東京大学 大学院
理学系研究科・理学部
SCHOOL OF SCIENCE, THE UNIVERSITY OF TOKYO

RIKEN

Using (d,p) Transfer Reactions at OEDO-SHARAQ to Measure Astrophysical Reactions Important in *r*- and *νp*- processes

Thomas Chillery

For the SAKURA Collaboration

Postdoc Researcher

~~CNS, School of Science~~
~~The University of Tokyo~~ → INFN-LNGS

DREB 2024

25th June 2024

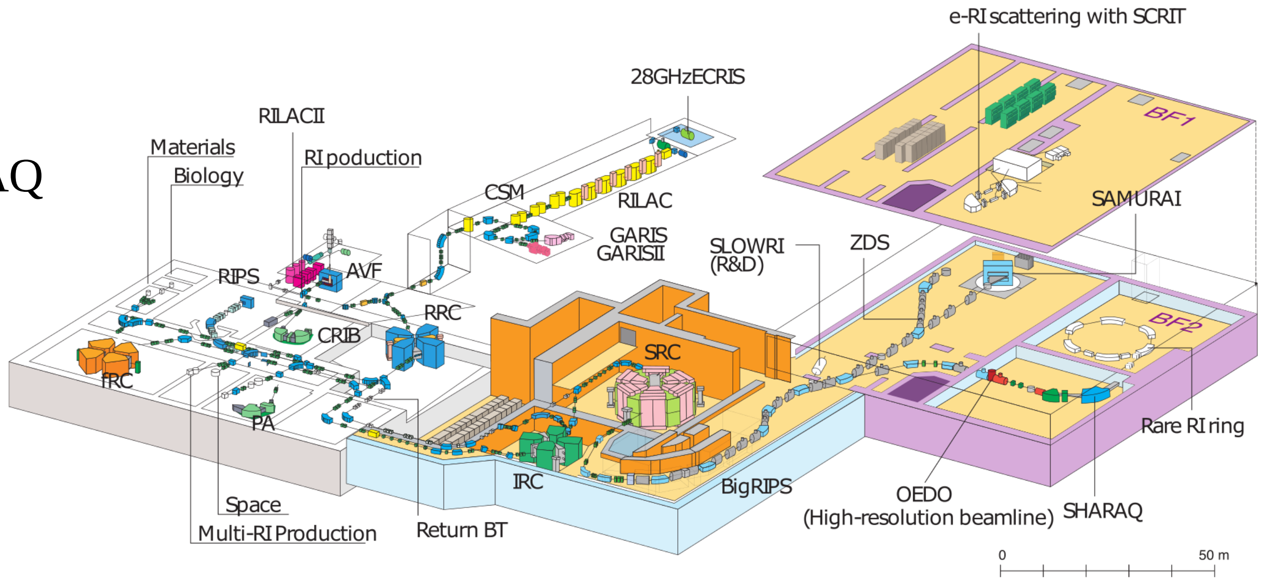
Outline

- Motivation + Goal
  - SH18: *r*-process Nucleosynthesis **^{130}Sn(d,p)**
  - SH19: *vp*-process in CCSNe **^{56}Ni(d,p)**

  } Spring 2022

- Experimental Method
  - Surrogate Ratio

- Experimental Setup
  - BigRIPS + OEDO-SHARAQ
  - TiNA Detector Array

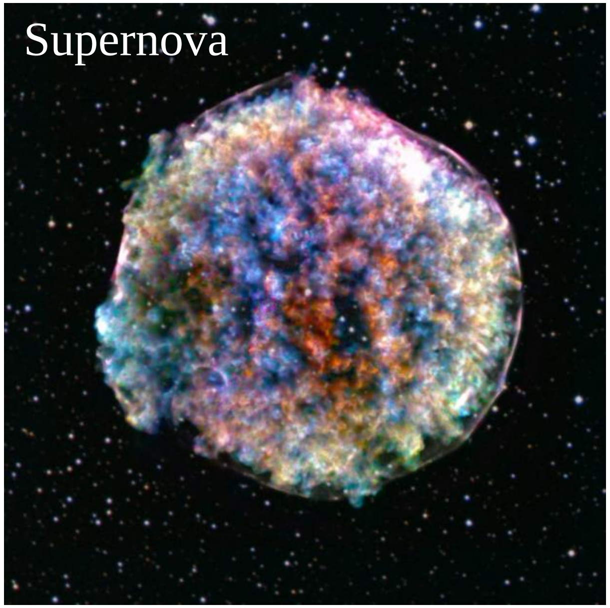


- Preliminary Analysis
  - Beam PID
  - TiNA Proton Spectra
  - Ionisation Chamber

- Conclusions and Future Outlook

^{130}Sn(n,γ) Motivation

^{130}Sn(d,p)



Credit: X-ray: NASA/CXC/RIKEN & GSFC/T. Sato *et al*; Optical: DSS

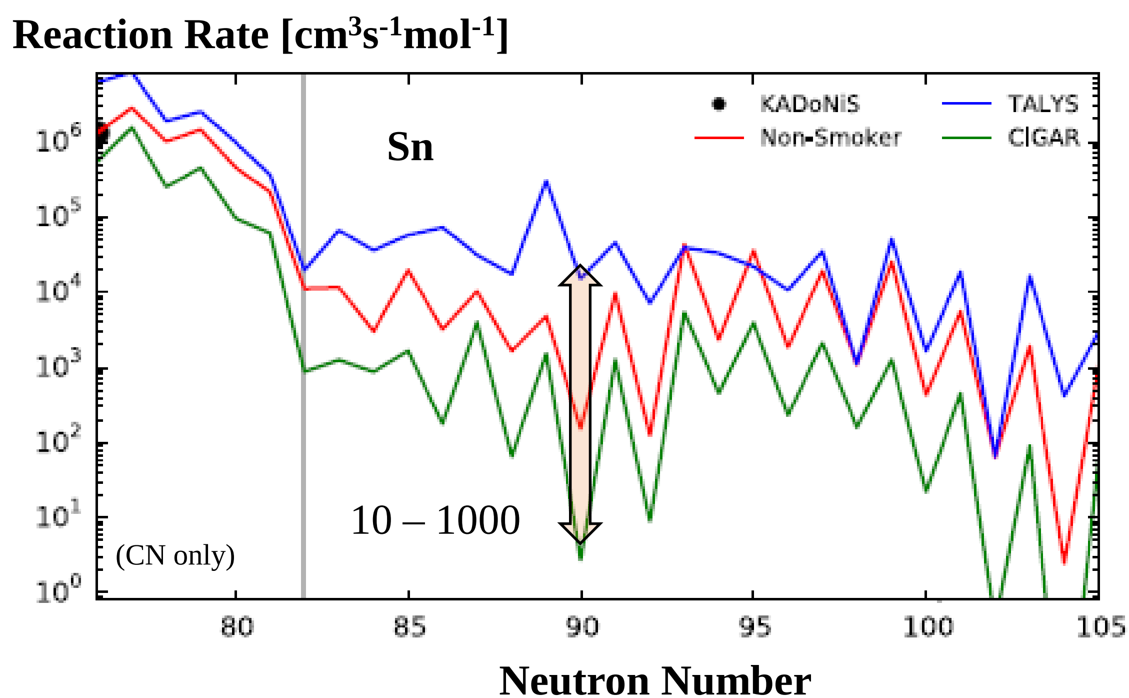
Credit: University of Warwick/Mark Garlick

Where do the heavy neutron-rich isotopes come from?

- *r*-process nucleosynthesis
  - CCSNe and/or NS-mergers
  - Large neutron density: $10^{20\text{-}26}$ cm^{-3}

n-capture on Tin

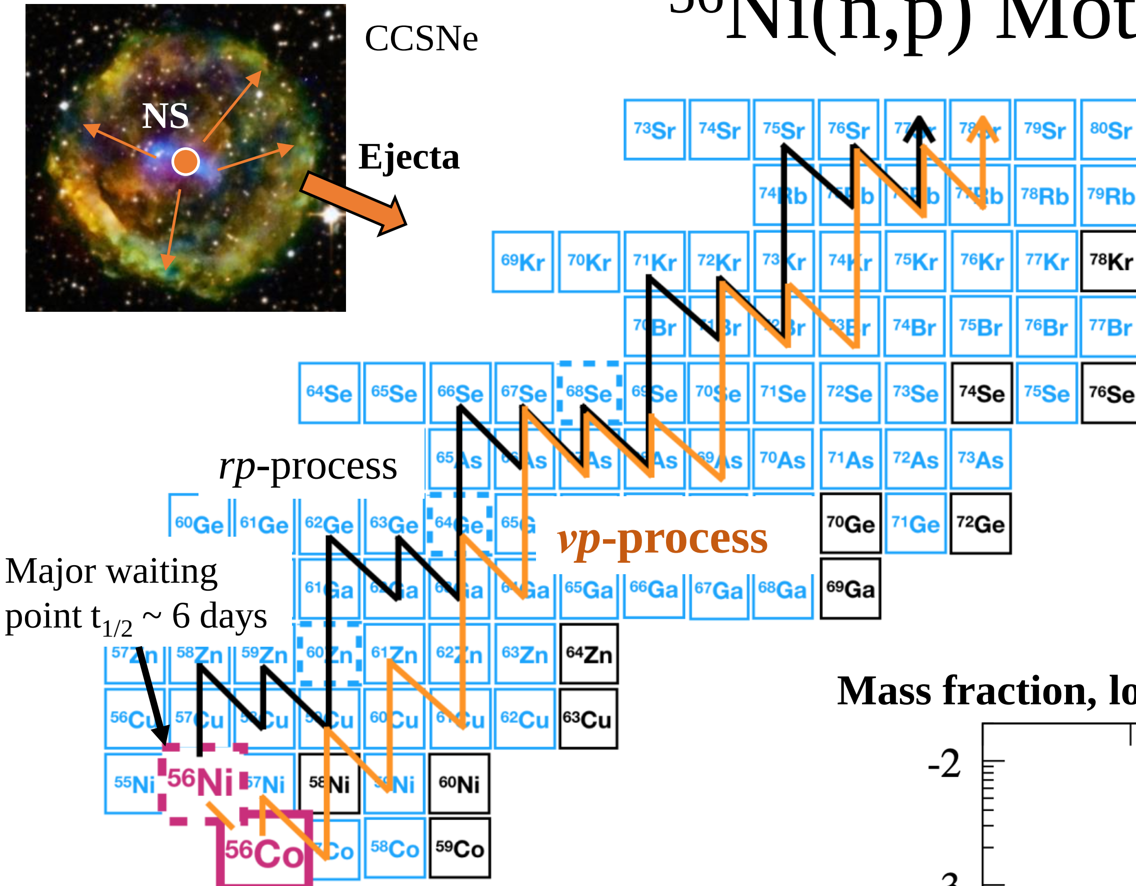
- Models disagree on reaction rate by several orders magnitude



M.R. Mumpower *et al.* Prog. Part. Nucl. Phys. 86 (2016) 86-126

^{56}Ni(n,p) Motivation

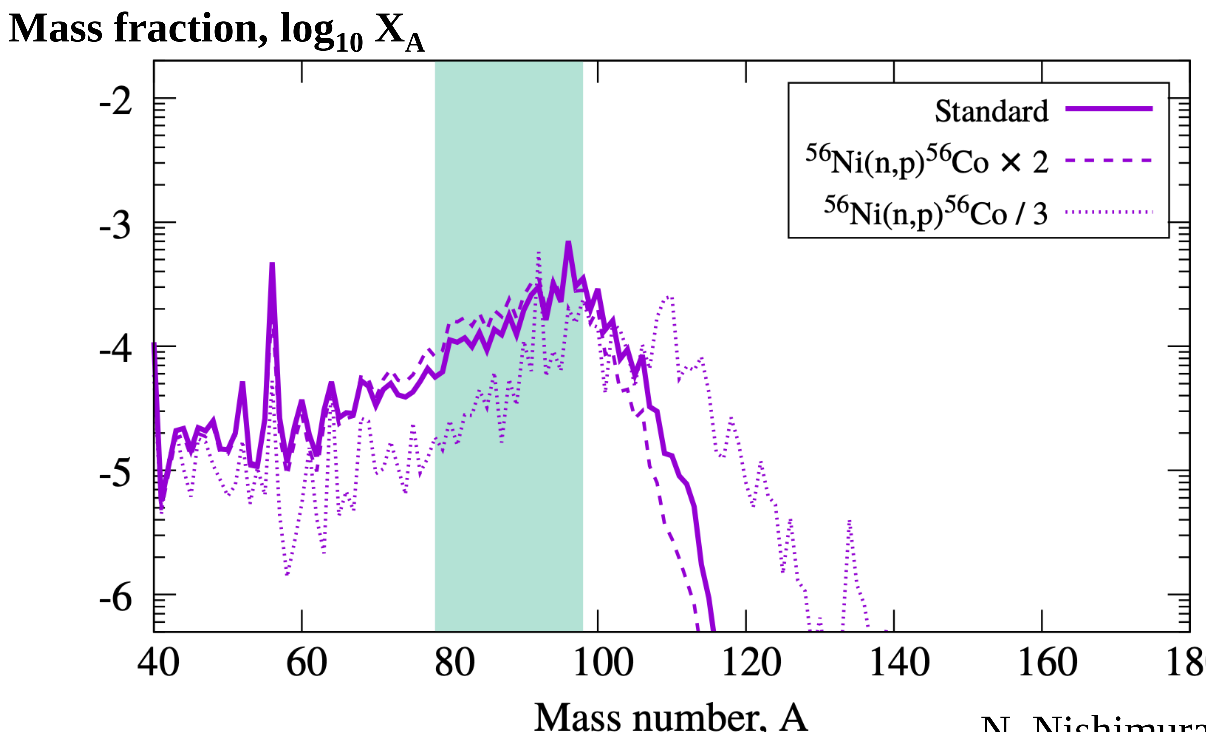
^{56}Ni(d,p)



Where do the heavy proton-rich isotopes come from?

X-ray bursts: *rp*-process?
- Products trapped by NS gravity!

CCSNe: *νp*-process?
- ^{56}Ni β-decay too long but…
- ^{56}Ni(n,p)^{56}Co → flow to heavy p-nuclei



N. Nishimura

Different assumptions
→ large abundance changes

^{60}Zn,^{64}Ge(n,p) important but less so…

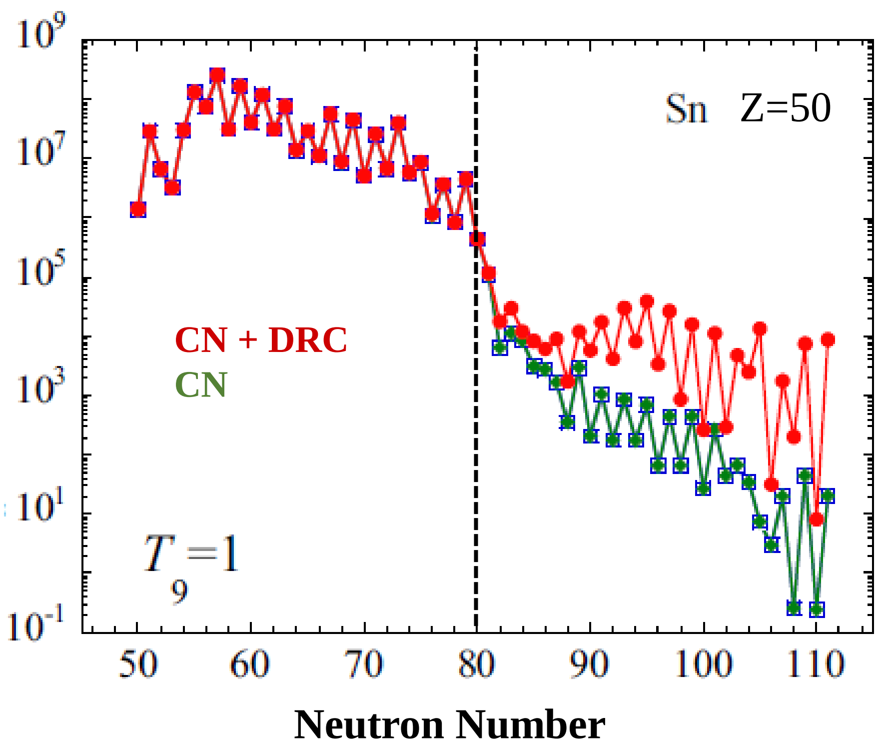
Goals

^{130}Sn(d,p)

Measure ^{130}Sn(d,p) ~ 22 MeV/nucleon

Determine CN and DRC cross-section components for γ-decay channel

Reaction Rate [cm^{3}s^{-1}mol^{-1}]



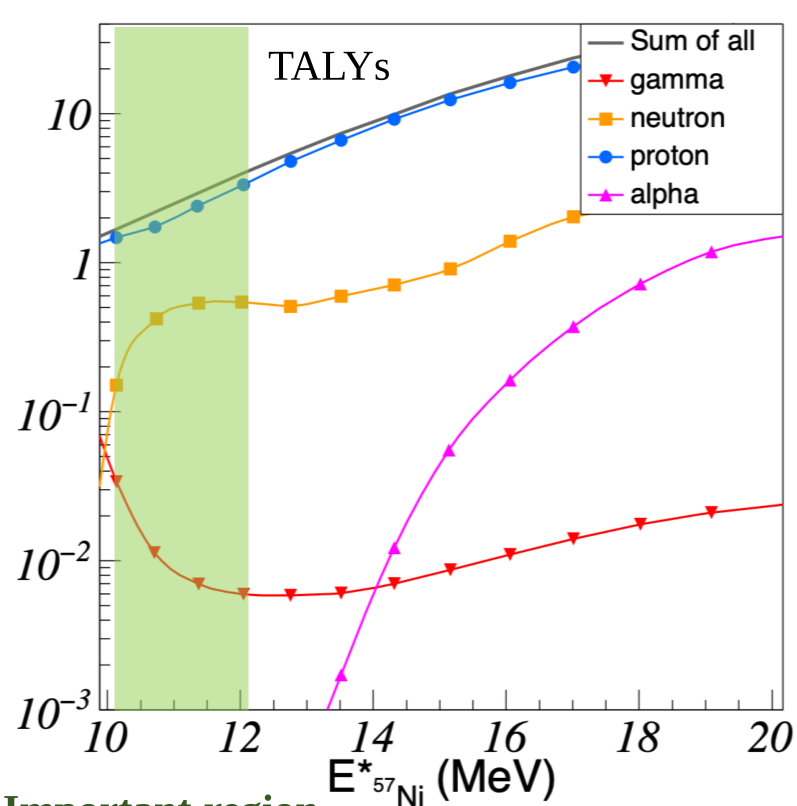
Y. Xu and S. Goriely *et al.* PRC 90 (2014) 024604

^{56}Ni(d,p)

Measure ^{56}Ni(d,p) ~ 15 MeV/nucleon

Determine cross sections for p-decay channel

Cross Section [mb/MeV]



Important region for *νp*-process

B. Mauss & D. Suzuki

Surrogate Ratio

For CN component of $\sigma_{(n,\gamma)}$:
Surrogate ratio method

$$\sigma_{^{130}Sn(n,\gamma)} = \qquad ???$$

Goal

Surrogate Ratio

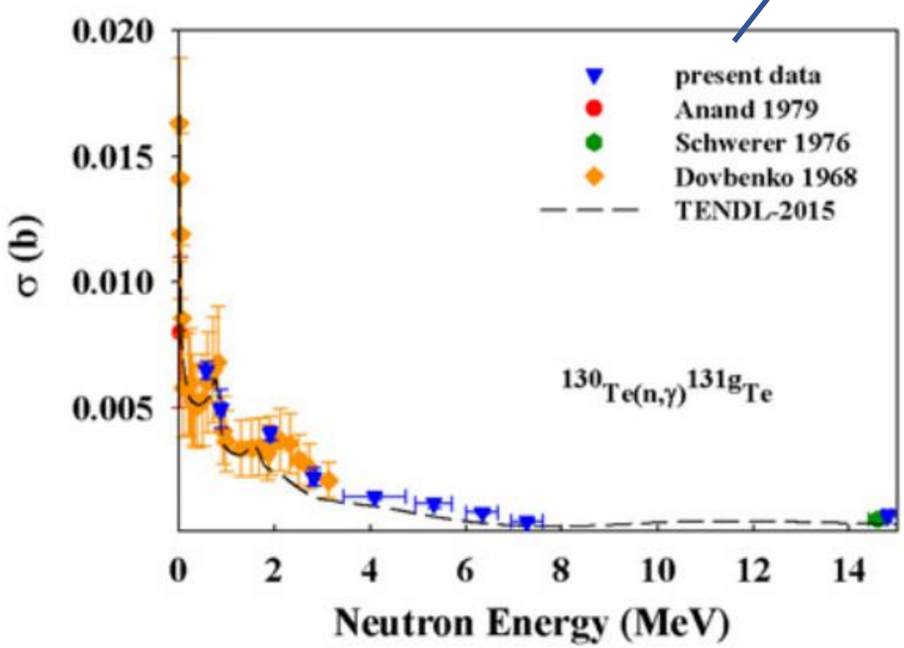
For CN component of $\sigma_{(n,\gamma)}$:
Surrogate ratio method

Theory (Optical Model)

$$\sigma_{130Sn(n,\gamma)} = \sigma_{130Te(n,\gamma)} \times \frac{\sigma^{CN}_{131Sn}}{\sigma^{CN}_{131Te}} \times \quad ???$$

Goal

Reference



W. Tornow *et al.* EPJ Web. Conf. 146 (2017) 09013

Surrogate Ratio

Similar technique applied for $^{56}Ni(d,p)^{57}Ni$

For CN component of $\sigma_{(n,\gamma)}$:
Surrogate ratio method

Theory (Optical Model)

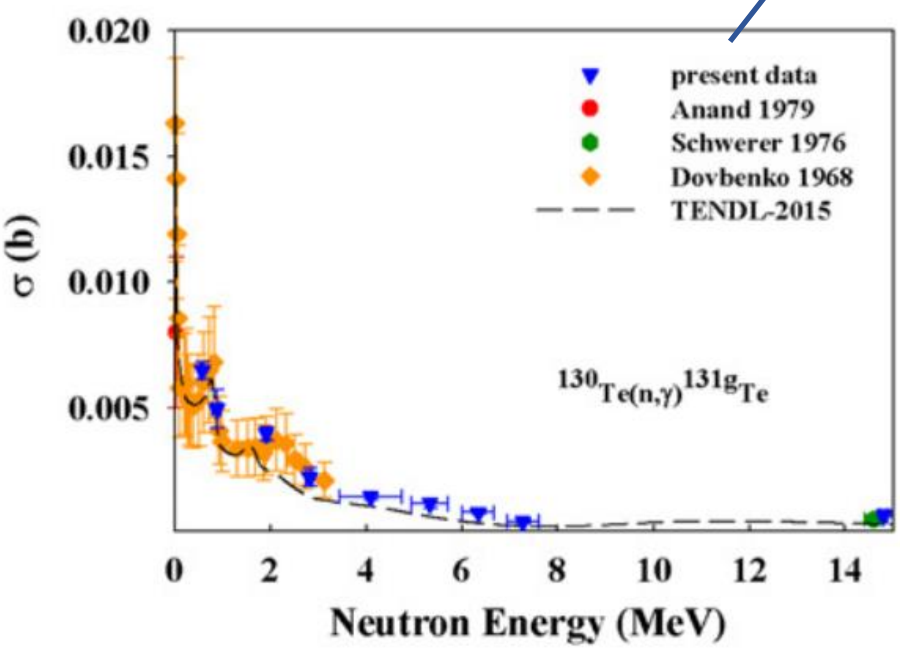
$$\sigma_{130Sn(n,\gamma)} = \sigma_{130Te(n,\gamma)} \times \frac{\sigma^{CN}_{131Sn}}{\sigma^{CN}_{131Te}} \times \frac{P_\gamma^{131Sn}}{P_\gamma^{131Te}}$$

