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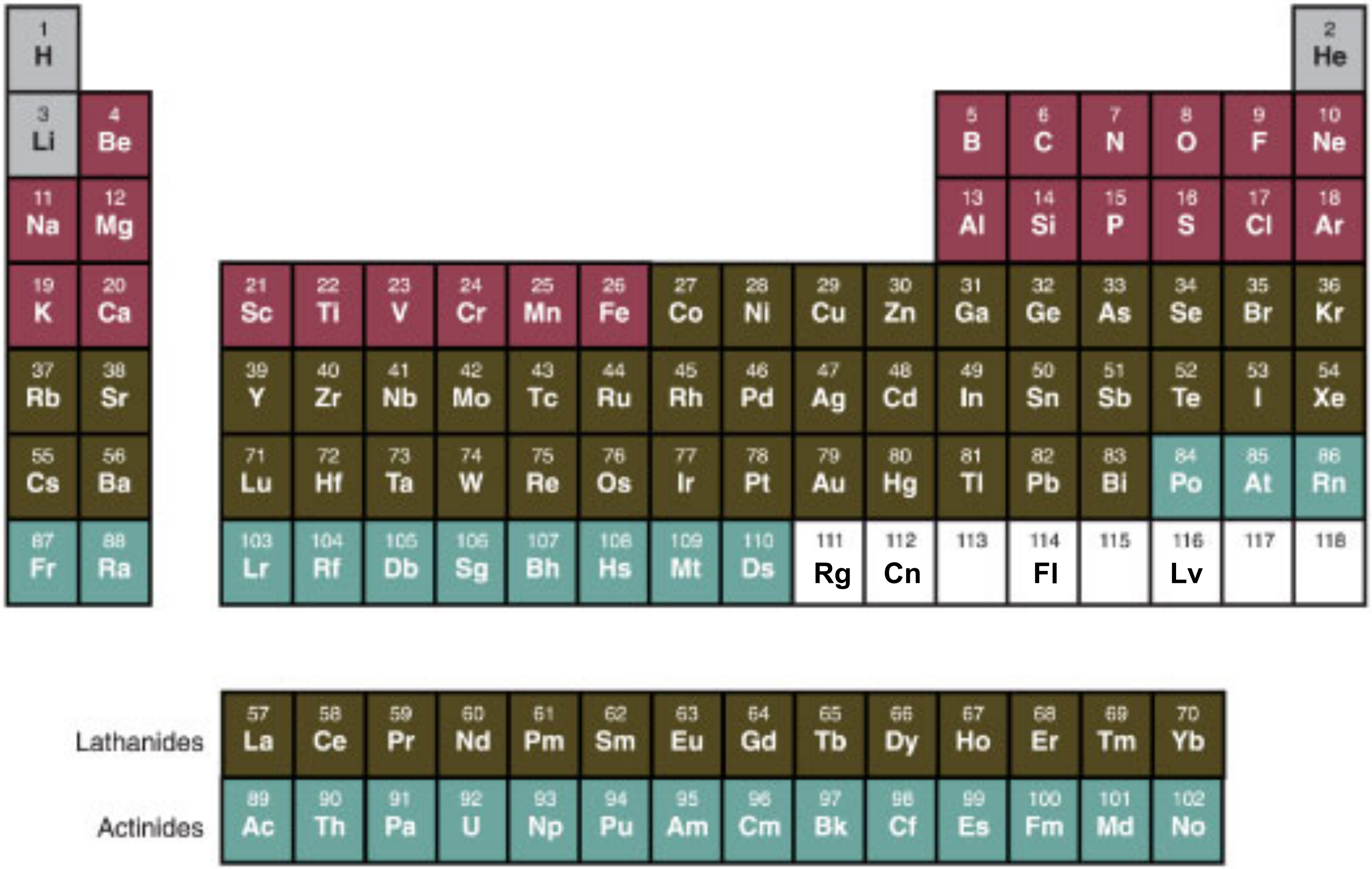
Gamma-ray spectroscopy from the (d,p) reaction and a surrogate for neutron capture

Jolie A. Cizewski
Rutgers University

5th Workshop on Nuclear Level Density and Gamma Strength
Oslo, Norway May 18 - 22, 2015

One of top 11 outstanding questions in astrophysics:

How are the elements heavier than iron synthesized in stars?



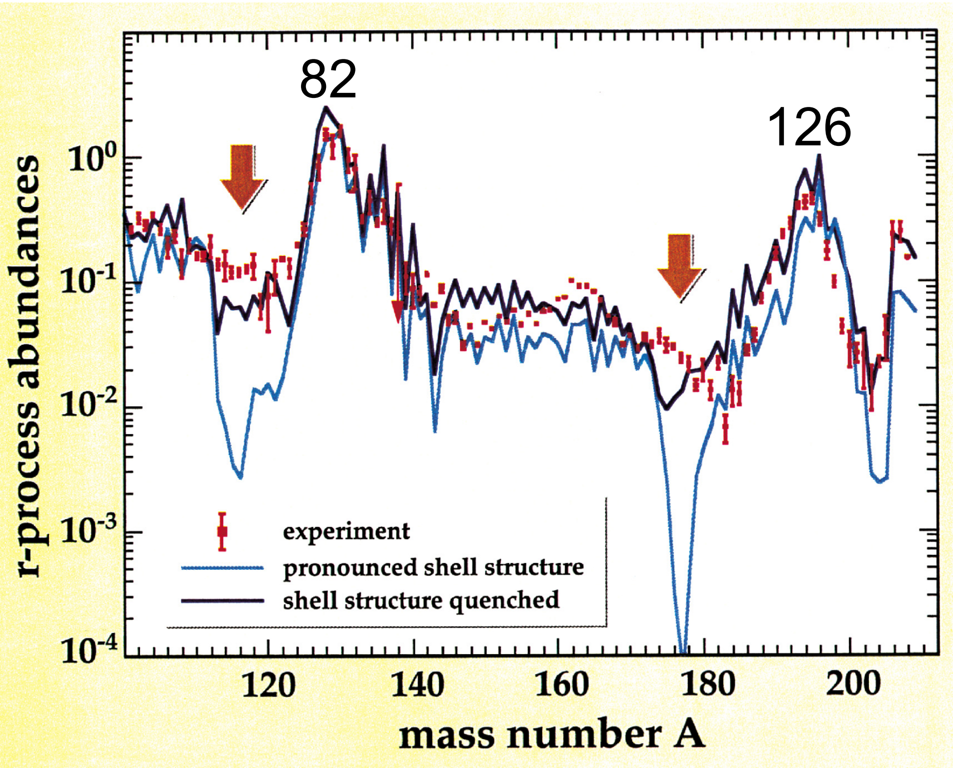
L.A. Bernstein, LLNL S&TR July 2007

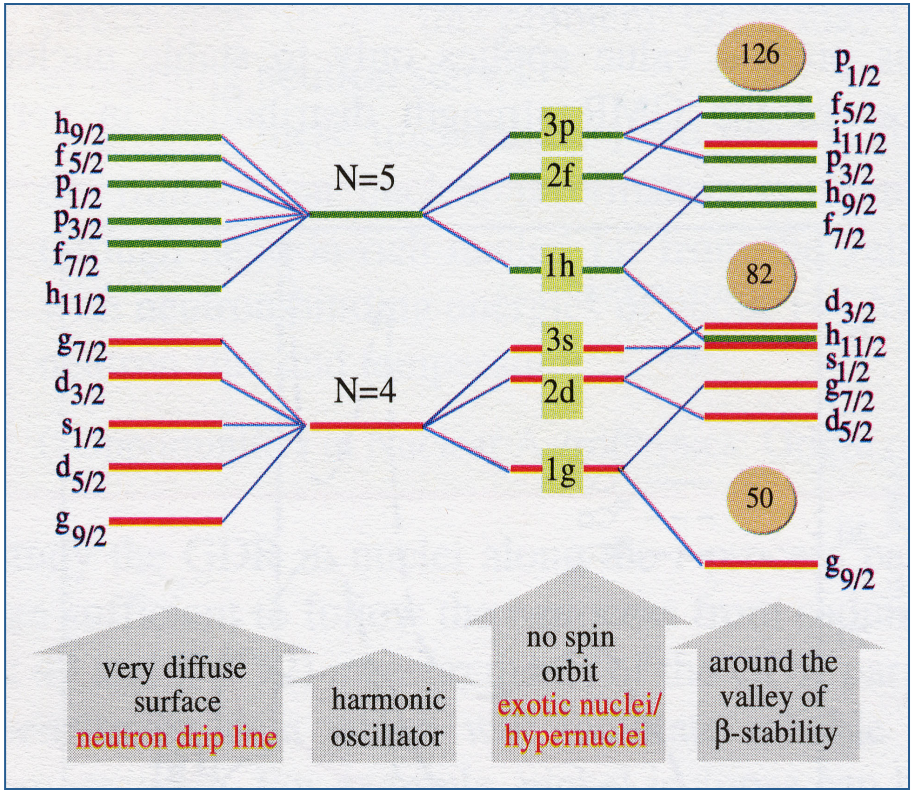
Neutron Capture

$A(n,\gamma)A+1$ Reactions

- Important for basic and applied nuclear science
  - Nucleosynthesis processes
    - s and r process responsible for elements heavier than iron
  - Nuclear reactors
    - Cross sections on fission fragments
  - Nuclear forensics
  - Stockpile stewardship
    - Fission fragments, radchem detectors, actinides
- On stable isotopes: well studied
- On rare isotopes:
  - Direct measurements when $t_{1/2}$ > 100 days
- **Can a reliable surrogate for (n,γ) be developed?**

