Surrogate neutron capture reaction prospects for r-process nuclei

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FRIB and the GW170817 Kilonova

Facility for Rare Isotope Beams, 23-27 July 2018

Surrogate neutron capture reaction prospects for r-process nuclei

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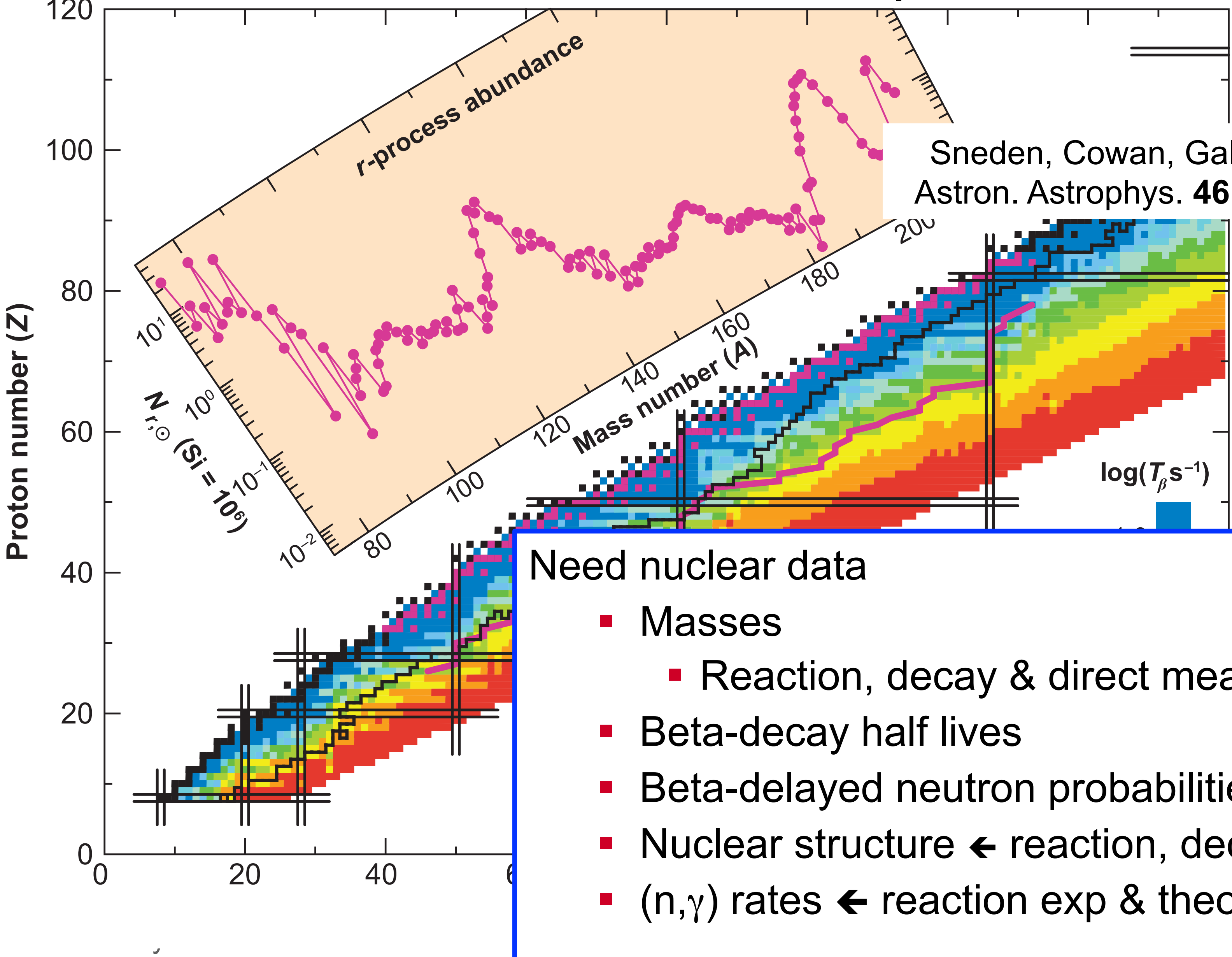
(1) Rutgers University
(2) Lawrence Livermore National Laboratory
(3) Oak Ridge National Laboratory
(4) Michigan State University & FRIB

and the **ORRUBA, STAR-LiTeR and GODDESS collaborations**

Funded in part by the U.S. Department of Energy National Nuclear Security Administration & Office of Nuclear Physics and the National Science Foundation

Understanding r-process nucleosynthesis depends on nuclear data



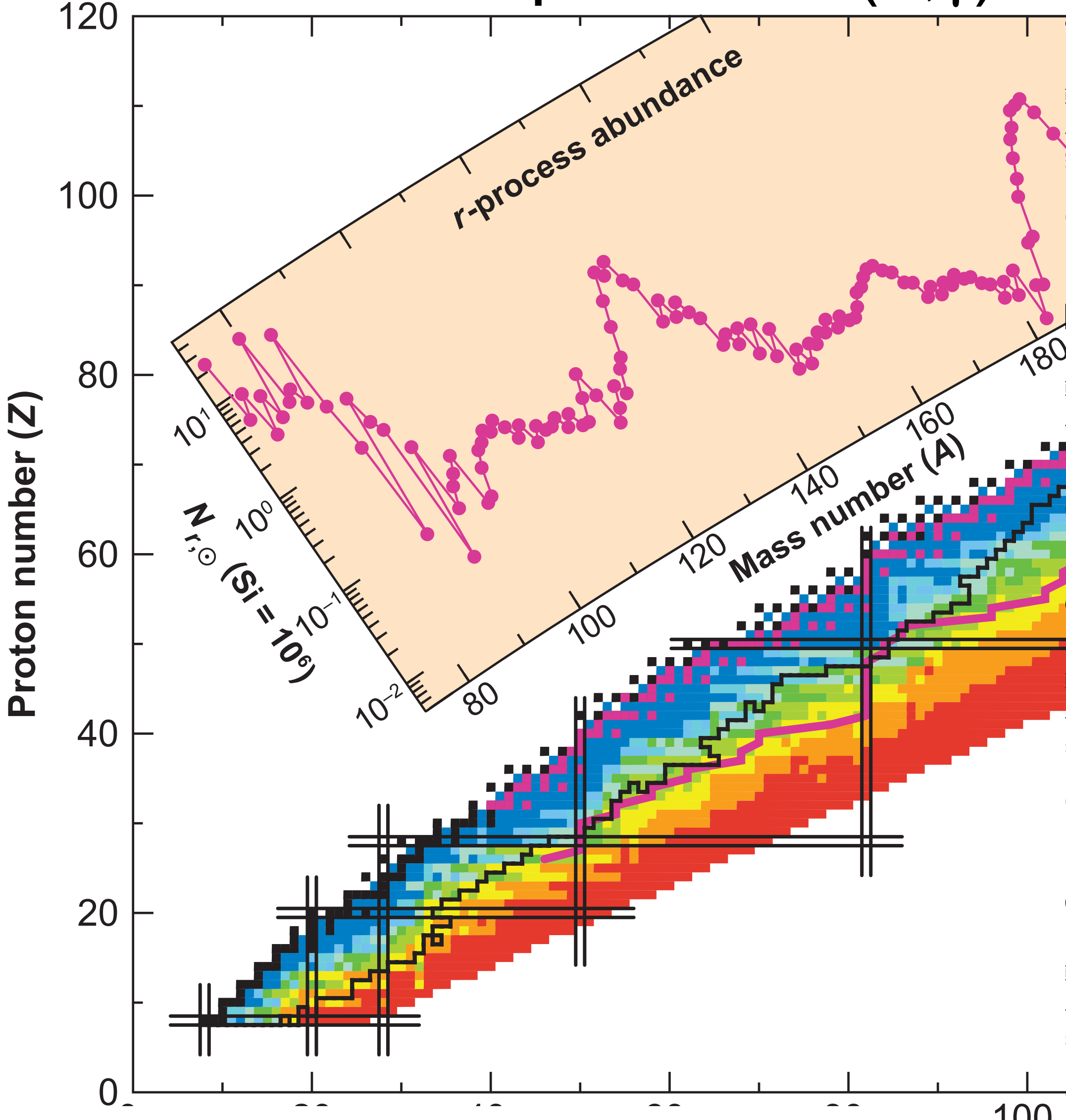
Sneden, Cowan, Gallino, Annu. Rev. Astron. Astrophys. **46**:241-288 (2008)

