RUTGERS
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# Neutron transfer (d,p) reactions to inform neutron capture

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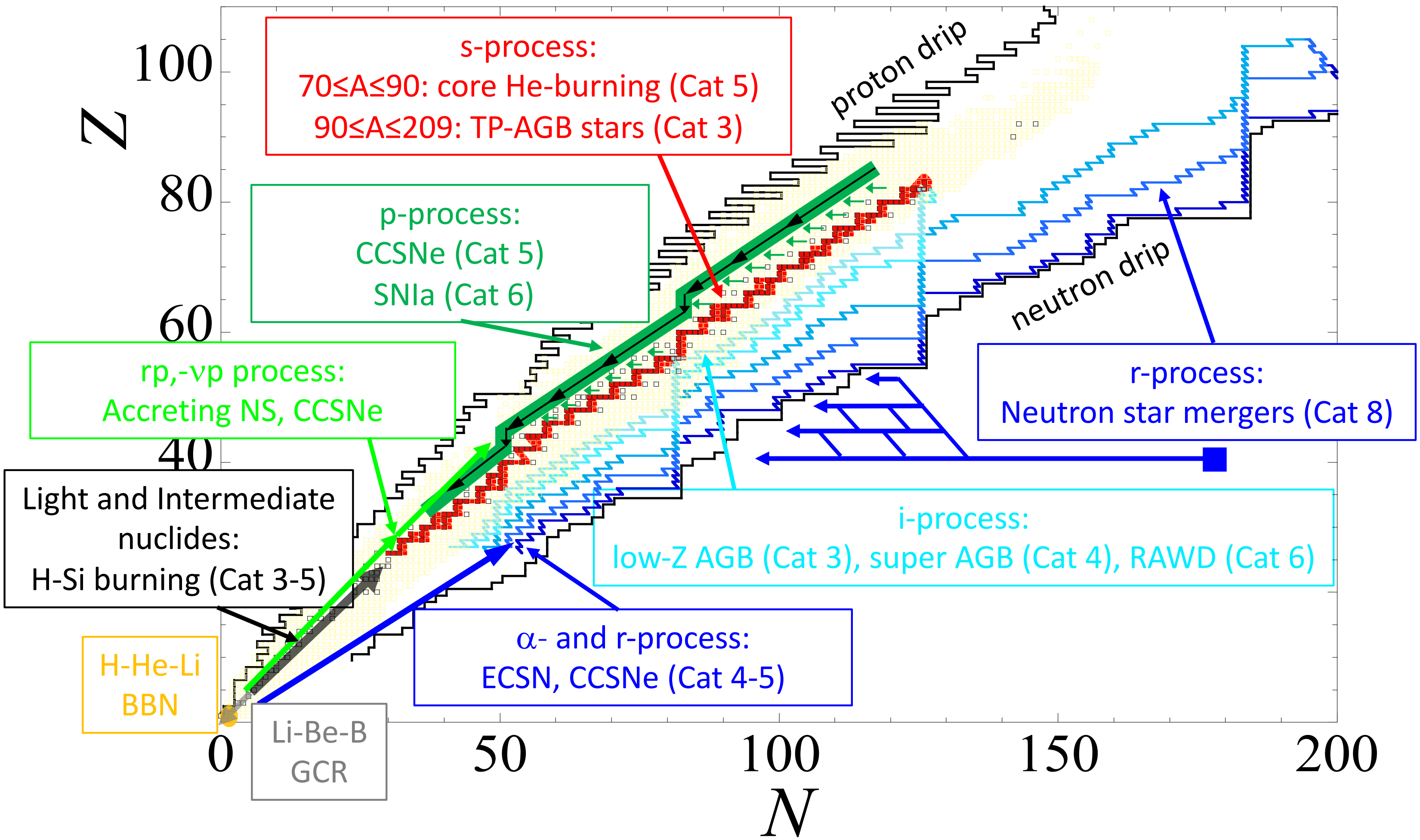
WESTERN MICHIGAN UNIVERSITY

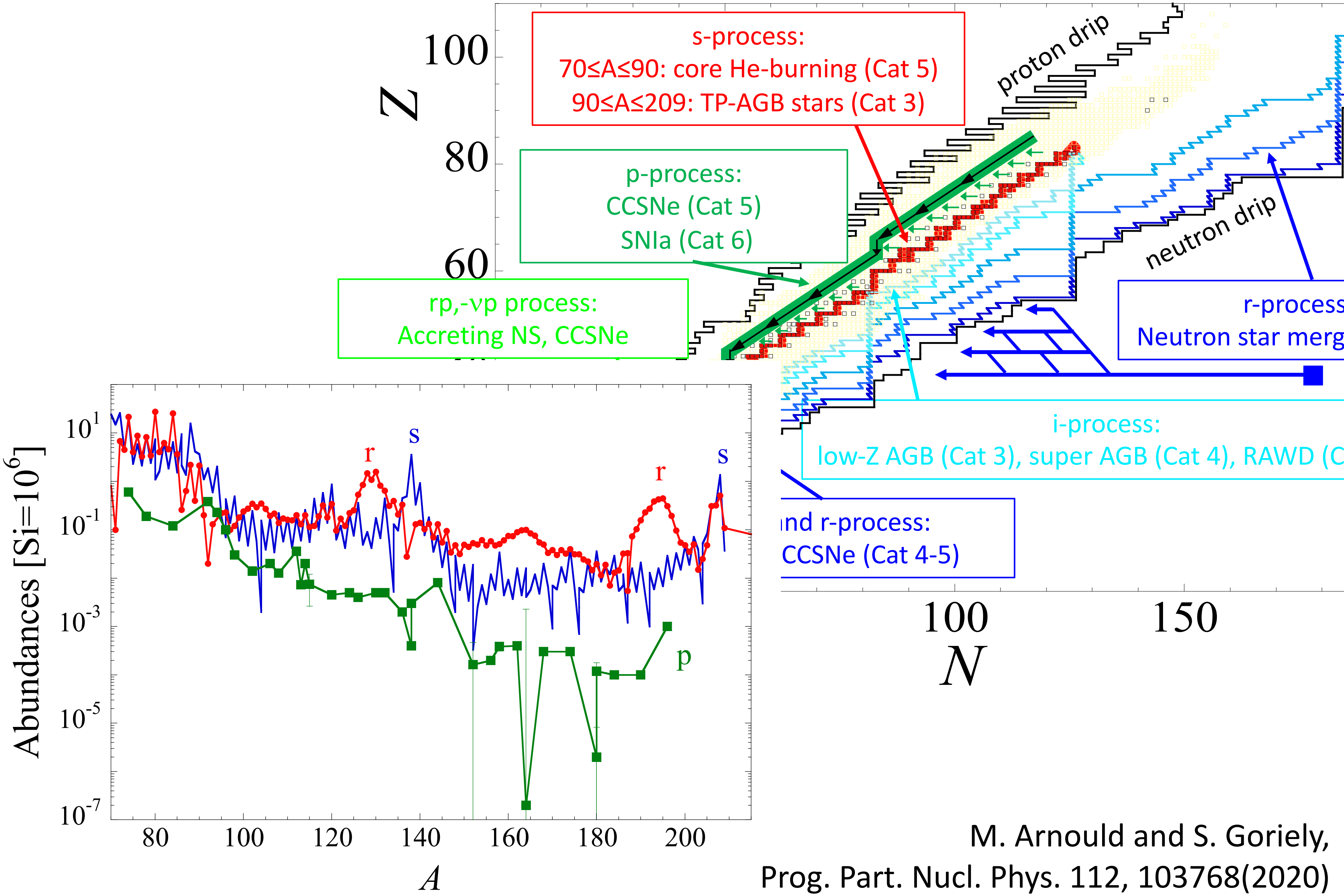
Los Alamos NATIONAL LABORATORY EST. 1943

# Synthesis of heavy elements requires (n,γ)



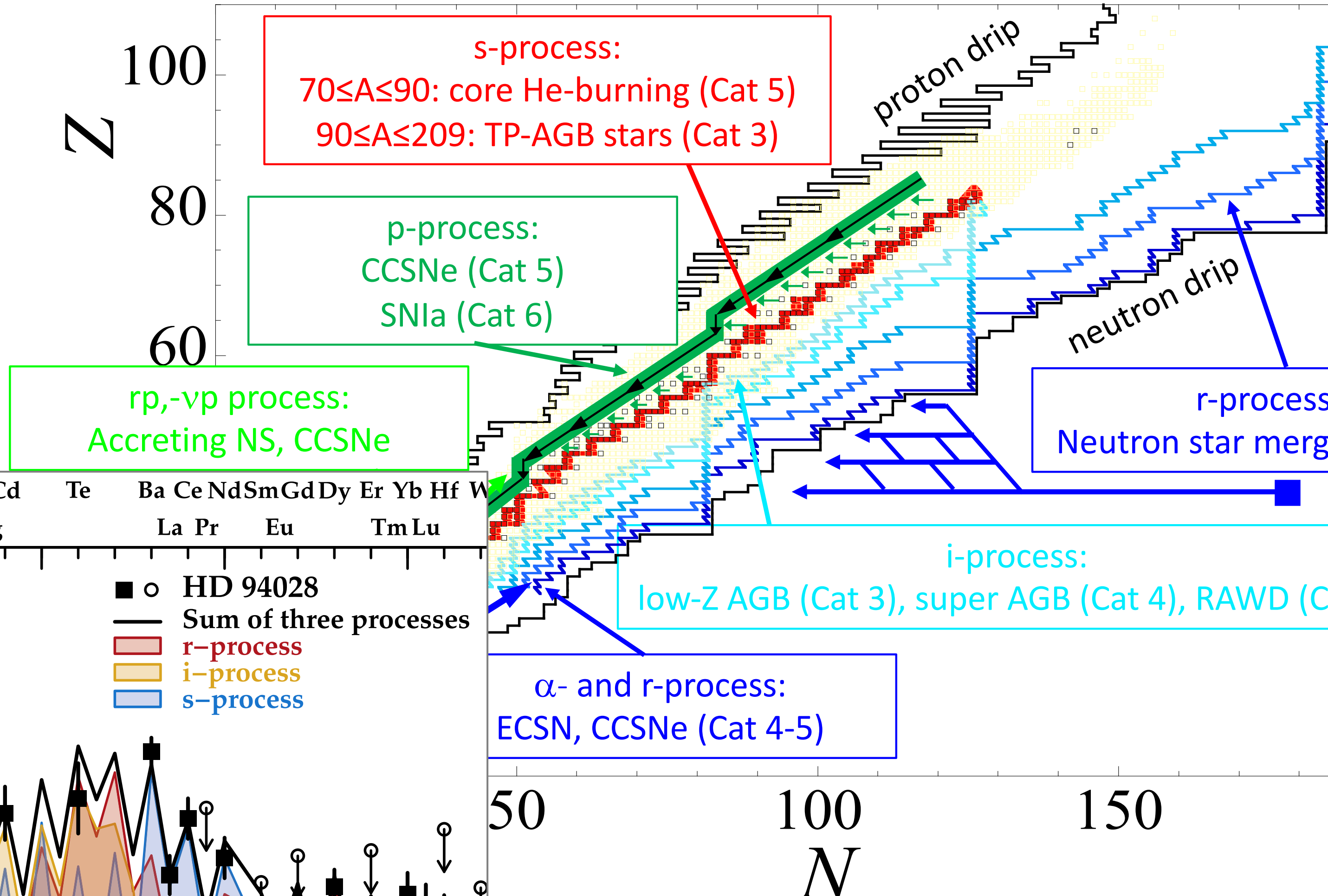

M. Arnould and S. Goriely,
Prog. Part. Nucl. Phys. 112, 103768(2020)

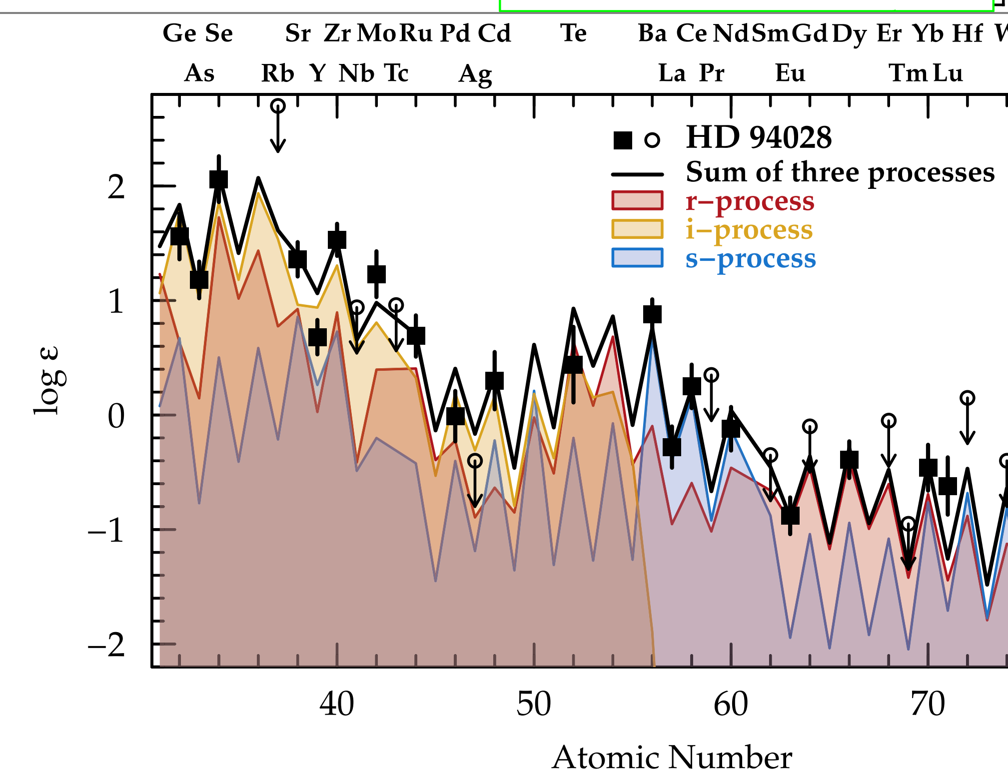
# Synthesis of A≈80: many (n,γ) processes




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

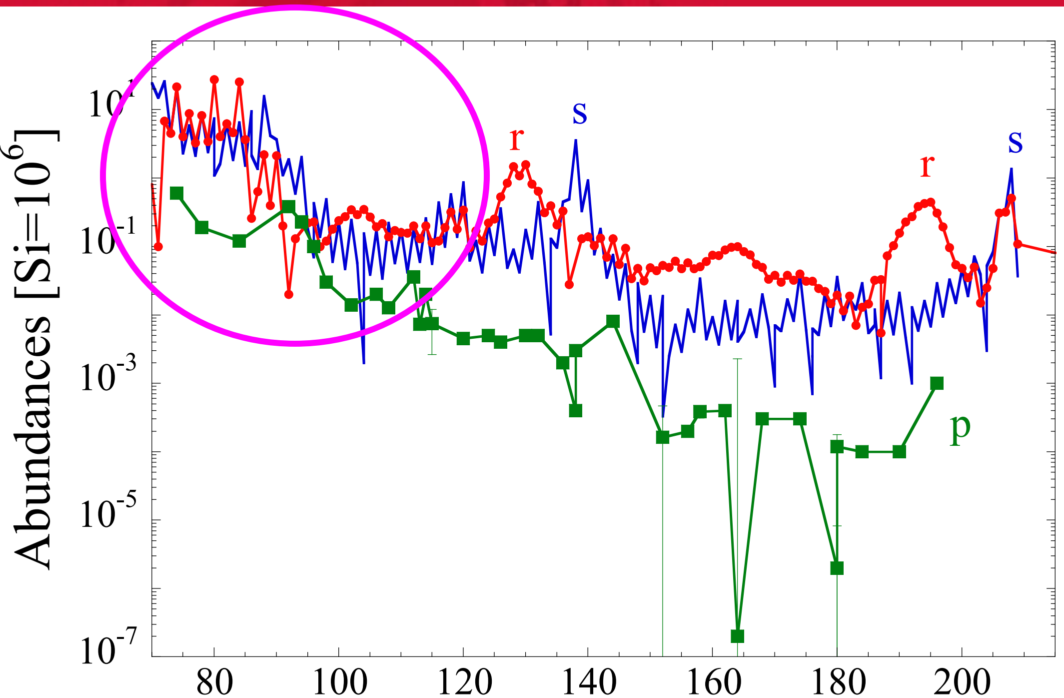
# Single (old) stars: many (n,γ) processes