r process abundances

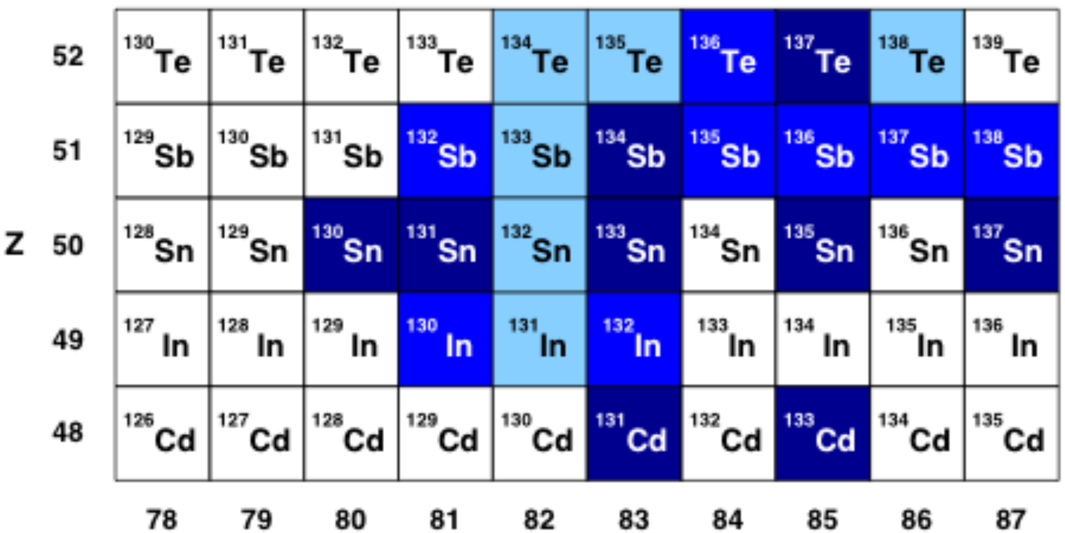


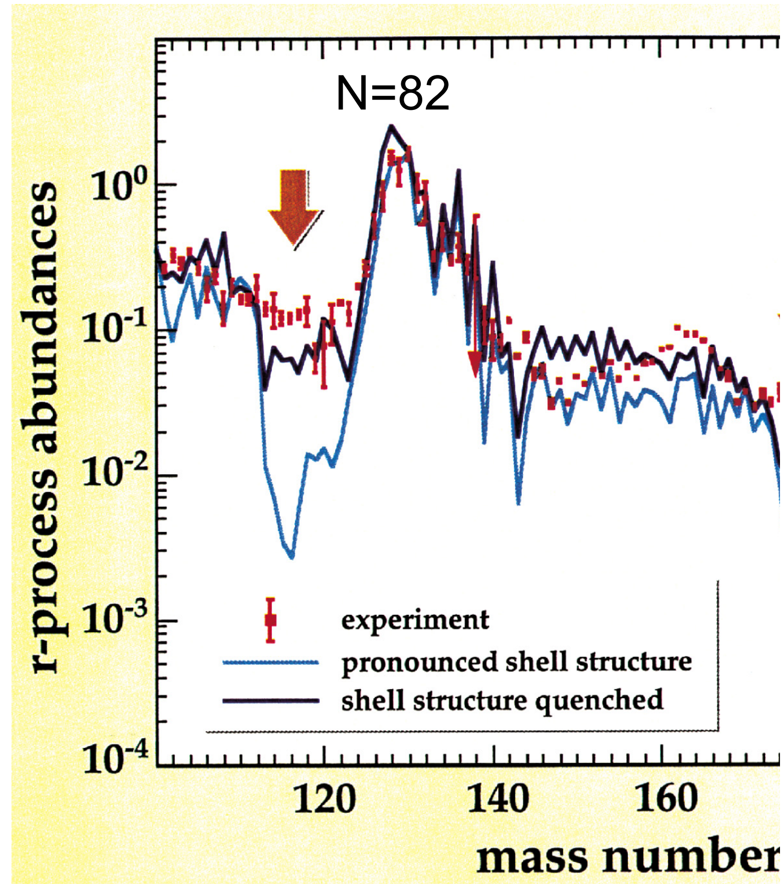


Challenges in reproducing r process abundances for n-rich N≈82 and ≈126 nuclei

A≈^{130}Sn σ(n,γ) and sensitivities

(n,γ) important during r process freezeout

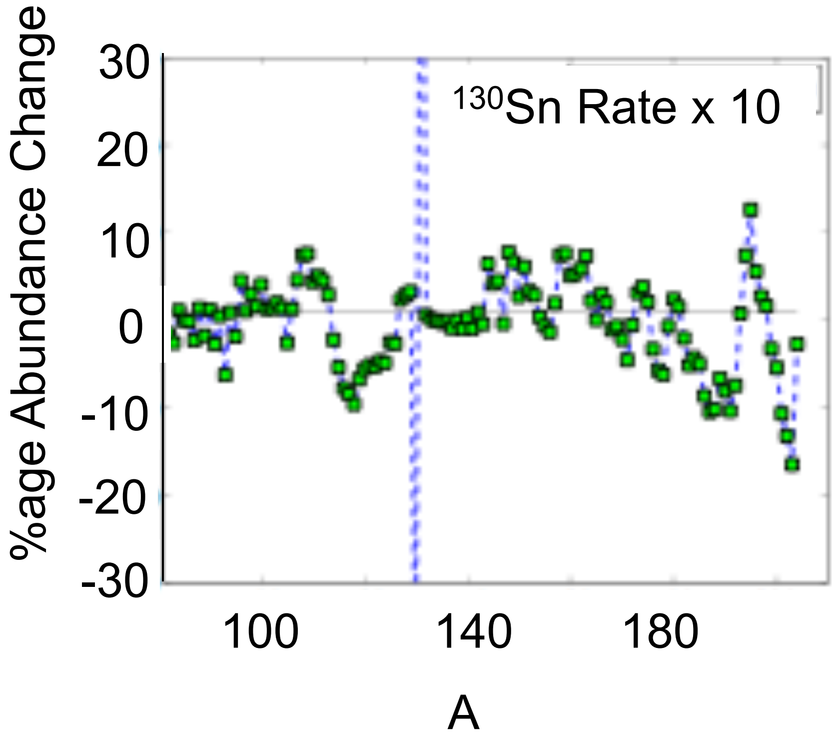


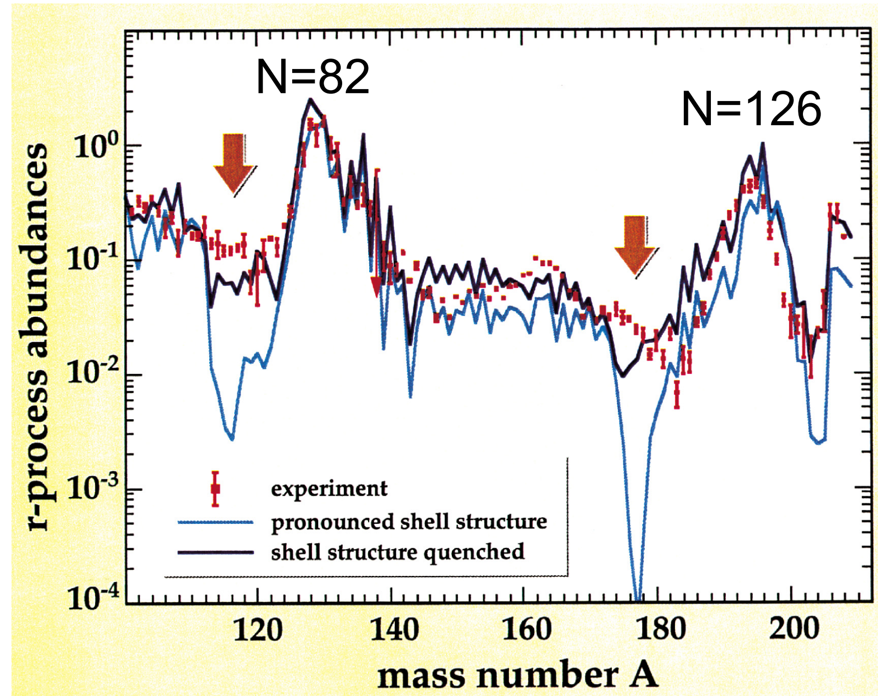


Changes in (n,γ) rates that change abundance patterns by at least 5%
Change factors:
Dark blue: x10; become neutron sinks

R. Surman, J. Beun, G.C. Mclaughlin, W.R. Hix, Phys. Rev. C **79**, 045809 (2009)

r-process sensitivity studies





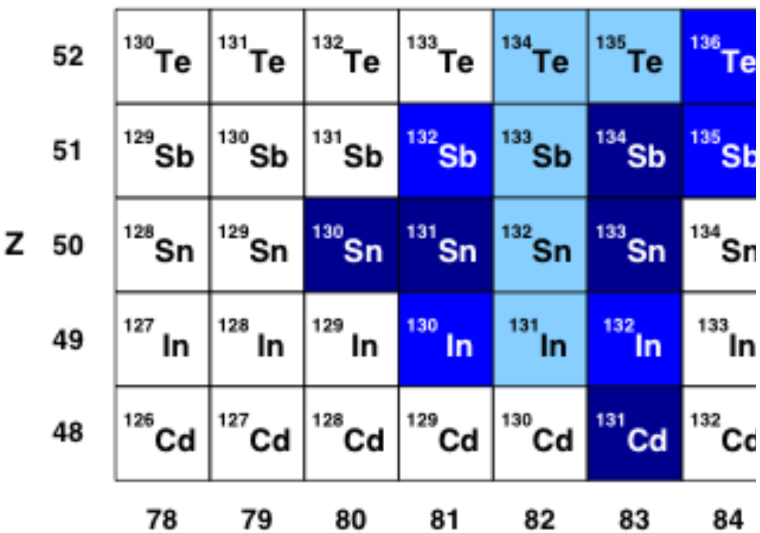
Simulations of the r-process show huge, **global** sensitivity to the ^{130}Sn(n,γ) rate, in contrast to the ^{132}Sn(n,γ) rate.

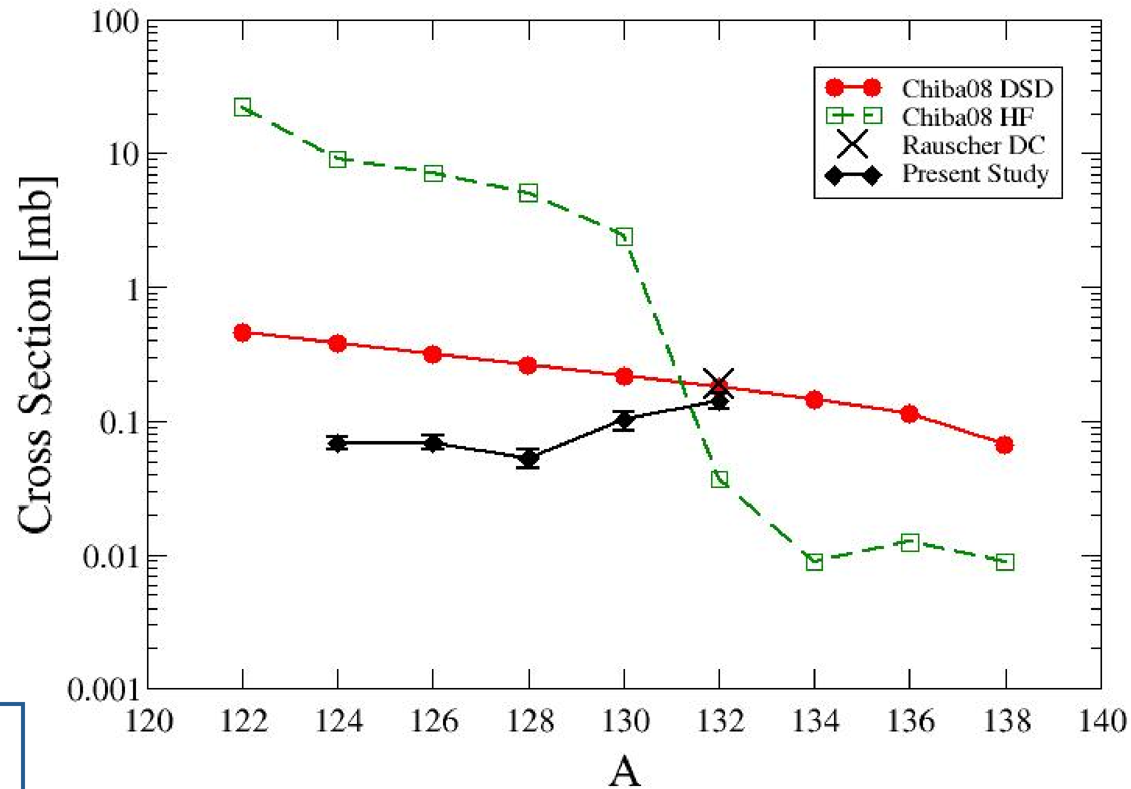
$t_{1/2}(^{130}\mathrm{Sn}) = 162\mathrm{s}$

J. Beun, *et al.* J. Phys. G 36, 025201 (2009)

A≈^{130}Sn σ(n,γ) and sensitivities

Direct-semi-direct and CN (n,γ)





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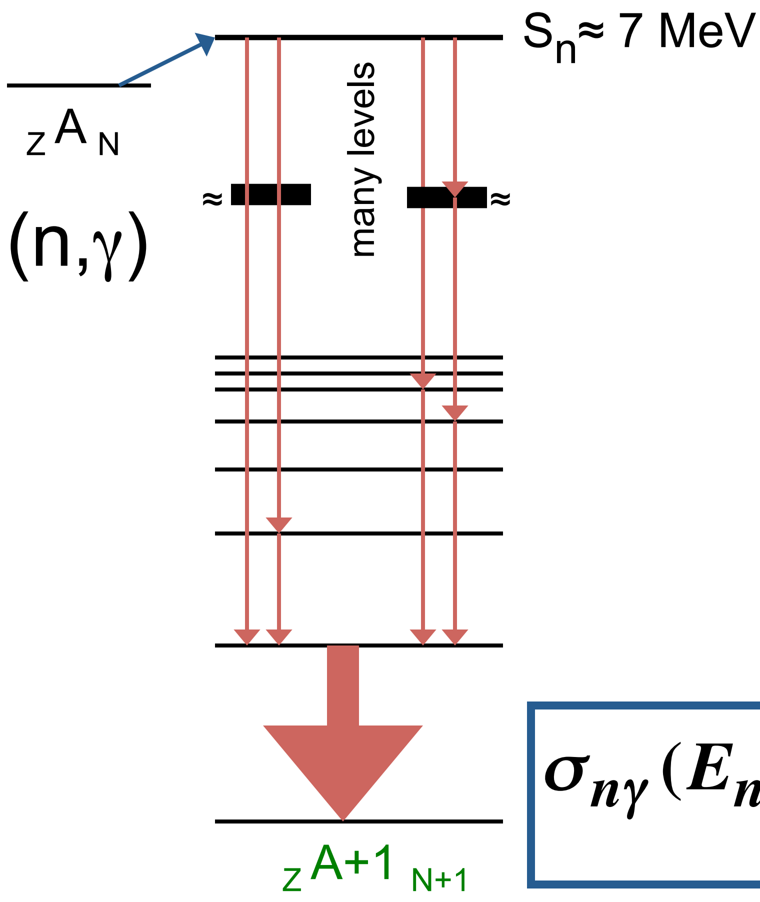
R. Surman, J. Beun, G.C. Mclaughlin, W.R. Hix, Phys. Rev. C **79**, 045809 (2009)

Sn(n,γ) vs A
Chiba, et al. PRC **77**, 015809 (2008)
B. Manning PhD Dissertation (2014)

A(n,γ)(A+1)



- Cross section vs neutron energy depends upon product of cross section of formation of compound nucleus AND decay of the compound nucleus
  - In principle for each spin,parity
- Theorists can calculate formation; difficult to calculate decay
  - Need level density and strength function far from stability

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

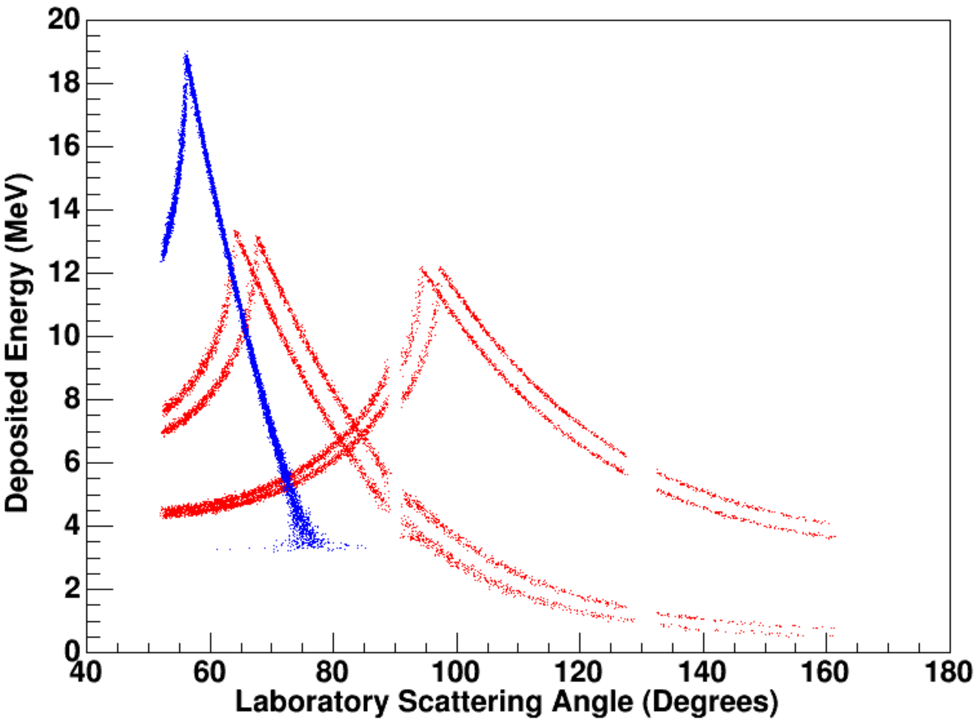
r process nucleosynthesis

- Need surrogate (n,γ) to determine $\sigma(n,\gamma)$
  - Inform decay of CN
  - Constrain level density and strength function
- Reaction well-suited for radioactive ion beam studies in inverse kinematics
- CN $\sigma(n,\gamma)$ for very neutron-rich nuclei AND near N=82 shell closures
  - What is the gamma strength function?
  - What is the level density?