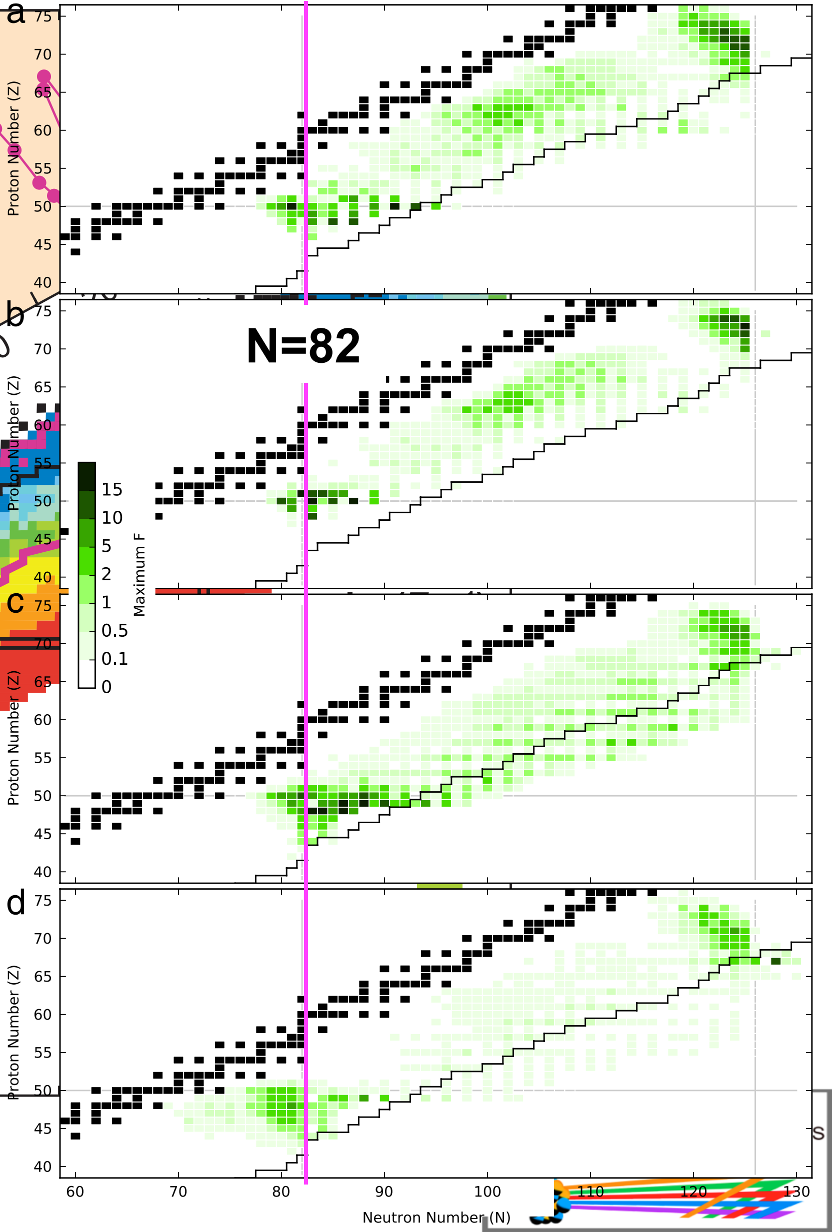
Need nuclear data

- Masses
  - Reaction, decay & direct measurements
- Beta-decay half lives
- Beta-delayed neutron probabilities
- Nuclear structure ← reaction, decay & theory
- (n,γ) rates ← reaction exp & theory studies

r-process nucleosynthesis

depends on (n,γ) rates and site of r process





M.R. Mumpower, R. Surman, G.C. McLaughlin, A. Aprahamian, PPNP **86**, 86 (2016)

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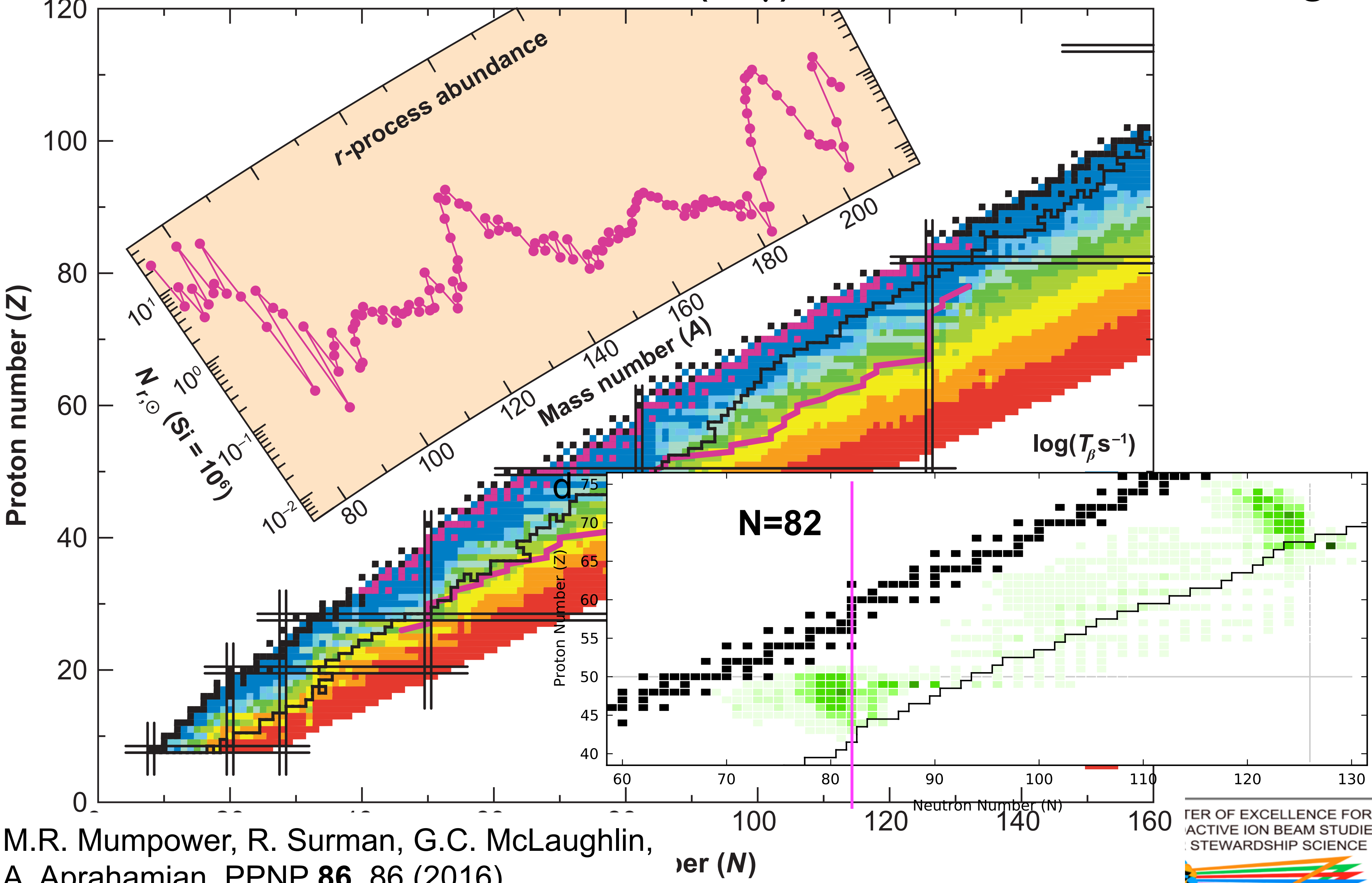
r-process nucleosynthesis

(n,γ) rates and n star merger



M.R. Mumpower, R. Surman, G.C. McLaughlin, A. Aprahamian, PPNP **86**, 86 (2016)