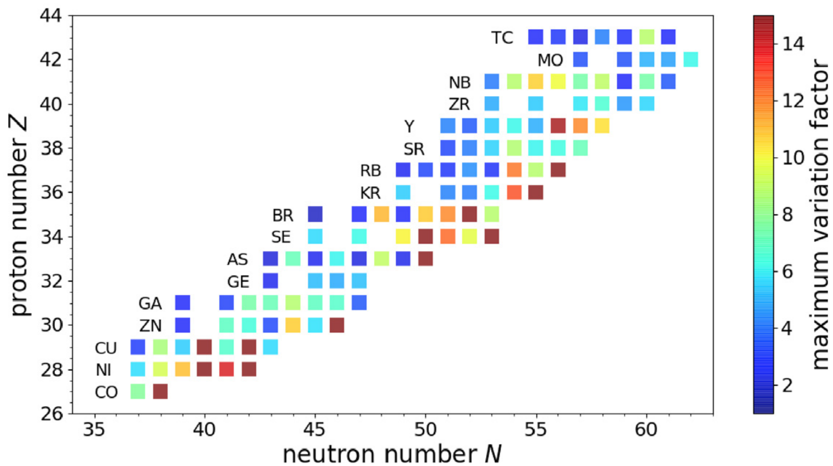


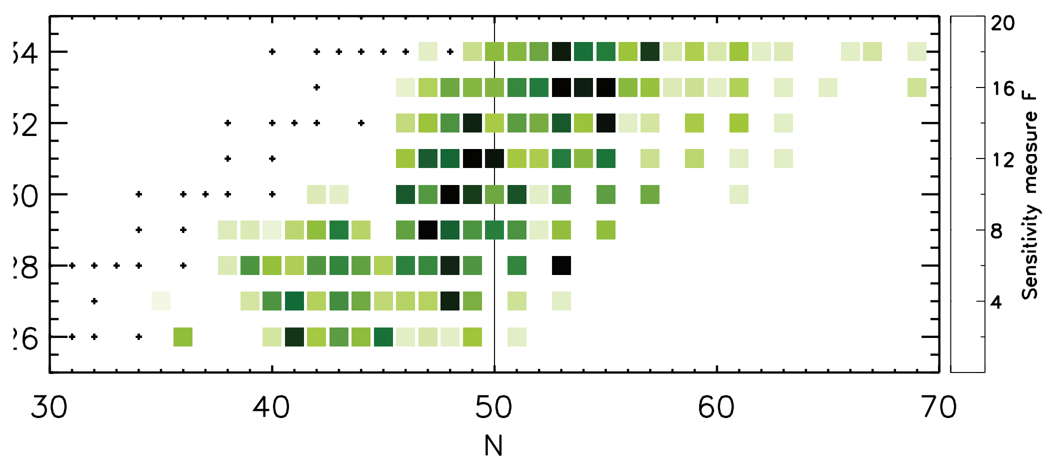




M. Arnould and S. Goriely (2020)
I.U. Roderer, et al., ApJ 821, (2016)

# Understanding A>60 nucleosynthesis & (n,γ)



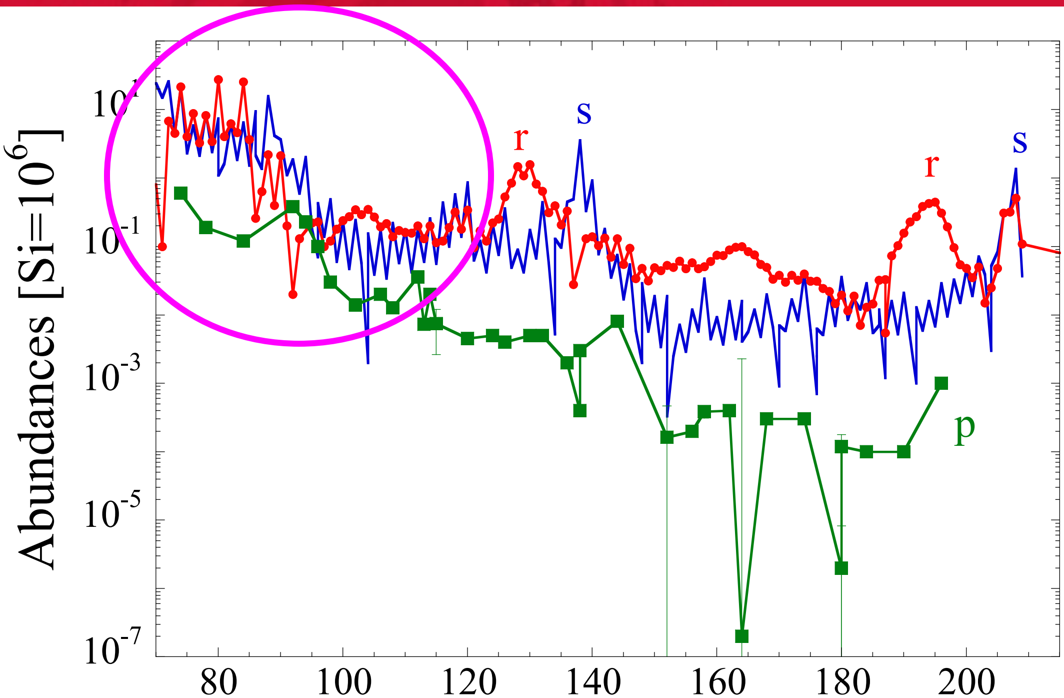



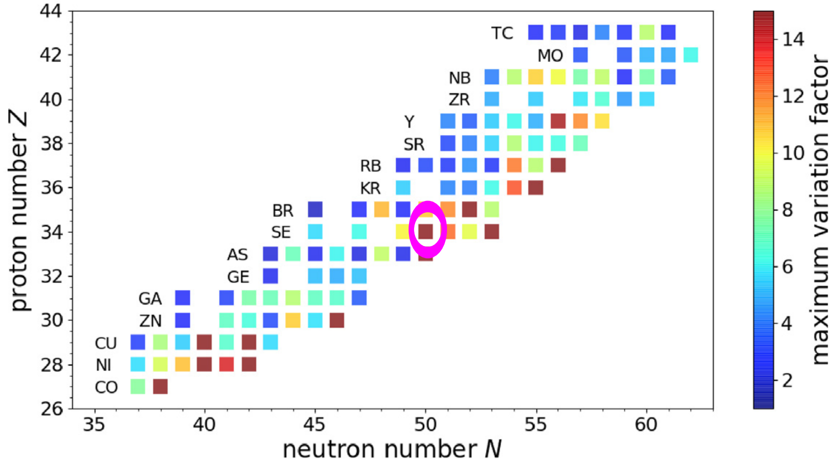



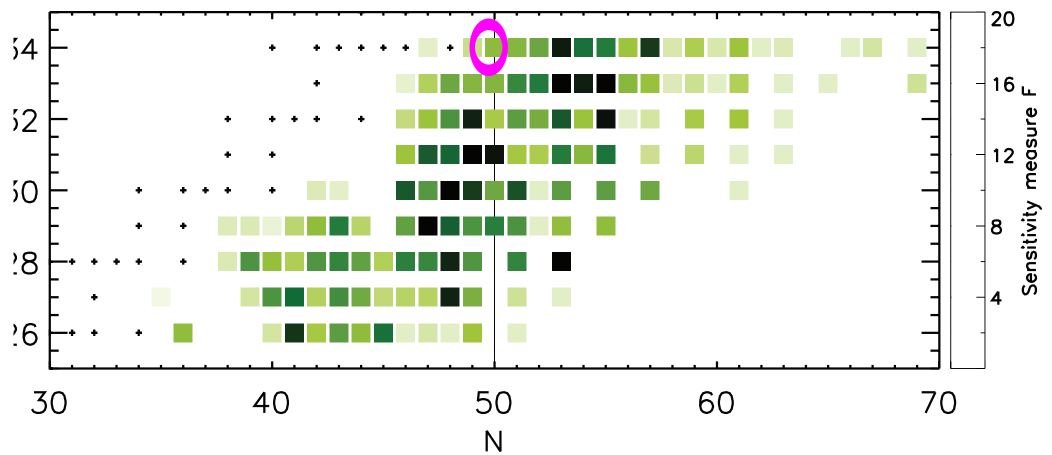

McKay et al., (i process)
MNRAS **491,** 5179–5187 (2020)

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

# Focus on informing $^{84}Se(n,\gamma)$




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

R. Surman et al., (weak-r process)
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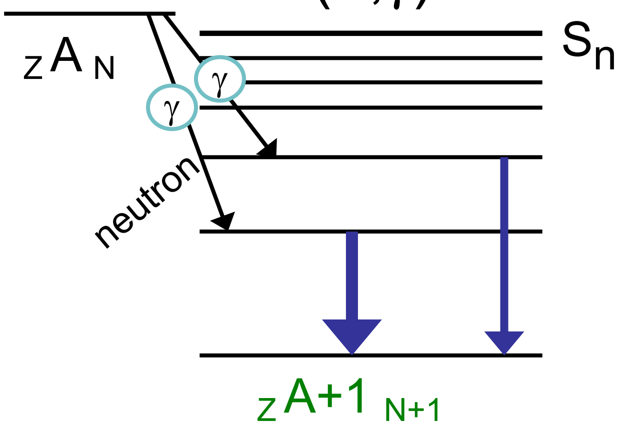
# A≈80 peak and (d,p) reactions

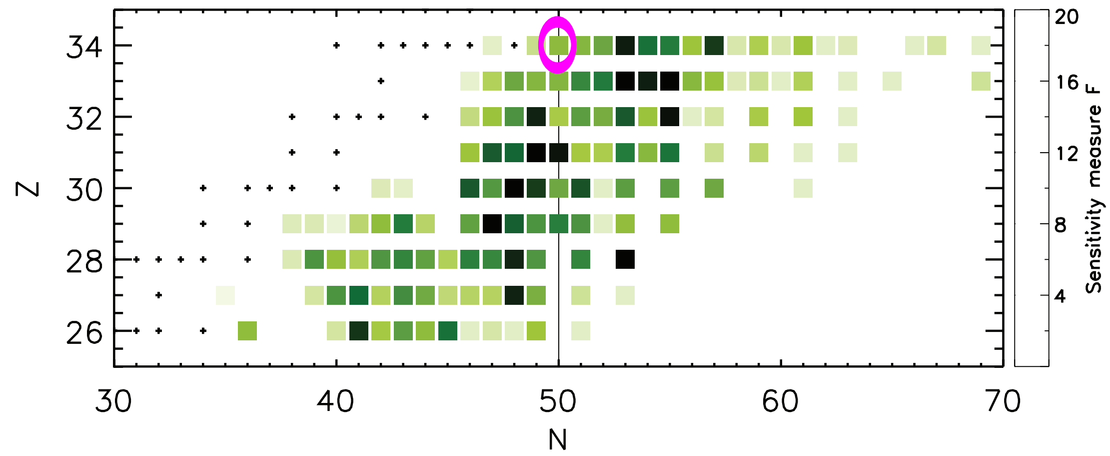
## Focus: N=50 $^{84}$Se

Direct-semi-direct

Near N shell closures

(n,$\gamma$)




Near closed shells

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

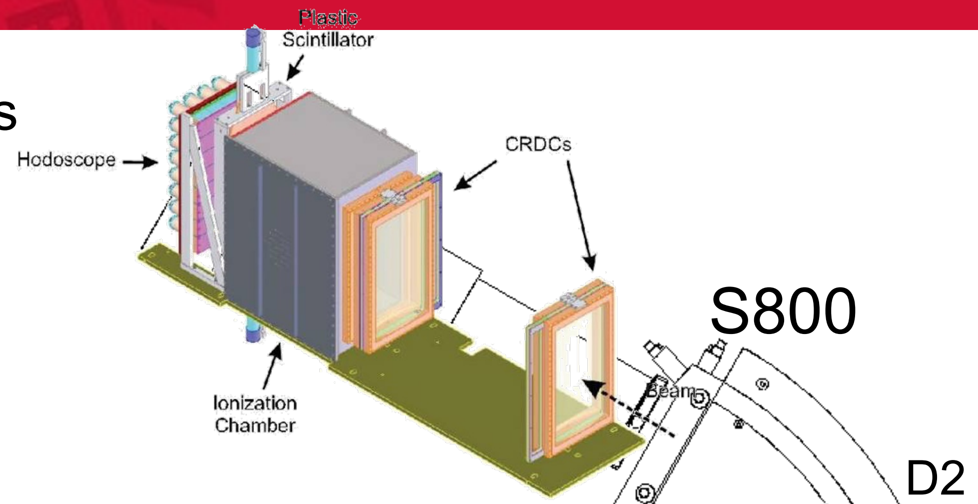
$$S = \left(\frac{d\sigma}{d\Omega}\right)_{exp} / \left(\frac{d\sigma}{d\Omega}\right)_{thy}$$

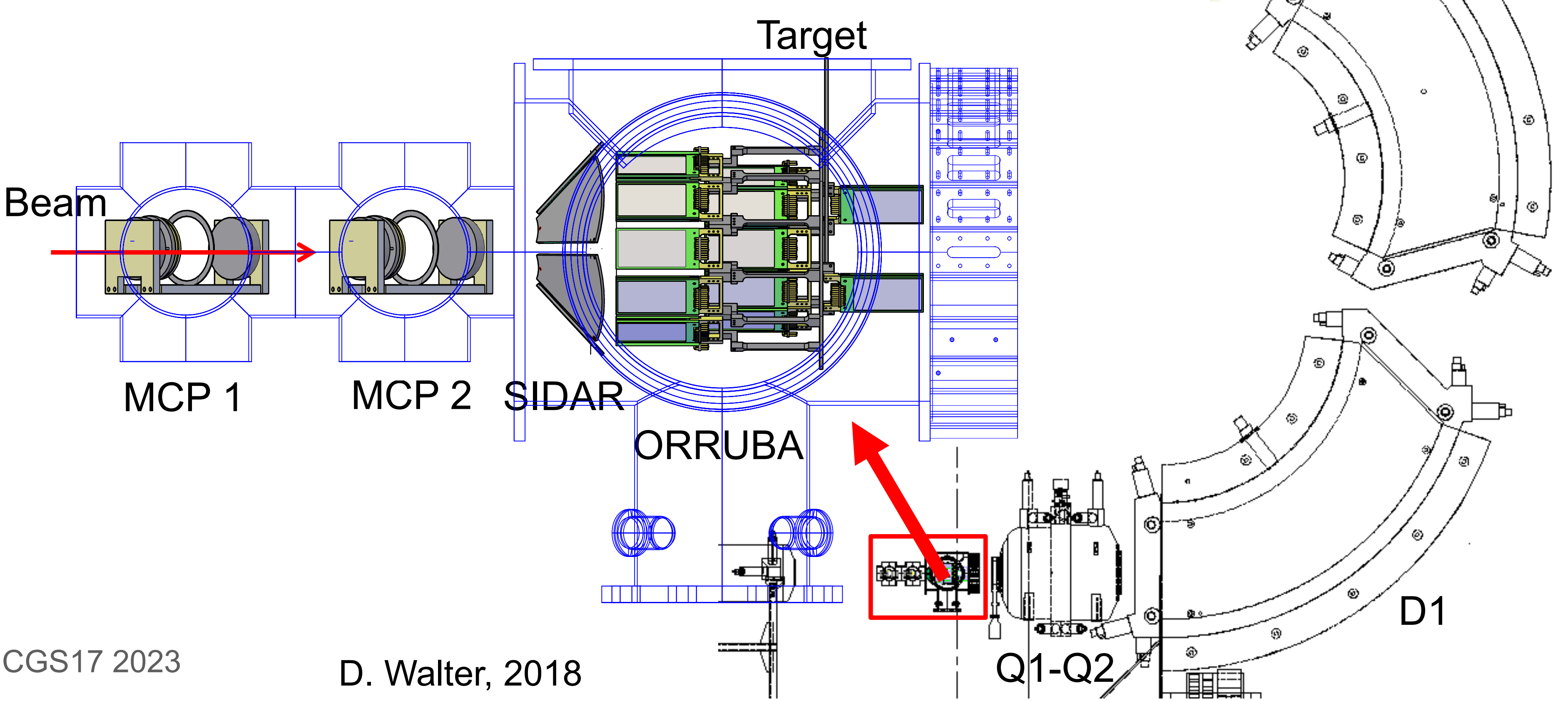
R. Surman et al., (weak-r process)
AIP Advances **4**, 041008 (2014)