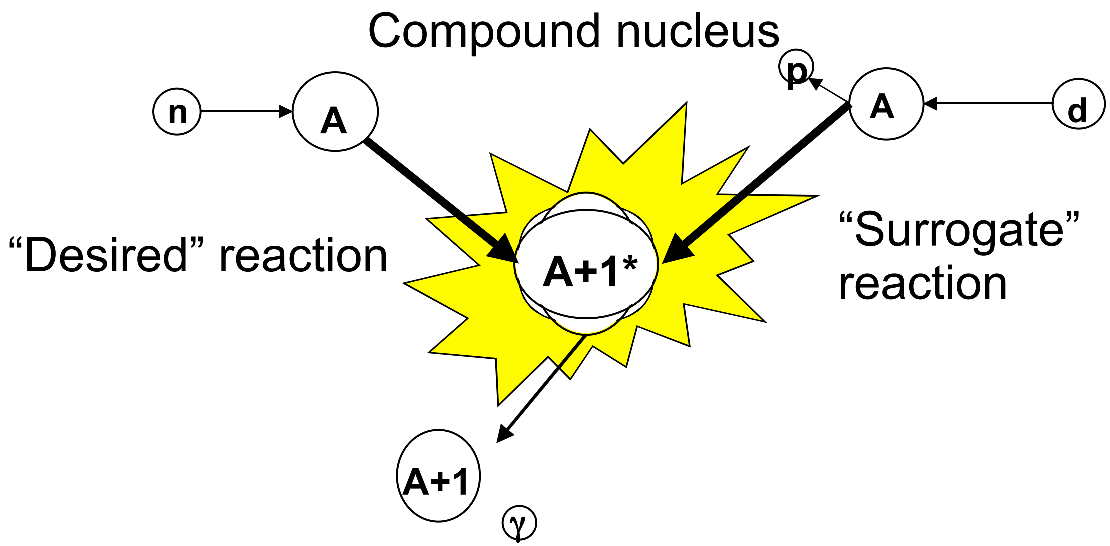
(d,pγ)

Good candidate for (n,γ) surrogate with beams

- Relatively good match with spin distribution in (n,γ) which is dominated by $\ell=0$
- "Lower" beam energies (than heavier targets) to get above neutron separation energy
- Reaction predominantly one-step transfer of $j=\ell\pm1/2$ neutrons
- "Easy" to produce CD_2 targets
- Kinematics favors cleaner reaction



Surrogate reaction concept



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

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

Surrogate cross section can be written as product of compound nucleus formation and decay for every spin and parity:

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

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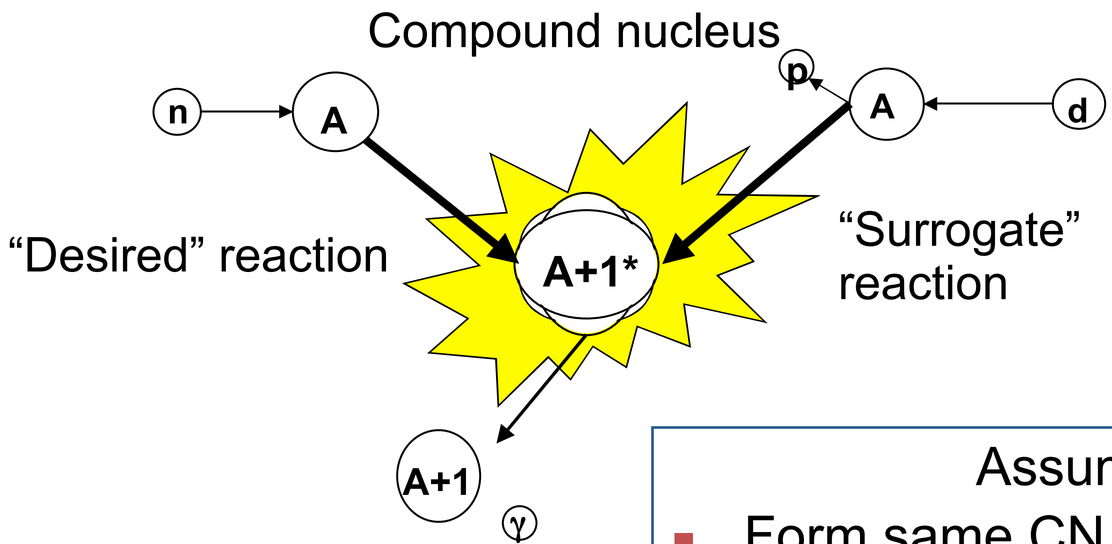
Surrogate reaction W-E Limit



Assumptions:

- Form same CN with surrogate and F=1
- Weisskopf-Ewing limit: CN pop & decay indep of spin, parity

$$\sigma_{n\gamma}^{WE}(E_n) = \sigma_n^{CN}(E_n) G_\gamma^{CN}(E_n) = \sigma_n^{CN}(E_n) \frac{N(d,p\gamma)}{\varepsilon N(d,p)}$$

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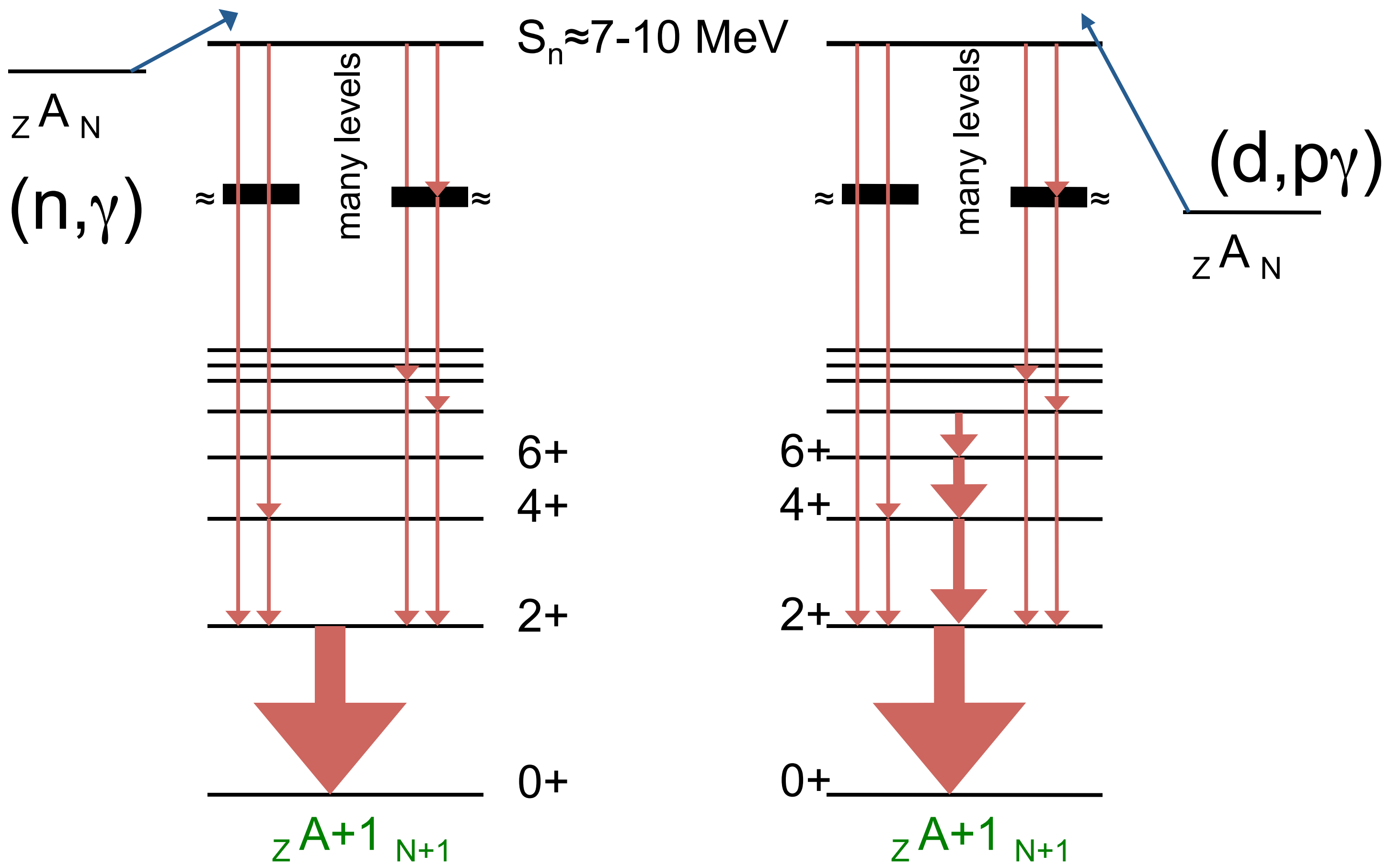
Surrogate for (n,γ) and discrete transitions



Collecting transition(s) OR

Sidefeeding, e.g., subtract $I(4^+ \Rightarrow 2^+)$ from $I(2^+ \Rightarrow 0^+)$

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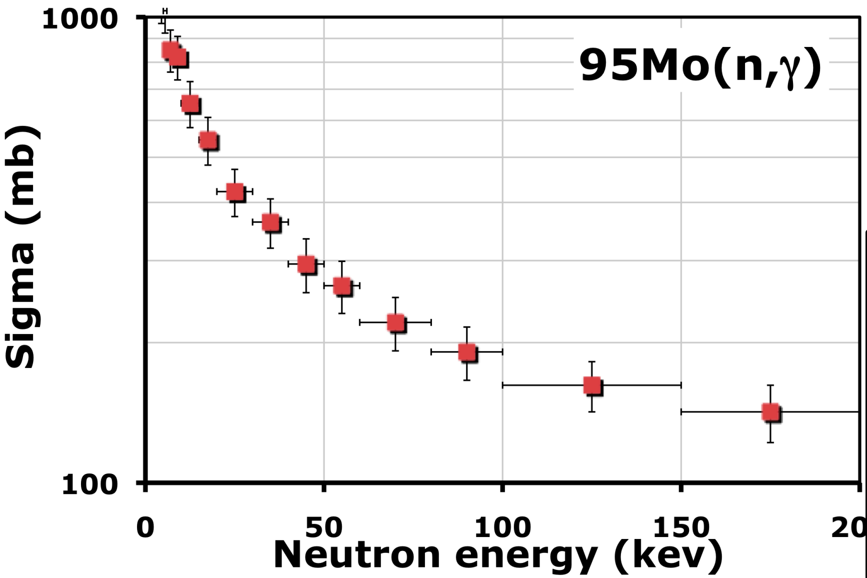
Preparing for surrogate (n,γ) with RIBs