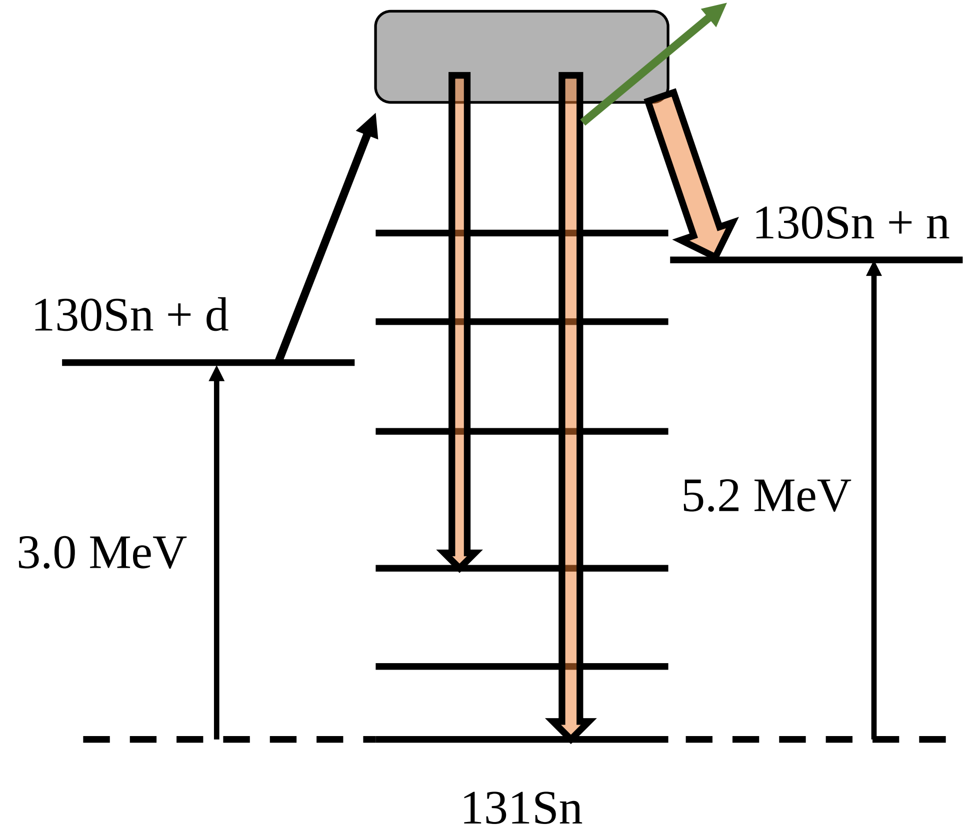
MEASURE

Goal

Reference

P_γ^{131Sn}



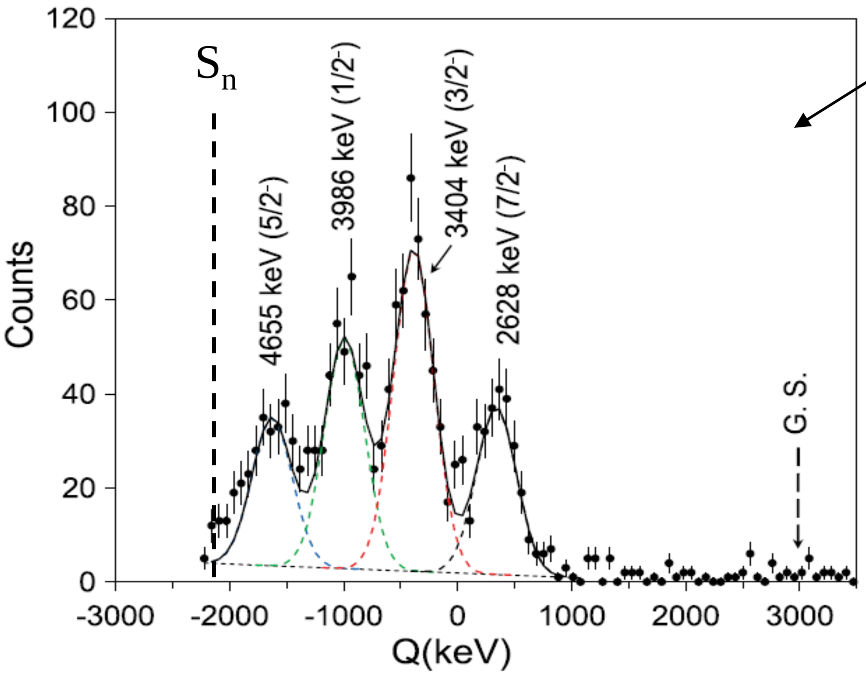


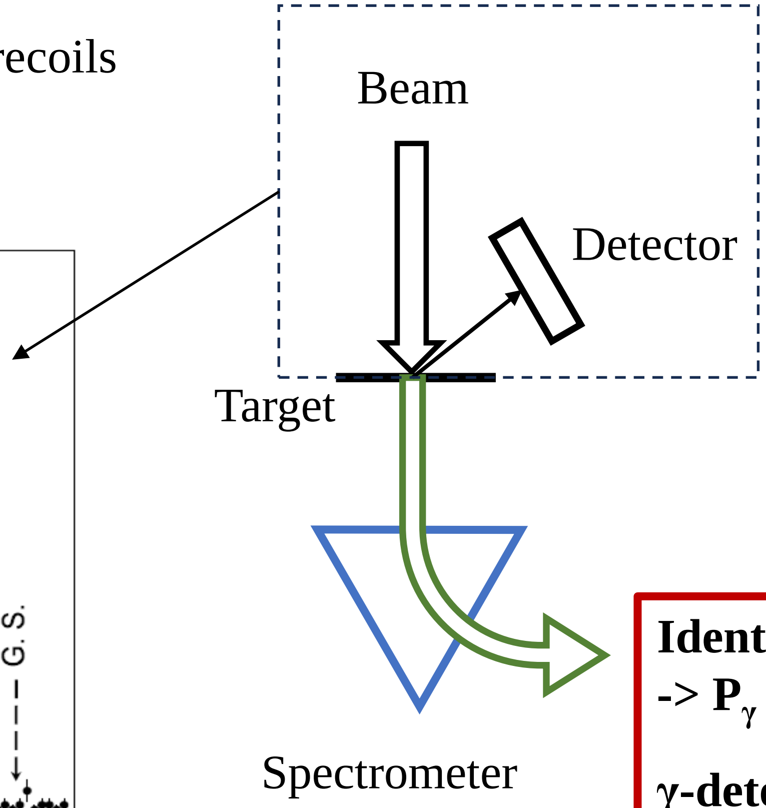
W. Tornow *et al.* EPJ Web. Conf. 146 (2017) 09013

How to measure decay probability? (P_γ)

^{130}Sn(d,p)^{131}Sn measured at 4.8 MeV/u by Kozub *et al.*

- DRC determined
- Only protons measured – no γ's or recoils
- **Could not extract CN component**



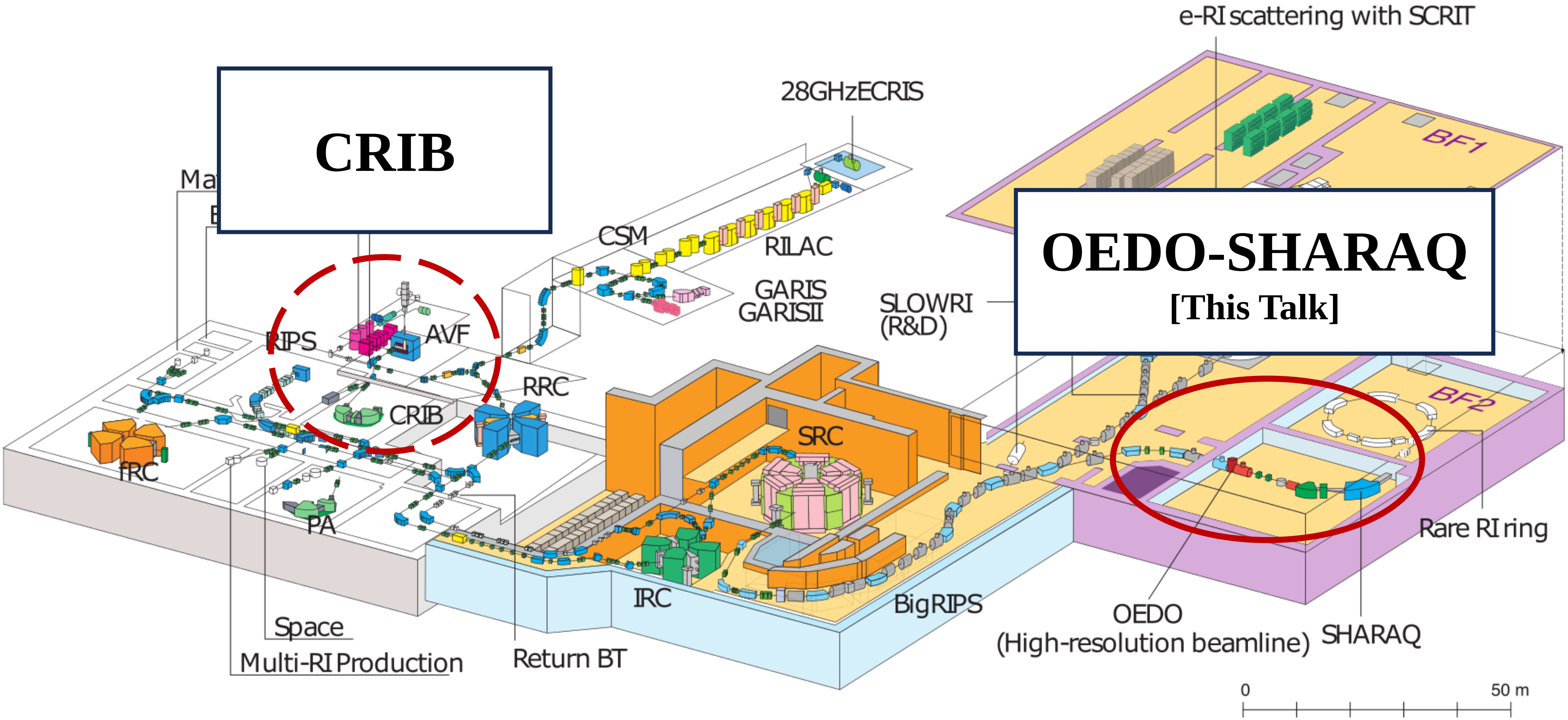


Identify reaction products -> P_γ

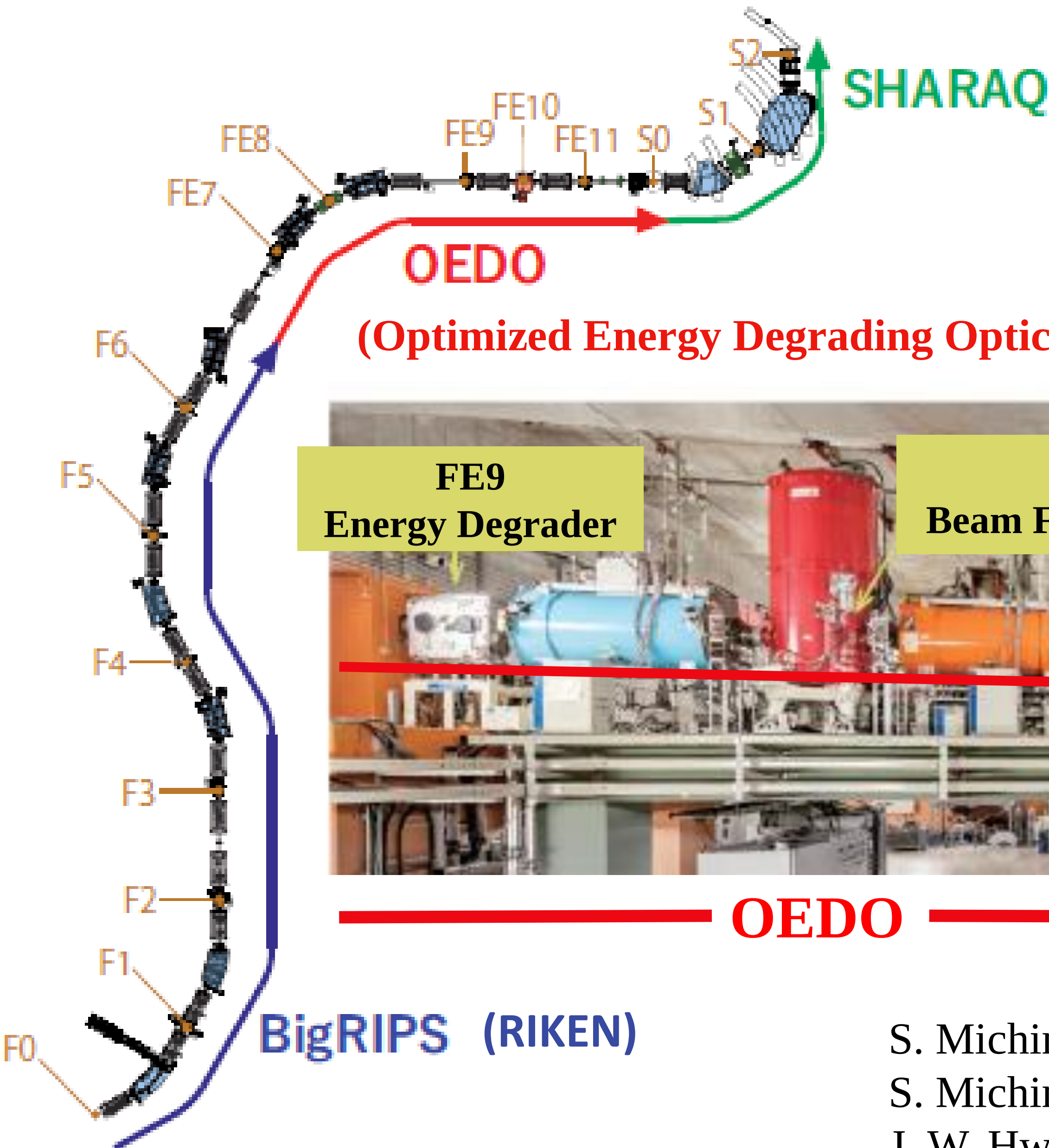
γ-detection unnecessary

R.L. Kozub *et al.* PRL 109 (2012) 172501

Experimental Setup



Experimental Setup



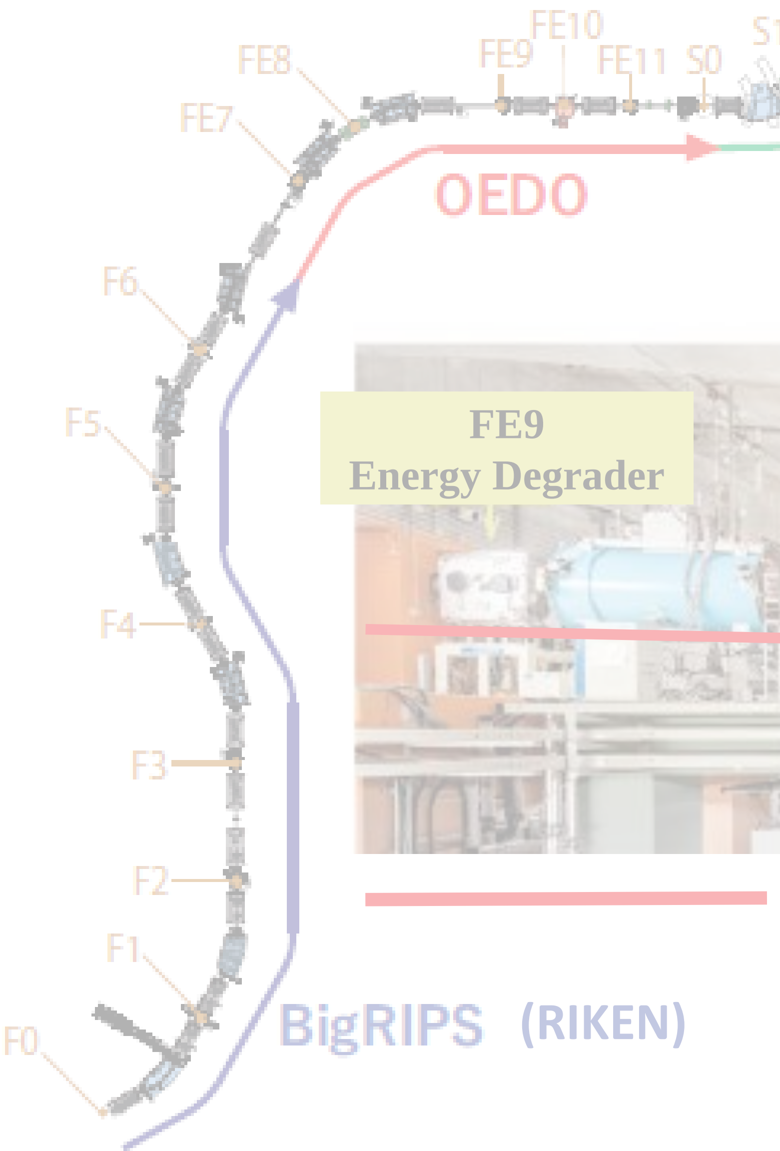
(Optimized Energy Degrading Optics)

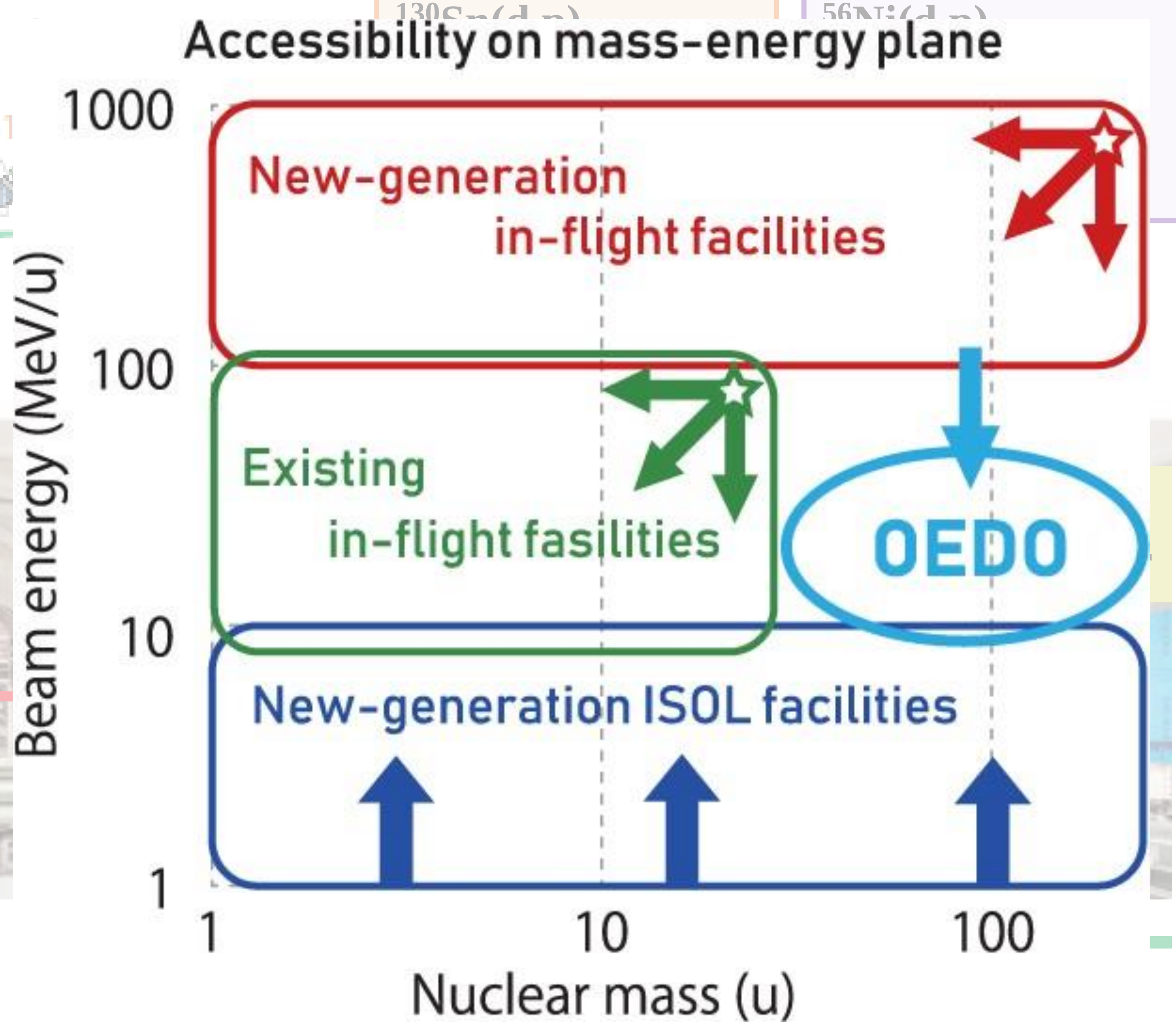
^{130}Sn(d,p)
April 2022
1. **^{130}Sn**
2. **^{130}Te**
3. **^{124}Sn**

^{56}Ni(d,p)
May 2022
1. **^{56}Ni**
2. **^{58}Ni**

S. Michimasa *et al.* NIM B 540 (2023) 194 - 198
S. Michimasa *et al.* PTEP 043D01 (2019)
J. W. Hwang *et al.* PTEP 043D02 (2019)

Experimental Setup





S. Michimasa *et al.* NIM B 540 (2023) 194 - 198
S. Michimasa *et al.* PTEP 043D01 (2019)
J. W. Hwang *et al.* PTEP 043D02 (2019)

Recent OEDO Publications

S. Michimasa *et al.* NIM B 540 (2023) 194 - 198
T. Chillery *et al.* PTEP 121D01 (2023)
N Imai *et al.* PLB 850 (2024) 138470

July 2023
OEDO Beam Optics

ELSEVIER
Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms
Volume 540, July 2023, Pages 194-198

OEDO-SHARAQ system: Multifaceted performances in low-energy RI production and high-resolution spectroscopy

S. Michimasa[a], T. Chillery[a], J.W. Hwang[b], T. Sumikama[c], S. Hanai[a], N. Imai[a], M. Dozono[d], S. Ota[e], D.S. Ahn[b], S. Hayakawa[a], Y. Hijikata[d], K. Kameya[f], K. Kawata[a], R. Kojima[a], K. Kusaka[c], J. Li[a], K. Miki[f], M. Ohtake[c], Y. Shimizu[c], D. Suzuki[c], H. Suzuki[c], H. Takeda[c], K. Yako[a], Y. Yanagisawa[c], K. Yoshida[c], M. Yoshimoto[c], S. Shimoura[c a]

November 2023
OEDO Day-0 Experiment

JOURNAL ARTICLE

Studying the impact of deuteron non-elastic breakup on ^{93}Zr + d reaction cross sections measured at 28 MeV/nucleon

Thomas Chillery, Jongwon Hwang, Masanori Dozono, Nobuaki Imai, Shin'ichiro Michimasa, Toshiyuki Sumikama, Nobuyuki Chiga, Shinsuke Ota, Shinsuke Nakayama, Deuk Soon Ahn, Olga Beliuskina, Kazuya Chikaato, Naoki Fukuda, Seiya Hayakawa, Eiji Ideguchi, Kotaro Iribe, Chihiro Iwamoto, Shoichiro Kawase, Keita Kawata, Noritaka Kitamura, Kensuke Kusaka, Shoichiro Masuoka, Hareru Miki, Hiroari Miyatake, Daisuke Nagae, Ryo Nakajima, Keita Nakano, Masao Ohtake, Shunichiro Omika, Hooi Jin Ong, Hideaki Otsu, Hiroyoshi Sakurai, Philipp Schrock, Hideki Shimizu, Yohei Shimizu, Xiaohui Sun, Daisuke Suzuki, Hiroshi Suzuki, Motonobu Takaki, Maya Takechi, Hiroyuki Takeda, Satoshi Takeuchi, Takashi Teranishi, Rieko Tsunoda, He Wang, Yukinobu Watanabe, Yutaka X Watanabe, Kathrin Wimmer, Kentaro Yako, Hiroki Yamada, Kazunari Yamada, Hidetoshi Yamaguchi, Lei Yang, Rikuto Yanagihara, Yoshiyuki Yanagisawa, Hiroya Yoshida, Koichi Yoshida, Susumu Shimoura

