Oslo法と(p,2p)反応を用いた
中性子過剰核の
中性子捕獲反応測定計画

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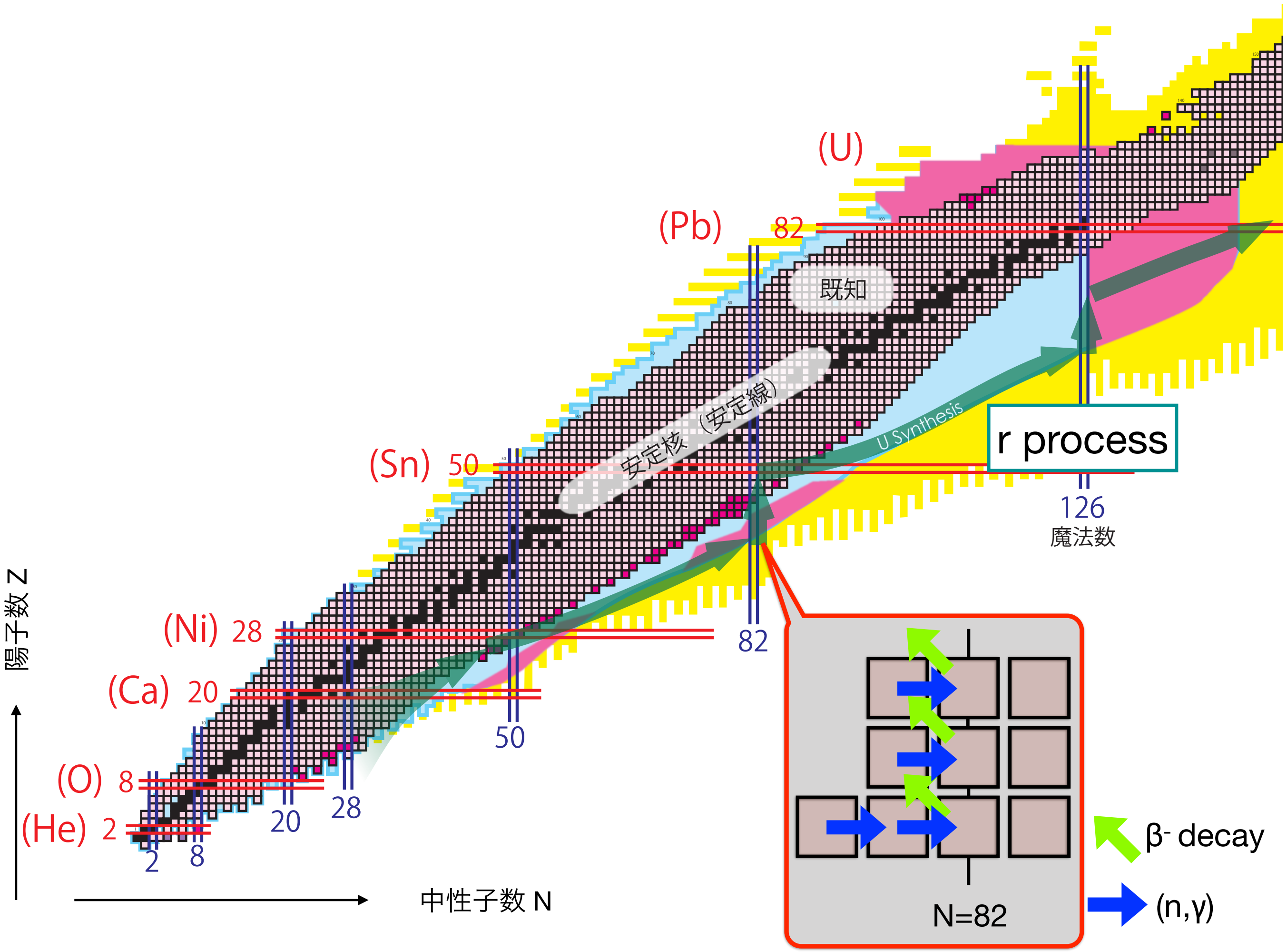
Outline

- Neutron capture reactions in r process
- Oslo method
- (p,2p)-Oslo method
- Experimental setup: STRASE + CATANA
- Future plan
- Proof of principle experiment at RIBF

