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^{86}Kr(d,p) reaction studies: constraining the single-particle ANC

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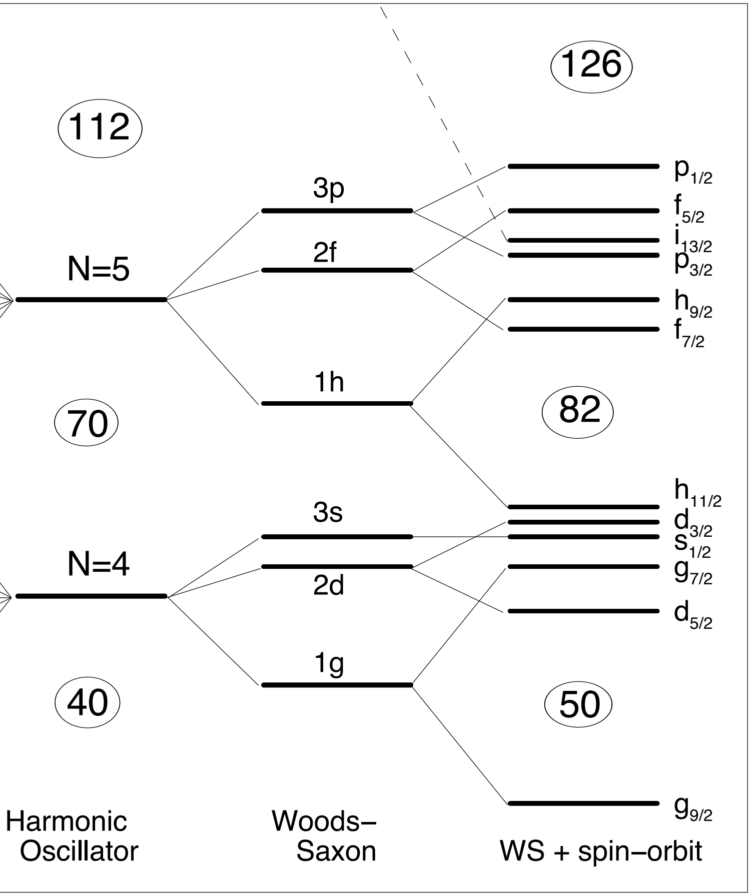
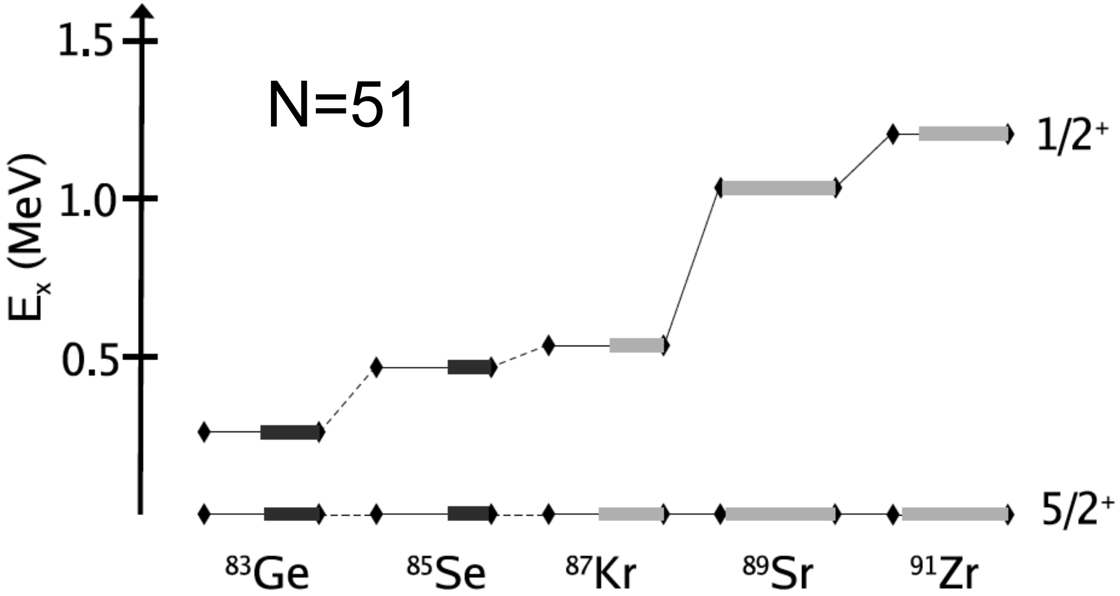
INT 17-1a: Toward Predictive Theories of Nuclear Reactions Across the Isotopic Chart

March 13-16, 2017

Spectroscopic factors are important

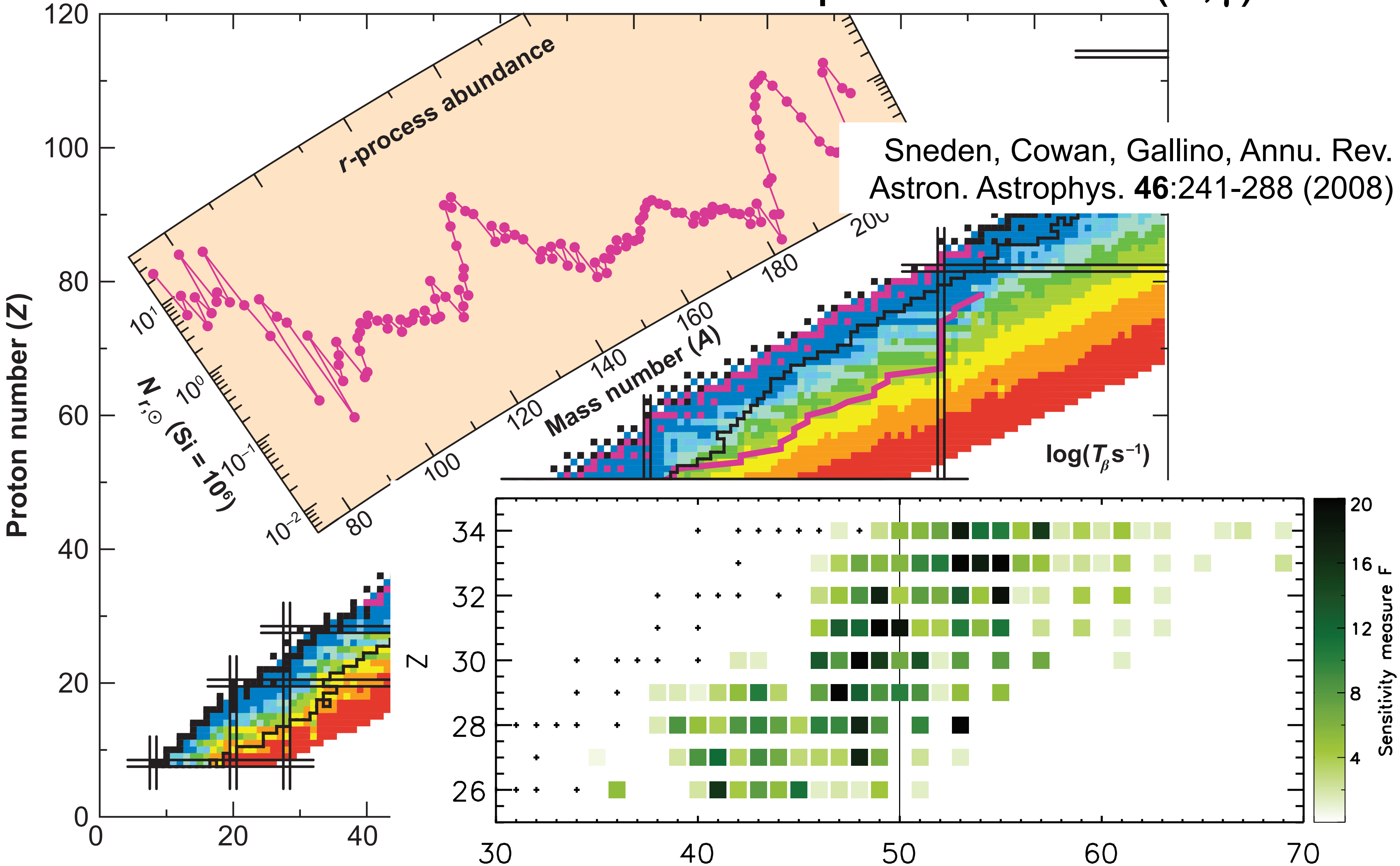
- Inform the single-particle nature of states
- Inform direct neutron-capture on stable & unstable nuclei





J. S. Thomas *et al.*, Phys. Rev. C **76**, 044302 (2007)

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

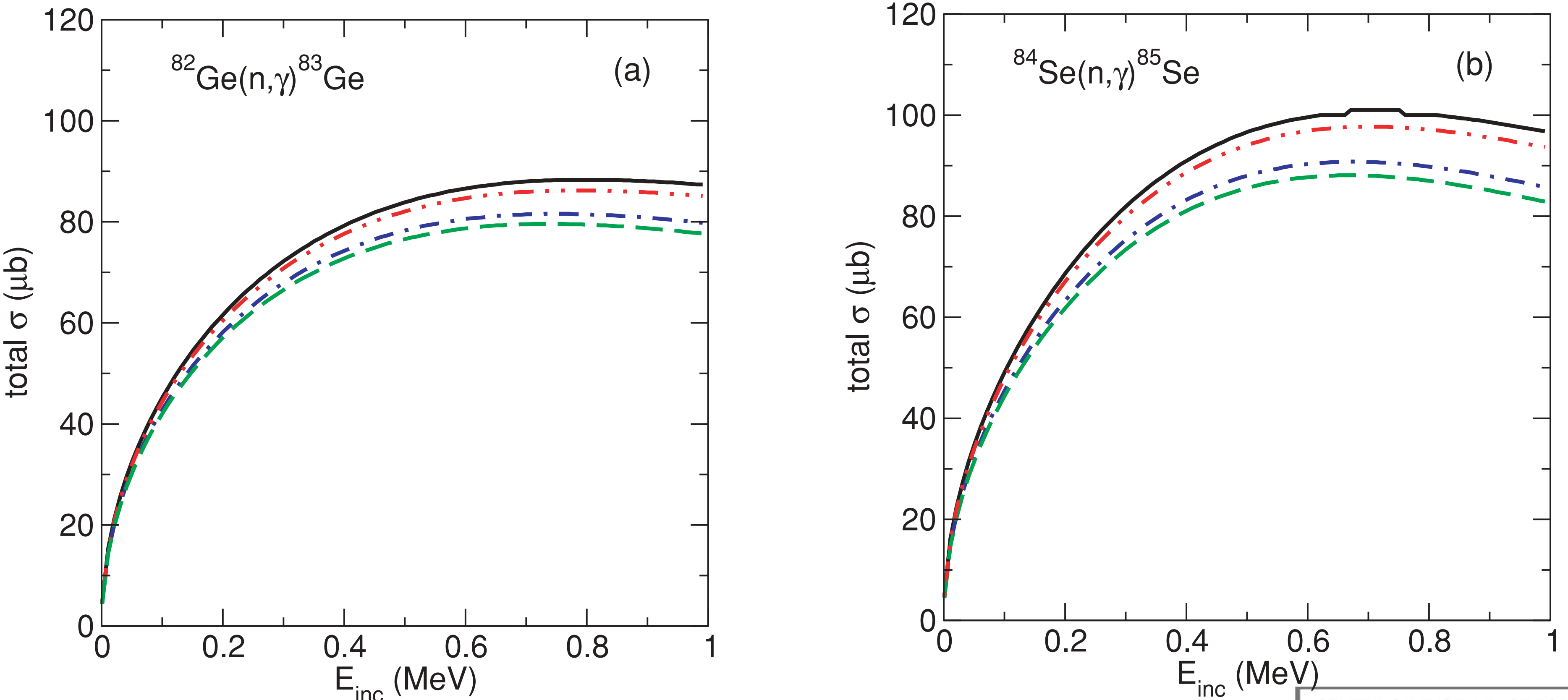


Sneden, Cowan, Gallino, Annu. Rev. Astron. Astrophys. **46**:241-288 (2008)