March 2024
First Transfer Measurement at OEDO

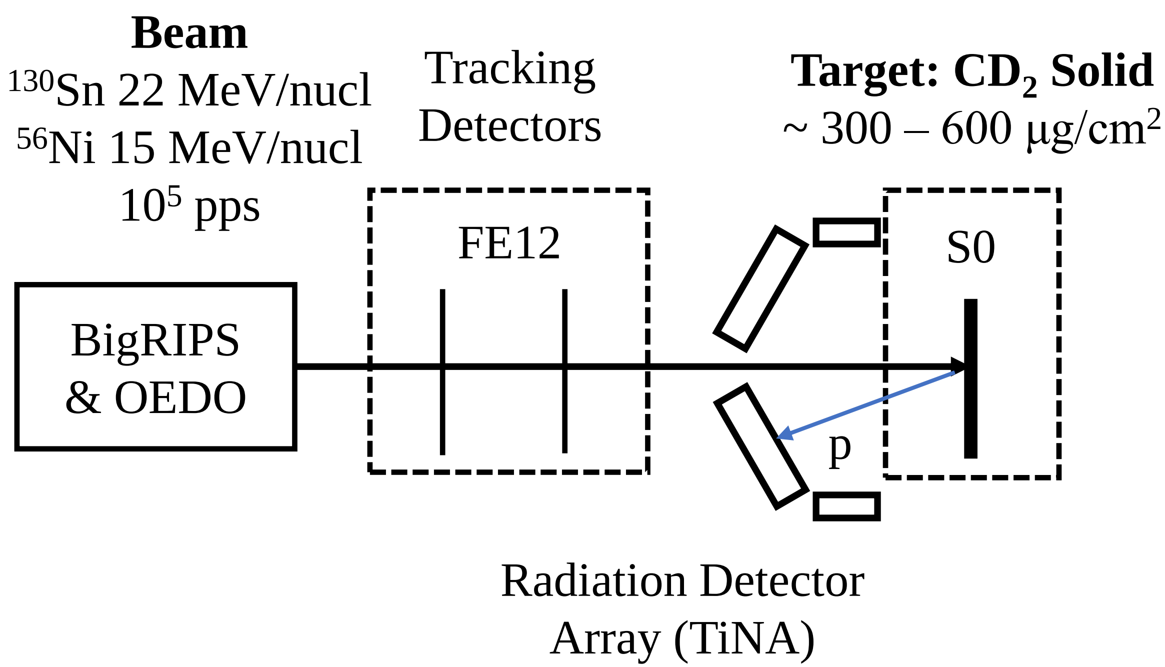
ELSEVIER
Physics Letters B
Volume 850, March 2024, 138470

Letter

Neutron capture reaction cross-section of ^{79}Se through the ^{79}Se(*d*,*p*) reaction in inverse kinematics

N. Imai[a], M. Dozono[a 1], S. Michimasa[a], T. Sumikama[c], S. Ota[a 2], S. Hayakawa[a], J.W. Hwang[a b], K. Iribe[d], C. Iwamoto[a], S. Kawase[e], K. Kawata[a], N. Kitamura[a], S. Masuoka[a], K. Nakano[e], P. Schrock[a], D. Suzuki[c], R. Tsunoda[a], K. Wimmer[f 3], D.S. Ahn[c b], O. Beliuskina[a 4], N. Chiga[c], N. Fukuda[c], E. Ideguchi[h], K. Kusaka[c], H. Miki[i], H. Miyatake[g], D. Nagae[c], S. Ohmika[j], M. Ohtake[c], H.J. Ong[h], H. Otsu[c], H. Sakurai[c], H. Shimizu[a], Y. Shimizu[c], X. Sun[c], H. Suzuki[c], M. Takaki[a], H. Takeda[c], S. Takeuchi[i], T. Teranishi[d], Y. Watanabe[e], Y.X. Watanabe[g], K. Yako[a], H. Yamada[i], H. Yamaguchi[a], L. Yang[a], R. Yanagihara[h], Y. Yanagisawa[c], K. Yoshida[c], S. Shimoura[a]

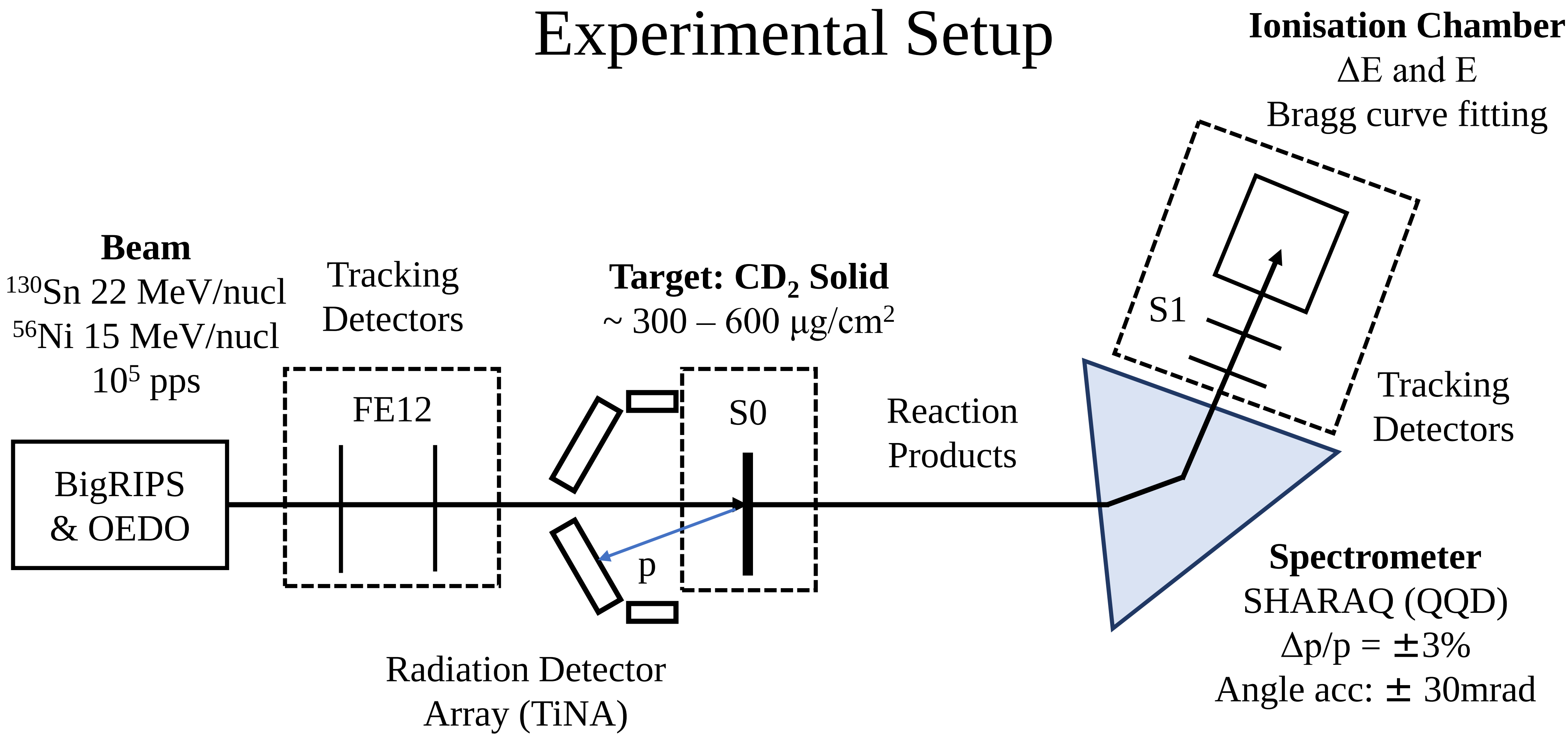
Experimental Setup



Analysis:

$^{130}Sn(d,p)$		$^{56}Ni(d,p)$	
S. Bae	(South Korea)	**J. Li**	(CNS)
H. Tanaka	(Kyushu)	**S. Ishio**	(Tohoku)
T. Haginouchi	(Tohoku)		
T. Chillery	(CNS)		

Experimental Setup



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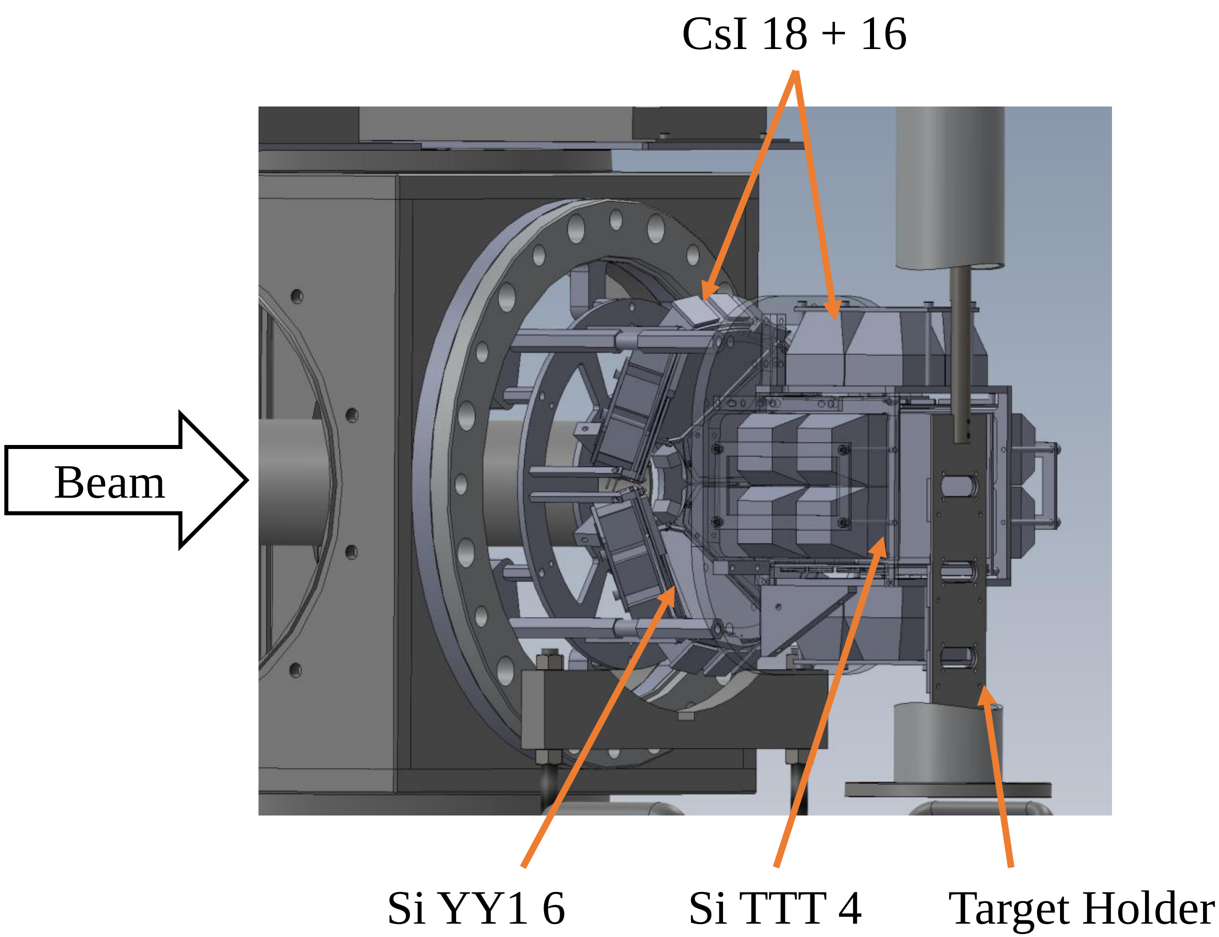
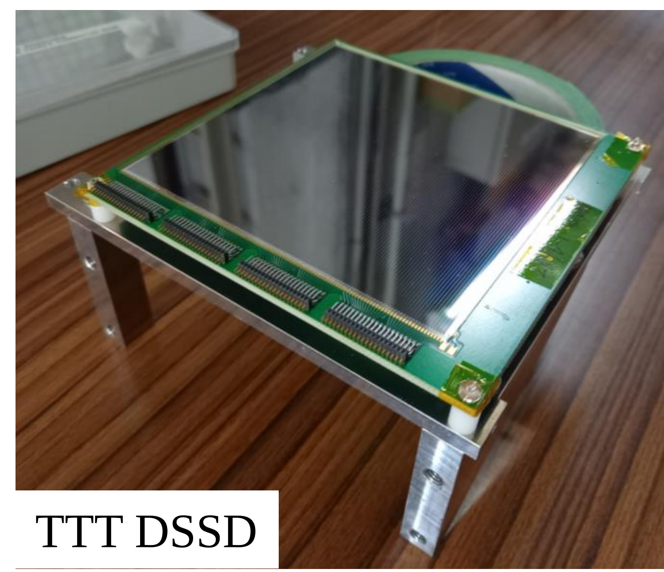
T. Haginouchi	(Tohoku)		
T. Chillery	(CNS)		

Experimental Setup: TiNA

TiNA: **Silicon + CsI telescope detector array**

- Measure charged particles at $\theta_{lab} = 100^o – 172^o$
- Solid angle coverage: ~ 50%

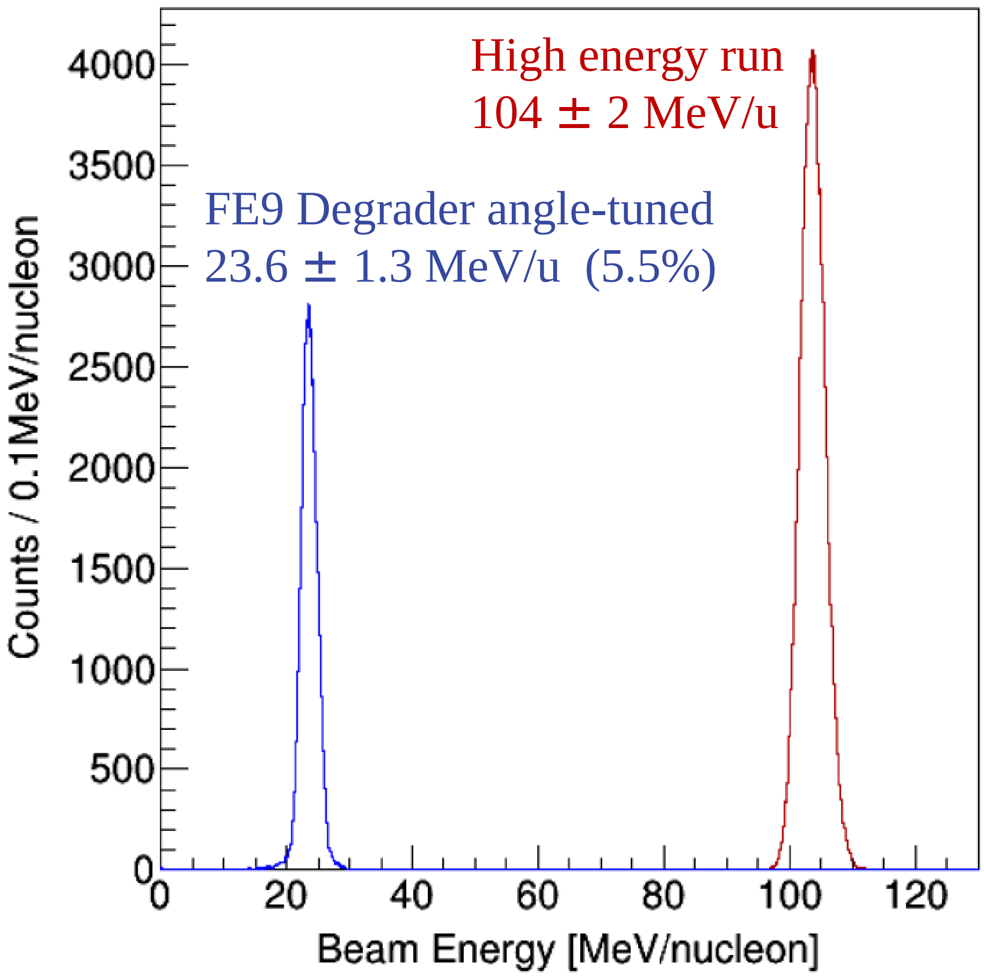


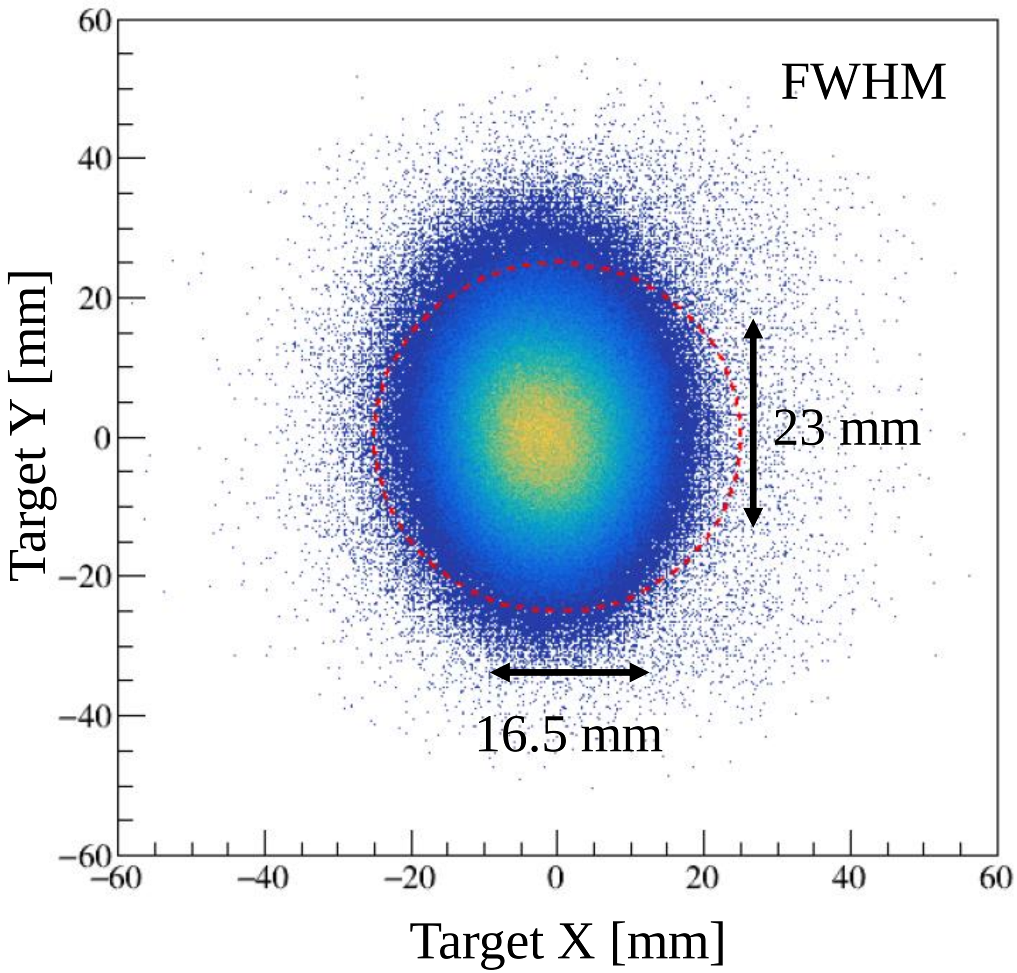


^{130}Sn Condition at Secondary Target

^{130}Sn(d,p)

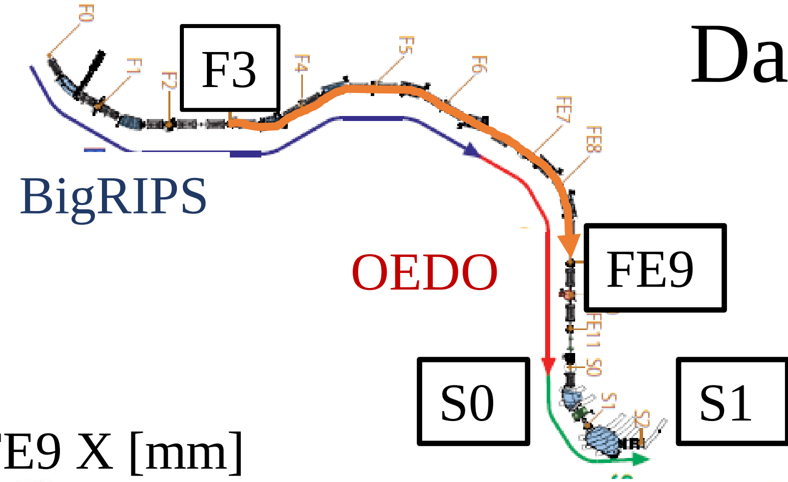
- Good energy compression, ~ 5%
- Well-focused beamspot on Φ = 50 mm target