Neutron capture reactions in r process



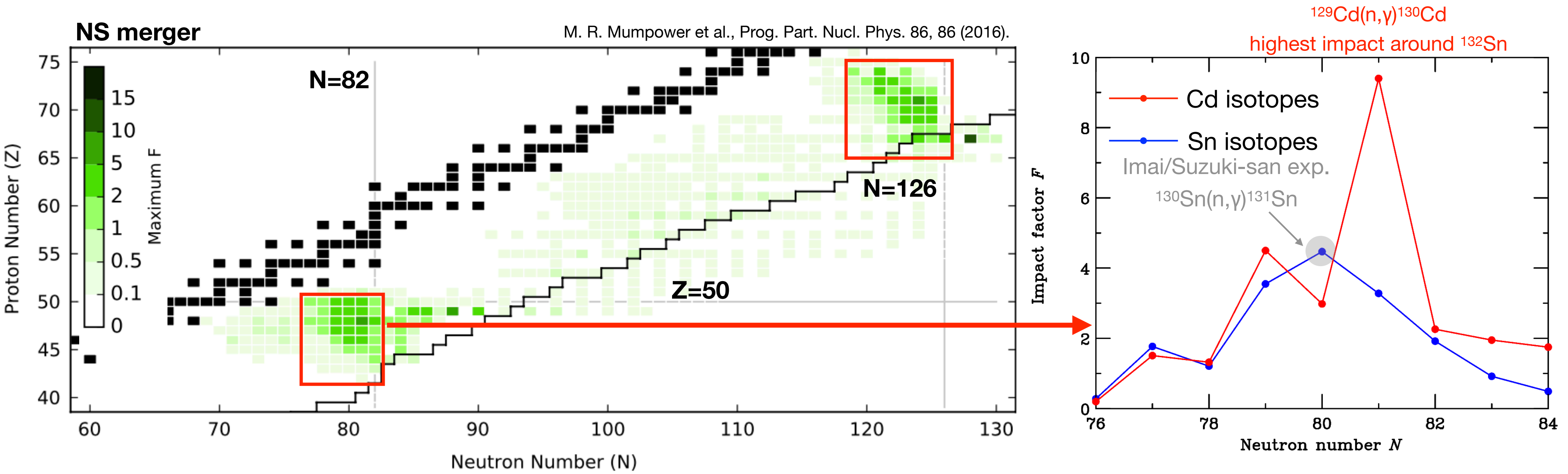
(n, γ) reaction: Almost no data

Neutron + unstable nuclei	
15min	< a few min

Constrain important (n,γ) rates by indirect methods

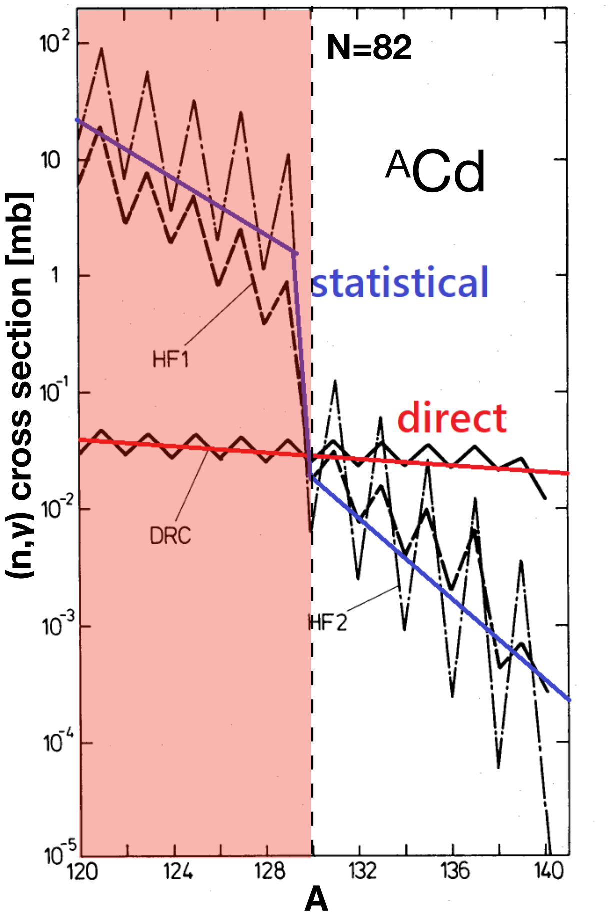
Important (n,γ) rates in r process

Important (n,γ) rate = (n,γ) rates with huge impacts on final abundance

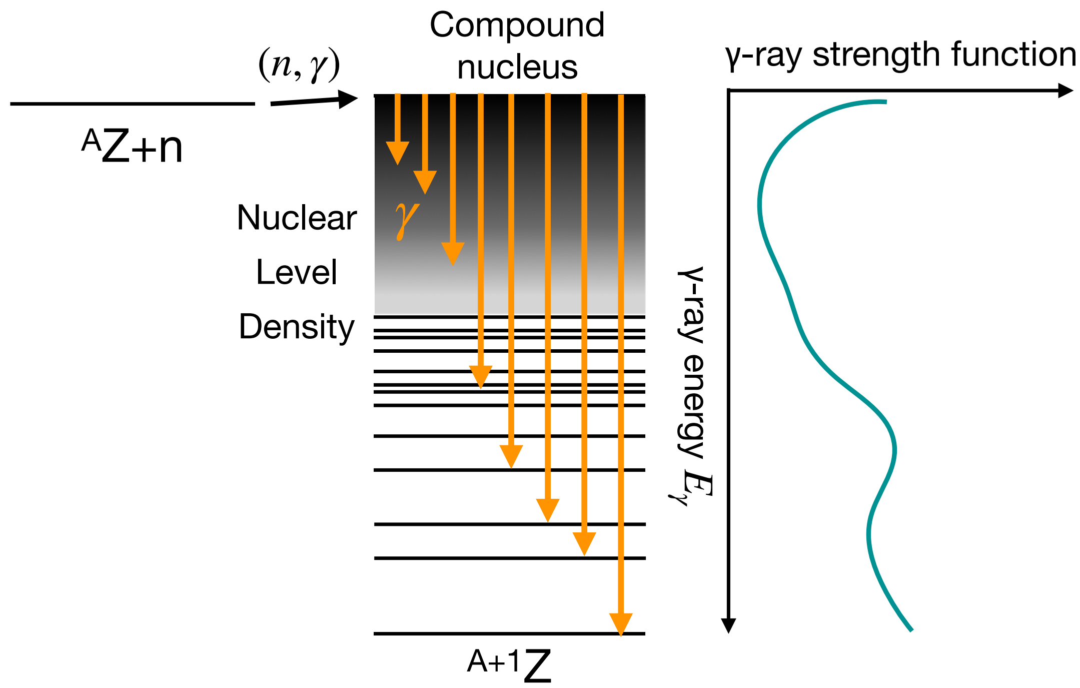


Constrain (n,γ) rates on more neutron-rich nuclei → New indirect method

Neutron captures at east side of N=82 & 126: statistical capture



G.J. Mathews et al., Astrophys. J. 270, 740



$$\sigma_{n\gamma} = \frac{\pi}{k_n^2} \sum_{J,\pi} g_J \frac{\mathcal{T}_\gamma(E_x, J, \pi)\mathcal{T}_n(E_x, J, \pi)}{\mathcal{T}_{tot}}$$

$$\mathcal{T}_n \gg \mathcal{T}_\gamma \rightarrow \sigma_{n\gamma} \propto \mathcal{T}_\gamma$$

$$\mathcal{T}_\gamma(E_x, J, \pi) = \sum_\nu \mathcal{T}_\gamma^\nu(E_\gamma) + \int \mathcal{T}_\gamma(E_\gamma)\, \rho(E, E_\gamma) dE_\gamma$$

Nuclear Level Density(NLD)

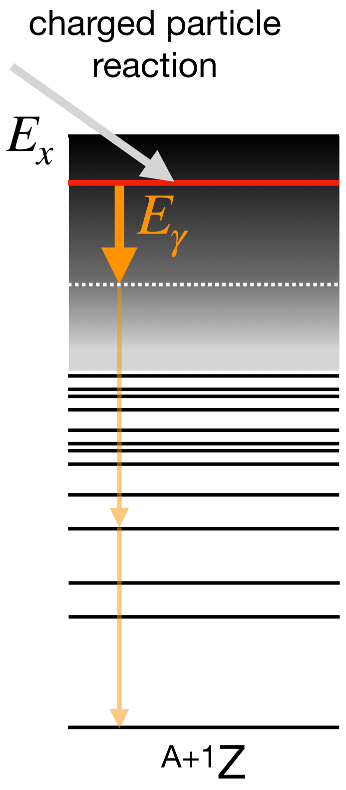
$$\mathcal{T}_\gamma(E_\gamma) = 2\pi E_\gamma^3 f(E_\gamma)$$