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

Spectroscopic factors are important

- Inform the single-particle nature of states
- Inform direct (semi-direct) neutron-capture on unstable nuclei including near (weak) r-process path



J. S. Thomas *et al.*, Phys. Rev. C **76**, 044302 (2007)

Reaction theory input

(d,p) cross sections & spectroscopic factors

- Absolute exp cross sections ⇐ normalization of data from elastic scattering of deuterons
  - Theoretical calculations of elastic scattering

$$S = N \left\langle I^{B}_{An} \middle| I^{B}_{An} \right\rangle .$$

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

- Input for theoretical reaction cross section output
  - Optical model potentials
    - Incoming deuteron, outgoing proton, neutron bound state
    - Traditionally: empirical, not microscopic
  - Wave function of the deuteron
    - Nucleon-nucleon vs composite
  - Wave function of transferred particle, e.g., $2d_{5/2}$ neutron
    - Woods-Saxon potential for s.p. wave function

Reaction calculations

(d,p) cross sections & spectroscopic factors

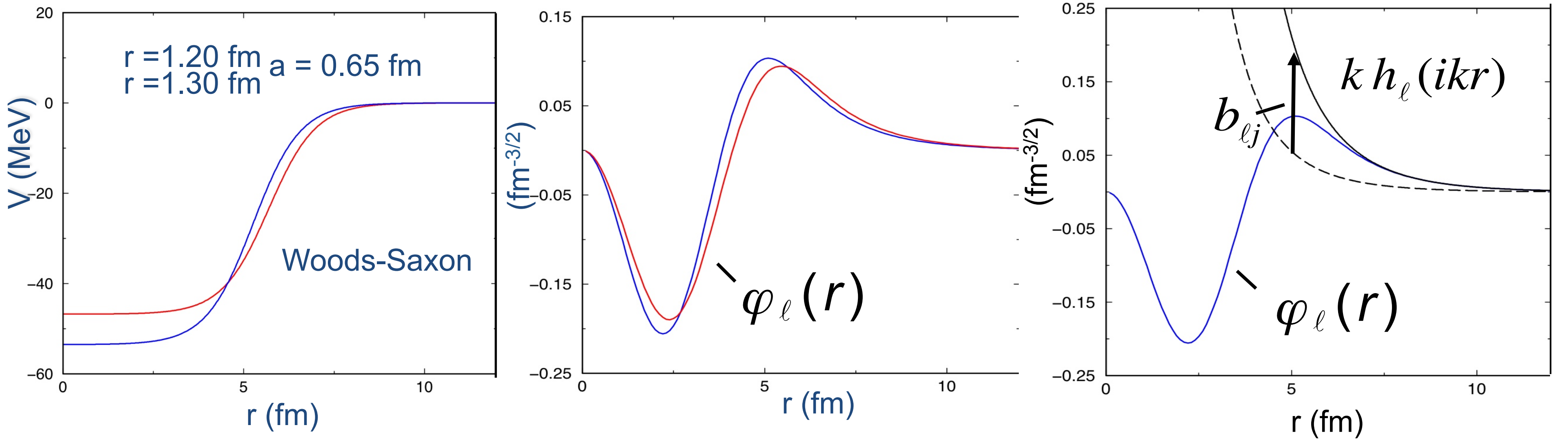
$$S = \left(\frac{d\sigma}{d\Omega}\right)_{\exp} \Big/ \left(\frac{d\sigma}{d\Omega}\right)_{thy}$$

Theoretical reaction cross section with FRESCO (TWOFNR)
Finite Range-ADiabatic Wave Approximation (FR-ADWA)

- Wave function of the deuteron
  - Reid soft-core
- Global optical model potentials
  - Johnson-Tandy and Koning-Delaroche
- Bound state parameters for the transferred neutron
  - $R=r_0A^{1/3}$ diffuseness *a* Woods-Saxon potential
- Wave function of transferred particle, e.g., $2d_{5/2}$ neutron

Spectroscopic factors valid from peripheral reactions?

Bound state potential & asymptotic normalizations



- Determining Spectroscopic factor S
  - Dependence on single-particle parameters: radius (r_0) & diffuseness (a)
  - Changes shape of bound-state potential
  - Changes shape of calculated single particle wave function
- Peripheral reaction probes tail of WF
- Change in geometry => change in single particle asymptotic normalization coefficient spANC $b_{\ell j}$
- Nuclear asymptotic normalization coefficient ANC $C_{\ell j} = S_{\ell j}^{1/2}\, b_{\ell j}$

Asymptotically:

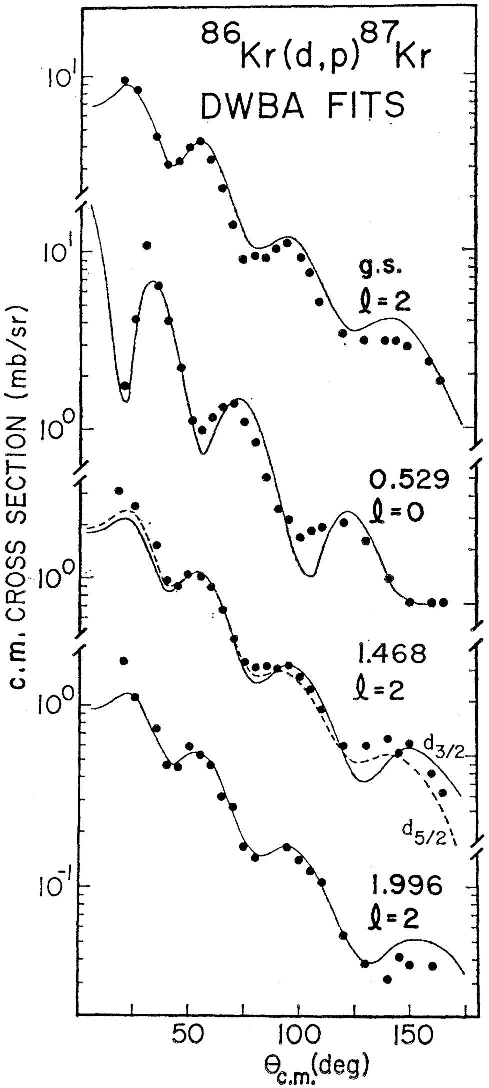
$$\varphi_\ell(r) \rightarrow b_{\ell j}\, k\, h_\ell(ikr)$$

$$I^B_{An} \rightarrow C_{\ell j}\, k\, h_\ell(ikr) = S^{1/2}_{\ell j}\, b_{\ell j}\, k\, h_\ell(ikr)$$

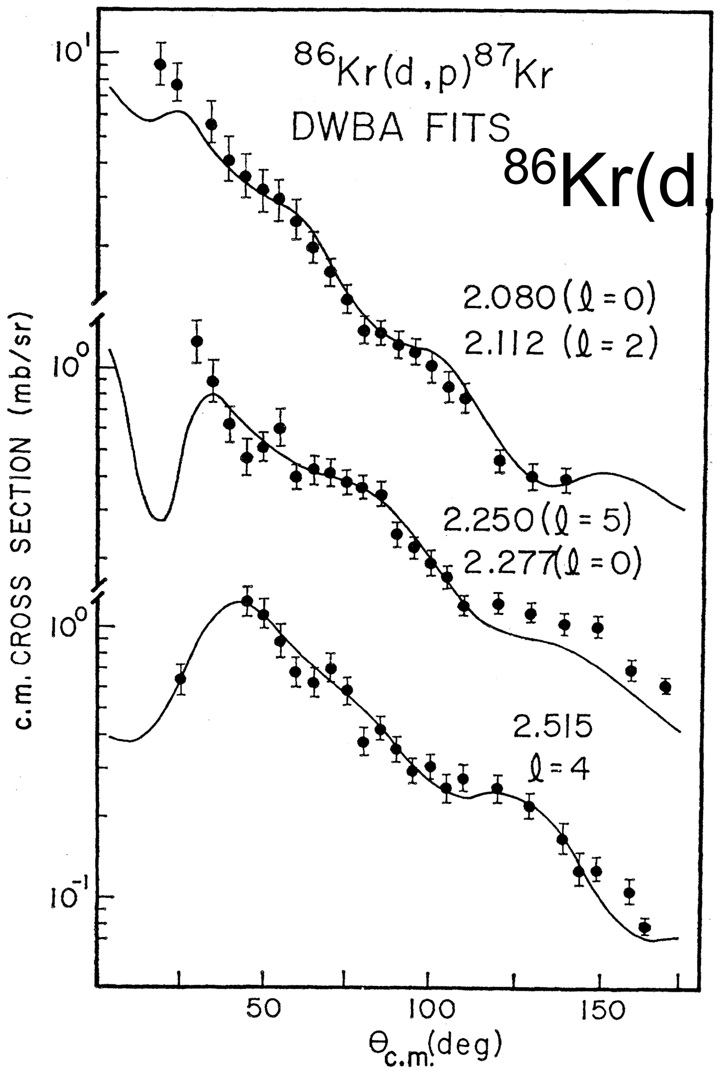
$$C^2_{\ell j} = S_{\ell j}\, b^2_{\ell j}$$

Haravu et al. Phys. Rev. C **1**, 938 (1970)

^{86}Kr(d,p) E(d) = 11 MeV

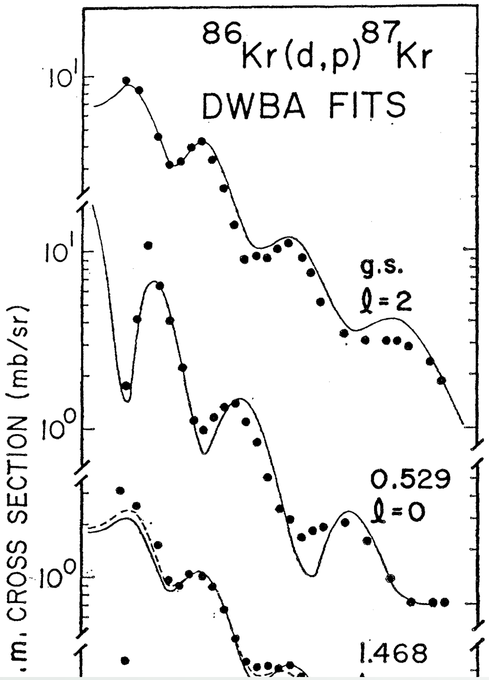


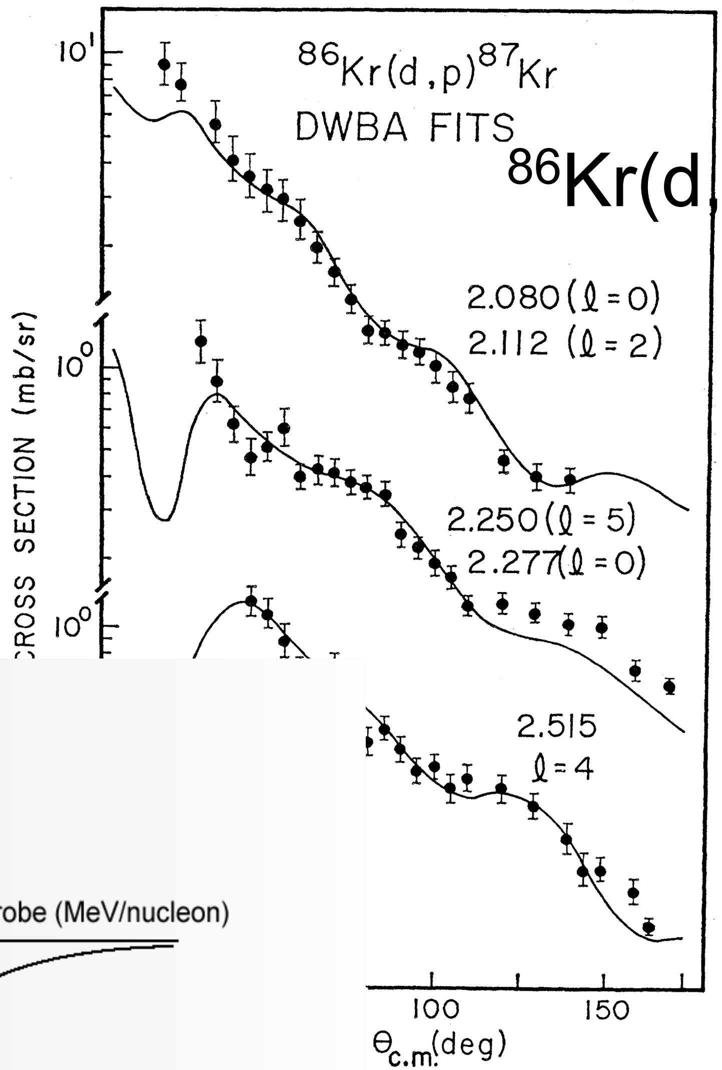
(a)