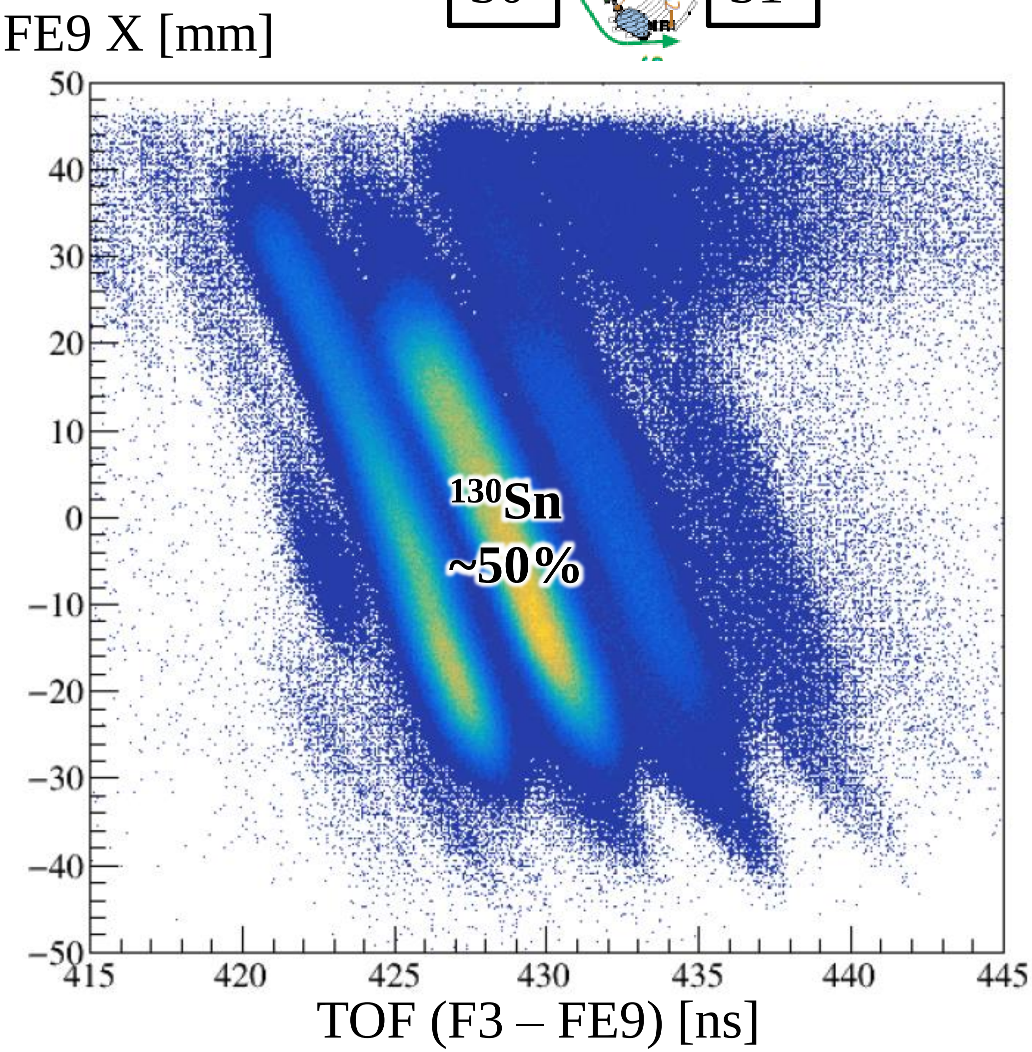


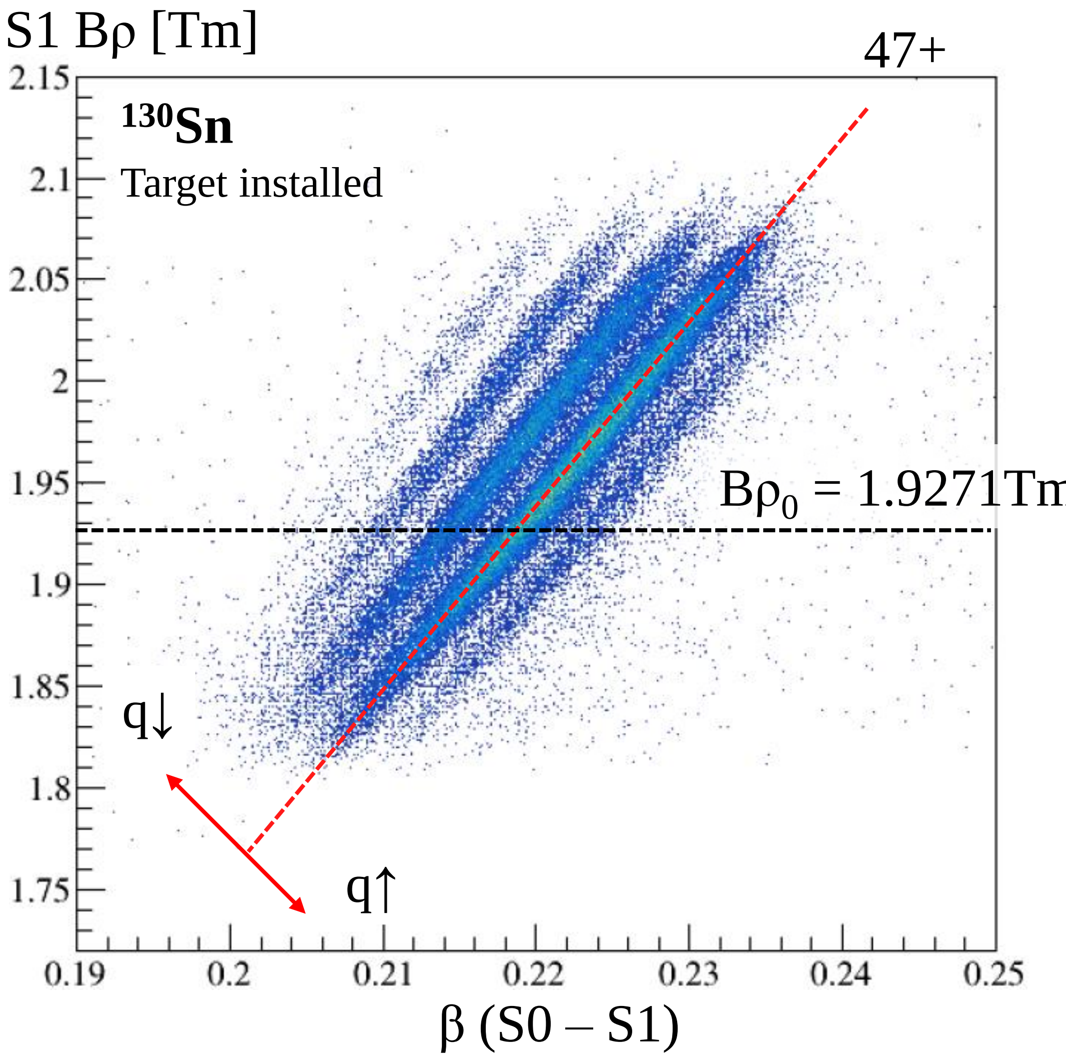
Data Analysis: PID

^{130}Sn(d,p)



PPAC calibrations courtesy
S. Ishio & H. Tanaka



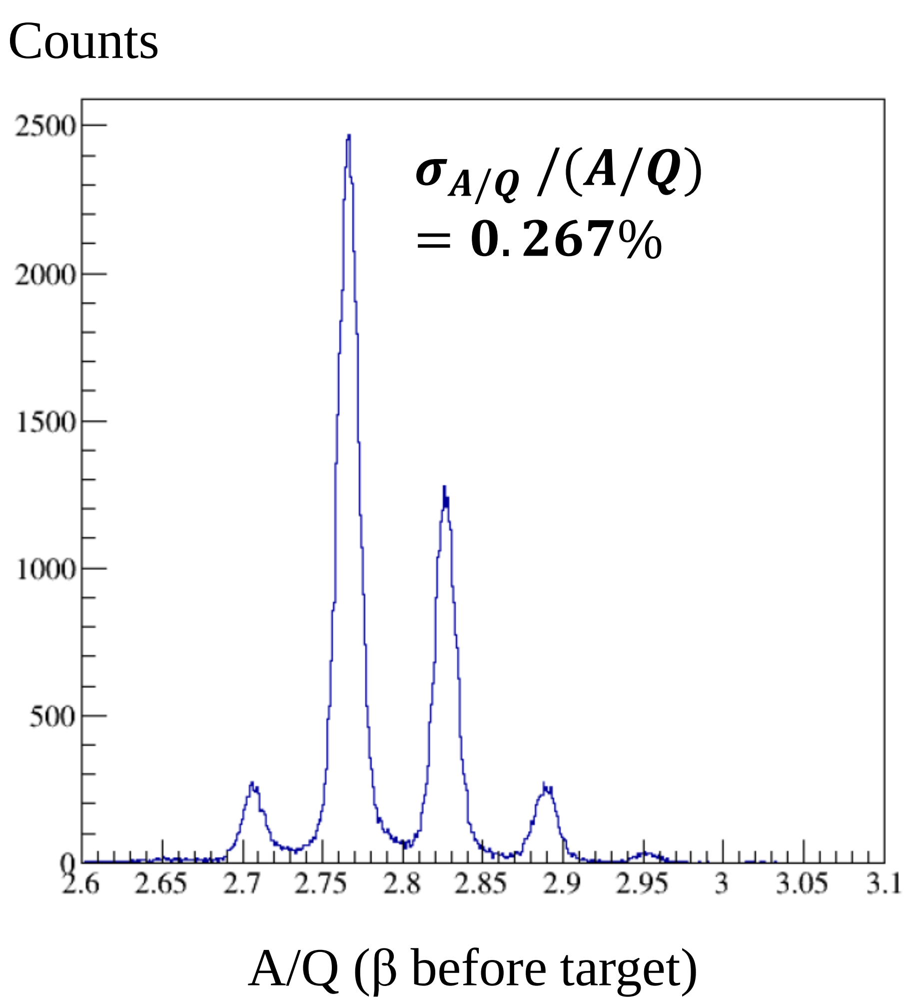


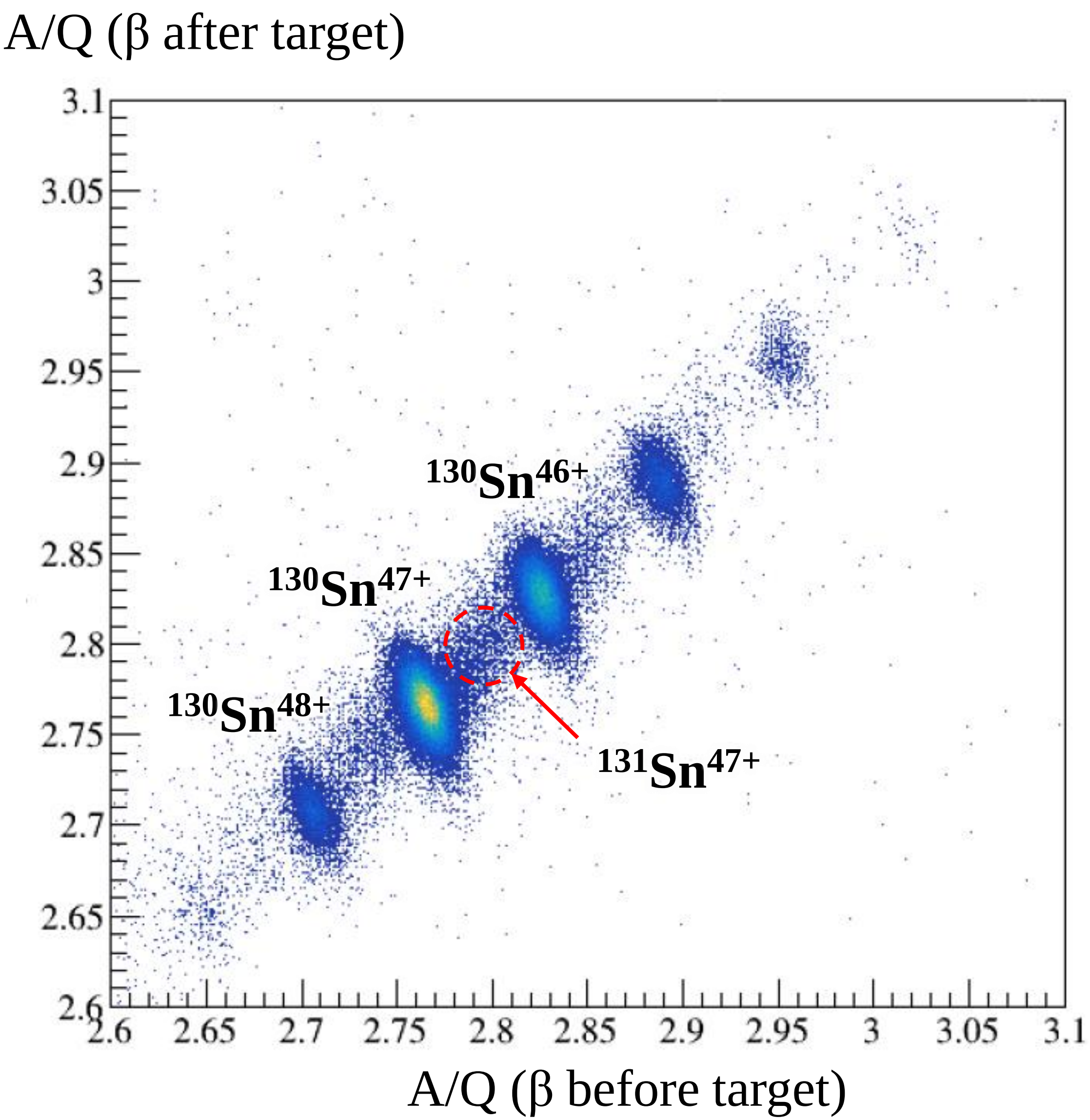
$$\frac{e}{cm_u} = 3.1071310\ \frac{kg\ m}{C\ s}$$

Data Analysis: A/Q

^{130}Sn(d,p)

$$\frac{A}{Q} = \frac{B\rho}{\beta\gamma}\frac{e}{cm_u}$$



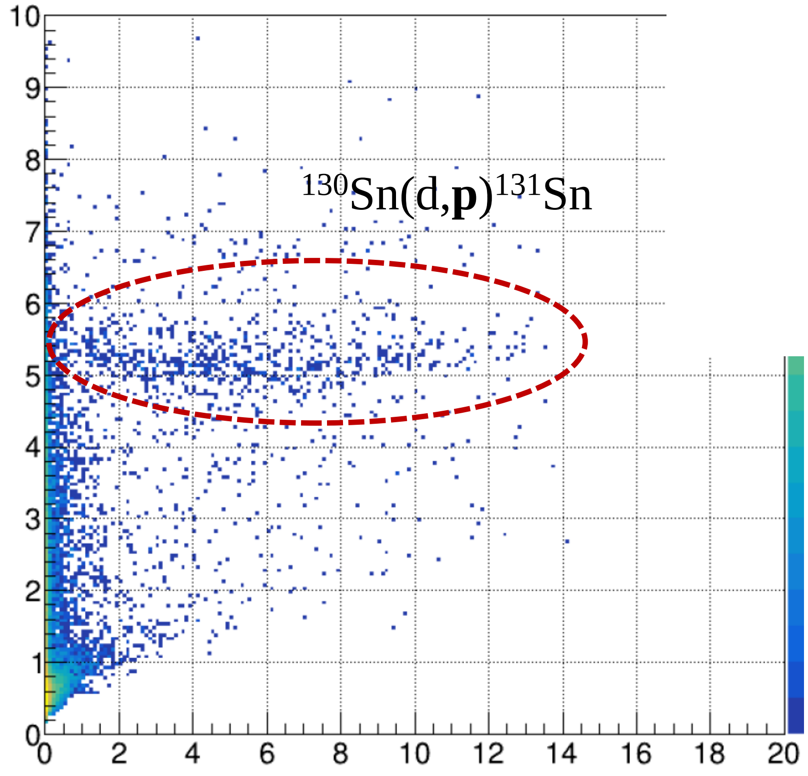


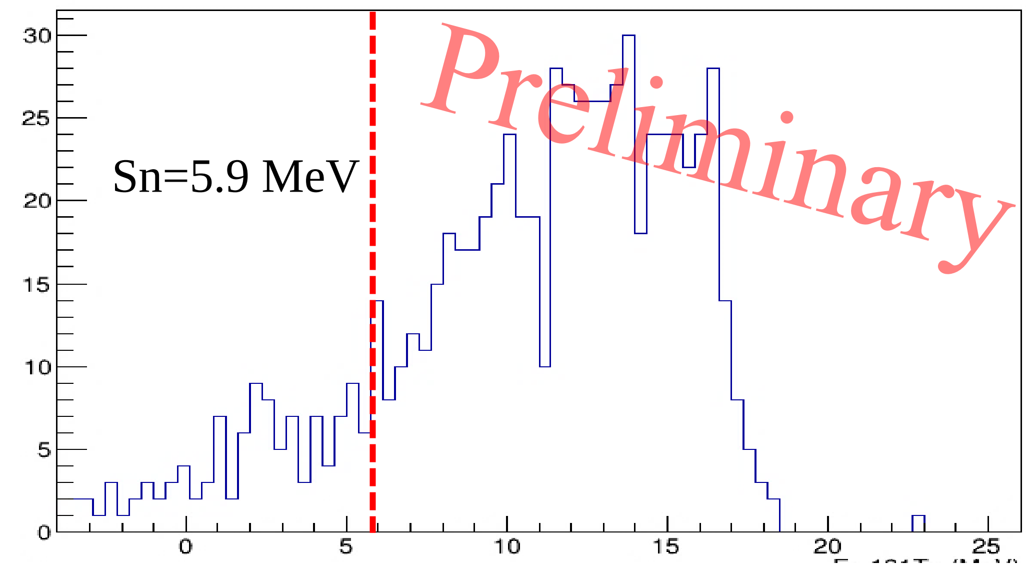
Data Analysis: TiNA

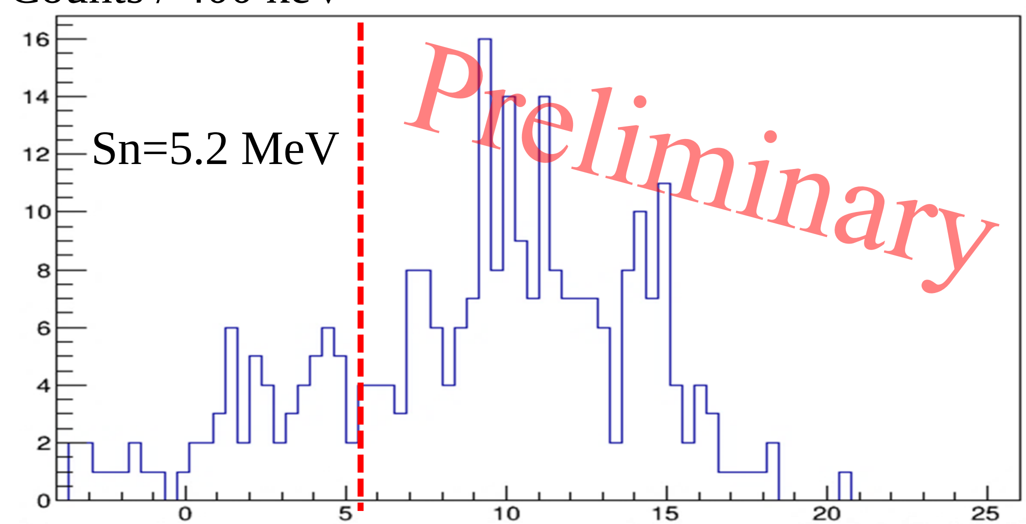
^{130}Sn(d,p)

- ^{131}Te and ^{131}Sn Level Density
  - Part of total data (YY1)
  - Gates: Beam PID, beamspot
  - **Very preliminary!**

$$Z \propto \sqrt{E_{TTT}(E_{TTT} + E_{CsI})} \ [\text{MeV}]$$



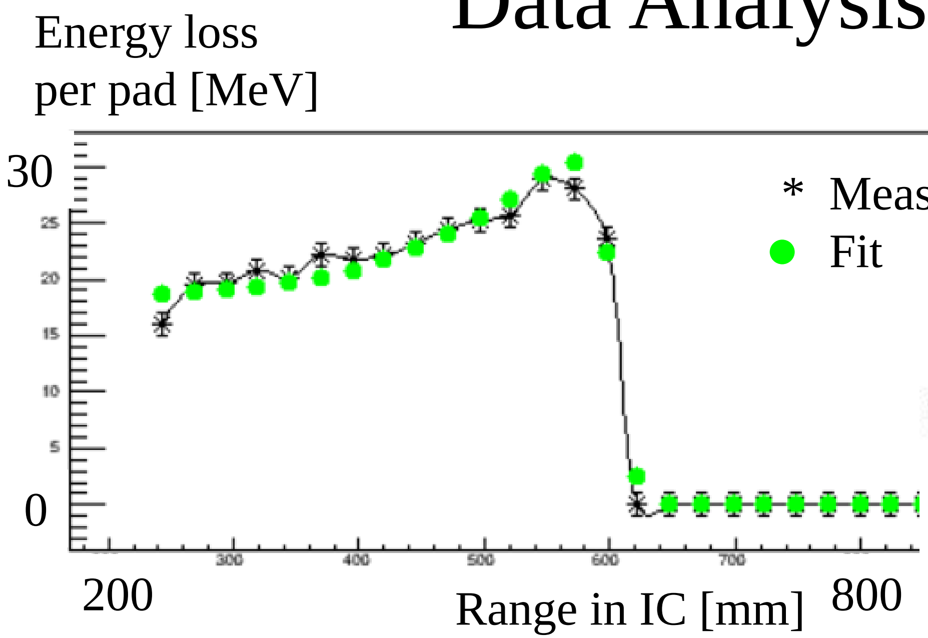


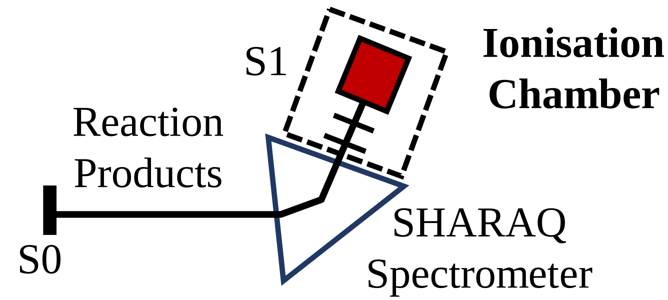


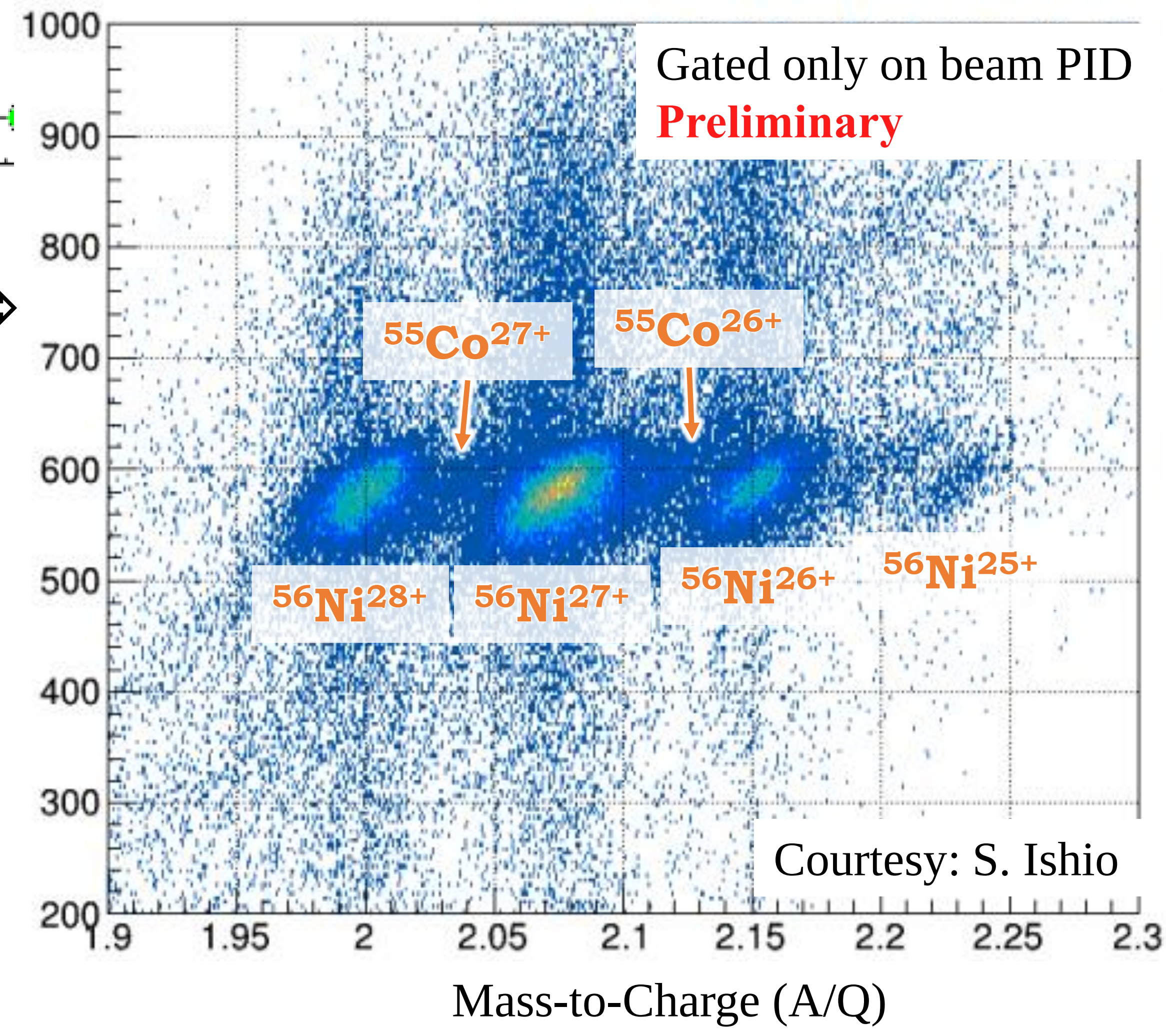
Online Analysis
Courtesy Prof. N. Imai

Data Analysis: Ionisation Chamber

^{56}Ni(d,p)







Bragg curve fit using spline + SRIM-2013

- peak ~ Z
- range ~ A, β, (Z)

Future:

Checking IC correlations

Use IC data to clean TiNA spectra

Conclusions and Future Outlook

- Spring 2022: BigRIPS-OEDO beamline successfully produced low-energy beams

- SH18: ^{124,130}Sn, and ^{130}Te [**S. Bae, H. Tanaka**, T. Chillery, T. Haginouchi]
  - $\sigma_{n\text{-capture}}$ → *r*-process models → astrophysics sites
  - Reaction components (CN vs DRC)

- SH19: ^{56,58}Ni [**S. Ishio, J. Li**]
  - $\sigma_{p\text{-decay}}$ → *νp*-process in CCSNe → p-rich nucleosynthesis

- Offline analysis is ongoing
  - Ionisation chamber PID
  - TiNA proton energy spectra -> Excitation functions for ^{130}Sn and ^{56}Ni

- **Wednesday 11:20 Talk by Carlos Ferrera: ^{50}Ca(d,p)^{51}Ca @ 15 MeV/u**
- Future nuclear structure experiment: ^{80}Sr(p,t)^{78}Sr [J. W. Hwang]

The SAKURA Collaboration

- **T. Chillery**, N. Imai, S. Hanai, S. Michimasa, R. Yokoyama, K. Okawa, S. Hayakawa, R. Kojima, J. Li, N. Ma, T. Saito, K. Kawata, S. Shimoura | Center for Nuclear Study, University of Tokyo
- J. W. Hwang, D.S. Ahn | Center for Exotic Nuclear Studies, Institute for Basic Science (IBS)
- T. Sumikama, D. Suzuki, H. Suzuki, N. Fukuda, H. Takeda, Y. Shimizu, M. Yoshimoto, Y. Togano | RIKEN Nishina Center for Accelerator-Based Science
- Y. Hijikata, M. Dozono, R. Yoshida | Department of Physics, Kyoto University
- F. Endo, T. Haginouchi, N. Iwasa, S. Ishio, M. Egeta | Department of Physics, Tohoku University
- H. Tanaka, T. Teranishi | Department of Physics, Kyushu University
- S. Ota | Research Center for Nuclear Physics, Osaka
- B. Mauss | Nuclear Physics Laboratory, DAM, French Atomic Energy Commission (CEA)

Funding from

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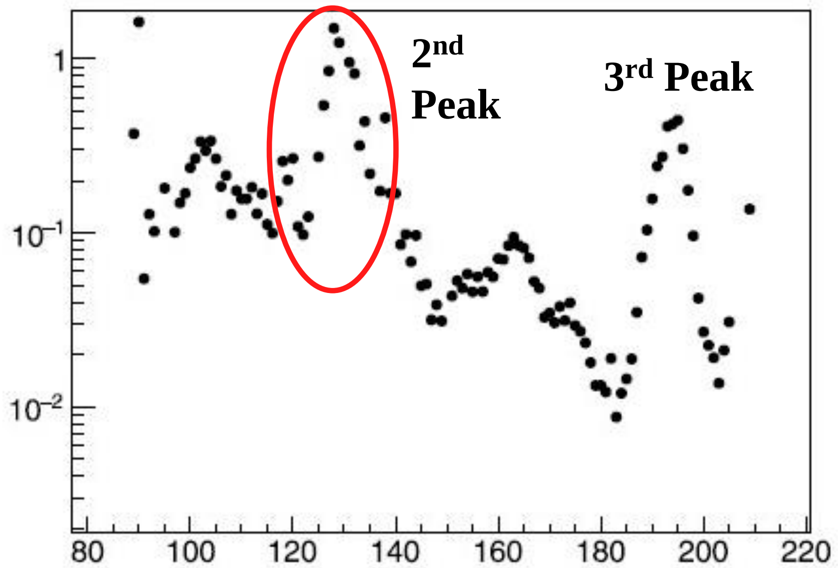
Ministry of Science and ICT, Korea grants IBS-R031-D1 and IBS-R031-Y2

CAS Western Light research fund.

