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Informing direct neutron capture for the weak r-process via the (d,p) reaction with ^{84}Se beams at two energies

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Direct Reactions with Exotic Beams 2022

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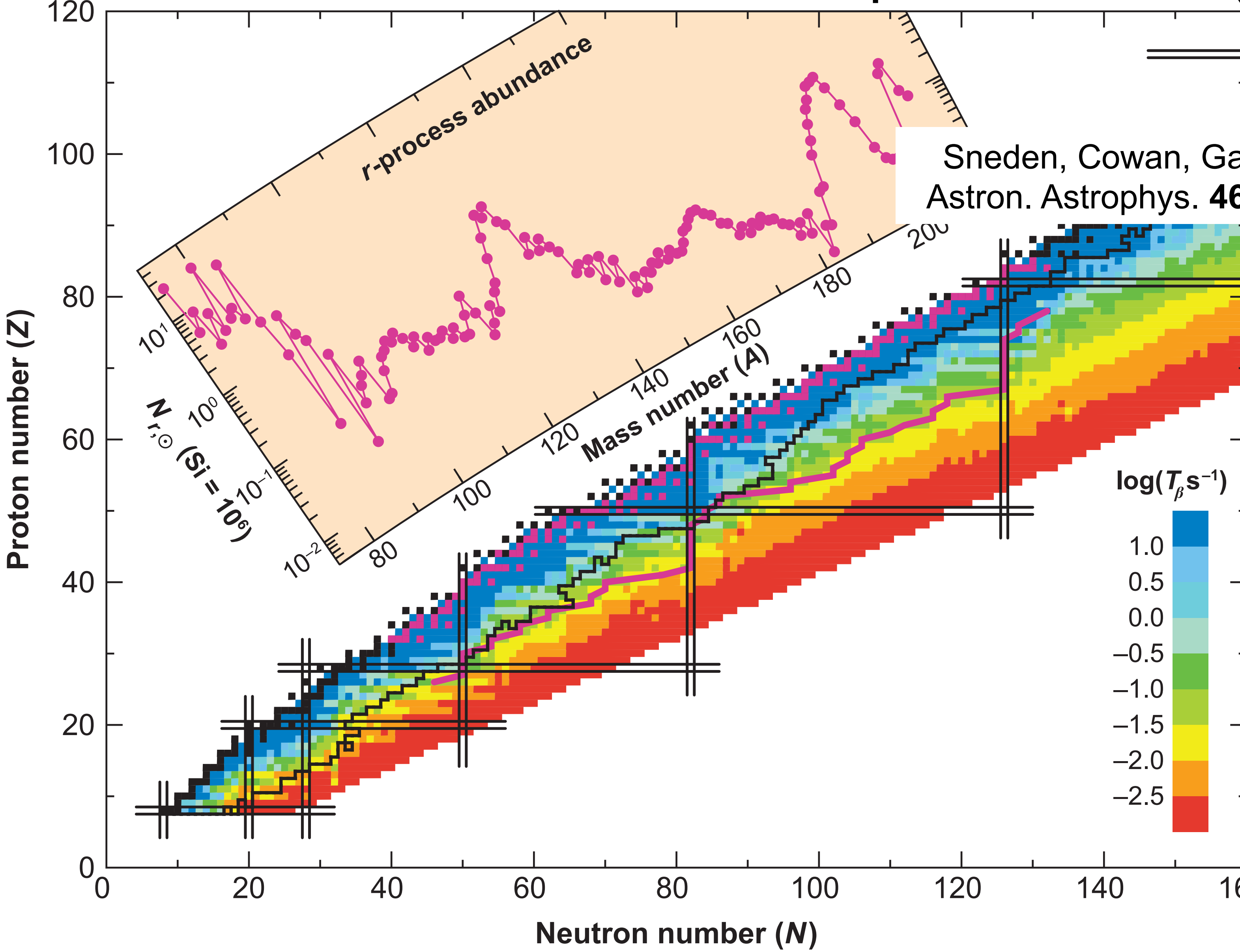
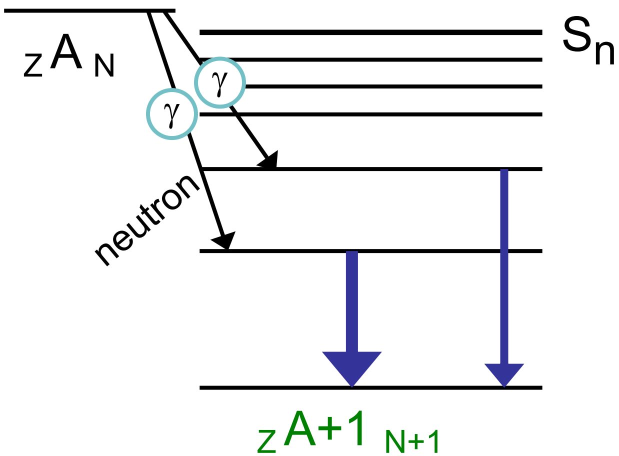
r-process nucleosynthesis
and dependence on (n,γ) rates

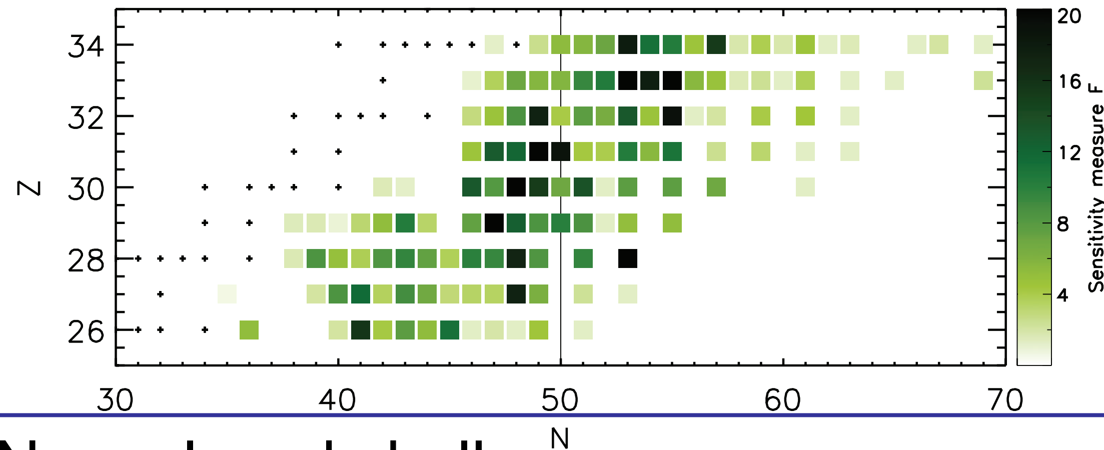


Sneden, Cowan, Gallino, Annu. Rev. Astron. Astrophys. **46**:241-288 (2008)

(d,p) reactions & the r process

Direct-semi-direct
Near waiting points
(n,γ)





Near closed shells

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

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

(weak) *r*-process N≈50, A≈80 (n,γ) sensitivities
(freeze-out from hot process)

R. Surman, M. Mumpower, R. Sinclair, K. L. Jones, W. R. Hix, and G. C. McLaughlin, AIP Advances **4**, 041008 (2014)

(d,p) cross sections & spectroscopic factors

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

Theoretical reaction cross section with FRESCO

Finite Range-ADiabatic Wave Approximation (FR-ADWA)

- 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

Spectroscopic factors valid from peripheral reactions?

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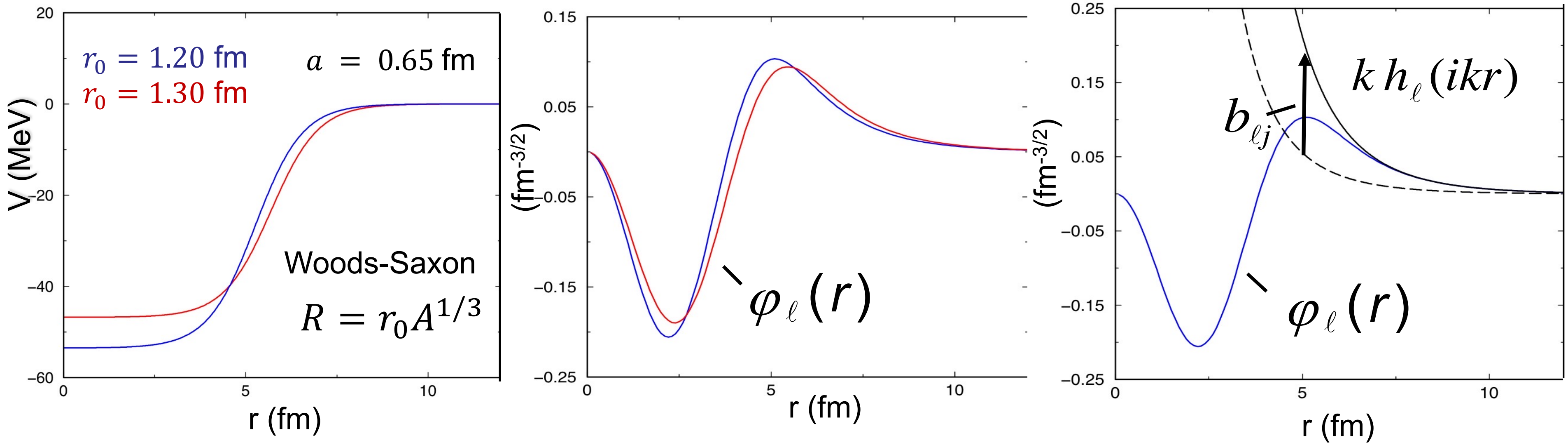
Bound state potential & nuclear wave function



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

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

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)