(b)

Haravu et al. Phys. Rev. C **1**, 938 (1970)





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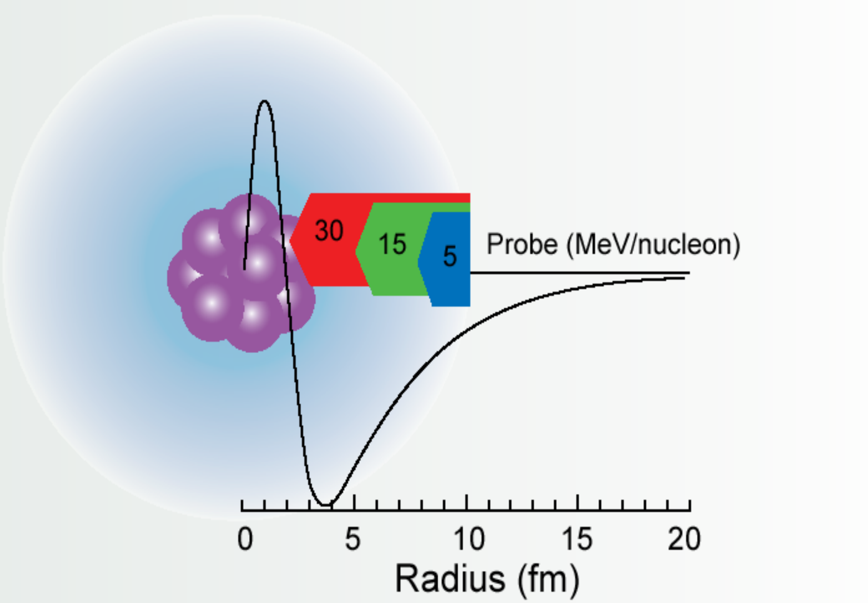

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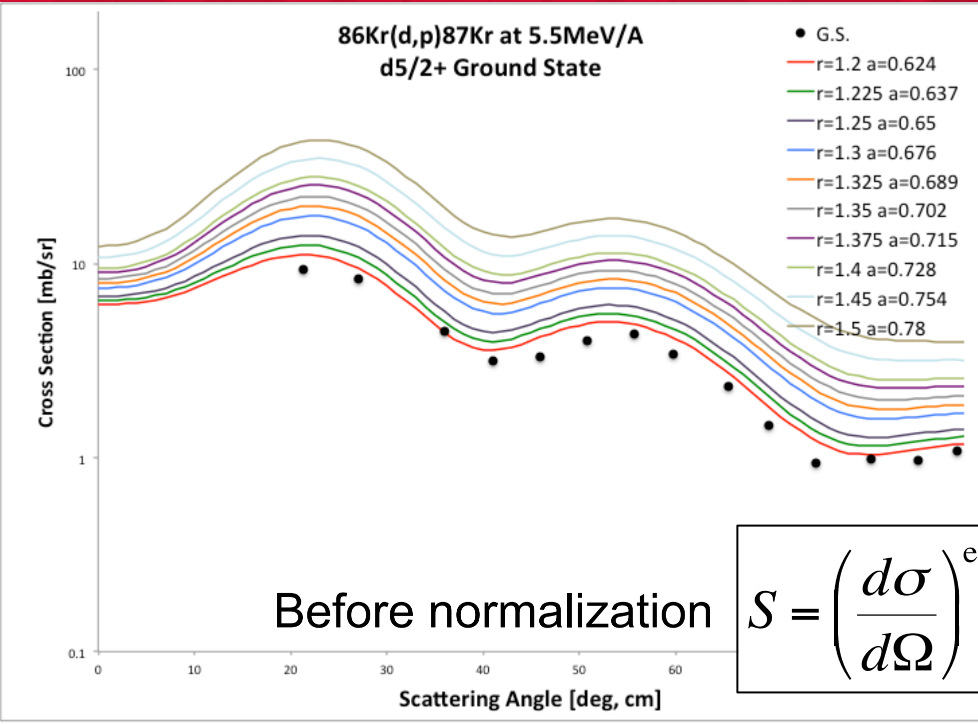
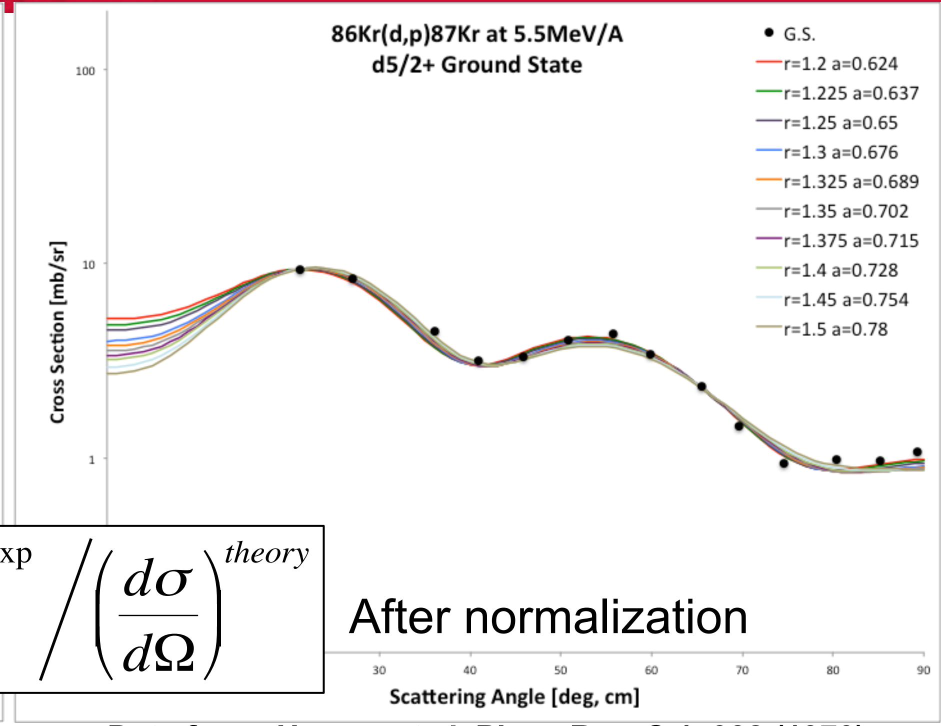
^{86}Kr(d,p)^{87}Kr at 5.5 MeV/A



Before normalization

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



After normalization

Data from: Haravu et al. Phys. Rev. C 1, 938 (1970)

- Changing r_0 and a in bound state potential
  - $b_{\ell j}$ from shape of potential
  - S from ratio to theoretical calculation

$$C_{\ell j} = S_{\ell j}^{1/2}\, b_{\ell j}$$

Koning Delaroche Global Optical Model Parameters

State	S_{Haravu}	$S_{present}$	C_{lj}^2[fm^{-1}]
Ex=0 MeV d5/2+, ℓ=2	0.56	0.43 ± 0.05	18 ± 3
Ex=0.53 MeV s1/2+, ℓ=0	0.46	0.31 ± 0.04	52 ± 6
Ex=2.52MeV g7/2+, ℓ=4	0.49	0.40 ±0.05	0.011 ± 0.002

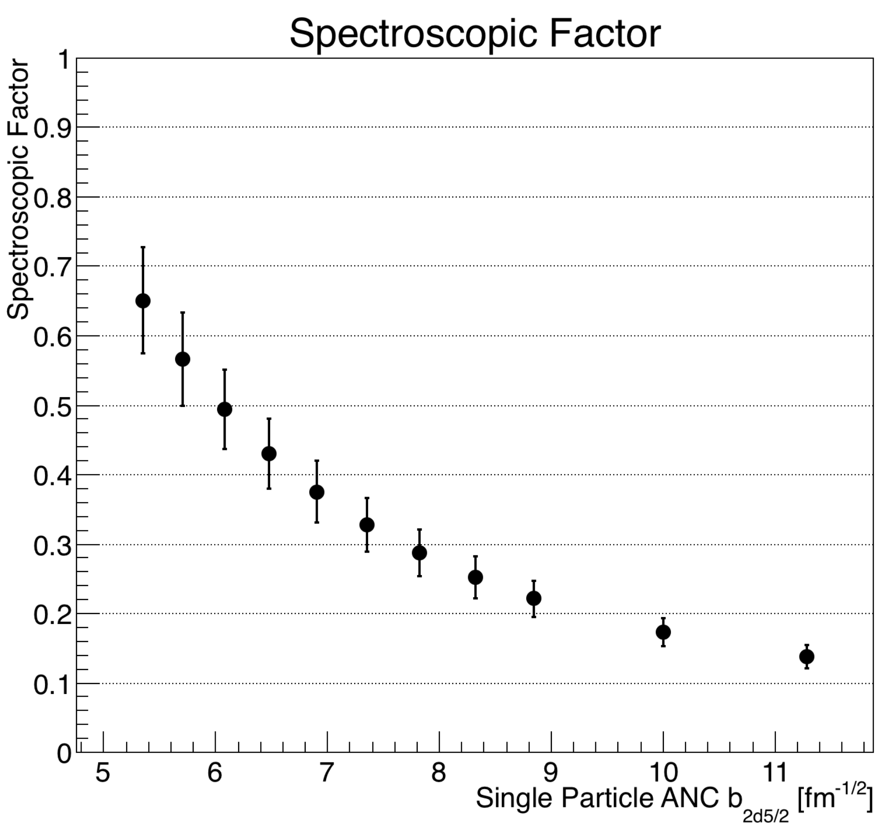
Extracting ANC at low energy

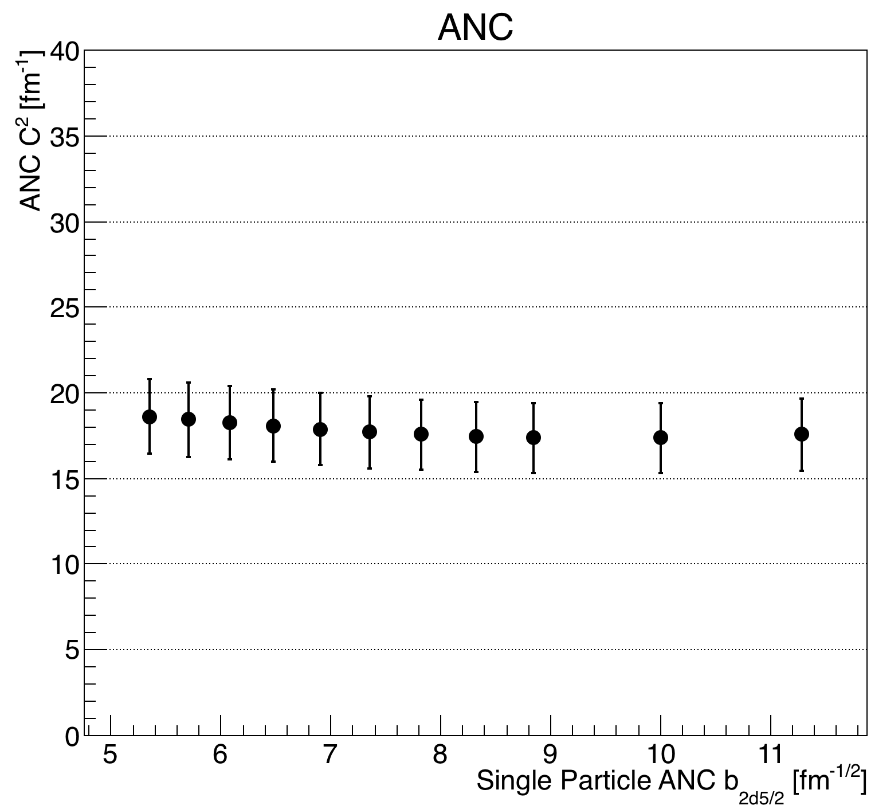
- Vary the bound state parameters, r and a_0
- S strongly depends on $b_{\ell j}$
- $C_{\ell j}$ nearly independent of $b_{\ell j}$
  - Peripheral reaction

$$I_{An}^{B} \rightarrow C_{\ell j}\, k h_{\ell}(ikr) = S_{\ell j}^{1/2}\, b_{\ell j}\, k h_{\ell}(ikr)$$