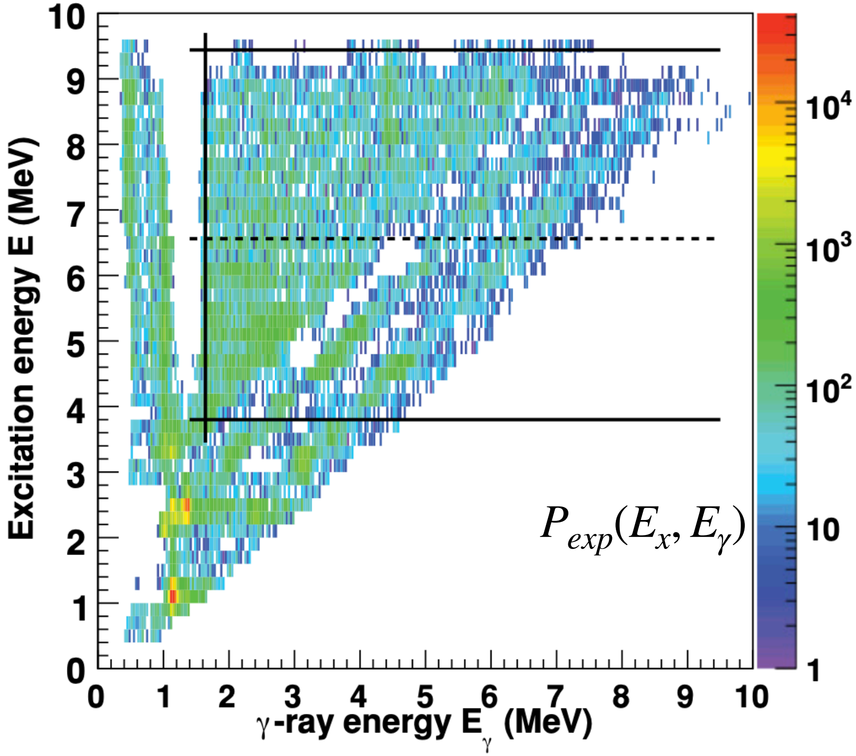
γ-ray strength function (γSF)

Indirect method for $^{A}Z(n,\gamma)^{A+1}Z$: **Oslo method**

Produce $^{A+1}Z^{*}$ → Fit E_x vs E_γ matrix → **Function forms** of NLD & γSF

A. C. Larsen et al., Prog. Part. Nucl. Phys. 107, 69 (2019).





$$P_{\exp}\left(E_x, E_\gamma\right) \propto \mathscr{T}\left(E_\gamma\right)\rho\left(E_x - E_\gamma\right)$$