# (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



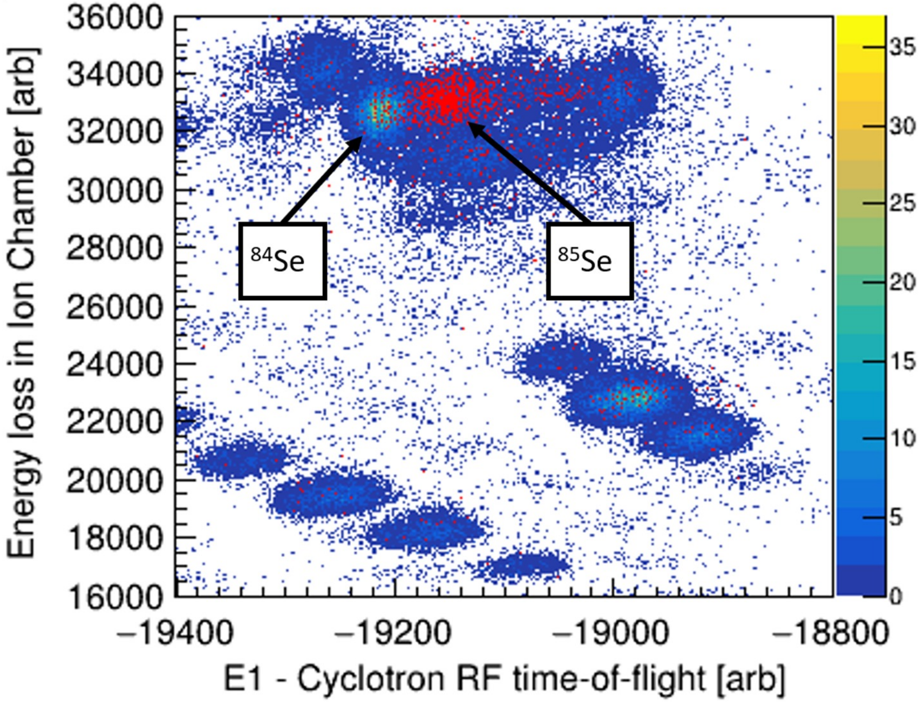



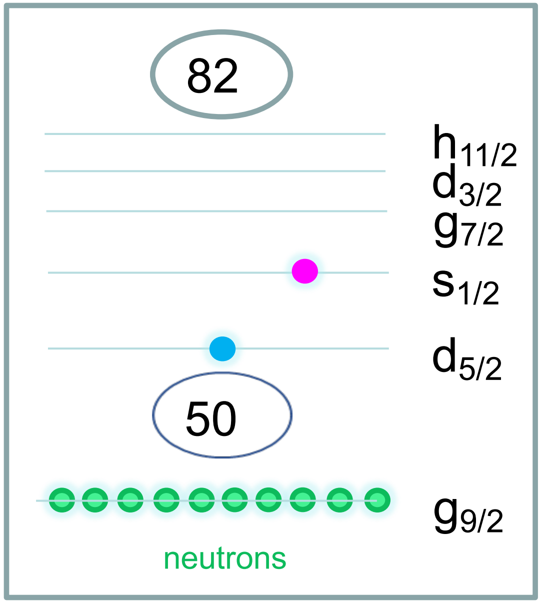

D. Walter, 2018

# Extracting Spec Factors => Direct capture

- 45 MeV/u at NSCL

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




Excitations in $^{85}$Se

S800 FP particle ID

- (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)

# Extracting Spec Factors => Direct capture

- 45 MeV/u at NSCL

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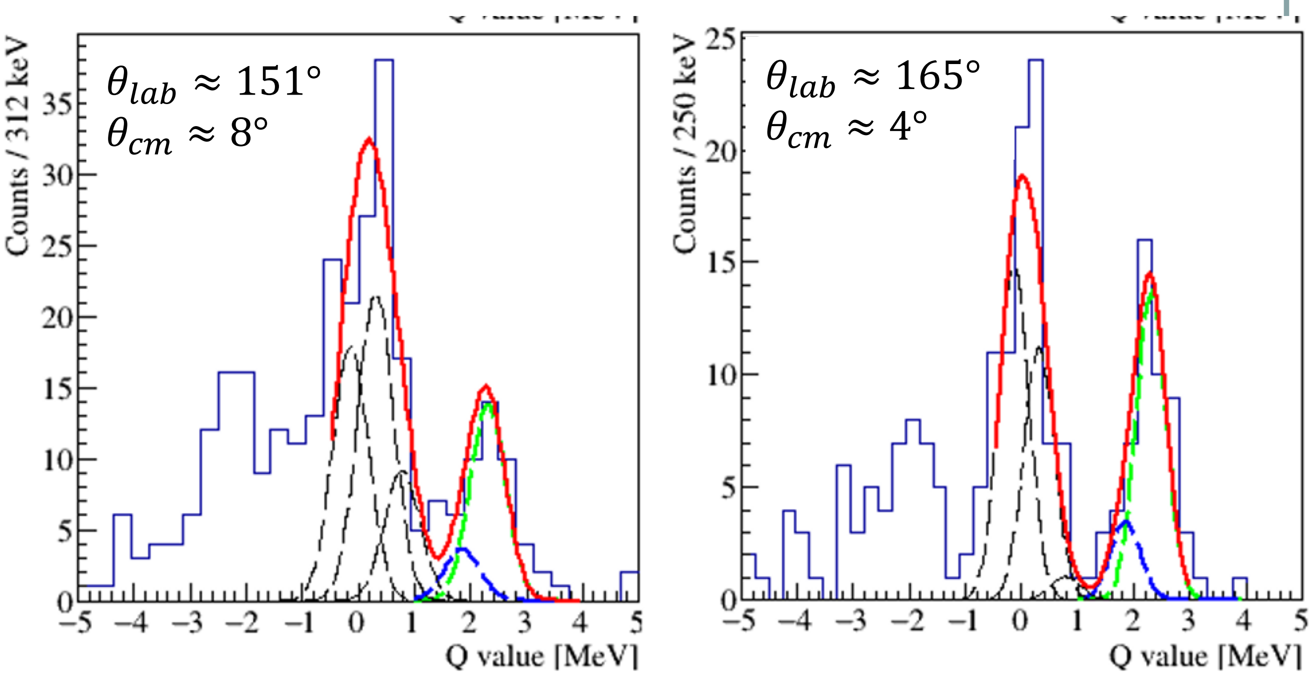
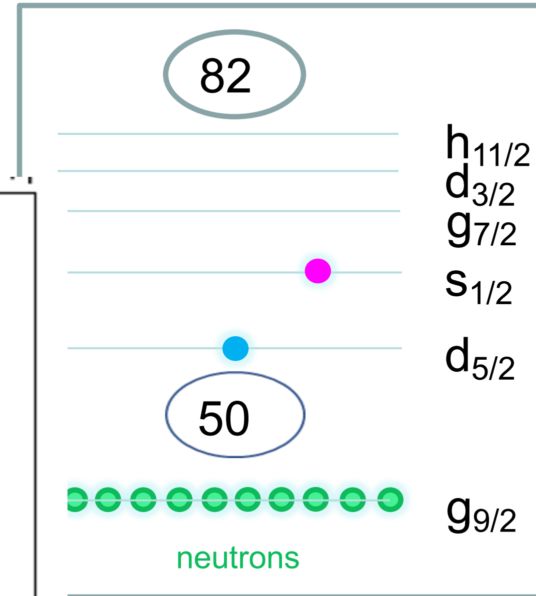



Excitations in $^{85}$Se

FR-ADWA w/ KD OPM

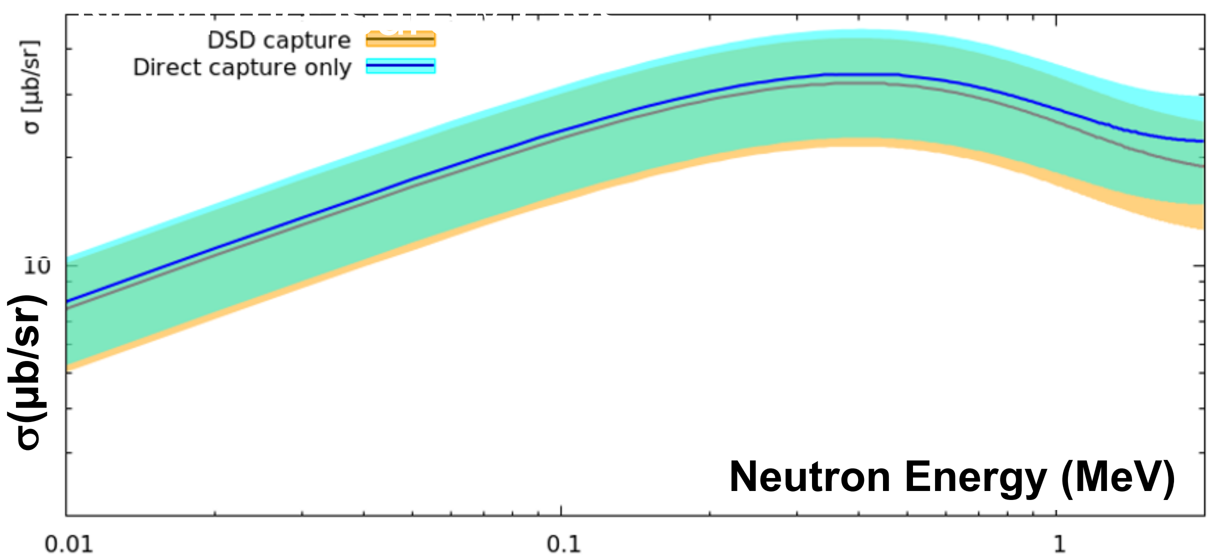
| | |
|---|---|
| $5/2^{+}$ $E_x = 0$ | $S = 0.28\ (4)$ |
| $1/2^{+}$ $E_x = 0.462$ MeV | $S = 0.26\ (6)$ |

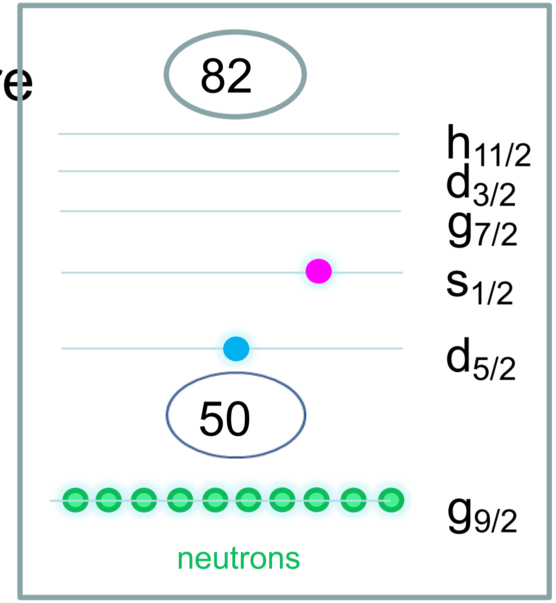
H.E. Sims Phd Dissertation (2020)
H.E. Sims, D Walter et al.,
in preparation for PRC (2023)

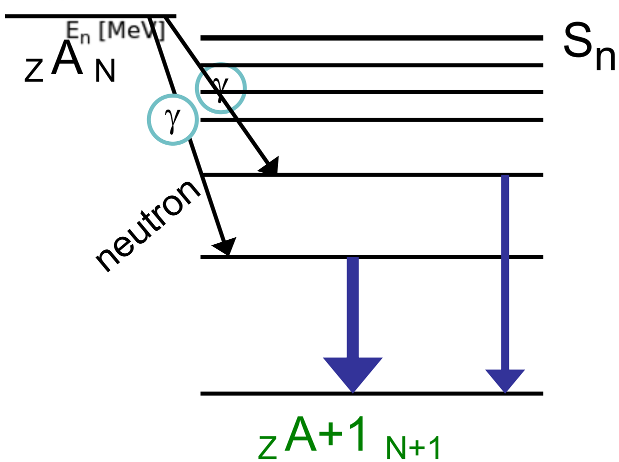
# (d,p) studies with 4.5 MeV/u & 45 MeV/u $^{84}$Se beams

## Direct-semi-direct (DSD) capture

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



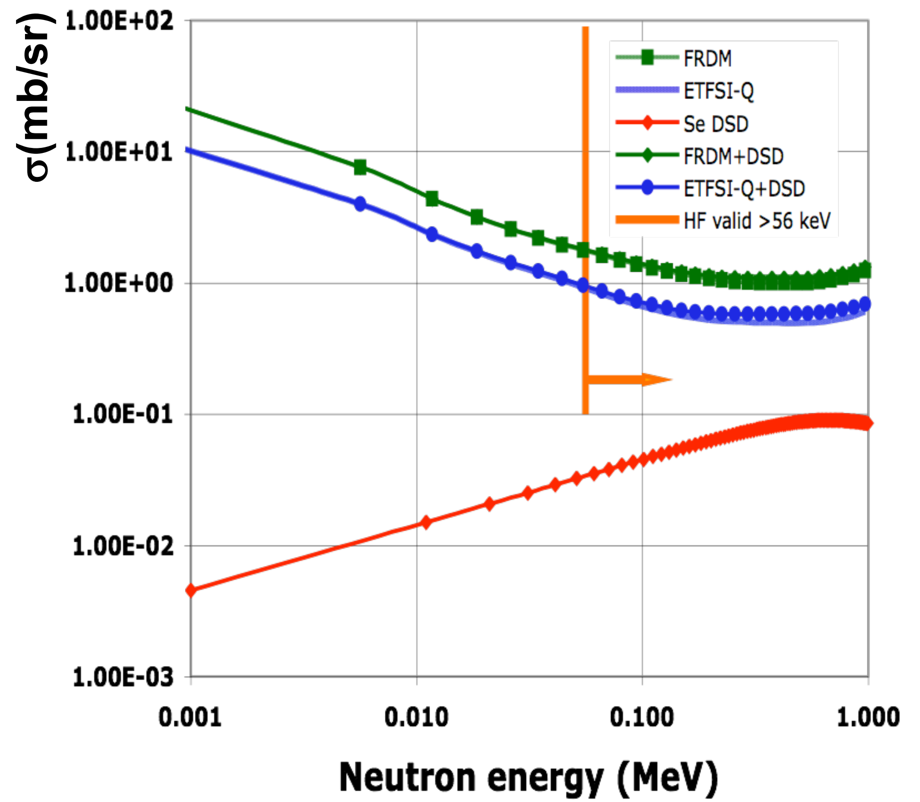



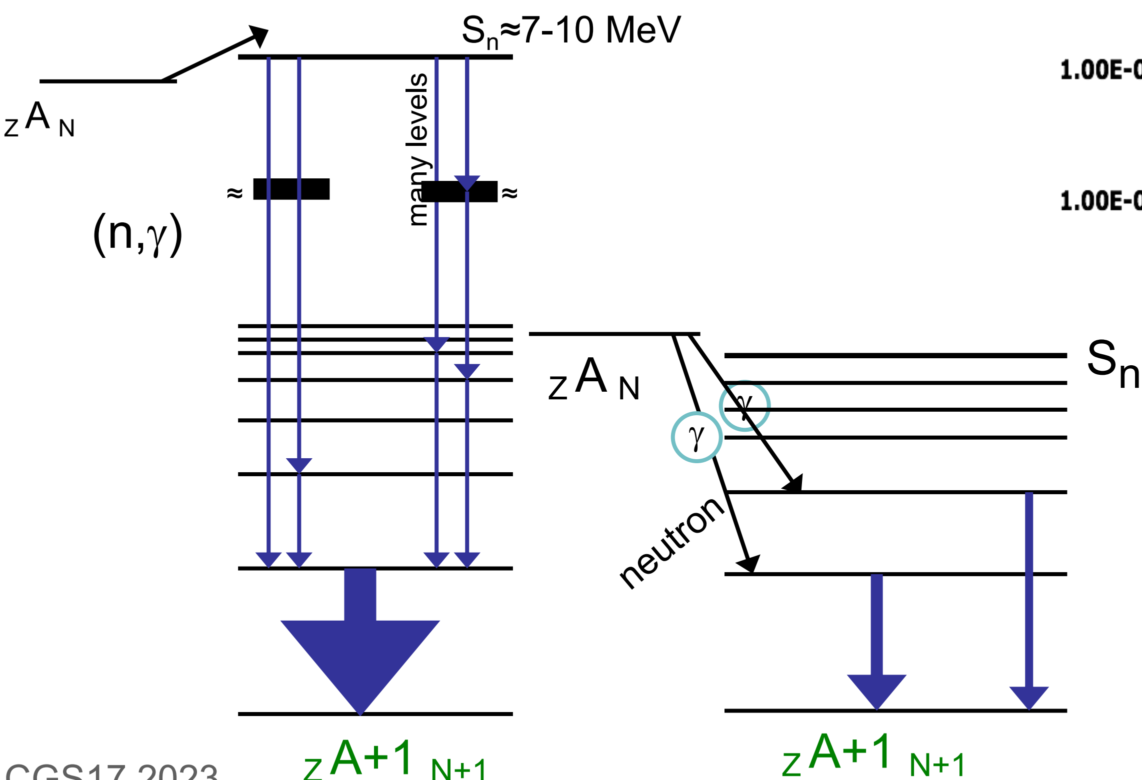

H.E. Sims Phd Dissertation (2020)
H.E. Sims, D Walter et al.,
in preparation for PRC (2023)

