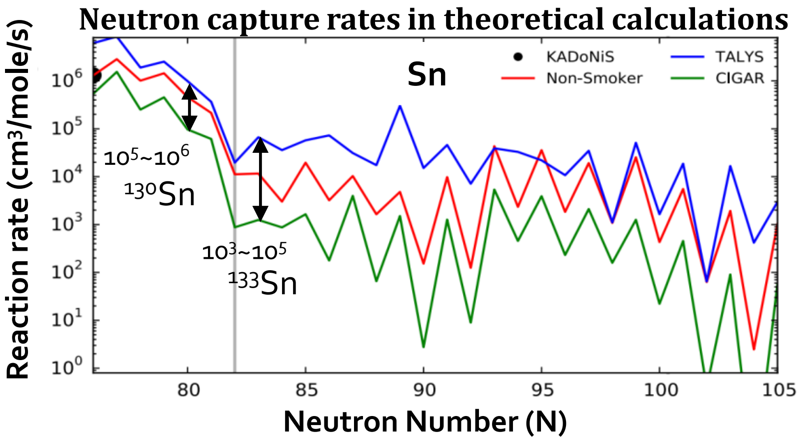
P_γ(E) of ^{131}Sn/^{131}Te

- P_γ drops before S_{1n} due to excitation energy resolution (a few hundred keV),.
- Above S_{1n}, P_γ is larger in Te than Sn in general.



$^{130}Sn(n,\gamma)$ cross section





Prog. Part. Nucl. Phys. 86, 86-126 (2016)

- Things to do…
  - Validity check with $^{124}Sn(d,p)$ data
  - Absolute surrogate approach with J,π consideration
  - Evaluate the impact using *r*-process models
  - New proposal for $^{133}Sn(d,p)$ measurement

^{56}Ni(d,pp) reaction

J.T. Li (U-Tokyo), B. Mauss (CEA-DAM) & D. Suzuki (RIKEN/U-Tokyo)

Abundance puzzle of certain p-nuclei

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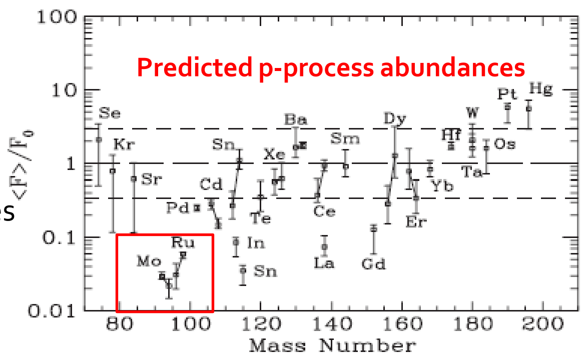
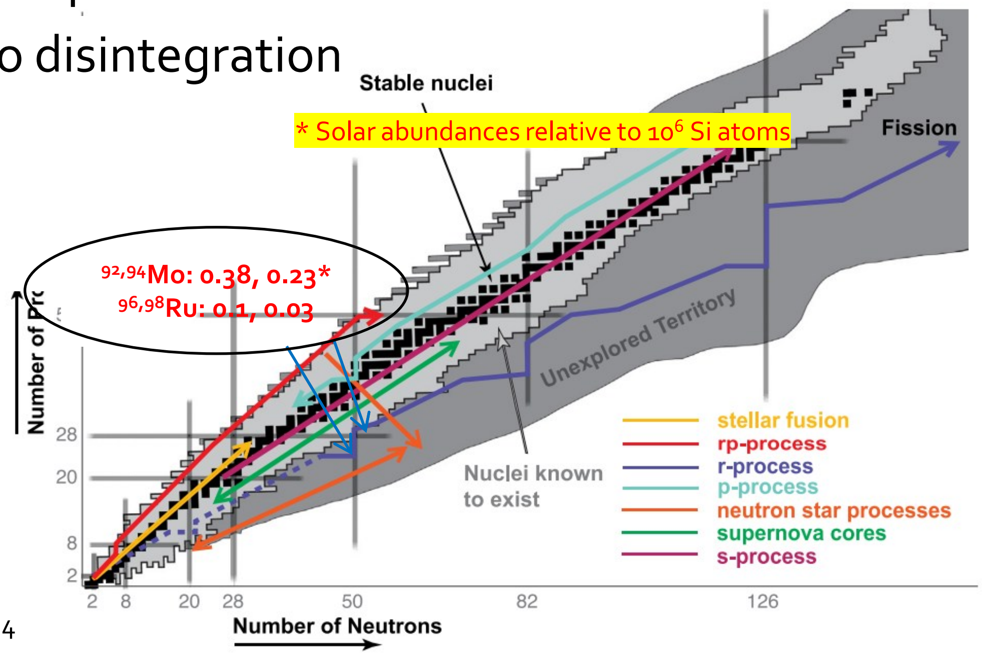
- Anomalously large abundance of light p-nuclei such as ^{92,94}Mo, ^{96,98}Ru
- How are light Mo and Ru p-isotopes formed?
  - Cannot be produced by s- and r-process
  - Cannot be explained by photo disintegration (p-process) alone

F: Overproduction factor with respect to solar abundances



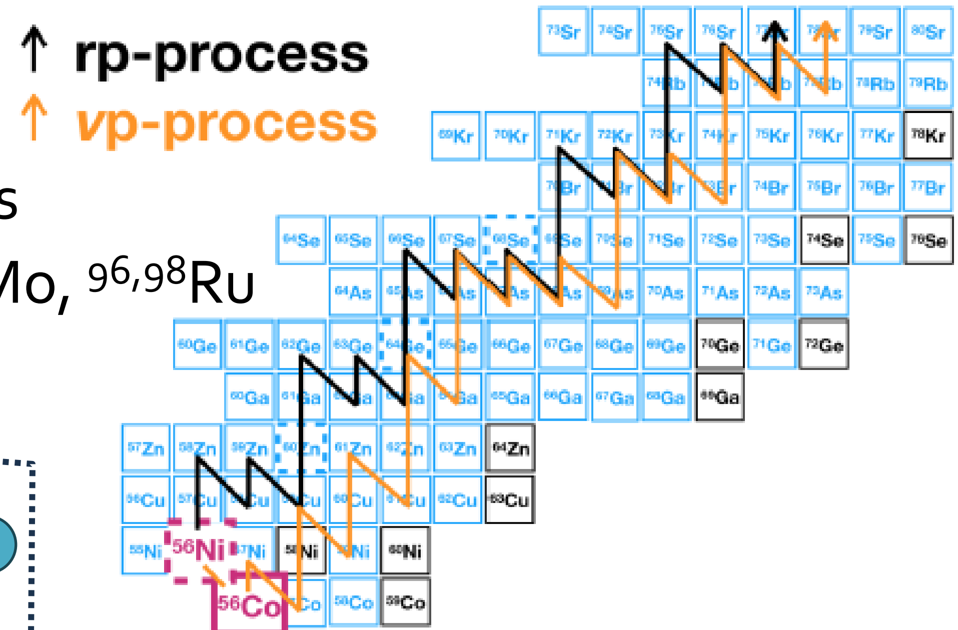
M. Arnould and S. Goriely, Physics Reports **384** (2003) 1-84