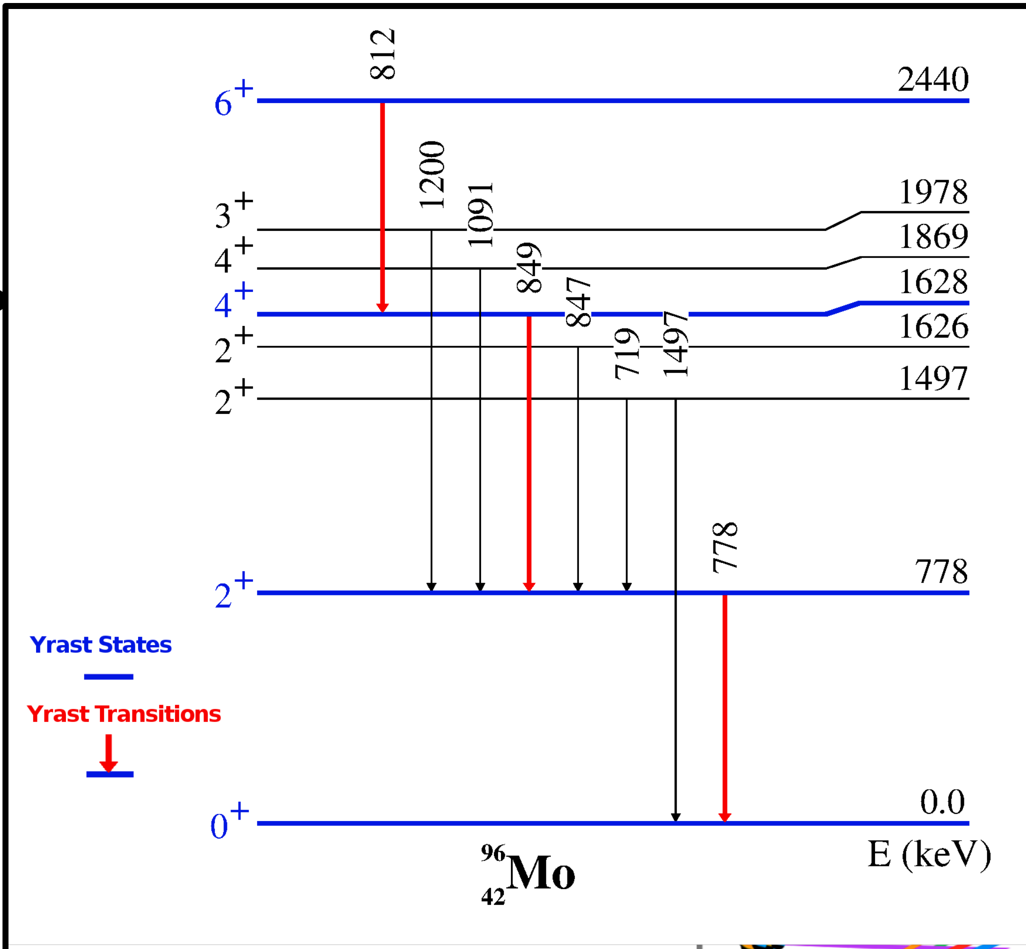
Validating surrogate method for $\sigma(n,\gamma)$ on ^{95}Mo

- Measure $(d,p\gamma)$ normal kinematics with STAR-LiTeR
    - Preliminary results
- Measure $(d,p\gamma)$ inverse kinematics
    - Plans for approved experiment

^{95}Mo: Known (n,γ) and ^{96}Mo levels

Musgrove, et al., NPA **270**, 109 (1976)





^{96}Mo level scheme

778 keV collecting transition

^{95}Mo(d,pγ) Collaboration

A. Ratkiewicz, J.A. Cizewski, S. Burcher, B. Manning, S.L. Rice, C. Shand *Rutgers University*

J. Burke, R.J. Casperson, J.E. Escher, N.D. Scielzo, I. Thompson, *Lawrence Livermore National Laboratory*

M. McCleskey, *Texas A&M University*

S. Ota, *Japan Atomic Energy Agency*

C.W. Beausang, R.O. Hughes, T.J. Ross, *University of Richmond*

R.A.E. Austin, *St. Mary's University*

W.A. Peters, *Oak Ridge Associated Universities*

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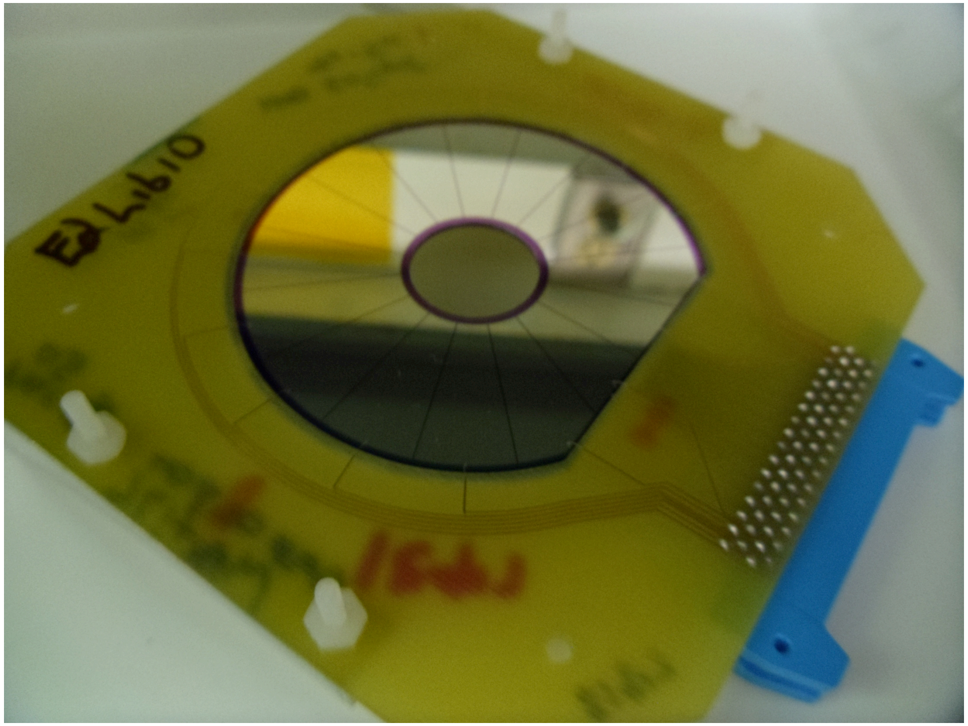
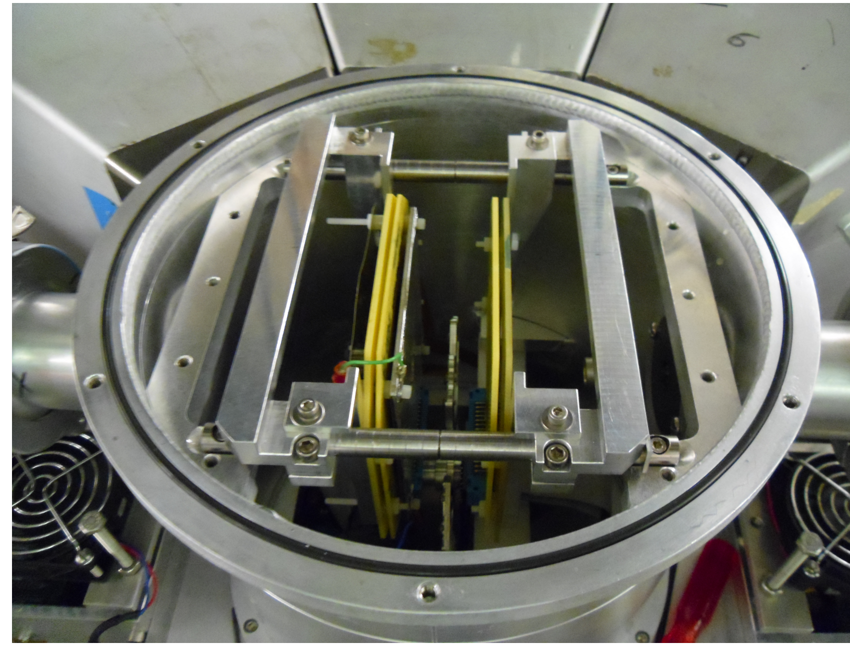
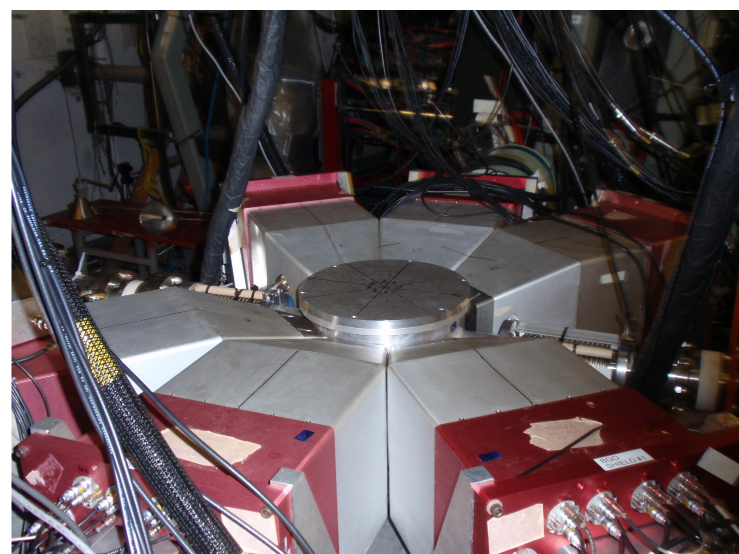
^{95}Mo(d,pγ) at TAMU with STARLiTeR







- 0.960 mg/cm^2 thick ^{95}Mo target (~95% ^{95}Mo, 1.5% ^{96}Mo)
- Beam energy of 13 MeV.
- 140 μm +1000 μm segmented telescopes at forward, backward angles.
- Four HPGe Compton-suppressed clovers at 90, 220, 270, 320 degrees (lab frame).