NLD

$$f(E_\gamma) = \frac{\mathscr{T}(E_\gamma)}{2\pi E_\gamma^3}$$

γSF

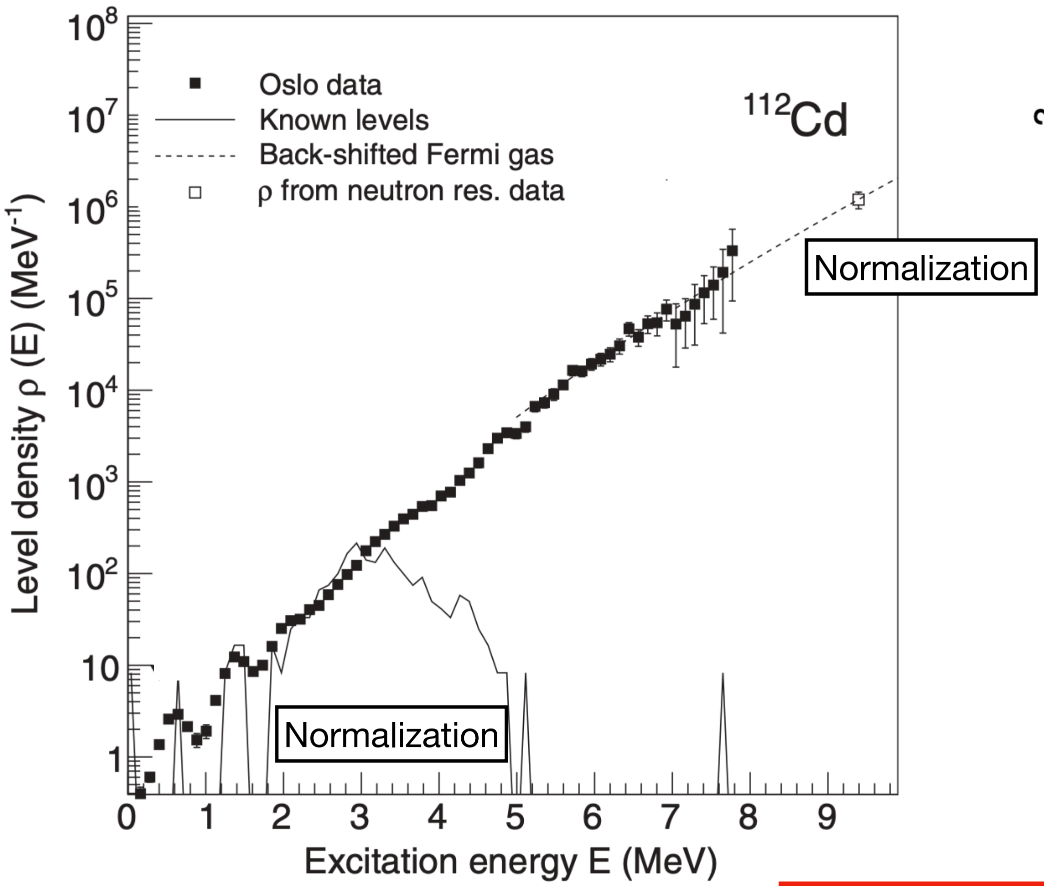
Assumption

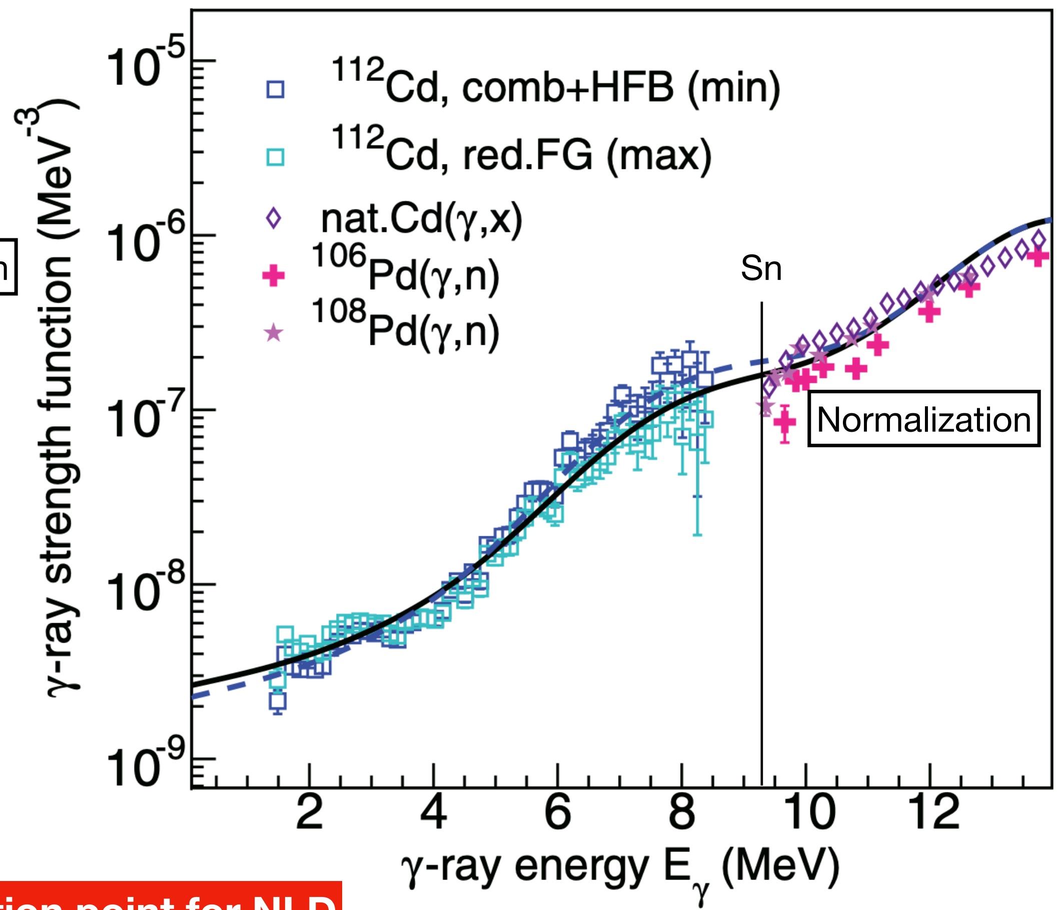
- Populated states are all compound states
- γ decay between states: L=1
- Brink-Axel hypothesis

Function form: Need normalization

Oslo method: ^{112}Cd(^{3}He,^{3}He'γ)^{112}Cd

A. C. Larsen et al., Phys. Rev. C 87, 014319 (2013).

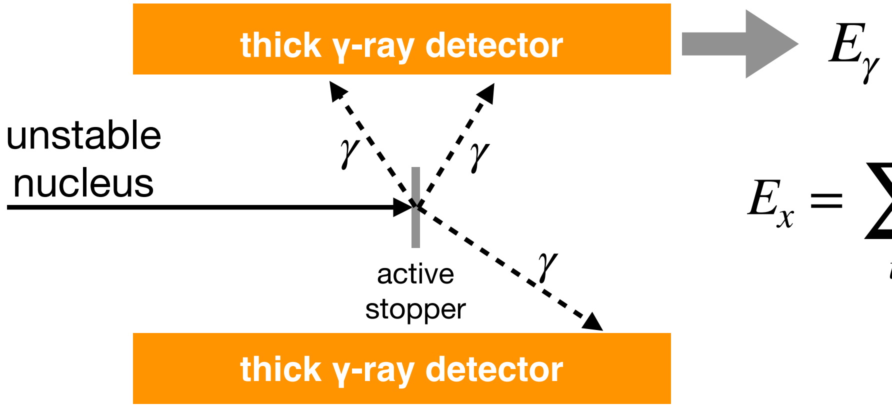




2 normalization point for NLD

1 normalization point for γSF

Oslo method for unstable nuclei: β-Oslo method

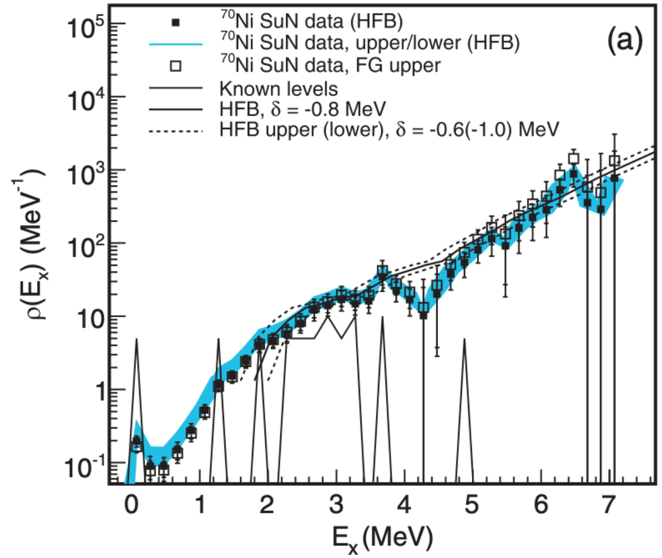


$$E_x = \sum_i E_{\gamma_i}$$

Reaction: β decay

Detector: high efficiency (thick NaI, ~85% for 0.661 MeV)

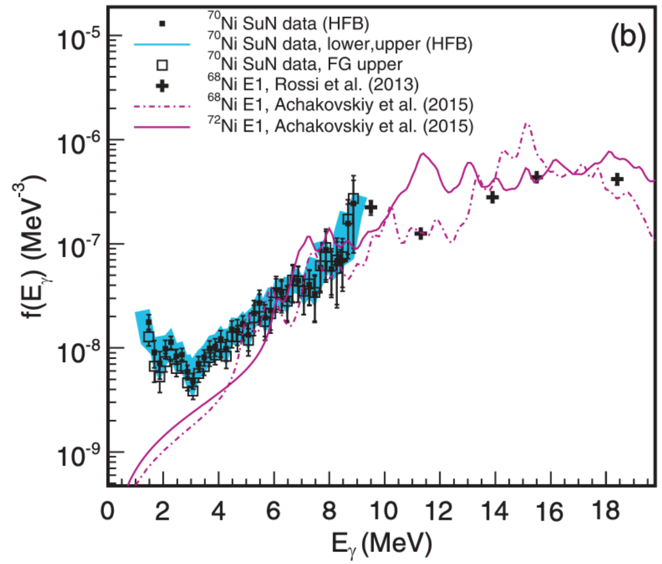
- Feasible with ~ 1cps beam
- Jπ of implanted nucleus: must be known
- Lack of normalization points



Normalizations

low-E: known NLD

high-E: HFB calc.