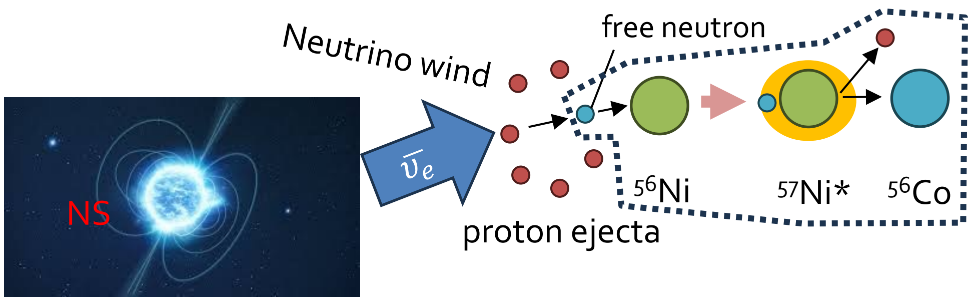
A. Arcones et al., Progress in Particle and Nuclear Physics **94** (2017) 1-67

Neutrino driven rapid-proton capture (νp) process

- Proton-rich ejecta in core collapse supernovae
  + strong neutrino flux from central neutron star (NS)
  - $p + \bar{\nu}_e \rightarrow n + e^+$
- Most critical waiting point:
  - ^{56}Ni, $T_{1/2}$ = 6 days
- ^{56}Ni + n → ^{57}Ni* → p + ^{56}Co
  - Bypass from rp- to νp-process
  - Flow to heavier p-nuclei ^{92,94}Mo, ^{96,98}Ru
  - Cross section not measured



^{56}Ni(n,p)^{56}Co



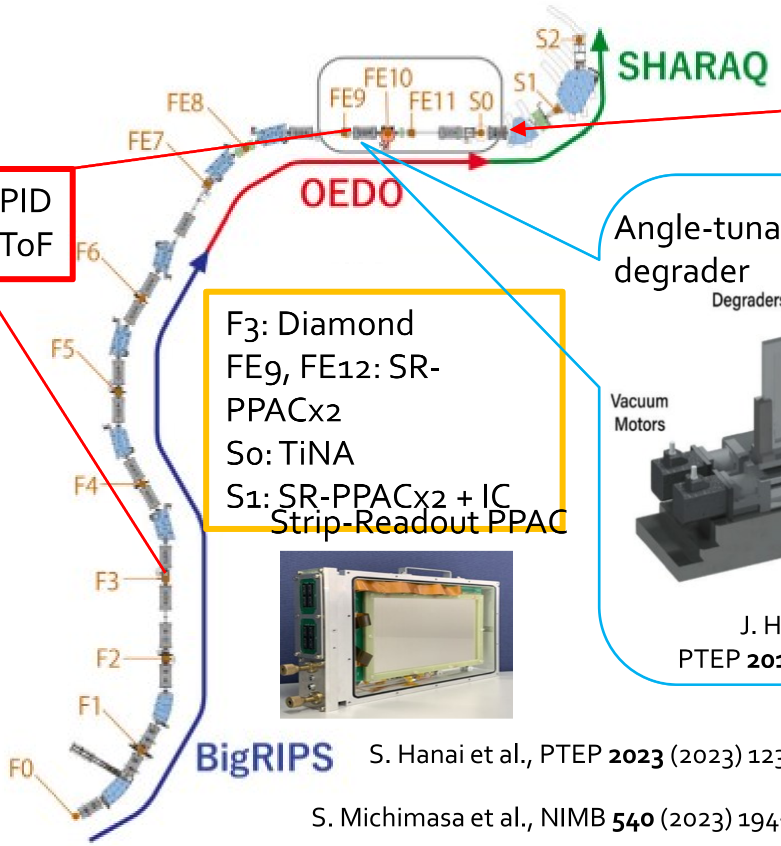
Beam parameters

Primary beam: ^{78}Kr 345 MeV/u
Secondary beam: ^{56}Ni, ^{58}Ni
- Produced and purified by BigRIPS
  - before FE9: 113 MeV/u
- Energy-degraded by OEDO
  - after FE9: 15.5 ± 0.5 MeV/u

Transmission from F3 to FE12: ~75%

Secondary target

Beam PID by B_ρ-ToF



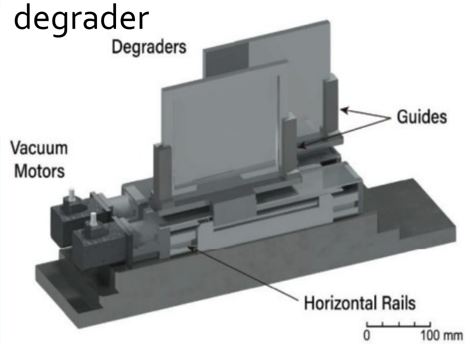
F3: Diamond
FE9, FE12: SR-PPACx2
S0: TiNA
S1: SR-PPACx2 + IC