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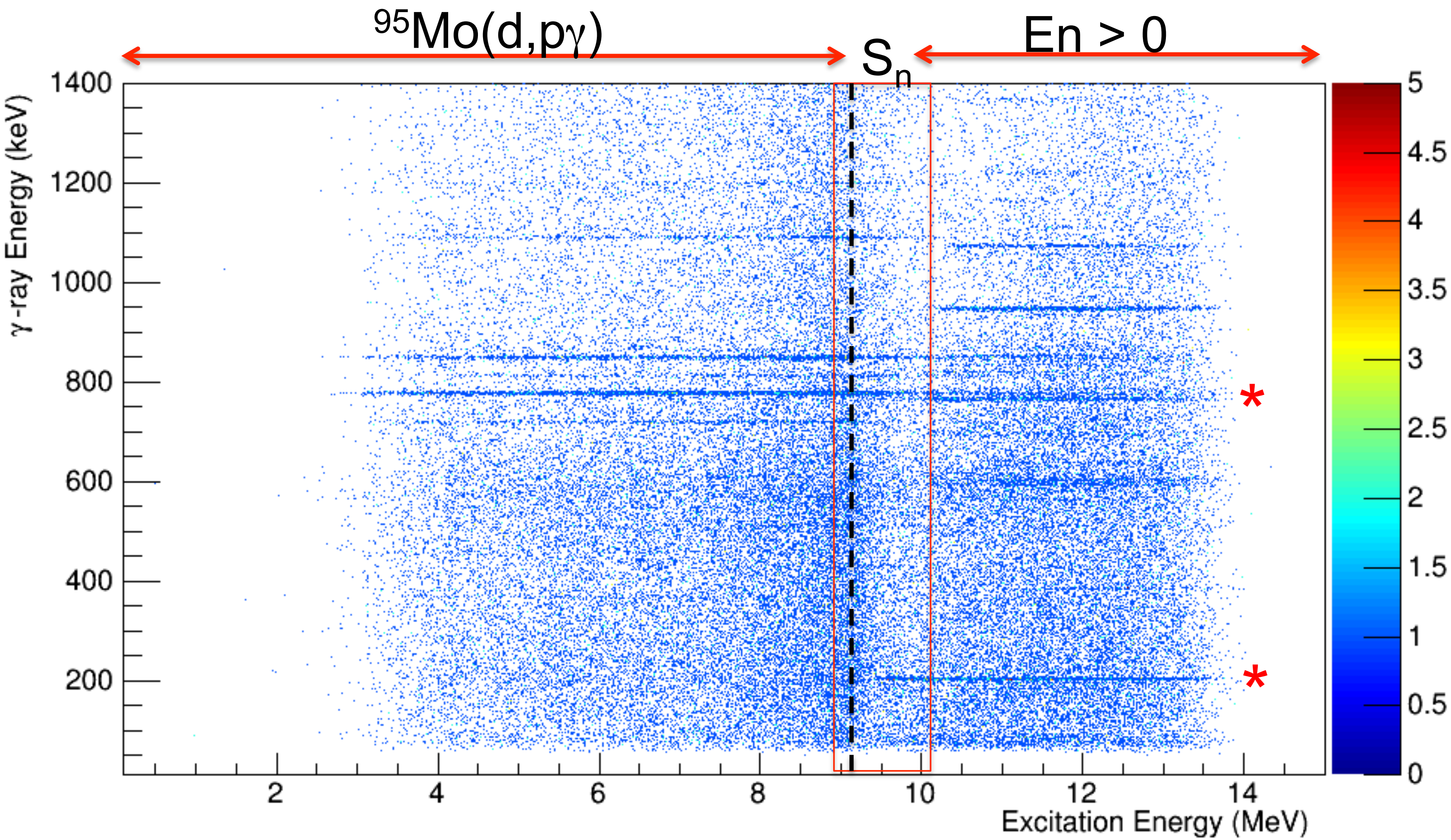
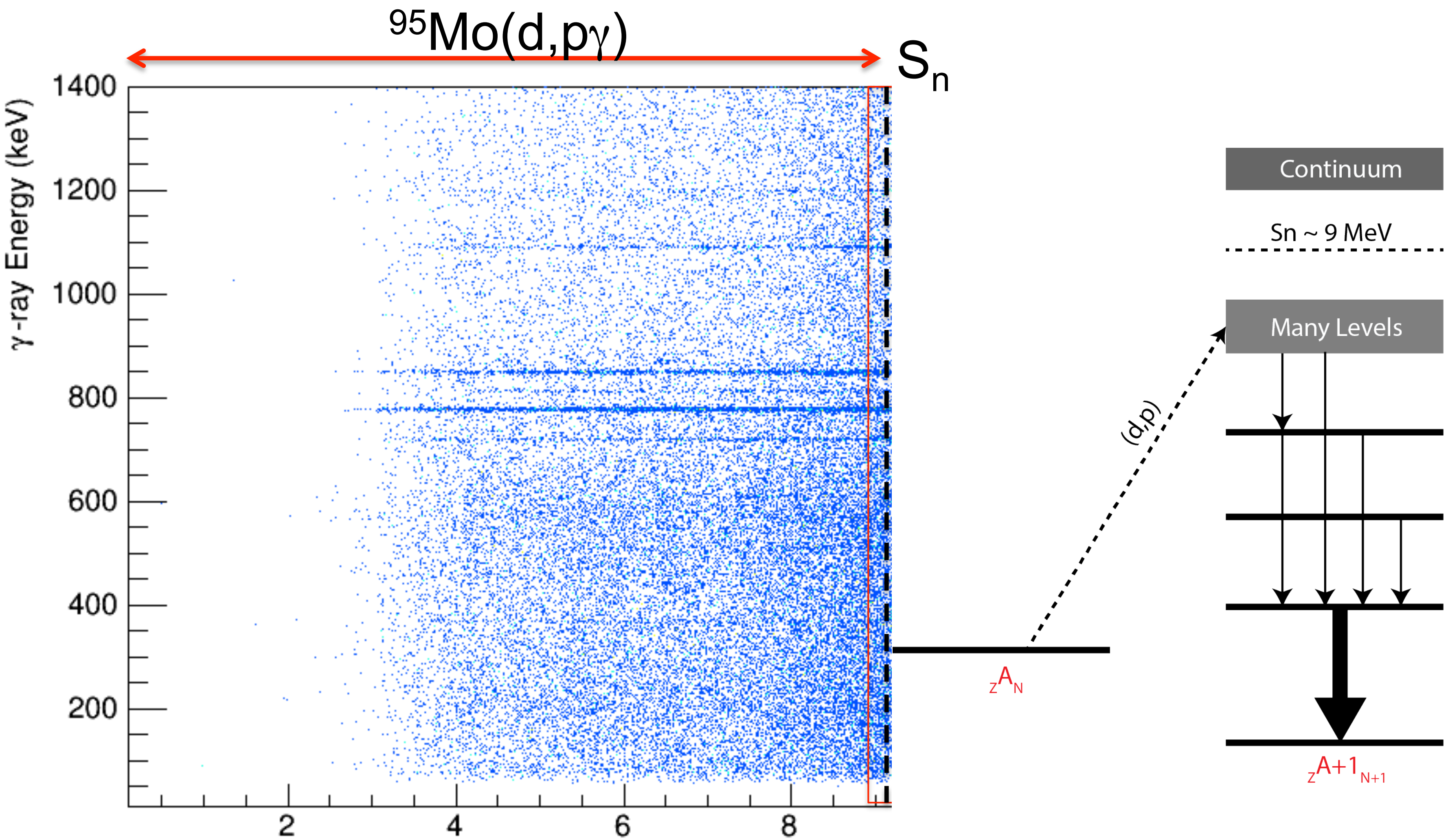
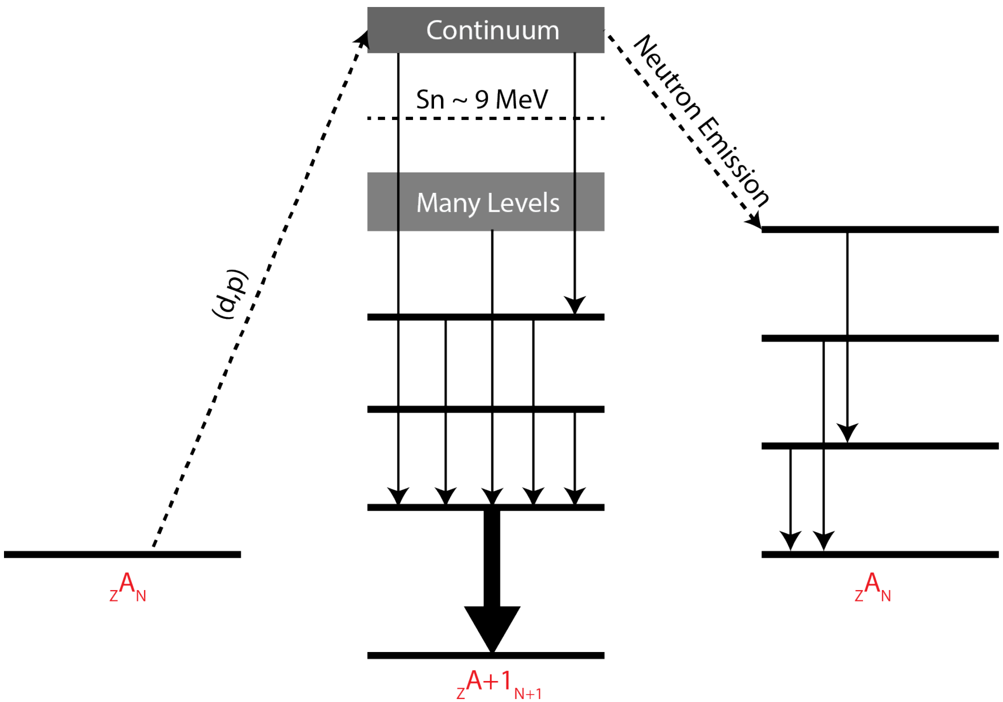
Particle-Gamma Matrix

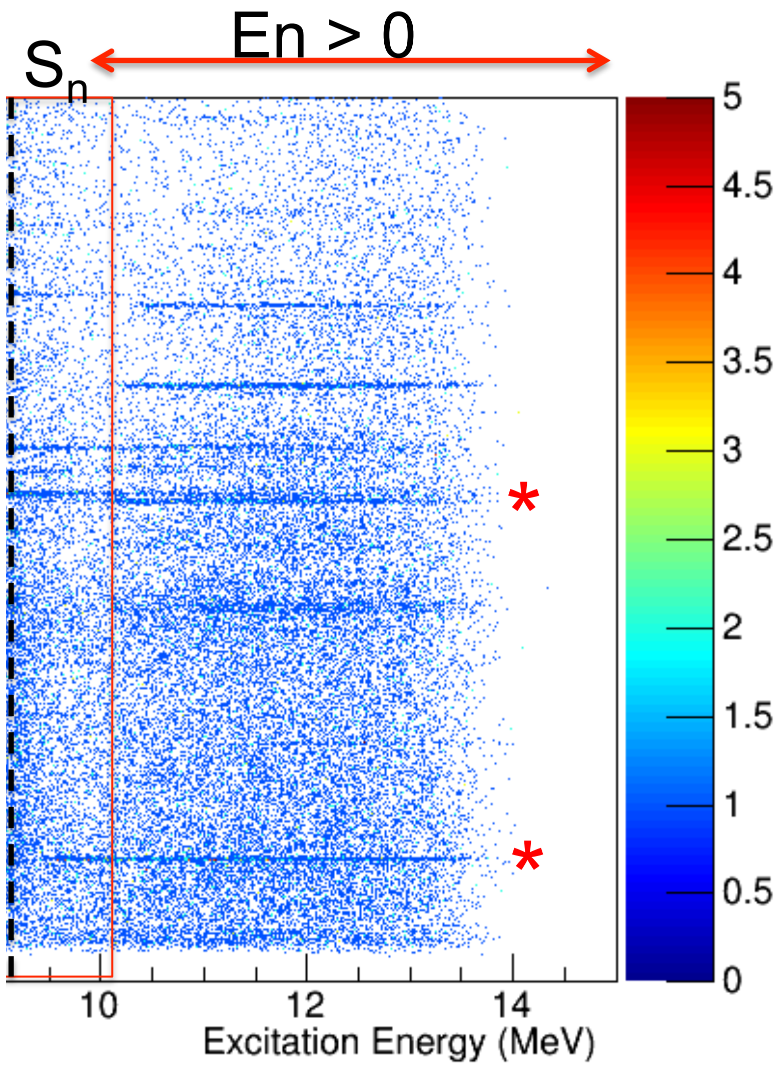


Particle-Gamma Matrix



Particle-Gamma Matrix





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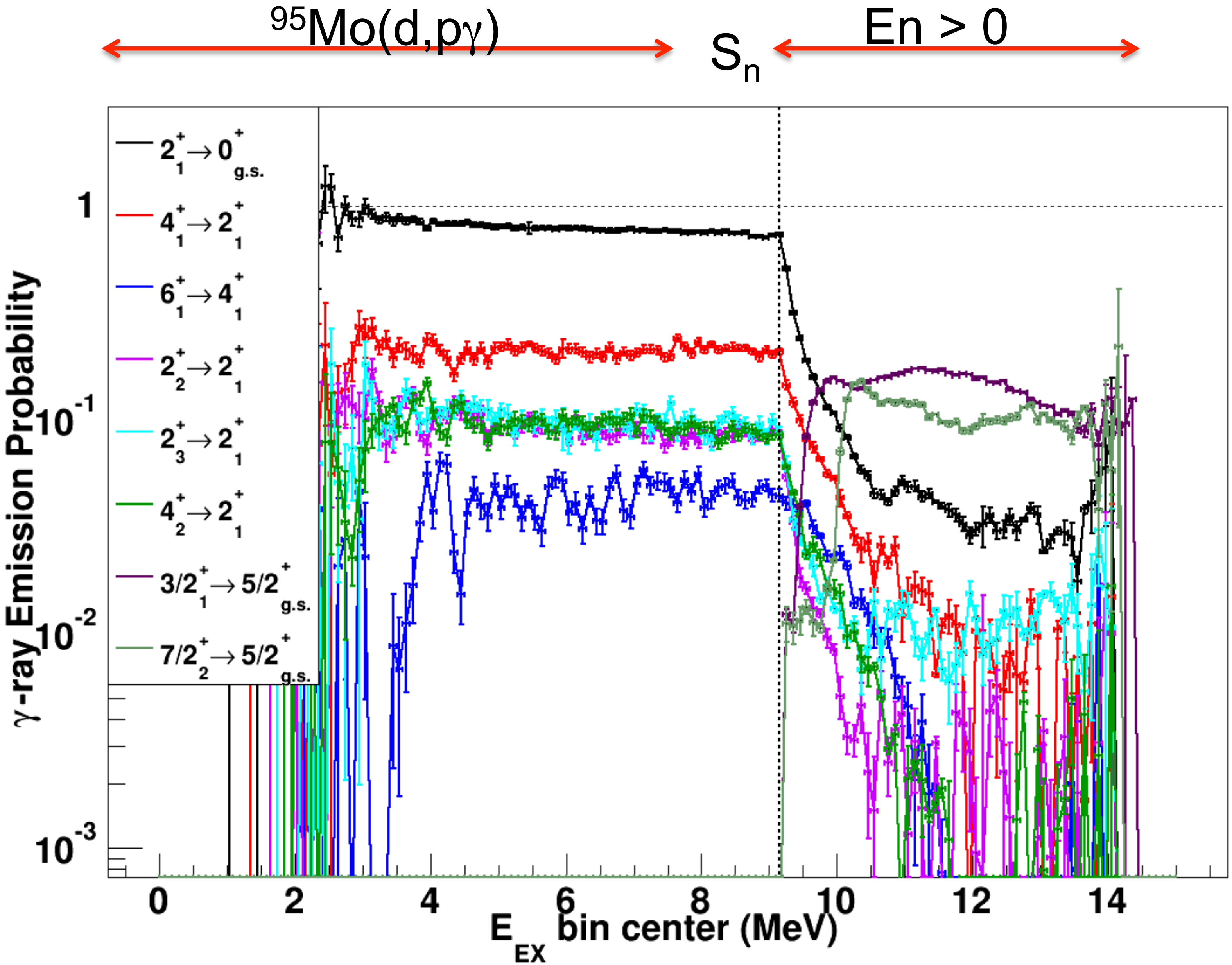
Gamma-ray Emission Probability