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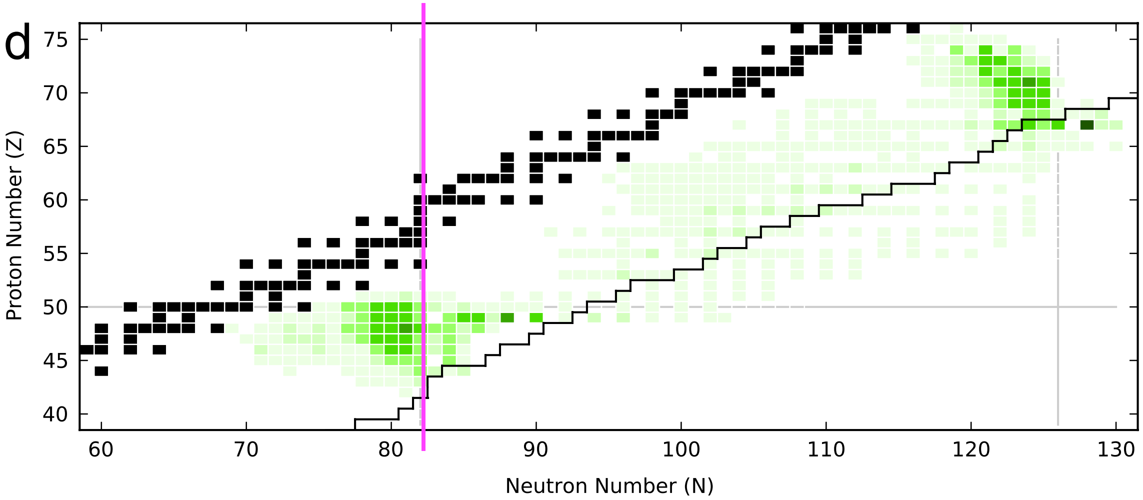
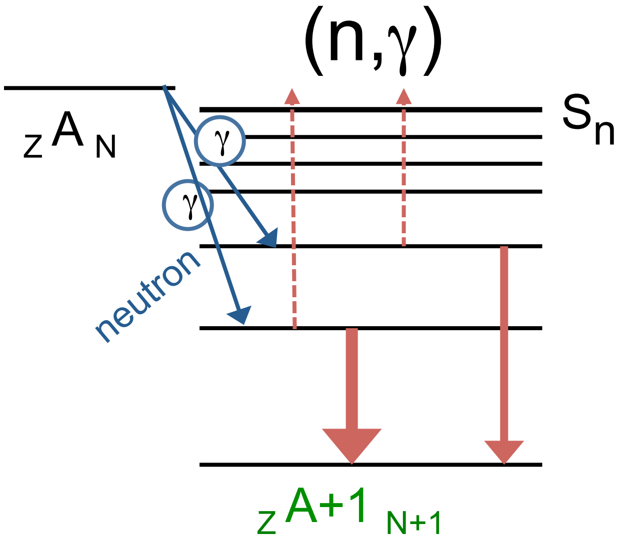
Near shell closure & waiting points

neutron capture dominated by direct capture





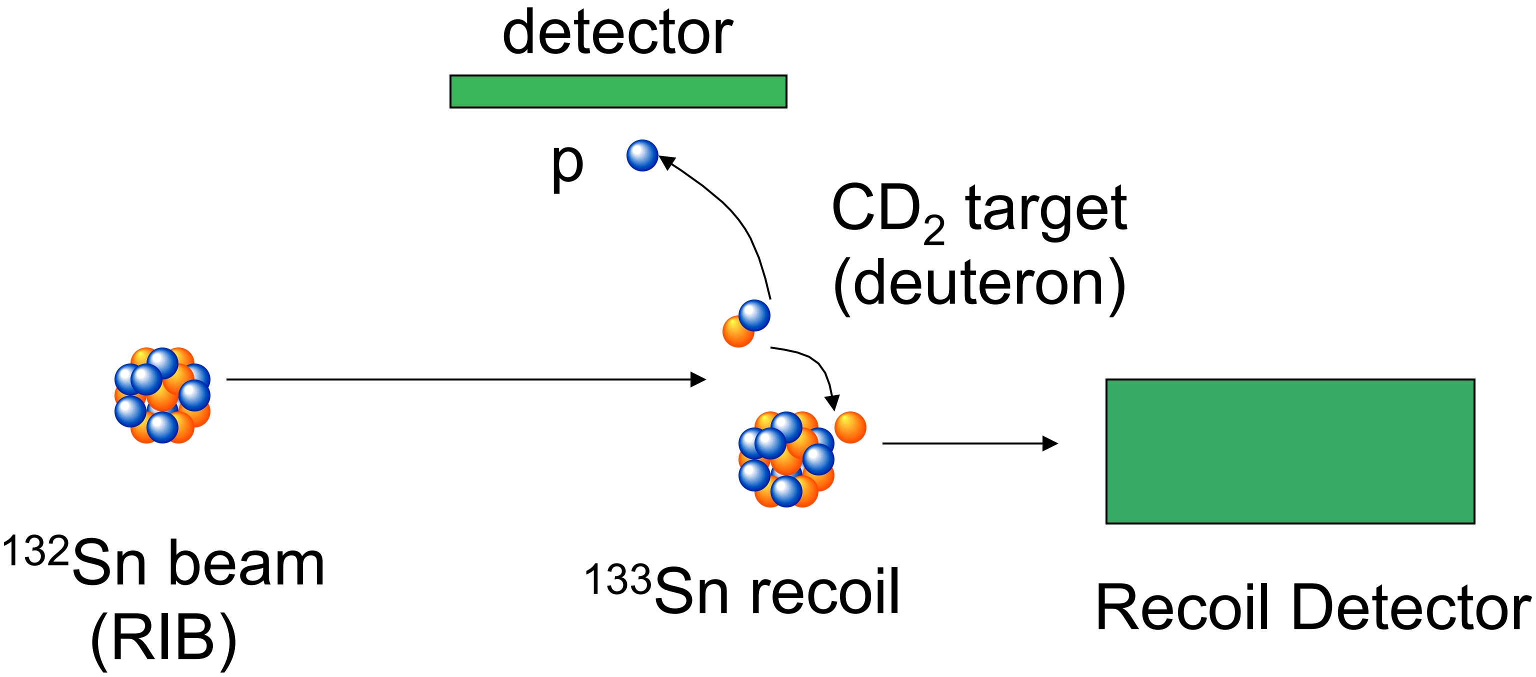
Tin Z=50 isotopes n-star merger

Mumpower, et al. PPNP 2016

77	127	1.77
78	128	1.21
79	129	3.55
80	130	4.47
81	131	3.28
82	132	1.92

Inform by measuring neutron transfer
e.g., (d,p) with n-rich RIBs

Neutron transfer (d,p) Reactions in Inverse Kinematics



detector

p

CD_2 target (deuteron)

^{132}Sn beam (RIB)

^{133}Sn recoil

Recoil Detector

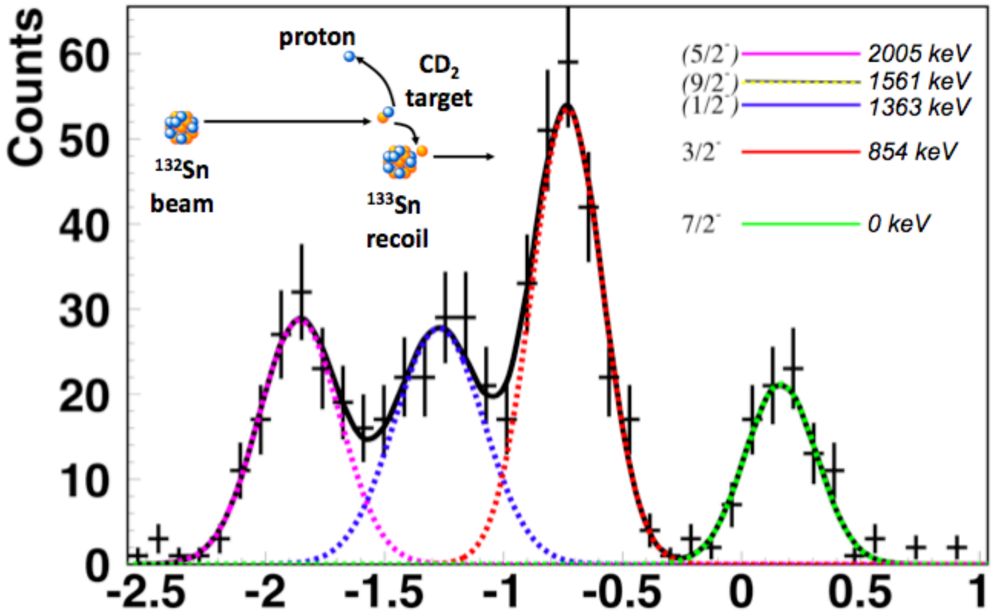
- Unfavorable kinematics → Reduced Q-value Resolution
- Rare Ion Beams (RIBs) are difficult and expensive to produce

Applicable to all isotopes which can be made into a beam

^{132}Sn(d,p): N=83 single neutron states

Identified $2f_{7/2}$, $3p_{3/2}$, ($3p_{1/2}$), $2f_{5/2}$ neutron strength in ^{133}Sn

K.L. Jones et al.
Nature, **465**,454 (2010)
Phys. Rev. C **84**, 034601 (2011)



$$S_{lj} = \frac{d\sigma_{exp}}{d\sigma_{DW}} = \left|A_{lj}\right|^2$$

E_x(keV)	J^π	Config	SF (DWBA)	SF (FR-ADWA)
0	$7/2^-$	$2f_{7/2}$	0.86(14)	1.00(8)
854	$3/2^-$	$3p_{3/2}$	0.92(14)	0.92(7)
1363(31)	$(1/2^-)$	$3p_{1/2}$	1.1(3)	1.2(2)
2005	$(5/2^-)$	$2f_{5/2}$	1.1(2)	1.2(3)