東京大学 大学院
理学系研究科·理学部
SCHOOL OF SCIENCE, THE UNIVERSITY OF TOKYO

Extra Slides

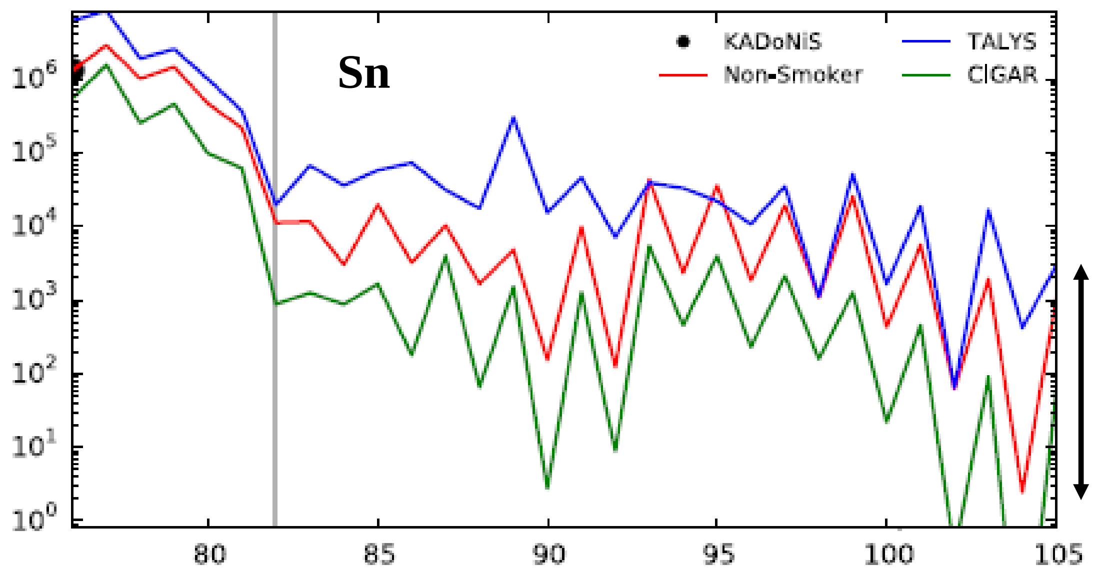
SH18 Motivation



T. Kajino *et al*. Prog. Part. Nucl. Phys. 107 (2019) 109-166

Where do the heavy elements come from?

- *s*- and ***r***-process nucleosynthesis
  - CCSNe and/or NS-mergers
  - Large neutron density: $10^{20\text{-}26}$ cm^{-3}



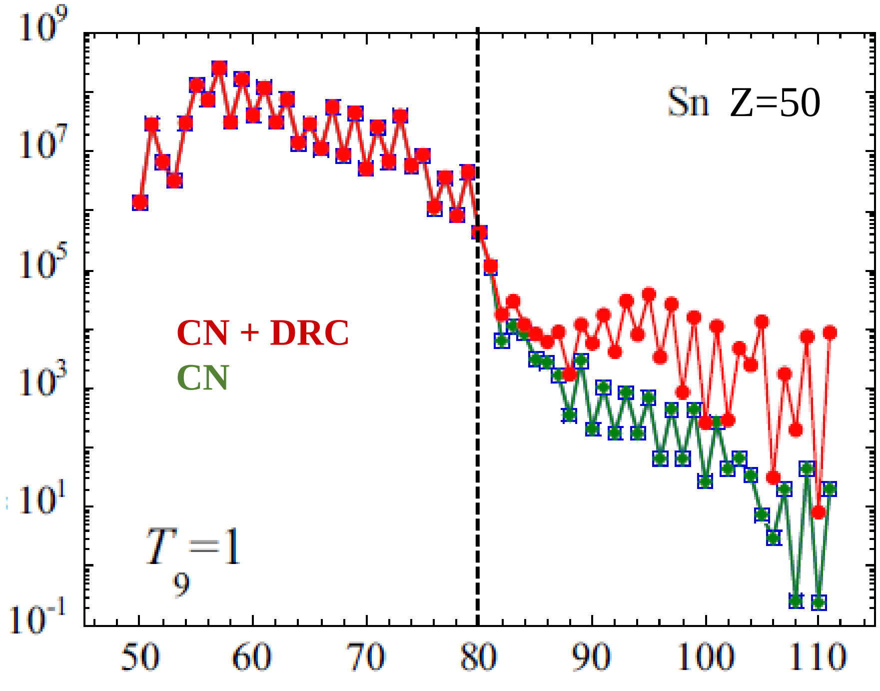
M.R. Mumpower *et al*. Prog. Part. Nucl. Phys. 86 (2016) 86-126

n-capture on Tin

- Models disagree on reaction rate by several orders magnitude

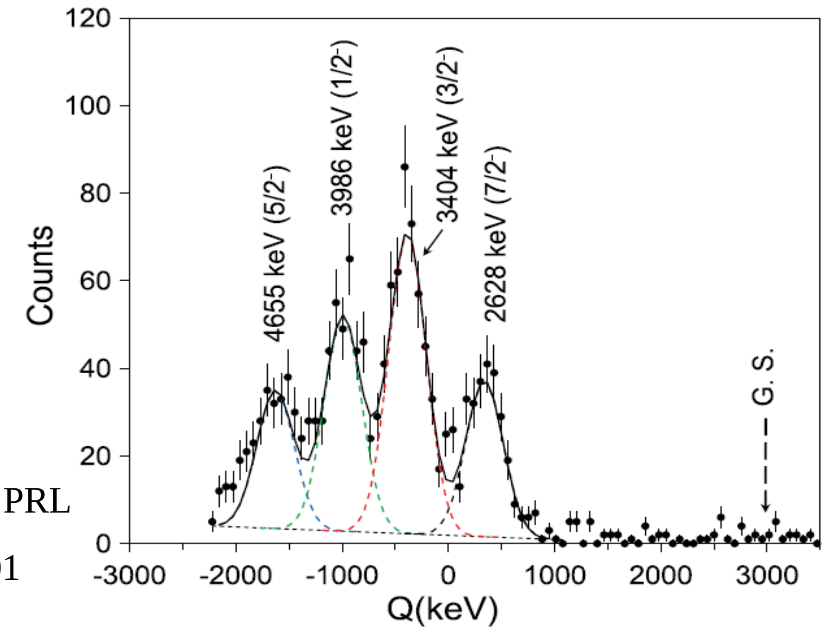
Y. Xu and S. Goriely *et al.*
PRC. 90 (2014) 024604

SH18 Goal



Reaction Mechanisms

- Two processes: DRC and CN
- Largely unmeasured in exotic region
- **CN dominates at N = 80**

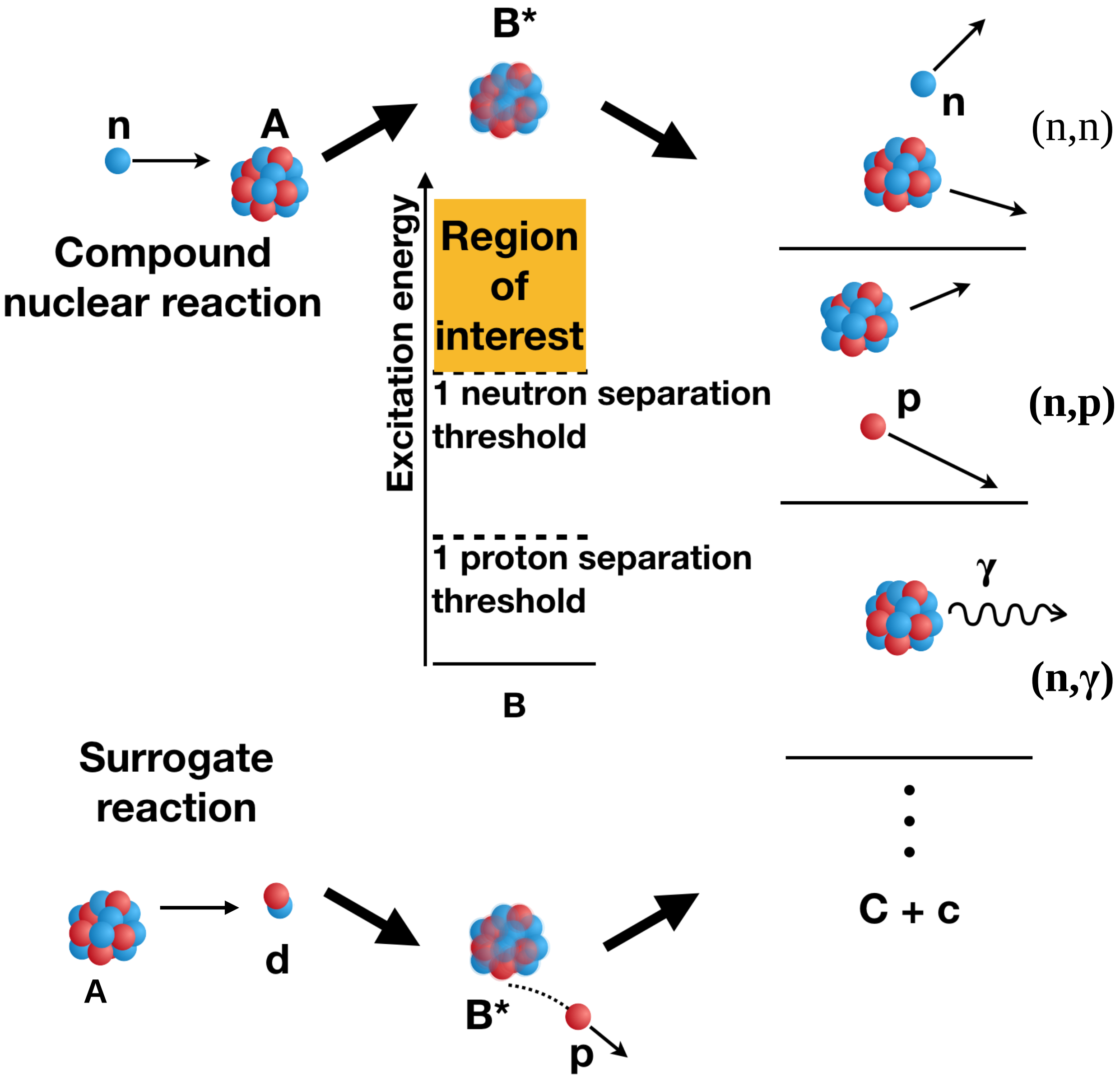


R.L. Kozub *et al.* PRL 109 (2012) 172501

- $^{130}Sn(d,p)^{131}Sn$ measured at 4.8 MeV/u by Kozub *et al.*
  - **DRC determined**
  - Only protons measured – no γ's or recoils
  - **Could not extract CN component**

GOAL: Measure $^{130}Sn(d,p)$ ~ 23 MeV/u

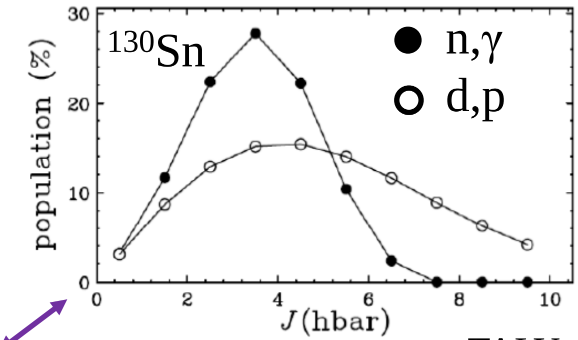
Experimental Method: Surrogate Ratio



^{56}Ni(d,p)^{57}Ni* → ^{56}Co + p
Reference: ^{58}Ni(d,p)^{59}Ni*

^{130}Sn(d,p)^{131}Sn* → ^{131}Sn + γ
Reference: ^{130}Te(d,p)^{131}Te*

Surrogate Ratio



TALYs courtesy N. Imai

For CN component of $\sigma_{(n,\gamma)}$: Surrogate ratio method

Theory (Optical Model)

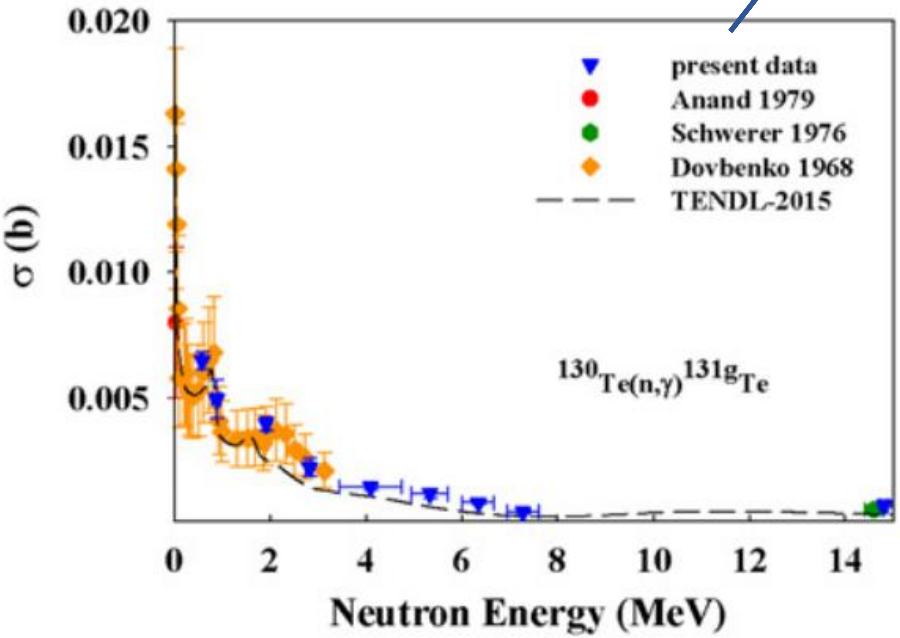
$$\sigma_{130Sn(n,\gamma)} = \sigma_{130Te(n,\gamma)} \times \frac{\sigma^{CN}_{131Sn}}{\sigma^{CN}_{131Te}} \times \frac{P_{\gamma}^{131Sn}}{P_{\gamma}^{131Te}}$$

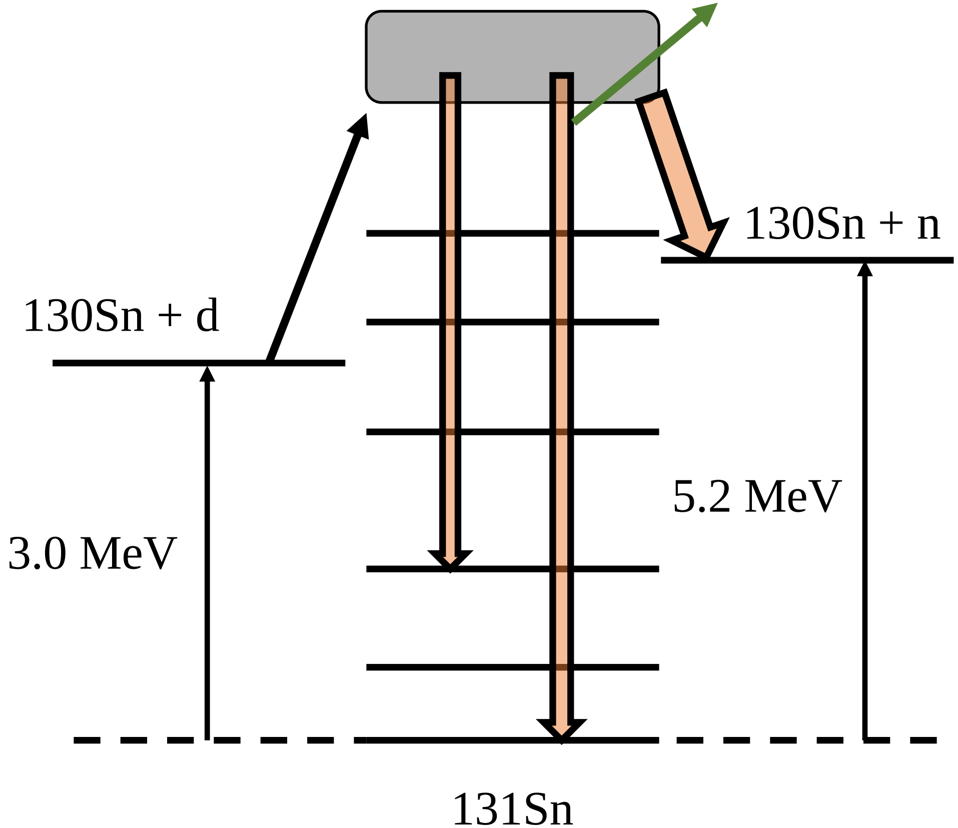
MEASURE

Goal

Reference

$\boldsymbol{P_{\gamma}^{131Sn}}$

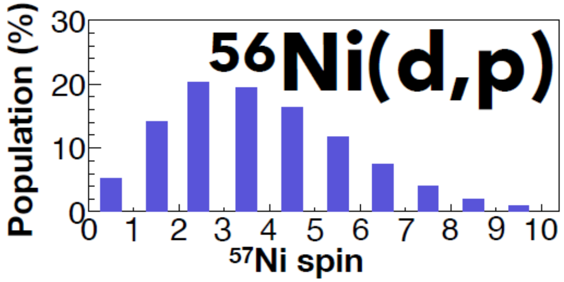




W. Tornow *et al.* EPJ Web. Conf. 146 (2017) 09013

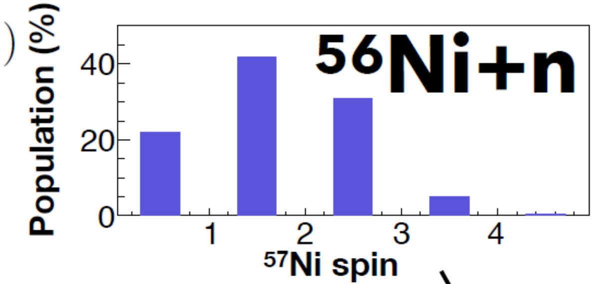
New method applied to the ^{56}Ni(d,p)X reaction

Courtesy: D. Suzuki

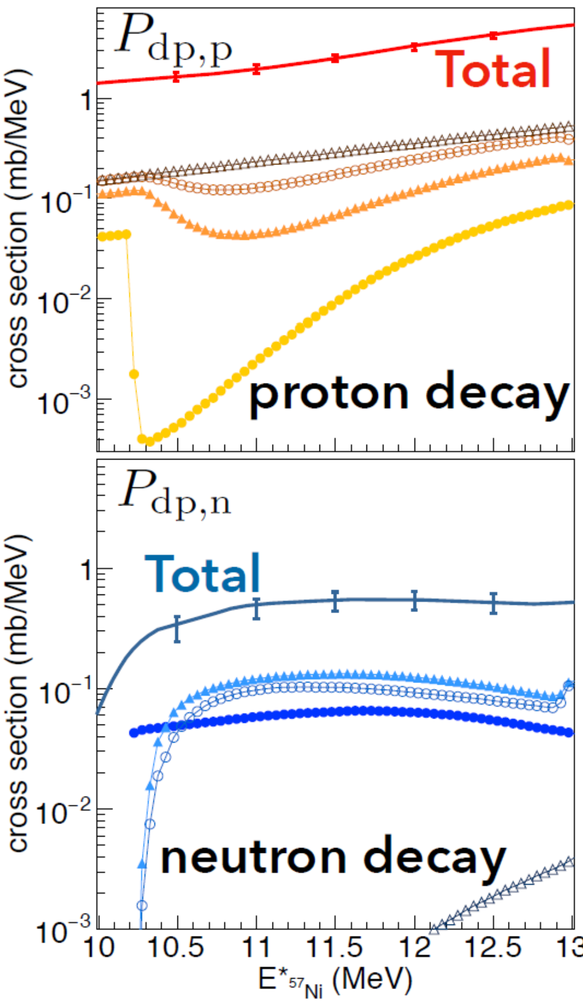


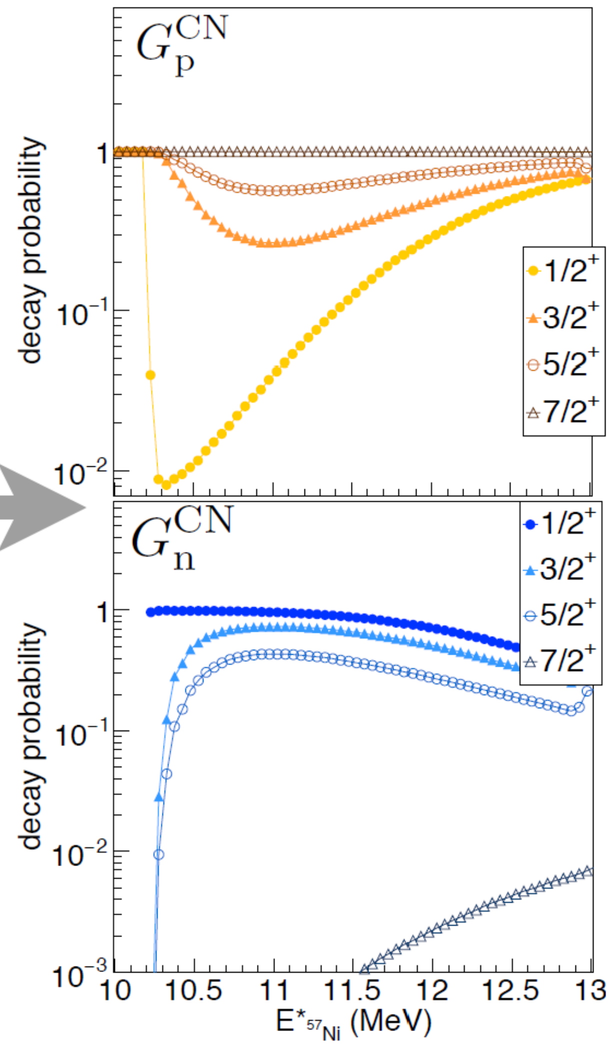
$$P_{\delta\chi}(E_{\rm ex}) = \sum_{J,\pi} F_\delta^{\rm CN}(E_{ex}, J, \pi) G_\chi^{\rm CN}(E_{\rm ex}, J, \pi)$$