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

## Direct-semi-direct capture

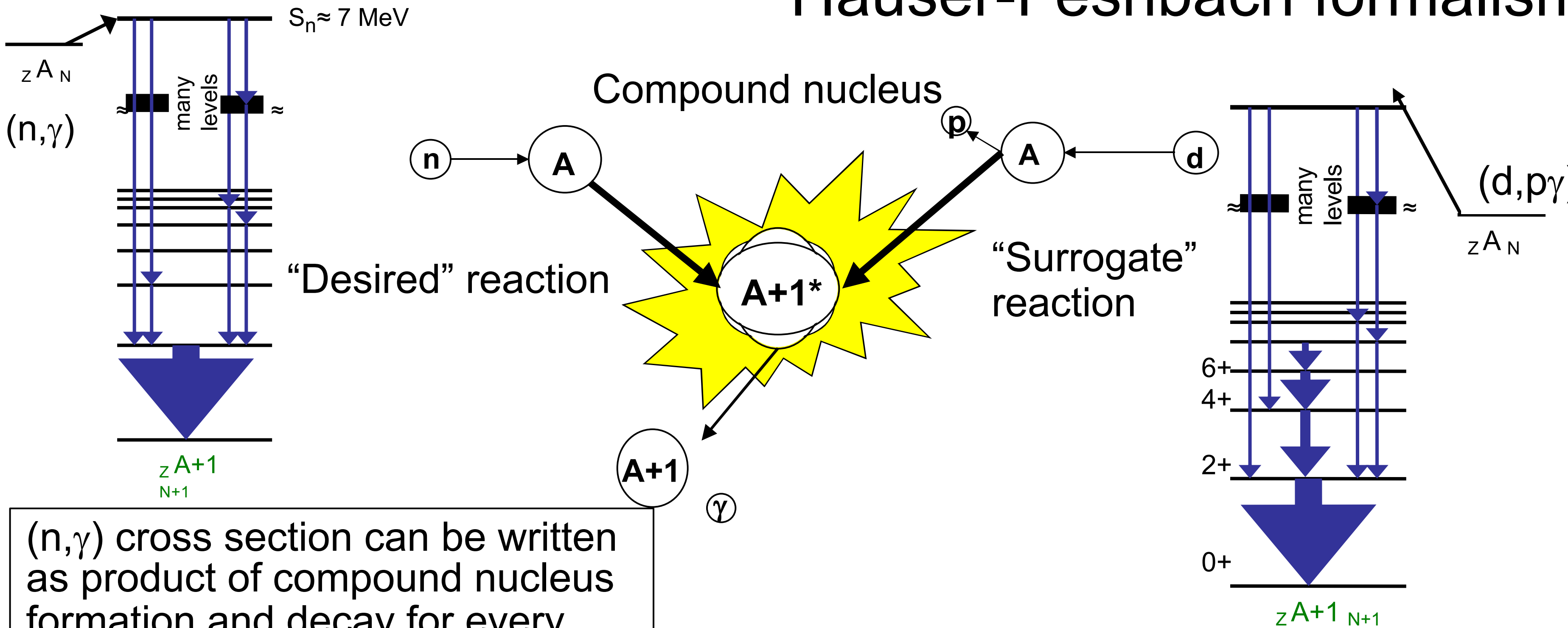
- Cross sections small ≈20 μb/sr for $p$-wave capture
- Statistical capture? $\sigma$ much larger?
- ➢ Need valid (n,γ) surrogate reaction




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:

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

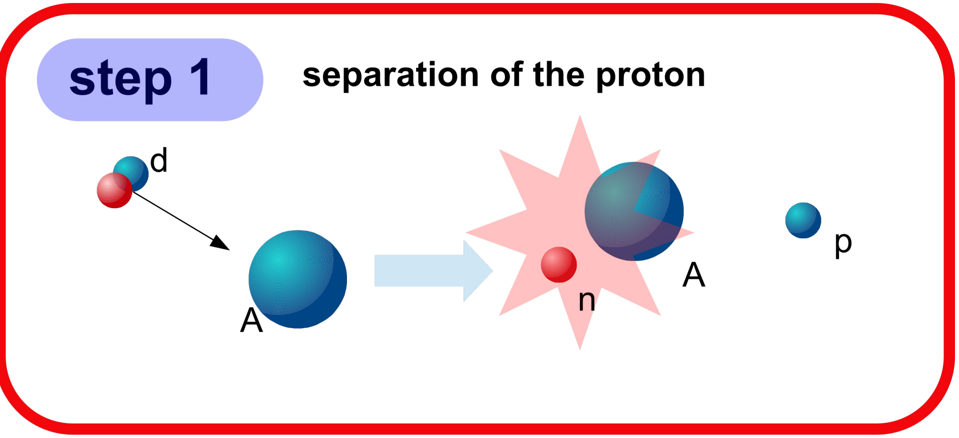
Surrogate particle-gamma coincidence can be written as product of compound nucleus formation and decay for every spin and parity:

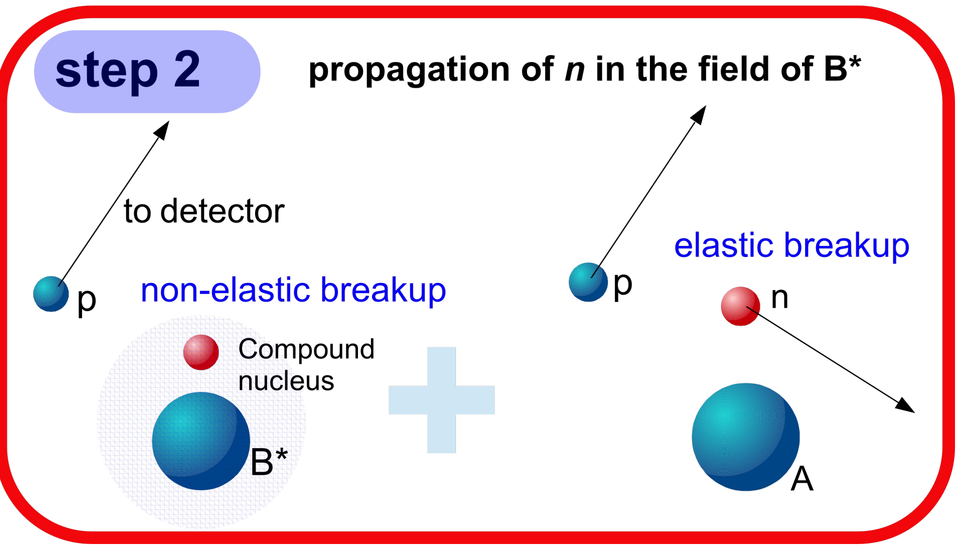
$$P_{p\gamma}(E_x, \theta) = \sum_{J,\pi} F_{dp}^{CN}(E_x, J, \pi, \theta) G_\gamma^{CN}(E_x, J, \pi)$$

# 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,$\gamma$)




<u>Two-step process</u>

- d breakup; B.E. = 2.2 MeV
- n propagation
  - Elastic breakup
  - Non-elastic breakup ⇒ CN and surrogate (n,$\gamma$)
  - Predicts $J^{\pi}$ 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: $G^{CN}$

$$P_{p\gamma}(E_x,\theta) = \sum_{J,\pi} F^{CN}_{dp}(E_x,J,\pi,\theta) G^{CN}_{\gamma}(E_x,J,\pi)$$

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

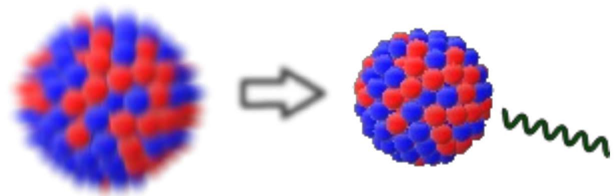
$\ell = 0$ capture on $5/2^+$ => $2^+, 3^+$

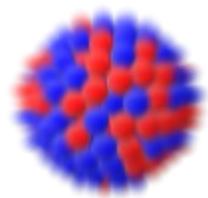
σ(n,γ) was measured and informed

# What need for SRM

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

$P_{pY}(E_x) =$





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

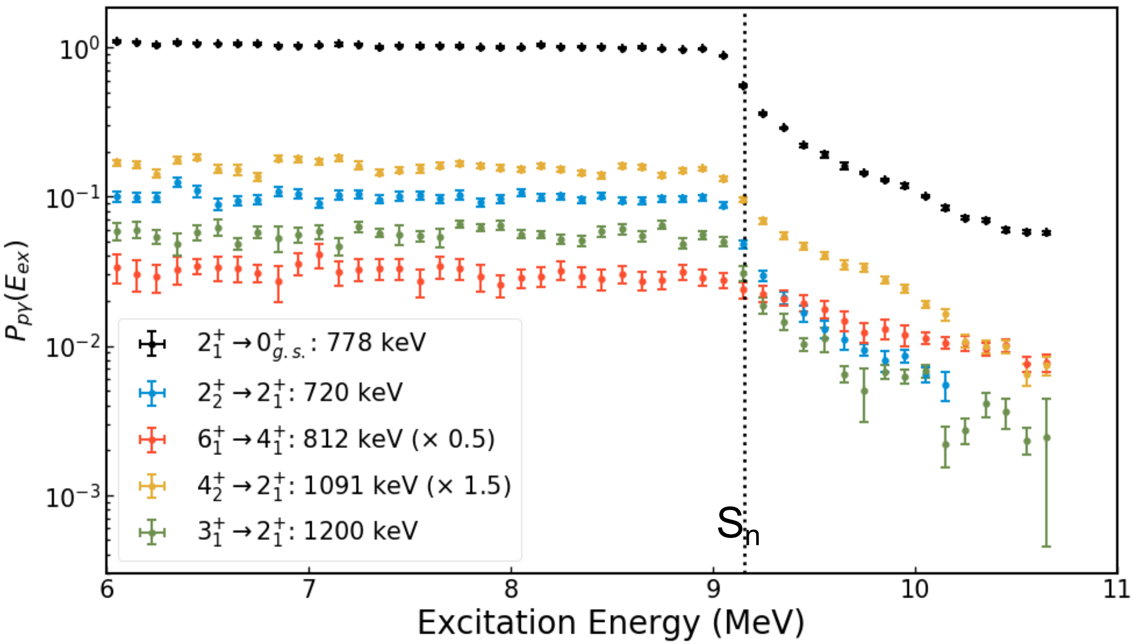
# What we measured in normal kinematics

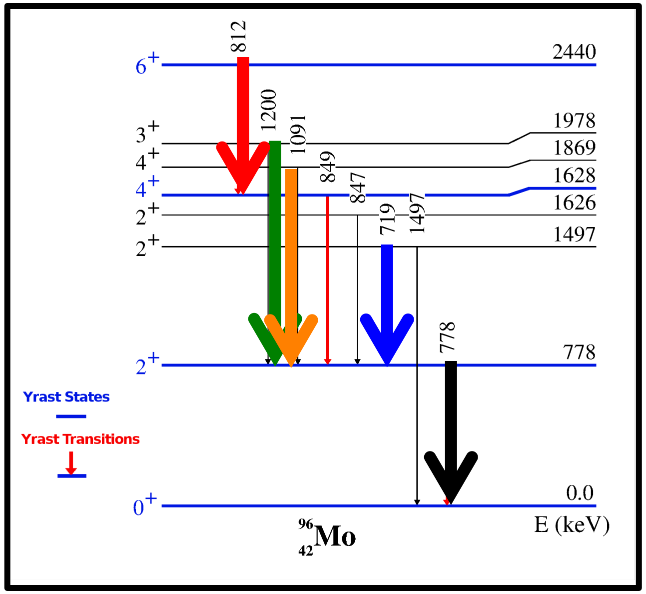
$$P_{pY}(E_x) = \frac{Number\ of\ CN\ decays\ via\ channel\ Y}{Number\ of\ times\ the\ CN\ is\ formed}$$

- 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 $E_x$

$$P_{pY}(E_x) = \left. \frac{N_{pY}(E_x)}{\varepsilon_Y} \middle/ N_p(E_x) \right.$$

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



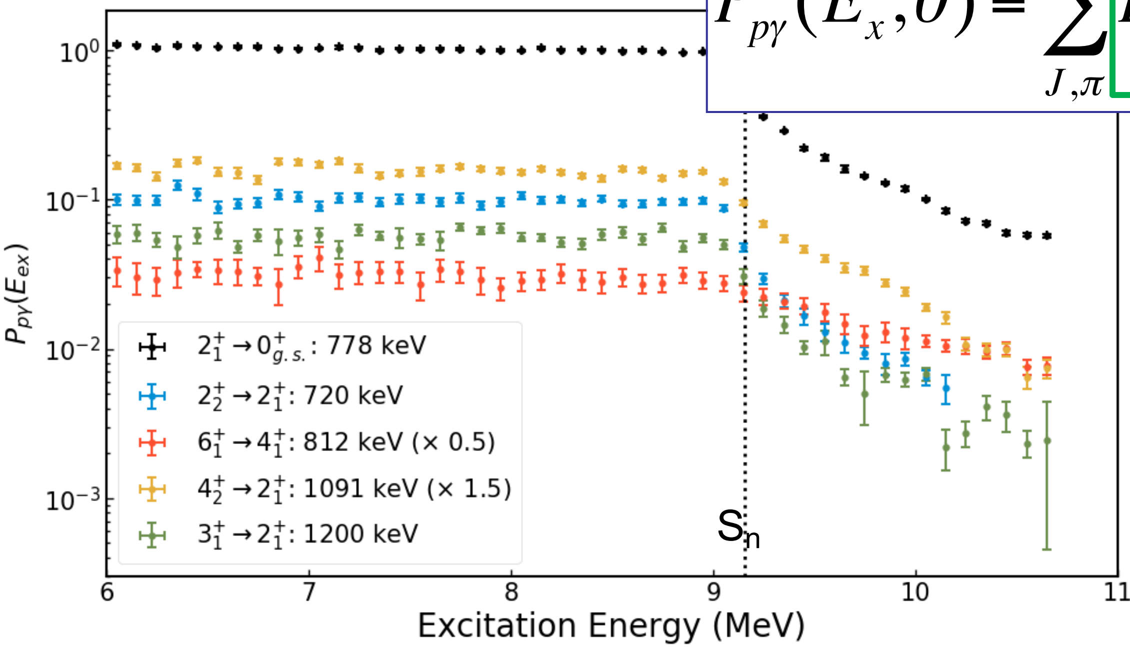

$$P_{p\gamma}(E_x) = \frac{N_{p\gamma}(E_x)/\varepsilon_\gamma}{N_p(E_x)} = \sum_{J,\pi} F_{dp}^{CN}(E_x, J, \pi, \theta) G_\gamma^{CN}(E_x, J, \pi)$$

Surrogate (d,pγ) data

Measure $P_{p\gamma}(E_x)$ inform $G_\gamma^{CN}(E_x, J, \pi)$

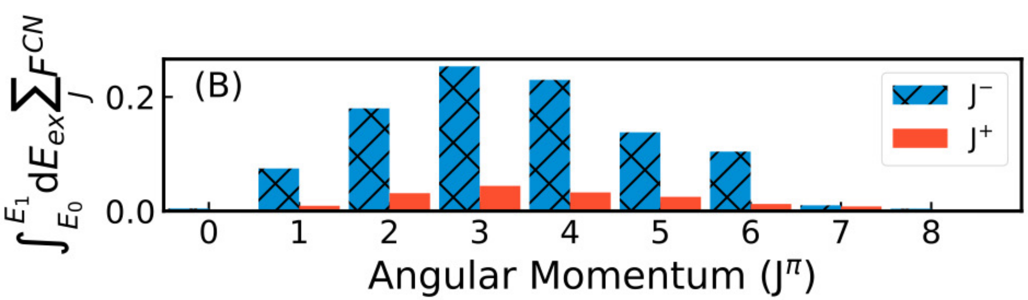
# $^{95}$Mo(d,pγ): Input for $G_\gamma^{CN}(E_x, J, \pi)$