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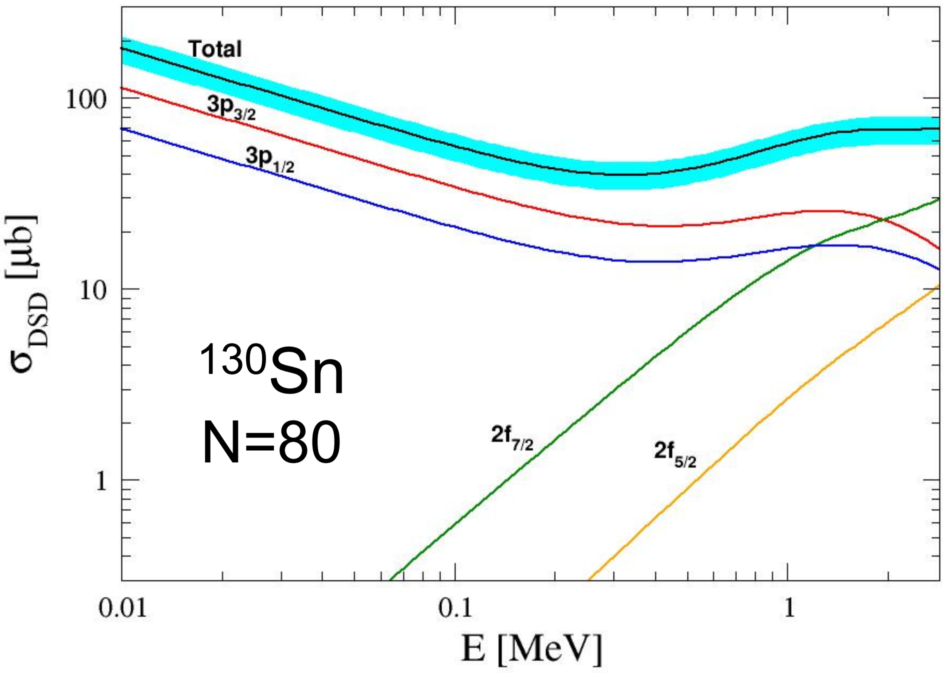
Direct-semi-direct neutron capture calculations

Direct semi-direct direct capture with CUPIDO

- Incident n channel: Koning Delaroche potential
- Bound state: Bear Hodgson potential
- Semi-direct capture via GDR
    - Add GDR to s.p. EM operator
- Used measured SF and E_x to constrain
- Uncertainties ≈ 20%

	30 keV σ(n,γ) (μb)
^{132}Sn(d,p)	134(17)
^{130}Sn(d,p)	90(15)
^{128}Sn(d,p)	51(8)
^{126}Sn(d,p)	59(7)
^{124}Sn(d,p)	56(6)



DSD: B. Manning, G. Arbanas et al. submitted to PRL

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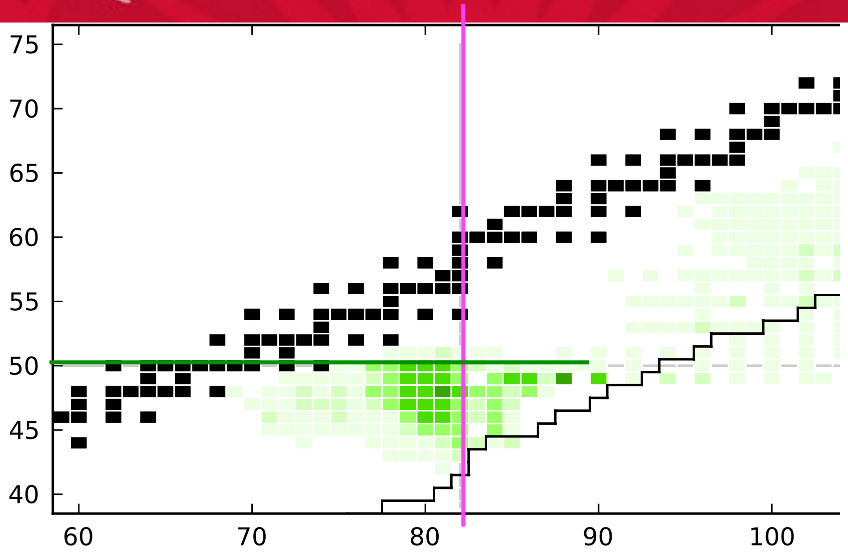
^{132,130,128,126,124}Sn DSD (n,γ)



Neutron star merger

	30 keV $\sigma(n,\gamma)$ (μb)
^{132}Sn(d,p)	134(17)
^{130}Sn(d,p)	90(15)
^{128}Sn(d,p)	51(8)
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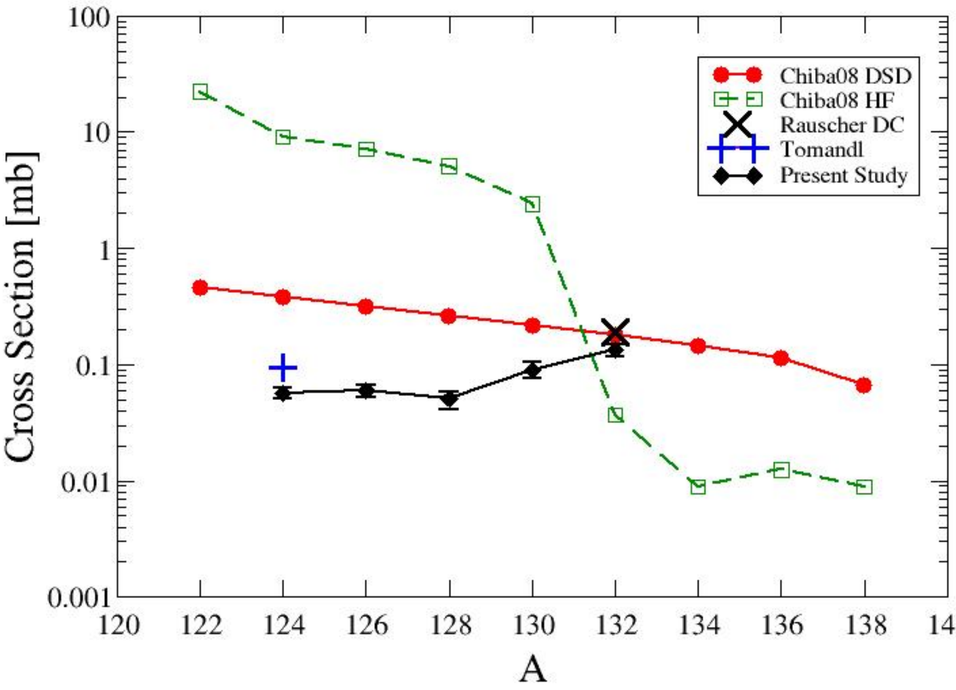

Sn(n,γ) vs A

Theory: Chiba, et al. PRC **77**, 015809 (2008)
DSD from exp: G. Arbanas, B. Manning

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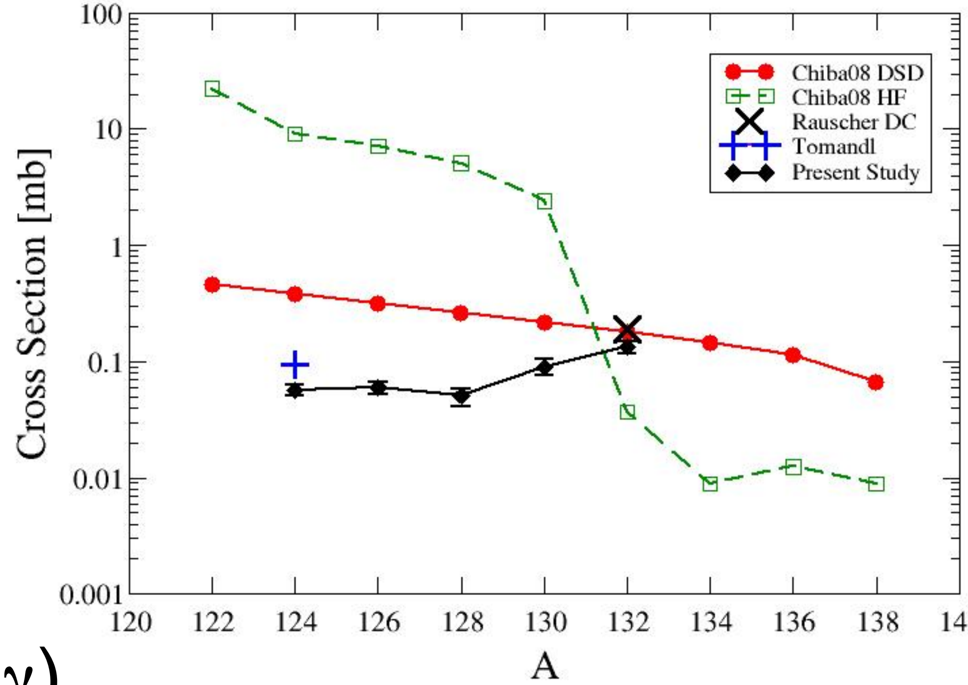
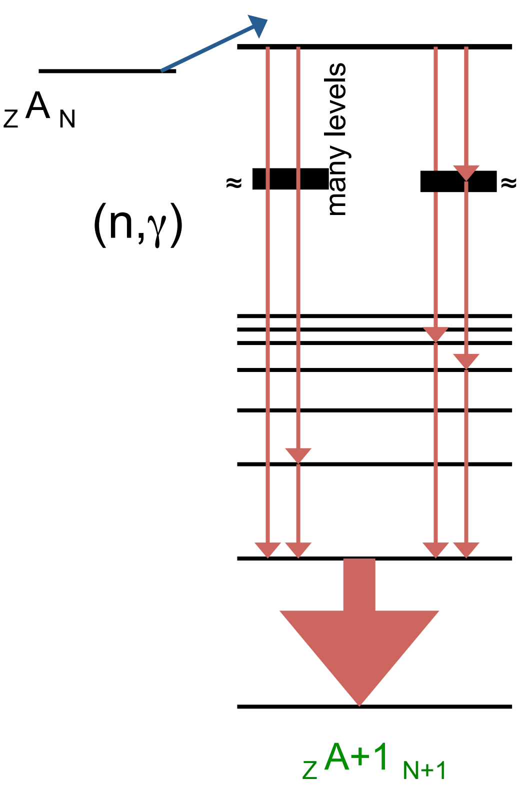
^{132,130,128,126,124}Sn statistical (n,γ)?