Strip-Readout PPAC

S. Hanai et al., PTEP **2023** (2023) 123H02

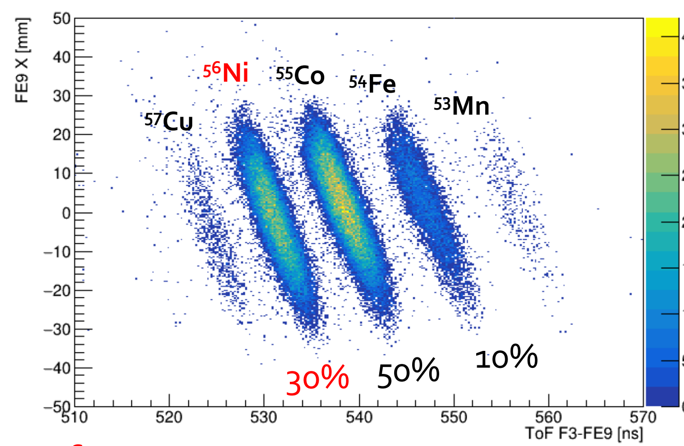
S. Michimasa et al., NIMB **540** (2023) 194-198

Angle-tunable wedge degrader



J. Hwang et al., PTEP **2019** (2019) 043D02

Beam Identification @ FE9

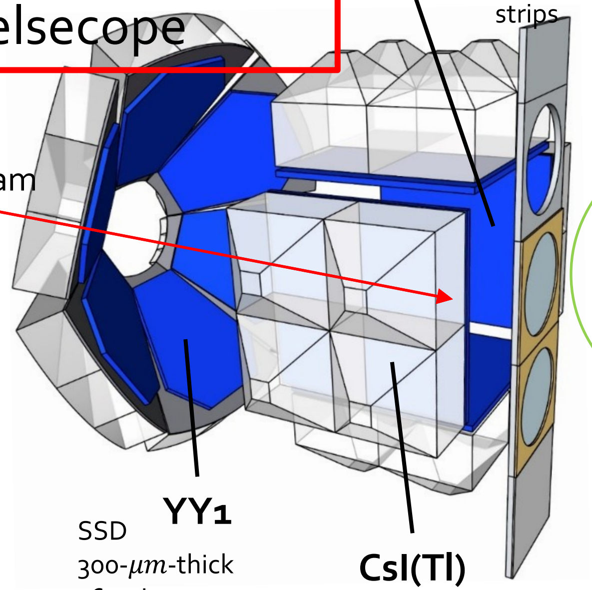


^{56}Ni rate ~150 kcps

Missing mass of ^{57}Ni

TiNA @ So
Si-CsI
telsecope

TTT
DSSD
300-μm-thick
128x128
strips



YY1
SSD
300-μm-thick
16 strips

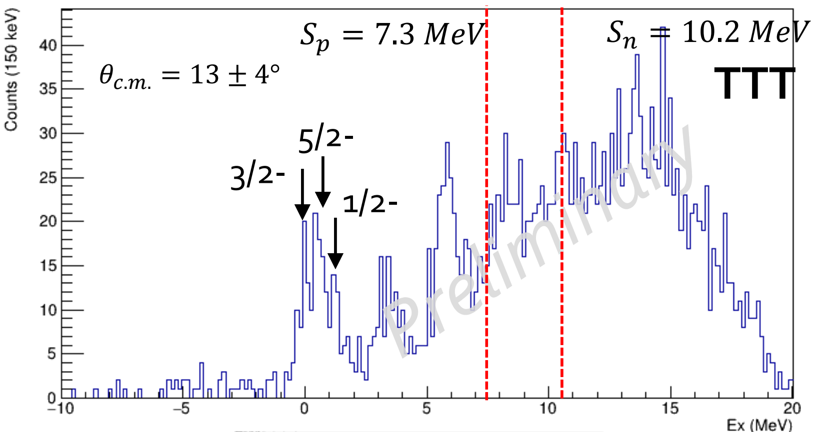
CsI(Tl)

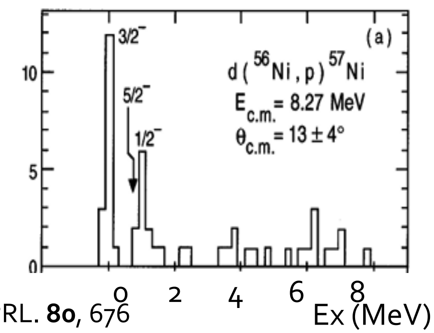
B. Mauss et al., RIKEN Accel. Prog. Rep. **54**, 114 (21)

CD2 target
644 & 285 μg/cm²

Angular Coverage
$100^{\circ}\sim170^{\circ}$ lab
$0^{\circ}\sim40^{\circ}$ c.m.
Angular Resolution
TTT: $< 0.8^{\circ}$
YY1: $< 1.2^{\circ}$

^{56}Ni(d,p)^{57}Ni at 15.5 MeV/u ($E_{c.m.} = 30\ MeV$)

