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THE STATE UNIVERSITY OF NEW JERSEY

New experimental techniques to inform neutron-induced reaction cross sections on rare isotopes with surrogate reactions

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Rutgers University

Compound-Nuclear Reactions and Related Topics (CNR*24)

Vienna, Austria

July 8-12, 2024

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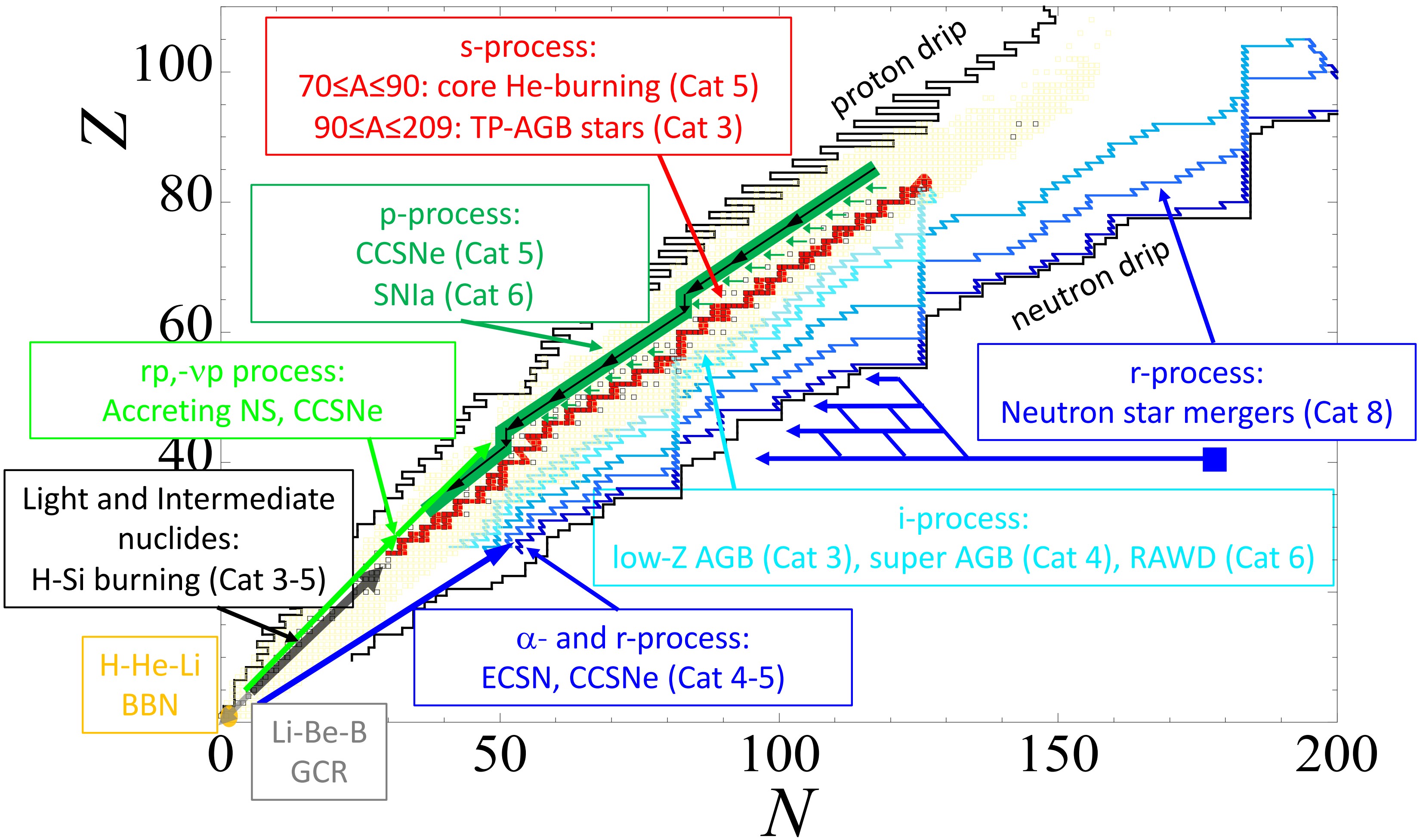
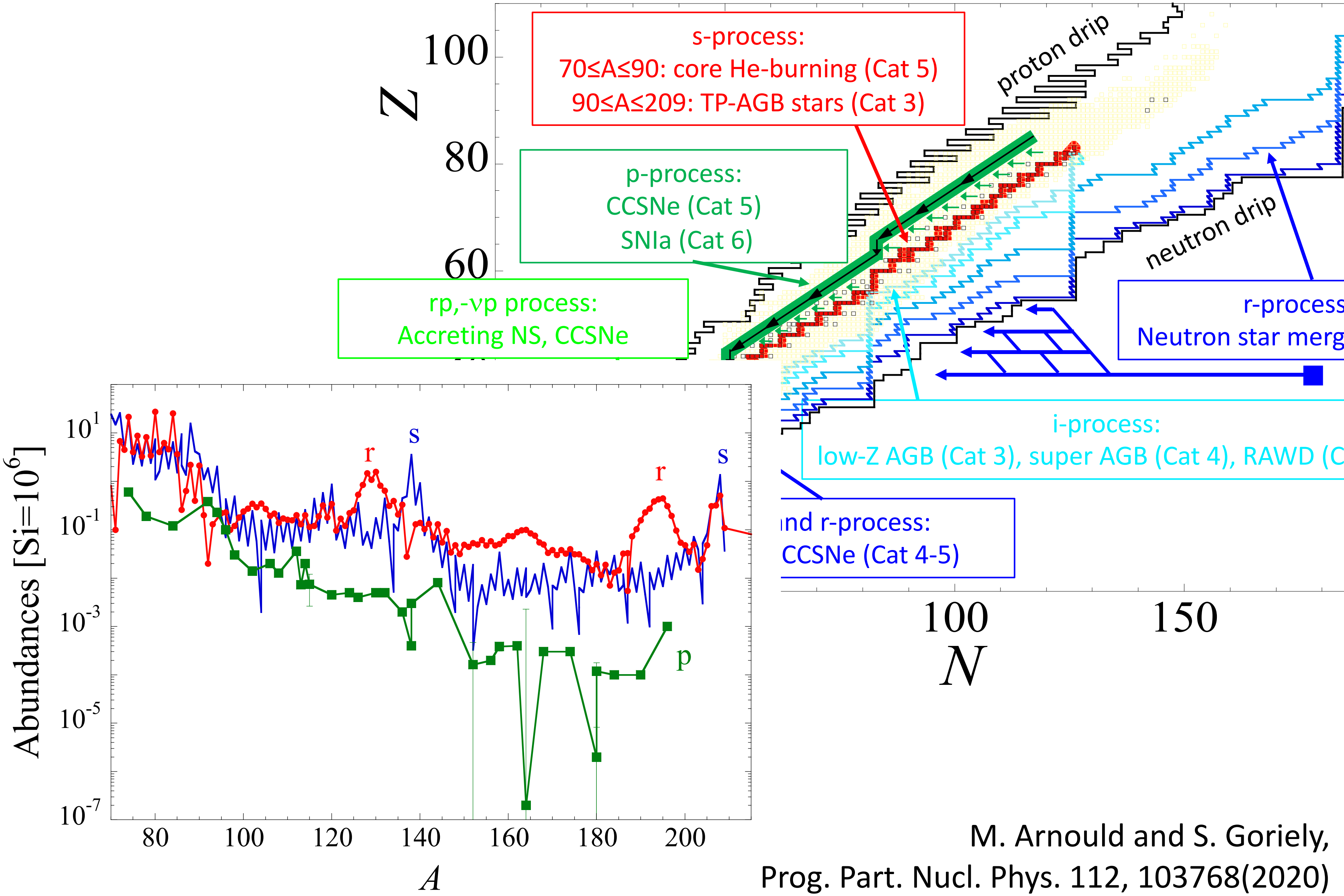
Synthesis of heavy elements requires (n,γ)



M. Arnould and S. Goriely,
Prog. Part. Nucl. Phys. 112, 103768(2020)

Synthesis of A≈80: many (n,γ) processes



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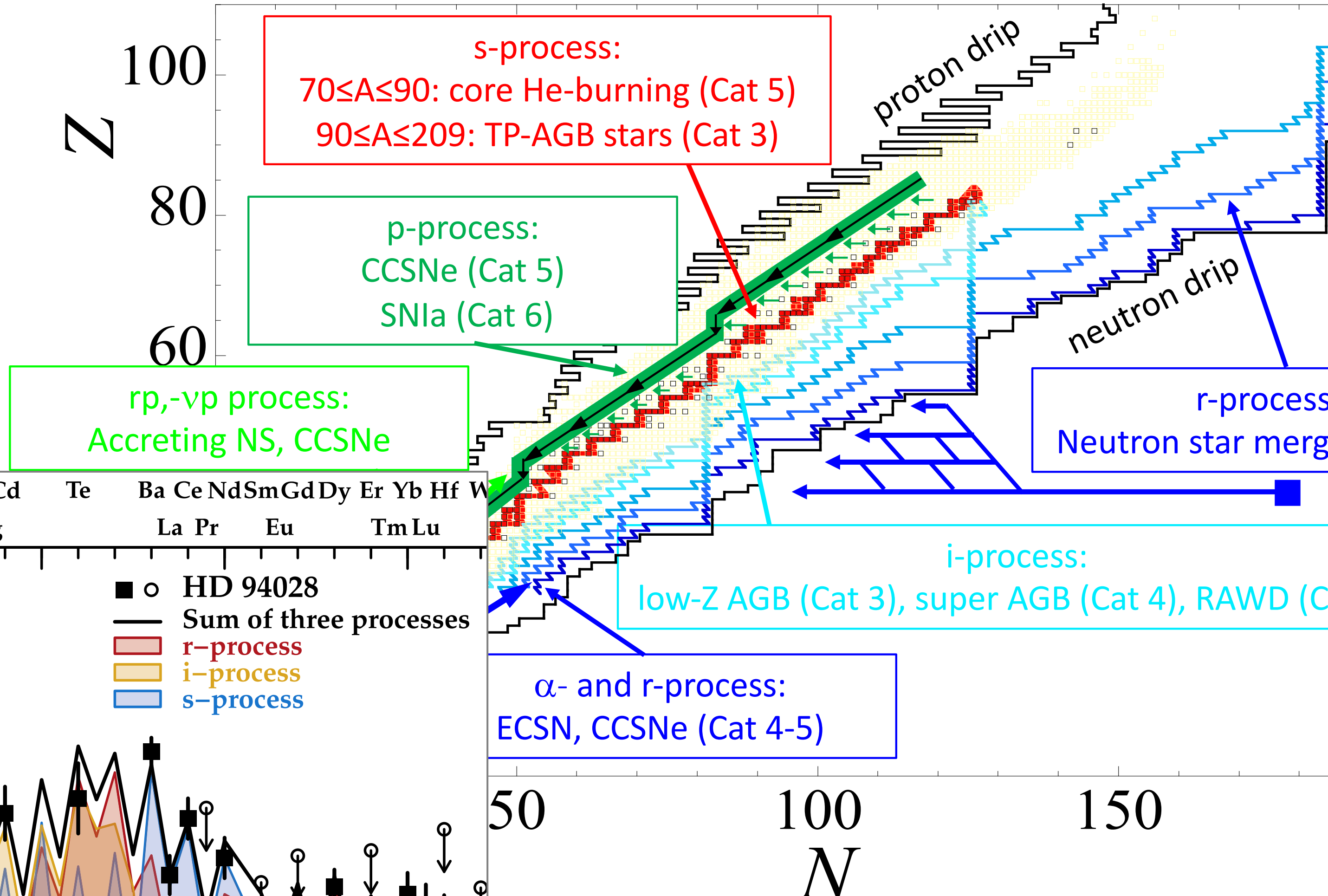
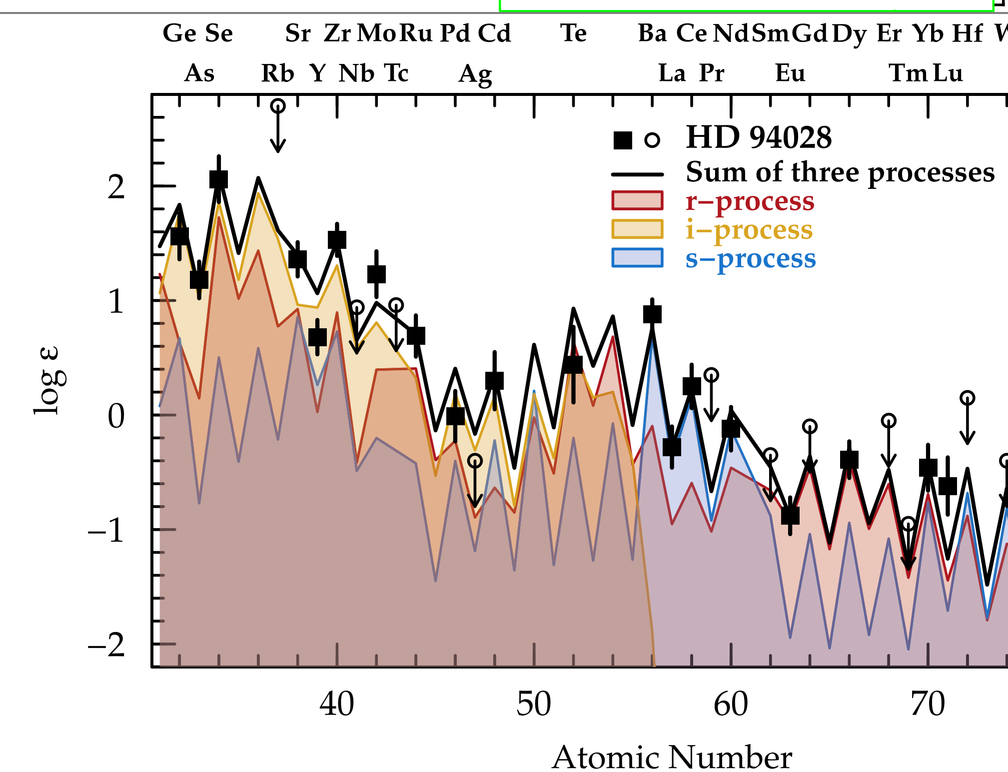
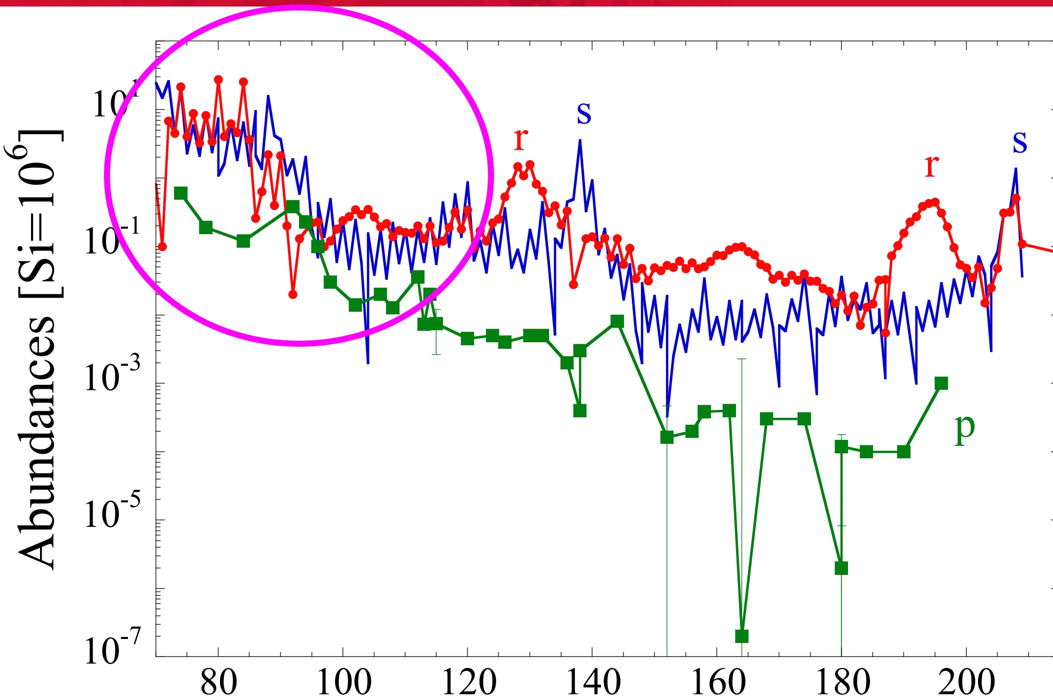
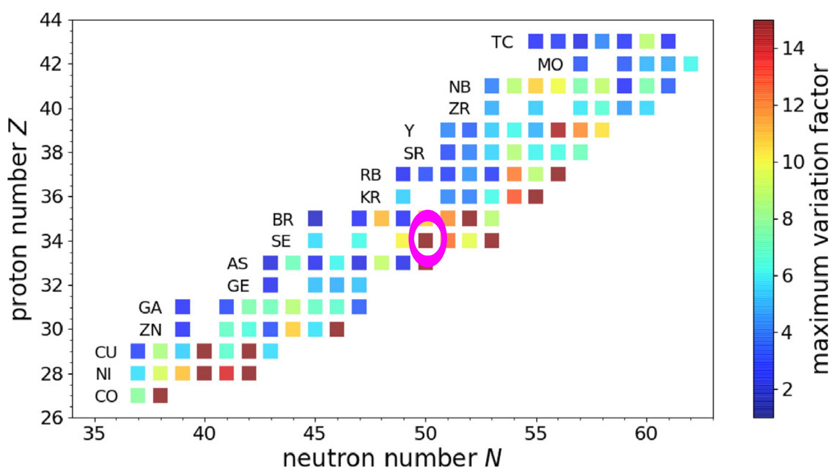