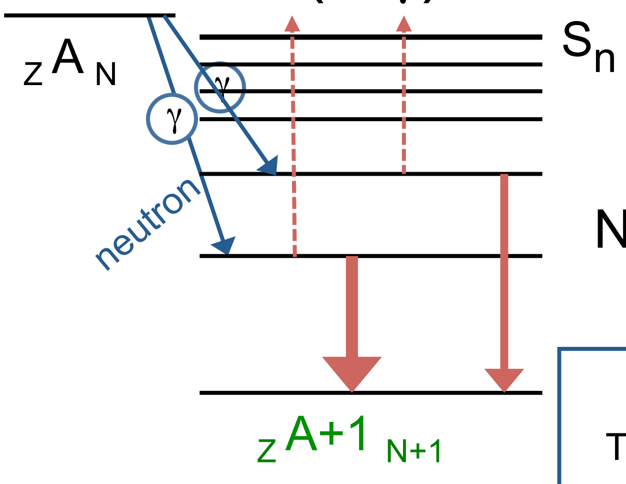
Statistical (n,γ) dominates σ when $N<N_{magic}$



Near stability



(n,γ)

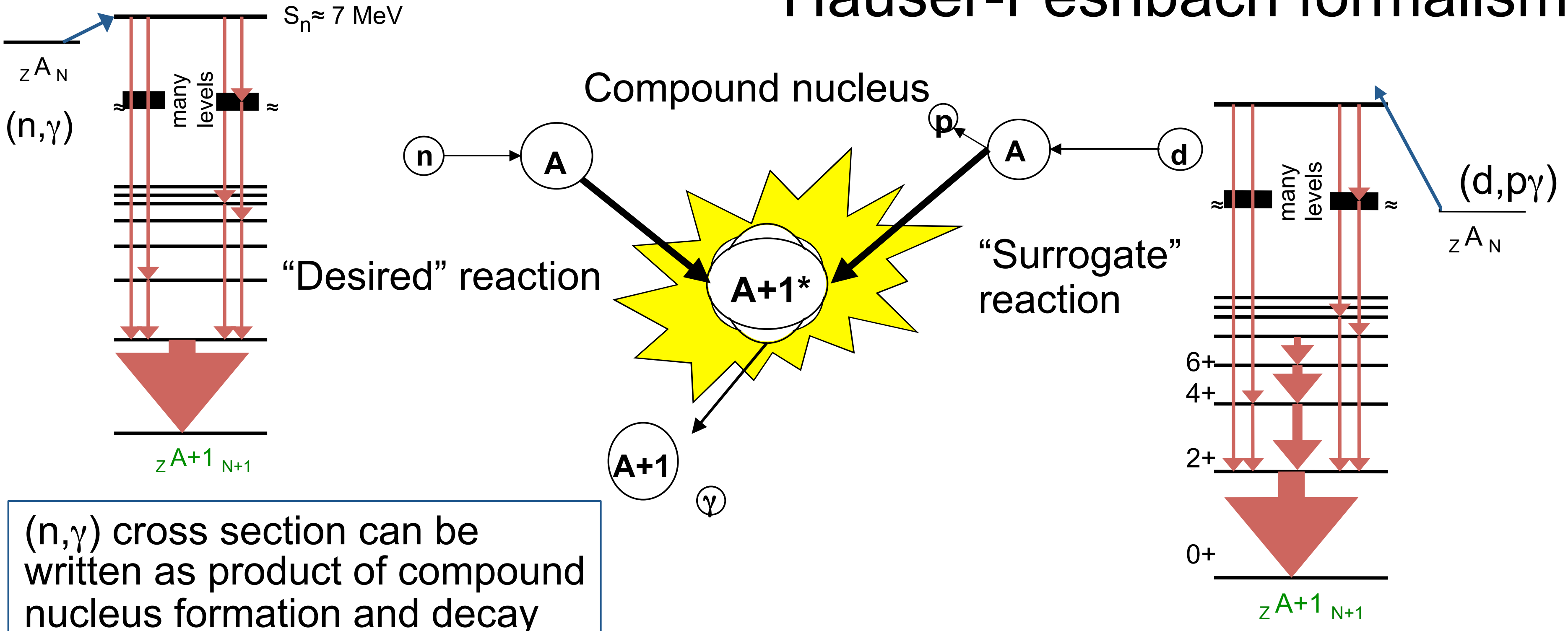


Near waiting points

Sn(n,γ) vs A

Theory: Chiba, et al. PRC **77**, 015809 (2008)
DSD from exp: G. Arbanas, B. Manning

Surrogate reaction concept & Hauser-Feshbach formalism



Compound nucleus

“Desired” reaction

“Surrogate” reaction

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

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

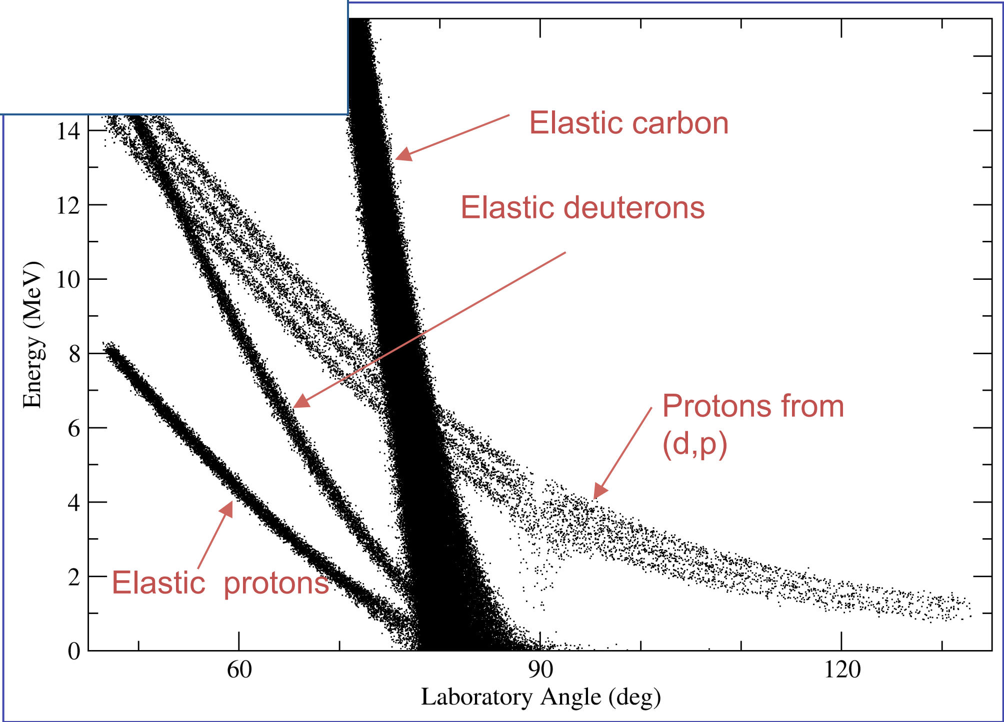
Surrogate particle-gamma coincidence can be written as product of compound nucleus formation and decay for every spin and parity:

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

(d,pγ)