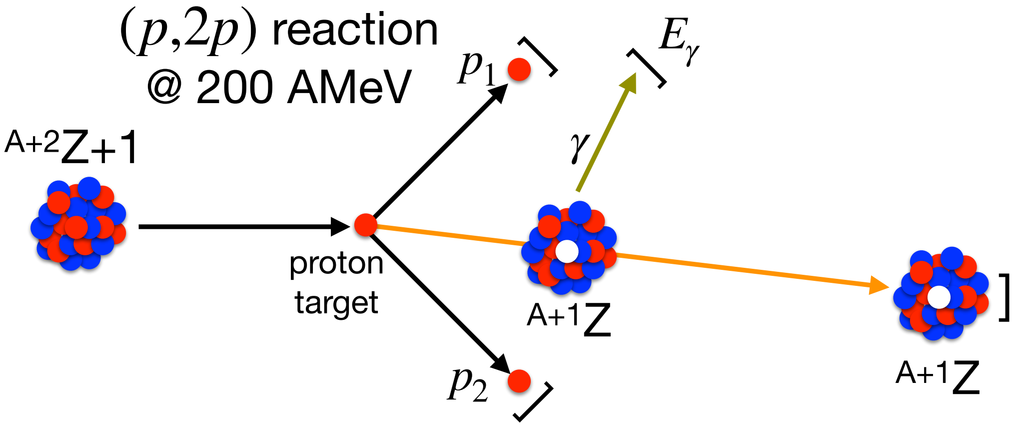
Normalization

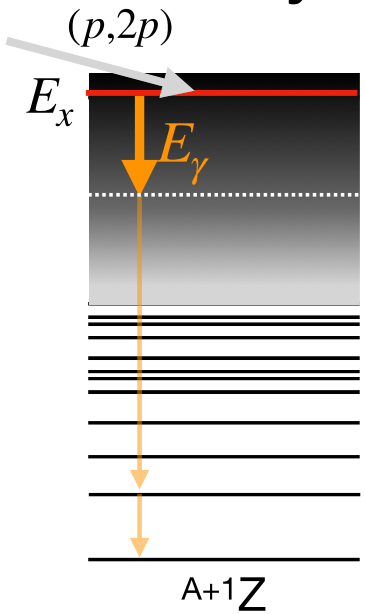
γSF of ^{68}Ni

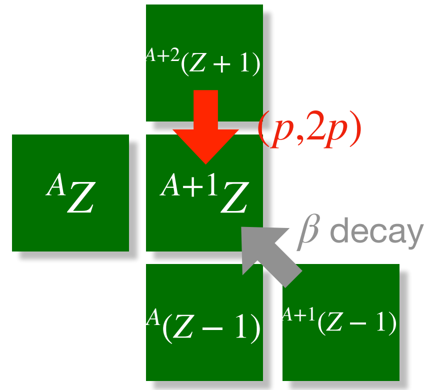
from E1 strength

S.N. Liddick et al., PRL 116, 242502 (2016).

(p,2p)-Oslo method to study $^{A}Z(n,\gamma)^{A+1}Z$







Momenta of p_1 and p_2 → E_x

Missing momentum → Jπ

Advantages

High (p,2p) cross section (~mb)

Less neutron-rich beam: high intensity

→ beam rate: ~ 4 kcps

Disadvantage

Low E_x resolution (σ~2 MeV > $\sigma_{\text{standard Oslo}}$)

Lack of normalization points (same as β-Oslo)