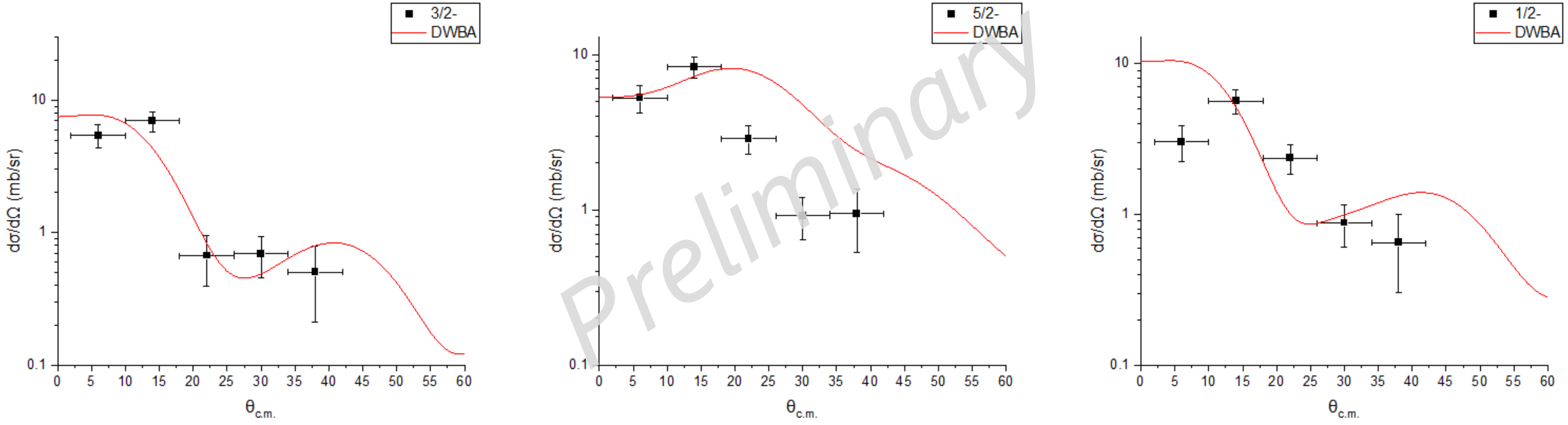




K. Rehm et al., PRL. **80**, 676 (1998)

Angular distribution

- First three bound states in ^{57}Ni

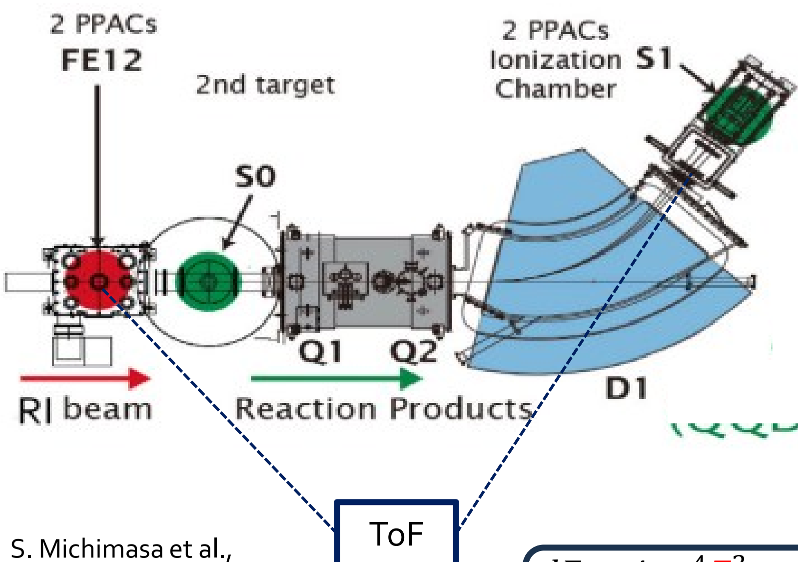


25-29/Aug/2025

Decay channels

SHARAQ QQD mode

- Direct measurement of reaction residues
- Momentum Acc.: ±3%
- Angle Acc.: ±30 mrad
- Transmission: ~ 50%



S. Michimasa et al.,
NIMB **540** (2023) 194-198

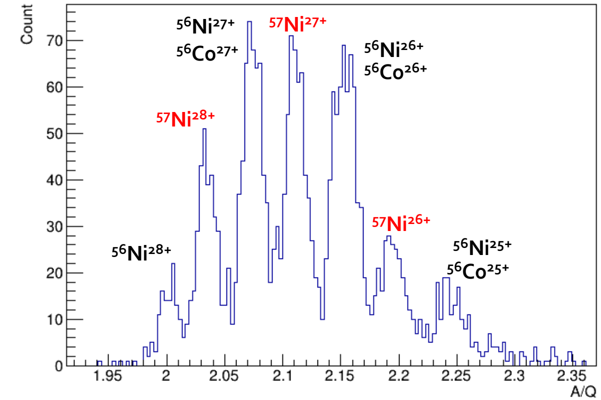
Particle identification
ToF-B_ρ-ΔE method

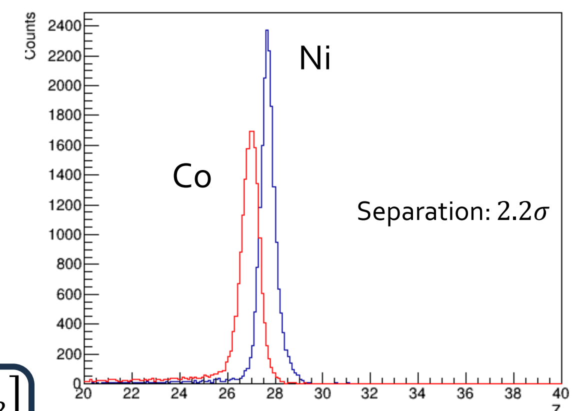
- A/Q
  - Time of Flight: FE12 – S1
  - Magnetic rigidity: position @ S1

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

- Z
  - Energy loss in IC

$$\frac{dE}{dx} = \frac{4\pi e^4 Z^2}{m_e v^2} N_z \left[ln\frac{2m_e v^2}{I} - \ln(1-\beta^2) - \beta^2 \right]$$





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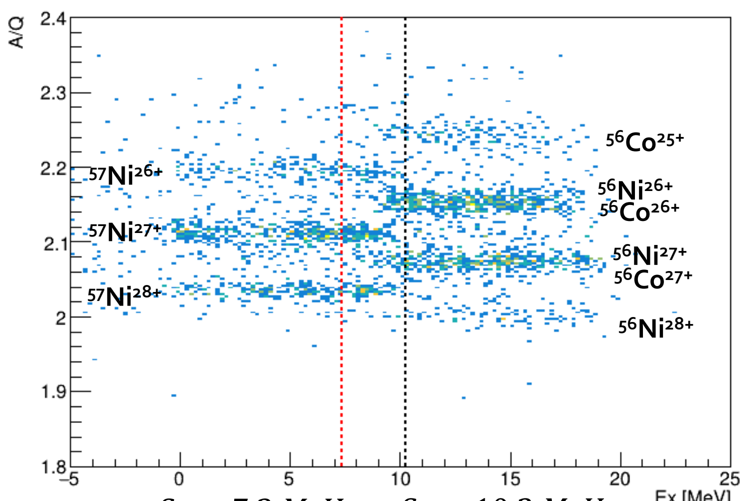
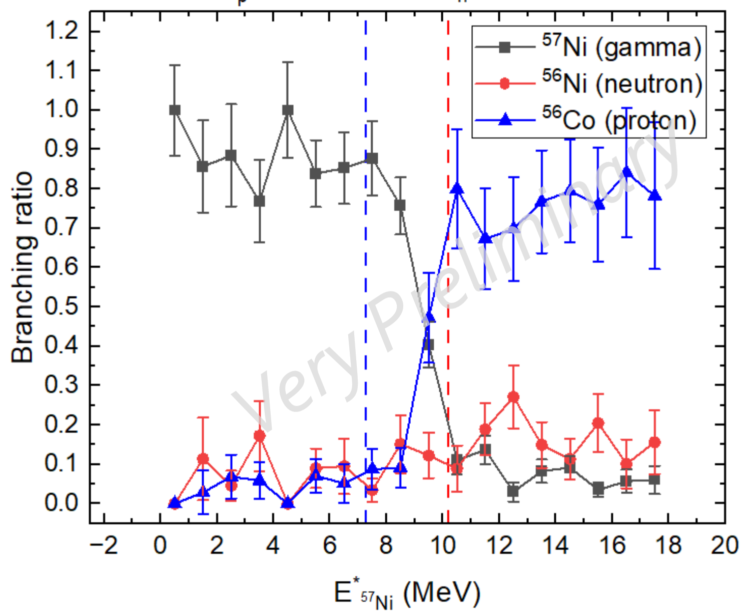
Decay branch of ^{57}Ni