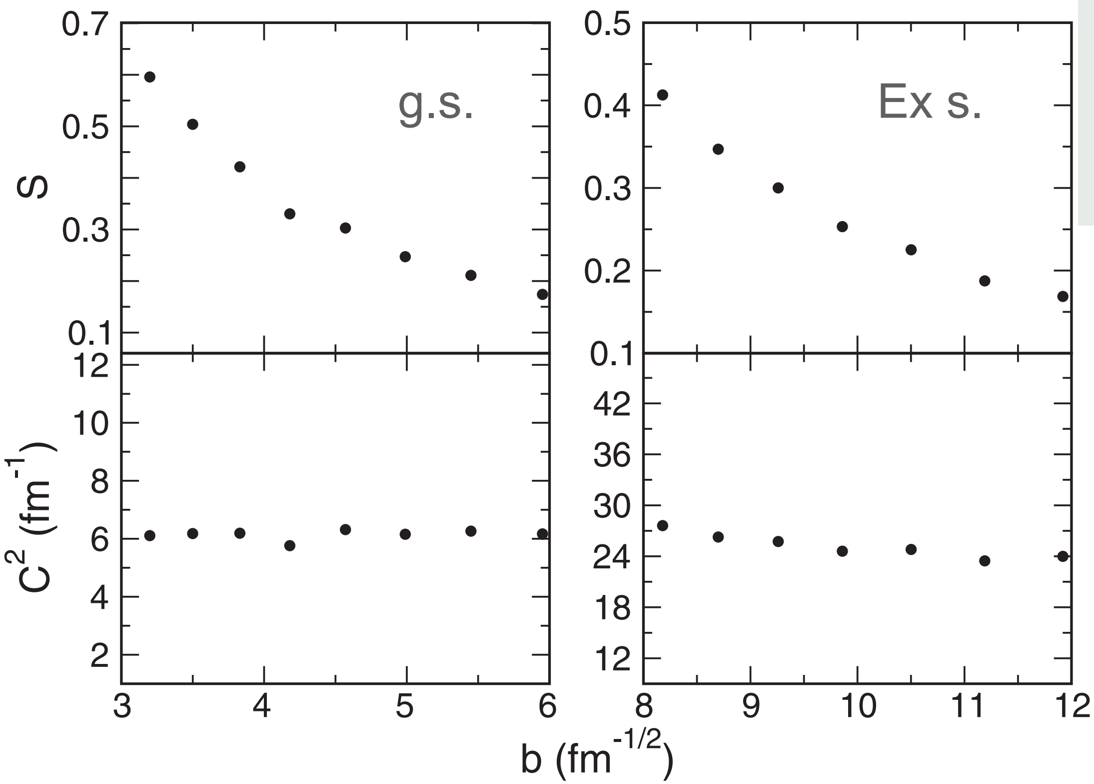
- proportional to the spANC $\boldsymbol{b}^2$
- proportionality constant $\boldsymbol{S}$, the spectroscopic factor

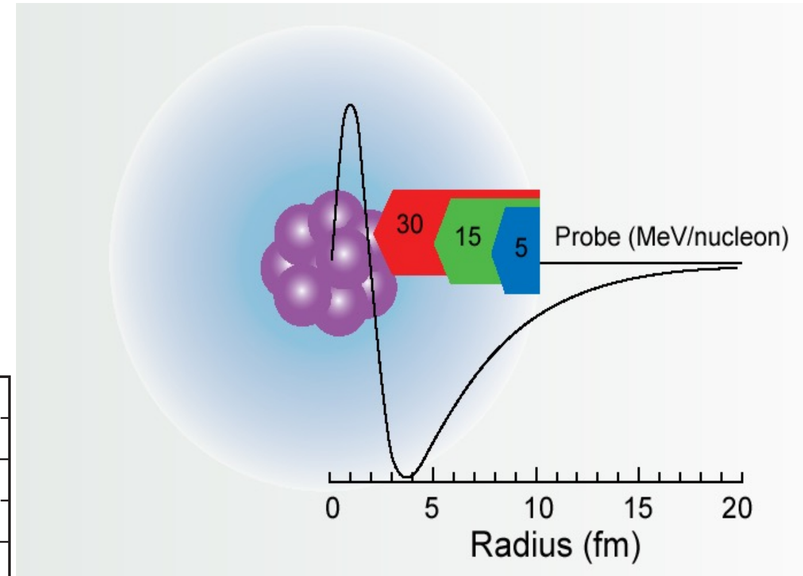
$$C_{\ell j}^2 = S_{\ell j} b_{\ell j}^2$$

Most reactions are peripheral

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

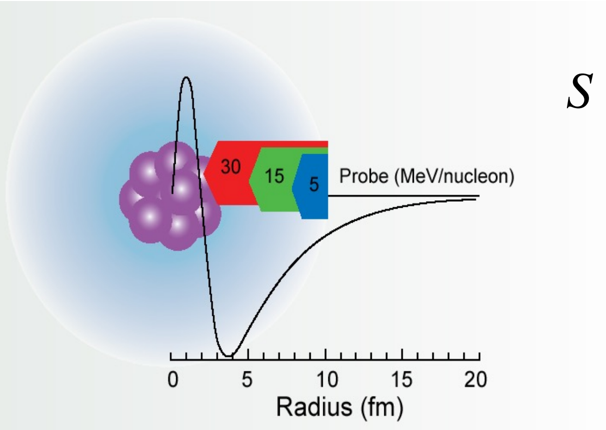
$$C_{\ell j}^2 = S_{\ell j}\, b_{\ell j}^2$$





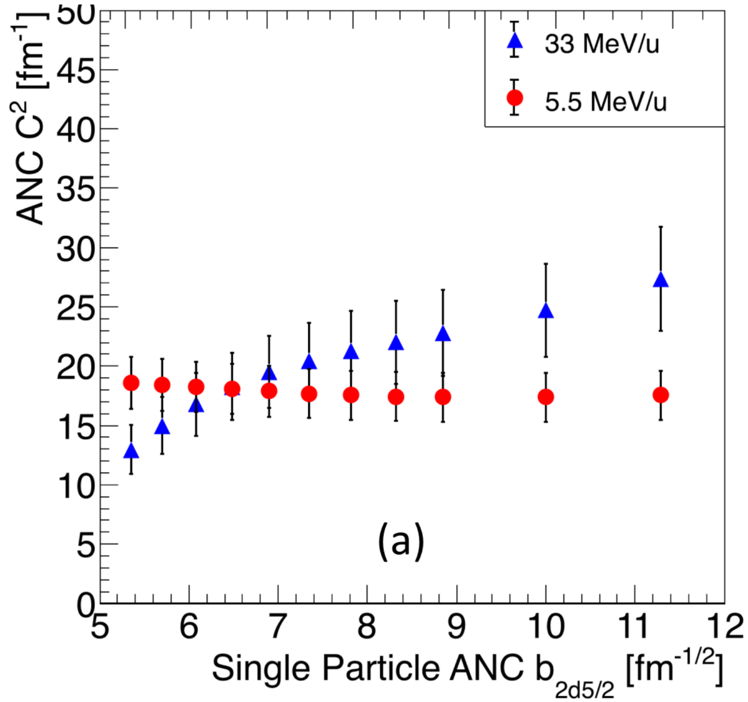
$^{84}Se(d,p)$ at 4.5 MeV/u; J.S. Thomas et al. PRC **76**, 044302 (2007)

Most reactions peripheral → Combined Method



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

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



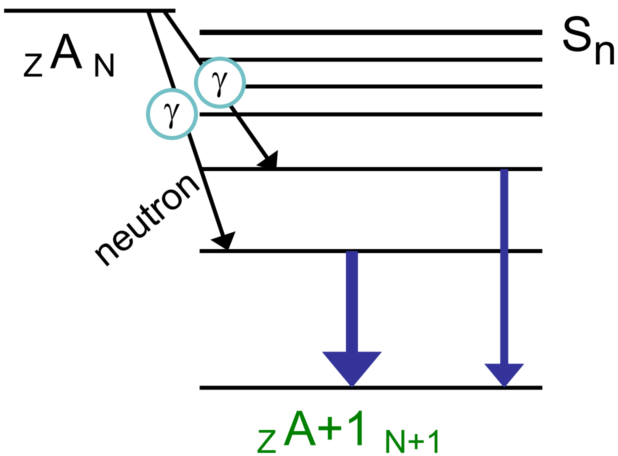
^{86}Kr(d,p) g.s.
D. Walter et al. PRC **99**, 054625 (2019)

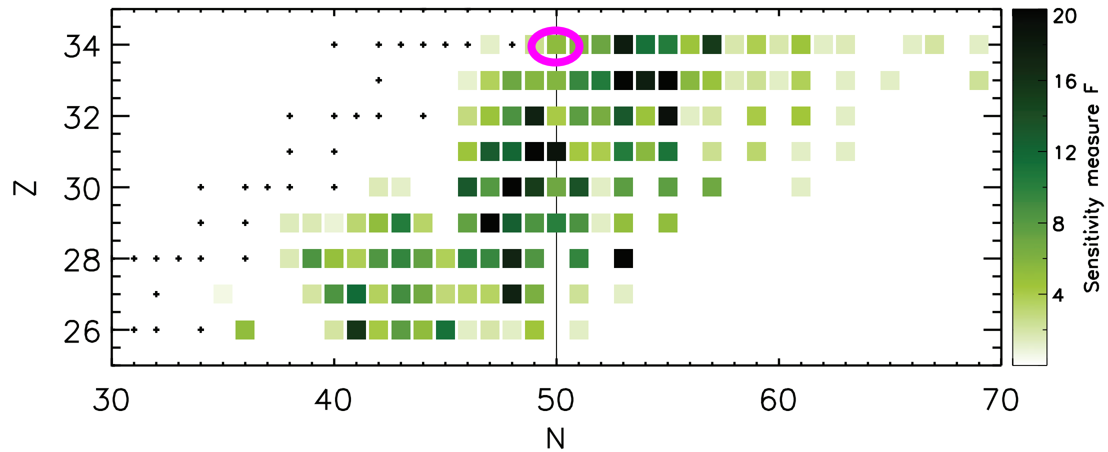
- Fix nuclear ANC ($C_{\ell j}$) using peripheral reaction (lower energy)
- Probe the nuclear interior with higher energy reaction
  - ANC is property of state NOT reaction
- Constrain single-particle ANC
- S dominated by uncertainties in the experimental cross-section measurement rather than uncertainties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