Expected accuracy of (p,2p)-Oslo method

Disadvantages: poor resolution & normalization

Smooth Ex of standard Oslo data → Obtain NLD & γSF → Extract $\sigma_{n\gamma}$

mimic the (p,2p)-Oslo method resolution

Estimated error of (p,2p)-Oslo method

40%: effect of poor resolution

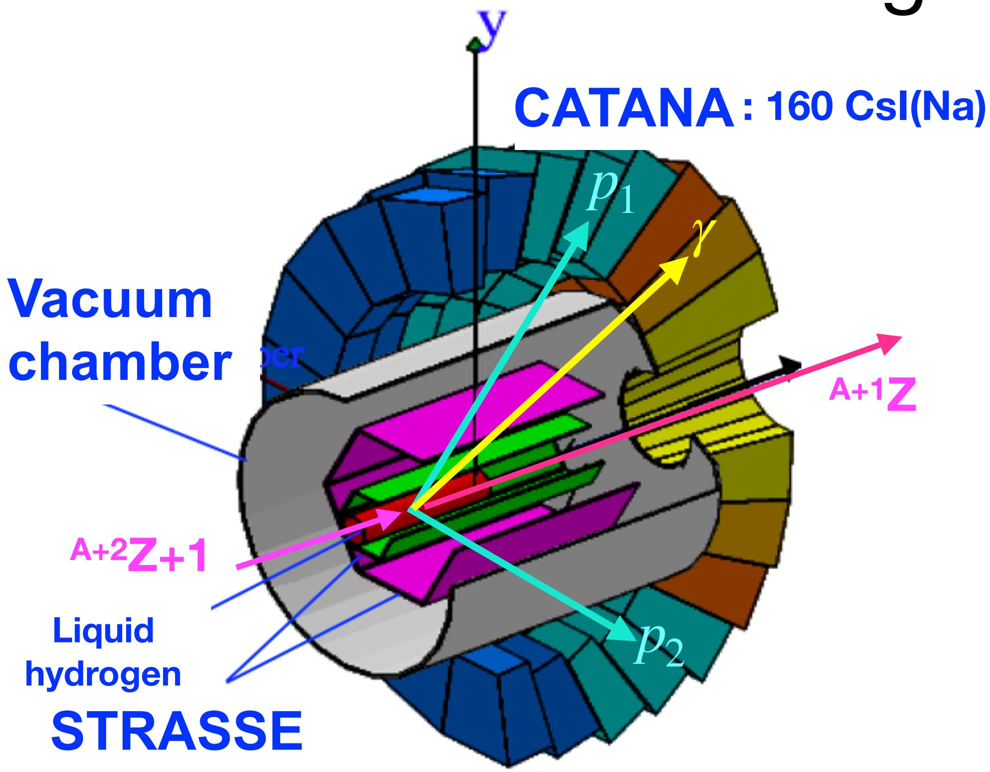
~ factor 3: normalization

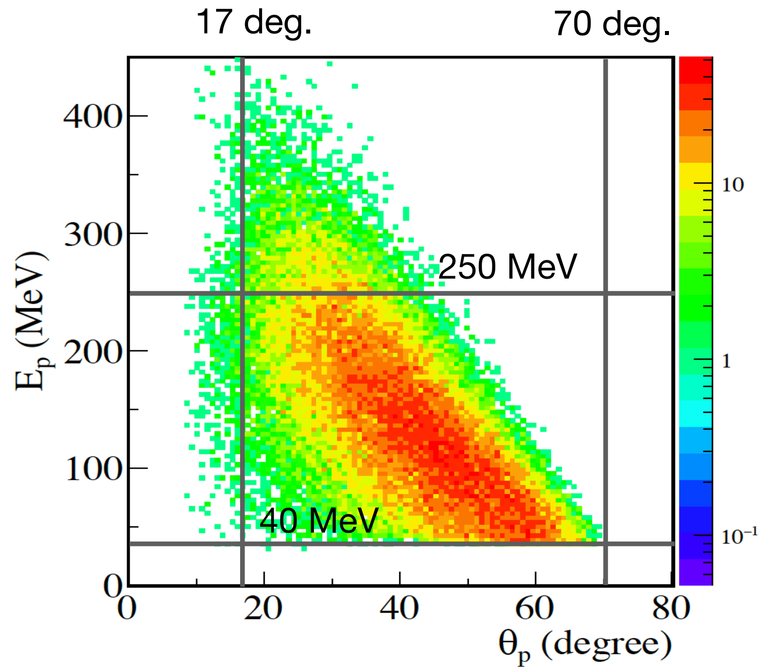
↕

Error of theoretical estimate

> factor 10

STRASSE+CATANA: large acceptance missing mass setup