Good candidate for (n,γ) surrogate with beams

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

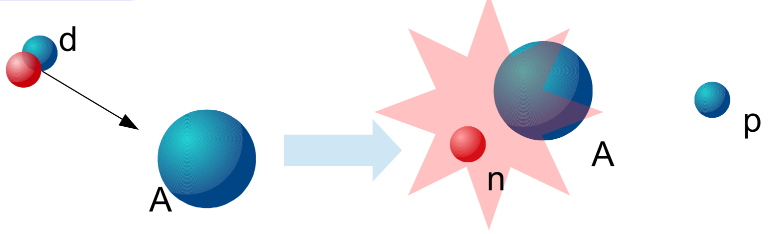


Forming compound nucleus in (d,p)

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

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

step 1 **separation of the proton**



Two-step process

- d breakup; B.E. = 2.2 MeV

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

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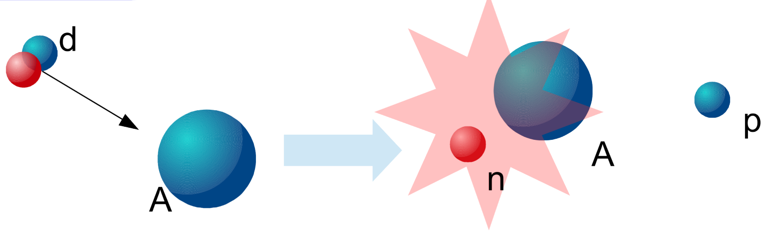
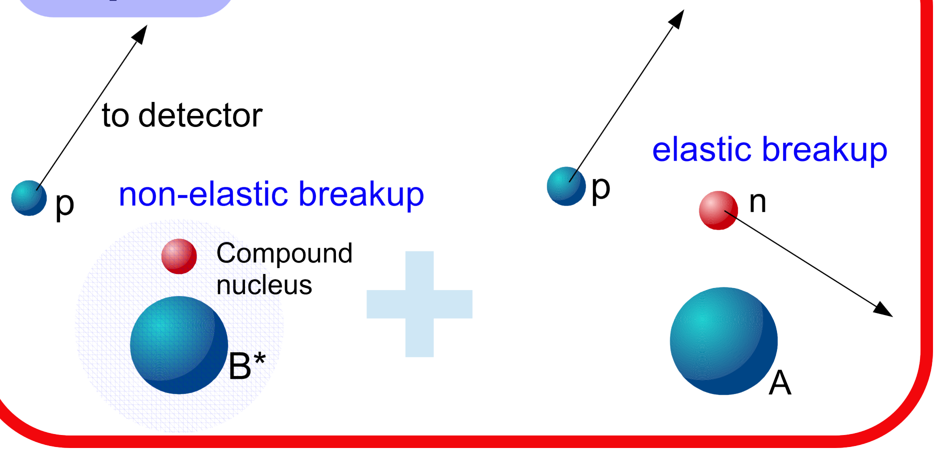
Neutron transfer (d,p) to unbound states, non-elastic breakup and surrogate for (n,γ)

step 1 **separation of the proton**



step 2 **propagation of *n* in the field of B***



<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

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Surrogate (n,γ) with (d,pγ)

(d,p) reaction forms compound nucleus
Need to measure P(d,pγ)
Need to deduce G^{CN} by fit to P(d,pγ) accounting for F^{CN}

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

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

σ(n,γ) was measured and evaluated

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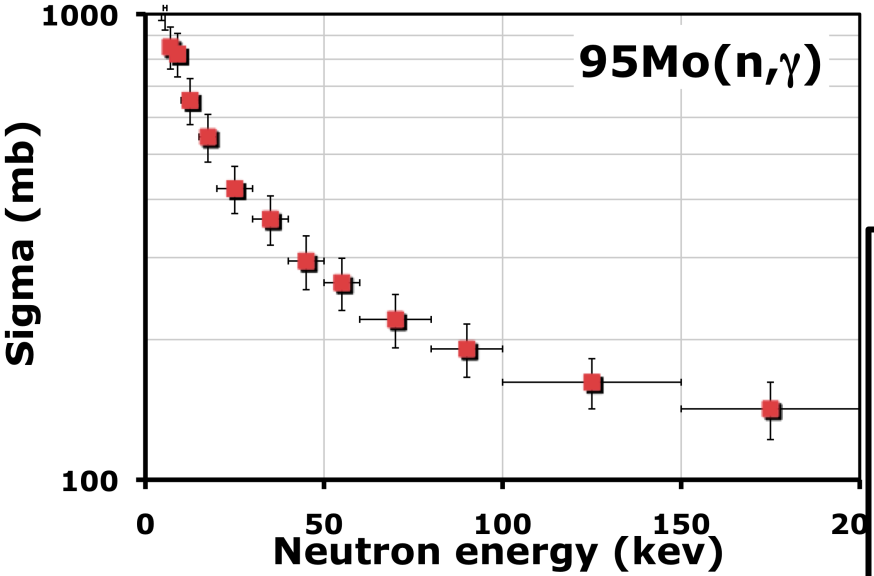
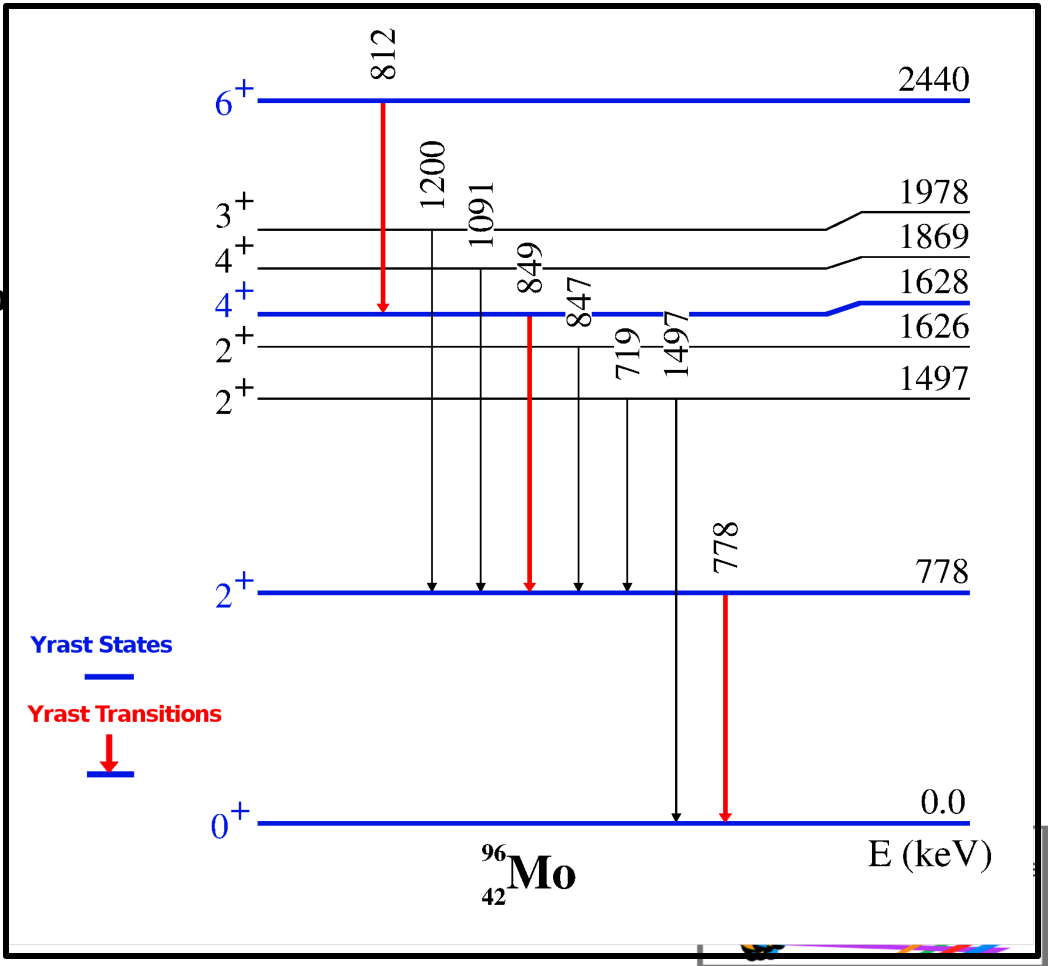
^{95}Mo: Known (n,γ) and ^{96}Mo levels