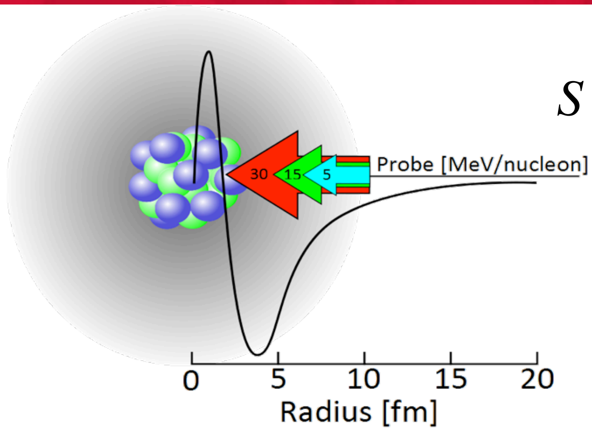
$$C_{\ell j} = S_{\ell j}^{1/2}\, b_{\ell j}$$

$^{86}Kr(d,p)^{87}Kr$ ground state calculation at 5.5 MeV/u



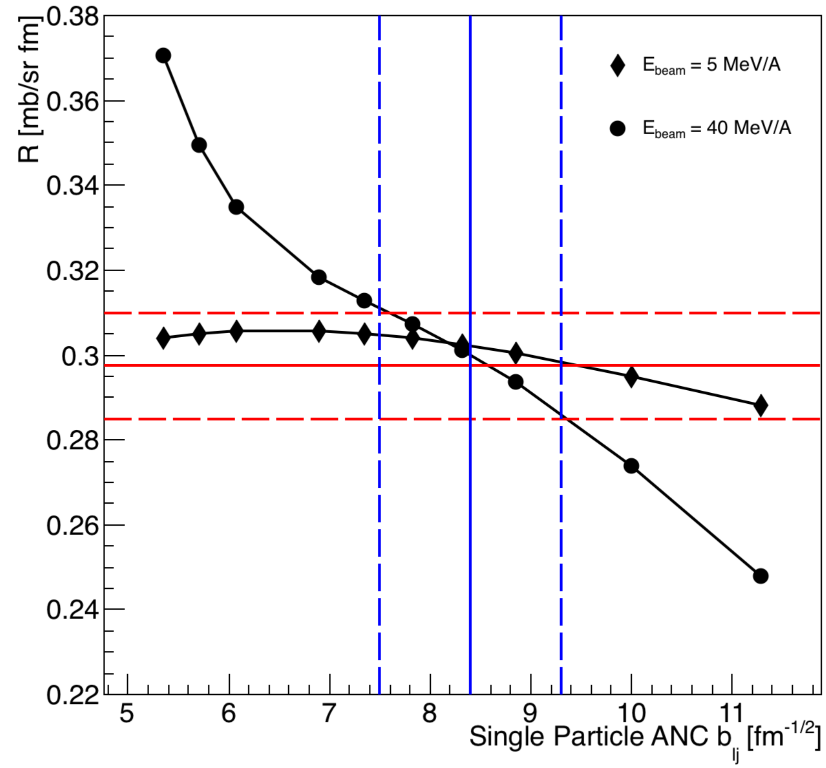


The Combined Method



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

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



- Fix external part with correct ANC (C_{lj}) using peripheral reaction (lower energy)
- Probe the nuclear interior with higher energy reaction and extract the SF consistent with that ANC
- Constrain single-particle ANC
- SF dominated by uncertainties in the experimental cross-section measurement rather than uncertainties in the bound state potential

$$R = \left(\frac{d\sigma}{d\Omega}\right)^{exp} \Big/ C_{\ell j}^2 = \sigma^{DW} \big/ b_{\ell j}^2$$

Mukhamedzhanov and Nunes. Phys. Rev. C <u>72</u>, 017602 (2005)

^{86}Kr(d,p)^{87}Kr at 35 MeV/u

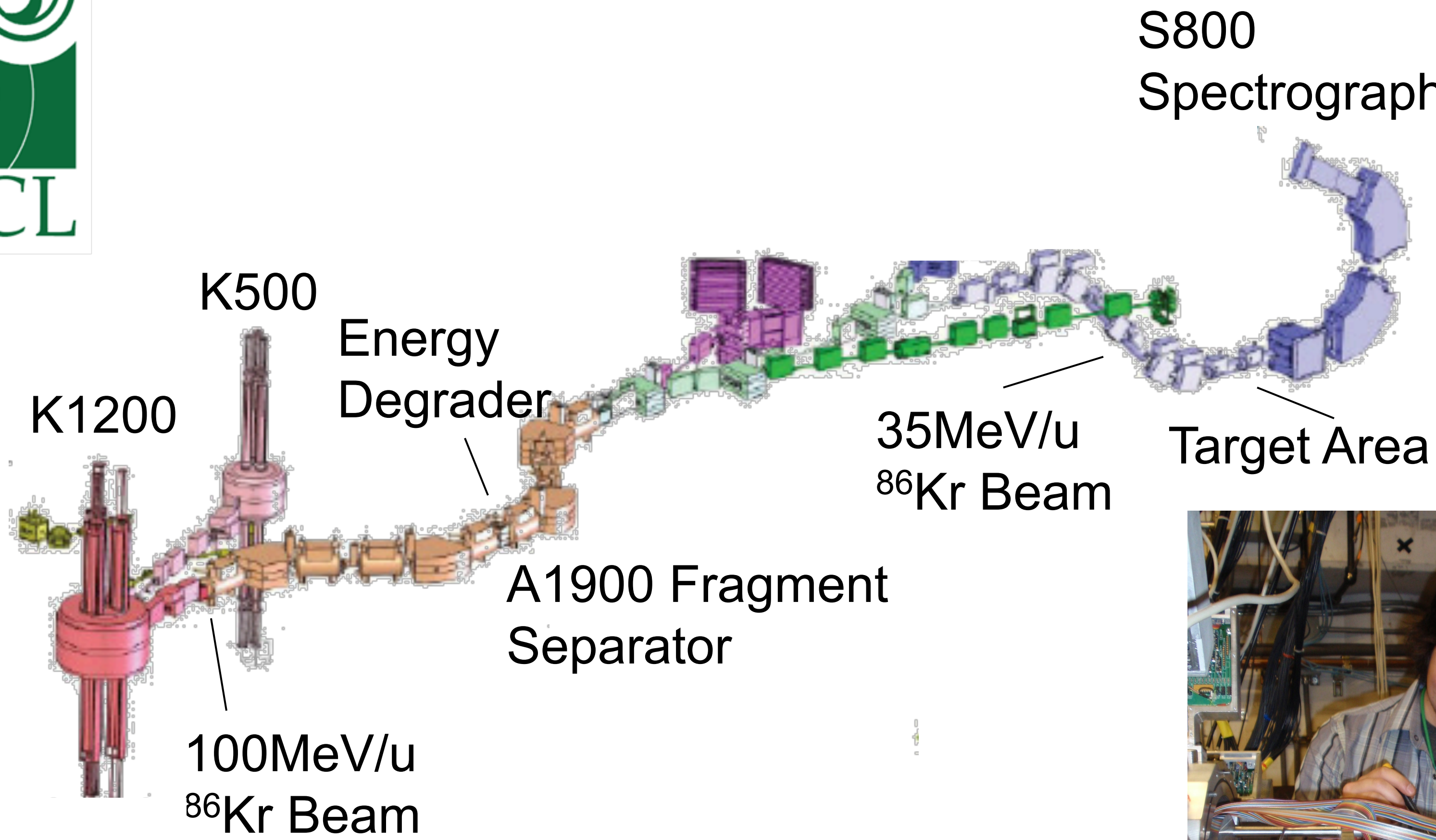
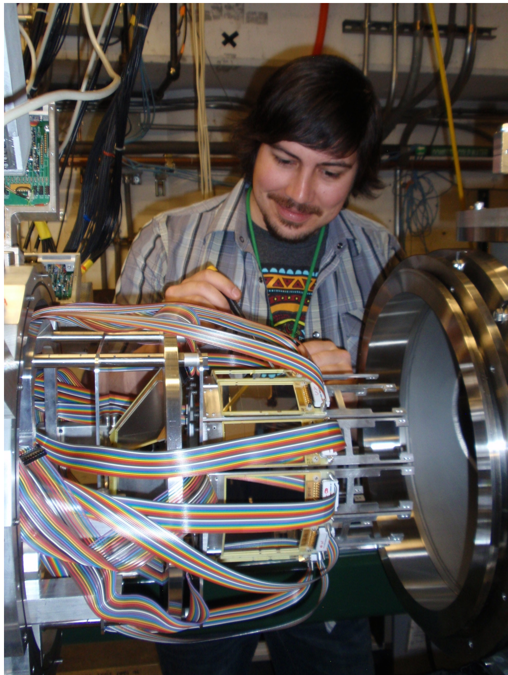
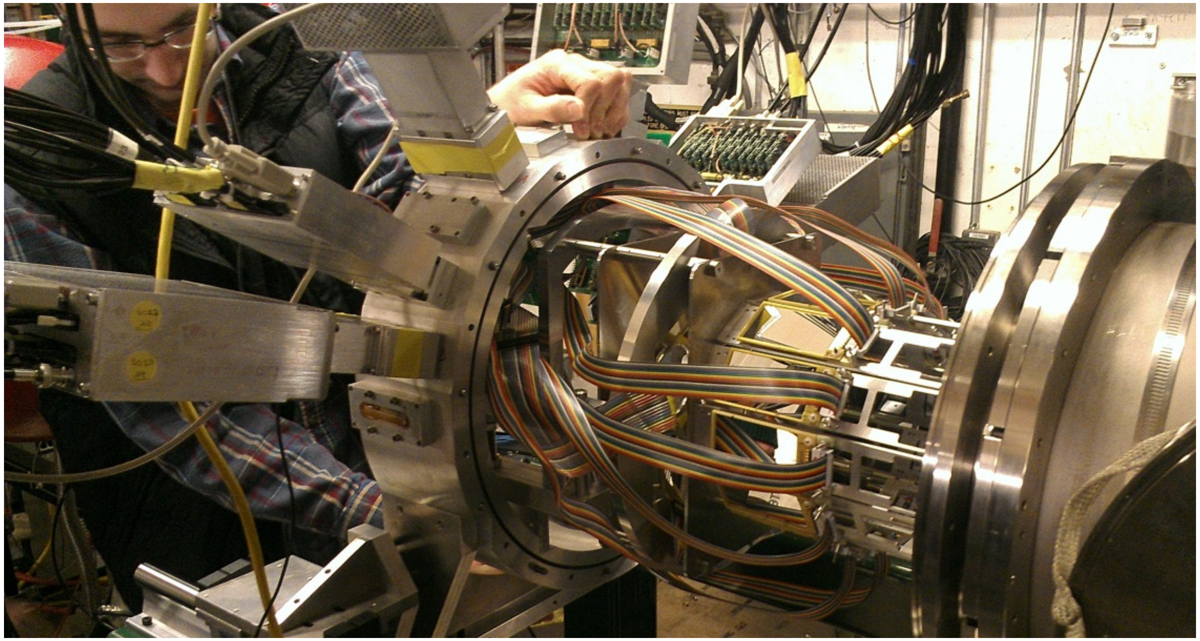