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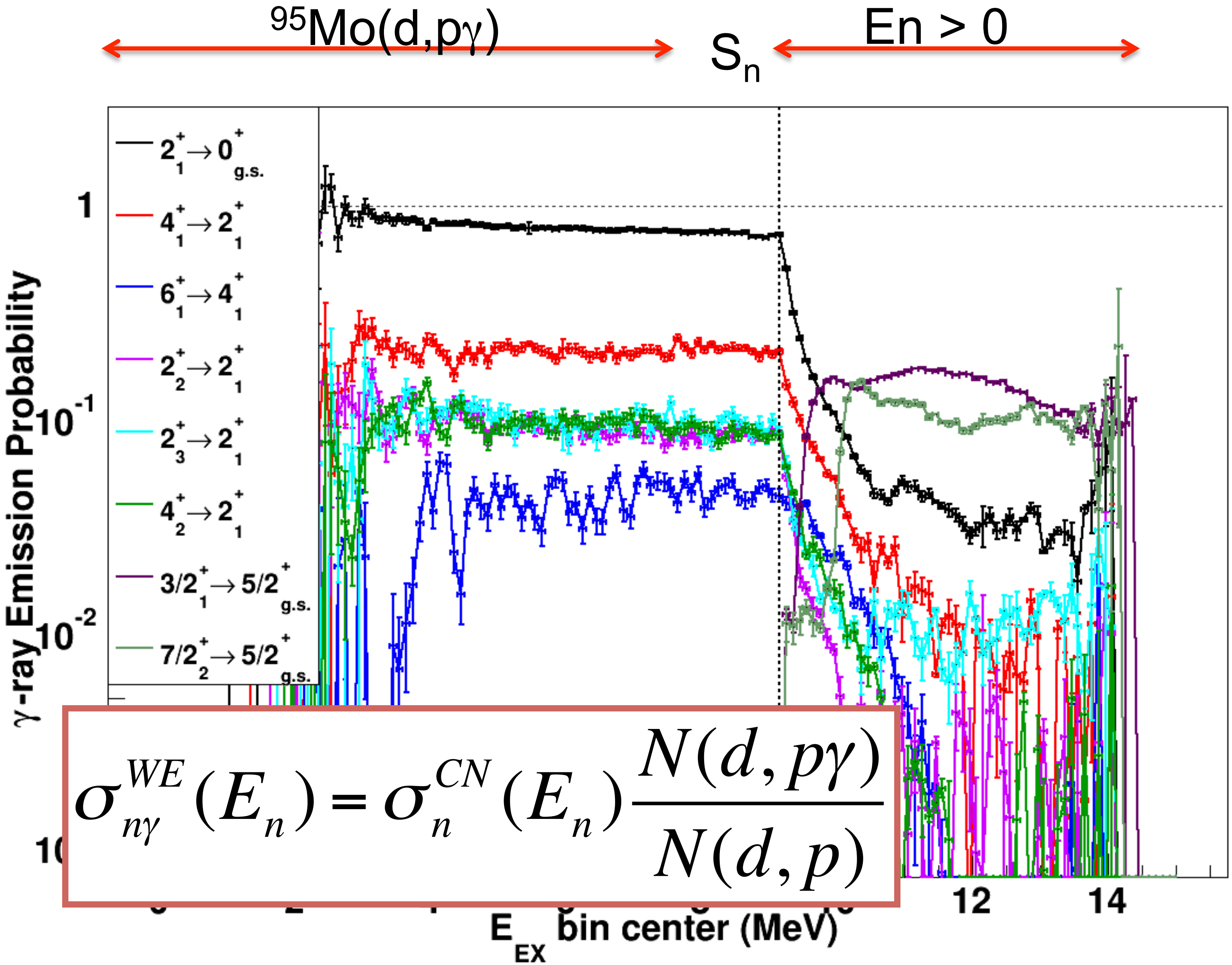

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^{95}Mo(d,pγ) Inverse kinematics collaboration

A. Ratkiewicz, T. Baugher, J.A. Cizewski, S. Burcher, S.M. Hardy, M.E. Howard, S. Lonsdale, B. Manning, C. Shand *Rutgers University*

S.D. Pain, *Oak Ridge National Laboratory*

K.L. Jones, *University of Tennessee-Knoxville*

M.P. Carpenter, D. Seweryniak, S.F. Zhu, *Argonne National Laboratory*

I. Marsh, *Univ. of Wisconsin-La Crosse*

D.W. Bardayan, *University of Notre Dame*

J. Blackmon, *Louisiana State University*

C.J. Lister, *Lowell University*

R.L. Kozub, *Tennessee Technological University*

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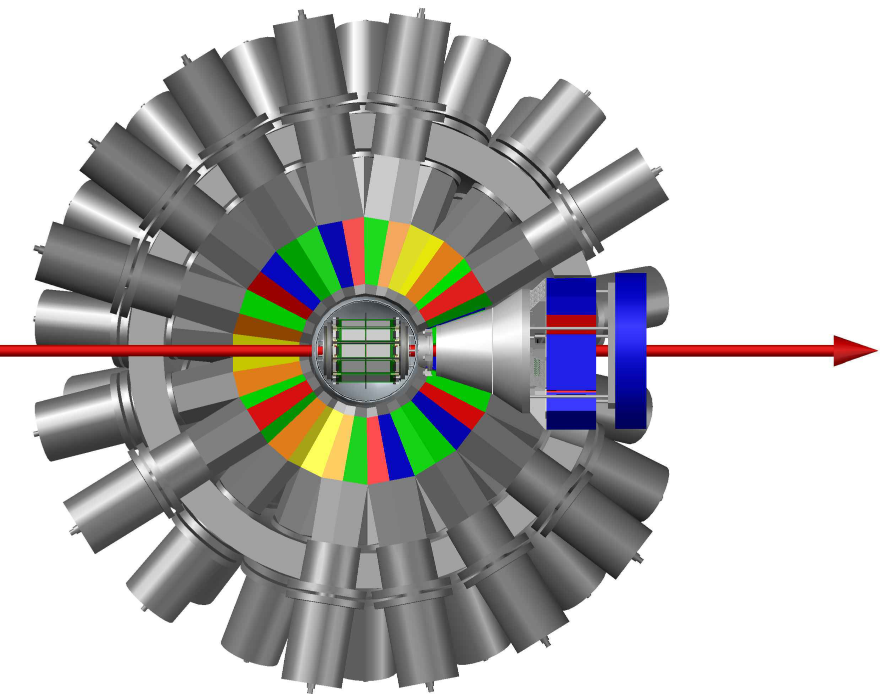
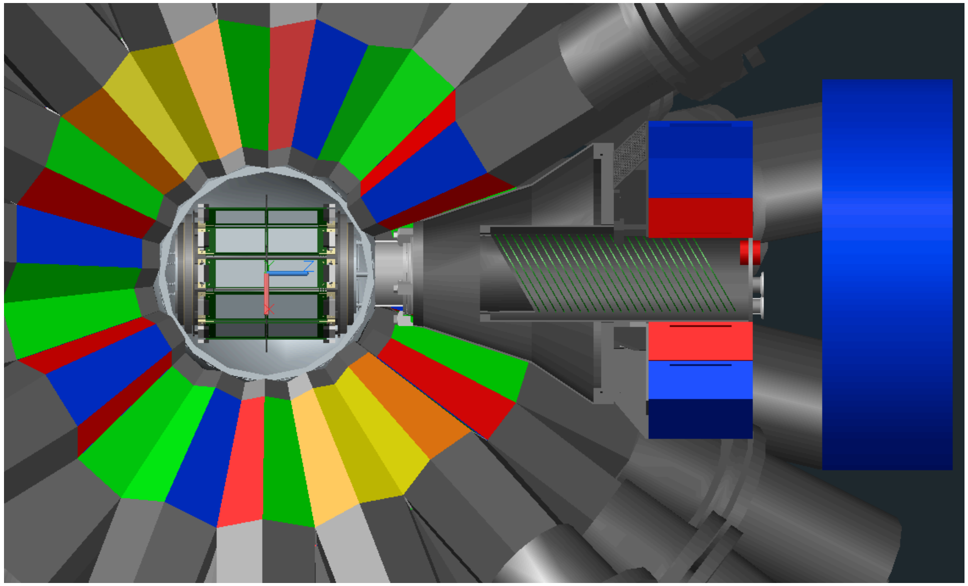
S. Ota, *Japan Atomic Energy Agency*

W.A. Peters, *Oak Ridge Associated Universities*

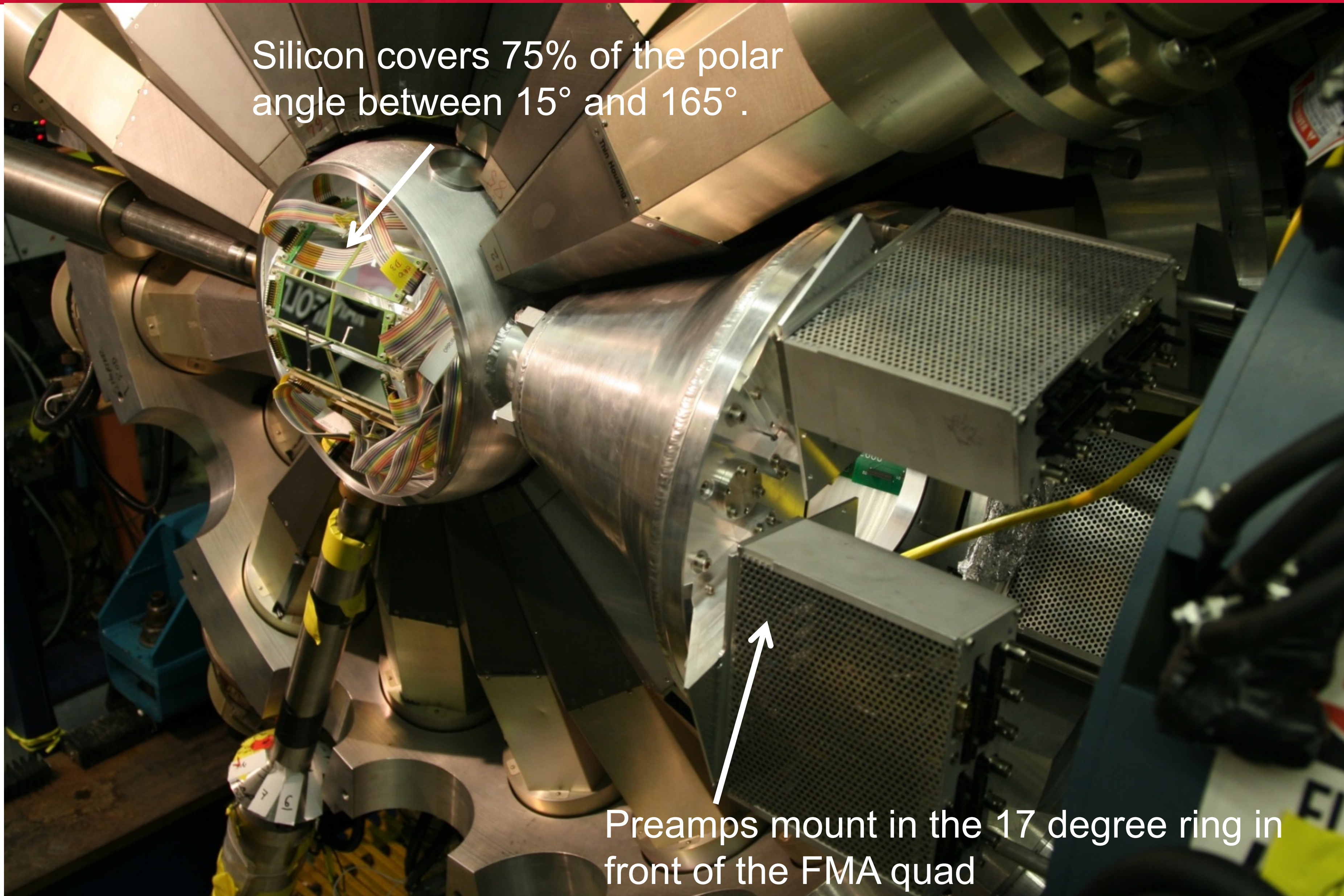
Future with ^{95}Mo beam and GODDESS (Gammasphere ORRUBA: Dual Detectors for Experimental Structure Studies)

- Development of (d,pγ) in inverse kinematics (with RIBs)
  - Coupling Si strip detector array ORRUBA + endcap to Gammasphere