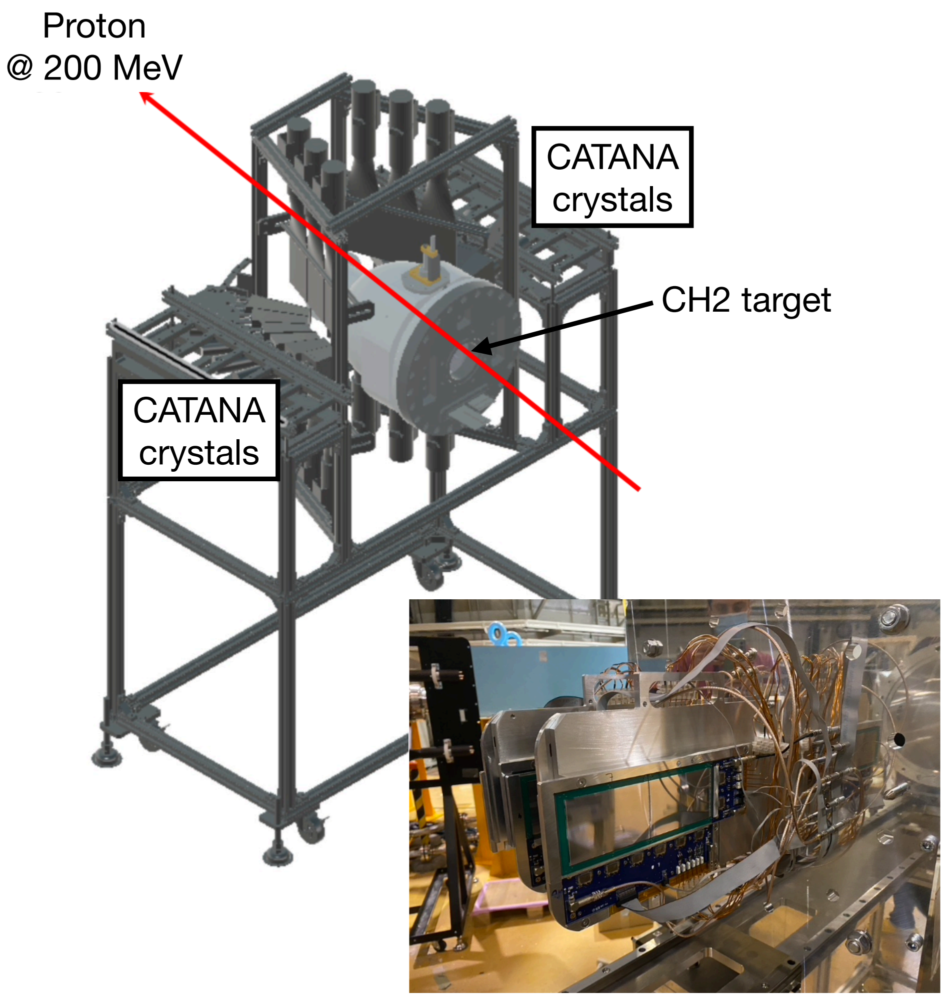


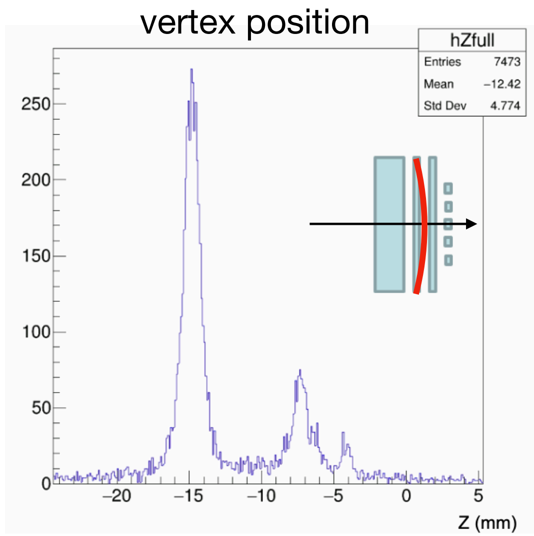


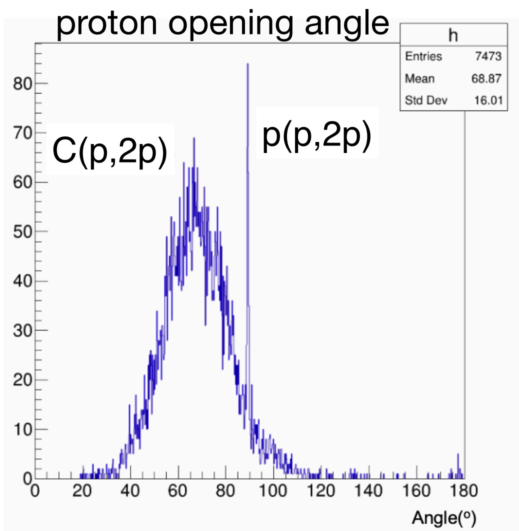
STRASSE: Si tracker with Sub-mm vertex resolution
CATANA: CsI(Na) array to detect protons and γ rays

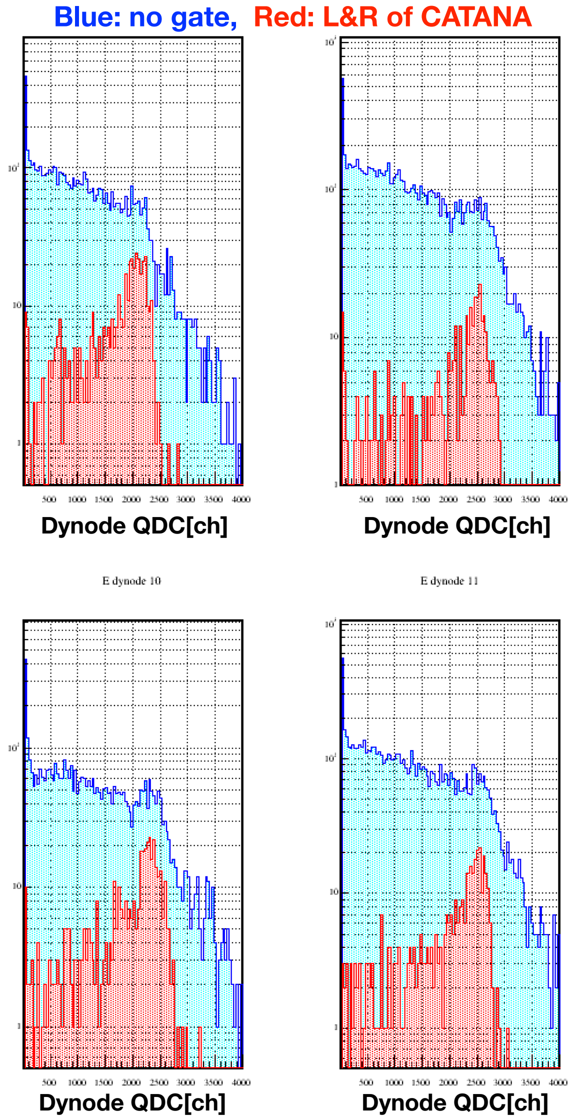
- ☑ Missing mass efficiency = 40% for (p,2p)
- ☑ Missing mass resolution = 1.7 MeV (σ)
- ☑ γ ray detection efficiency = 17% for 1 MeV
- ☑ Will be completed in Fall 2023

Prototype test at HIMAC (2022.05)