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

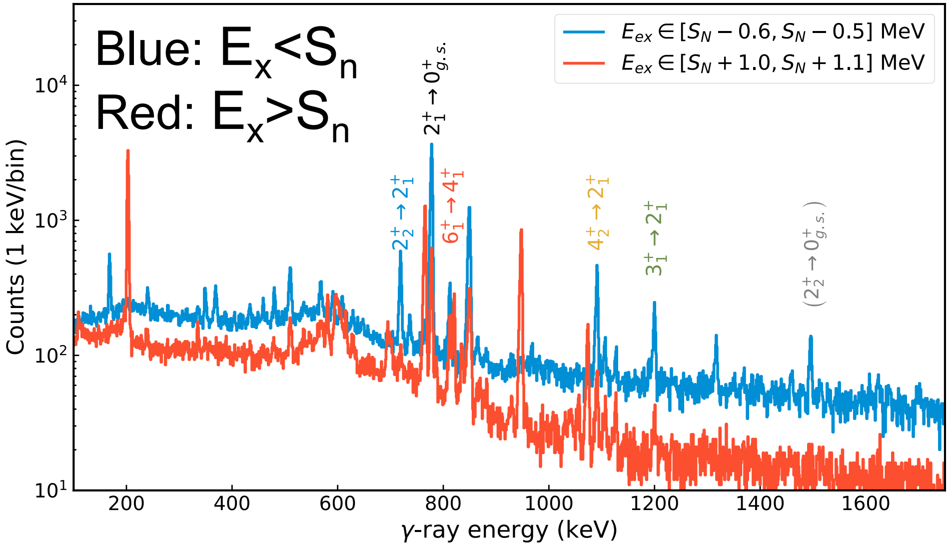


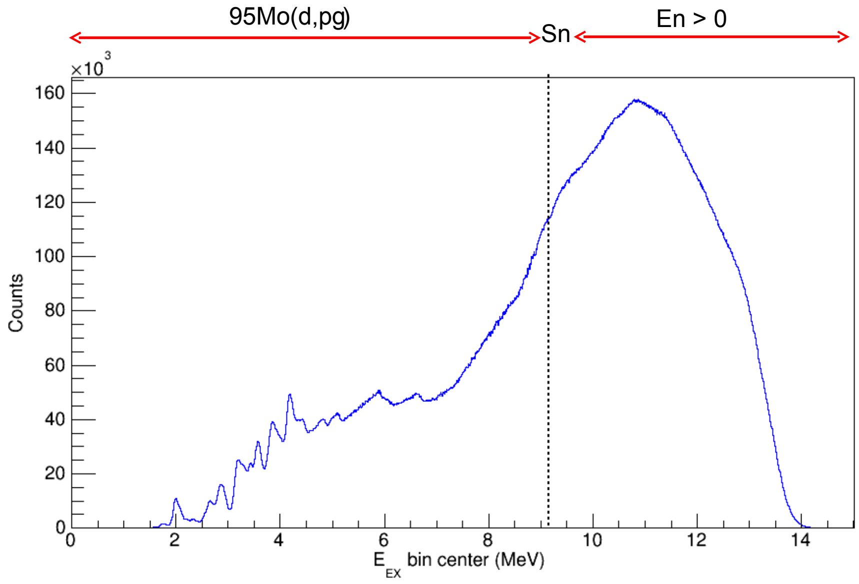


^{96}Mo level scheme

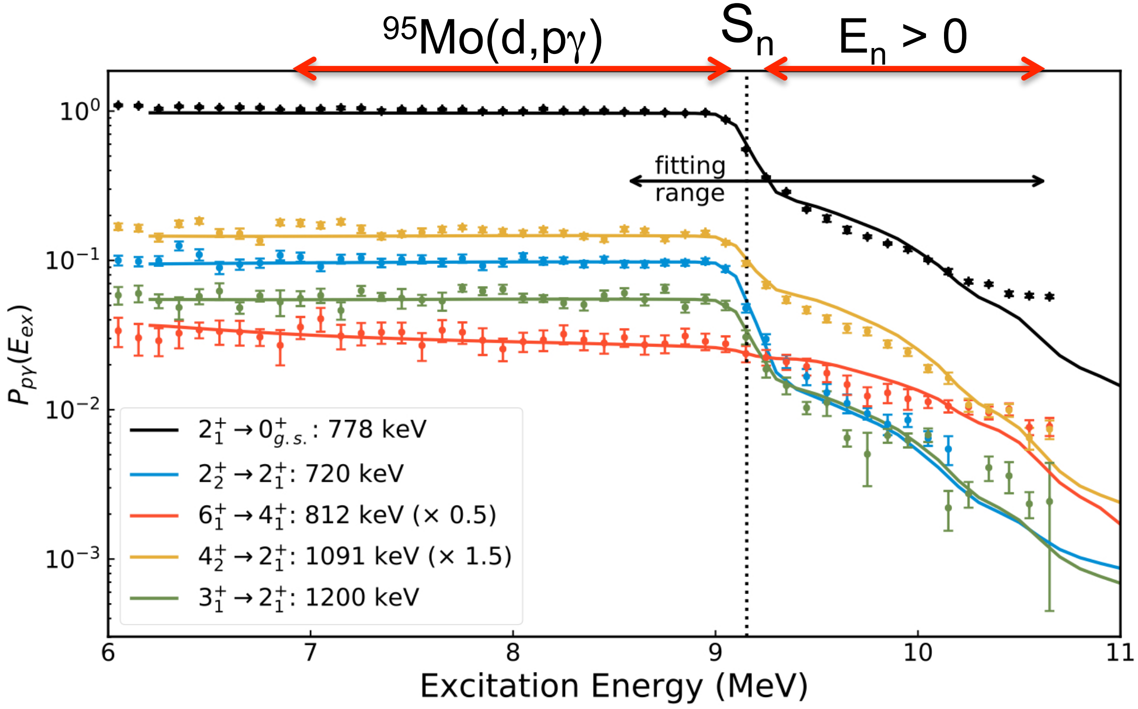
778 keV collecting transition

Gamma-ray Emission Probability

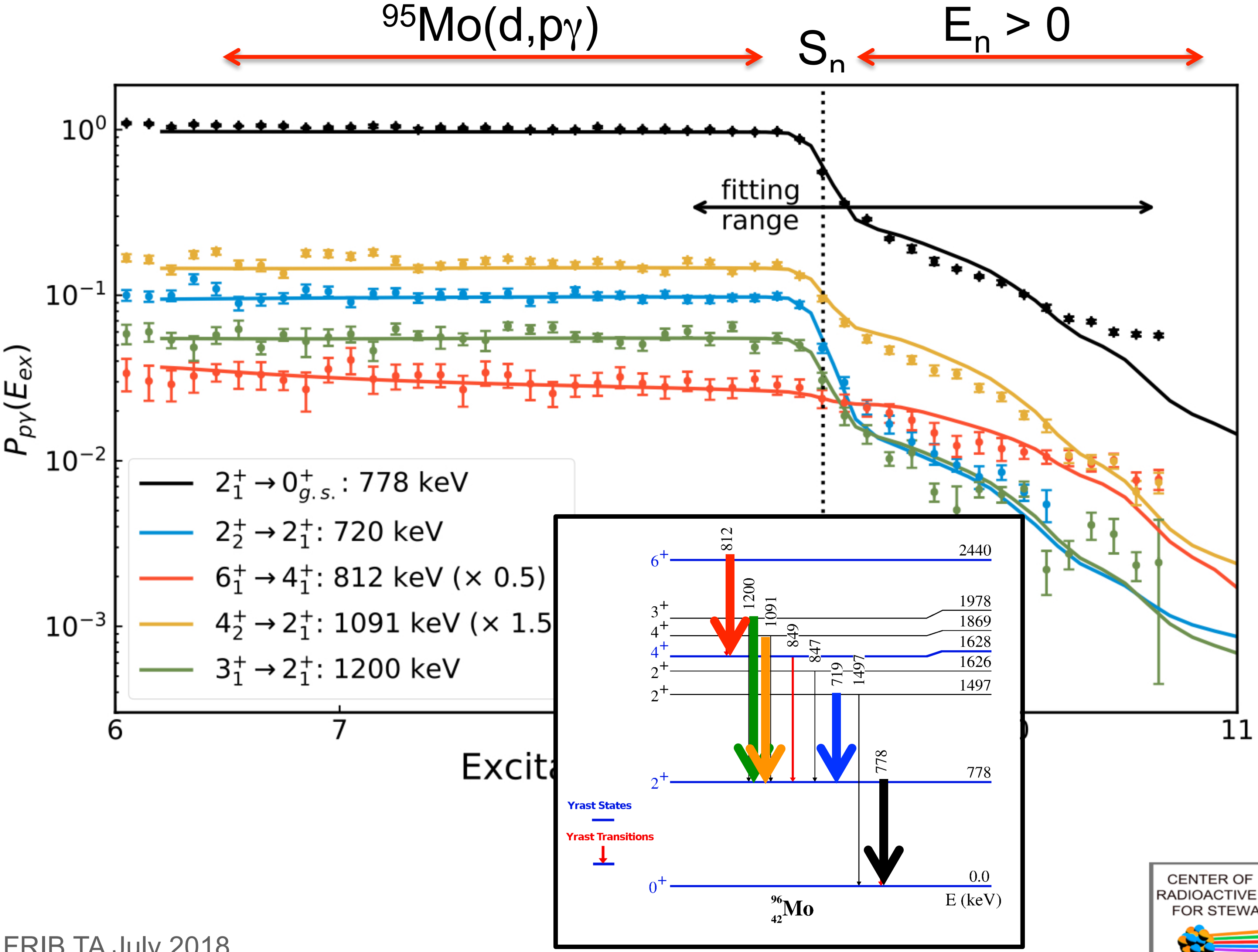




$$P(d,p\gamma) = \frac{N_{p-\gamma}}{N_p \varepsilon}$$



Gamma-ray Emission Probability



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

Measured P(d,pγ)
Calculate how (d,p) forms compound nucleus (E_x,J,π)