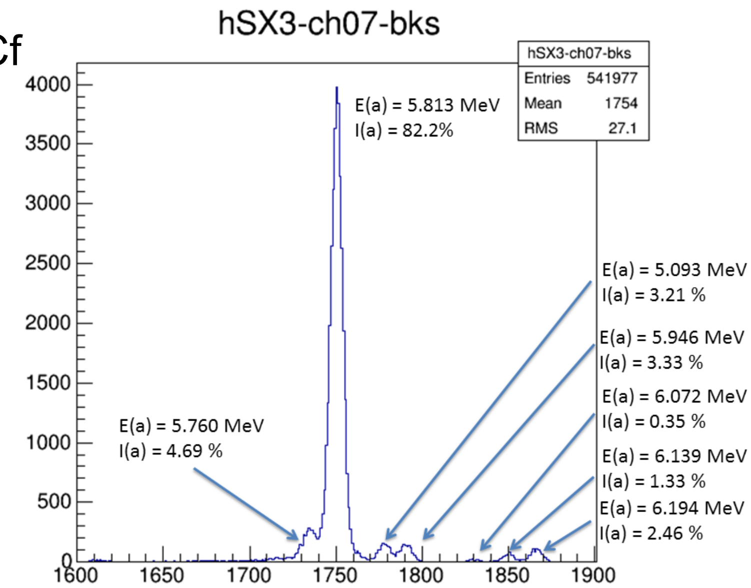


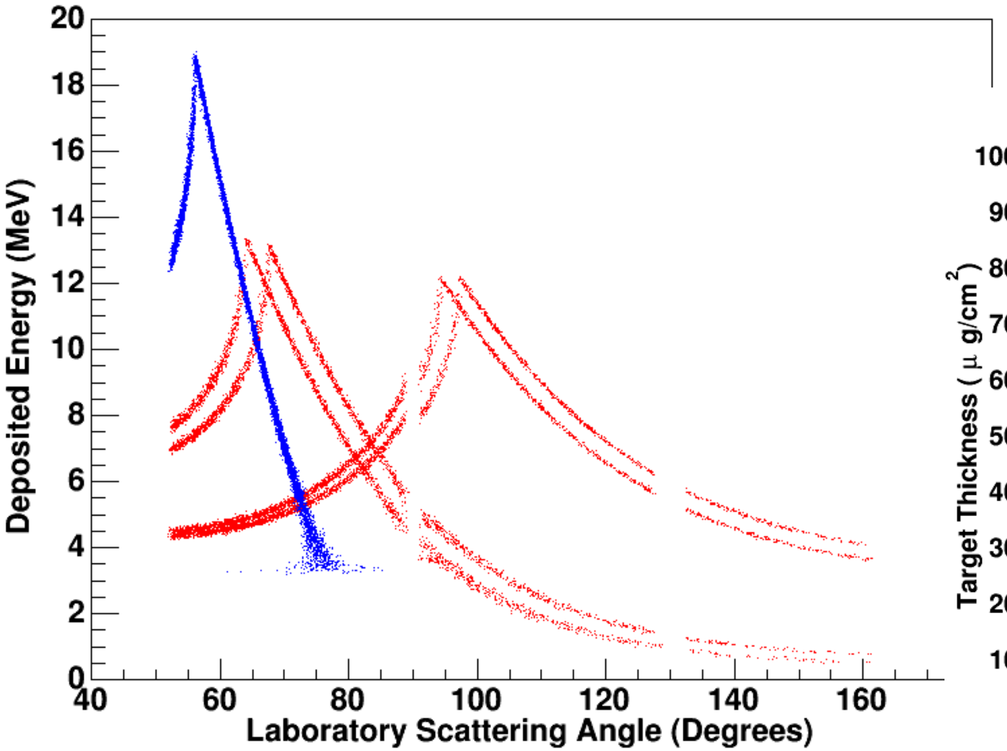
Engineering Test

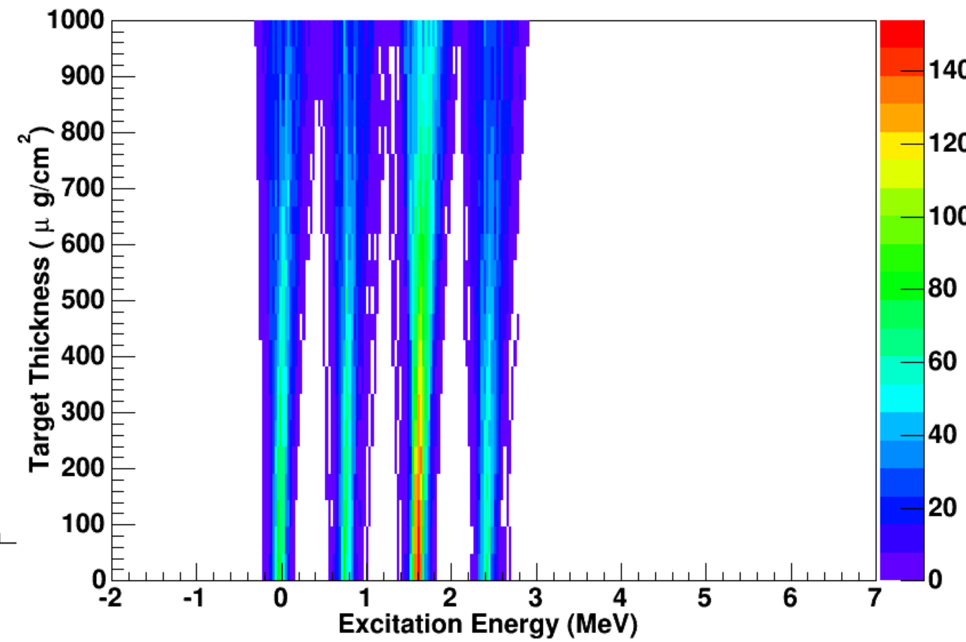


GODDESS Energy Resolution

- Energy resolution of ~26 keV FHWM for 5.8 MeV ^{249}Cf alpha particles – this is excellent.
- Position resolution < 0.75 mm – angular resolution is better than 1 degree.
- Great energy, position resolution means we can use thicker targets (shorter runs/more exotic beams) without sacrificing resolution.

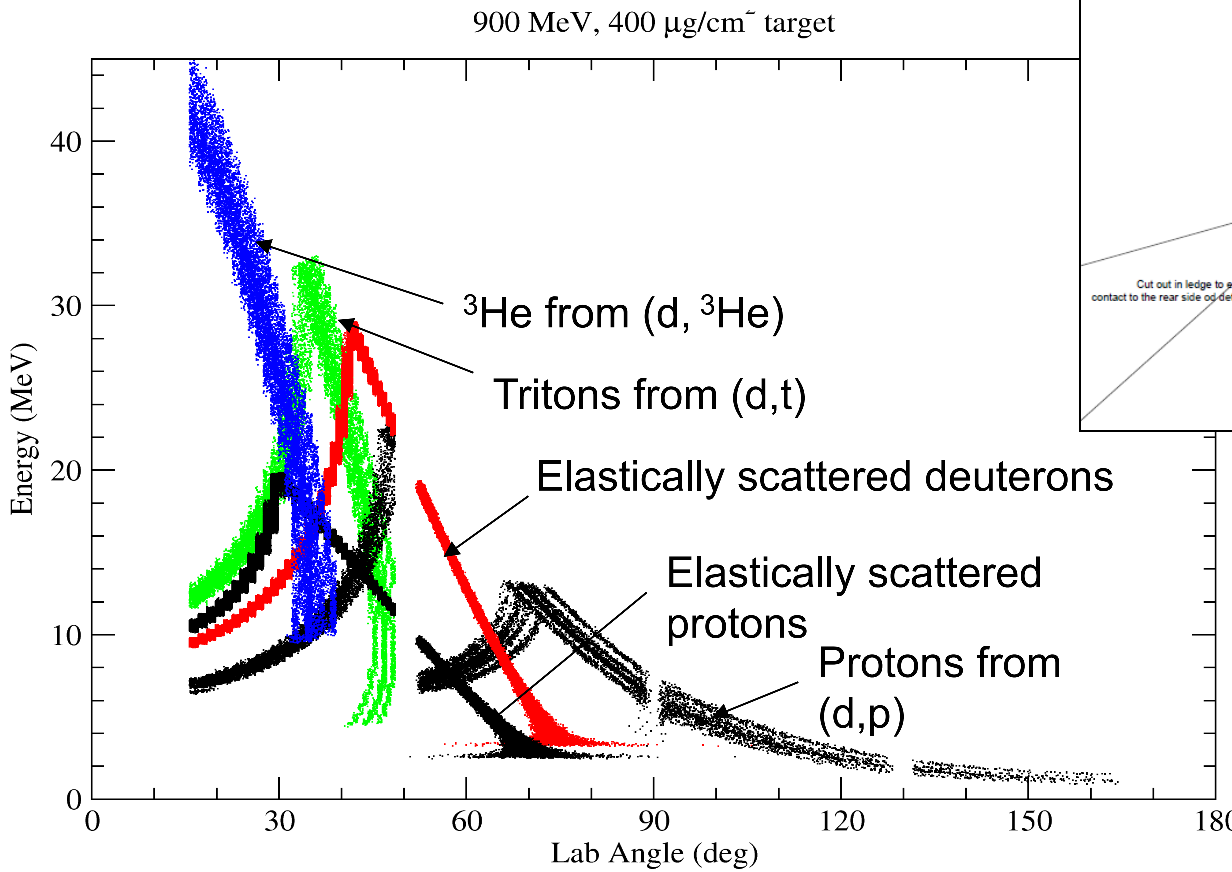


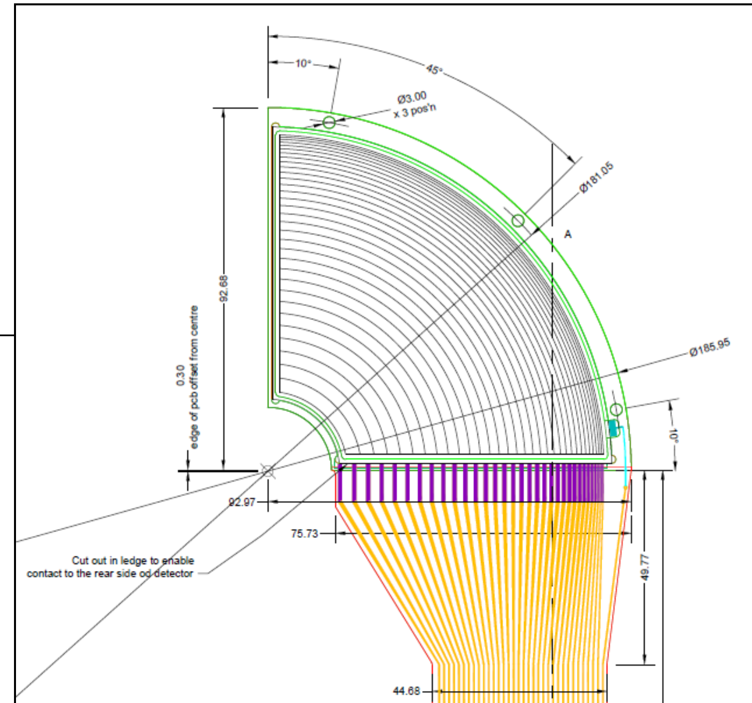




Endcap Detectors

- Annular endcap detectors were designed and purchased.
- Variable strip pitch to achieve angular resolution sufficient to measure (d,t).





- Instrument up to three layers of detectors (tritons and PID).
- Entire array covers ~75% of the polar angle between 15-165 degrees.

Forward endcap Barrel Backward endcap

Simulation Courtesy S.D. Pain

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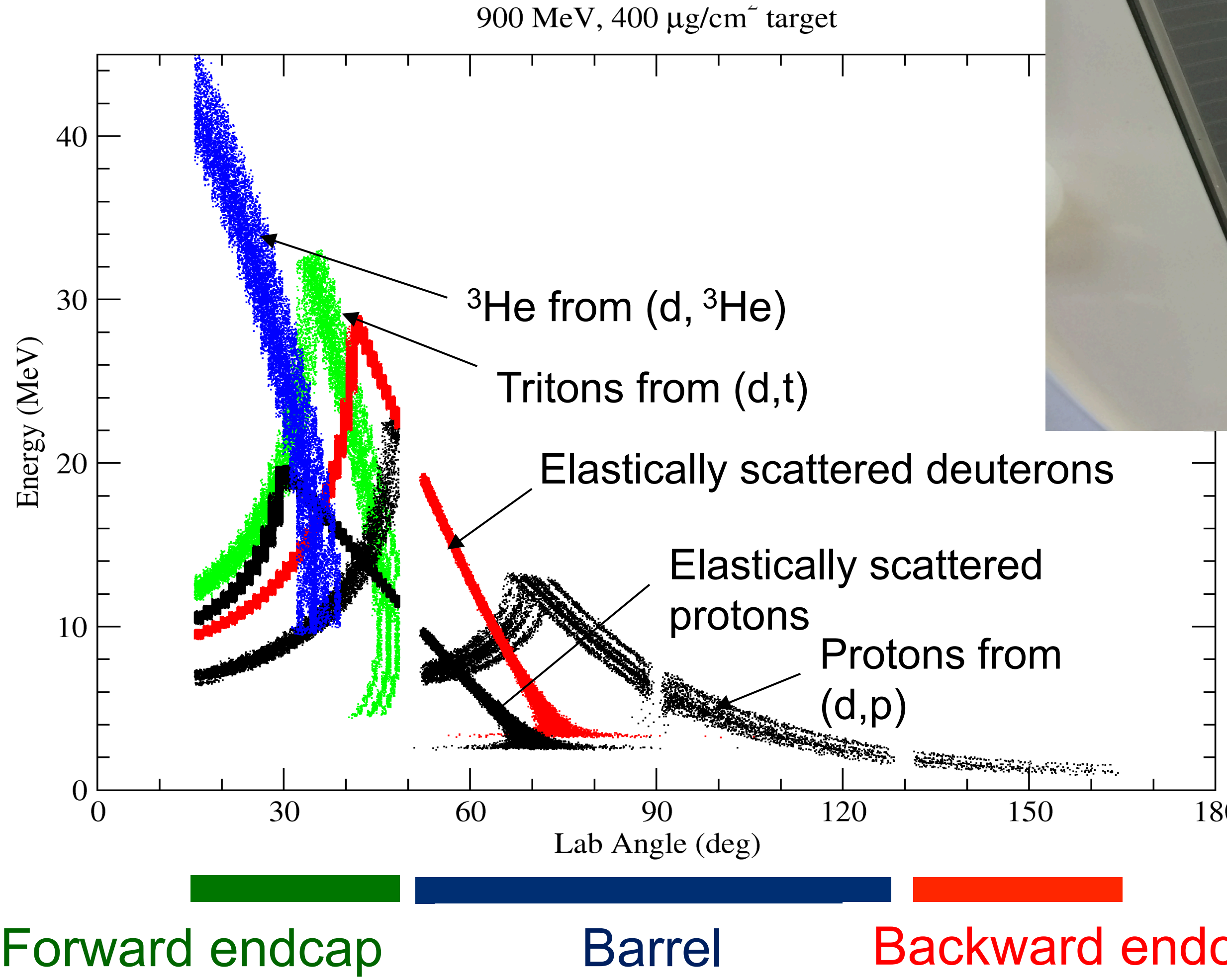