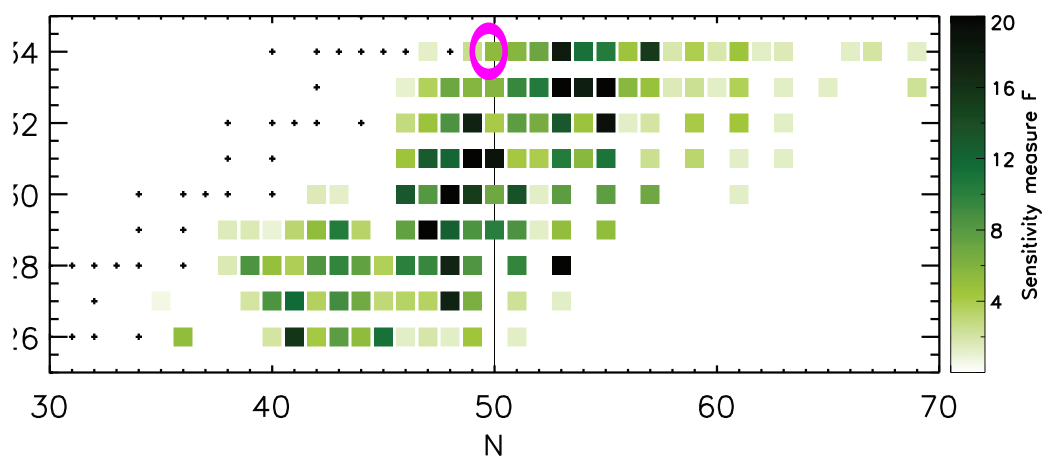


M. Arnould and S. Goriely (2020)
I.U. Roderer, et al., ApJ 821, (2016)

Focus on informing ^{84}Se(n,γ)







McKay et al., (i process)
MNRAS **491,** 5179–5187 (2020)

R. Surman et al., (weak-r process)
AIP Advances **4**, 041008 (2014)

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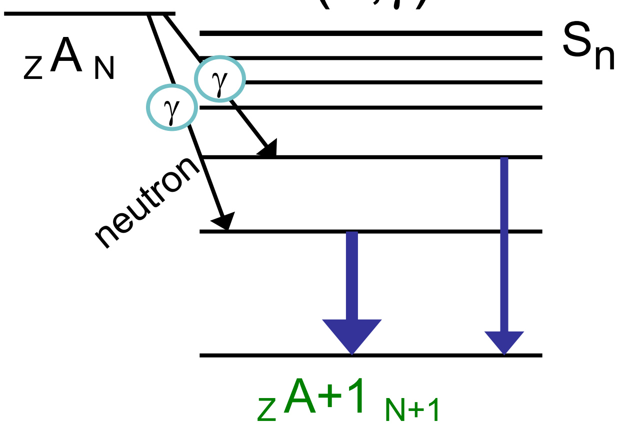
A≈80 peak and (d,p) reactions

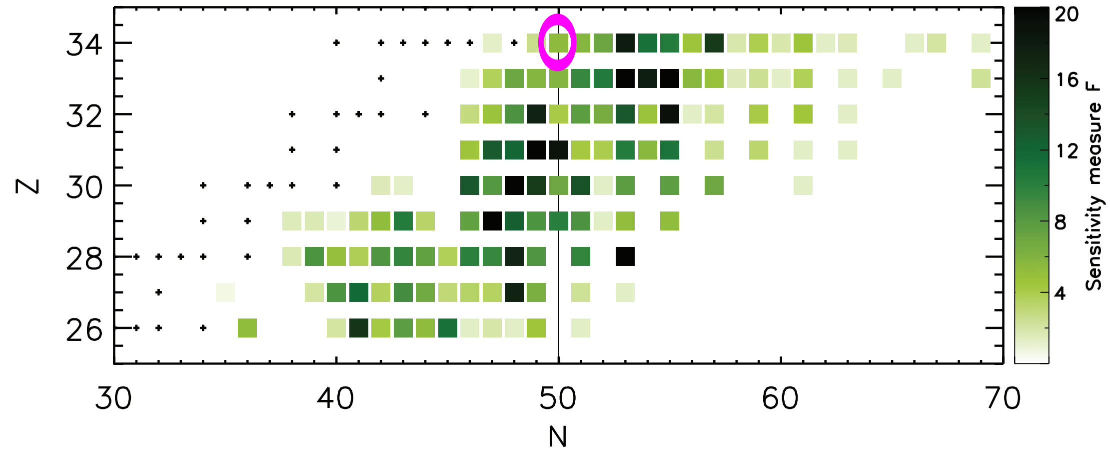
Focus: N=50 ^{84}Se

Direct-semi-direct

Near N shell closures

(n,γ)





Near closed shells

- Level density low near S_n
- Direct neutron capture important
- Depends on
  - E_x of low-ℓ single particle states
  - Spectroscopic factor S

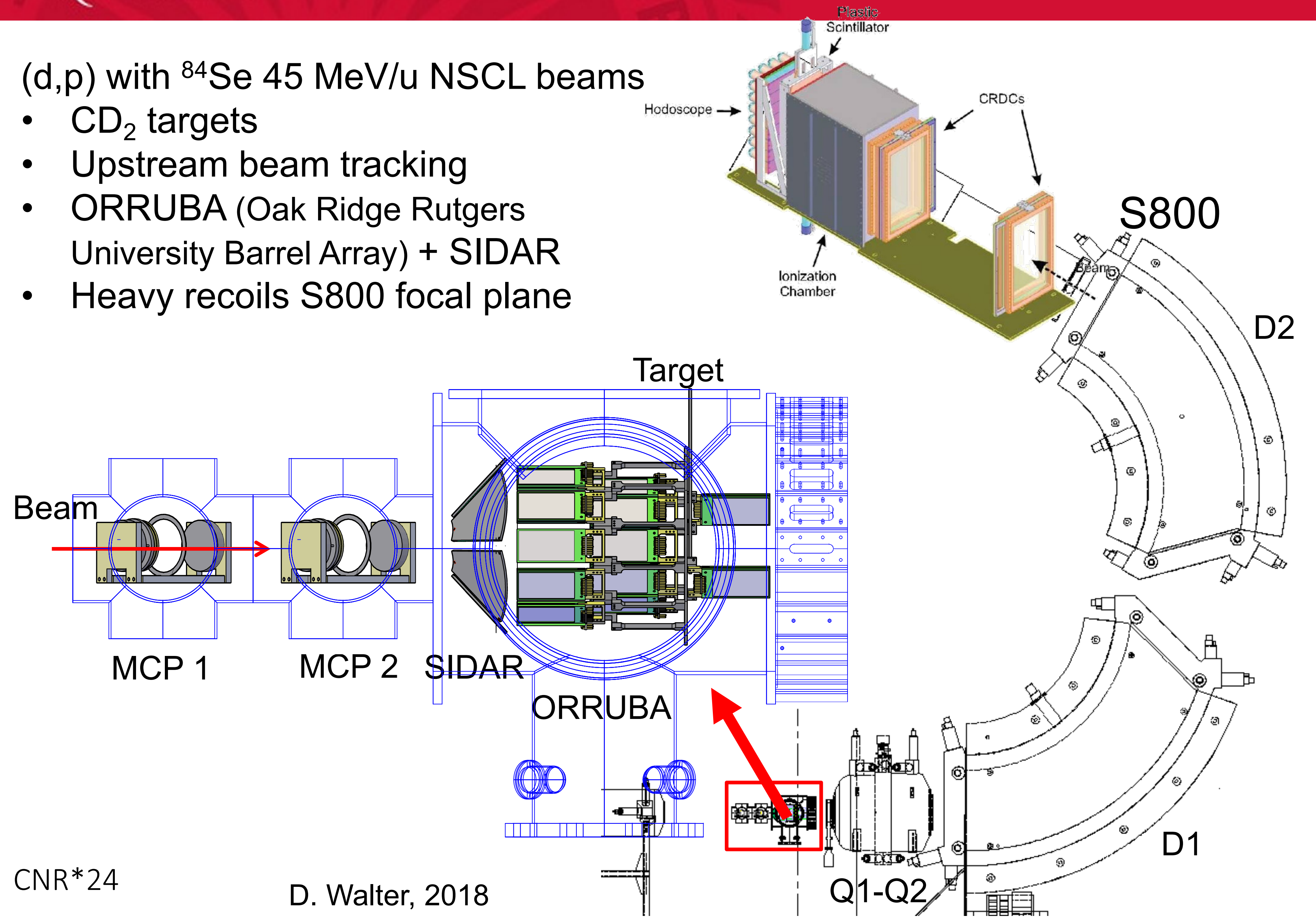
$$S = \left(\frac{d\sigma}{d\Omega}\right)_{exp} / \left(\frac{d\sigma}{d\Omega}\right)_{thy}$$

R. Surman et al., (weak-r process)
AIP Advances **4**, 041008 (2014)

(d,p) reaction 45 MeV/u N=50 ^{84}Se beams

(d,p) with ^{84}Se 45 MeV/u NSCL beams

- CD_2 targets
- Upstream beam tracking
- ORRUBA (Oak Ridge Rutgers University Barrel Array) + SIDAR
- Heavy recoils S800 focal plane

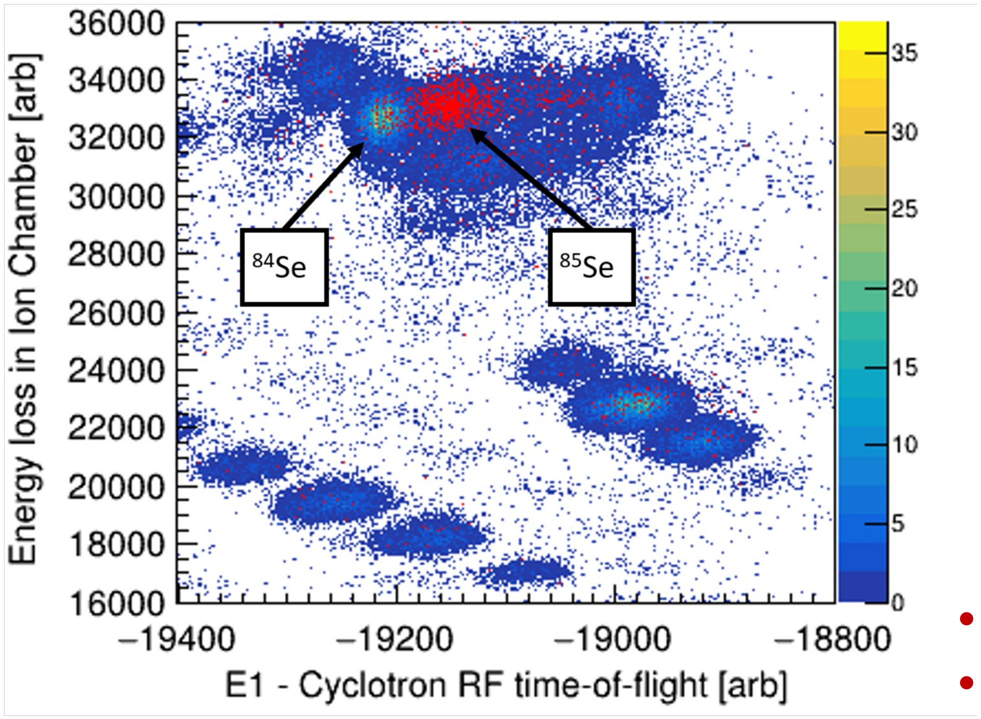


D. Walter, 2018

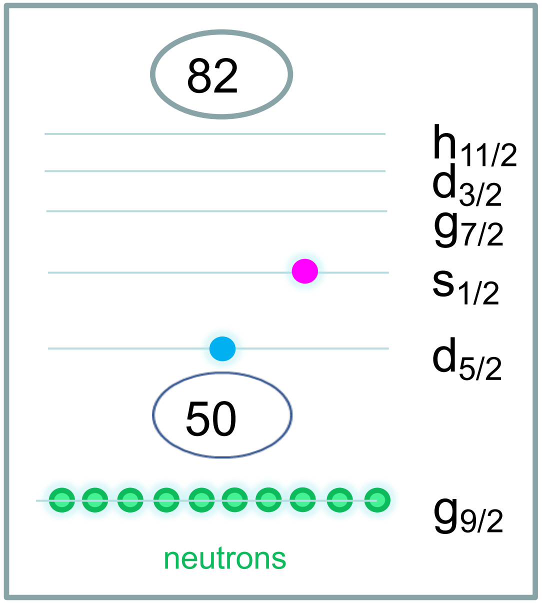
Extracting Spec Factors => Direct capture