- **A/Q vs Ex**

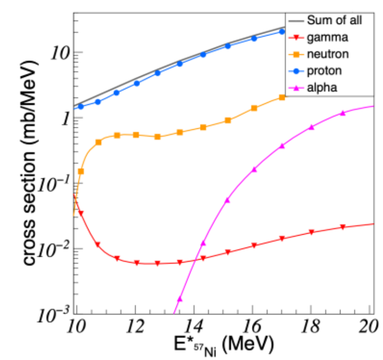


$S_p = 7.3\ MeV \qquad S_n = 10.2\ MeV$

- **Decay branching ratio of ^{57}Ni**

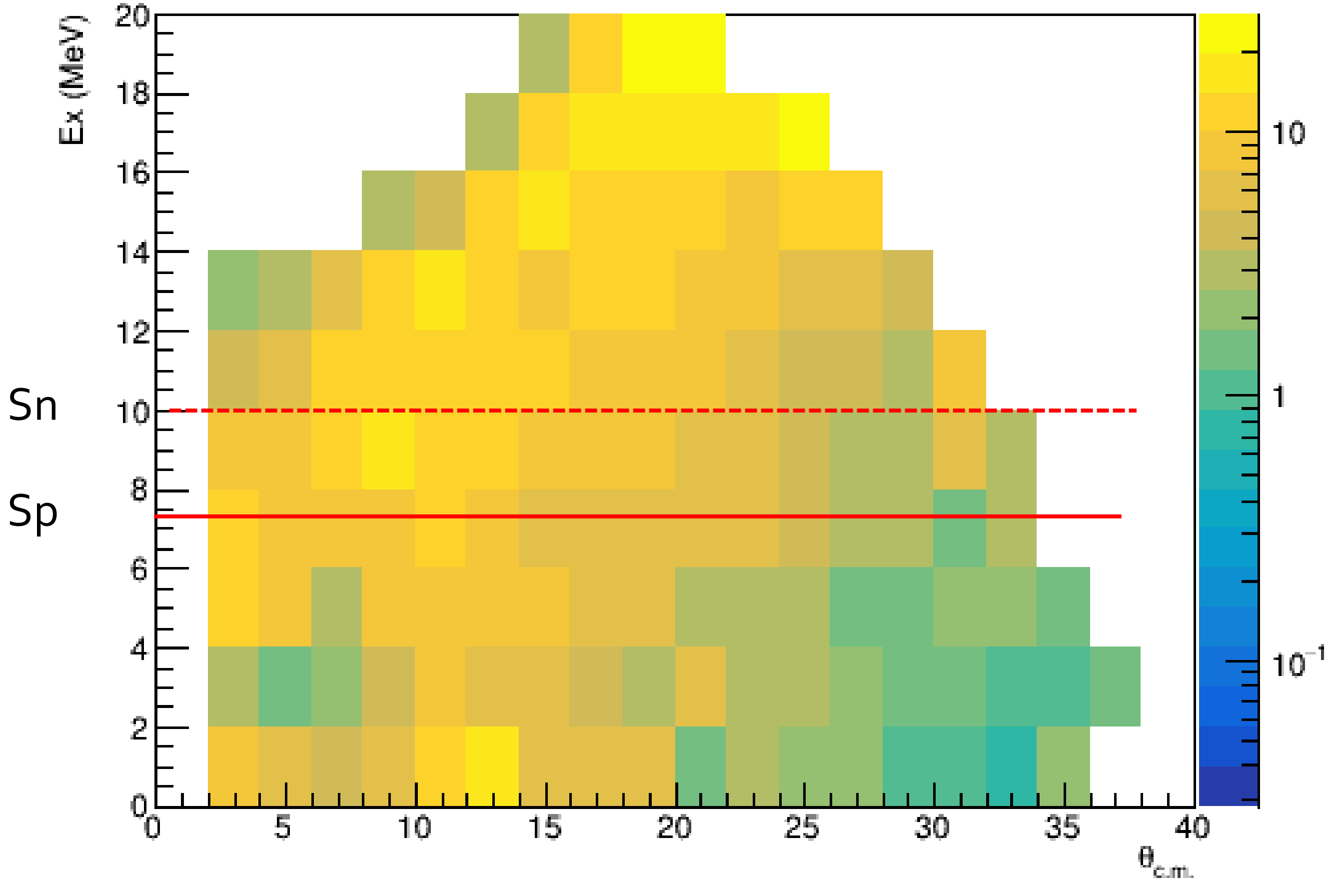


TALYS calc.