Figure from: http://www.nscl.msu.edu/

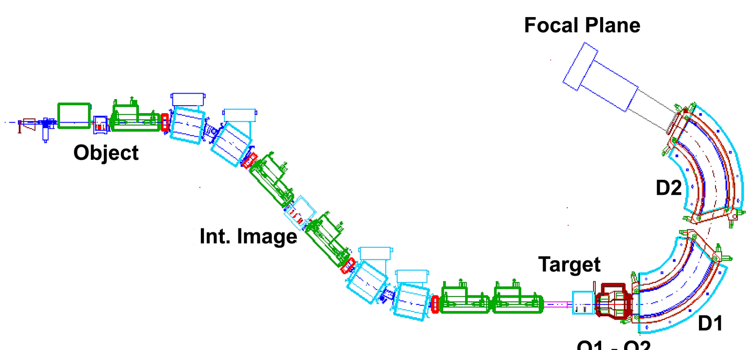


Experimental Setup



- SIDAR
  - Silicon Detector Array
  - Segmented Si strip detector
- ORRUBA
  - Oak Ridge Rutgers University Barrel Array
  - Position sensitive Si strip detectors

- Coupled to the S800 magnetic spectrograph at the NSCL for detecting the heavy recoils



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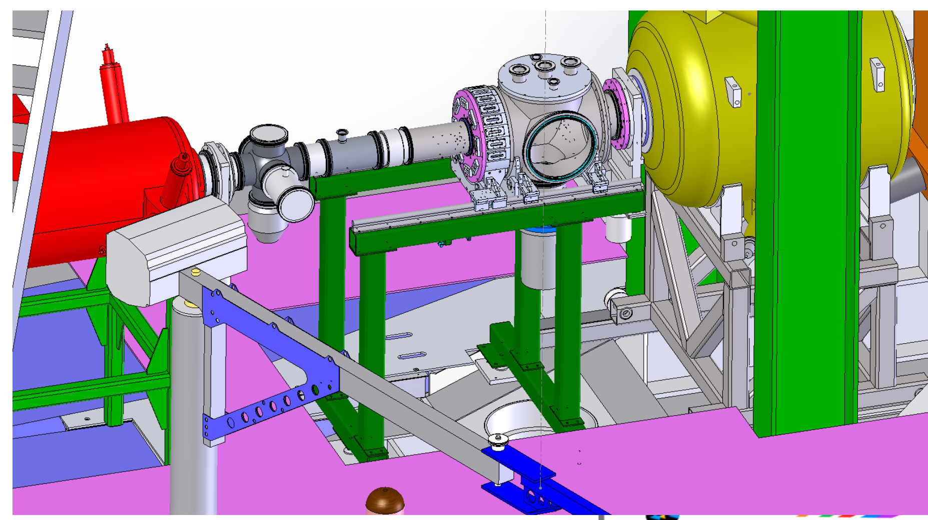
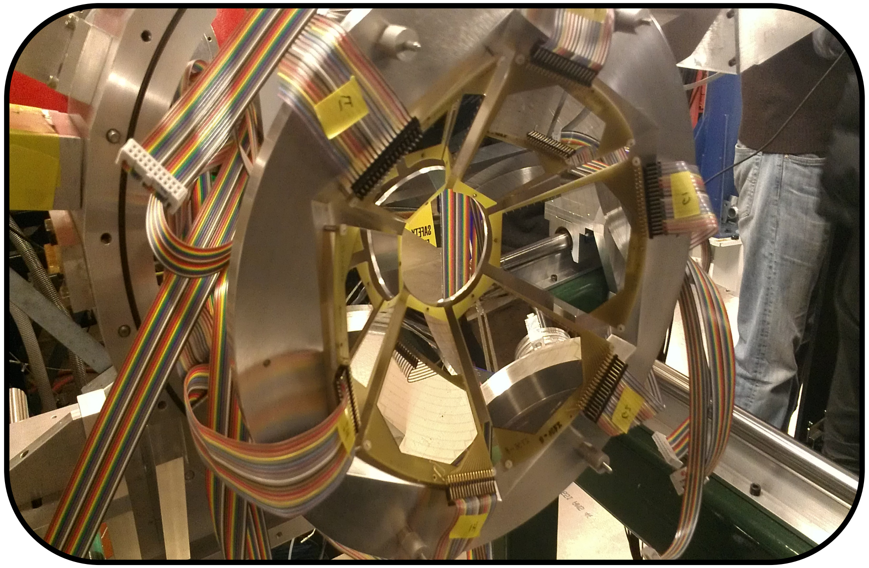
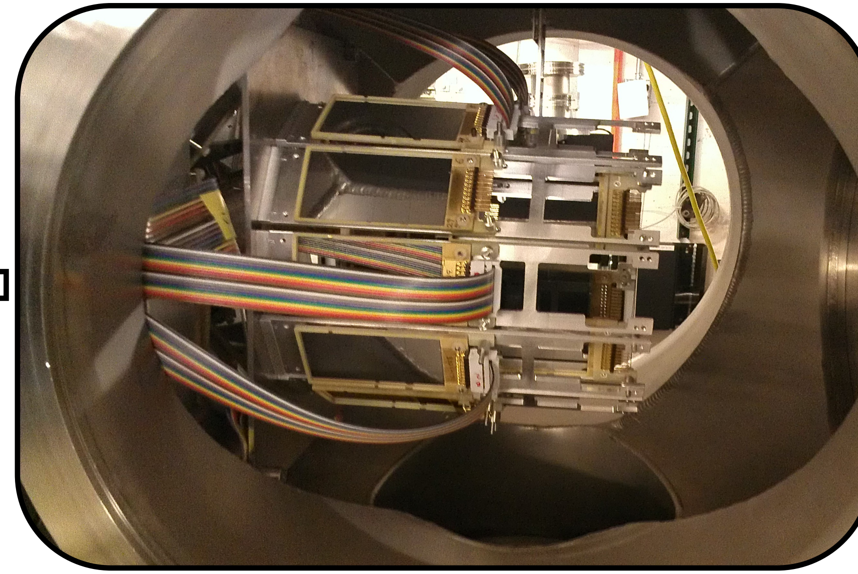