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




Surrogate (d,pγ) data

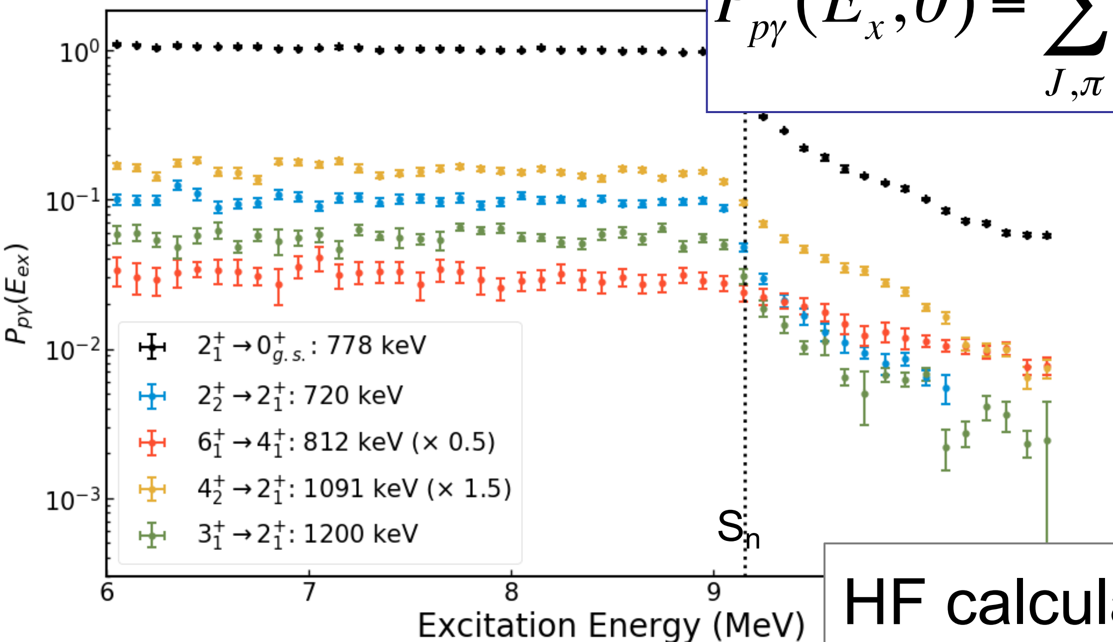
## Potel: $^{96}$Mo spin distribution




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

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

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




Surrogate (d,pγ) data

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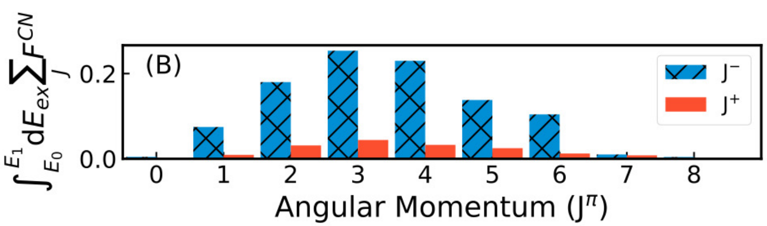



G. Potel et al, PRC 92, 034611(2015)

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)>

➢ $G^{CN}(E_x,J,\pi)$

# Calculating σ(n,γ)

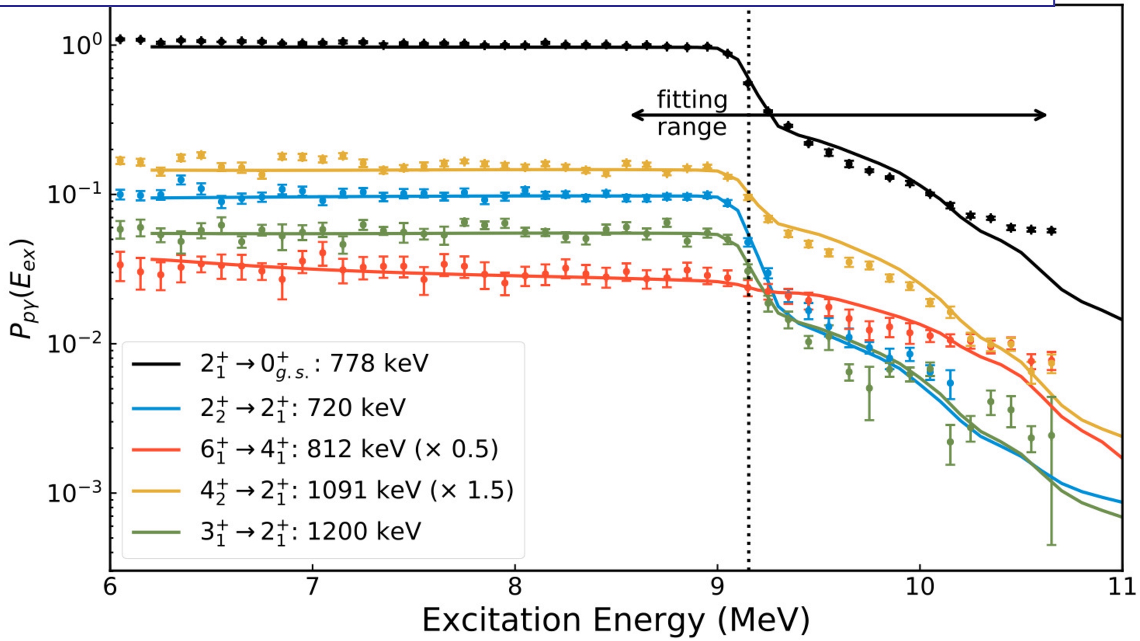
$$P_{p\gamma}(E_x,\theta) = \sum_{J,\pi} F_{dp}^{CN}(E_x,J,\pi,\theta)\, G_\gamma^{CN}(E_x,J,\pi)$$

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

- Deduce $G^{CN}(E_x,J,\pi)$ from fit to data
- Calculate $\sigma^{CN}$ w/ Koning-Delaroche optical potentials
- Deduce $\sigma(n,\gamma)$ vs $E_x$

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

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




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

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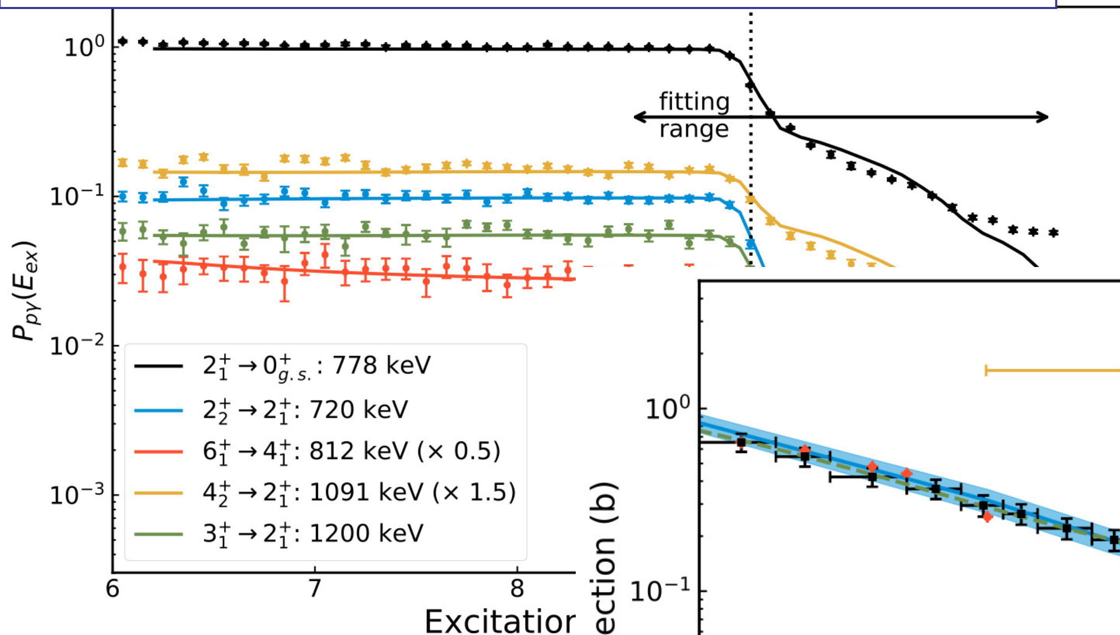
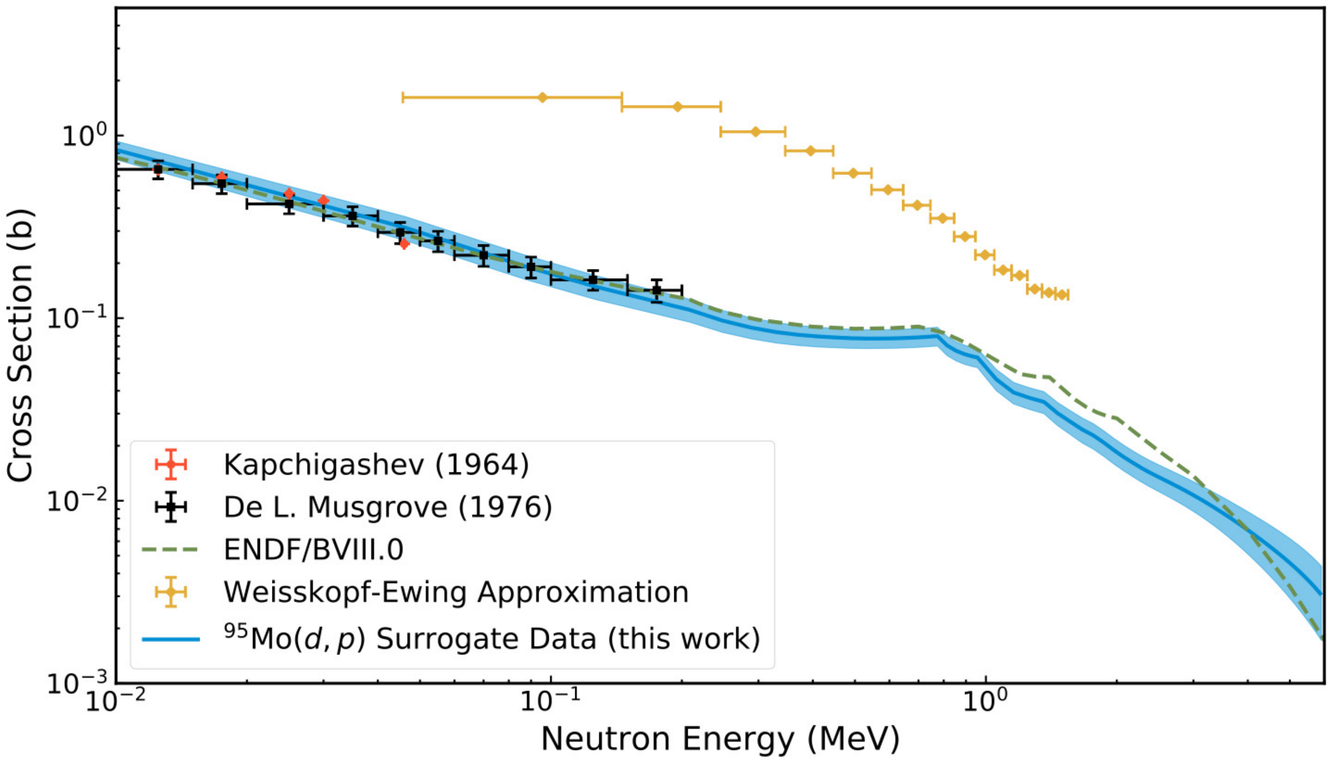



A. Ratkiewicz et al., PRL **122**, 052502 (2019)

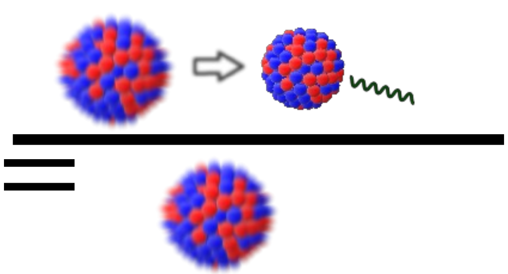
$$\sigma_{n\gamma}(E_n) = \sum_{J,\pi} \sigma_{n}^{CN}(E_x,J,\pi)\,G_{\gamma}^{CN}(E_x,J,\pi)$$

# 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 $\gamma$
  - 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

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

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



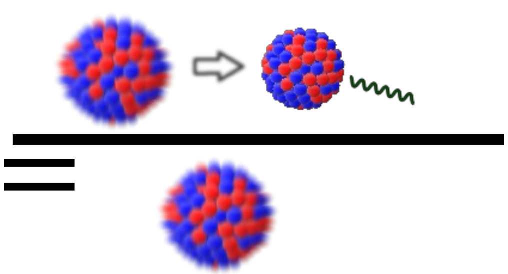
# Inform (n,$\gamma$) on $^{84}$Se (rare isotope) with (d,p)

- $^{84}$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

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

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

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



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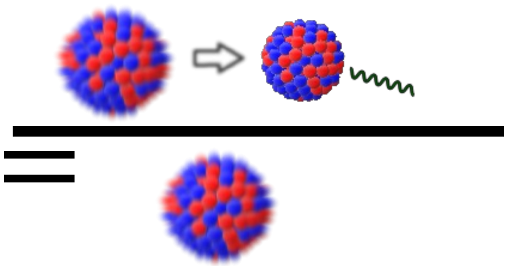
- CN at $E_x > S_n$ : if decays by neutron emission => $^{84}$Se