Measure reactions at TWO different energies:
A. Mukhamedzhanov and F. Nunes, Phys. Rev. C **72**, 017602 (2005)

(d,p) reactions & the r process

Direct-semi-direct
Near waiting points
(n,γ)





Measure (d,p) reaction with ^{84}Se ($t_{1/2} \approx 3$ m) beams

Reduce uncertainties in theory

- Measure reaction at 2 different energies
- Extract S with uncertainties dominated by exp rather than theory

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

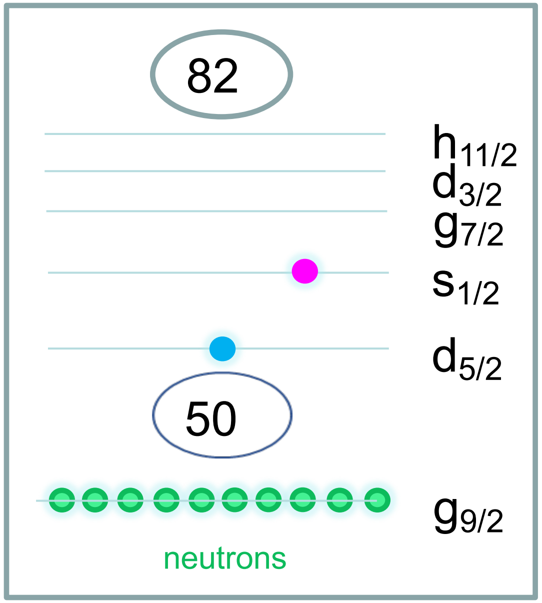
R. Surman et al., AIP Advances **4**, 041008 (2014)

(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)



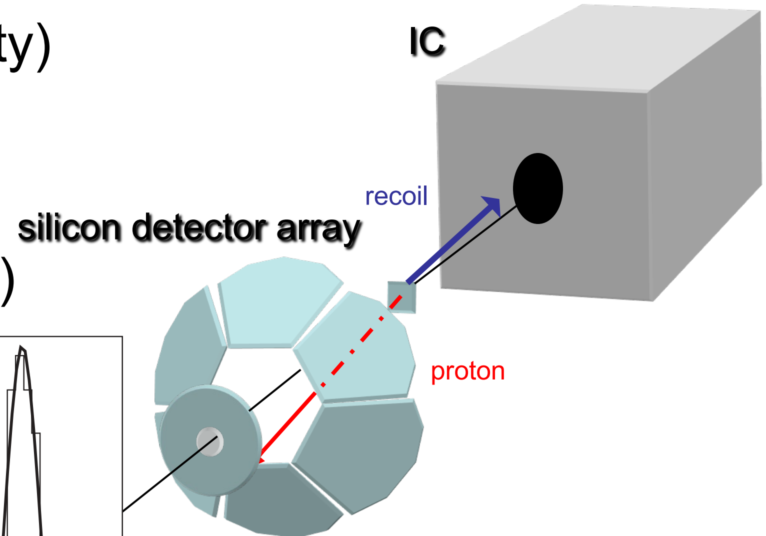
Excitations in ^{85}Se

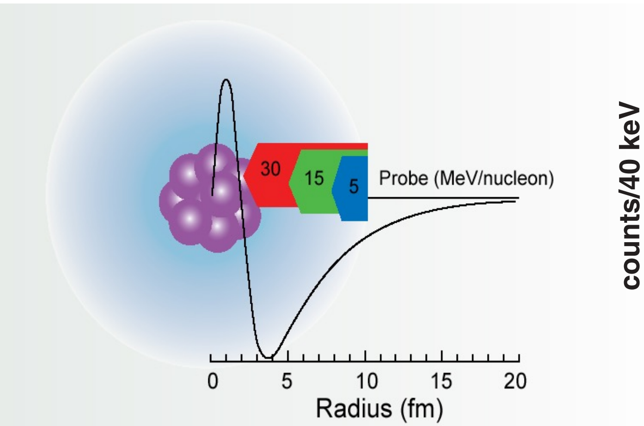
- FR-ADWA cross sections with FRESCO
  - Includes deuteron b/up (Johnson-Tandy)
  - Global optical model potentials
    - Koning-Delaroche
  - Bound state parameters for the transferred neutron
    - $R = r_0 A^{1/3}$ diffuseness a Woods-Saxon potential
  - Wave function of transferred particle, e.g.,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

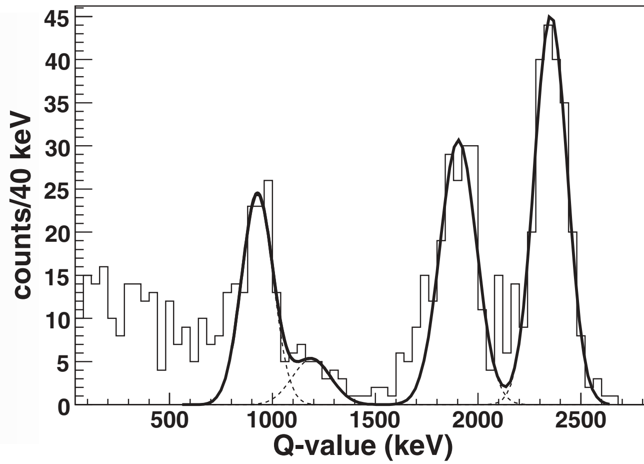
H.E. Sims PhD Dissertation (2020)
H.E. Sims, D. Walter et al., in preparation for PRC (2022)

(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)

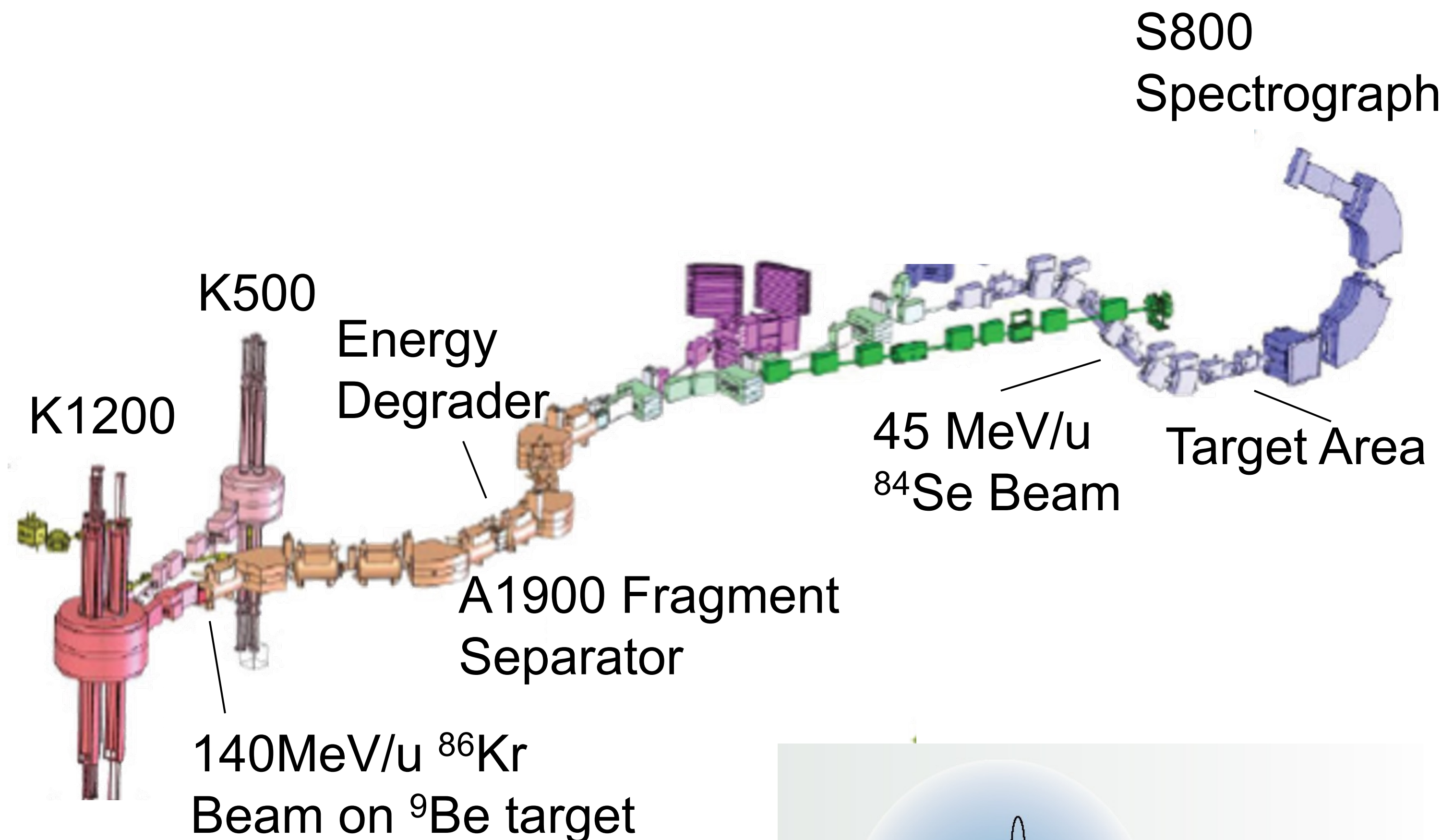






E_x (MeV)	J^{π}	ℓ	$C^2_{\ell j}$	$S_{\ell j}$ (DWBA)
0.000	5/2+	2	6.11±1.43	0.33±0.10
0.462	1/2+	0	25.3±5.9	0.30±0.09
1.115	(3/2+)	(2)	(0.42±0.11)	(0.06±0.02)
	(7/2+)	(4)	(0.049±0.012)	(0.77±0.27)
1.438+1.444				