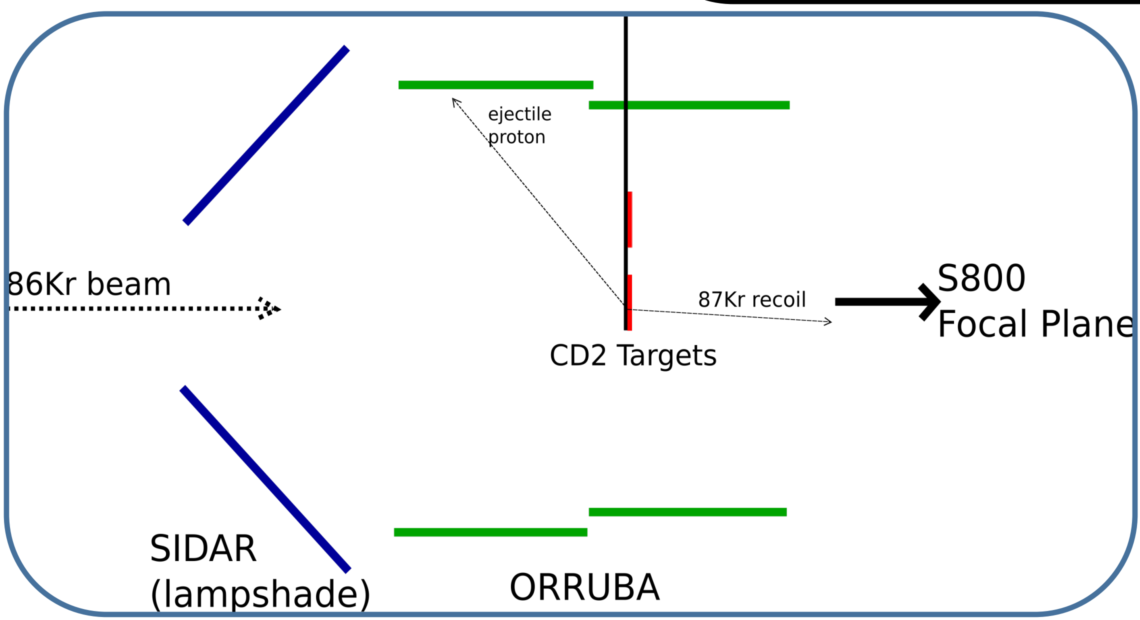
Experimental Setup

SIDAR



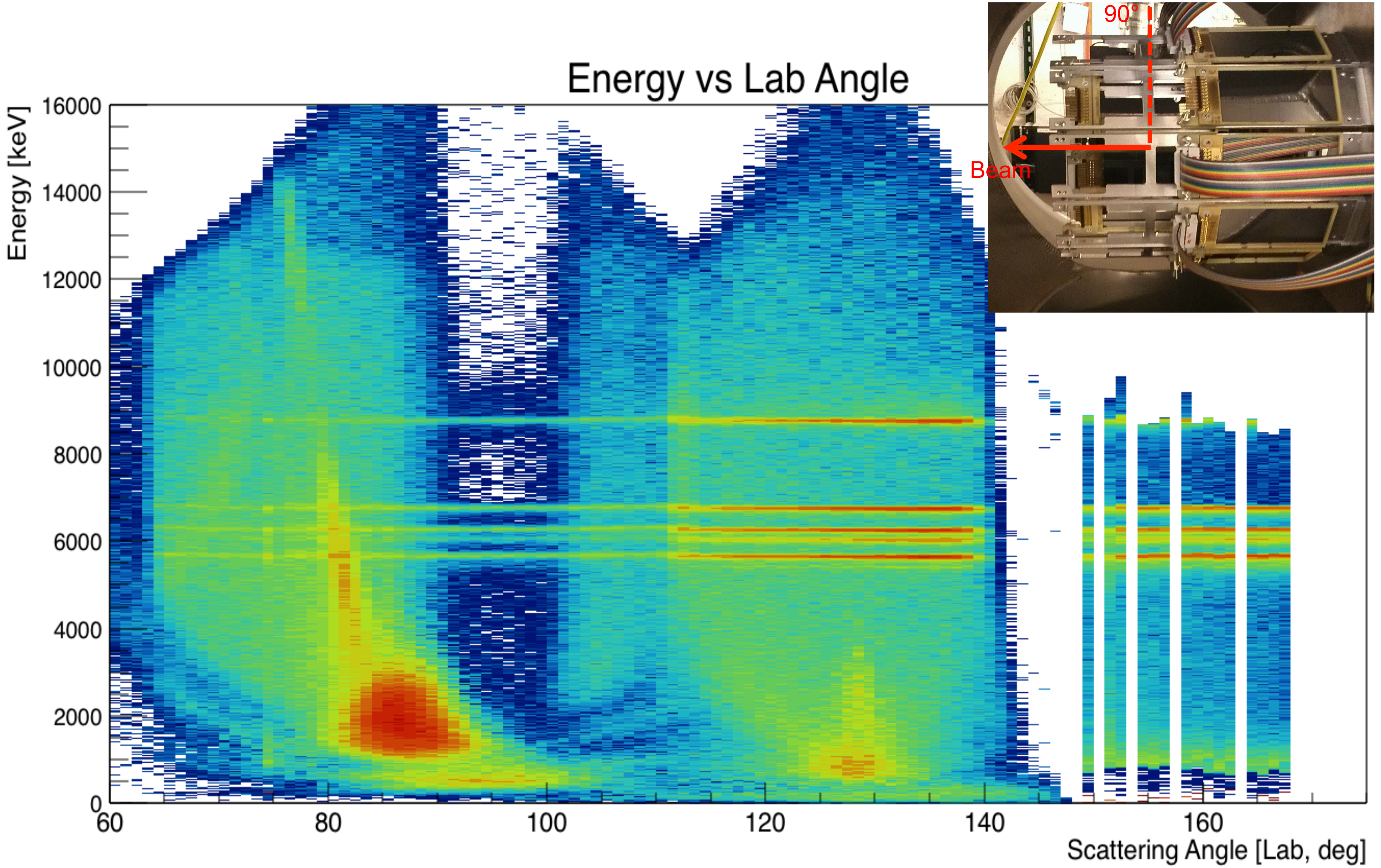
ORRUBA





Side view schematic

Preliminary Singles Data



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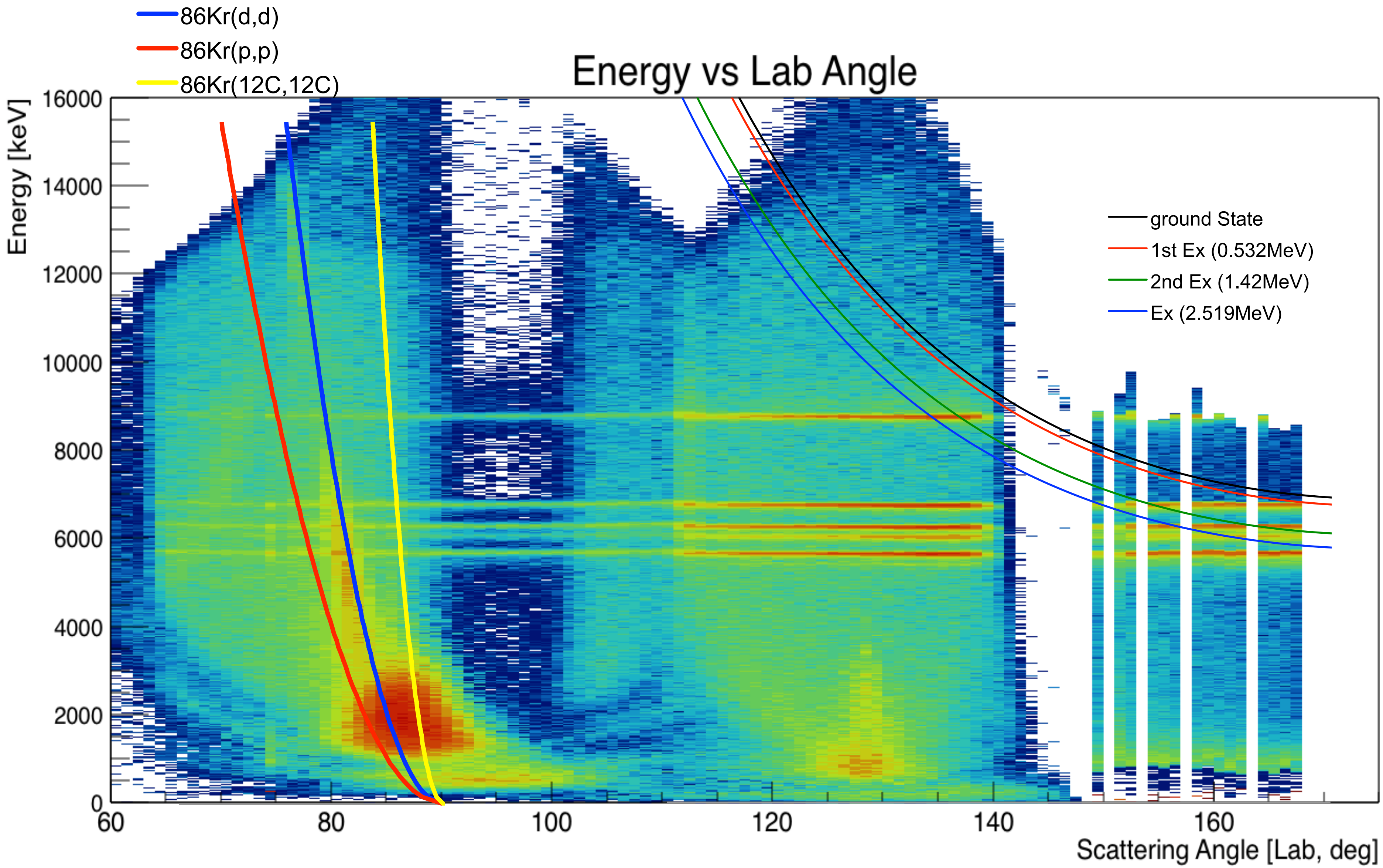

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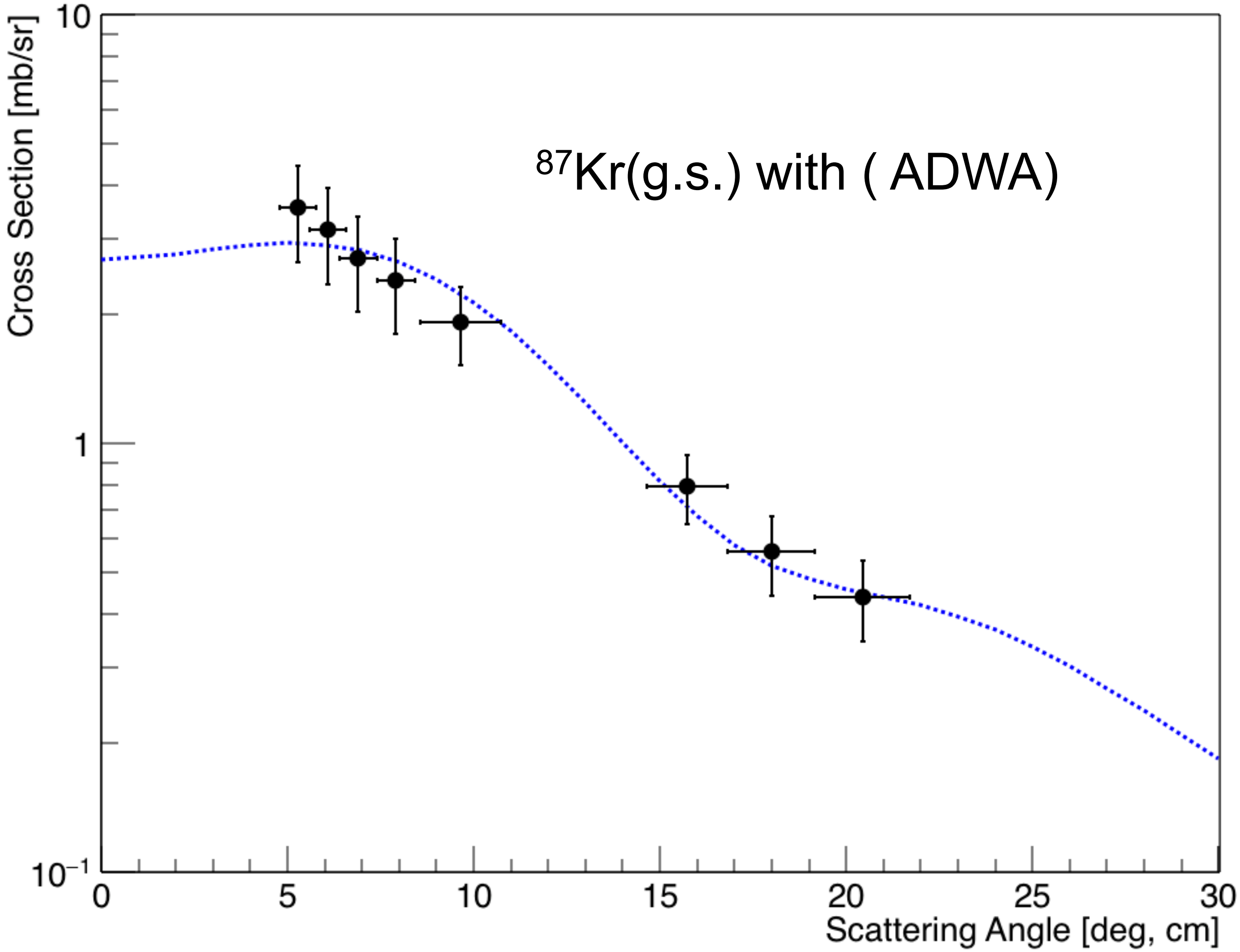
Preliminary Angular Distributions

- $5/2^+$ ground gtate, ℓ=2 $2d_{5/2}$ transfer
- Fit to data
  - Least squares method to extract SF



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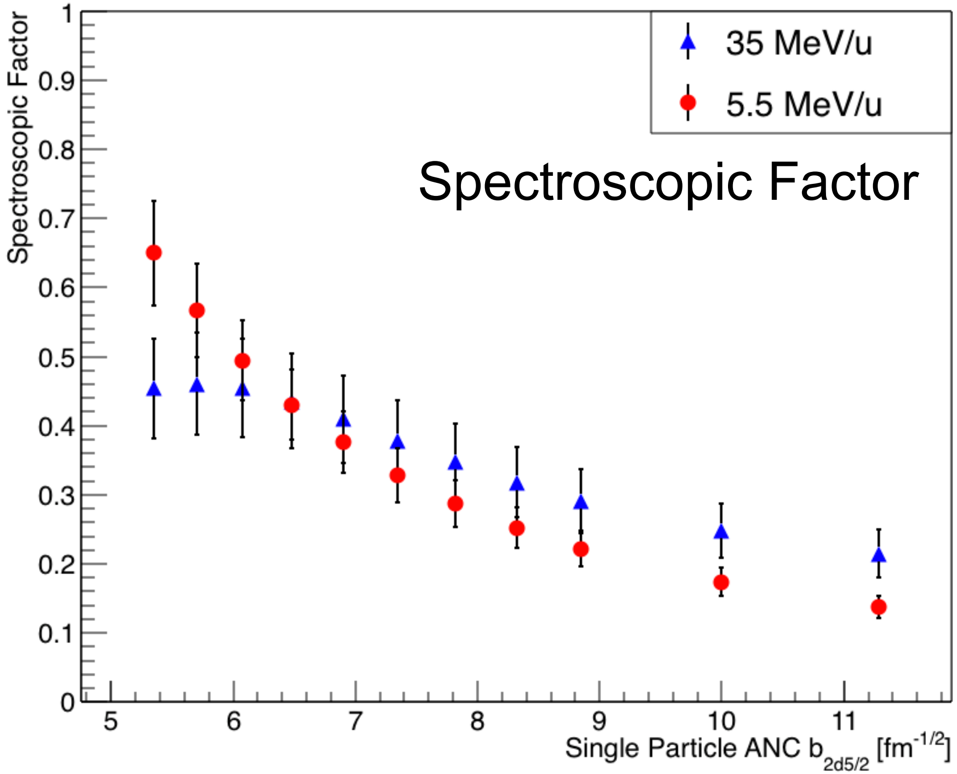