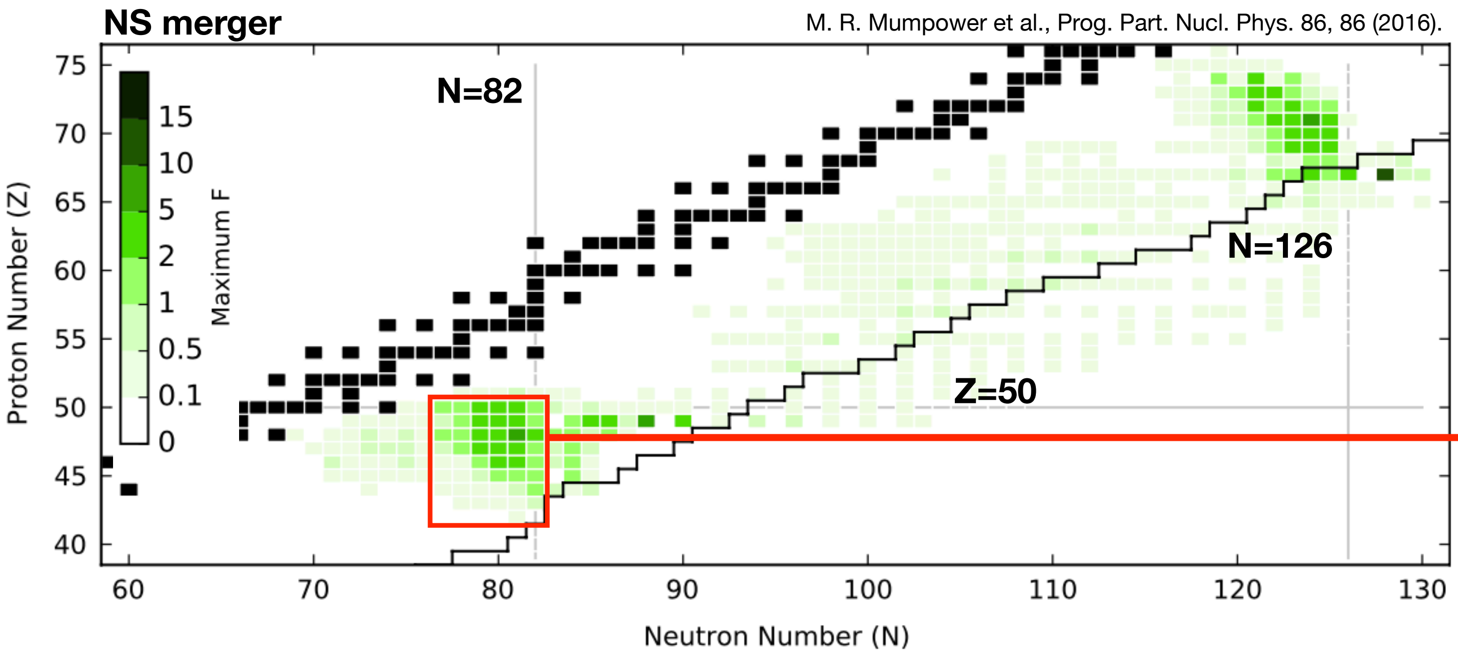


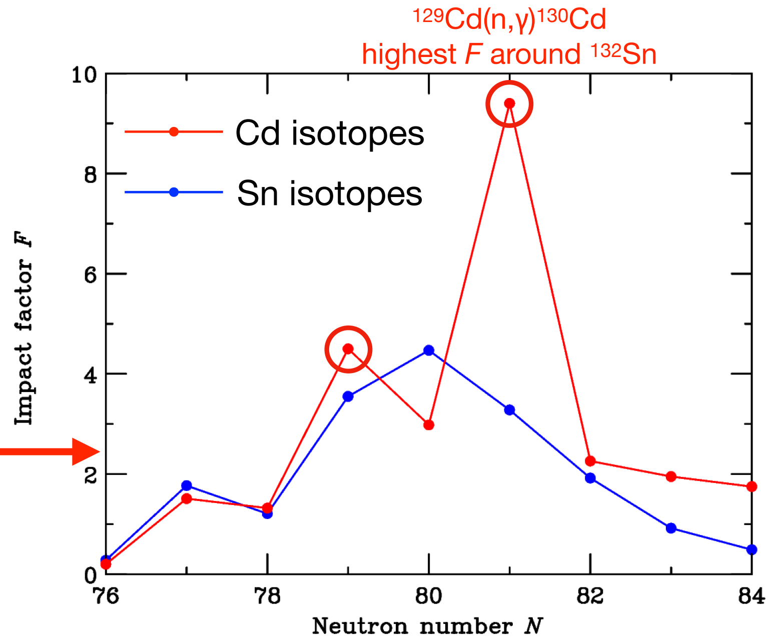


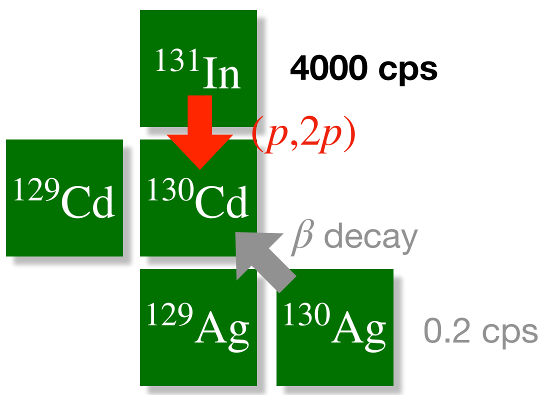




Future plan: (n,γ) of Cd isotopes







^{129}Cd(n,γ)^{130}Cd via ^{131}In(p,2p)^{130}Cd

^{127}Cd(n,γ)^{128}Cd via ^{129}In(p,2p)^{128}Cd

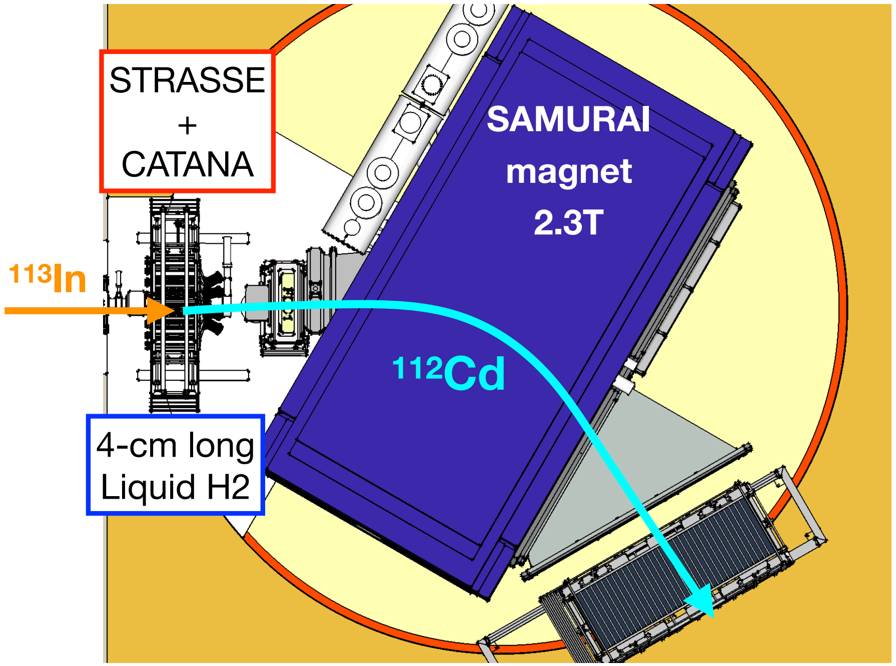
+

proof of principle experiment

^{111}Cd(n,γ)^{112}Cd via ^{113}In(p,2p)^{112}Cd reaction

Proof of principle: ^{113}In(p,2p)^{112}Cd @ RIBF

^{111}Cd(n,γ)^{112}Cd: 2 Direct + 1 standard Oslo data



3 days of beam time approved by RIKEN NP-PAC 2022

Construction of STRASSE and Liq. H2: ongoing (by Fall 2023)

CATANA: ready

Fall 2023 or Spring 2024

Summary

- (n,γ) reaction on n-rich nuclei: one of the major sources of r-process uncertainty
- New Indirect method: **(p,2p)-Oslo method** to obtain statistical n capture rate
  - Ex-Eγ matrix from (p,2p) → nuclear level density & γ-ray strength function
  - High efficiency + high luminosity: more n-rich region than existing methods
    - ^{129}Cd(n,γ)^{130}Cd
    - Around ^{132}Sn: more n-rich region accessible than β-Oslo method
- STRASSE + CATANA setup
  - Prototype test @ HIMAC in 2022.05
  - Full CATANA + STRASSE prototype: Spring 2023 @ SAMURAI RIBF
  - Full STRASSE + Full CATANA: Fall 2023

- 3 days of beam time approved for ^{113}In(p,2p)^{112}Cd as proof-of-principle experiment.

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