- 45 MeV/u at NSCL

$$S = \left(\frac{d\sigma}{d\Omega}\right)_{exp} / \left(\frac{d\sigma}{d\Omega}\right)_{thy}$$



S800 FP particle ID



Excitations in ^{85}Se

- (red) gate on ORRUBA
- Gate on ^{85}Se
- ➢ Q-value spectra
- ➢ $\left(\frac{d\sigma}{d\Omega}\right)$

H.E. Sims Phd Dissertation (2020)
H.E. Sims, D Walter et al.,
in preparation for PRC (2023)

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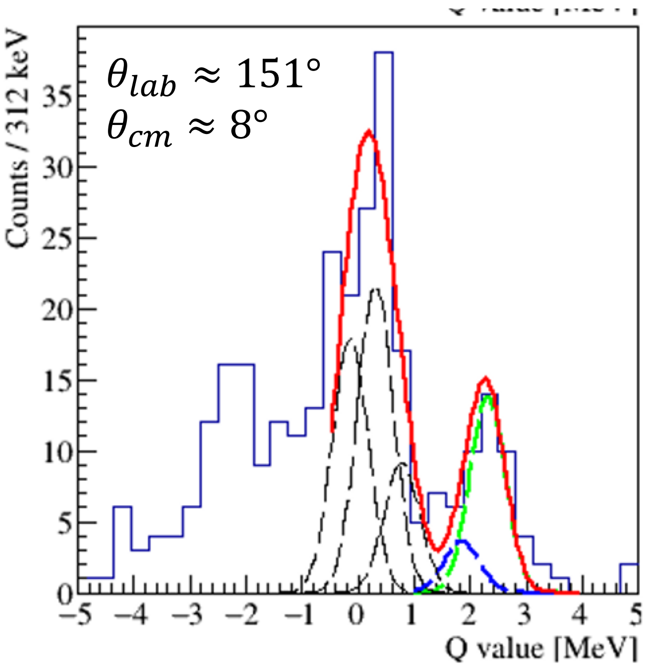
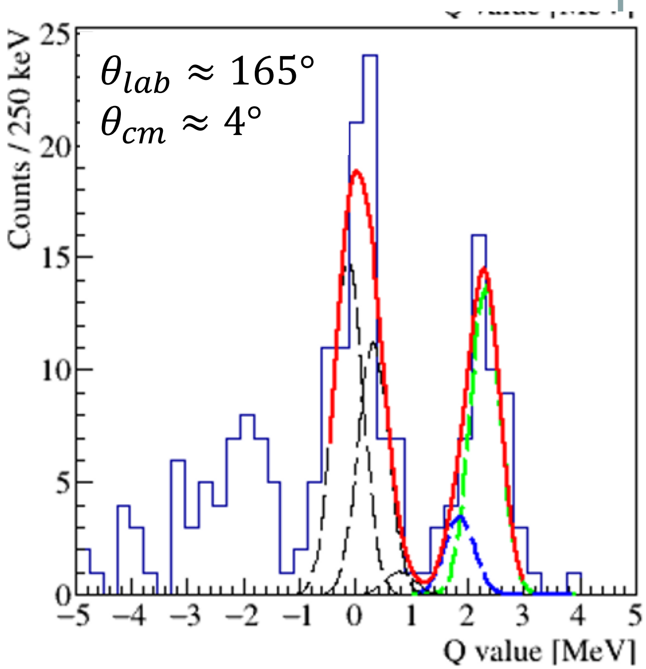
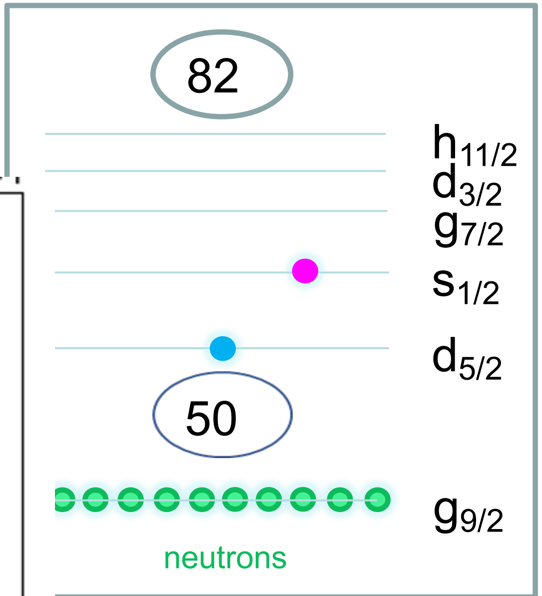






Excitations in ^{85}Se

FR-ADWA w/ KD OPM

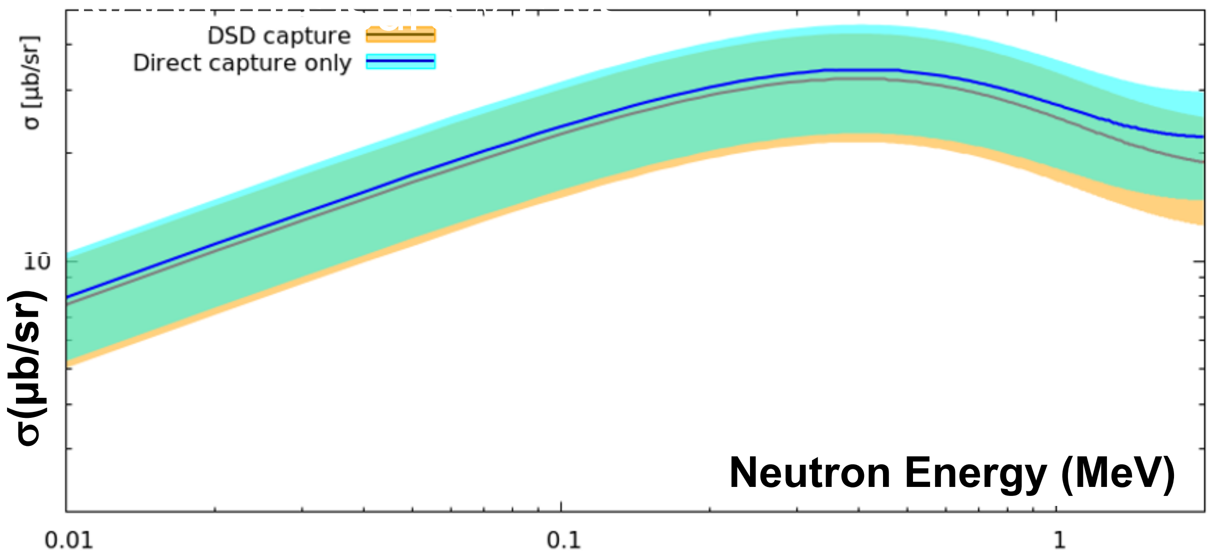
$5/2^+$ $E_x = 0$	$S = 0.28\ (4)$
$1/2^+$ $E_x = 0.462$ MeV	$S = 0.26\ (6)$

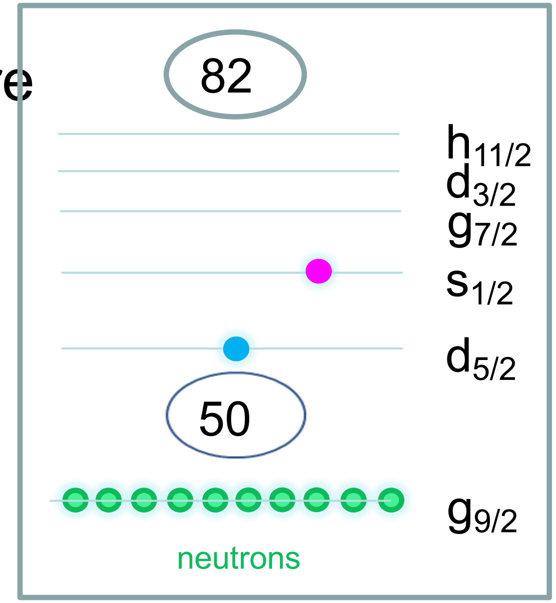
H.E. Sims Phd Dissertation (2020)
H.E. Sims, D Walter et al., in preparation for PRC (2023)

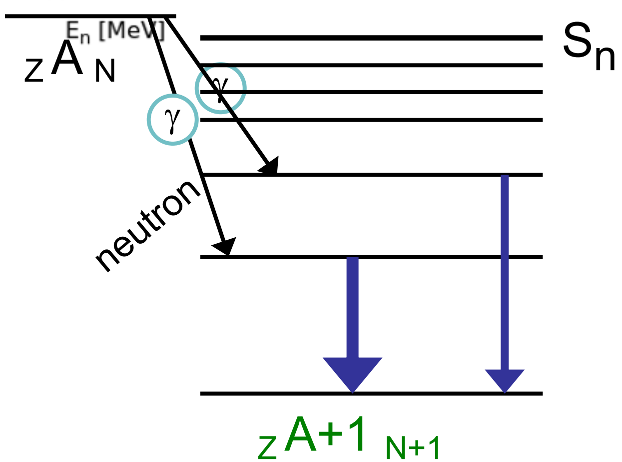
(d,p) studies with 4.5 MeV/u & 45 MeV/u ^{84}Se beams

Direct-semi-direct (DSD) capture

- Cross sections small ≈20 μb/sr; p-wave capture
- Statistical capture? σ much larger?





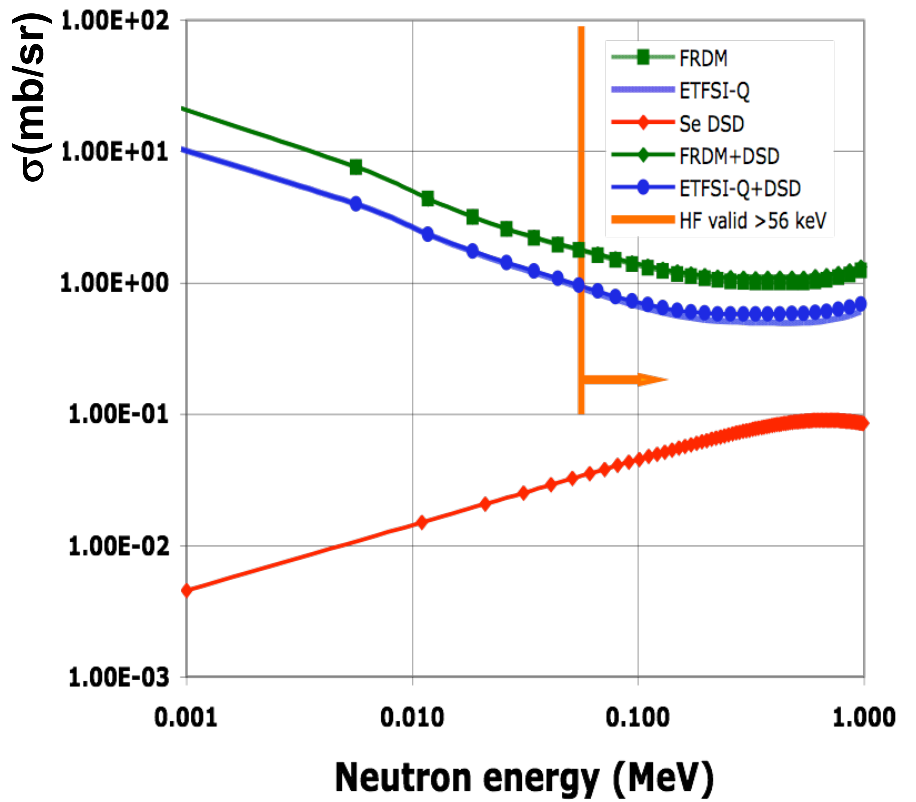


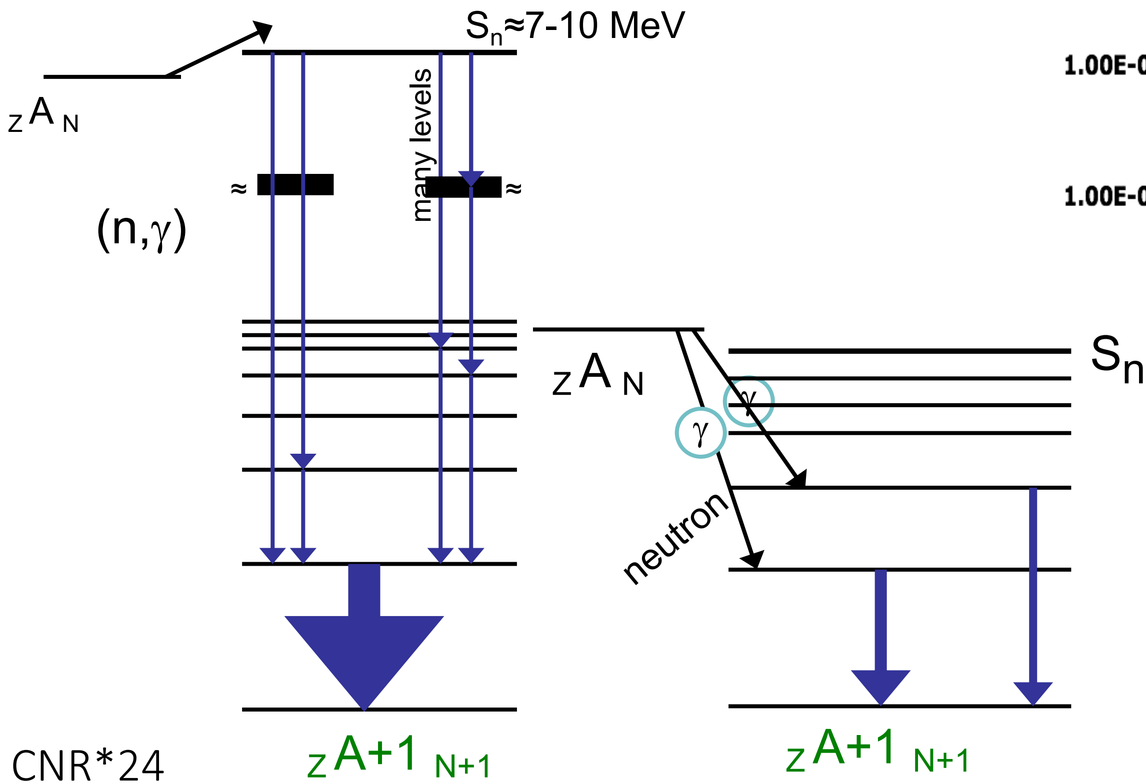
H.E. Sims Phd Dissertation (2020)
H.E. Sims, D Walter et al.,
in preparation for PRC (2023)