^{56}Ni(d,p) double differential cross section

Double differential cross section $\frac{d^2\sigma}{dE d\Omega}$



^{93}Zr(p,X) @30 MeV

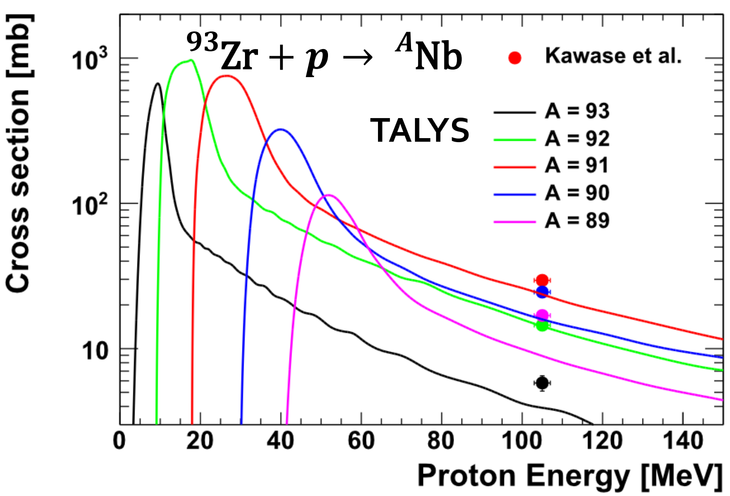
J.W. Hwang, M. Dozono

$^{93}Zr + p/d$: Introduction

- Long-lived fission products (LLFPs)
  - One of the most intractable components in high-level waste (HLW)
  - ^{93}Zr: most abundant LLFP
    - $t_{1/2} = 1.53 \times 10^6$ years
    - 6% of production yields of ^{235}U fission
- Nuclear transmutation (ADS) of ^{93}Zr
  - Neutron-induced: low cross section
  - $^{93}Zr + p/d$: expected to be effective
  - Previous study at higher energies
  - Larger cross sections expected at low *E*
  - Reaction mechanism of *d*-induced reaction

Abundant LLFPs

Nuclide	Half-life (years)	In 1 ton of spent fuel
^{129}I	1.57×10^7	0.2 kg
^{107}Pd	6.5×10^6	0.3 kg
^{135}Cs	2.3×10^6	0.5 kg
^{93}Zr	$\mathbf{1.53 \times 10^6}$	**1 kg**
^{79}Se	2.95×10^5	6 g
^{99}Tc	2.11×10^5	1 kg
^{126}Sn	1.0×10^5	30 g



S. Kawase et al., Prog. Theor. Exp. Phys. 2017, (2017) 093D03.

$^{93}\mathrm{Zr} + p/d$: Setup

- OEDO Day0 exp.(Nov. 2017)
- BigRIPS-OEDO-SHARAQ
- Inverse kinematics

Spectrometer

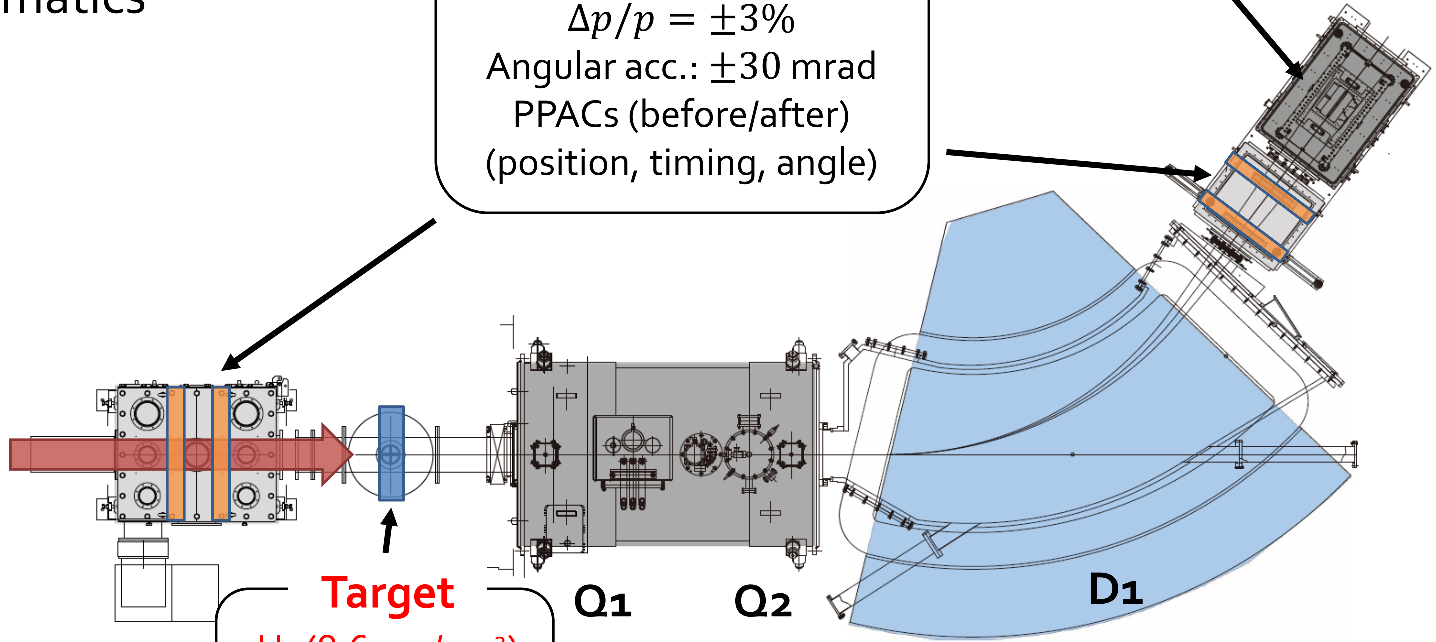
SHARAQ (QQD)
$\Delta p/p = \pm 3\%$
Angular acc.: ± 30 mrad
PPACs (before/after)
(position, timing, angle)

Ionization Chamber

ΔE and E
Bragg curve fitting

Beam

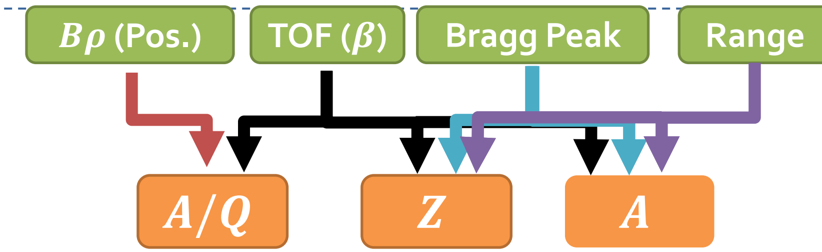
^{93}Zr
~27 MeV/u
1.5 x 10^3 cps
BigRIPS-OEDO