^{84}Se(d,p)^{85}Se at 45 MeV/u



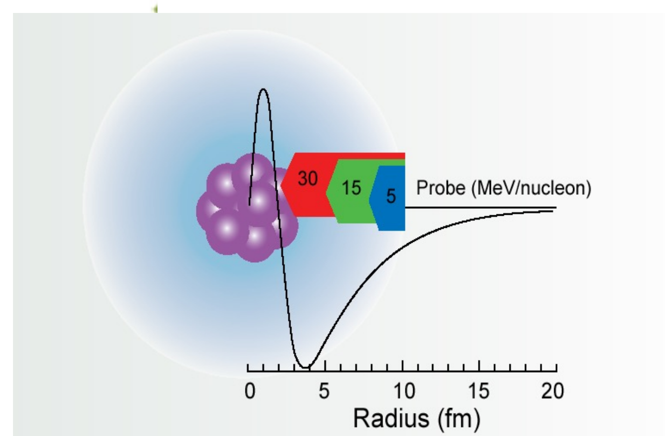
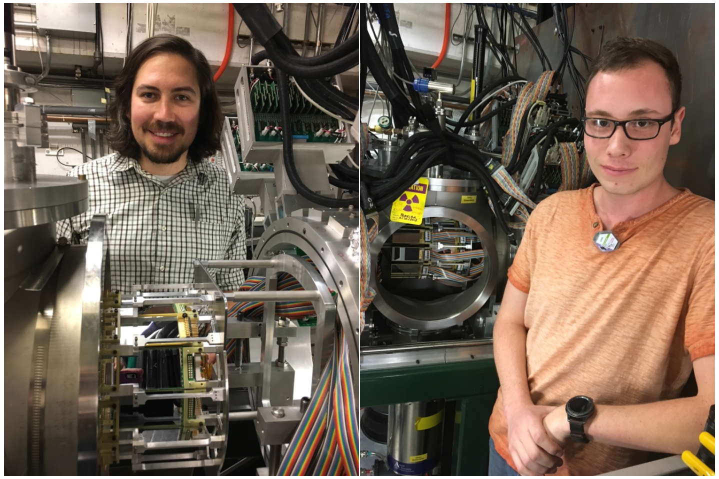
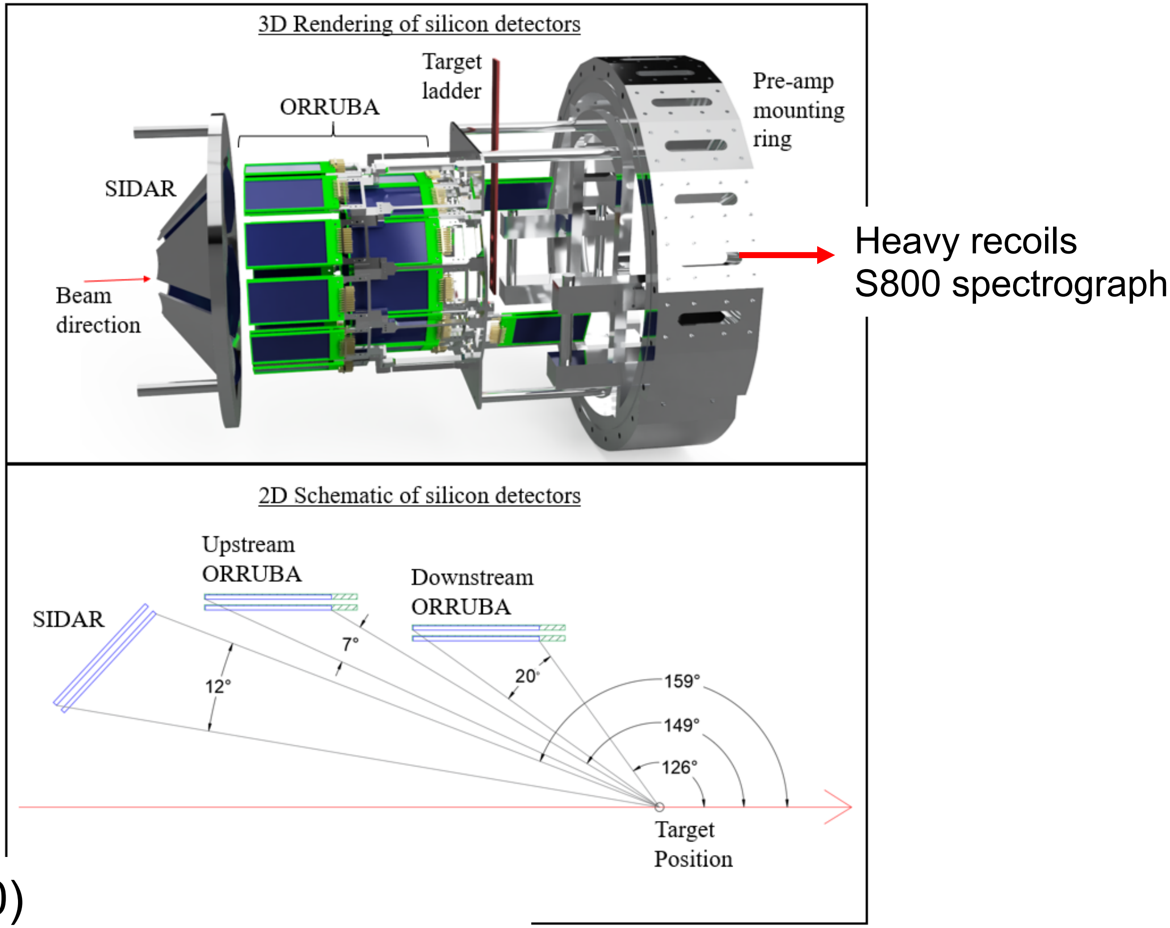


Figure from: http://www.nscl.msu.edu/

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

- 45 MeV/u at NSCL + 1.2 mg/cm^2 CD_2 target
  - SIDAR
  - Oak Ridge Rutgers University Barrel Array (ORRUBA)
    - Upstream of the target