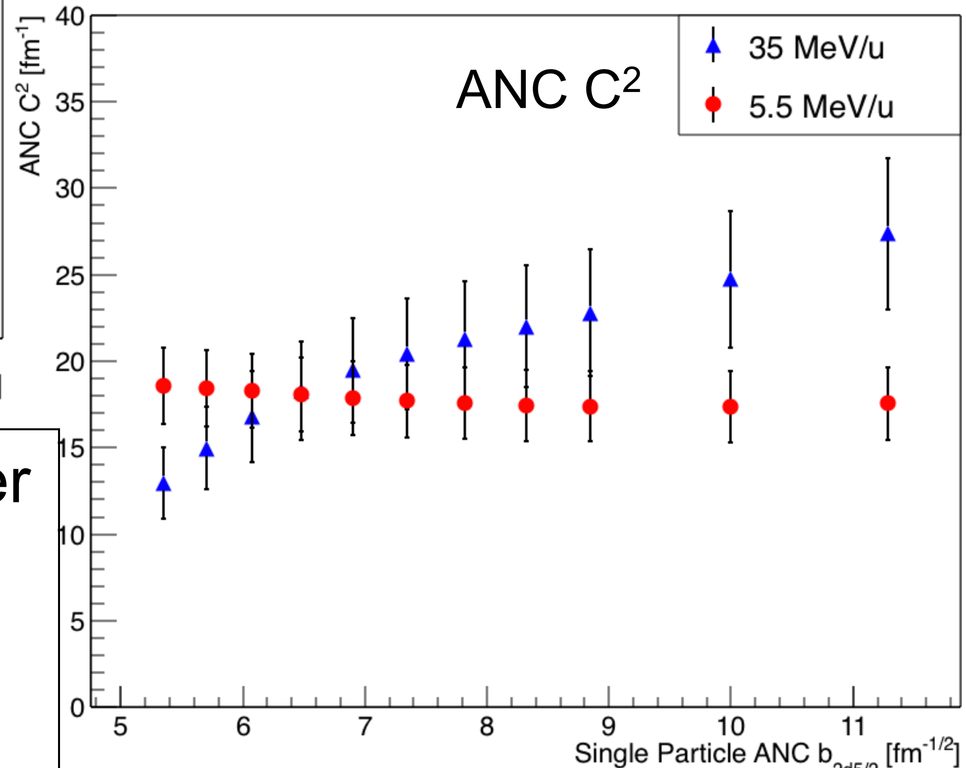

- $5/2^+$ Ground State $2d_{5/2}$ transfer
- Crossing point between two data sets $b_{\ell j} \approx 6.5\ fm^{-1/2}$

=> $r_0 \approx 1.28$ fm $a \approx 0.66$ fm

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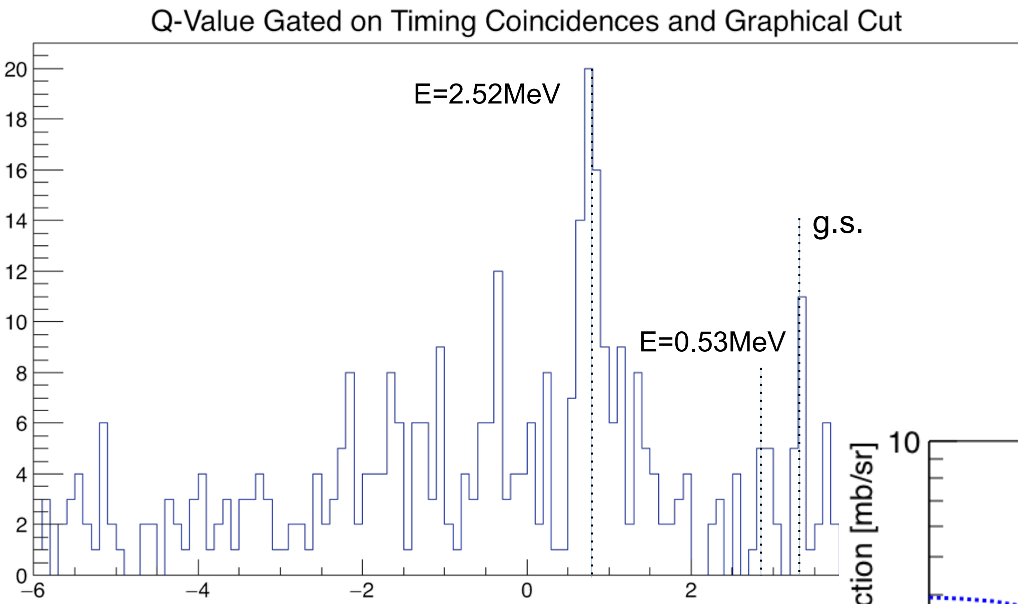
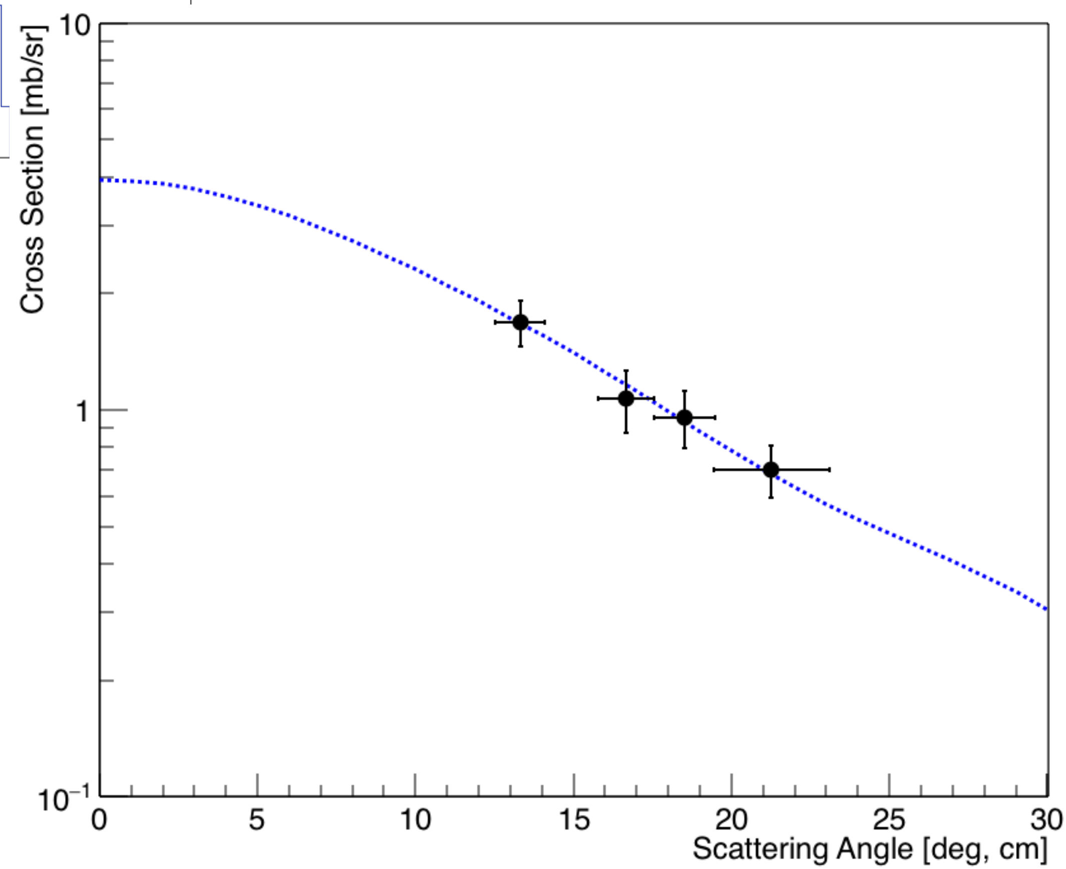
Preliminary Angular Distributions