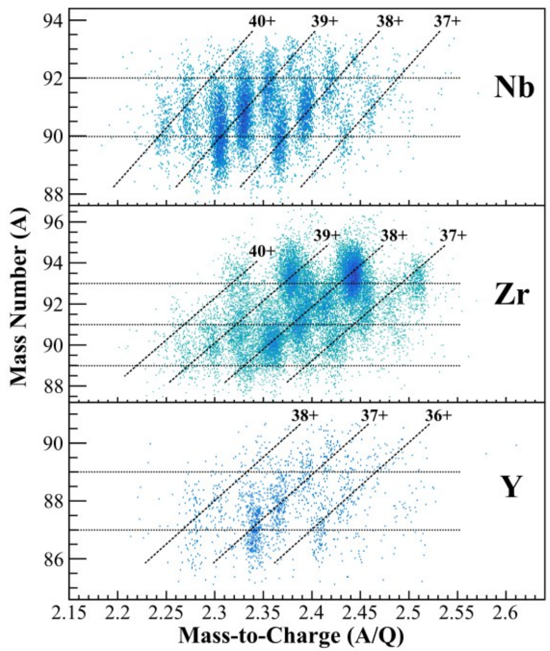
Target

H_2 (8.6 mg/cm^2)
D_2 (16.9 mg/cm^2)
~ 2 atm, ~ 40K

$^{93}Zr + p/d$: PID

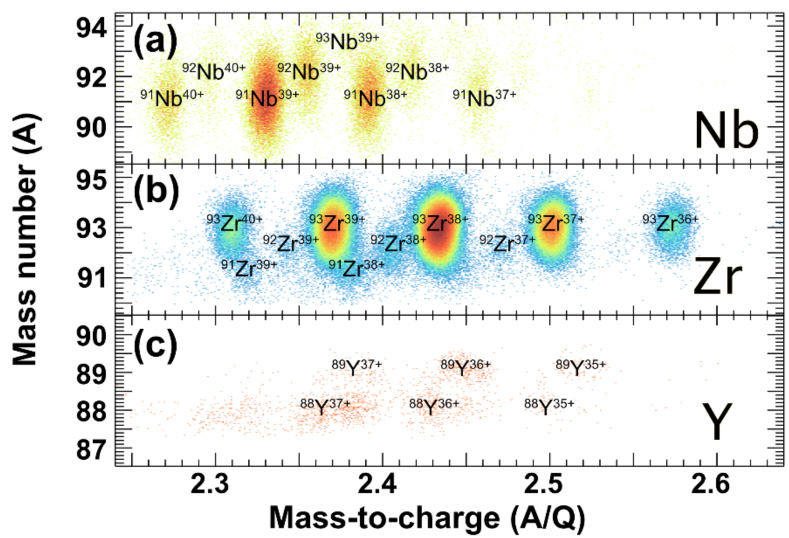


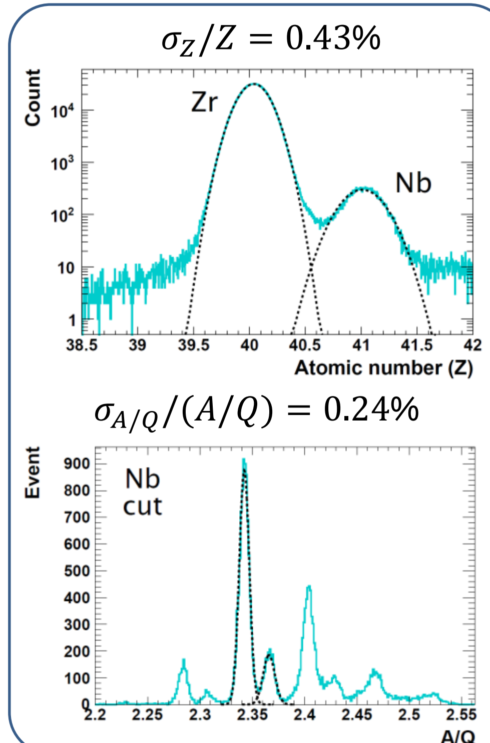
$^{93}Zr + d$: A vs A/Q



Courtesy of T. Chillery

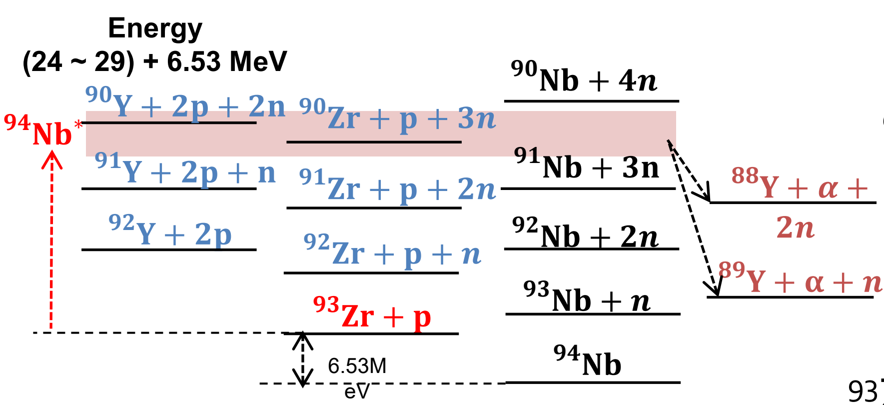
$^{93}Zr + p$: A vs A/Q

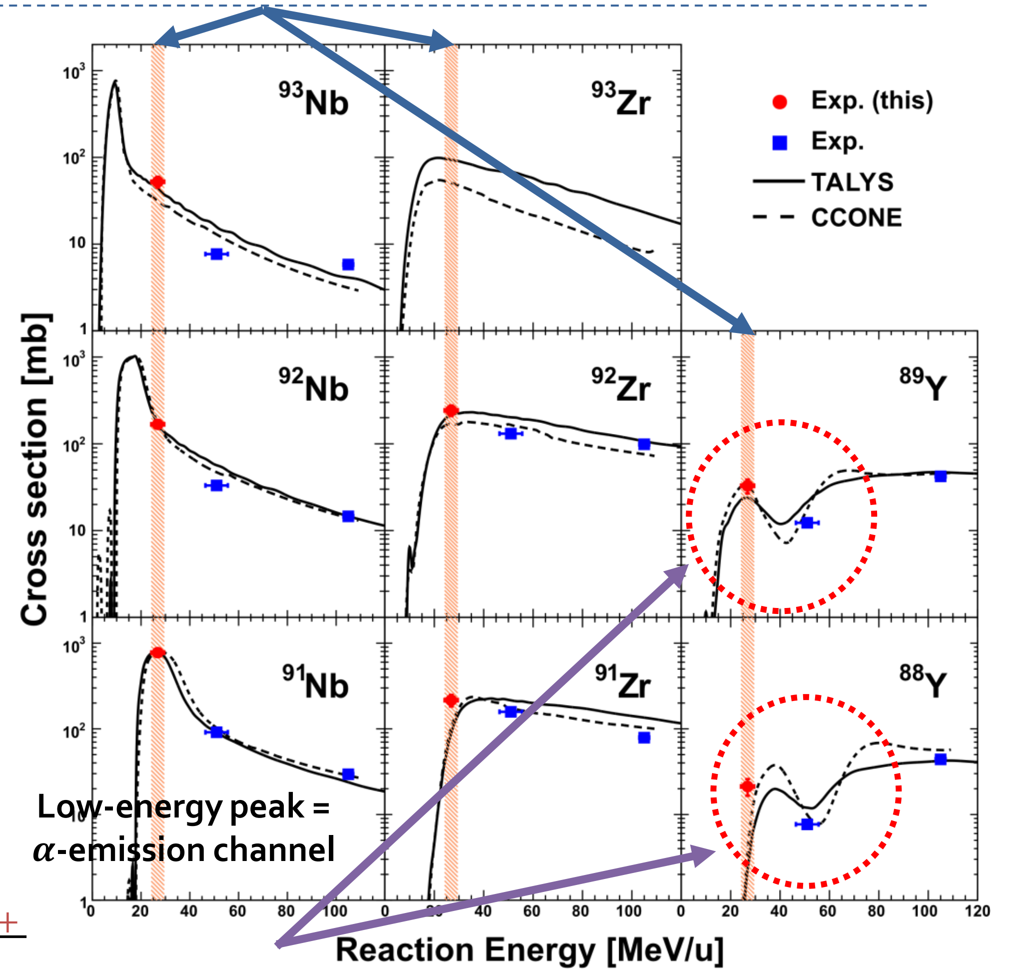




$^{93}\mathrm{Zr} + p$: Results

- Transmutation cross-sections
  - Experiment: **24 ~ 29 MeV/u**
  - TALYS & CCONE
  - $^{93}\mathrm{Zr} + p \rightarrow {}^{94}\mathrm{Nb}^*$
  - $^{94}\mathrm{Nb}^* \rightarrow \begin{cases} {}^{A}\mathrm{Nb} + xn \\ {}^{A}\mathrm{Zr} + p + xn \\ {}^{A}\mathrm{Y} + 2p + xn \end{cases}$





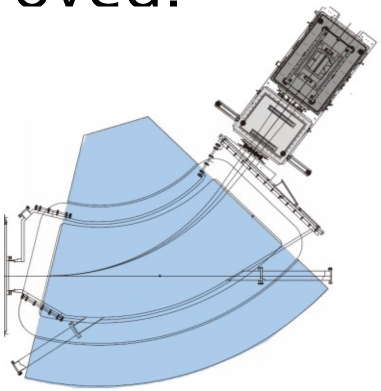
S. Kawase et al., Prog. Theor. Exp. Phys. 2017, (2017) 093D03.
K. Nakano et al., EPJ Web of Conferences 239, (2020) 20006.

^{93}Zr+p, J.W. Hwang et al., PTEP093D03 (2024).

Future plan

System to be updated

- Transmission of D1 magnet should be improved.
  - Larger acceptance
  - Optics study
- Improvement of recoil proton detection
  - CsI(Tl) will be replaced with SSD
  - Forward barrel to measure the elastic scattering.
- Gamma-ray detector array
  - GAGG or CsI(Tl)



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Univ. of Tokyo