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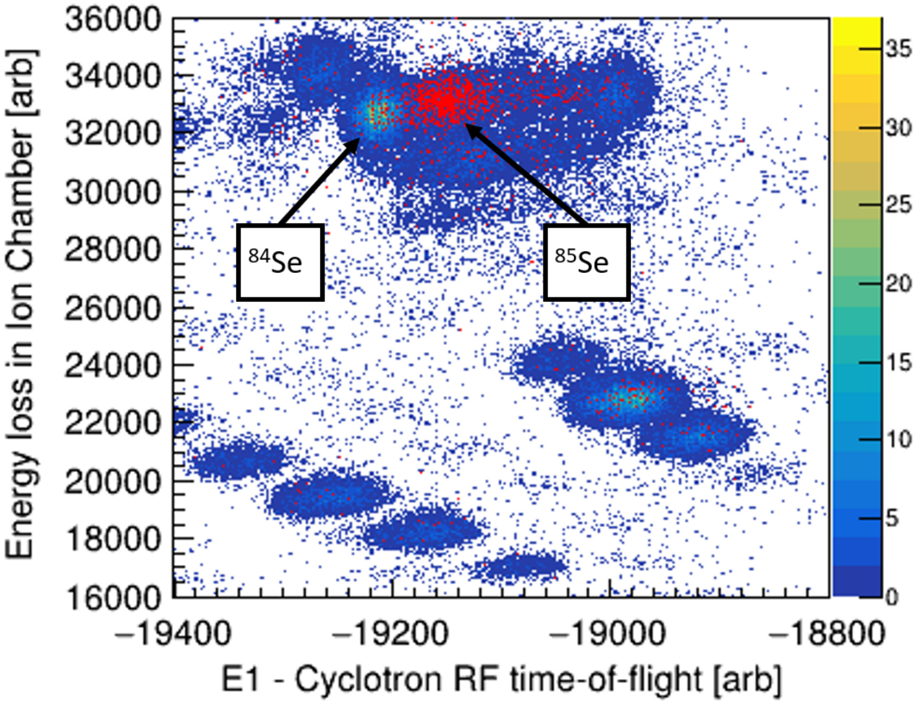
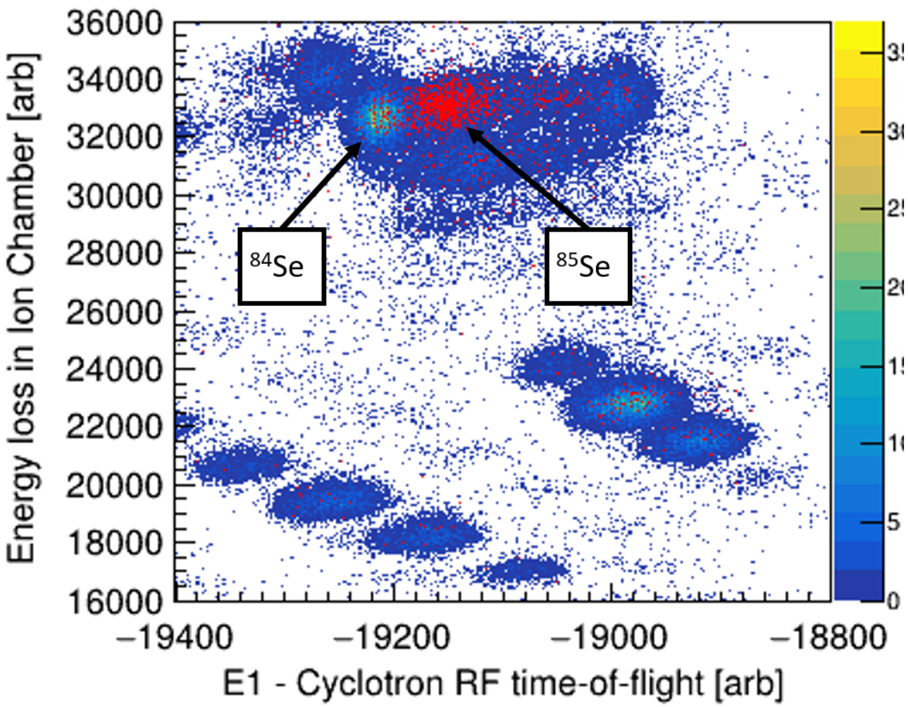
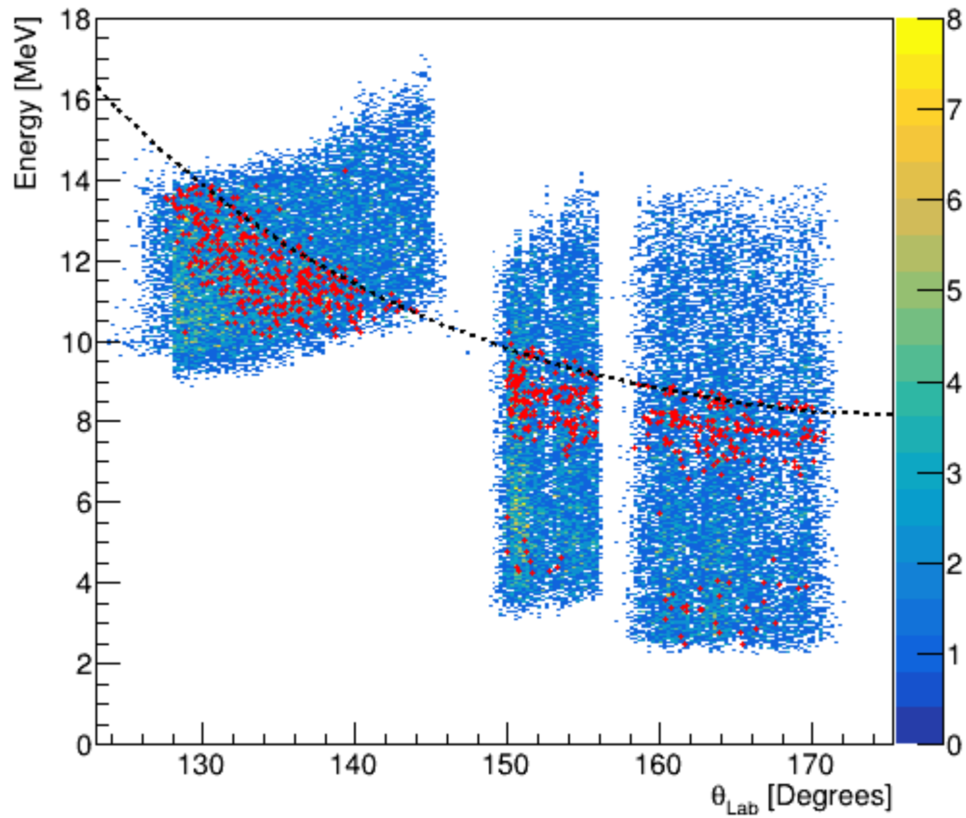
S800 beam-like recoil detection critical



- Gating on protons in SIDAR & ORRUBA
  - identify ^{85}Se recoils vs ^{84}Se beam

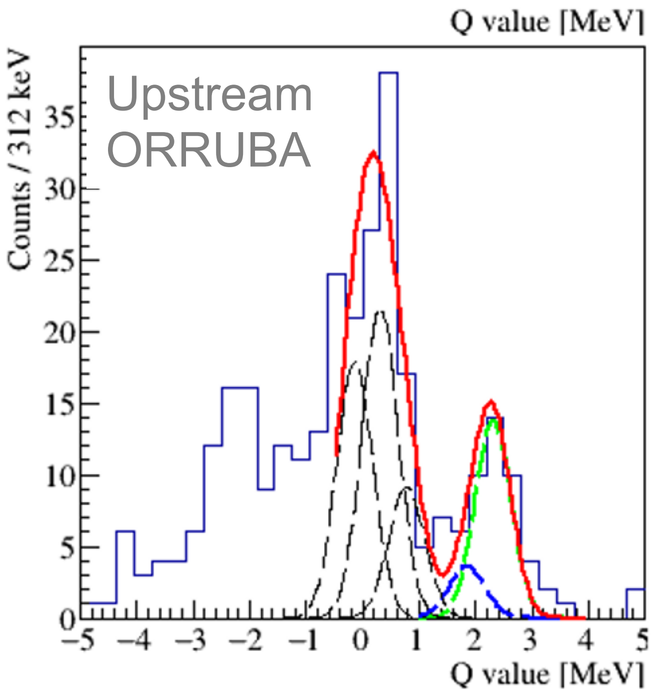
S800 beam-like recoil detection critical