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

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

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

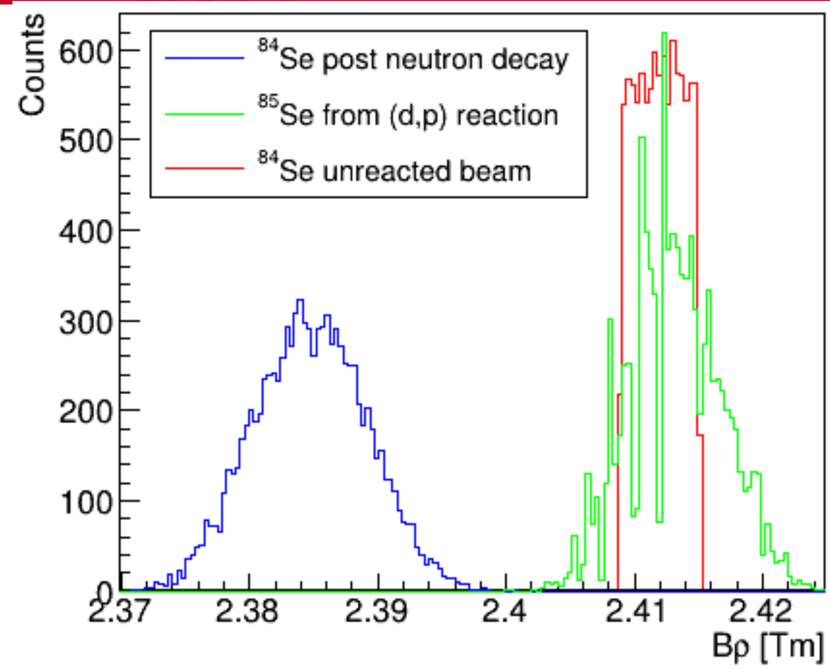


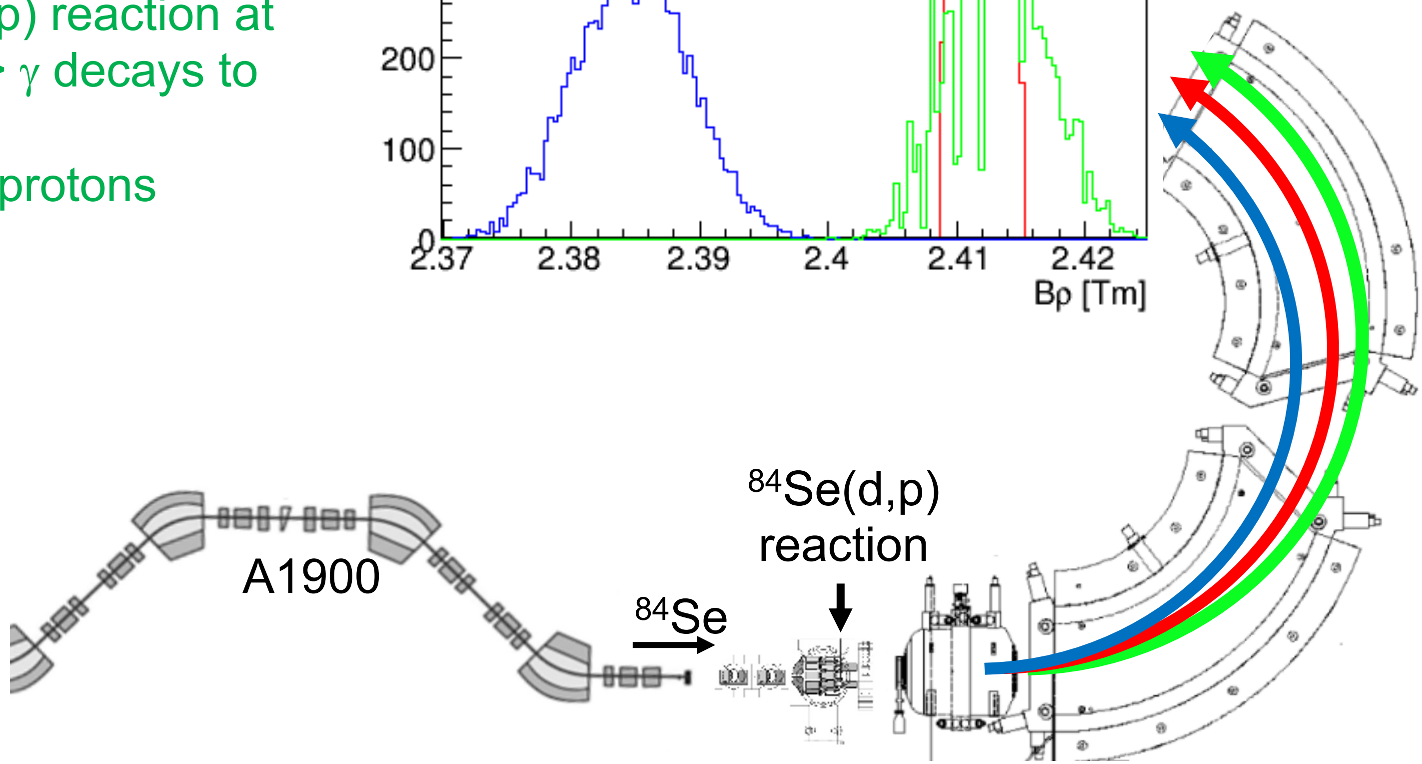
# SRM at S800 without detecting γ-rays

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 $^{85}Se$ => $\gamma$ decays to $^{85}Se$ g.s.
   - Know $E_x$ from protons




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



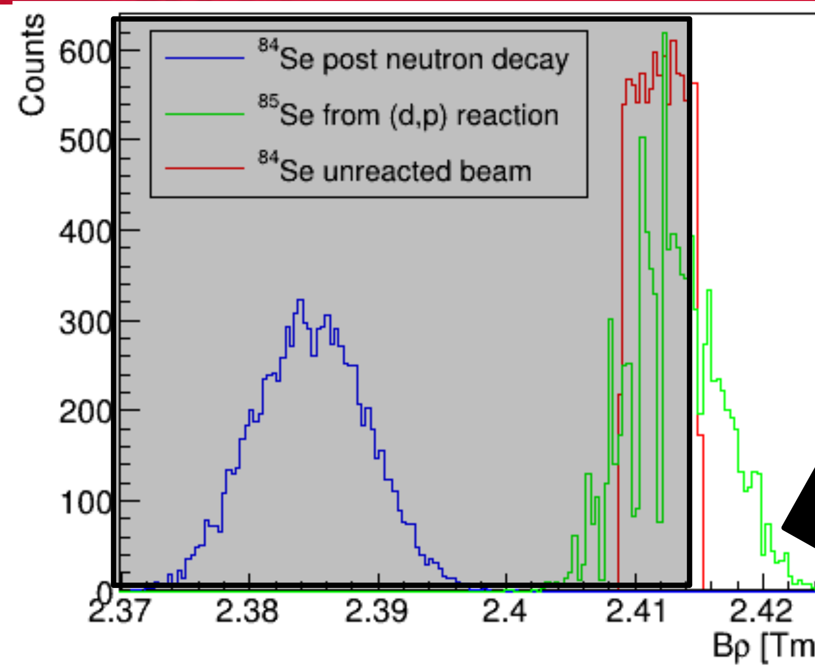
H.E. Sims, S.D. Pain, 2021

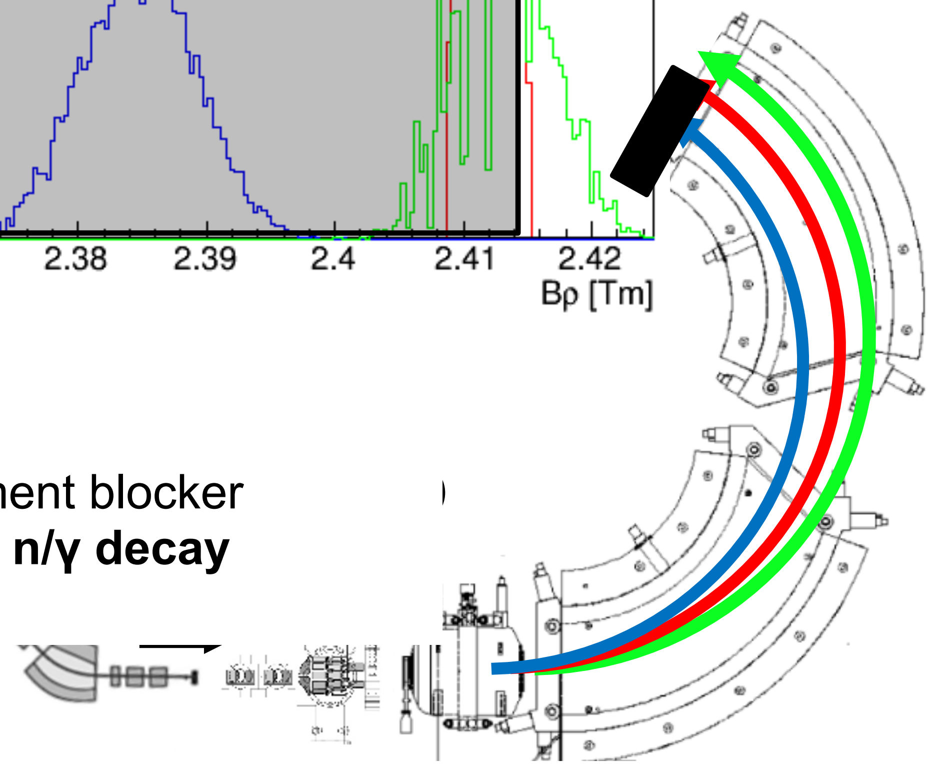
# SRM at S800 without detecting γ-rays

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



- 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

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# SRM at S800 without detecting γ-rays

Advantages:

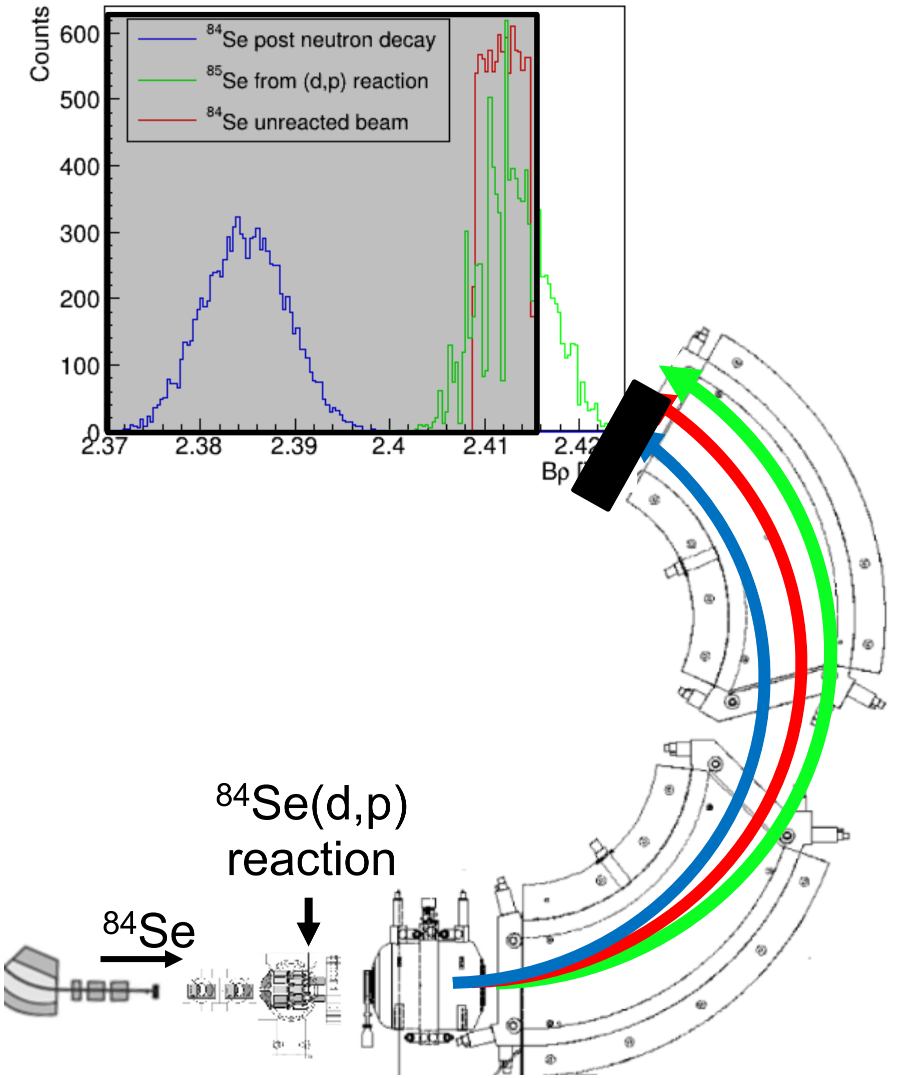
- With (low intensity RIBs) all statistics in single observable
- ~25-30% detection efficiency (much better than γ efficiency ≈13%)
    - Can measure by looking at bound states
    - Not reliant on simulations
    - If can tighten up momentum acceptance, less beam-recoil overlap
- No need for complicated 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

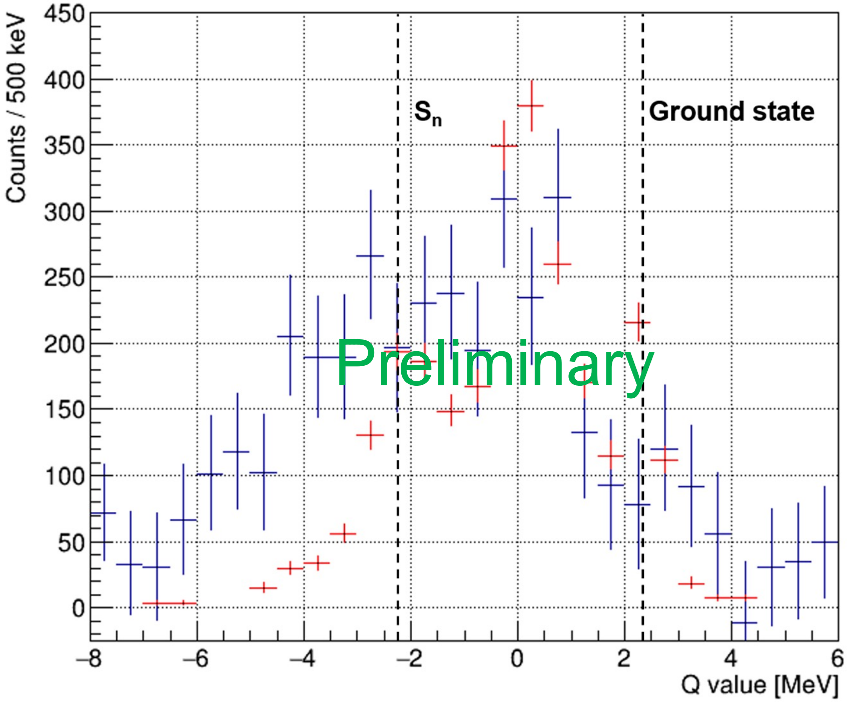
# SRM at S800 without detecting γ-rays: $P_\gamma$ from S800 coincidences

Proton-S800 coincidences

S800 acceptance

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

Proton singles (background subtracted)




H.E. Sims, 2023

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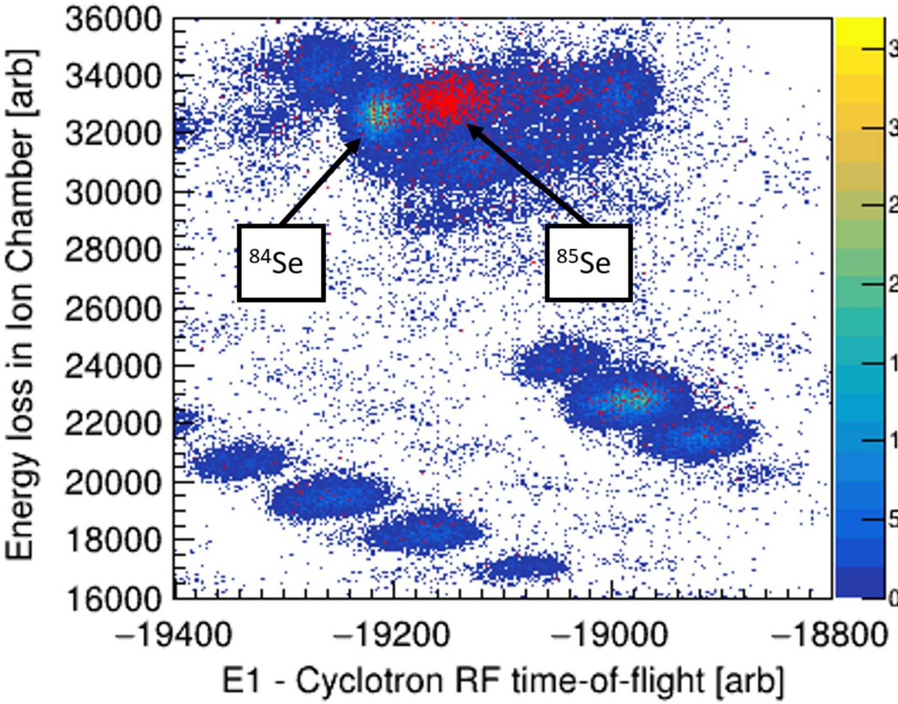