Collaborators of ImPACT-17

N.Imai, S.Michimasa, M.Dozono, S.Ota, M.Takaki, J.Hwang, C.Iwamoto, S.Masuoka, N.Kitamura, K.Kawata, H.Simizu, R. Tsunoda, S.Hayakawa, P.Schrock, O.Beliuskina, L.Yei, H.Yamaguchi, K.Yako, K.Wimmer,
T.Sumikama, H.Otsu, H.Wang, S.Takeuchi, S.Kawase, N.Chiga, X.Sun,
S.Naimi, D.Nagae, S.Omika, K.Chikaato, T.Teranishi, K.Iribe, K.Yoshida,
E.Ideguchi, Y.Fan, Y.Watanabe, K.Nakano, H.Miyatake, Y.X.Watanabe, T.Nakamura, K.Yoshida, N.Fukuda, Y.Shimizu,
H.Suzuki, H.Takeda, D.S.Ahn,
Y.Yanagisawa, K.Kusaka, T.Ohtake,
H.Sakurai, and S.Shimoura

ImPACT

RIKEN NISHINA CENTER

Collaborators of SAKURA project

(CNS, Univ. of Tokyo) S. Michimasa, S. Ota, M. Dozono, S. Hayakawa, N.Kitamura, K. Kawata, S. Masuoka, H. Shimizu, R. Tsunoda, S. Hanai, S. Shimoura, H. Tamaguhi, K. Yako

(Tohoku U) N.Iwasa, T. Haginouchi, M. Egeta, S. Ishio, S. Ishikawa, F. Endou, K. Sakuma,

(RIKEN Nishina Center)S. Kubono, D. Suzuki, B. Mauss, T. Sumikama,

(Seville)A. Moro, L. Jin,

(Santiago de Compostela)F-D. Beatriz,

(IJS lab) F. Serge, D. Beaumel,

(Univ. of Catania) S. Cherubini

(Kyushu univ) H. Tanaka, T. Teranishi, Y. Watanabe, S. Kawase

(RIKEN) N. Nishimura

(IMP) Hooi-Jin Ong, T. Xiaodong, Y. Xu, B.S. Gao,