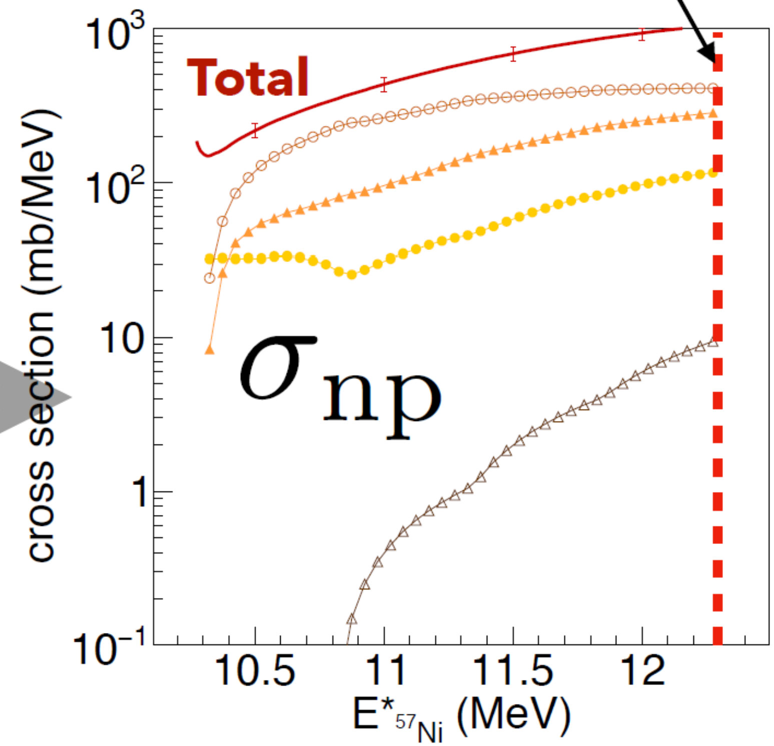
cross section — formation — decay



extracted $G_\chi(E^*_{57Ni}, J, \pi)$





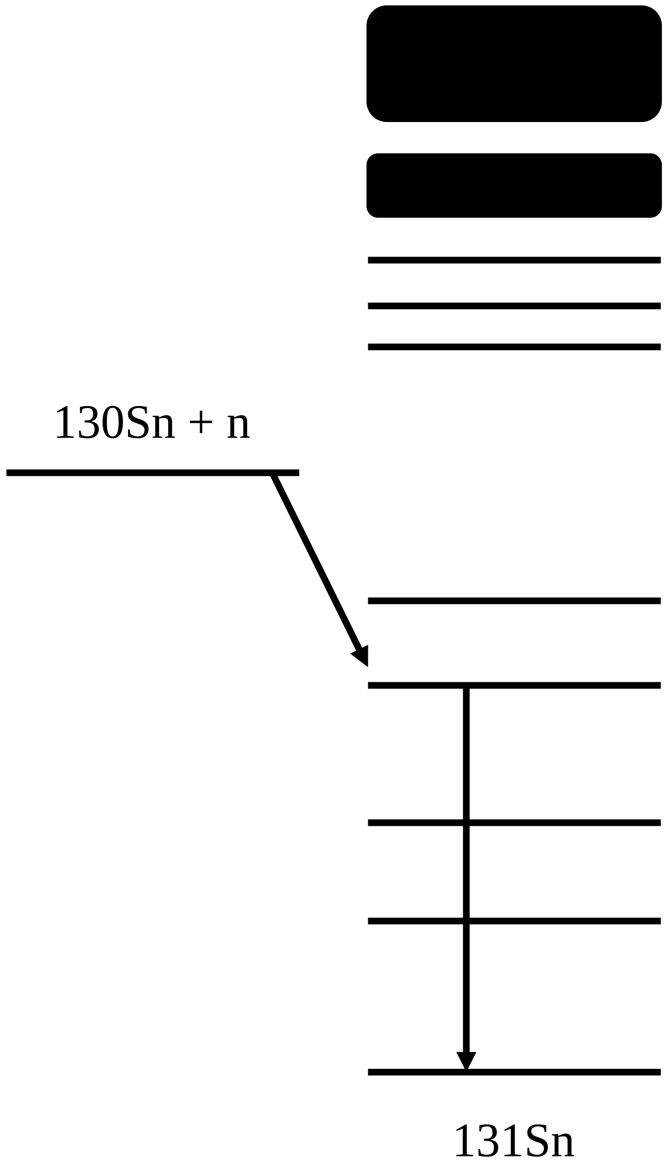


About 10% error expected

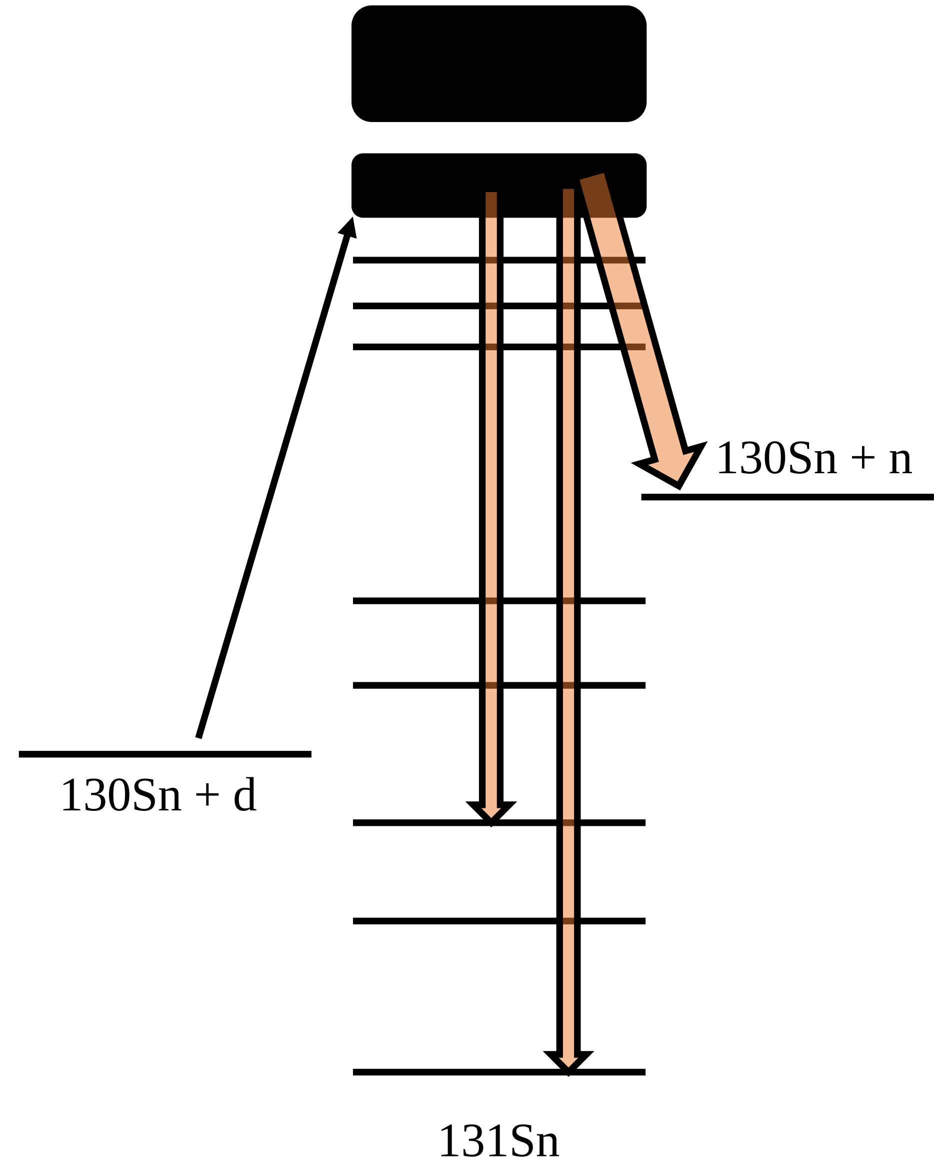
→ Reference surrogate data of ^{58}Ni will be used for control

DRC and CN Reaction Mechanisms

Direct Radiative Capture (DRC)



Compound Nuclear (CN)

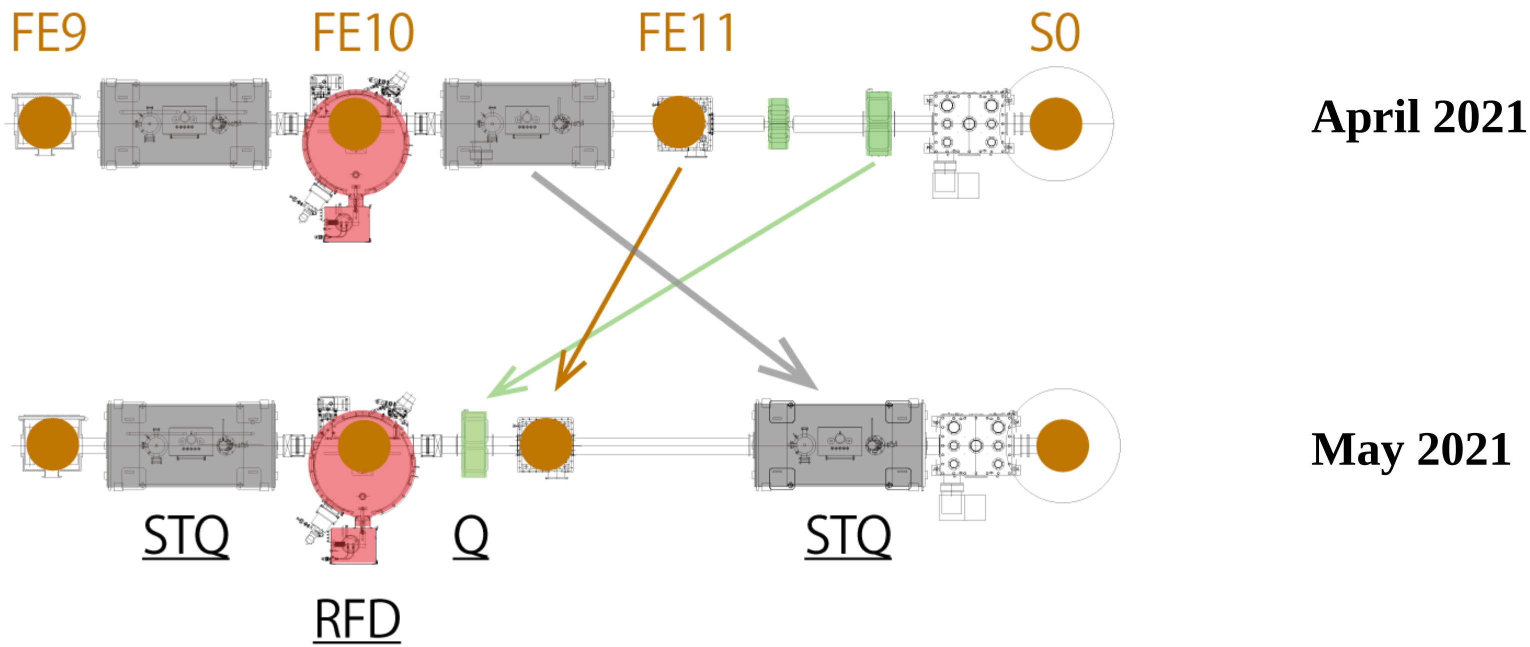


Data sets

Exp.	Purpose	Beam	Target	Irradiation Time [hr]
SH18	Physics	^{130}Sn	CD_2 287μg/cm^2	40
	Reference	^{130}Te		20
	Sys. Error	^{124}Sn		18
	Isomer Meas.	^{130}Sn	Al 0.8mm	1
		^{124}Sn		0.3
Exp.	**Purpose**	**Beam**	**Target**	**Irradiation Time [hr]**
SH19	Physics	^{56}Ni	CD_2 644μg/cm^2	22
			CD_2 285μg/cm^2	32
	Reference	^{58}Ni	CD_2 285μg/cm^2	24
	CsI Calibration	^{56}Ni	Al 0.8mm	3

Experimental Setup

Courtesy: Michimasa



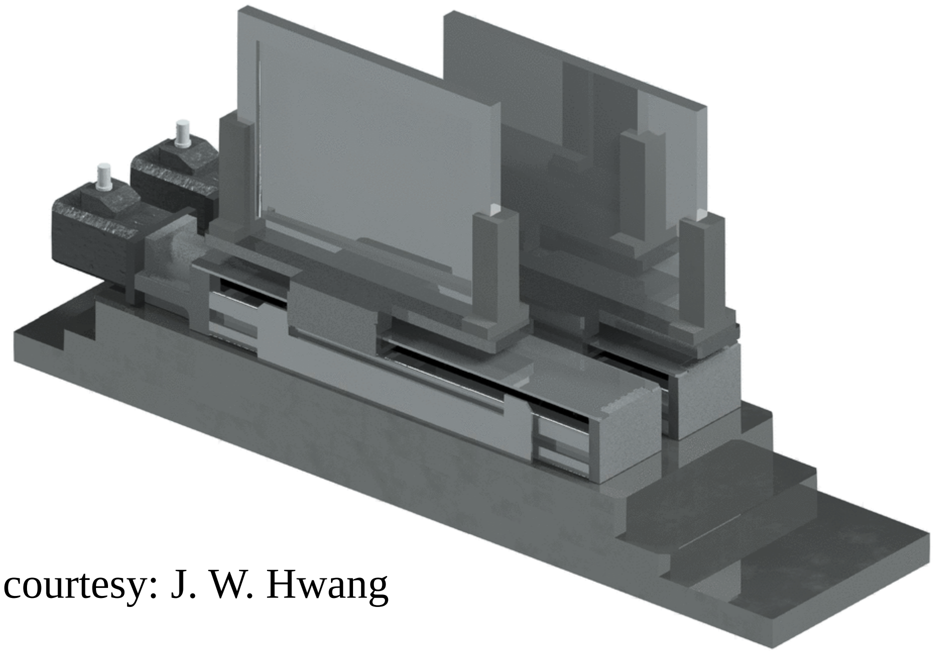
<table>
<tr><th rowspan="2">Beam</th><th rowspan="2">F1 Mom. Slit.</th><th colspan="2">Energy [MeV/u]</th><th colspan="2">Rate [kpps] (purity)</th><th rowspan="2">Trans. F3 – S0</th></tr>
<tr><th>F3</th><th>S0</th><th>F3</th><th>S0</th></tr>
<tr><td>^{130}Sn</td><td>± 0.5%</td><td>170</td><td>22.9</td><td>185 (50%)</td><td>160 (50%)</td><td>~ 85%</td></tr>
<tr><td>^{56}Ni</td><td>± 0.5%</td><td>113</td><td>15.5</td><td>482 (33%)</td><td>356 (33%)</td><td>~ 85%</td></tr>
</table>

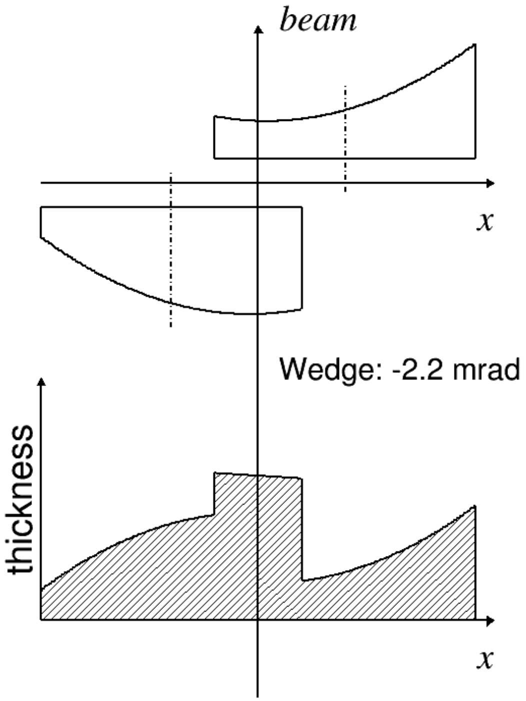
PTEP 2019
Trans. F3 – S0 18%
→ **4X increase**