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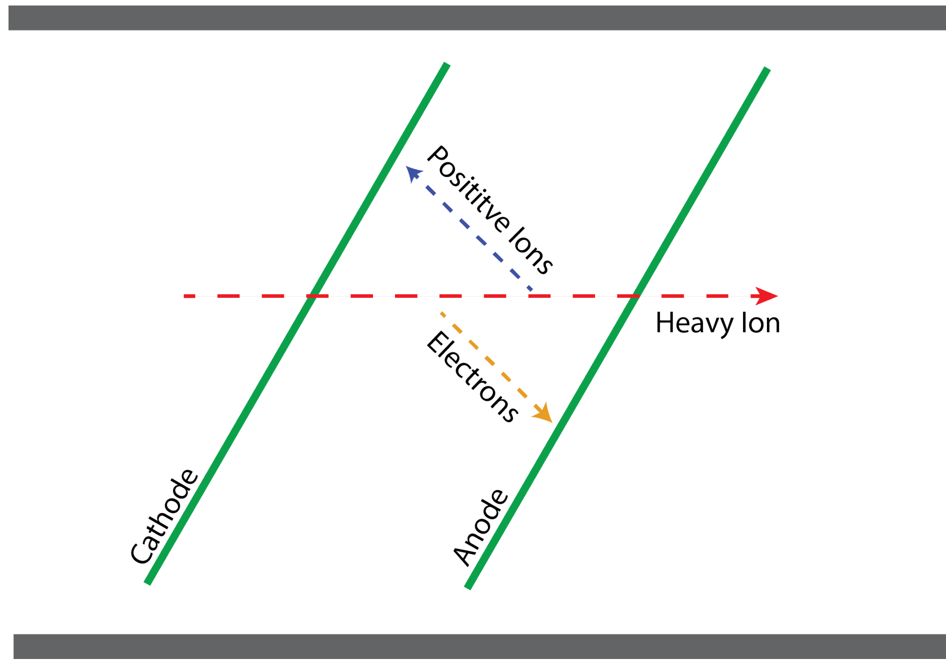
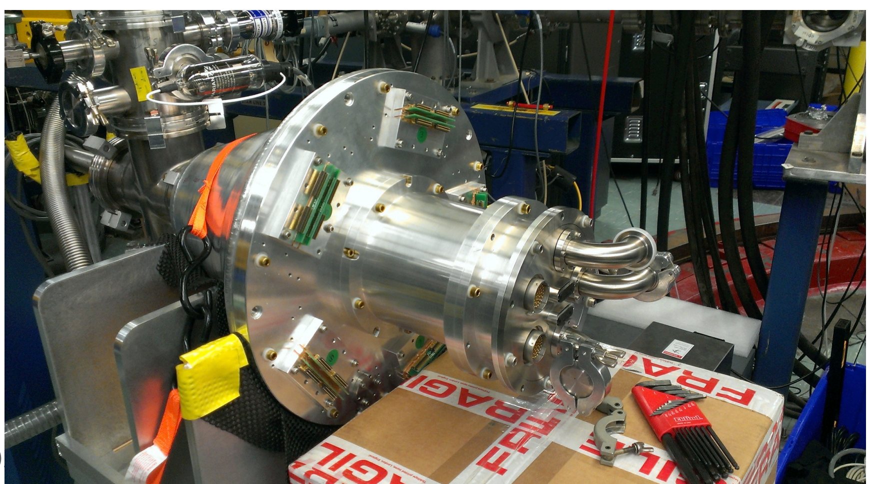
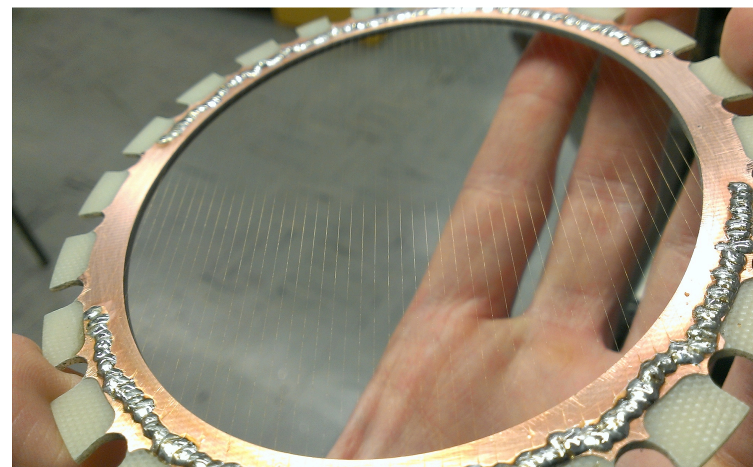
Simulation Courtesy S.D. Pain

Heavy recoils: High-Rate Ionization Chamber

- 11 anode-cathode pairs, 22 copper-plated PCB grids. ~120 wires/grid, spacing ~2 mm.
- Grids tilted at 30^{o} to mitigate recombination.
- Feedthroughs for 112 channels to allow for a future upgrade to position-sensitive first grids.
- A 5 mm thick plastic scintillator (~1 ns timing resolution) is located at the back of the IC in order to provide time-of-flight relative to the RF.
- Rates of up to 700 kHZ have been achieved with a similar IC [1].







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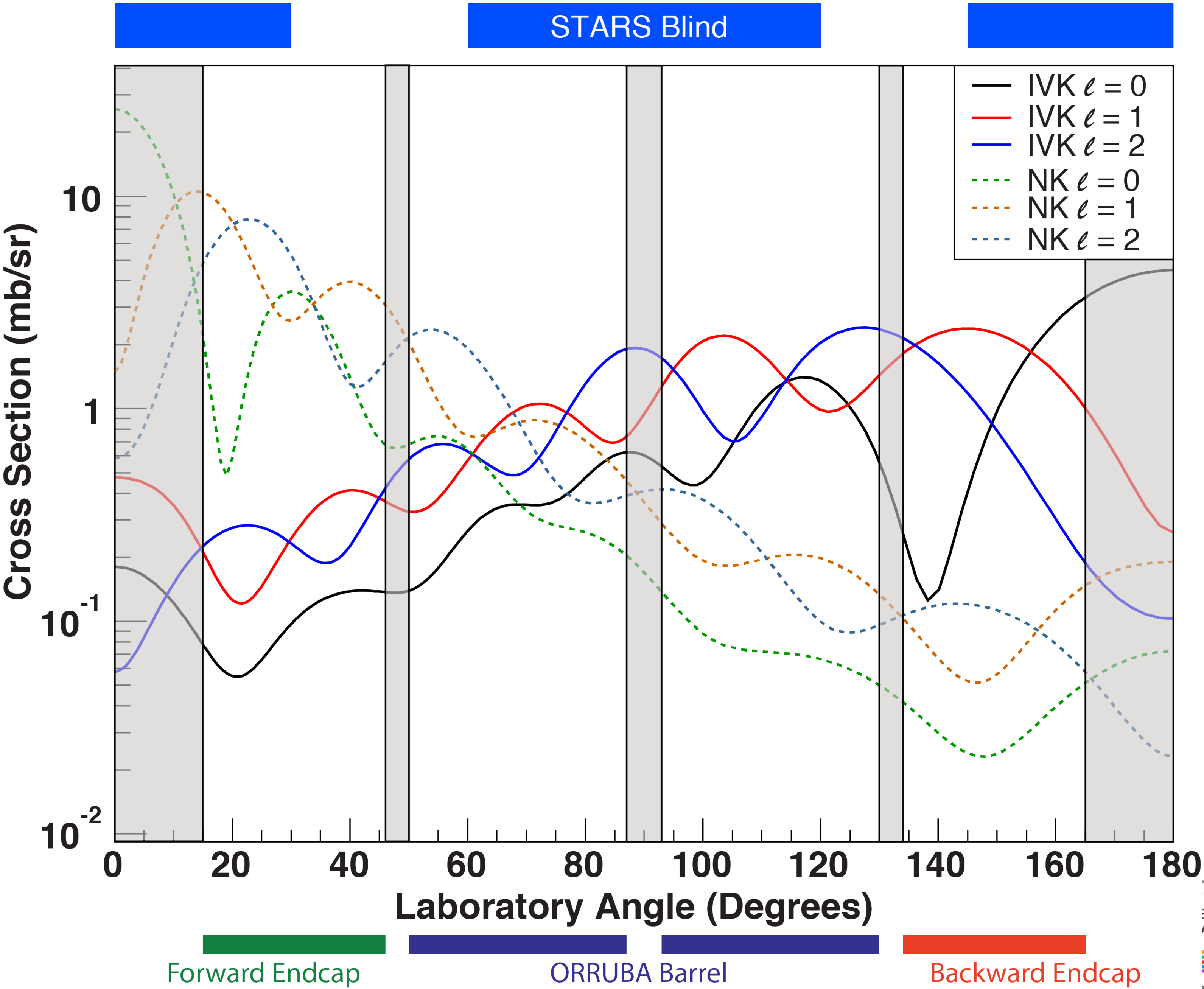
[1] K.Y. Chae *et al.* NIM A **751**, 6 (2014)

Angular Coverage



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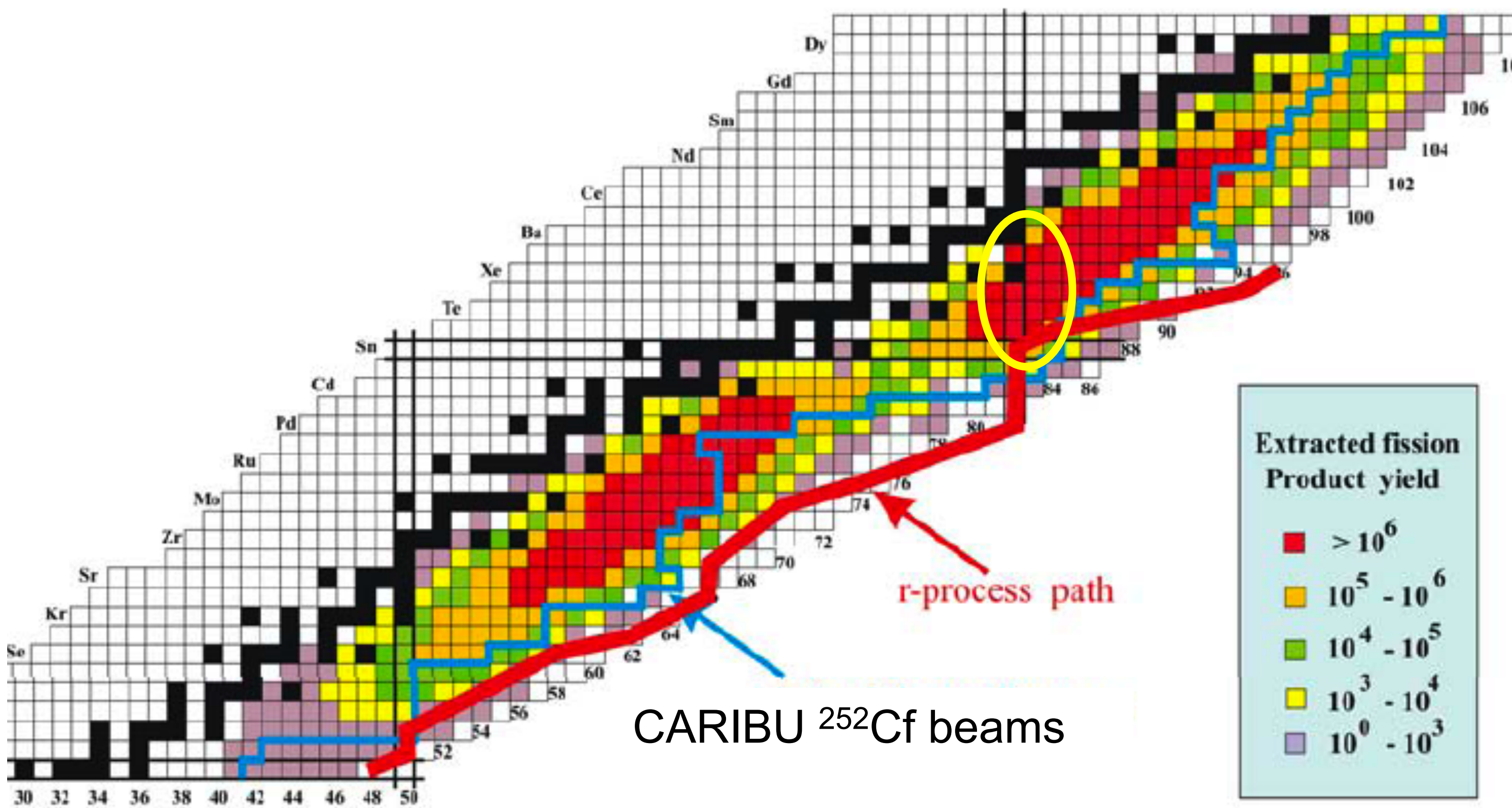
Experiments with GODDESS

Future ATLAS beams & ORRUBA + Gammasphere

- (d,pγ) with ^{95}Mo surrogate validation approved
- Heavy and light ^{252}Cf fission fragments
  - $^{134}Te(d,p\gamma)$ approved
- Other transfer reactions with fission fragment and stable beams



Summary

Validating surrogate method for $\sigma(n,\gamma)$ on ^{95}Mo

- $(d,p\gamma)$ good candidate for (n,γ) surrogate with RIBs in inverse kinematics
  - $^{95}Mo(d,p\gamma)$ normal kinematics cross sections same trend as Musgrove measured
- Inverse kinematics relatively “clean” proton spectra
- Next: GODDESS and $^{95}Mo(d,p\gamma)$ inverse kinematics
  - Discrete transitions in ^{96}Mo
  - Gammasphere w/out Hevimets
    - (Energy, Multiplicity) distributions
    - Application of Oslo method for surrogates
- Approved to measure $^{134}Te(d,p\gamma)$
  - Surrogate (n,γ) near r process path
- POSTDOC opening for experimentalist

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Thank you

Gamma-ray spectroscopy from the (d,p) reaction and a surrogate for neutron capture

Jolie A. Cizewski
Rutgers University

Supported in part by the U.S. Department of Energy National Nuclear Security Administration under the Stewardship Science Academic Alliances program