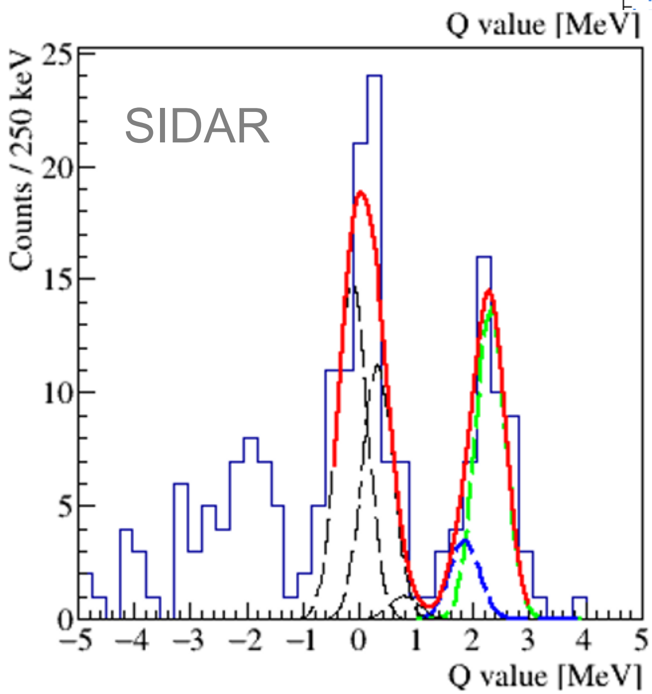


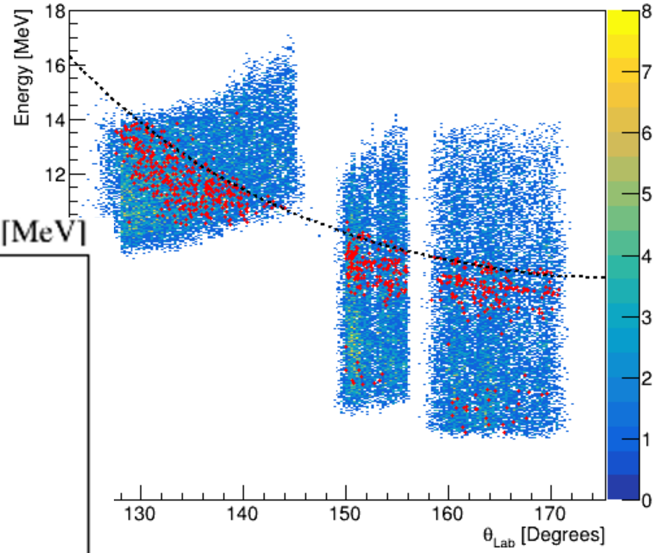


- Gating on ^{85}Se in S800
- ➢ (d,p) protons in SIDAR & ORRUBA

Q-value spectra for ^{85}Se

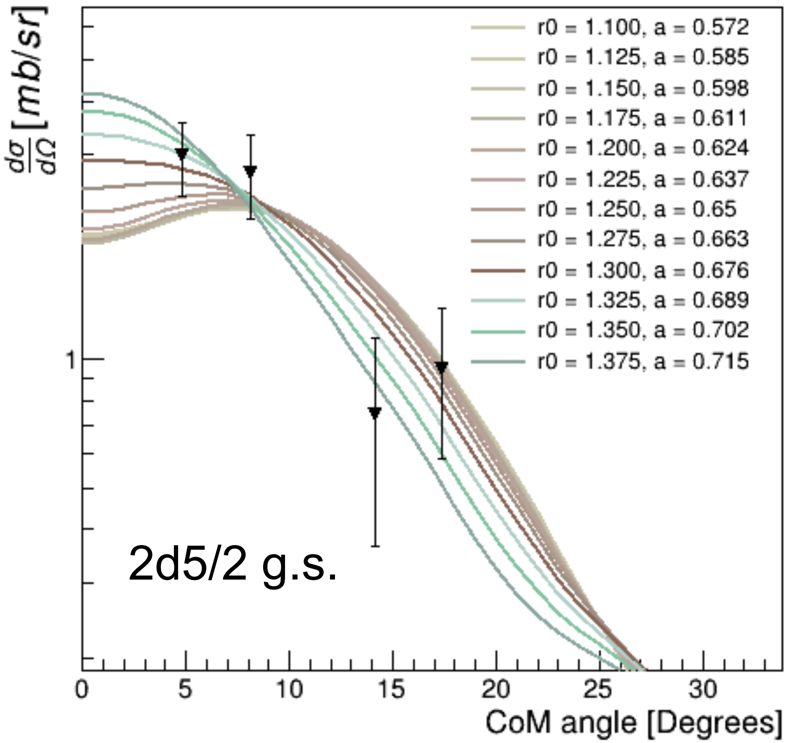


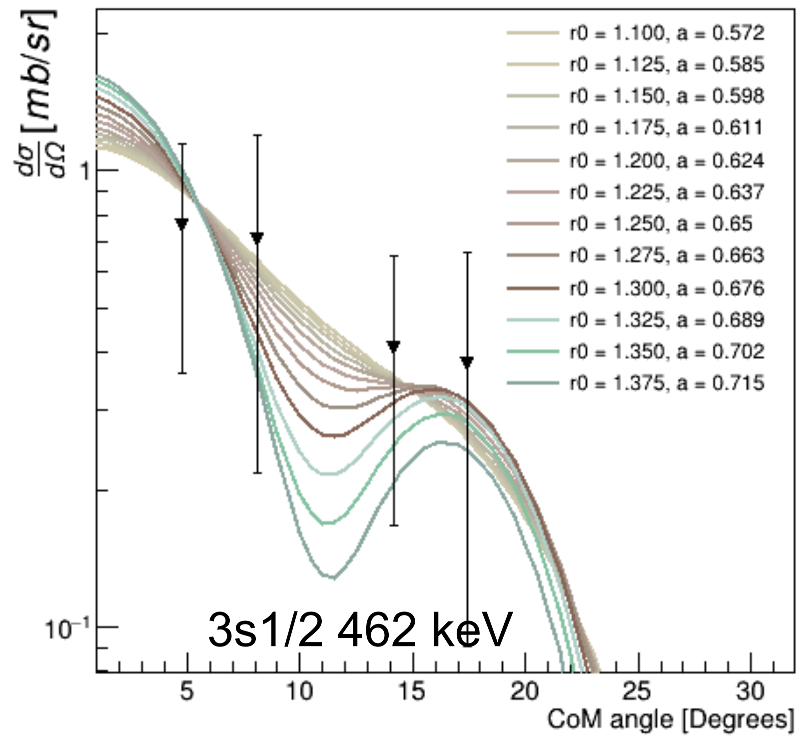




Q-value spectra vs angle

45 MeV/u Angular distributions & FR-ADWA





- Fit 4-point angular distributions with range of bound state parameters $(r_0, a) \leftrightarrow$ range of spANC $b_{\ell j}$

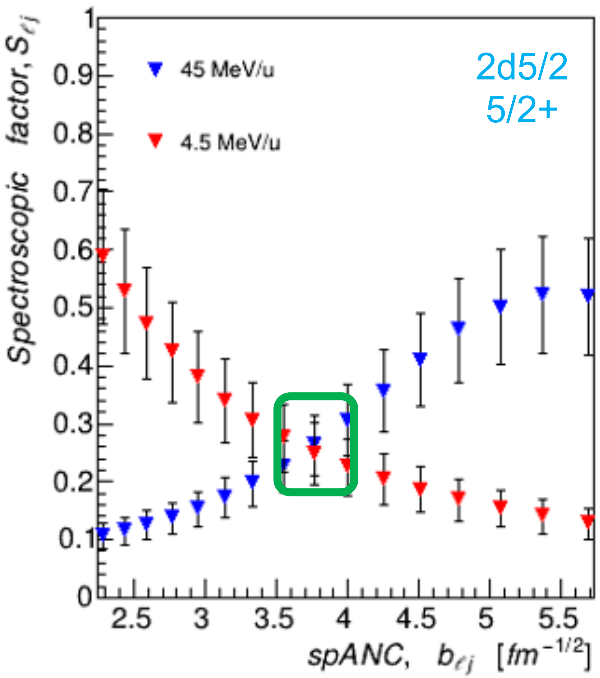
➢ For each fit: deduce S and $C_{\ell j}^2 = S b_{\ell j}^2$

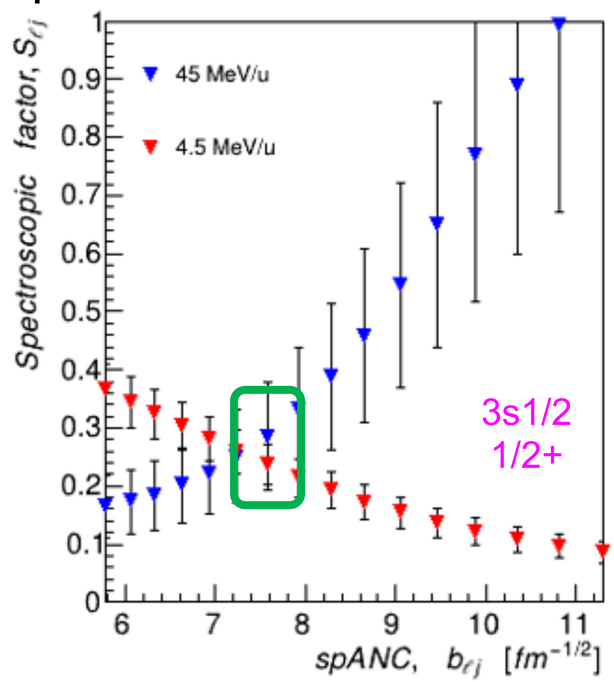
- Repeat for 4.5 MeV/u data

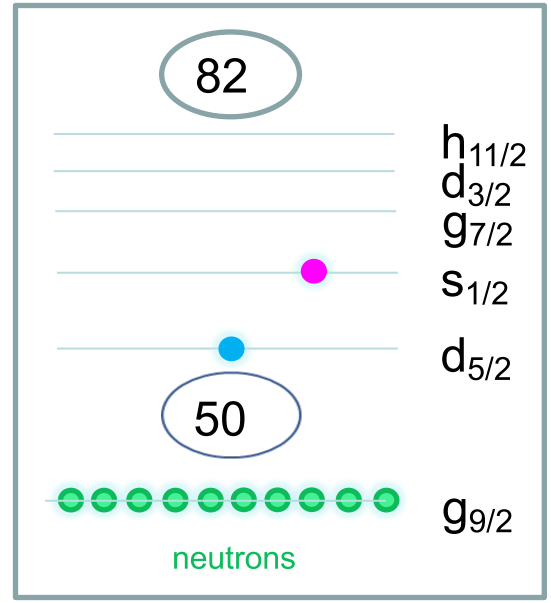
(d,p) studies with 4.5 MeV/u & 45 MeV/u ^{84}Se beams

- 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

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

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

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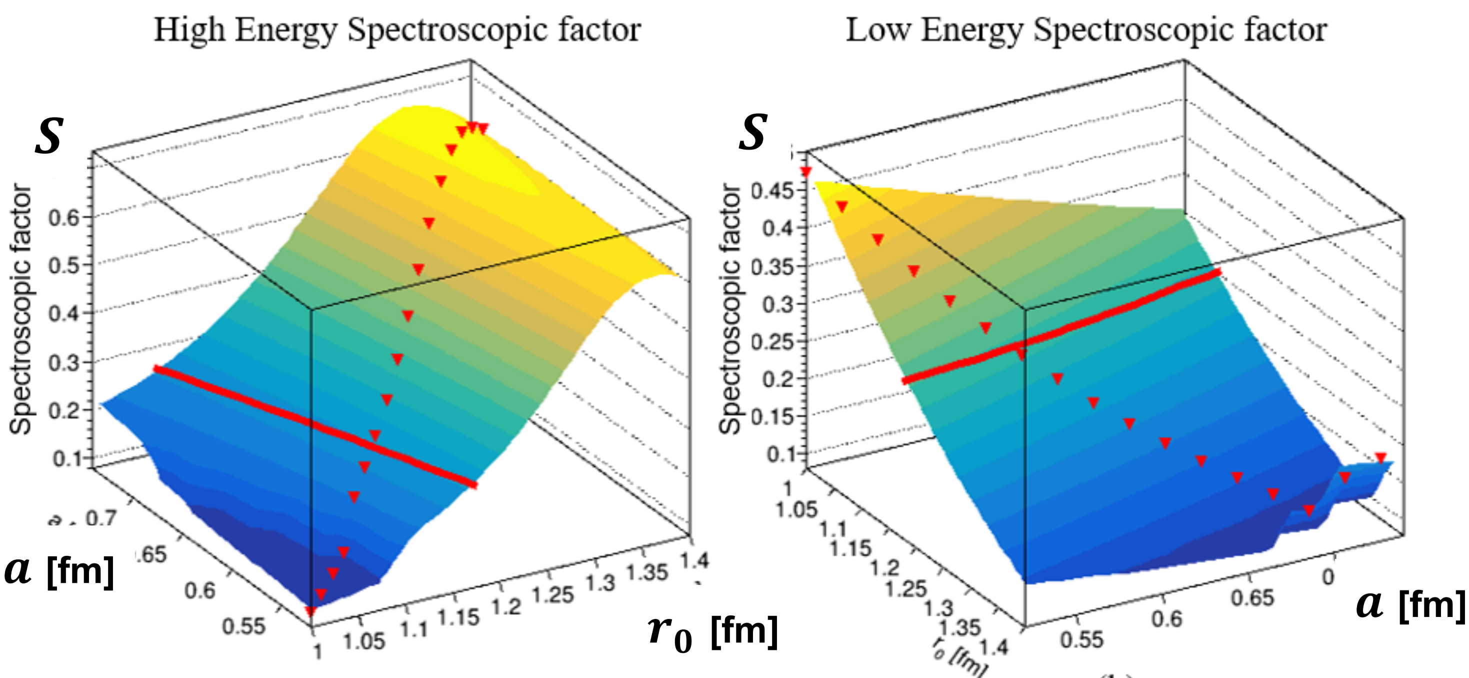
(d,p) studies with 4.5 MeV/u & 45 MeV/u ^{84}Se beams