(d,p) studies with 4.5 MeV/u & 45 MeV/u ^{84}Se beams

Direct-semi-direct capture

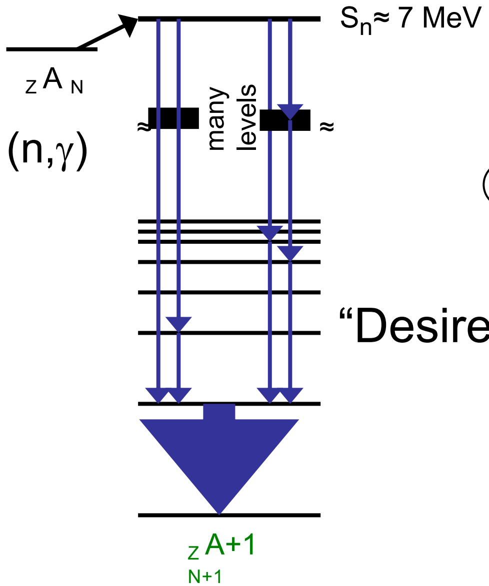
- Cross sections small ≈20 μb/sr for p-wave capture
- Statistical capture? σ much larger?
- ➢ Need valid (n,γ) surrogate reaction

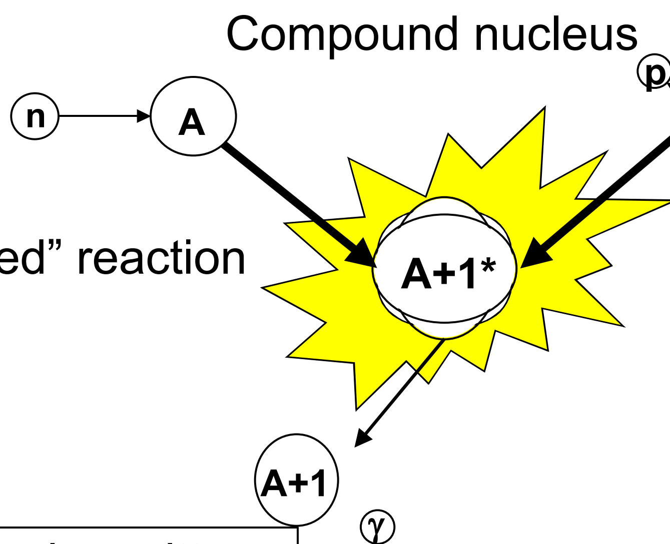


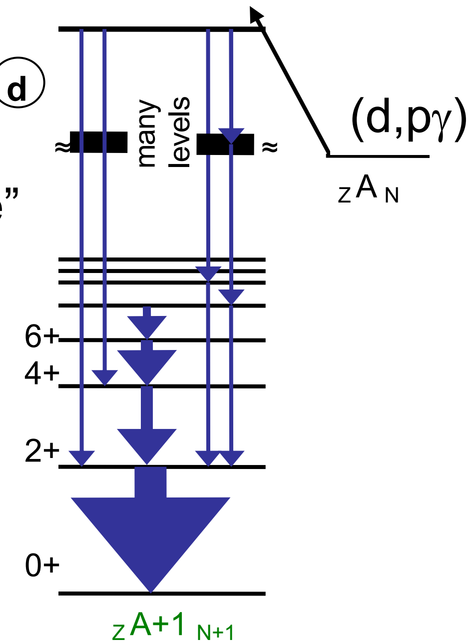


H.E. Sims Phd Dissertation (2020)
H.E. Sims, D Walter et al., in preparation for PRC (2023)
J.A. Cizewski et al, AIP CP **1090**, 463 (2009)

Surrogate reaction concept & Hauser-Feshbach formalism







(n,γ) cross section can be written as product of compound nucleus formation and decay for every spin and parity:

$$\sigma_{n\gamma}(E_n) = \sum_{J,\pi} \sigma_n^{CN}(E_x,J,\pi) G_\gamma^{CN}(E_x,J,\pi)$$

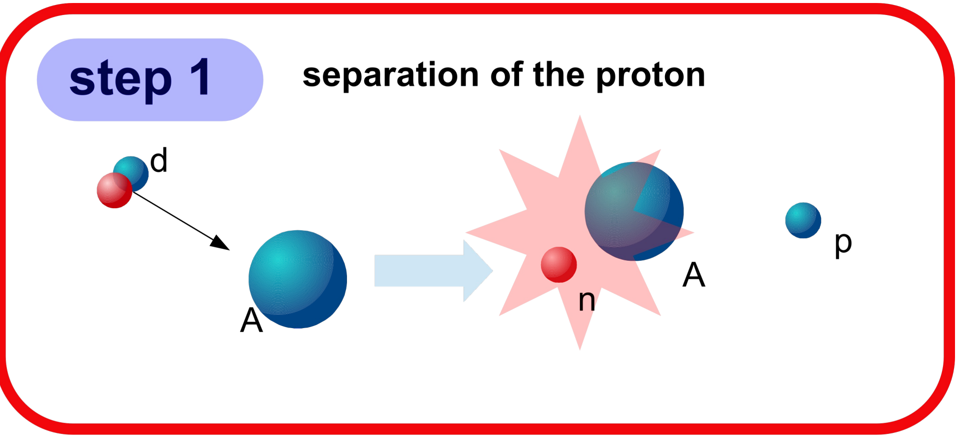
Surrogate particle-gamma coincidence can be written as product of compound nucleus formation and decay for every spin and parity:

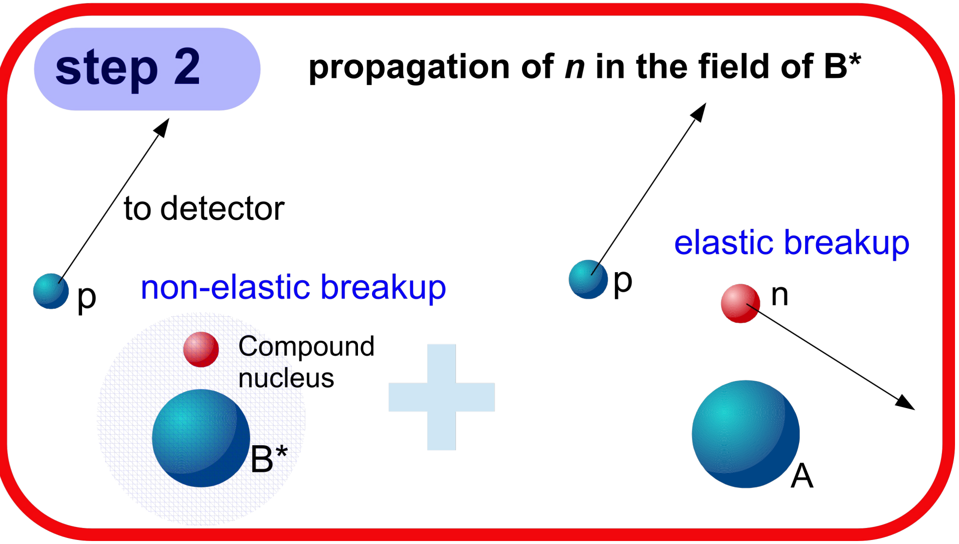
$$P_{p\gamma}(E_x,\theta) = \sum_{J,\pi} F_{dp}^{CN}(E_x,J,\pi,\theta) G_\gamma^{CN}(E_x,J,\pi)$$

Forming compound nucleus in (d,p)

$$P_{p\gamma}(E_x,\theta) = \sum_{J,\pi} F_{dp}^{CN}(E_x,J,\pi,\theta)\,G_{\gamma}^{CN}(E_x,J,\pi)$$

Neutron transfer (d,p) to unbound states, non-elastic breakup and surrogate for (n,γ)





<u>Two-step process</u>

- d breakup; B.E. = 2.2 MeV
- n propagation
  - Elastic breakup
  - Non-elastic breakup ⇒ CN and surrogate (n,γ)
  - Predicts J^{π} transfer

Gregory Potel et al. PRC <u>92</u>, 034611(2015) ⇒ path to CN formation

Surrogate (n,γ) with (d,pγ)

(d,p) reaction to forms compound nucleus

- Need to measure P(d,pγ)
- Need theory to calculate formation of CN: F^{CN}
- Need to deduce decay of CN: G^{CN}

$$P_{p\gamma}(E_x,\theta) = \sum_{J,\pi} F_{dp}^{CN}(E_x,J,\pi,\theta) G_{\gamma}^{CN}(E_x,J,\pi)$$

Validate with ^{95}Mo(d,pγ) reaction & ^{96}Mo gammas

$\ell = 0$ capture on $5/2^+$ => $2^+,3^+$

σ(n,γ) was measured and informed

What we measured in normal kinematics

$$P_{pY}(E_x) = \frac{Number\ of\ CN\ decays\ via\ channel\ Y}{Number\ of\ times\ the\ CN\ is\ formed}$$

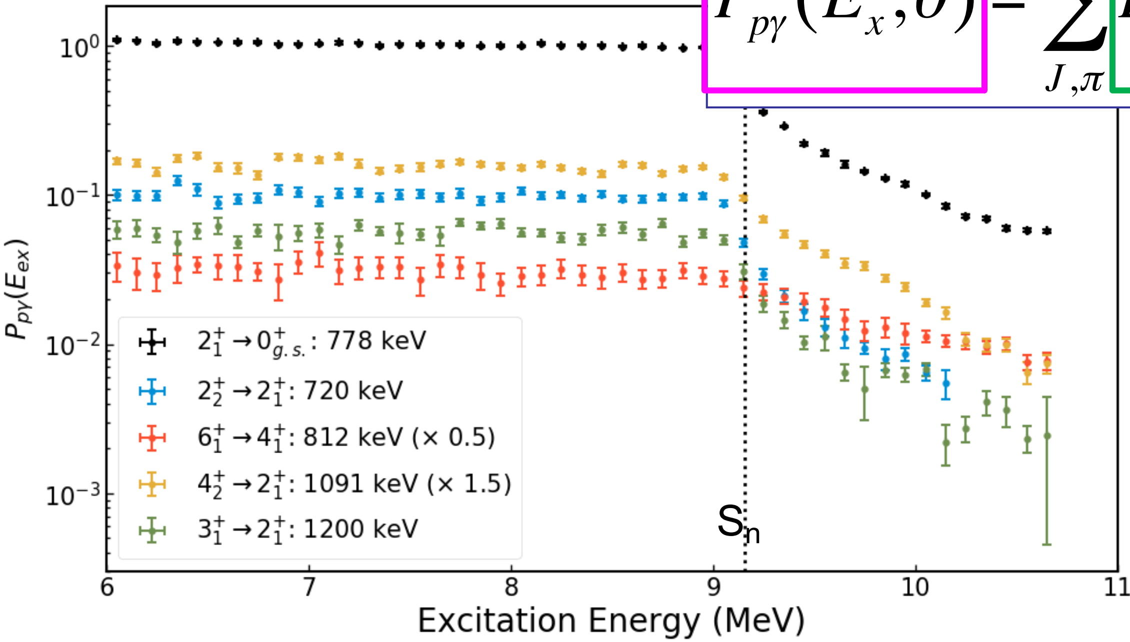
- Channel Y: individual discrete γ transitions to low-lying states
  - Intensity (=counts/efficiency) of specific transitions
- Number of times CN is formed
  - Intensity of single protons as a function of E_x

$$P_{pY}(E_x) = \frac{N_{pY}(E_x)}{\varepsilon_Y} \Big/ N_p(E_x)$$

- Normal kinematics ”easy”
  - Stable heavy target; light stable beam
  - Silicon detectors predominantly at forward angles
  - Don’t need heavy recoil detection

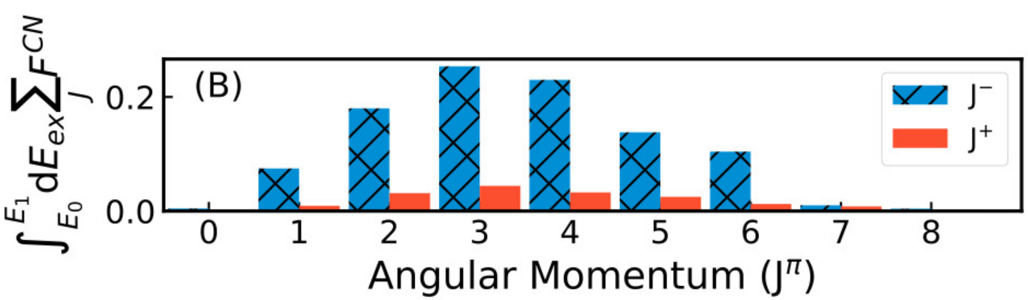
^{95}Mo(d,pγ)^{96}Mo: Input for $G_\gamma^{CN}(E_x, J, \pi)$

$$P_{p\gamma}(E_x,\theta) = \sum_{J,\pi} F_{dp}^{CN}(E_x,J,\pi,\theta)\, G_\gamma^{CN}(E_x,J,\pi)$$



Surrogate (d,pγ) data

Potel: ^{96}Mo J$^\pi$ population



A. Ratkiewicz et al., PRL **122**, 052502 (2019)

G. Potel et al, PRC 92, 034611(2015)

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^{95}Mo(d,pγ): Input for $G^{CN}(E_x,J,\pi)$

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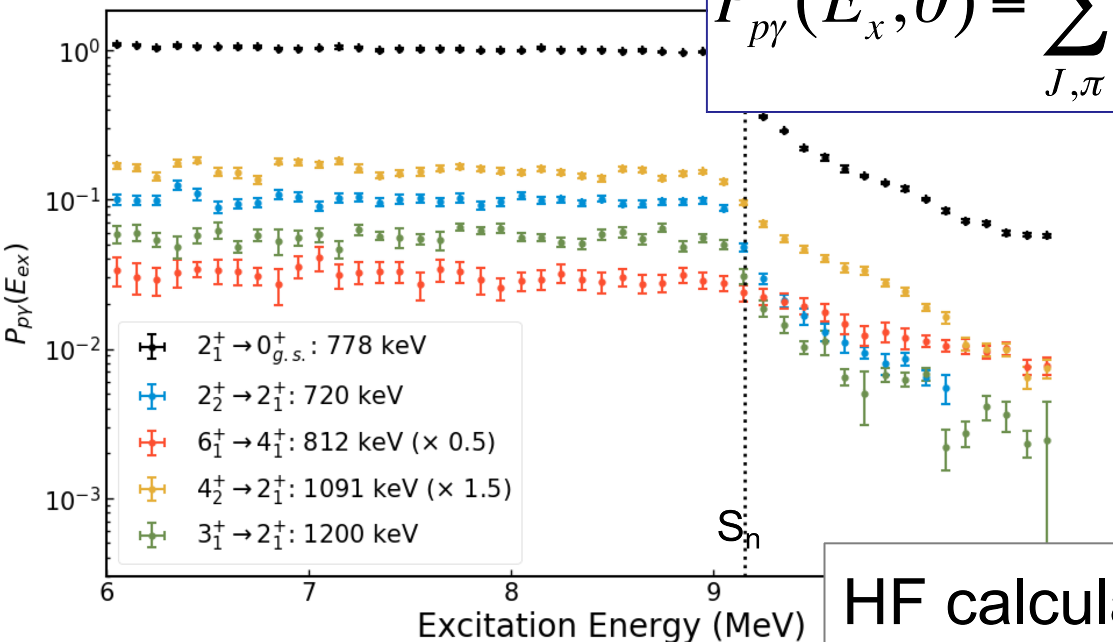