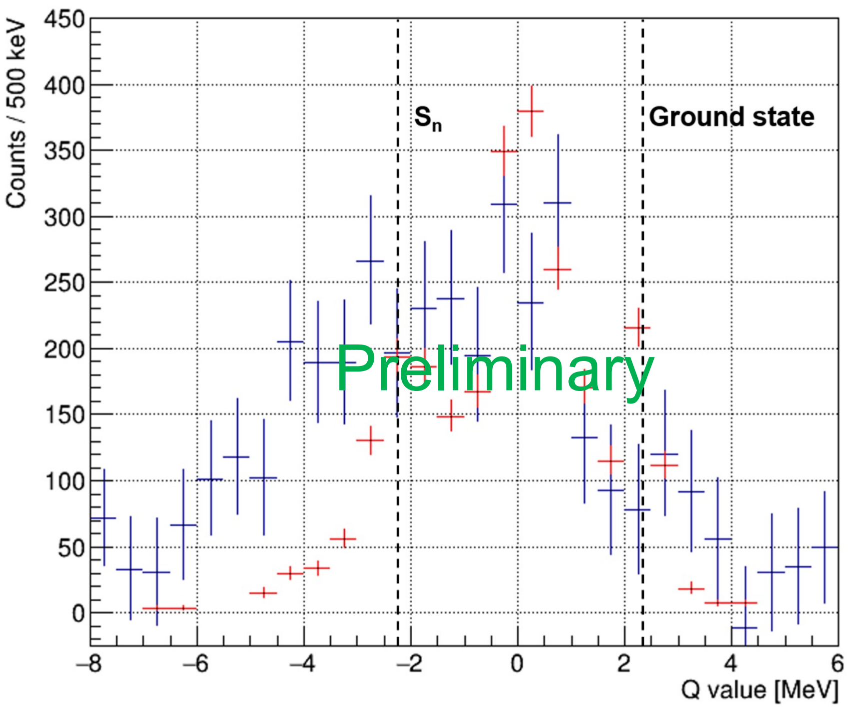




H.E. Sims, 2023

# SRM at S800 without detecting γ-rays: $P_\gamma$ from S800 coincidences

Proton-S800 coincidences

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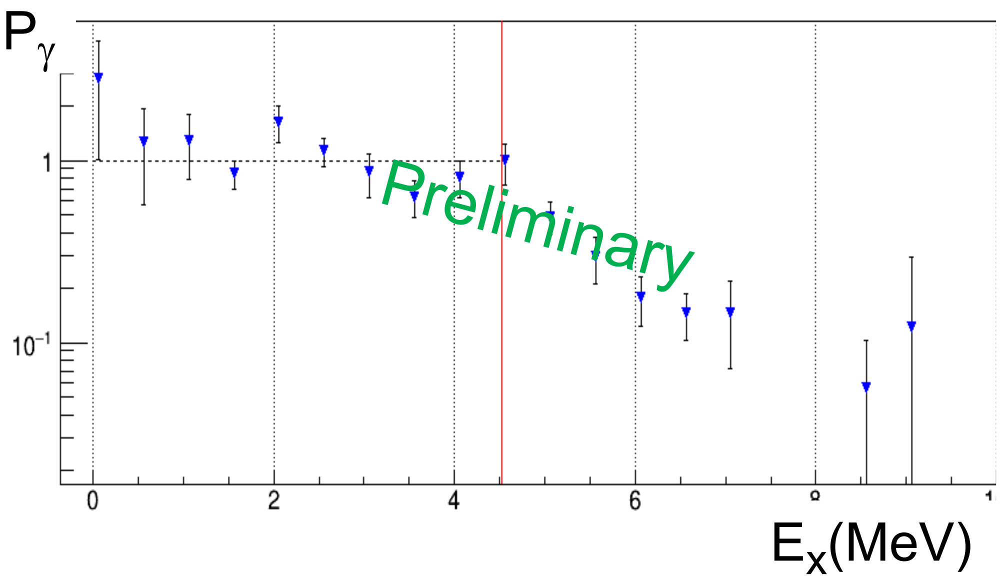
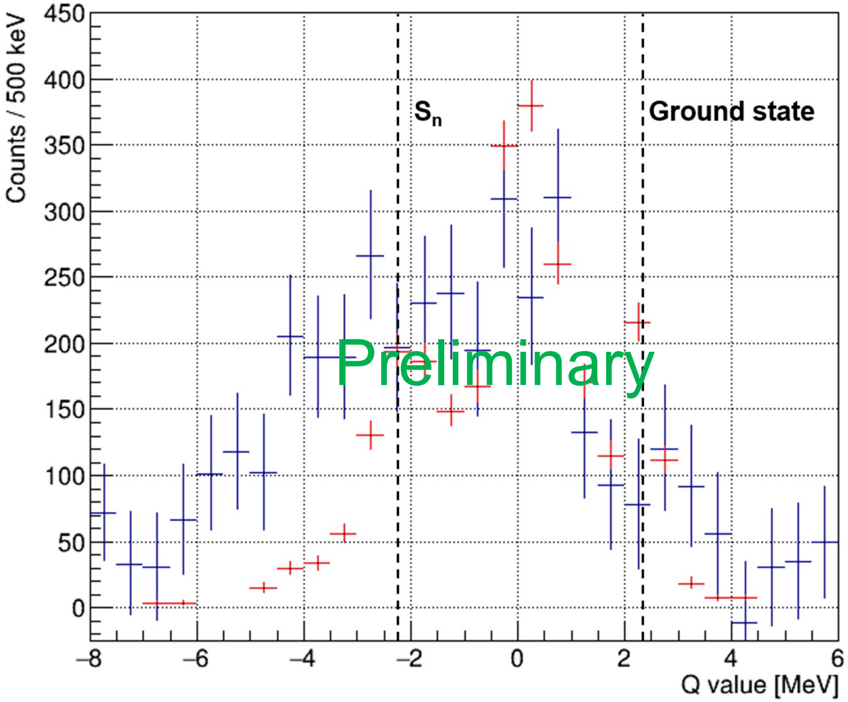


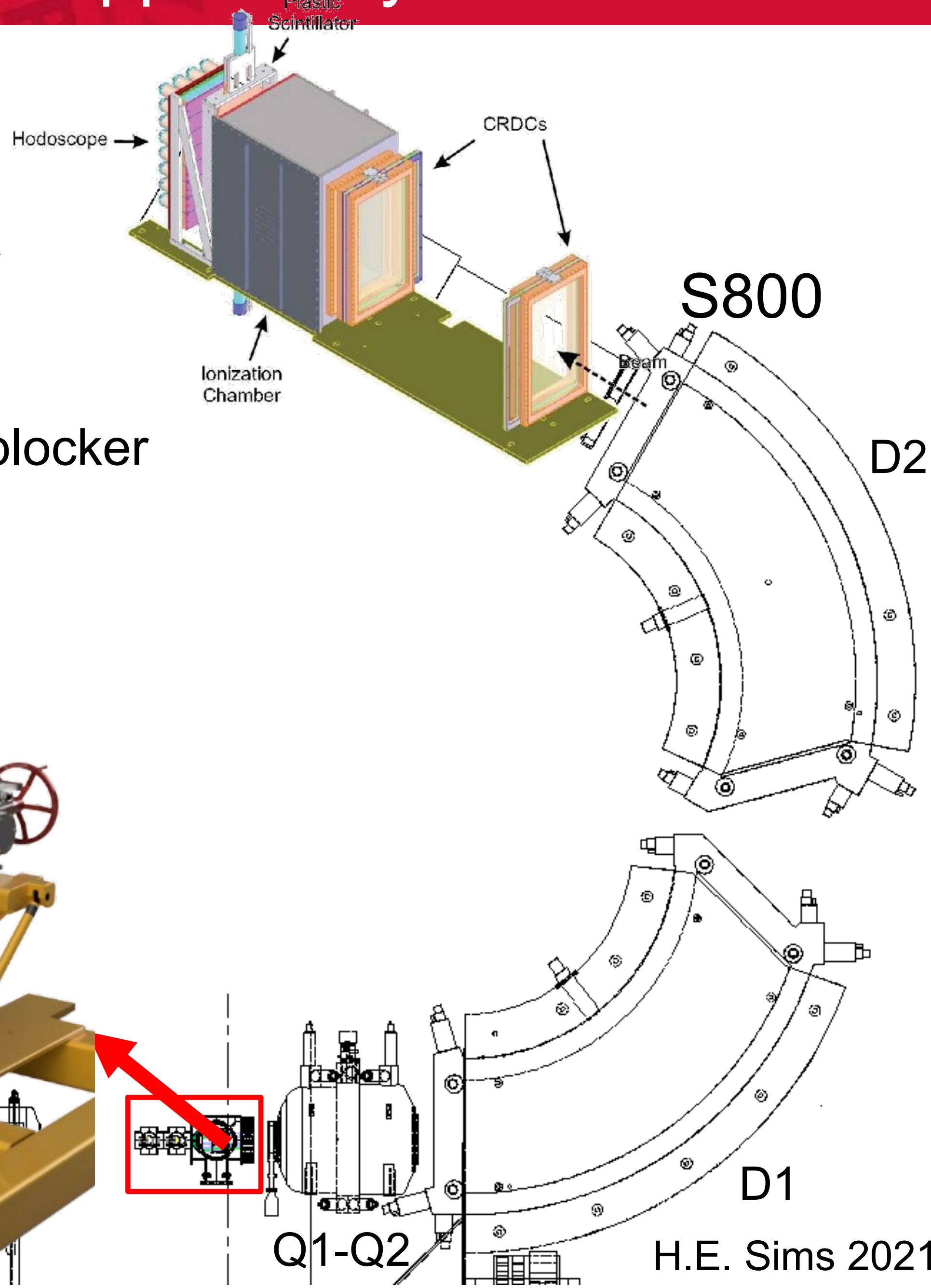



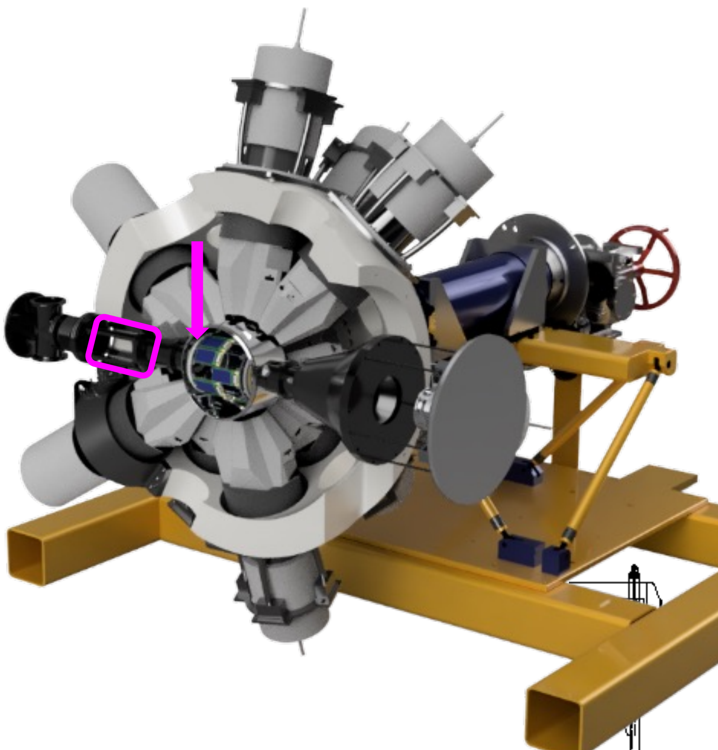



H.E. Sims, 2023

# Unique opportunity at FRIB & S800

- ORRUBA + GRETINA at S800
  - Upstream (gas) beam tracking detectors
  - New (smaller footprint) annular QQQ6 detectors
- S800 excellent PID
  - Can separate isotopes; beam blocker
- Requires $CD_2$ and $CH_2$ data



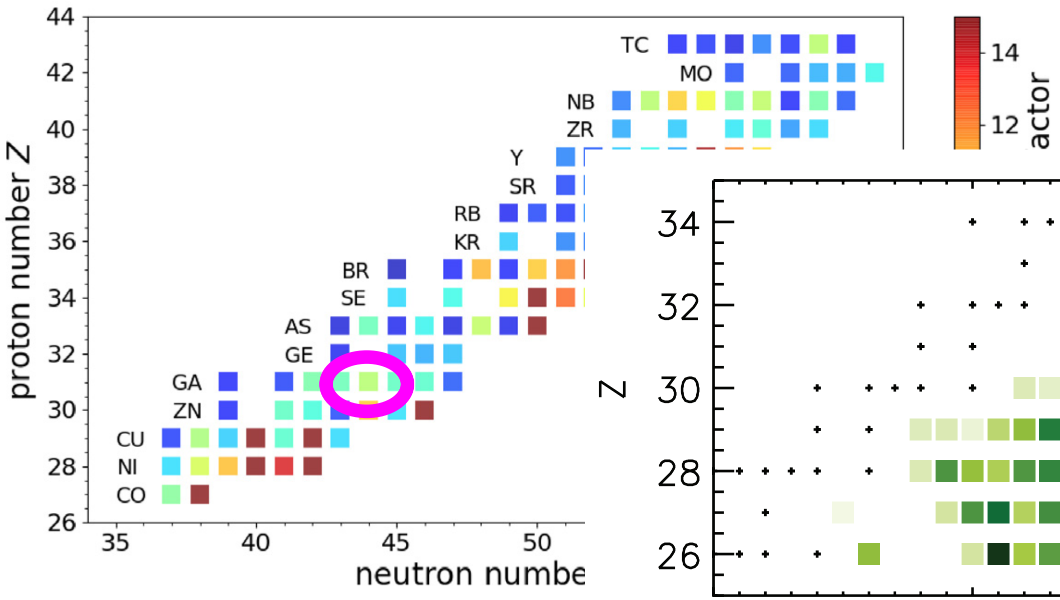



# Plans for (d,pγ): ORRUBA + GRETINA at FRIB

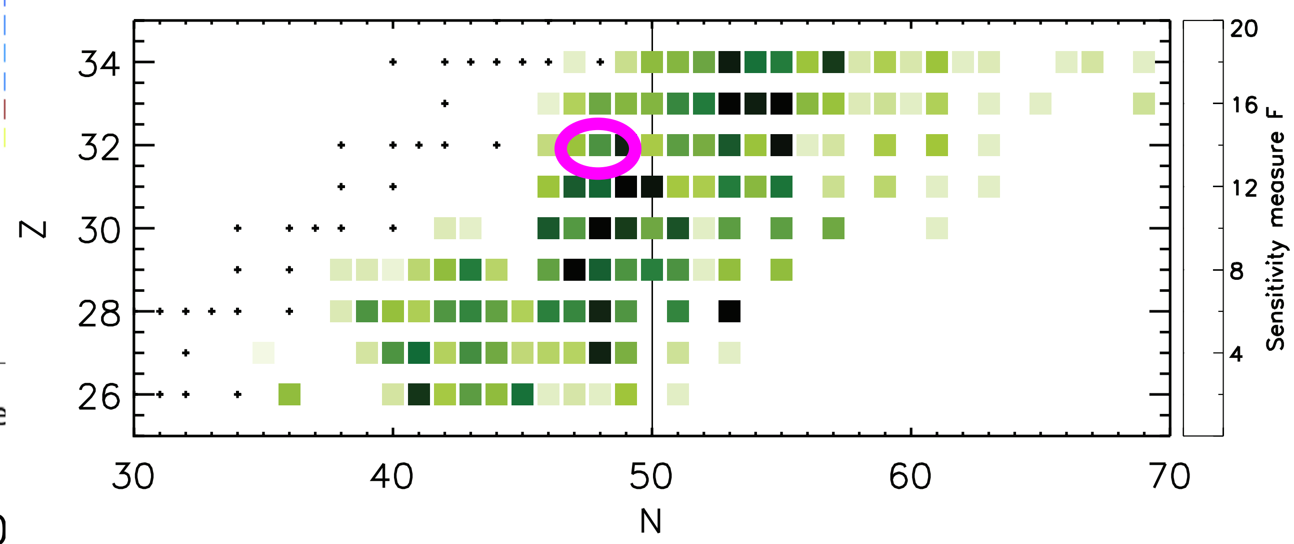
- Approved: (d,pγ) with ≈45 MeV/u $^{80}$Ge (N=48) and $^{75}$Ga beams + ORRUBA + GRETINA + S800

➢ 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)

# Summary

- (d,p) and (d,p$\gamma$) reactions inform i- and weak r- process A≈80 nucleosynthesis
- Direct-semi-direct capture near neutron closed shells
  - Measure spectroscopic factors with (d,p)
- (d,p$\gamma$) validated surrogate reaction method (SRM) for (n,$\gamma$)
  - Measure discrete gammas
  - ➢ Inform LD and $\gamma$SF => $G_{\gamma}^{CN}(E_x, J, \pi)$ => inform $\sigma$(n,$\gamma$)
- 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 $\sigma$(n,$\gamma$)
- Approved $^{80}$Ge, $^{75}$Ga(d,p$\gamma$) at FRIB

ORRUBA+GRETINA+S800

# Thank you for your attention

- (d,p) and (d,p$\gamma$) reactions inform i- and weak r- process A≈80 nucleosynthesis
- Direct-semi-direct capture near neutron closed shells
  - Measure spectroscopic factors with (d,p)
- (d,p$\gamma$) validated surrogate reaction method (SRM) for (n,$\gamma$)
  - Measure discrete gammas
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ORRUBA+GRETINA+S800