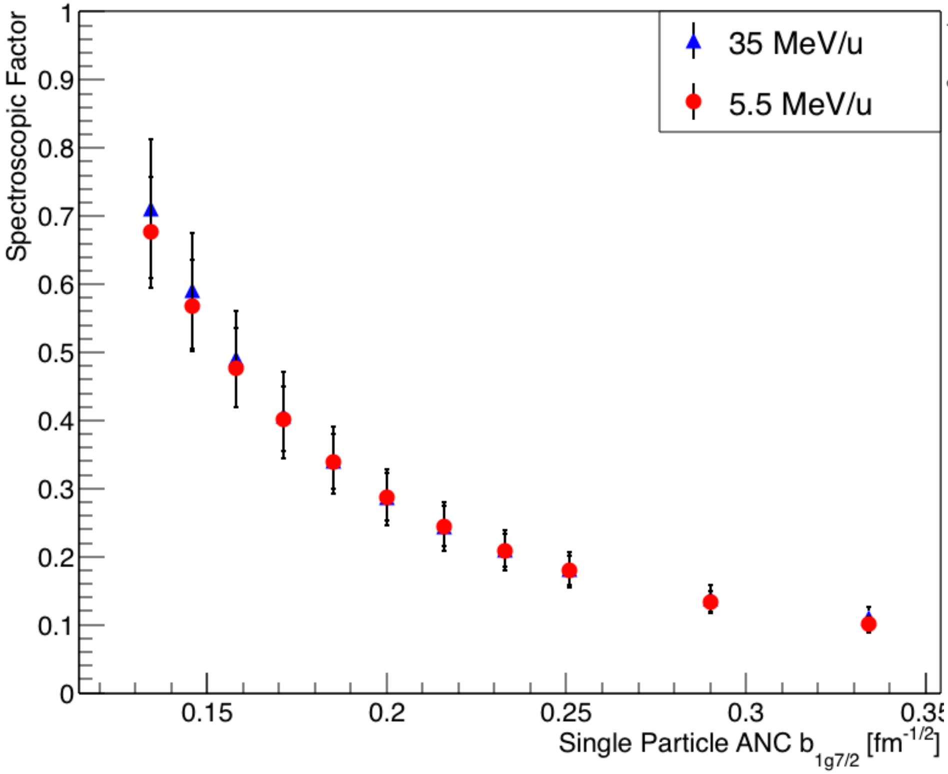


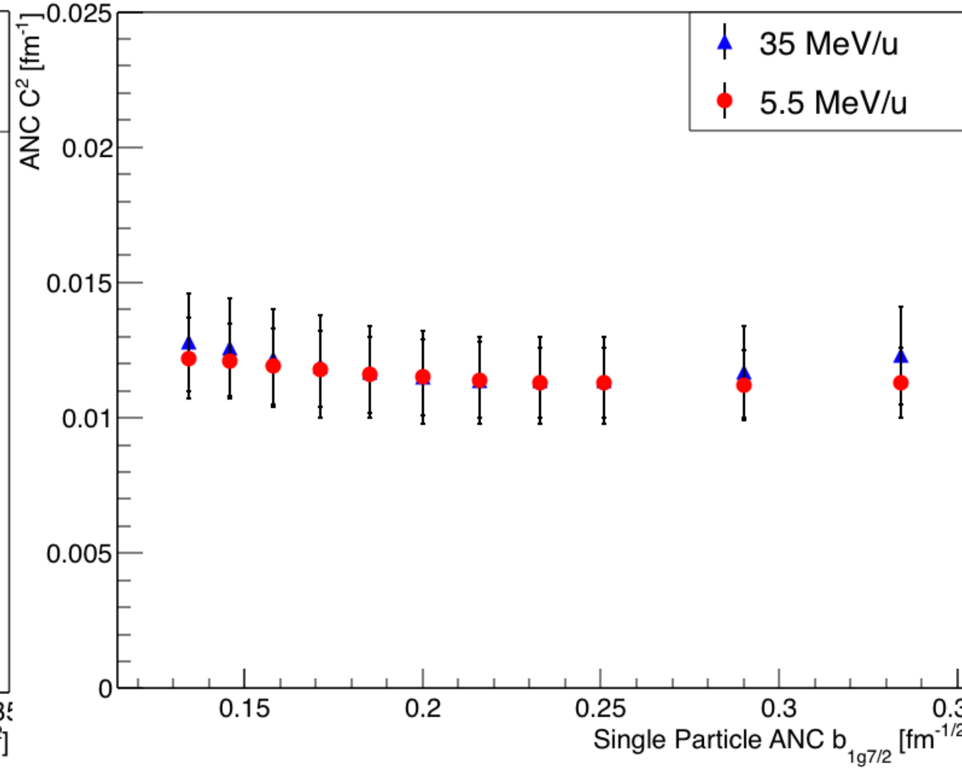
$7/2^{+}$ E_x = 2.5 MeV

ℓ=4 $1g_{7/2}$ transfer

Preliminary Angular Distributions

7/2+ Excited State, ℓ=4 $1g_{7/2}$ transfer E_x = 2.5 MeV





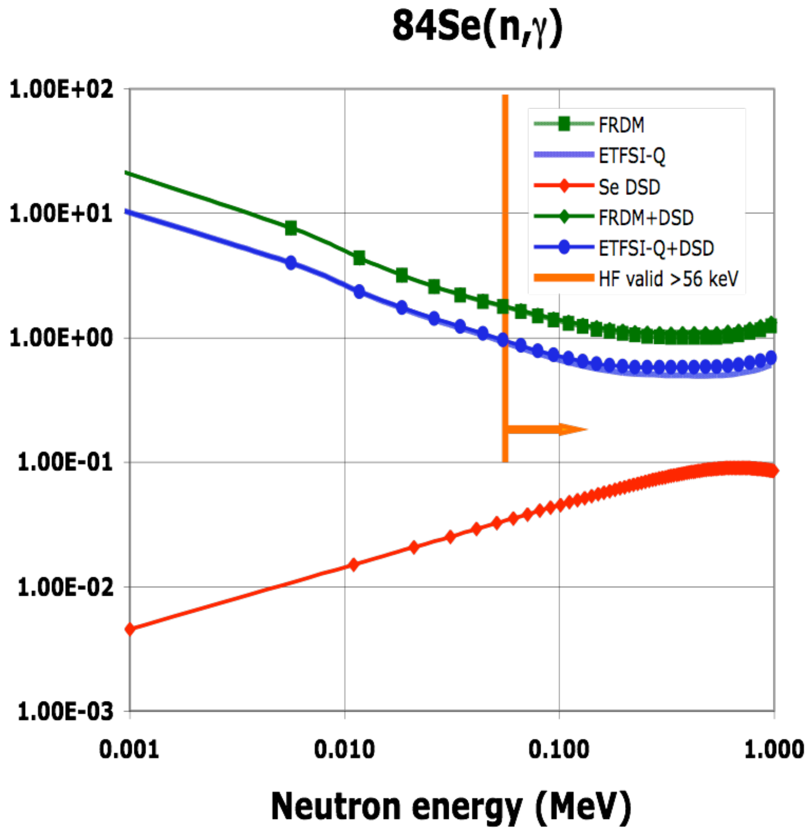
Even at 35 MeV/u ℓ=4 transfer is peripheral

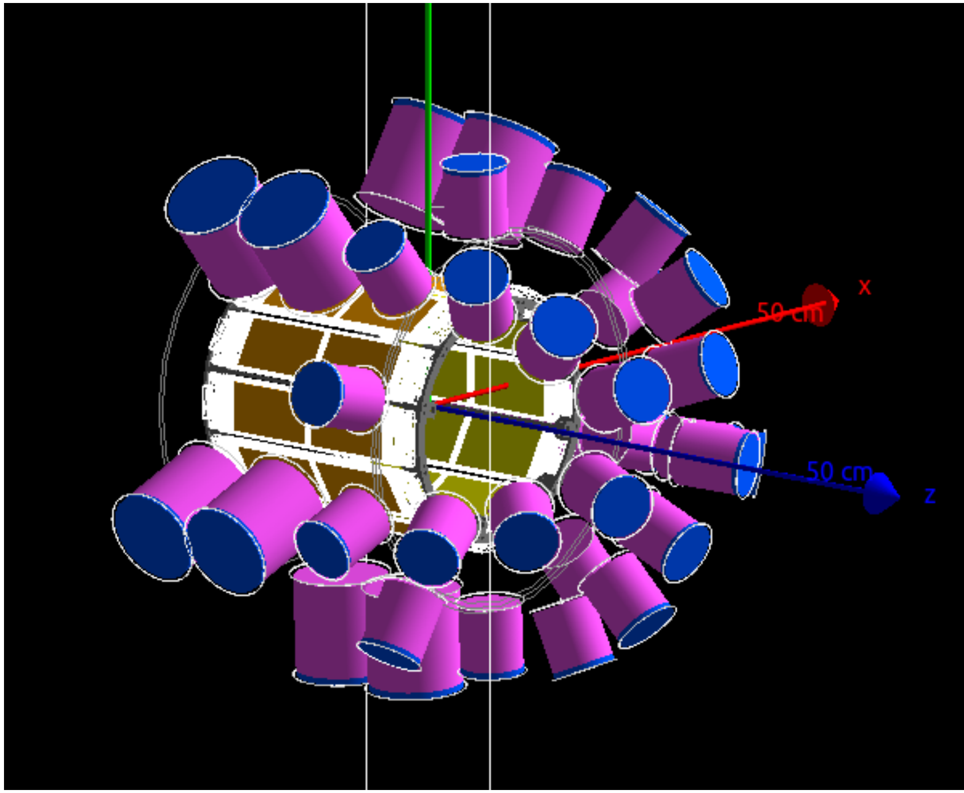
- Large centrifugal barrier?
- ℓ<3 transfer important for DSD capture

Next steps

- Demonstrated that by measuring (d,p) at different energies (and using modern reaction analysis) can constrain bound state potential parameters for ℓ<3 configurations
- Constraining properties of ^{85}Se states
  - Combine 4.5 MeV/u previous data
  - Approved to measure ^{84}Se(d,p) at 40 MeV/u
  - Goal: constrain bound state potential for ground (5/2+) and 1st excited (1/2+ states)
  - Recalculate DSD (n,γ)

Next steps





- Going beyond direct capture
  - Valid surrogate for (n,γ) = (d,pγ) – see Jutta Escher talk
  - Plans to measure ^{80}Ge(d,pγ) at NSCL with ORRUBA + HAGRiD

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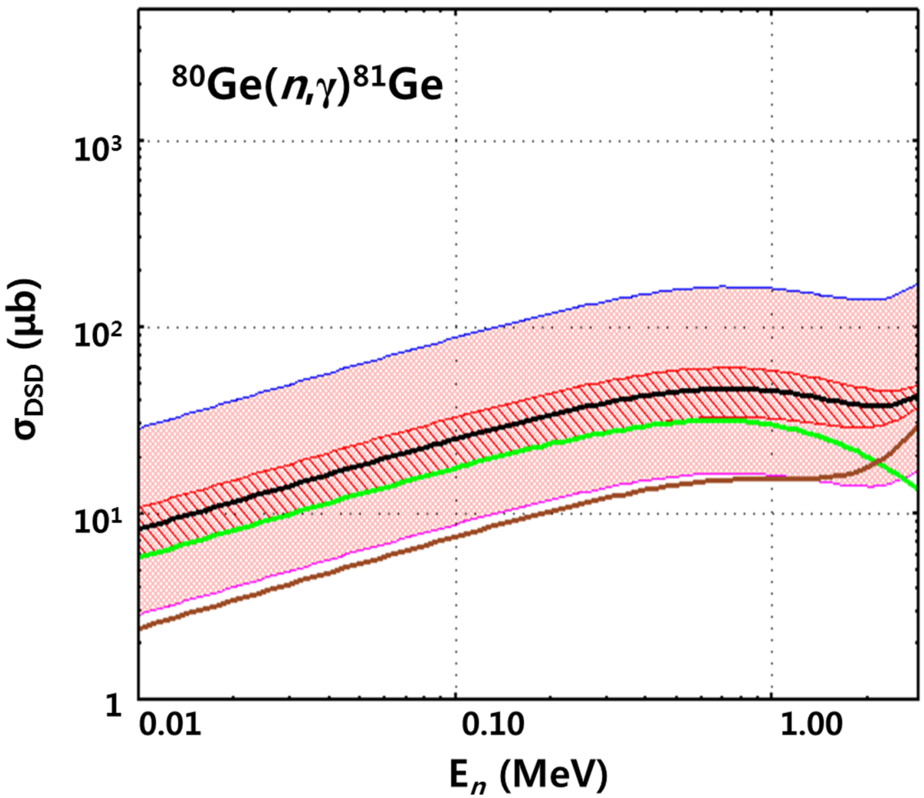
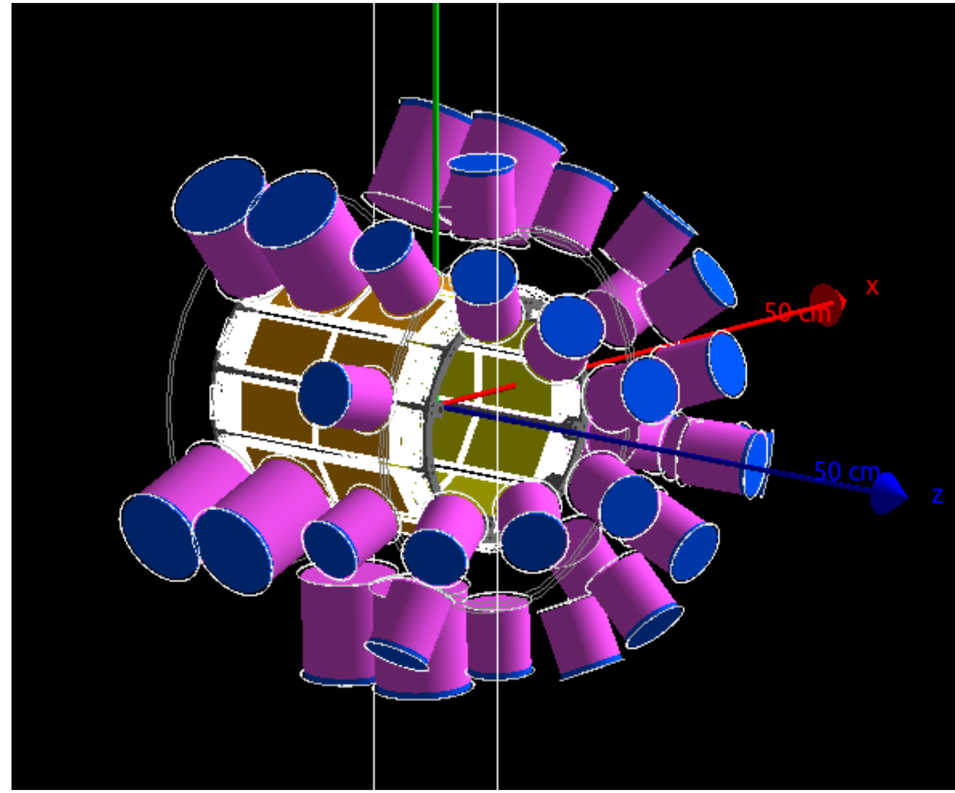
Next steps





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Summary and Outlook

- Combined method
  - Treating the ambiguities in S that arise from shape of bound state potential
- ^{86}Kr(d,p) proof of principle
  - Preliminary ground state results show constrained region of single particle ANC => determine r_0 and a
  - Challenge: not valid for ℓ>2
  - However, low-ℓ most important for (n,γ) surrogate
- Perspectives
  - Use method with radioactive ion beam of ^{84}Se(d,p) at ~40 MeV/u
    - Proposal has been approved at NSCL, to be run in 2018
  - Combine with previous measurements at 4.5 MeV/u at the Holifield Radioactive Ion Beam Facility (HRIBF)
    - J.S. Thomas et al., Phys. Rev. C **76**, 044302 (2007)
- Going beyond direct-semi-direct (n,γ) via (d,pγ) surrogate

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Thank you for your attention!

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Rutgers University

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Stewardship Science Academic Alliances Program