OEDO: Principle

^{130}Sn
170 MeV/u
+/- 3.4 MeV/u

1. Slow down beams using degrader





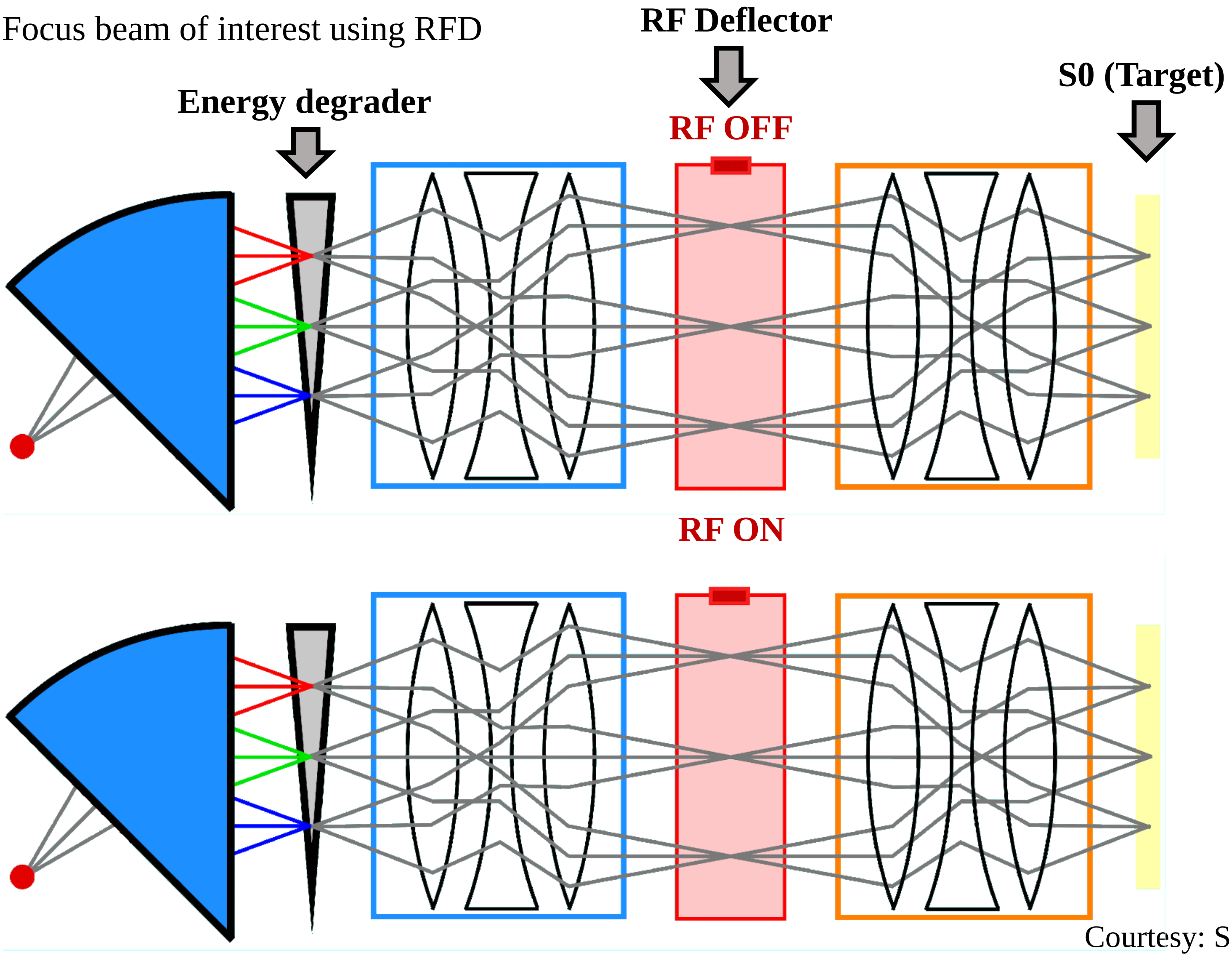
Animation courtesy: J. W. Hwang

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

23 MeV/u
+/- 1.4 MeV/u
(Straggling in Al)

OEDO: Principle

2. Focus beam of interest using RFD

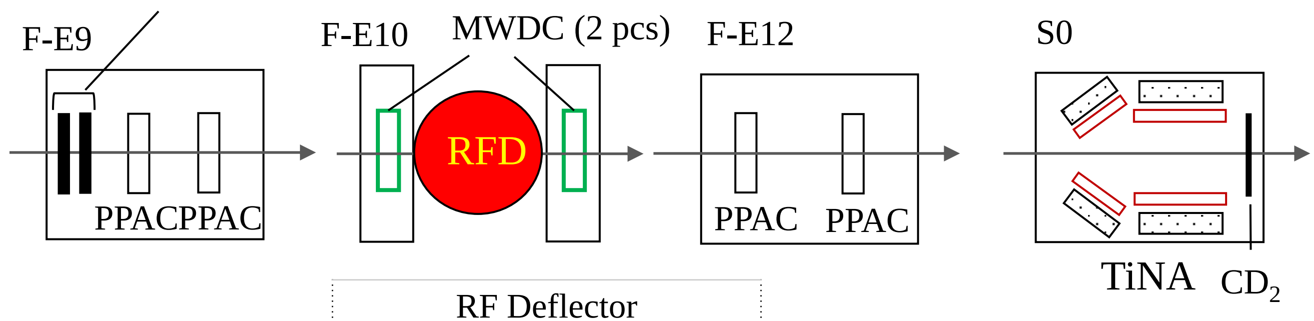


Courtesy: S. Michimasa

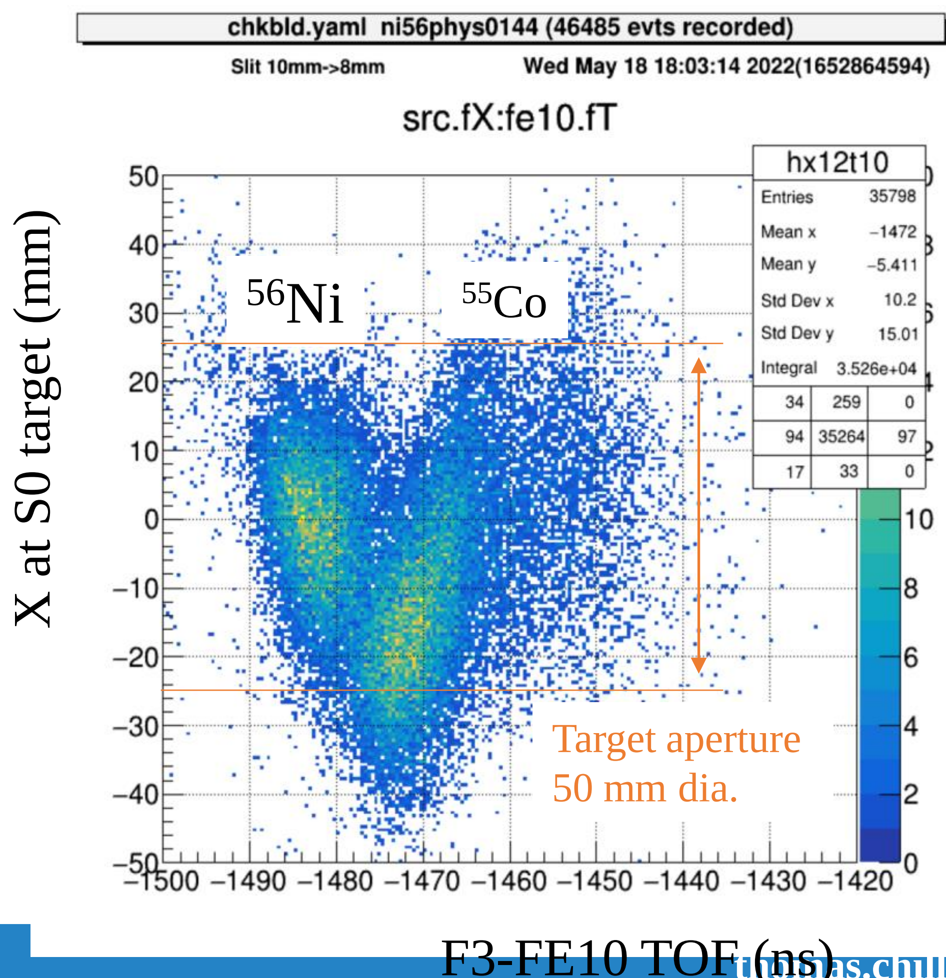
OEDO configuration

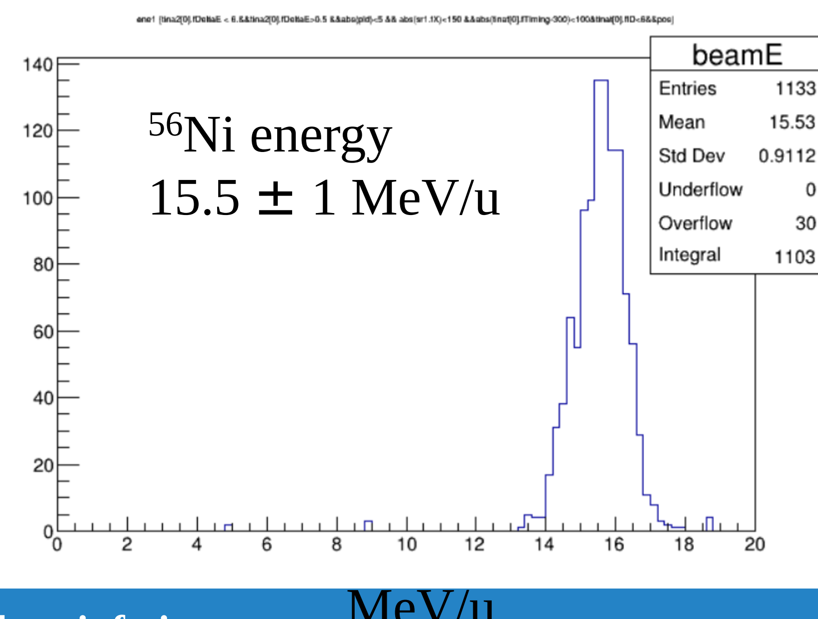
FE9 Degrader		
Wedge angle:	4	mrad
X0:	-36	mm
dX:	8.5	mm
Wedge central thickness:	2.966	mm
Flat thickness:	0.300	mm
Total degrader thickness:	3.266	mm

Courtesy: D. Suzuki

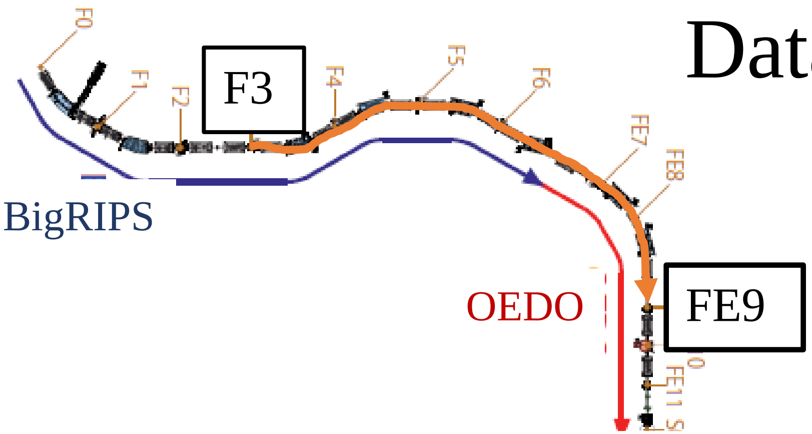


RF Deflector		
Voltage:	100	kV
Phase shift:	257	degrees

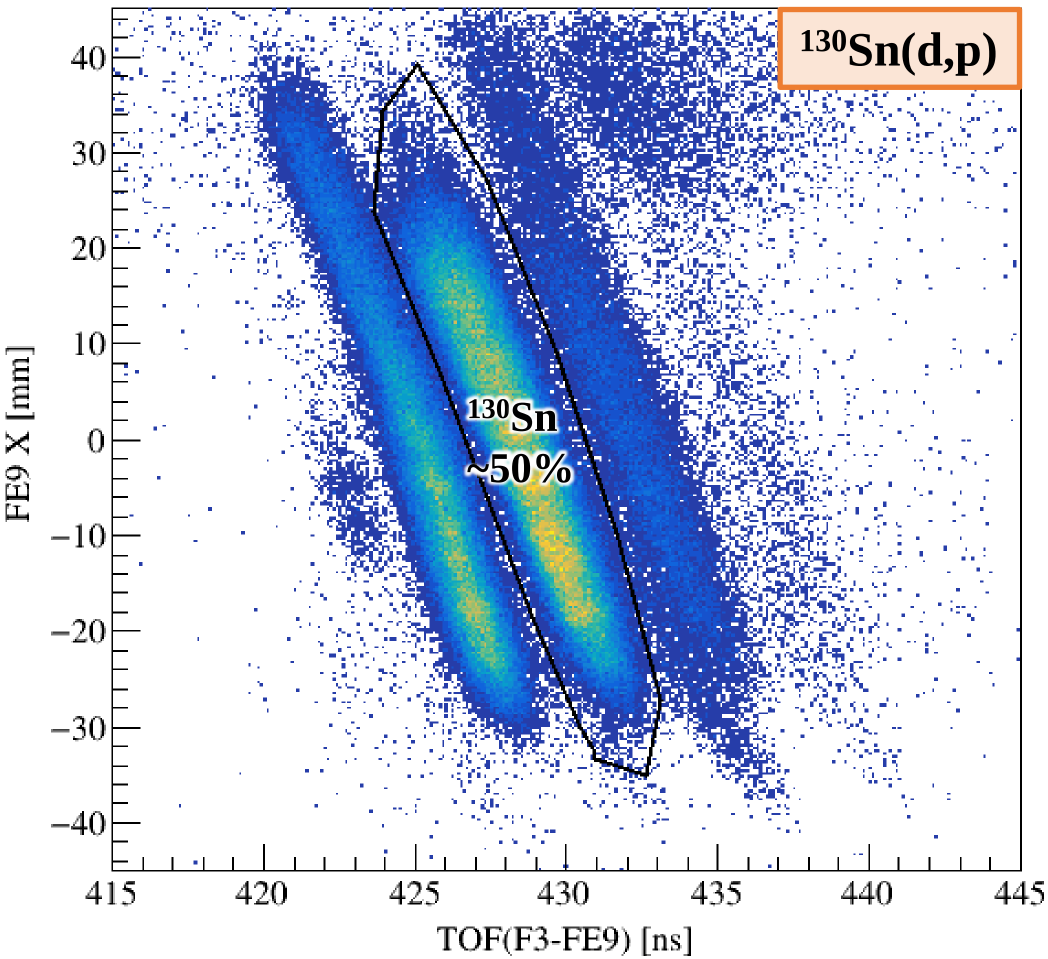


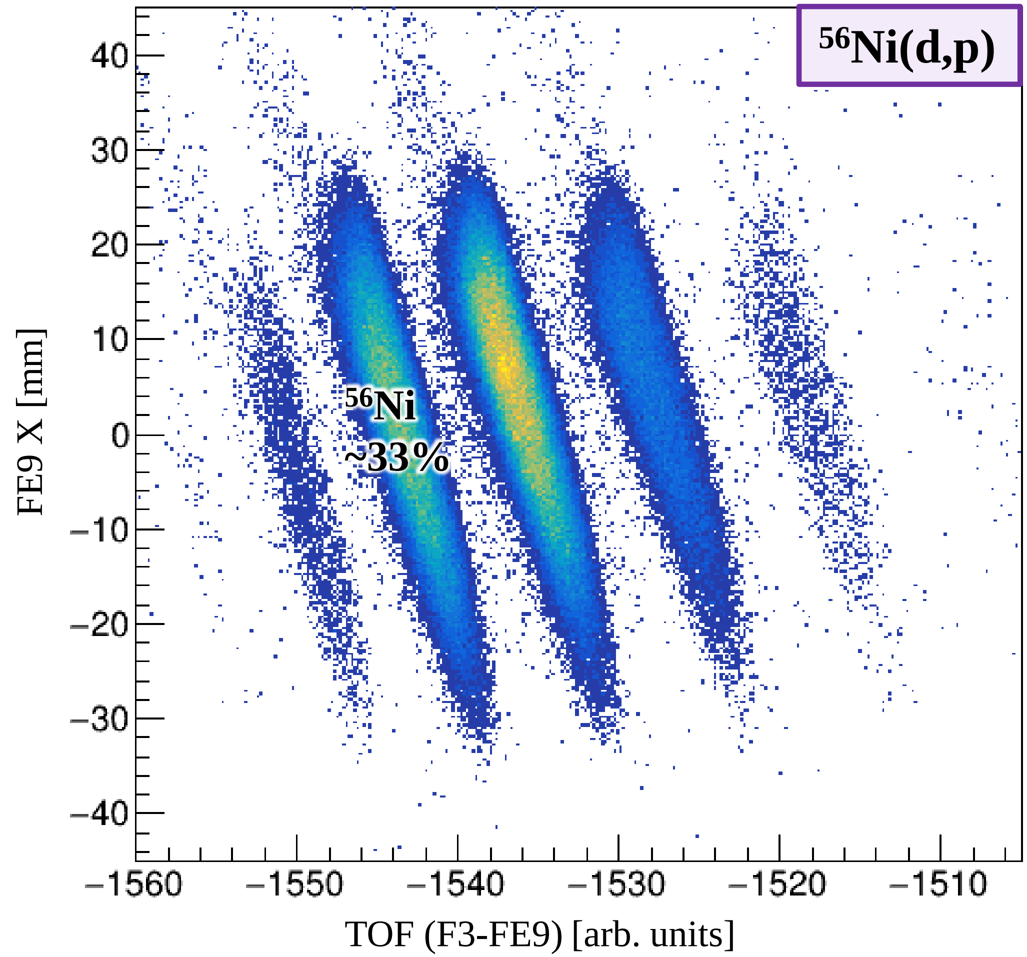


Data Analysis: Beam PID



FE9 PPAC calibration courtesy
S. Ishio & H. Tanaka

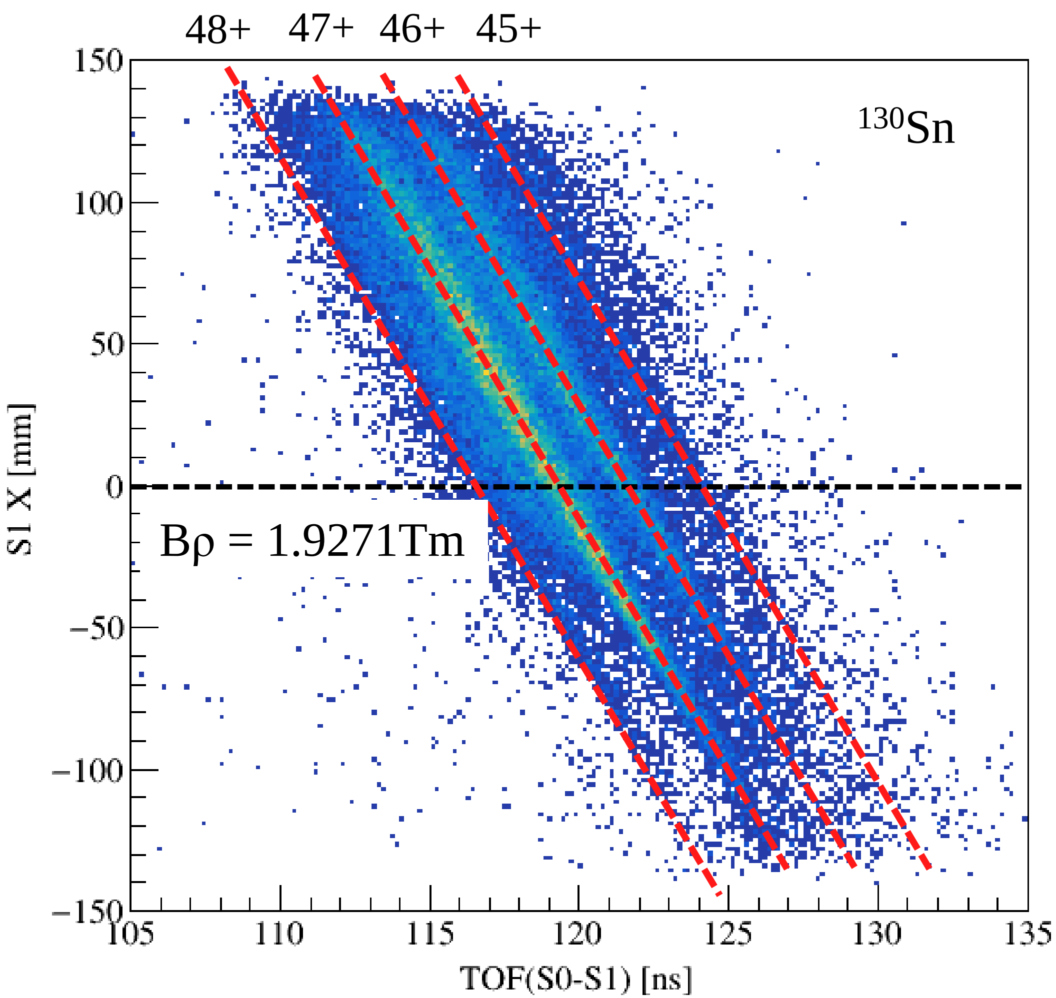


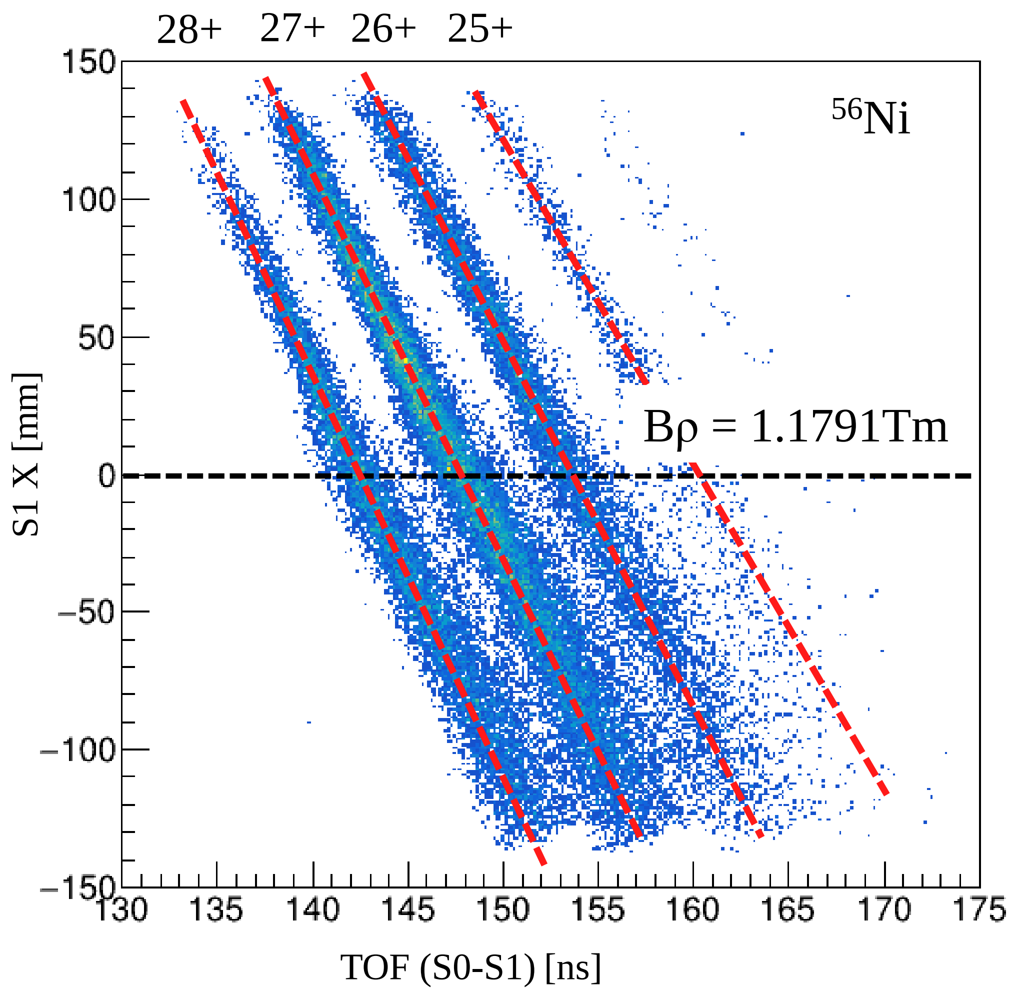


Data Analysis: Beam PID

SH18: ^{130}Sn(d,p)

SH19: ^{56}Ni(d,p)





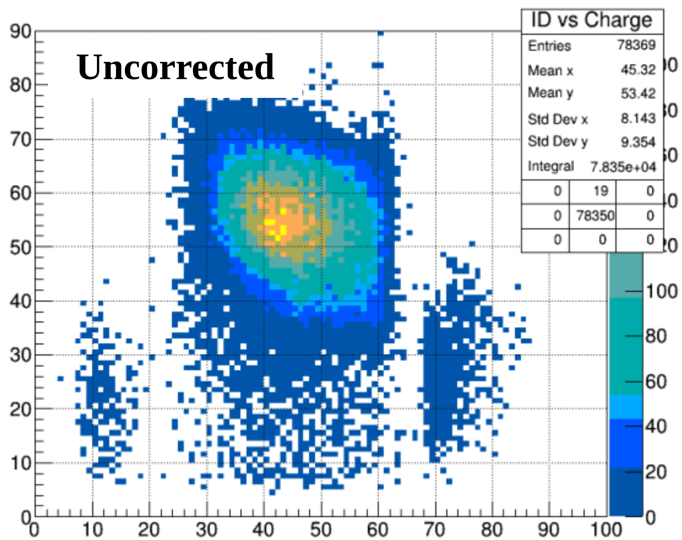
Data Analysis: SR-PPACs and TiNA

Courtesy: D. Suzuki

SR-PPAC: S. Ishio (Tohoku) / H. Tanaka (Kyushu)

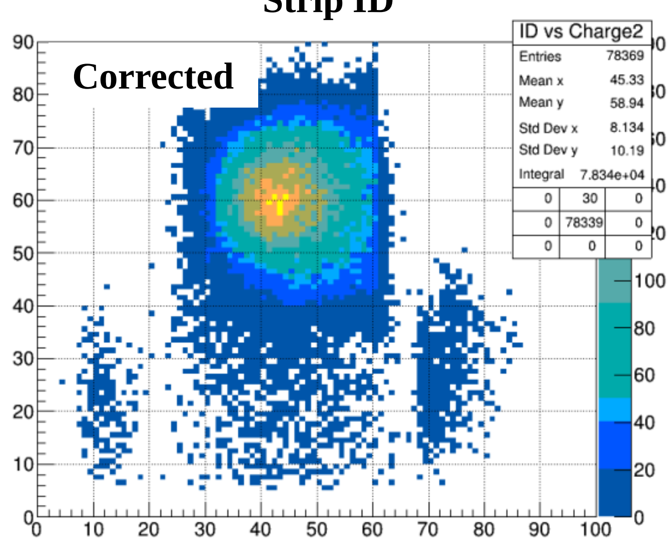
Relative gain calibration for the strips

Charge



Strip ID

Charge

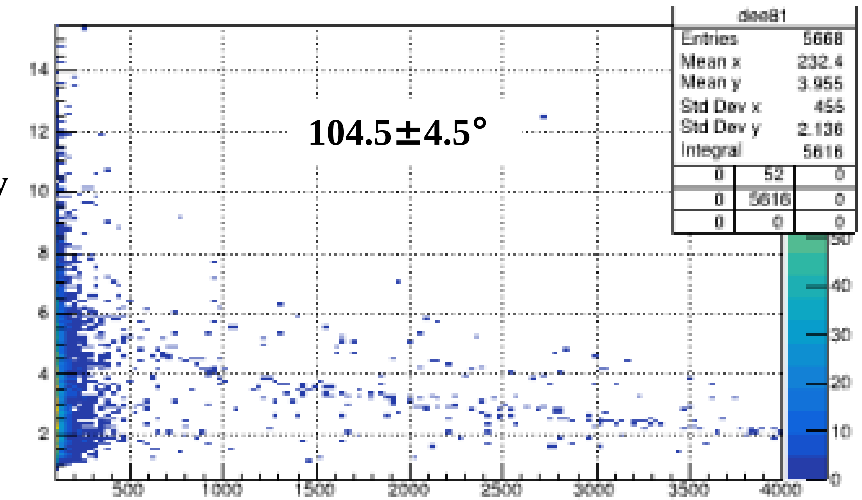


Strip ID

TiNA: T. Haginouchi (Tohoku)

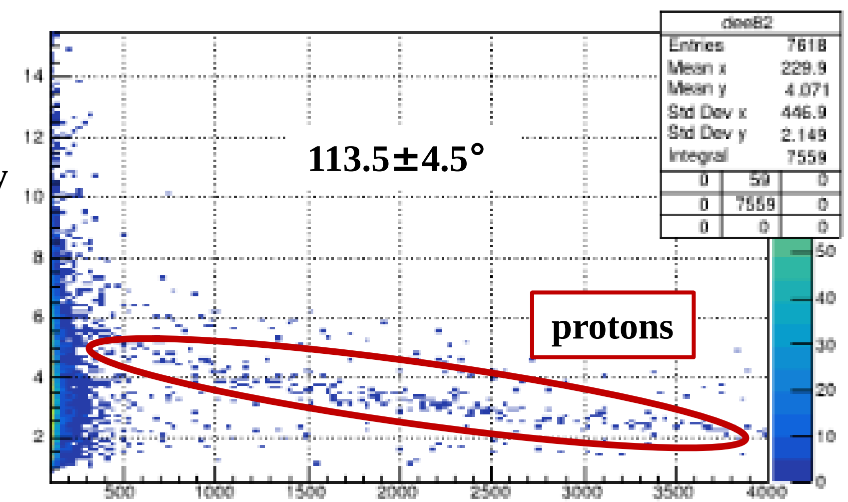
E-ΔE plot by selecting incident angles

Energy DSSD [MeV]



Energy CsI [a.u.]