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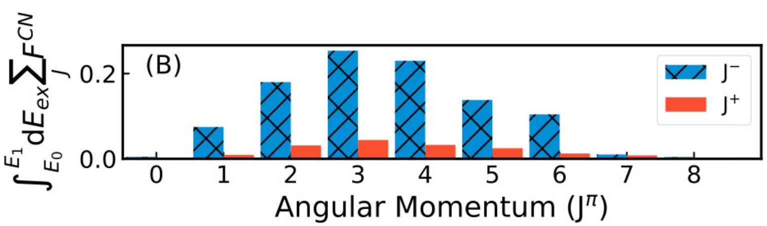


A. Ratkiewicz et al., PRL **122**, 052502 (2019)

G. Potel et al, PRC 92, 034611(2015)

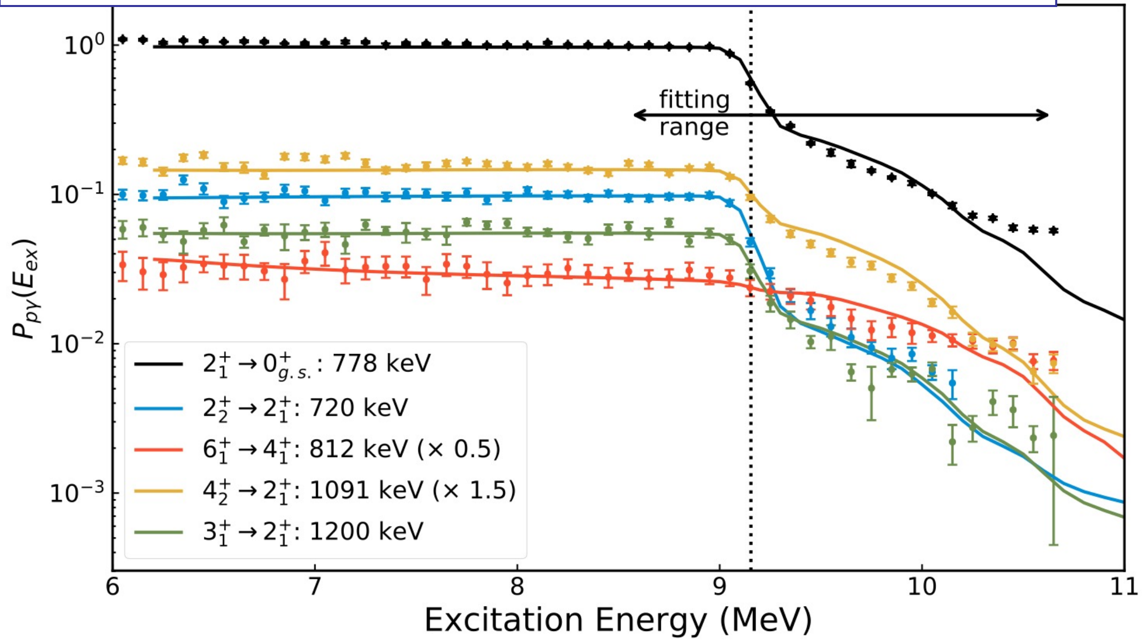
HF calculations (Jutta Escher)

- F^{CN} from Gregory Potel
- Bayesian fit to observed P(d,pγ)
  - Level density: Gilbert & Cameron
    - No norm to D_0
  - Lorentzian γ strength function;
    - No <Γ(γ)>

➢ $G^{CN}(E_x,J,\pi)$

^{95}Mo(d,pγ) validated (n,γ) surrogate

$$P_{p\gamma}(E_x,\theta) = \sum_{J,\pi} F_{dp}^{CN}(E_x,J,\pi,\theta)\,G_{\gamma}^{CN}(E_x,J,\pi)$$



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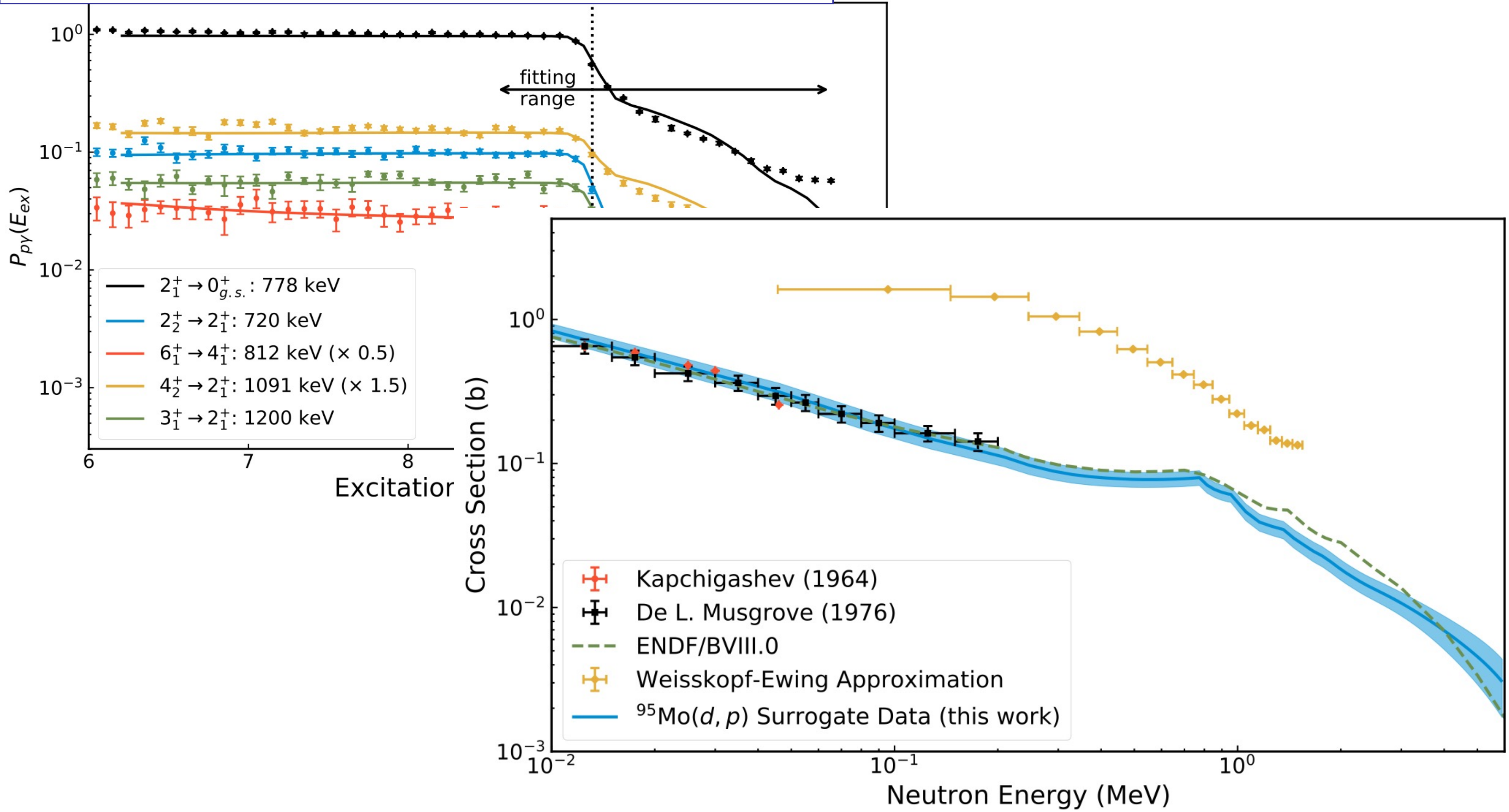

A. Ratkiewicz et al., PRL **122**, 052502 (2019)

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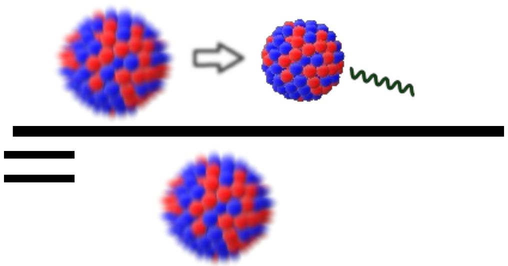
$$\sigma_{n\gamma}(E_n) = \sum_{J,\pi} \sigma_{n}^{CN}(E_x,J,\pi)\,G_{\gamma}^{CN}(E_x,J,\pi)$$

Goal: Inform (n,γ) on rare isotopes with (d,p)

- Heavy beam on light (CD_2) target = inverse kinematics
- Proton detection: good energy and angle resolution: ORRUBA
- Challenge: detecting discrete gammas
  - Relatively low gamma efficiency, especially discrete γ
  - Away from even-even closed shells
    - High level density even at low E_x
    - Especially final odd-odd nuclei
- Want Y – the gamma decay channel:
  - Not dependent on specific gammas

$$P_{pY}(E_x) = \frac{Number\ of\ CN\ decays\ via\ channel\ Y}{Number\ of\ times\ the\ CN\ is\ formed}$$

$$P_{pY}(E_x) \equiv$$



Inform (n,γ) on ^{84}Se (rare isotope) with (d,p)

- ^{84}Se(d,p) populates ^{85}Se* CN
- CN at $E_x < S_n$: only decays by gamma emission => ^{85}Se
- CN at $E_x > S_n$: if decays by gamma emission => ^{85}Se = channel Y
- CN at $E_x > S_n$: if decays by neutron emission => ^{84}Se

$$P_{pY}(E_x) = \frac{Number\ of\ CN\ decays\ via\ channel\ Y}{Number\ of\ times\ the\ CN\ is\ formed}$$

$$P_{pY}(E_x) = \frac{N_{p-{}^{85}Se}(E_x)}{\varepsilon} \Big/ N_p(E_x)$$

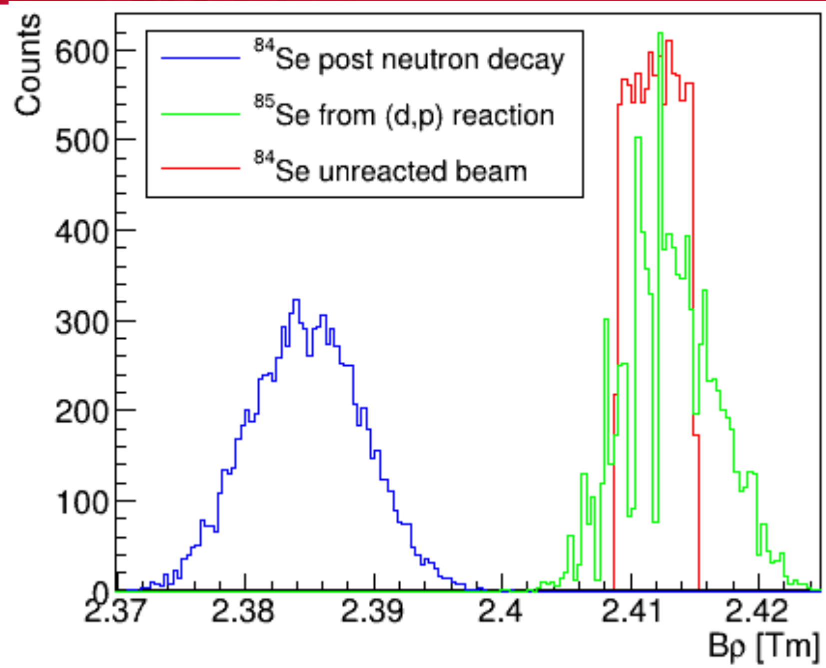
- Detection efficiency of heavy recoils > gammas
- No dependence on details of γ-decay
- Need excellent separation of ^{85}Se and ^{84}Se

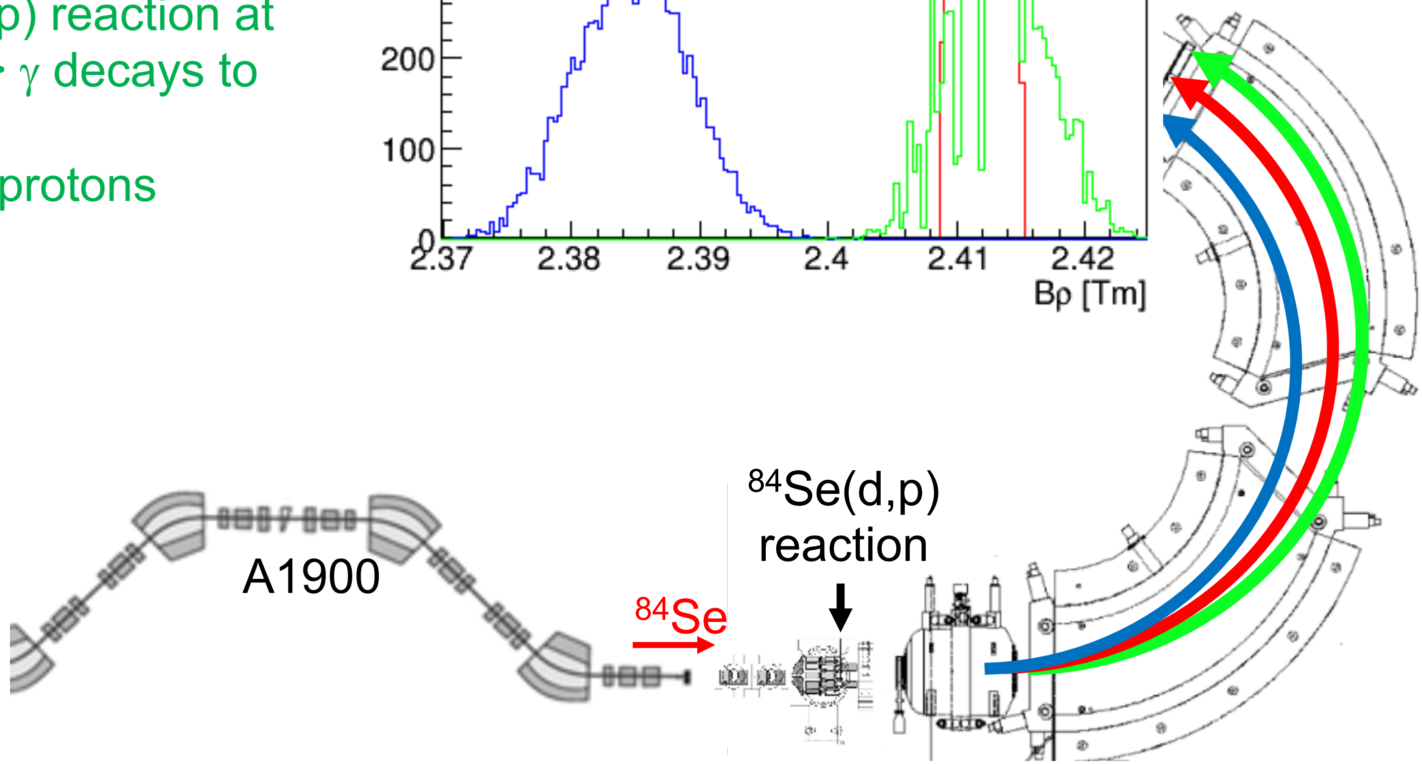
SRM at S800 without detecting γ-rays

Three scenarios:

1. ^{84}Se does not react with CD_2 target, continues with same momentum distribution as determined by slits in A1900

2. ^{84}Se undergoes (d,p) reaction at CD_2 => CN ^{85}Se => γ decays to ^{85}Se g.s.
   - Know E_x from protons





1. Same as point 2, except CN ^{85}Se emits neutron => ^{84}Se

H.E. Sims, S.D. Pain, 2021

SRM at S800 without detecting γ-rays

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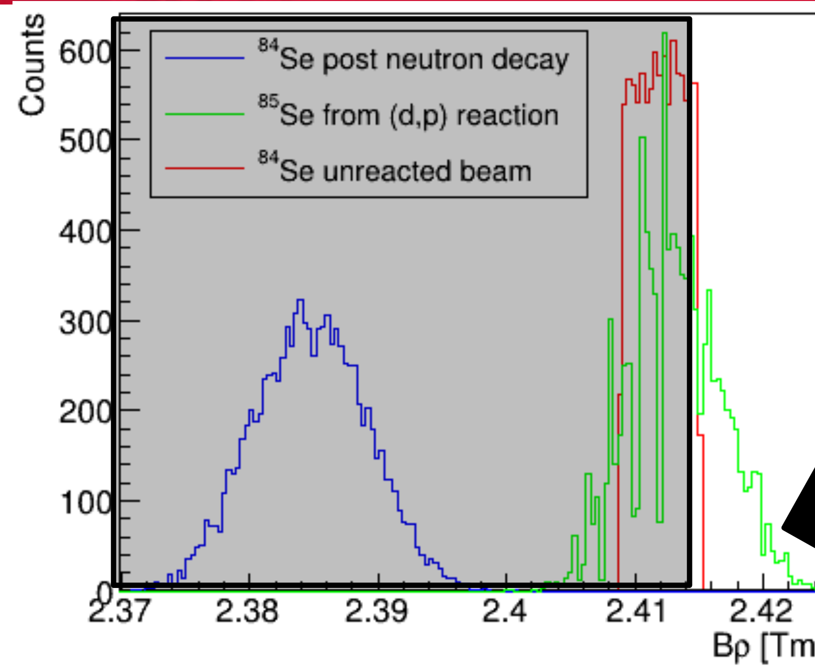
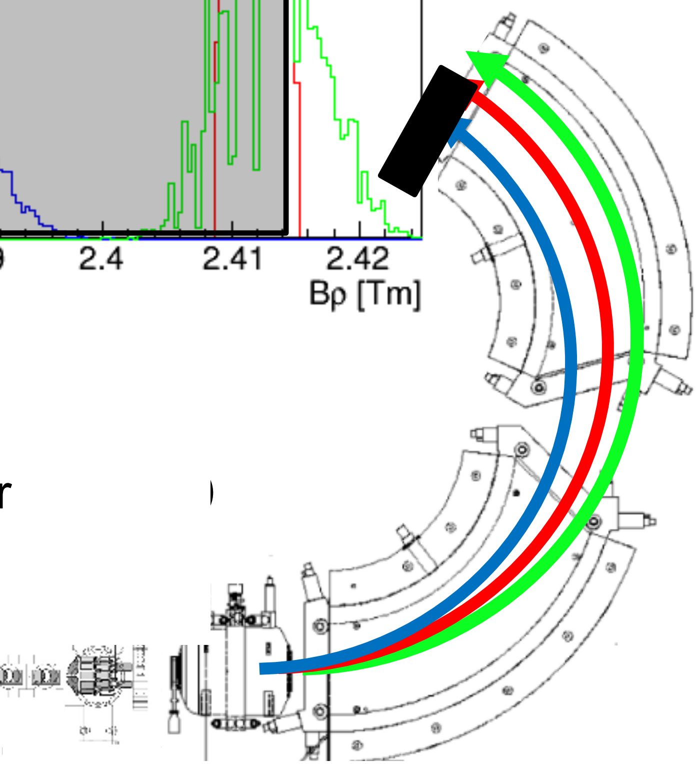


- S800 is rate-limited to ~5 kHz => implement blocker

➢ **Use the recoils to determine whether n/γ decay (^{84}Se/^{85}Se) – by tagging on the ^{85}Se**



3. Same as point 2, except CN ^{85}Se emits neutron => ^{84}Se

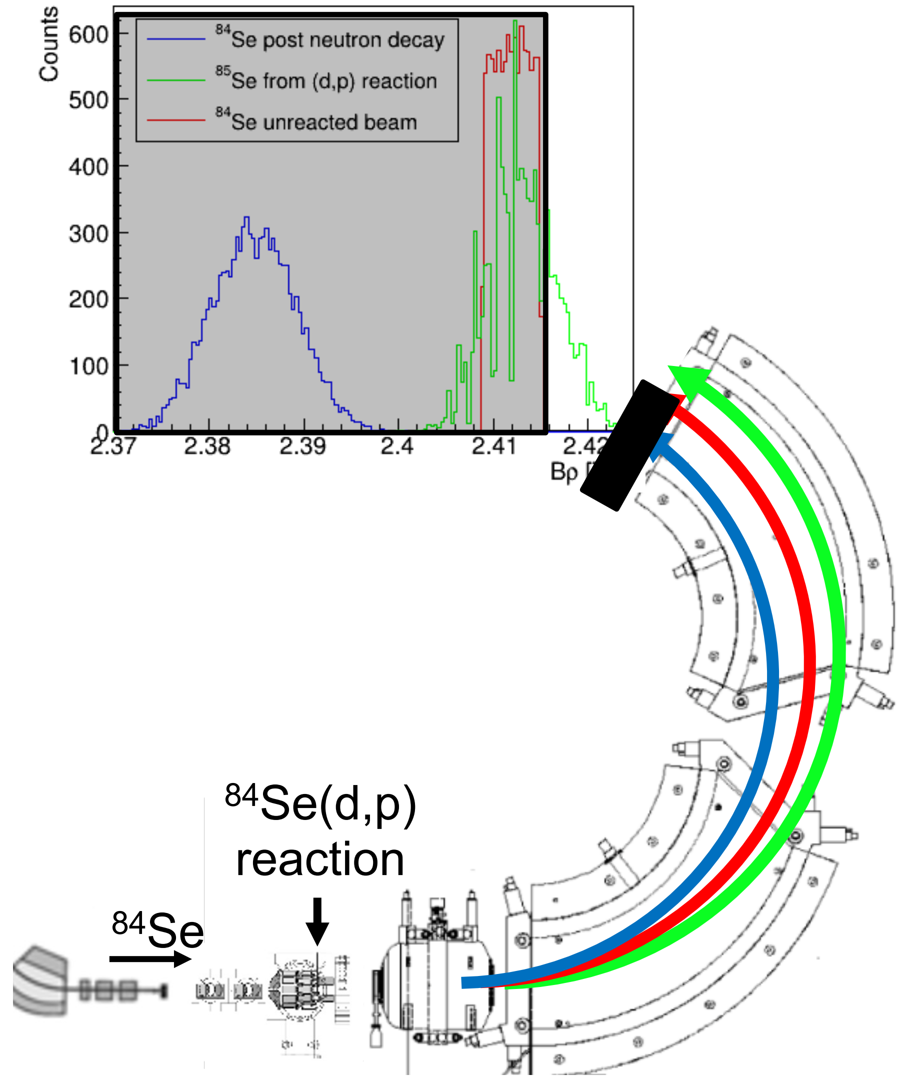
H.E. Sims, S.D. Pain, 2021

SRM at S800 without detecting γ-rays

Advantages:
- With (low intensity RIBs) all statistics in single observable
- ~25-30% detection efficiency (much better than γ efficiency ≈13%)
    - Can measure by looking at bound states
    - Not reliant on simulations
    - If can tighten up momentum acceptance, less beam-recoil overlap
- No need for complicated cascade info – get emission probability without knowledge of how gamma decay occurs

Difference:
- No details or constraint on specific gamma branches or cascade

Challenges:
- Need significant characterization of background from Carbon in target



H.E. Sims, S.D. Pain, 2021

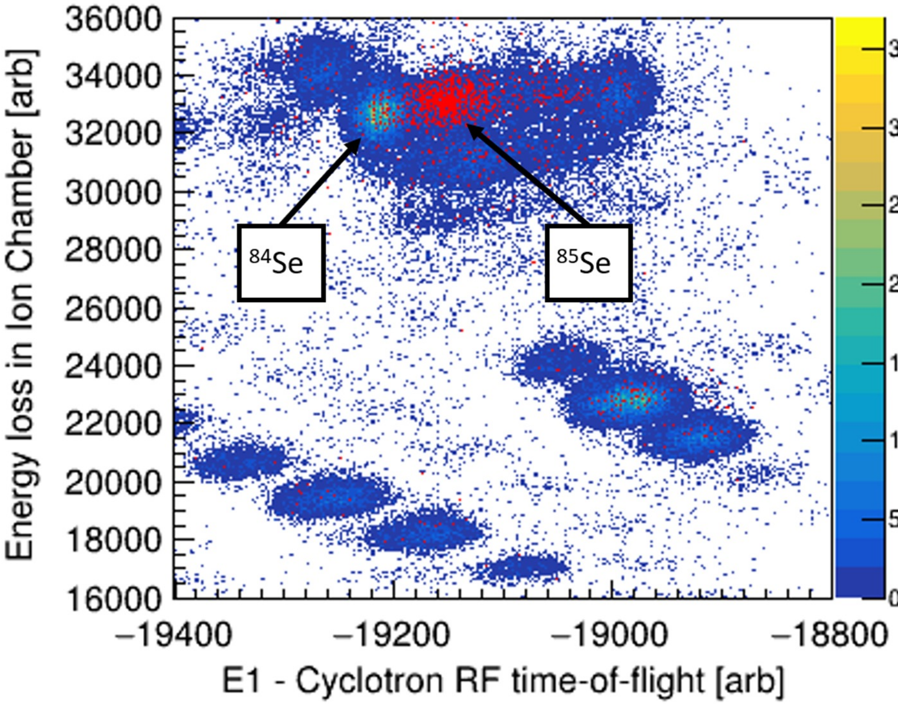
SRM at S800 without detecting γ-rays: P_γ from S800 coincidences

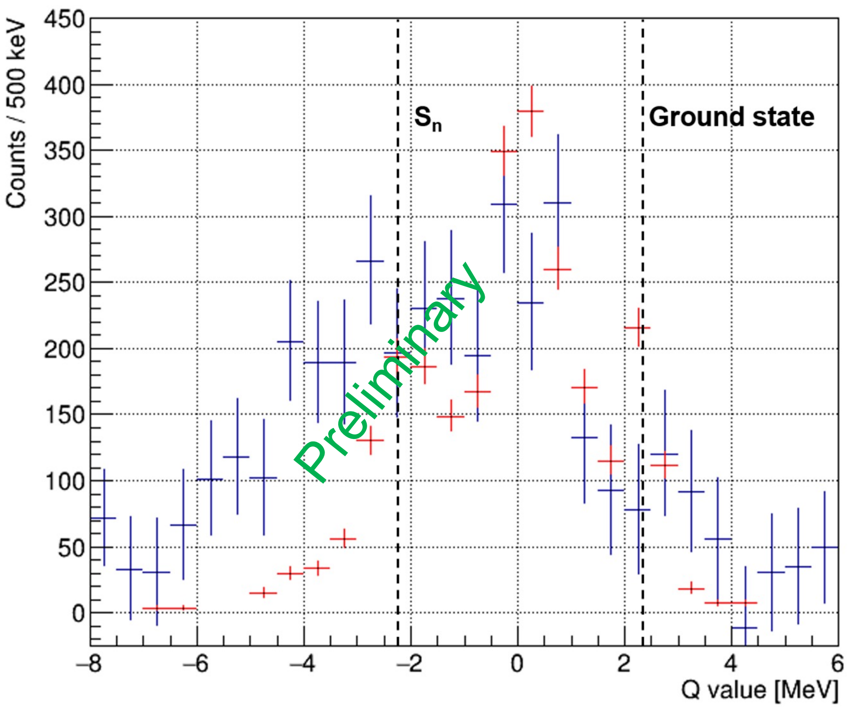
Proton-S800 coincidences

S800 acceptance

$$P_\gamma(E_x) = \frac{N_{p-{}^{85}Se}(E_x)/\varepsilon({}^{85}Se)}{N_{p-singles}(E_x)}$$

Proton singles (background subtracted)





H.E. Sims, 2023

SRM at S800 without detecting γ-rays: P_γ from S800 coincidences

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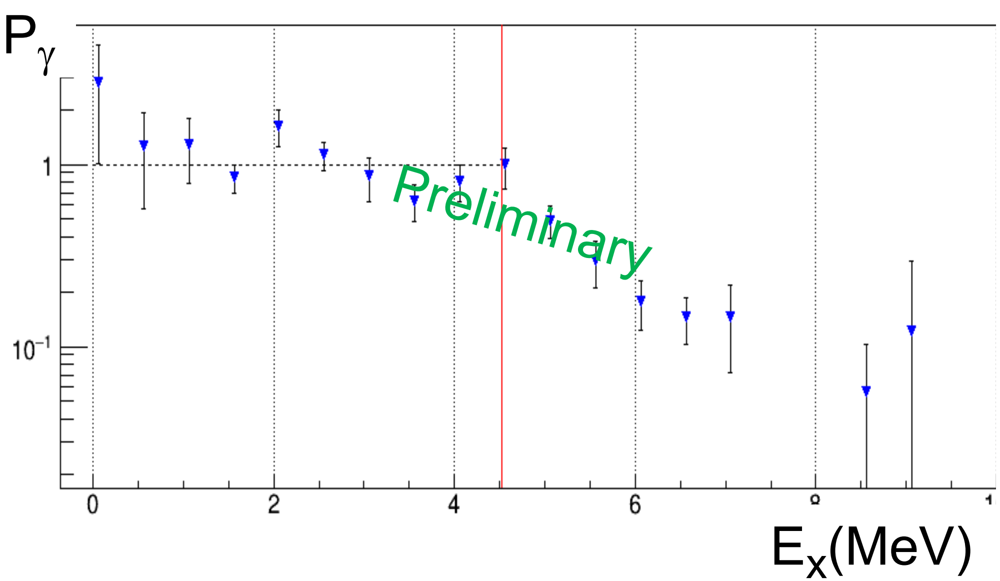
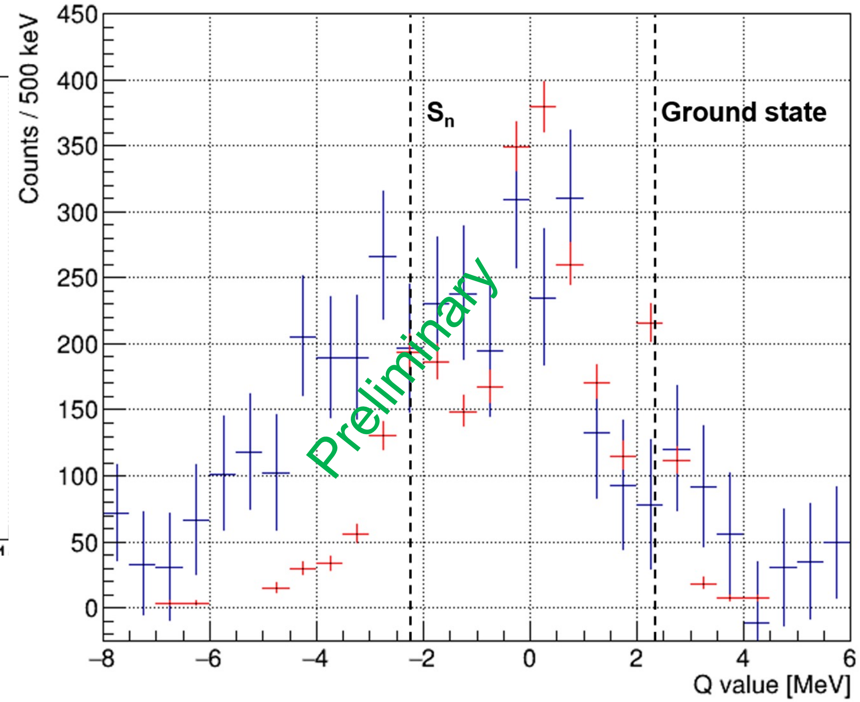
Proton singles (background subtracted)