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# EXTRA SLIDES

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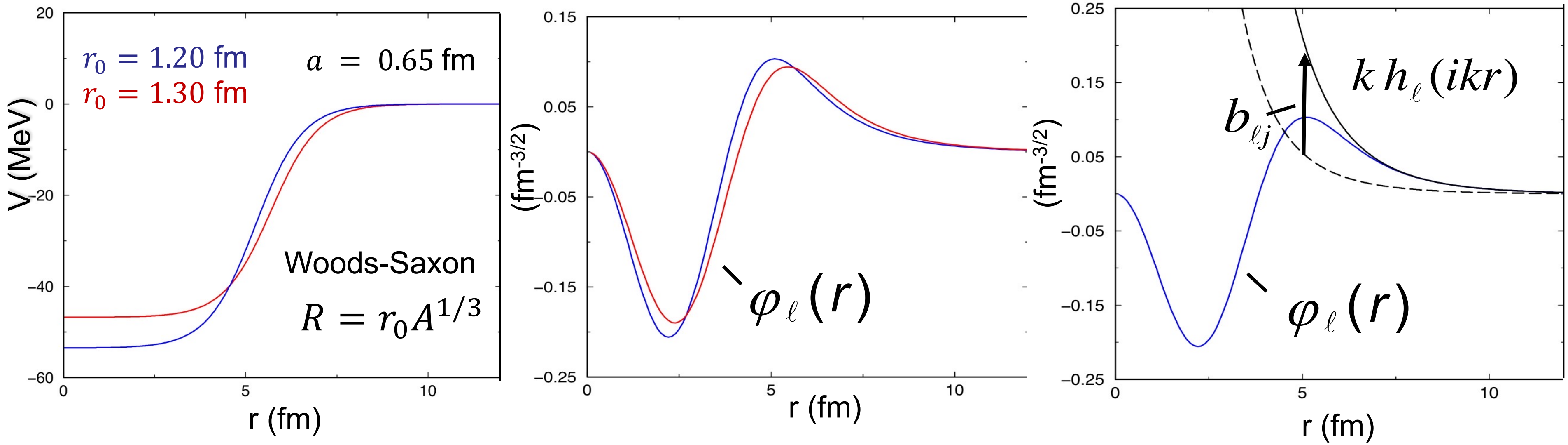
# Bound state potential & nuclear wave function




Asymptotically if wave function is pure single-particle, e.g., $2d_{5/2}$ neutron:

$$\varphi_\ell \rightarrow b_{\ell j} k h_\ell(ikr)$$

Single particle asymptotic normalization coefficient $b_{\ell j}$ reflects potential's $(r_0, a)$

But usually wave function is not a pure single-particle,

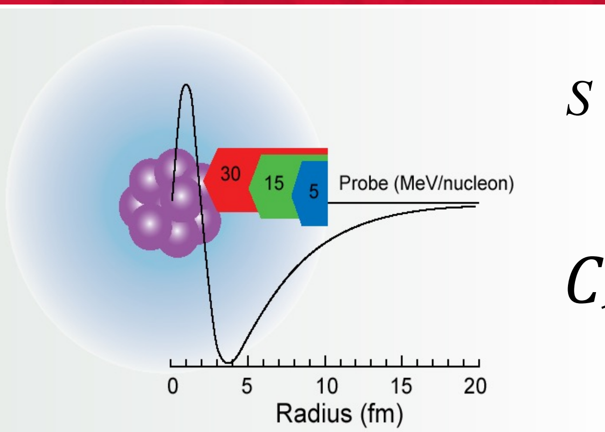
Rather overlap with a single particle w.f. $C_{\ell j} k h_\ell(ikr) = S_{\ell j}^{1/2} b_{\ell j} k h_\ell(ikr)$

Defines the nuclear ANC $\boldsymbol{C}^2$ (asymptotic normalization coefficient)

- proportional to the spANC $\boldsymbol{b}^2$
- proportionality constant $\boldsymbol{S}$, the spectroscopic factor

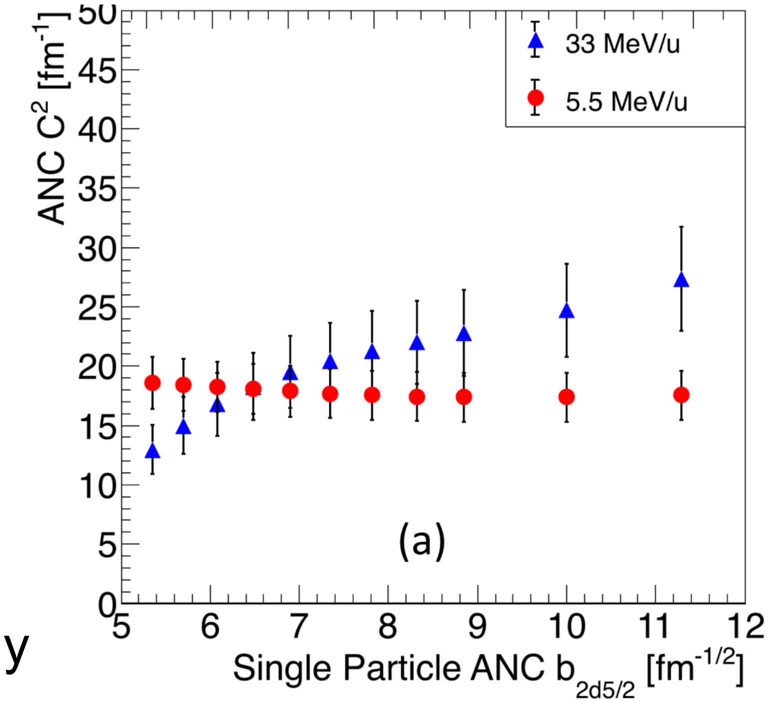
$$C_{\ell j}^2 = S_{\ell j} b_{\ell j}^2$$

# Most reactions peripheral → Combined Method




$$S = \left(\frac{d\sigma}{d\Omega}\right)^{exp} \Bigg/ \left(\frac{d\sigma}{d\Omega}\right)^{theory}$$

$$C^2_{\ell j} = S_{\ell j} b^2_{\ell j}$$




$^{86}$Kr(d,p) g.s.
D. Walter et al. PRC **99**, 054625 (2019)

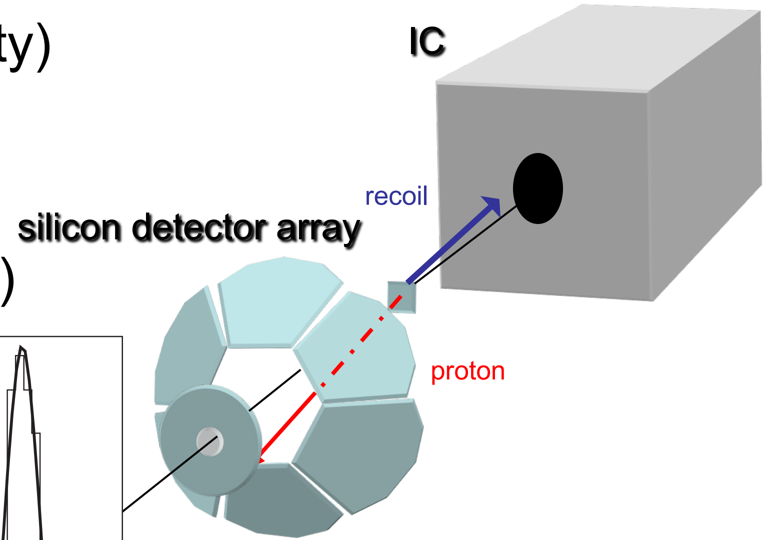
- Fix nuclear ANC ($C_{\ell j}$) using peripheral reaction (lower energy)
- Probe the nuclear interior with higher energy reaction
  - ANC is property of state NOT reaction
- Combine: Constrain single-particle ANC
- $S$ dominated by uncertainties in experimental cross-section measurement rather than uncertainties in bound state potential

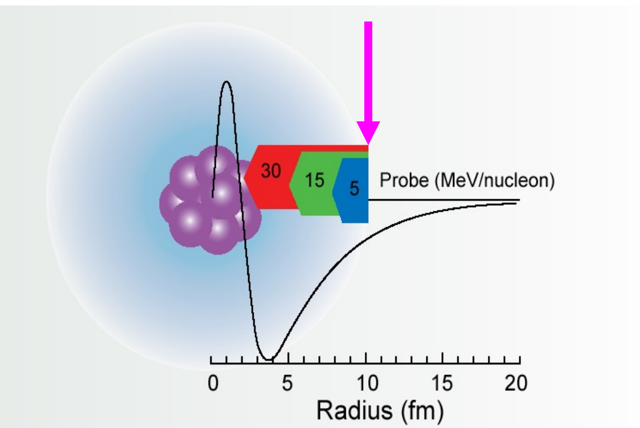
**Measure reactions at TWO different energies:**

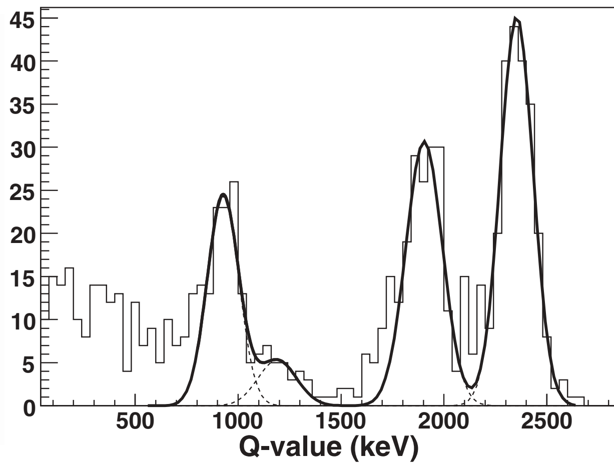
A. Mukhamedzhanov and F. Nunes, Phys. Rev. C **72**, 017602 (2005)

# (d,p) studies with 4.5 MeV/u $^{84}$Se beam

- 4.5 MeV/u at HRIBF (ORNL former facility)
  - Silicon detector array (SIDAR)
  - Ion chamber recoil detector
  - J.S. Thomas et al. PRC **76** 044302 (2007)



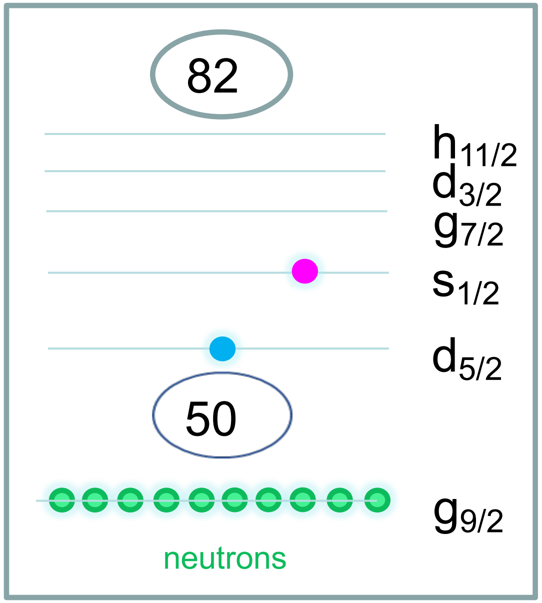

| $E_x$ (MeV) | $J^\pi$ | $\ell$ | $C^2_{\ell j}$ |
| --- | --- | --- | --- |
| 0.000 | 5/2+ | 2 | 6.11±1.43 |
| 0.462 | 1/2+ | 0 | 25.3±5.9 |

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

- 4.5 MeV/u at HRIBF
- 45 MeV/u at NSCL

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

- $^{85}$Se states: 2d5/2 and 3s1/2
- Probes different parts of wave function
  - Low energy = peripheral (only tail)
  - Higher energy = less peripheral (more interior)




Excitations in $^{85}$Se

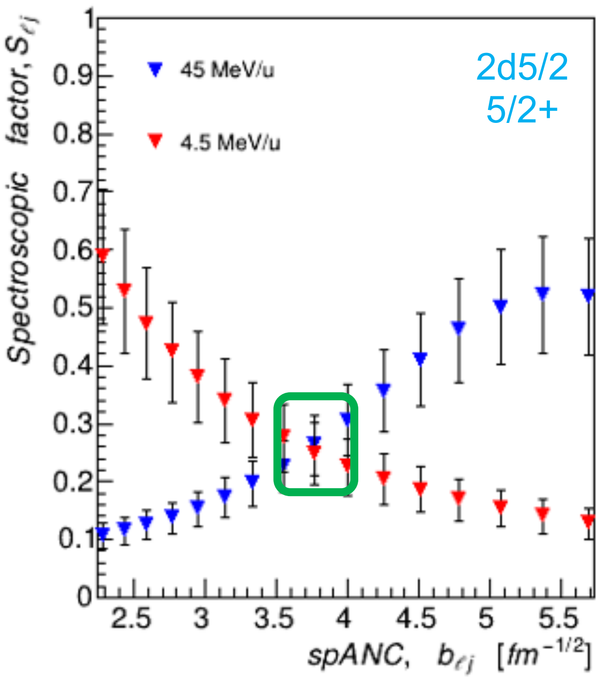
- FR-ADWA cross sections with FRESCO
  - Includes deuteron b/up (Johnson-Tandy)
  - Global optical model potentials
    - Koning-Delaroche
  - Bound state parameters for the transferred neutron
    - $R = r_0 A^{1/3}$  diffuseness $a$  Woods-Saxon potential
  - Wave function of transferred particle, e.g., $2d_{5/2}$ neutron

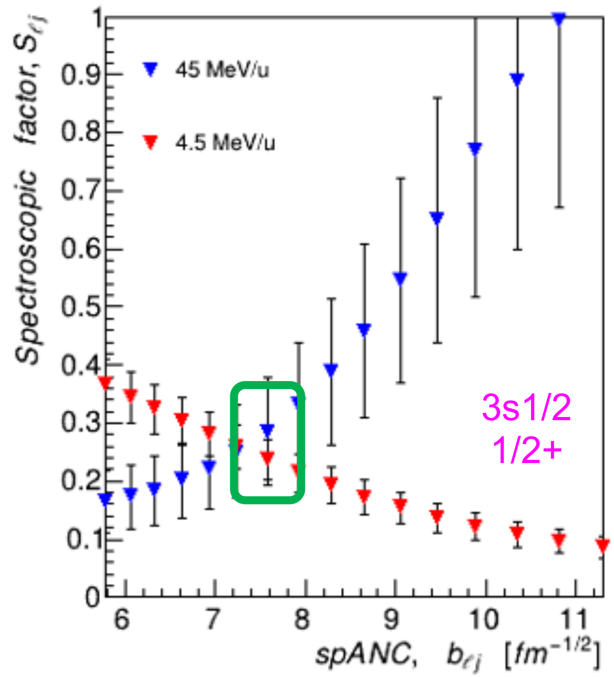
H.E. Sims PhD Dissertation (2020)
H.E. Sims, D. Walter et al., in preparation for PRC (2023)

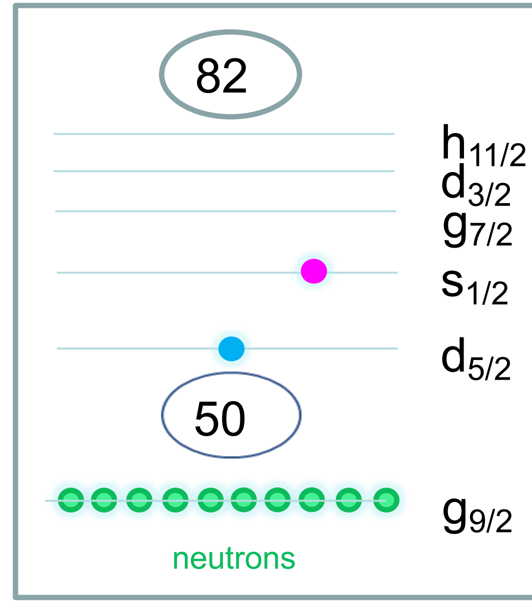
# (d,p) studies with 4.5 MeV/u & 45 MeV/u $^{84}$Se beams

- 4.5 MeV/u at HRIBF
- 45 MeV/u at NSCL
- spANC ↔ unknown Woods-Saxon potential $(r_0, a)$
- $S$ is property of state, independent of reaction

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




Excitations in $^{85}$Se

$$C_{\ell j}^2 = S_{\ell j} b_{\ell j}^2$$

| | | |
|---|---|---|
| $5/2^+$ $E_x = 0$ | $S = 0.28\ (4)$ | $r_0 = 1.14^{+.04}_{-.06}$<br>$a = 0.59^{+.02}_{-.03}$ |
| $1/2^+$ $E_x = 0.462$ MeV | $S = 0.26\ (6)$ | $r_0 = 1.16^{+.06}_{-.09}$<br>$a = 0.60^{+.04}_{-.04}$ |

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