Energy DSSD [MeV]

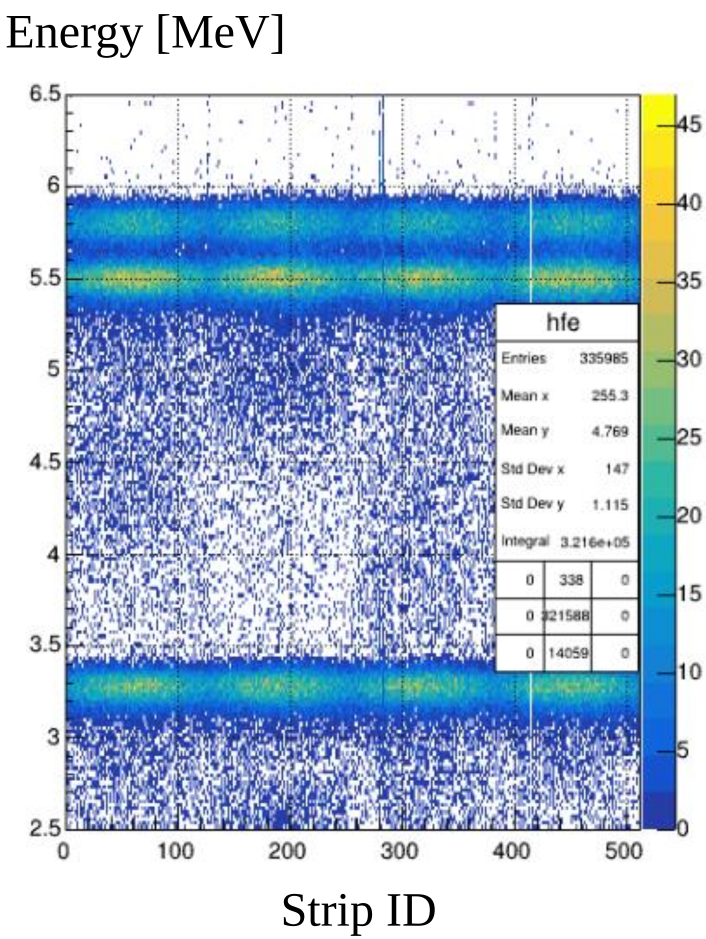


Energy CsI [a.u.]

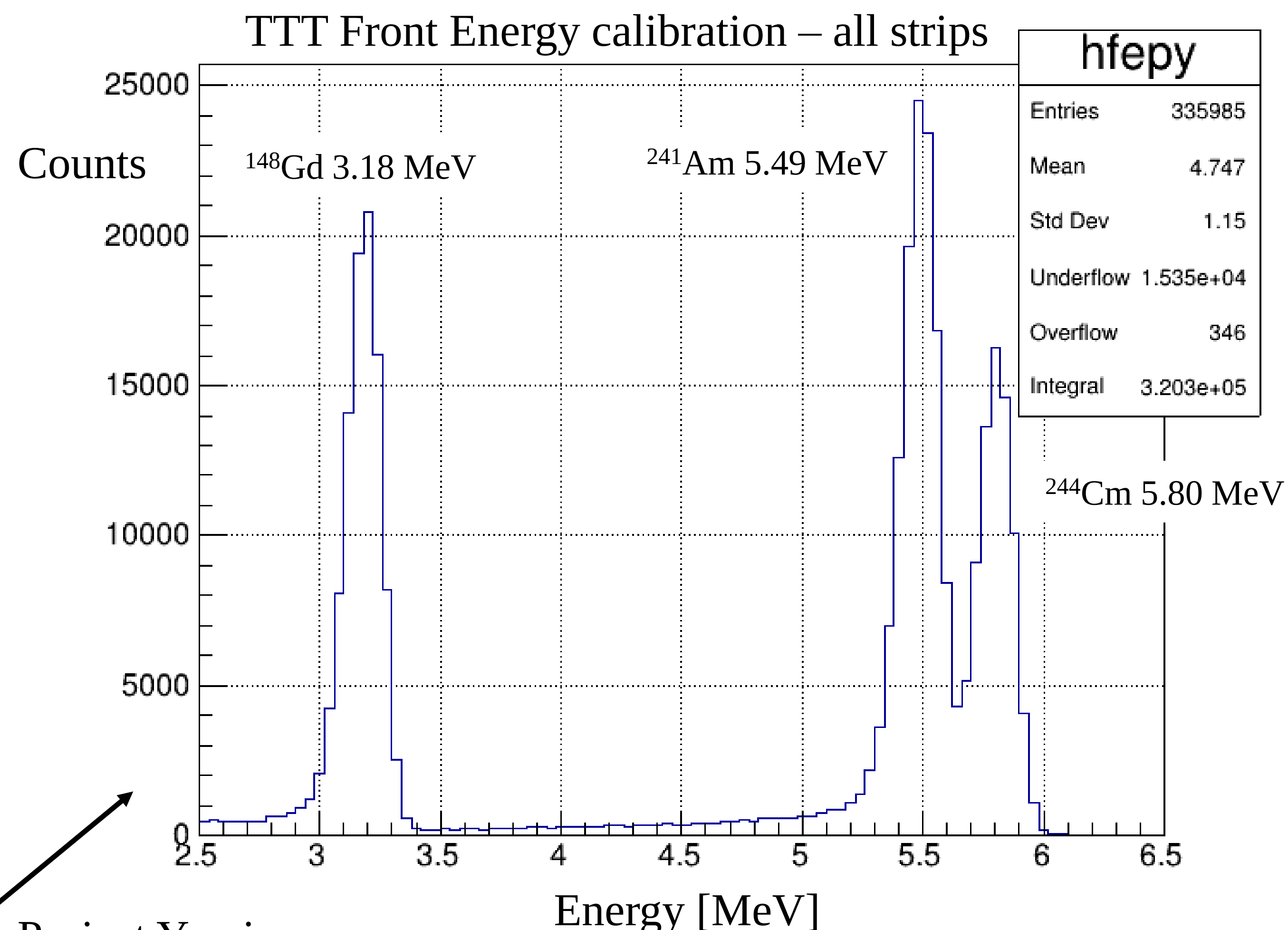
Data Analysis: TiNA

Courtesy: T. Haginouchi

TiNA: Energy calibration with triple-α source
- TTT and YY1
- CsI



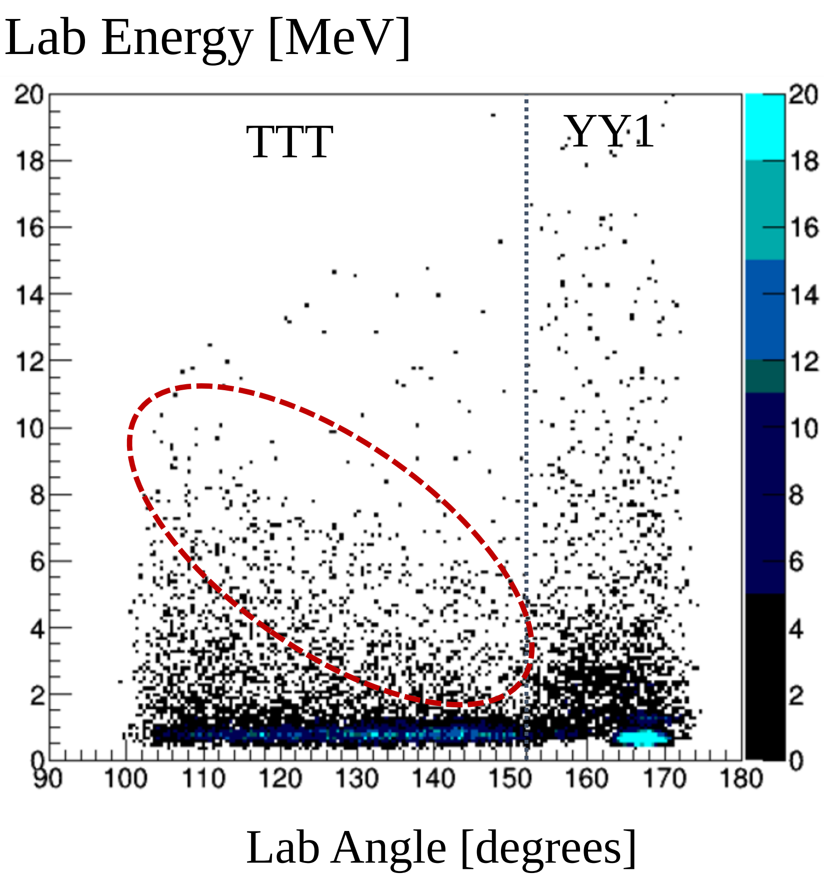
Project Y-axis

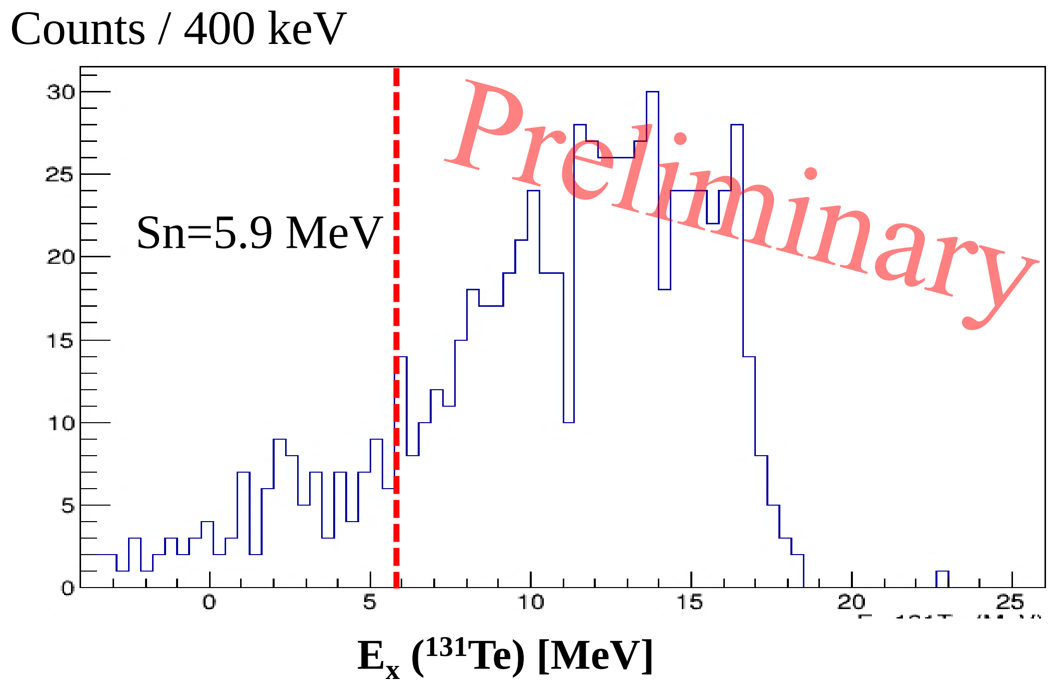


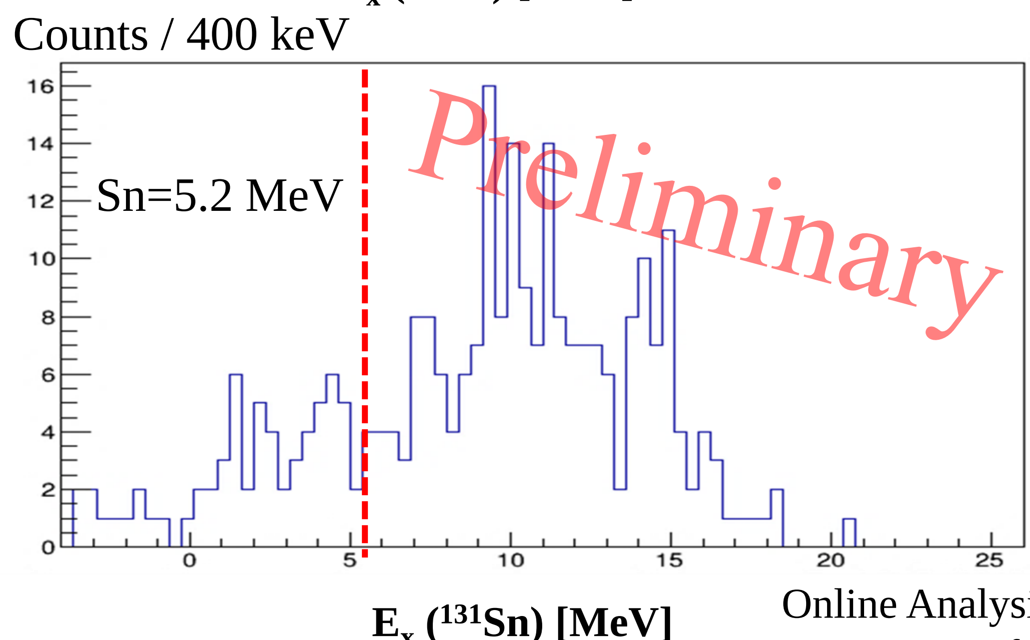
Data Analysis: TiNA

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

- ^{131}Te and ^{131}Sn Level Density
  - Part of total data (YY1)
  - Gates: Beam PID, beamspot
  - **Very preliminary!**





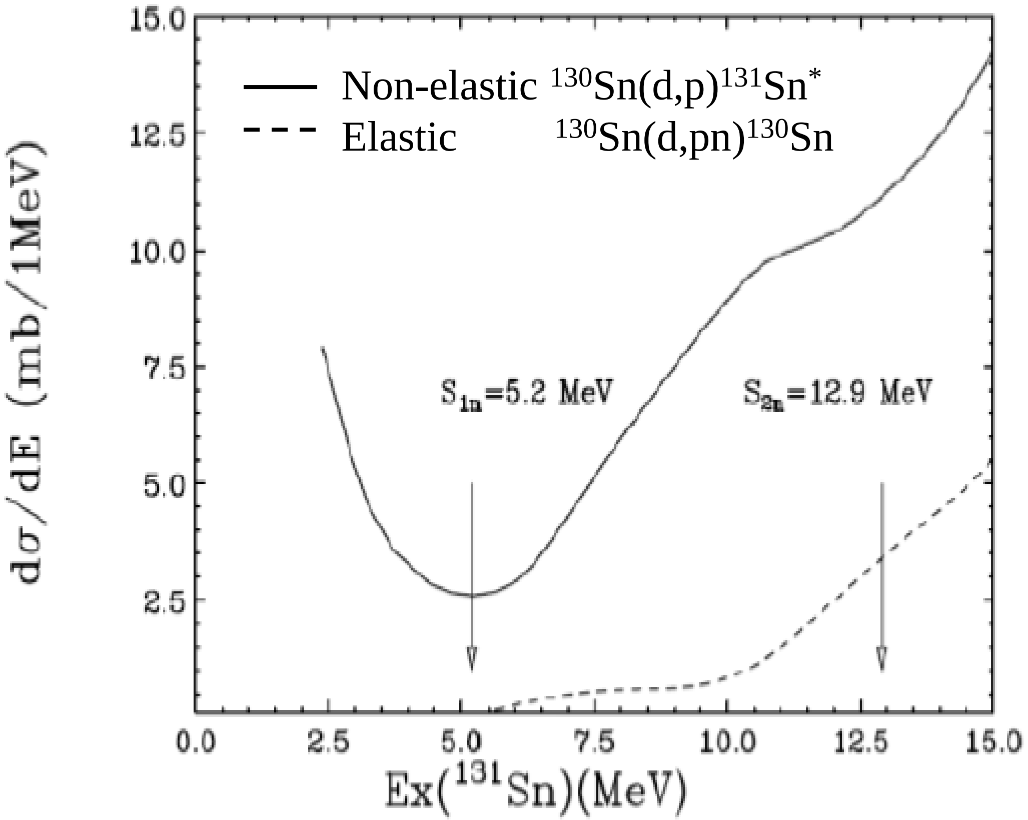


Online Analysis
Courtesy Prof. N. Imai

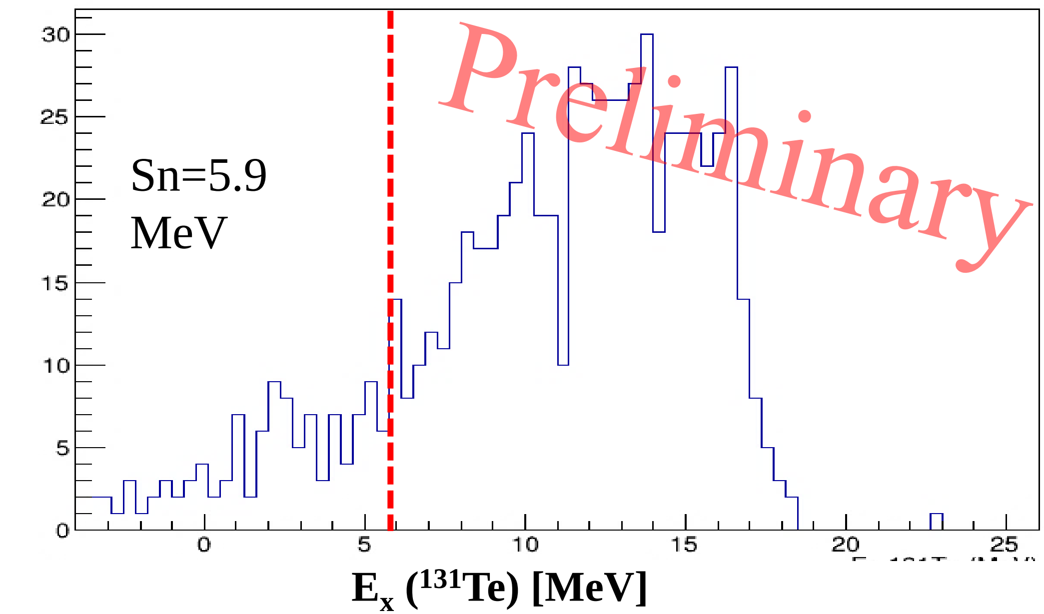
Data Analysis: TiNA

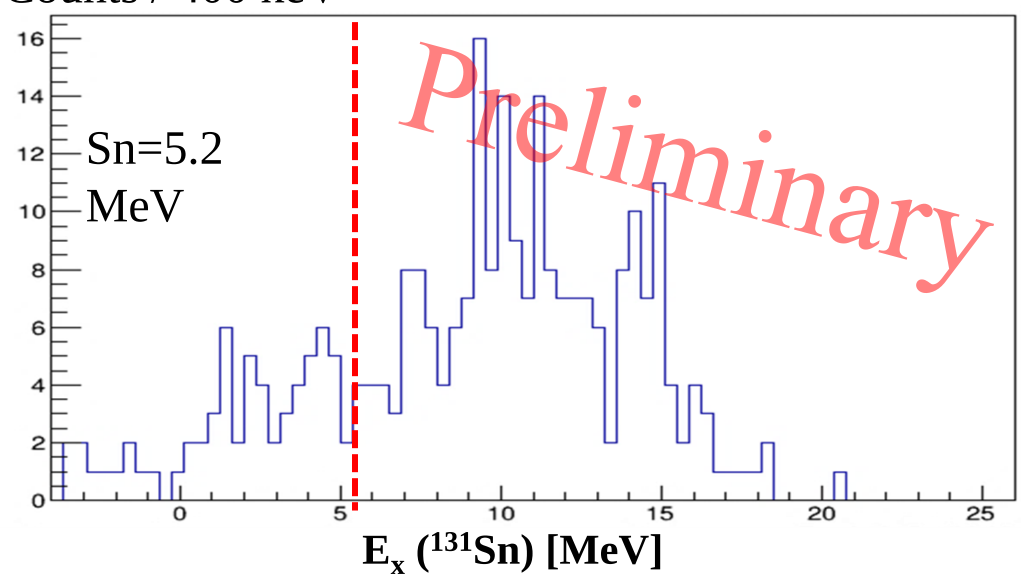
$^{130}Sn(d,p)$

- ^{131}Sn Level Density
  - Exp. lower than theory
  - Very preliminary!



dσ/dE integrated $\theta_{cm} = 0 – 38^o$

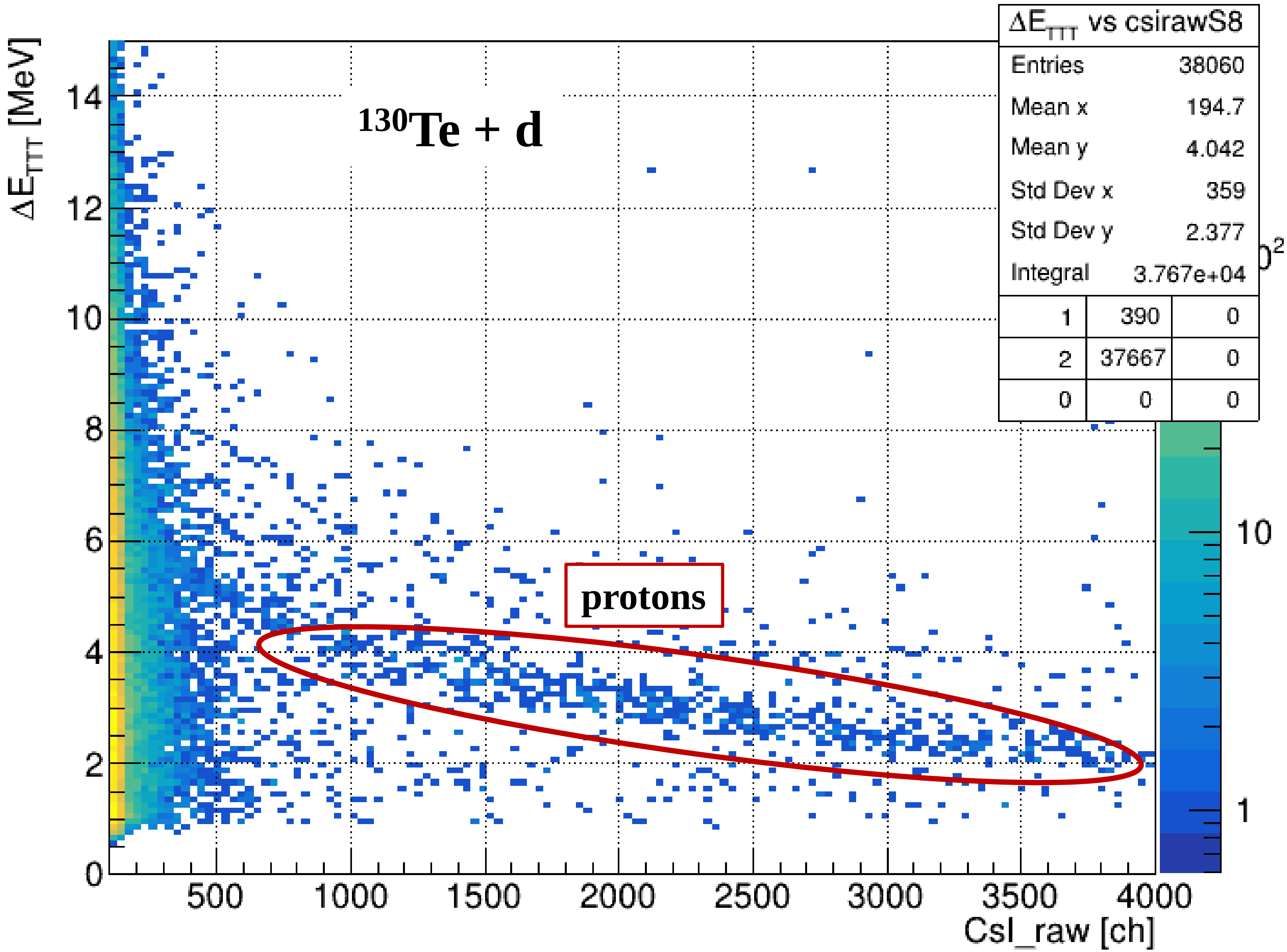




Online Analysis Courtesy Prof. N. Imai

Data Analysis: TiNA

Courtesy: T. Haginouchi



Ideal IC PID (^{93}Zr)

From OEDO day0 exp. measuring ^{93}Zr + d reactions