- 4.5 MeV/u at HRIBF
- 45 MeV/u at NSCL
- S is property of state, independent of reaction
- While spANC constrained NOT (r_0, a) Woods-Saxon potential



(a) (b)

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

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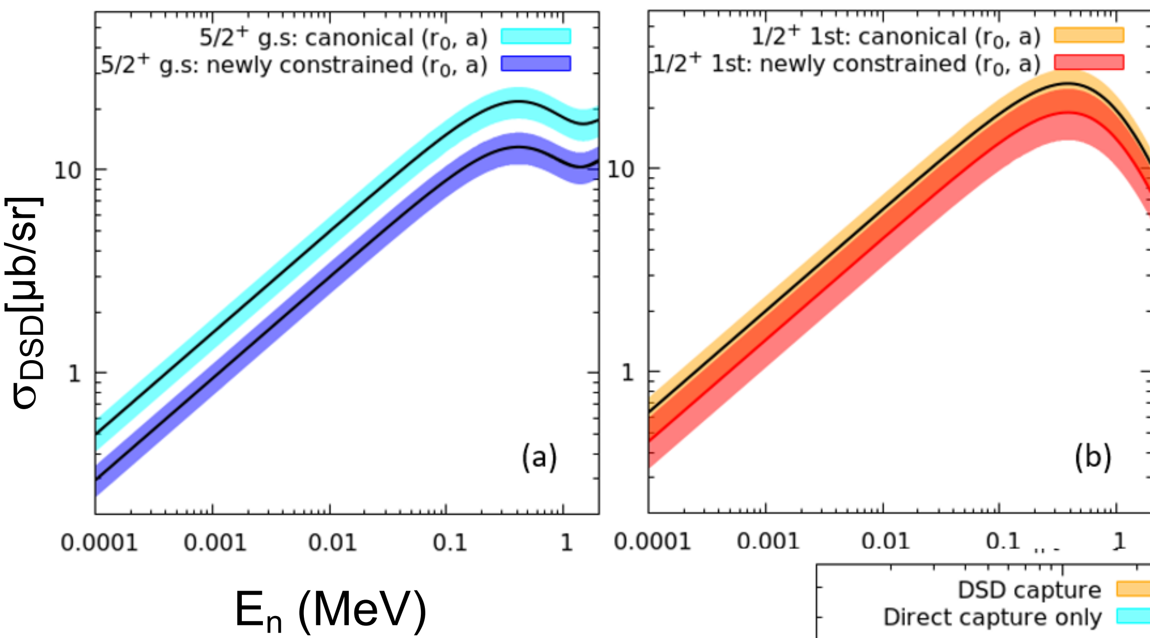
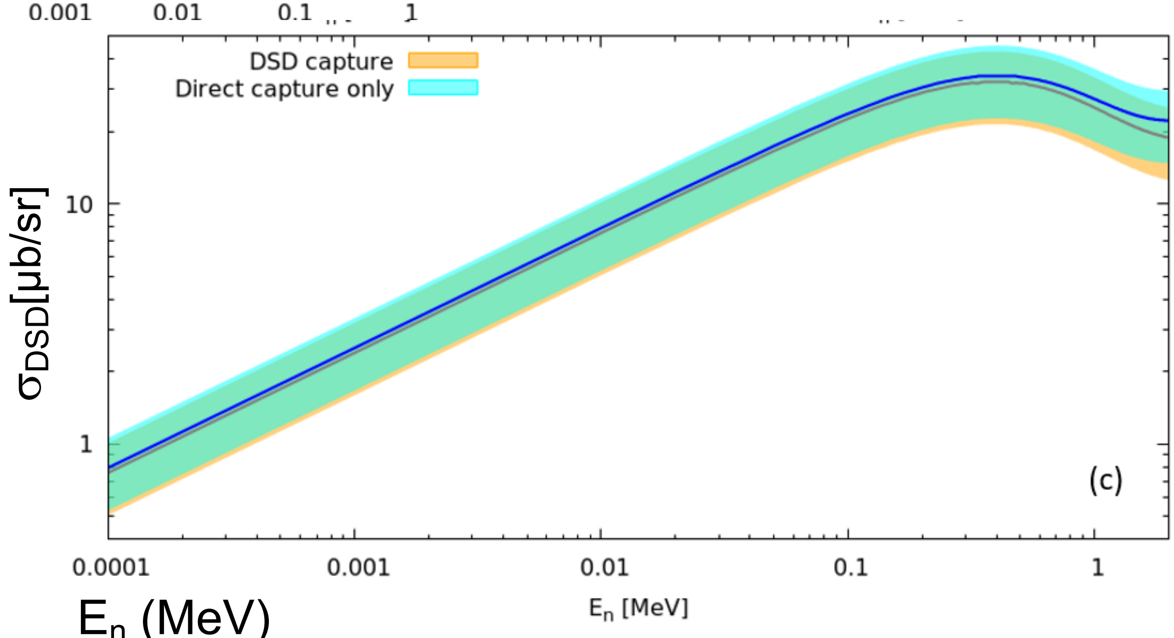
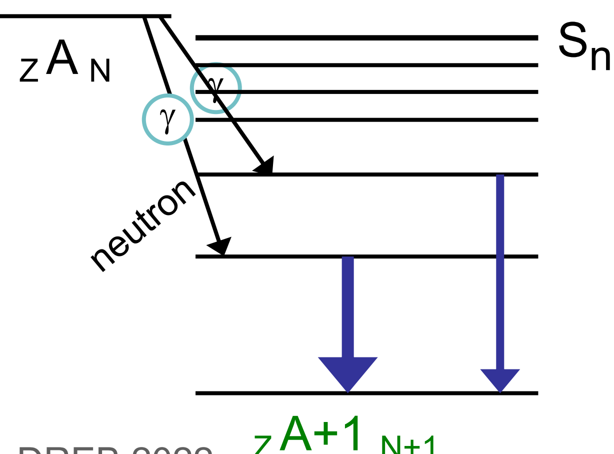
Direct capture cross sections on ^{84}Se

Using newly constrained S







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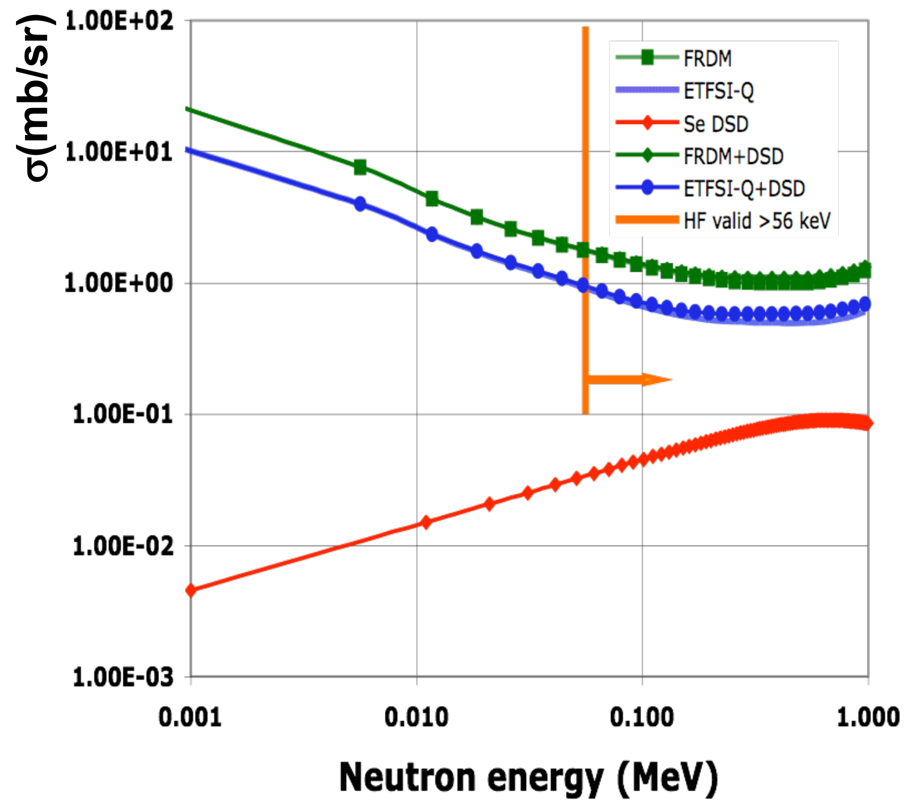
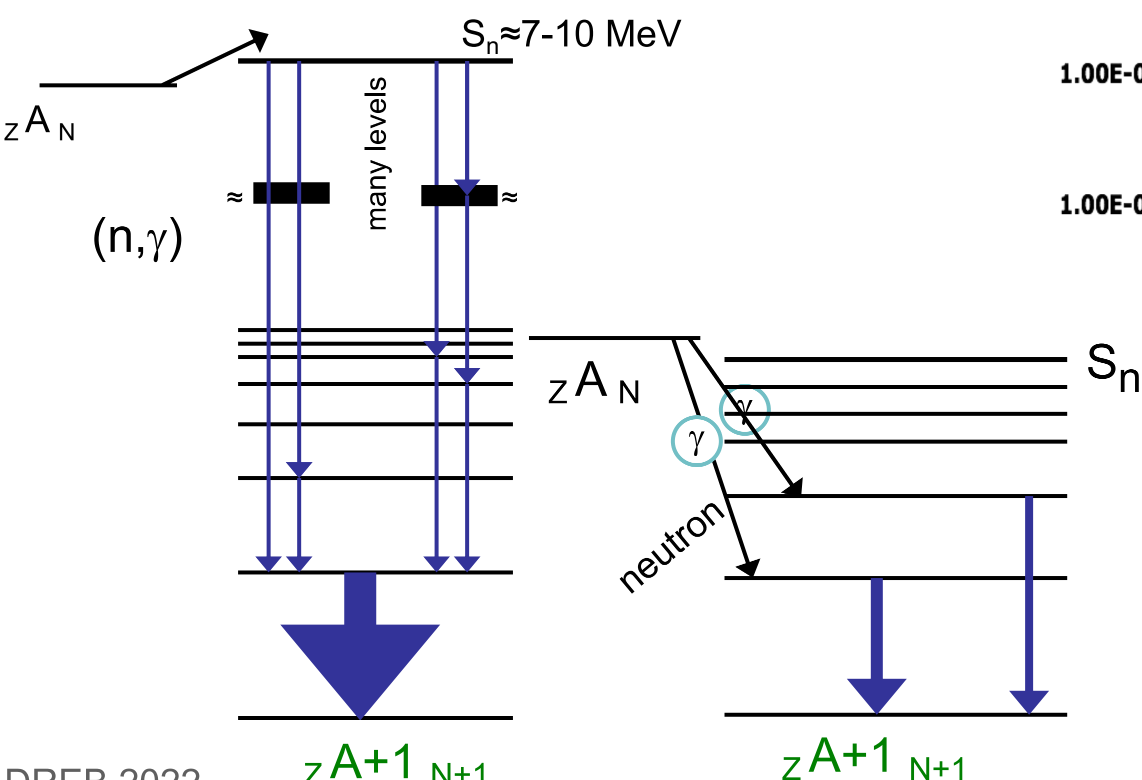
(d,p) studies with 4.5 MeV/u & 45 MeV/u ^{84}Se beams