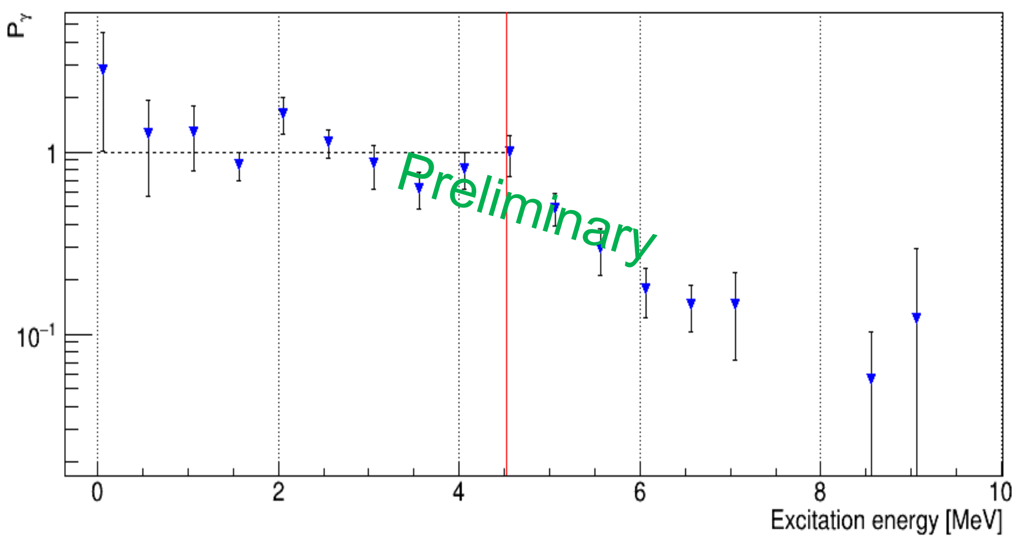
H.E. Sims, 2023

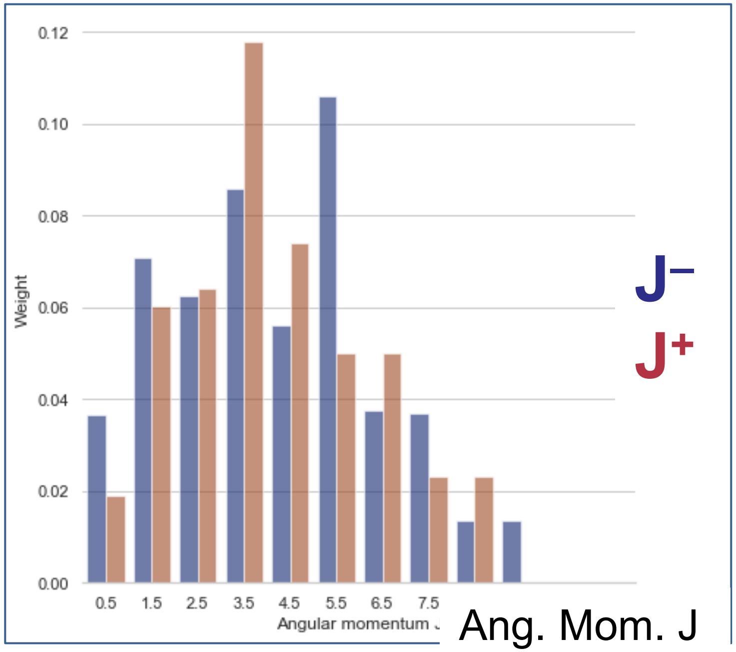
P_γ from S800 coincidences & theory

$\Longrightarrow \sigma(n,\gamma)$ from surrogate reaction data

$$P_\gamma(E_x) = \sum_{J,\pi} \boxed{F_{dp}^{CN}(E_x, J, \pi, \theta)} G_\gamma^{CN}(E_x, J, \pi)$$

$$\sigma_{n\gamma}(E_n) = \sum_{J,\pi} \sigma_n^{CN}(E_x, J, \pi) G_\gamma^{CN}(E_x, J, \pi)$$





45 MeV/u ^{84}Se(d,p) F_{dp}^{CN} at S_n

Theory: Escher, Potel, Gorton
(prelim, 6/2024)

H.E. Sims, 2023

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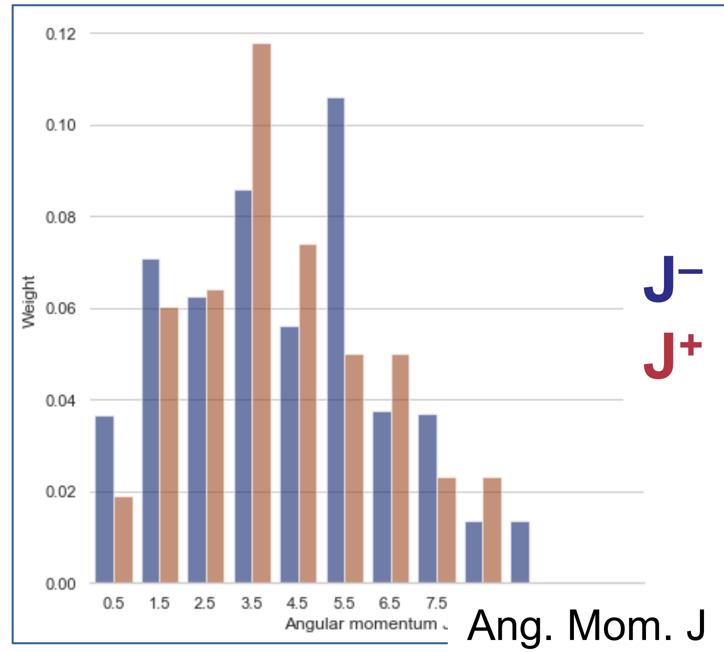
Theory:

1. Reaction mechanism for (d,p) J^π population vs E_x
2. Hauser-Feshbach code (YAHFC) and J^π
   - Decay of the CN ^{85}Se $G_\gamma^{CN}(E_x, J, \pi)$
3. Markov-Chain Monte-Carlo to fit HF decay parameters from surrogate observables
4. Calculate desired σ ^{84}Se(n,γ) by sampling posterior parameter distribution



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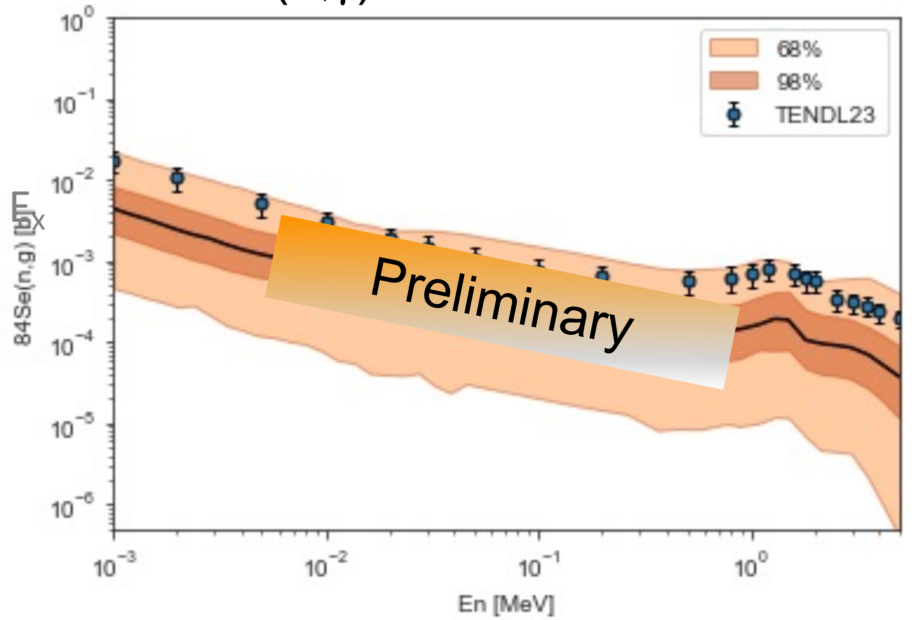
^{84}Se(n,γ) σ from SRM



Results

1. $\sigma(n,\gamma)$ constrained by data, no D_0 or $< \Gamma_\gamma >$
2. Not sensitive to details of γSF
3. Similar results w/ different parameter vectors

Theory: Escher, Potel, Gorton (prelim, 6/2024)

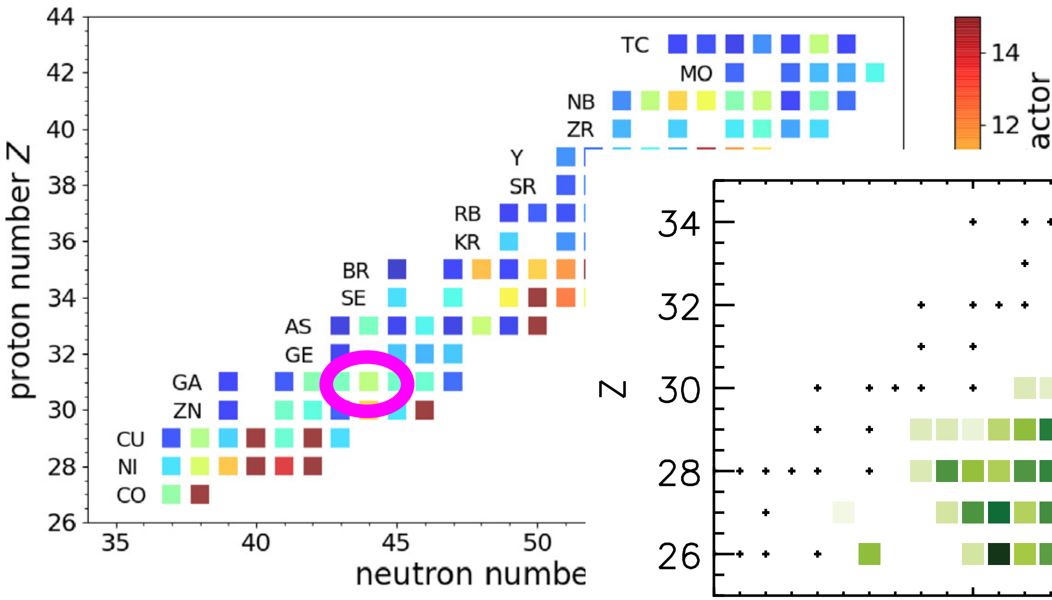
New: ORRUBA + GRETINA at FRIB

- Measure: (d,pγ) with ≈45 MeV/u ^{80}Ge (N=48) and ^{75}Ga beams + ORRUBA + GRETINA + S800

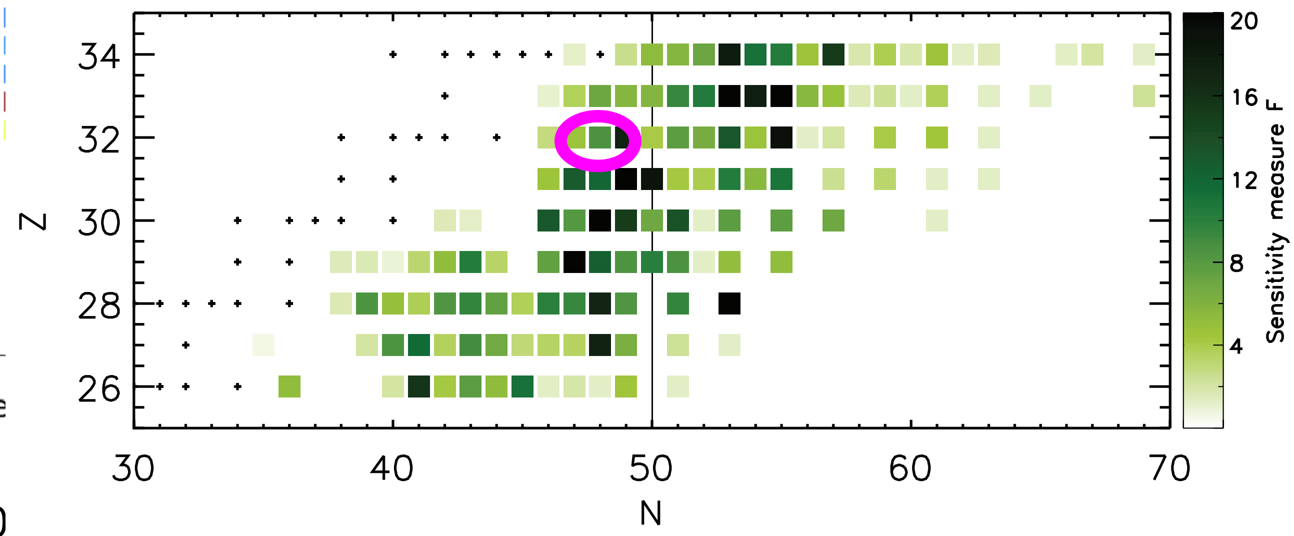
➢ Inform σ(n,γ)

  - No gamma surrogate reaction method
  - Discrete gamma SRM; Gamma rays would confirm isotopics

➢ Inform i- and weak r-process nucleoysnthesis



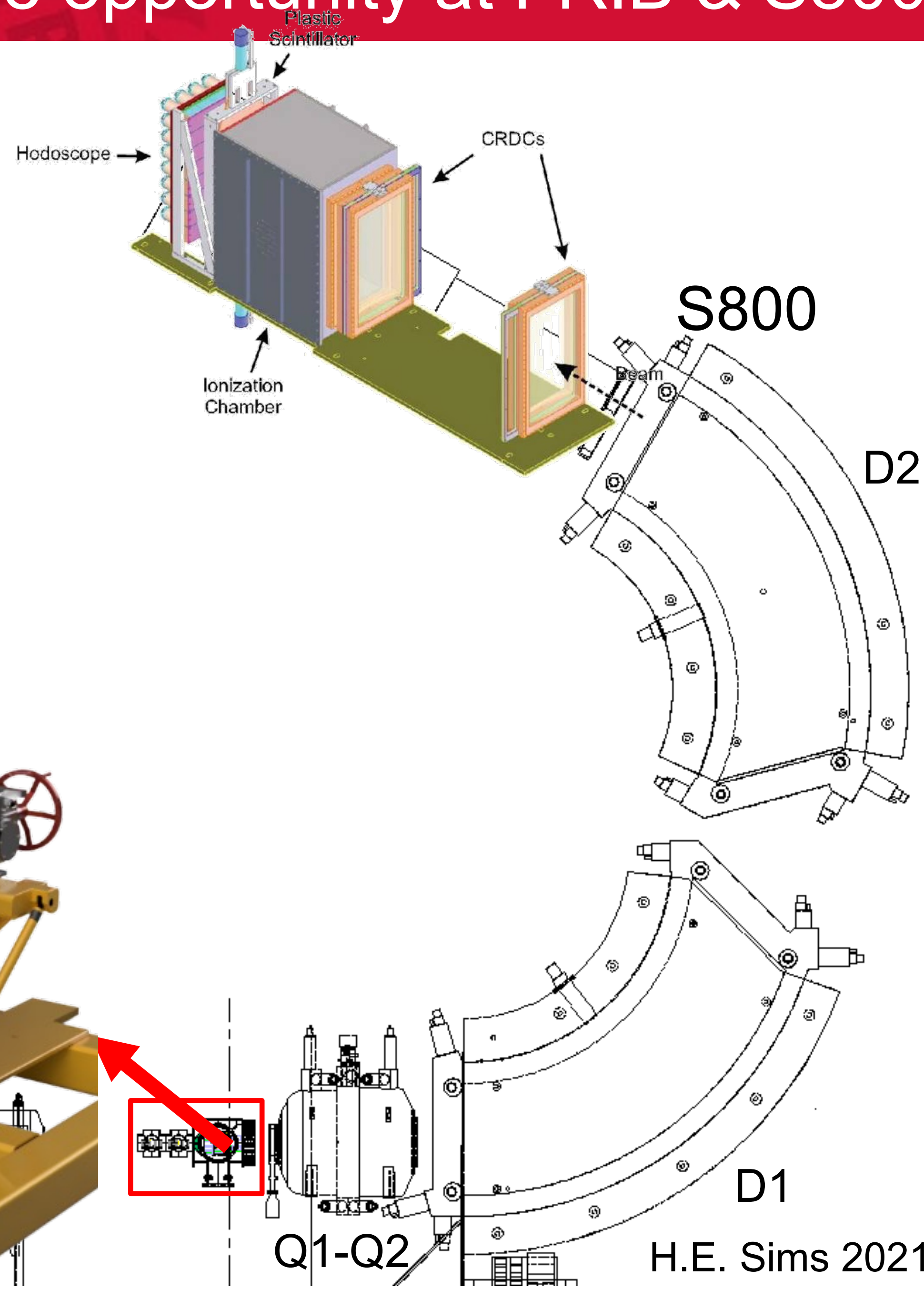
McKay et al.,
MNRAS **491**, 5179–5187 (2020

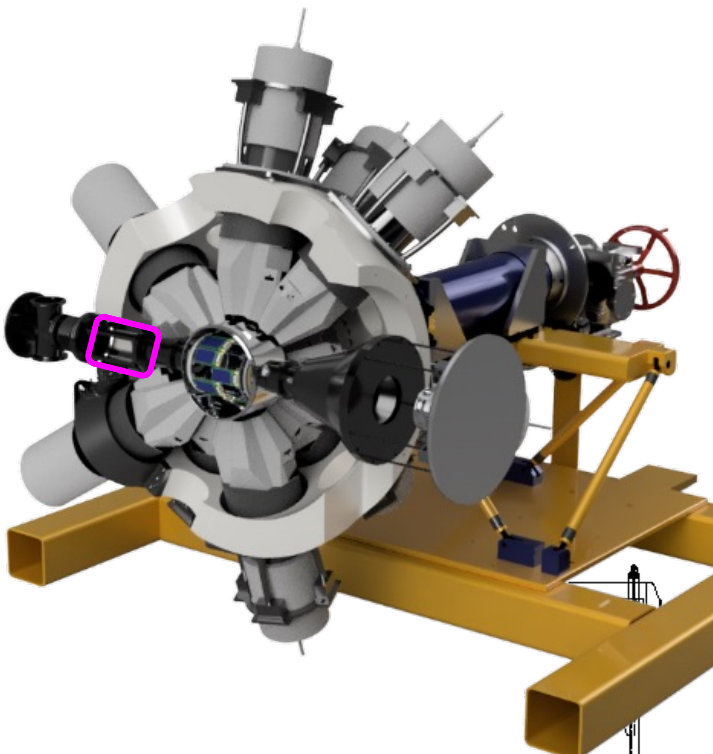


R. Surman et al., AIP Advances **4**, 041008 (2014)

Unique opportunity at FRIB & S800

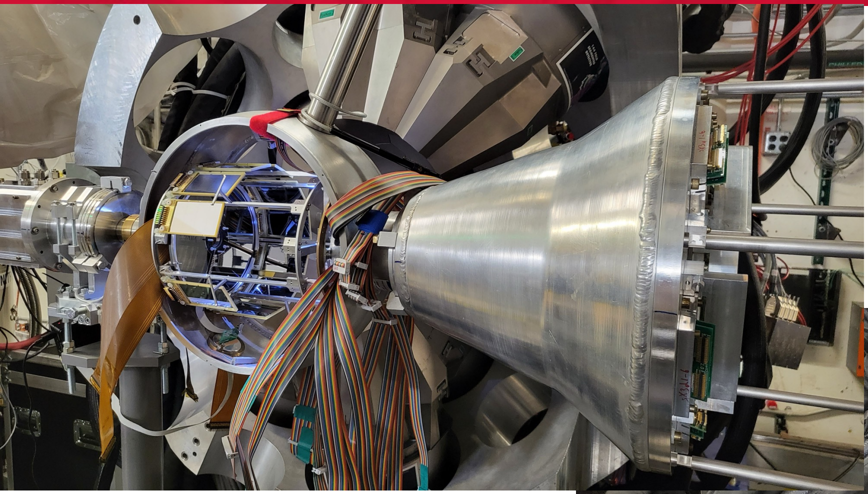
- ORRUBA + GRETINA at S800
  - beam tracking (gas) detectors
- S800 excellent PID
  - Can separate isotopes
  - Beam blocker
- Requires CD_2 and CH_2 data

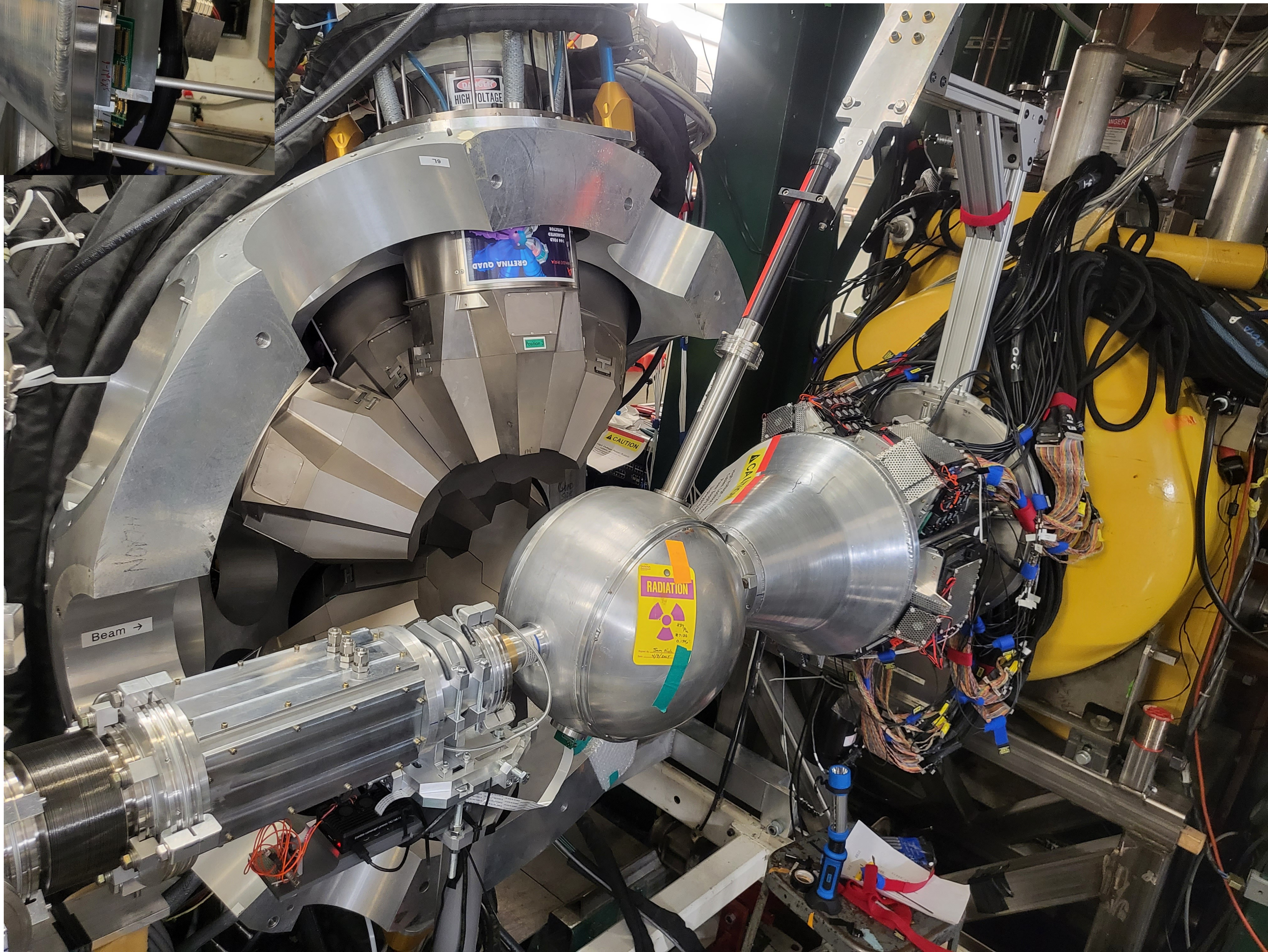




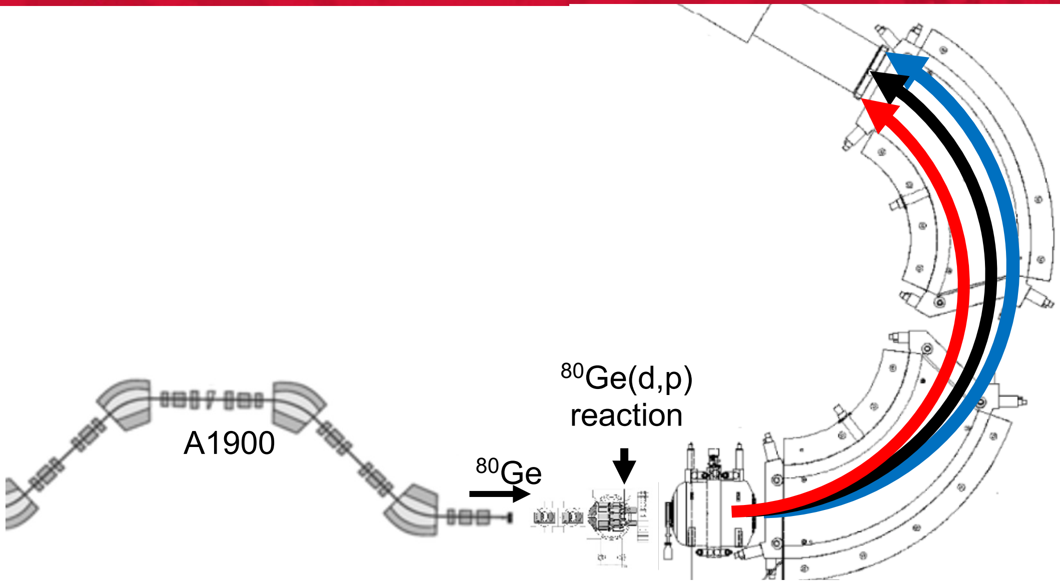
RUTGERS

GRETINA + ORRUBA +S800 at FRIB





SRM at S800 without detecting γ-rays



GODDESS at FRIB Spring 2024

- Upstream beam tracking chamber
- ORRUBA – charged particles
- GRETINA – gamma rays
- S800 – heavy recoils
  - Blocked ^{80}Ge(32^{+}) and ^{80}Ge(31^{+}) beams
- ORRUBA-GRETINA-S800 coincidences

Preliminary status

- Can cleanly identify ^{81}Ge channel from (d,p) on $^{80}Ge(32^+)$
  - Need full analysis
    - Maximize proton energy resolution: Beam tracking
    - Isolate (d,p) protons: Subtraction of CH_2 protons from CD_2 data
    - Maximize ID of ^{81}Ge recoils: use full suite of S800 FP detectors and TOF
  - ➢ Prospects for surrogate (n,γ) analysis promising
- Unexpected preliminary results
  - See $^{80}Ge(31^+)(d,p)^{81}Ge$ + n: prospects for surrogate (n,n')?
  - See $^{80}Ge(31^+)(d,p)^{81}Ge$ + 2n: prospects for surrogate (n,2n)?
- Also, $^{75}Ga(d,p\gamma)^{76}Ga^*$ for surrogate (n,γ) for i-process nucleosynthesis

Summary

- (d,p) and (d,pγ) reactions inform i- and weak r- process A≈80 nucleosynthesis
- Direct-semi-direct capture near neutron closed shells
  - Measure spectroscopic factors with (d,p)
  - Deduce DSD (n,γ)
- (d,pγ) validated surrogate reaction method (SRM) for (n,γ)
  - Measure discrete gammas
  - ➢ Inform LD and γSF => $G_\gamma^{CN}(E_x, J, \pi)$ => inform σ(n,γ)
- Prospects for No Gamma Surrogate (NGS) reaction method
  - Measure total population A+1 nucleus
  - Details of gamma decay not needed
  - ➢ $G_\gamma^{CN}(E_x, J, \pi)$ => inform σ(n,γ) with new SRM framework
- Recent measurements ^{80}Ge, ^{75}Ga(d,pγ) at FRIB ORRUBA+GRETINA+S800
  - Preliminary (and unexpected) results

RUTGERS

Thank you for your attention

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Work supported in part by U.S. Department of Energy and National Science Foundation