Direct-semi-direct capture

- Cross sections small ≈20 μb/sr at 30 keV for *p*-wave capture
- Statistical capture? σ much larger?
- ➢ Need measure γ rays





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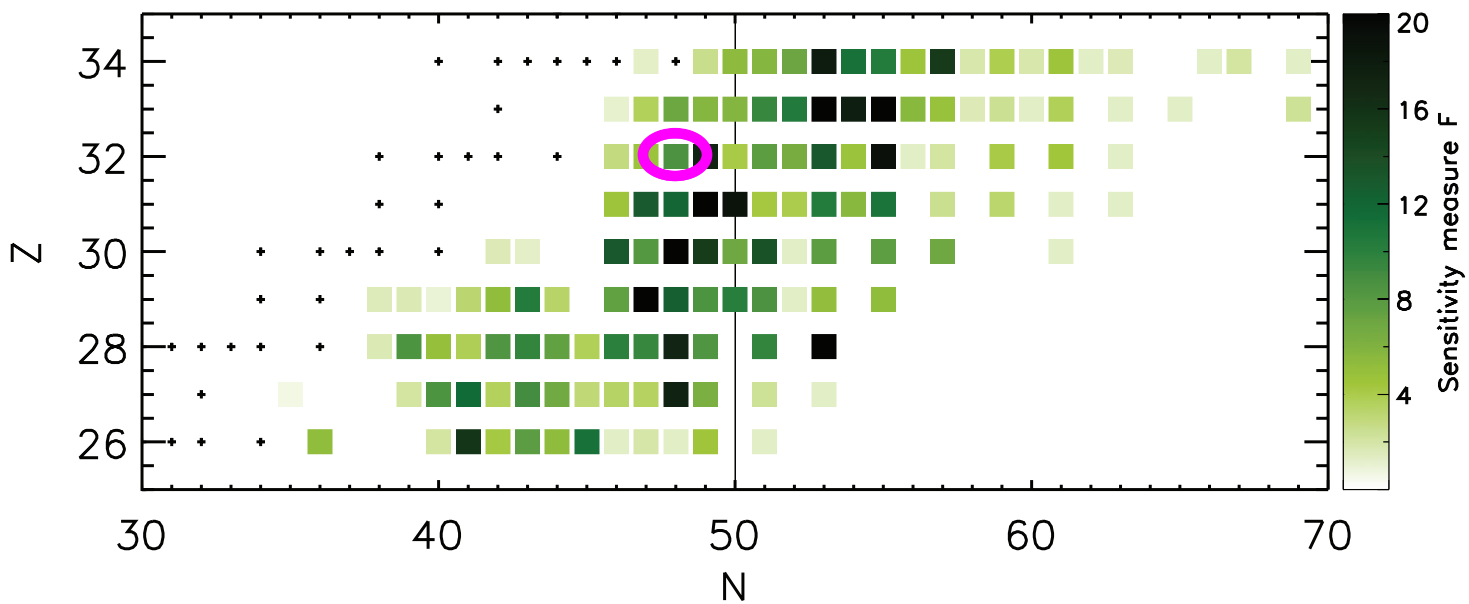
H.E. Sims, D. Walter et al., in preparation for PRC (2022)

J.A. Cizewski et al, AIP CP **1090**, 463 (2009)

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

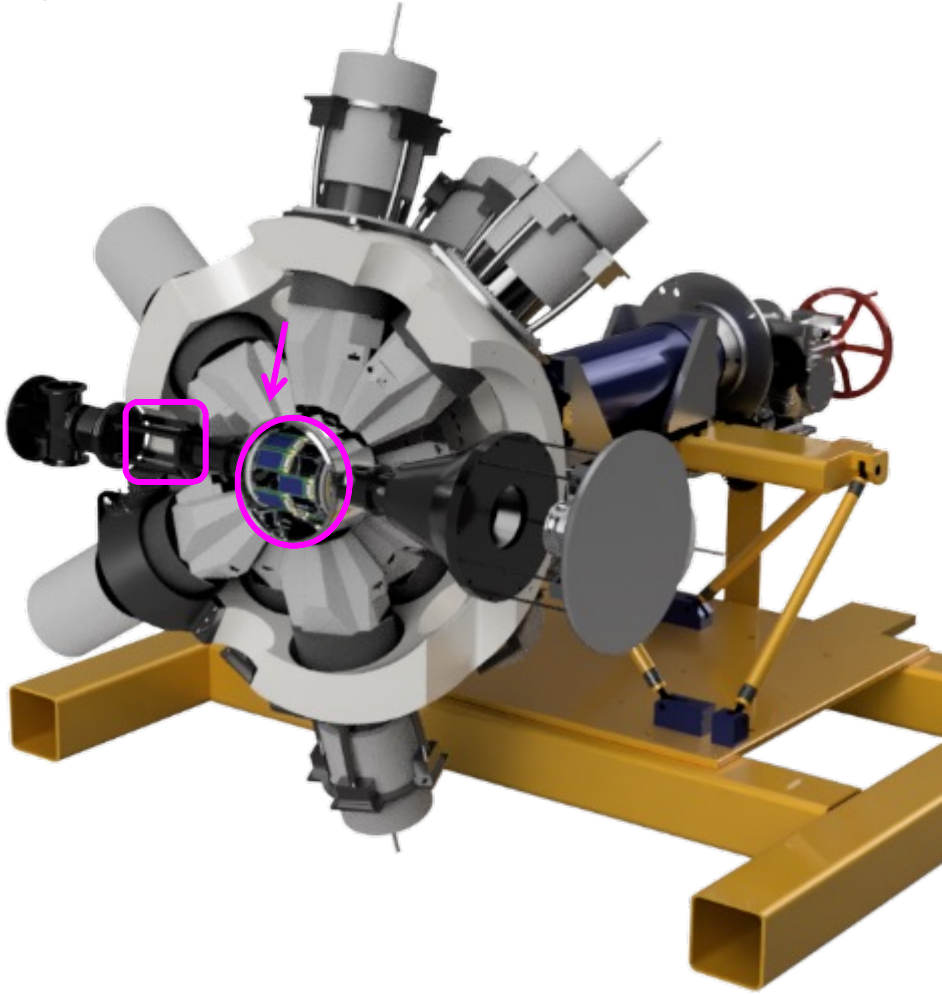
- (d,pγ) with ≈45 MeV/u ^{80}Ge (N=48) beams + GRETINA + ORRUBA + S800
  - High impact on (weak) r-process nucleosynthesis
  - 4.5 MeV/u ^{80}Ge(d,p) Ahn et al. Phys. Rev. C **100**, 044613 (2019)
  - Fast beam: Approved for FRIB - prelim schedule in Early 2023



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

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

- (d,pγ) with ≈45 MeV/u ^{80}Ge (N=48) beams + GRETINA + ORRUBA + S800 and FRIB
- Significant progress in developing infrastructure to couple ORRUBA+GRETINA/GRETA
  - Builds on 2019+2021 ATLAS GRETINA+ORRUBA campaigns
  - Smaller target chamber
    - Can fully close GRETINA/GRETA
  - Upstream (gas) beam tracking detectors
  - New (smaller footprint) annular QQQ6 detectors



H. Sims, private communication

Summary and conclusions

- Unknown (n,γ) rates impact understanding (weak) r process abundances and site of r process(es)
- Near shell closure direct (n,γ) dominates
  - Need properties of low ℓ excitations including S factors
- To deduce S with uncertainties dominated by exp statistics rather than unknown bound state
  - Theory: Mukhamedzhanov and Nunes, Phys. Rev. C **72**, 017602 (2005)
  - Measure (d,p) reaction at two different energies
- (d,p) with ^{84}Se beams
  - Demonstrated can perform (d,p) measurements with ≈40 MeV/u RIBs with ORRUBA + S800
  - Deduced S from combined measurements of 4.5 & 45 MeV/u beams
  - Calculated direct (semi-direct) σ(n,γ)

Poised to measure (d,pγ) with ^{80}Ge RIBs and ORRUBA+GRETINA+S800

Thank you for your attention!

Informing direct neutron capture for the weak r-process via the (d,p) reaction with ^{84}Se beams at two energies

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