- Deduce G^{CN} by fit to P(d,pγ) accounting for F^{CN}

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

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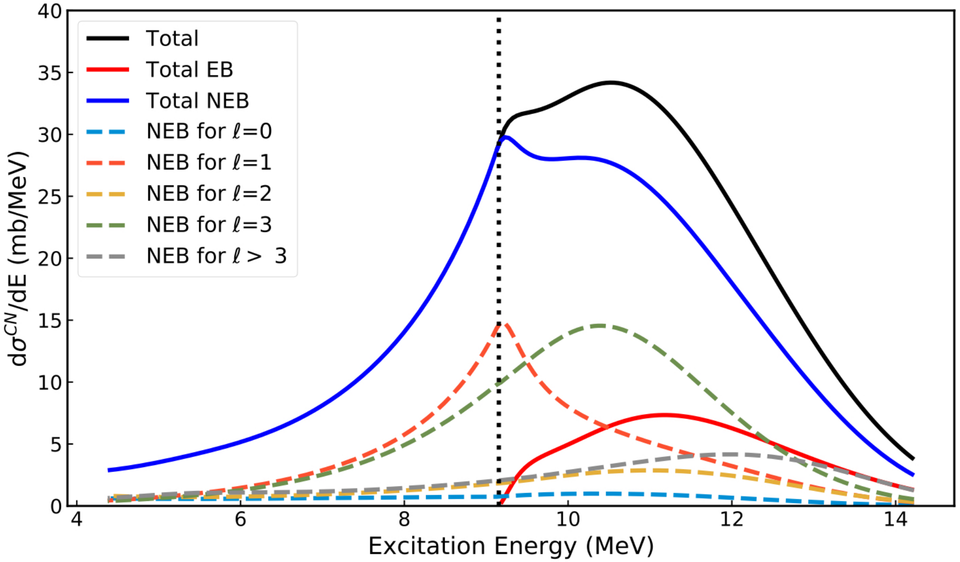
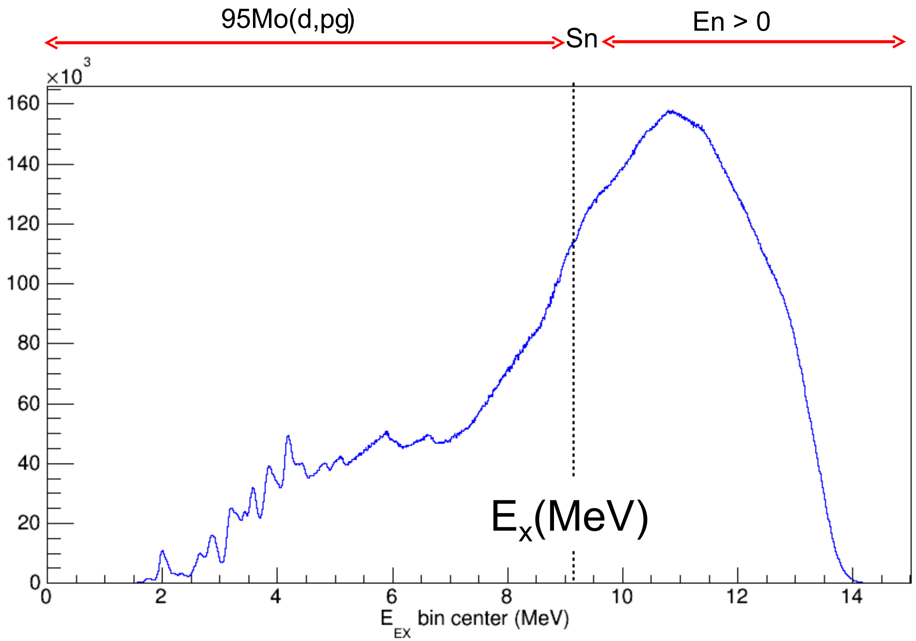
Potel model for d breakup and ℓ distributions

Potel d breakup calculations



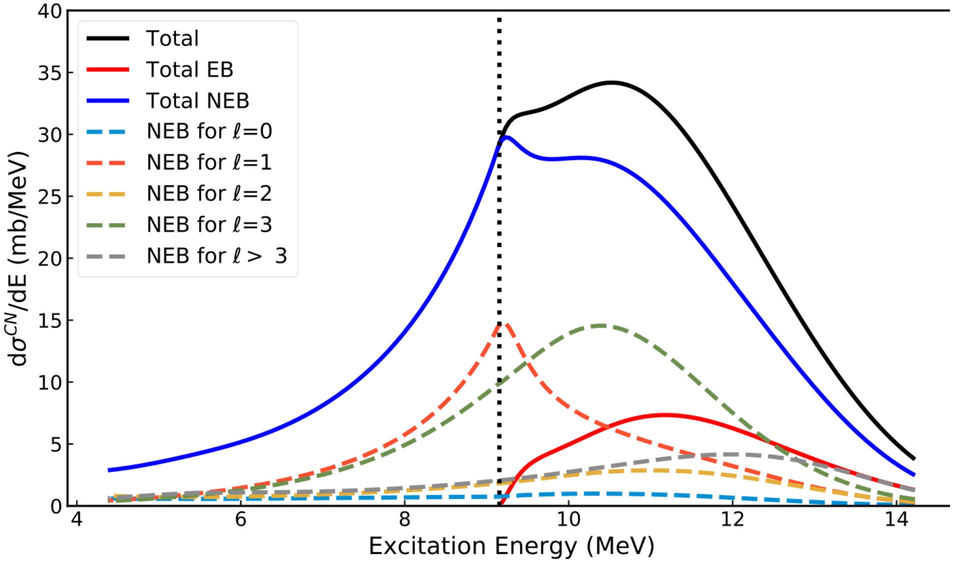


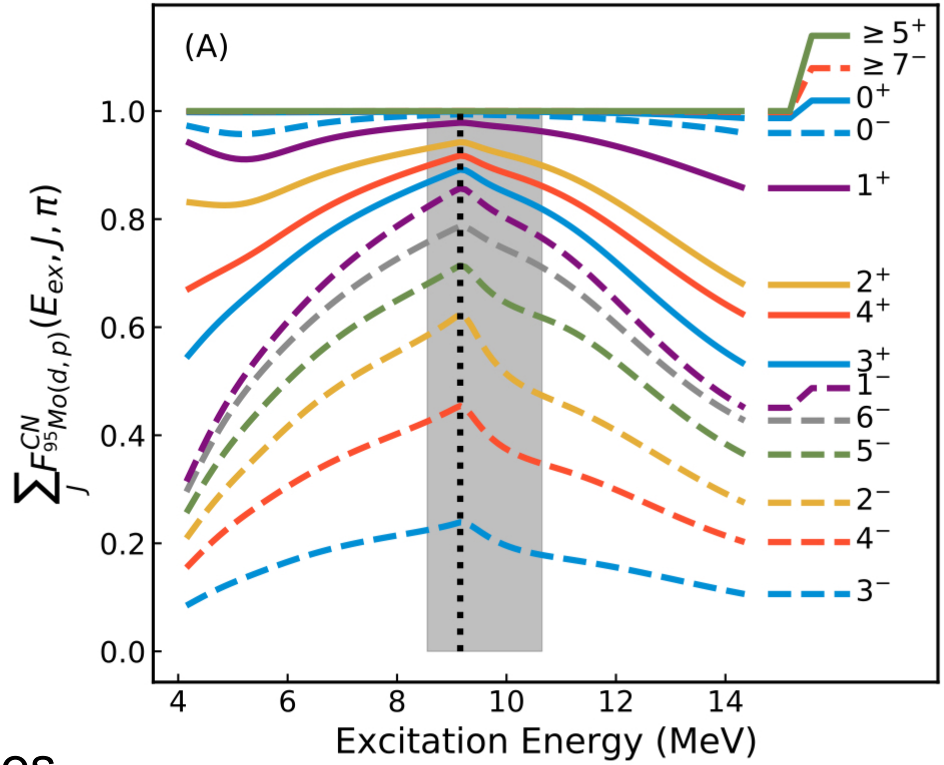
^{95}Mo(g.s)=5/2$^+$

ℓ=0 ⇒ 2$^+$,3$^+$ entry states

RUTGERS Potel model for d breakup and J^π distributions

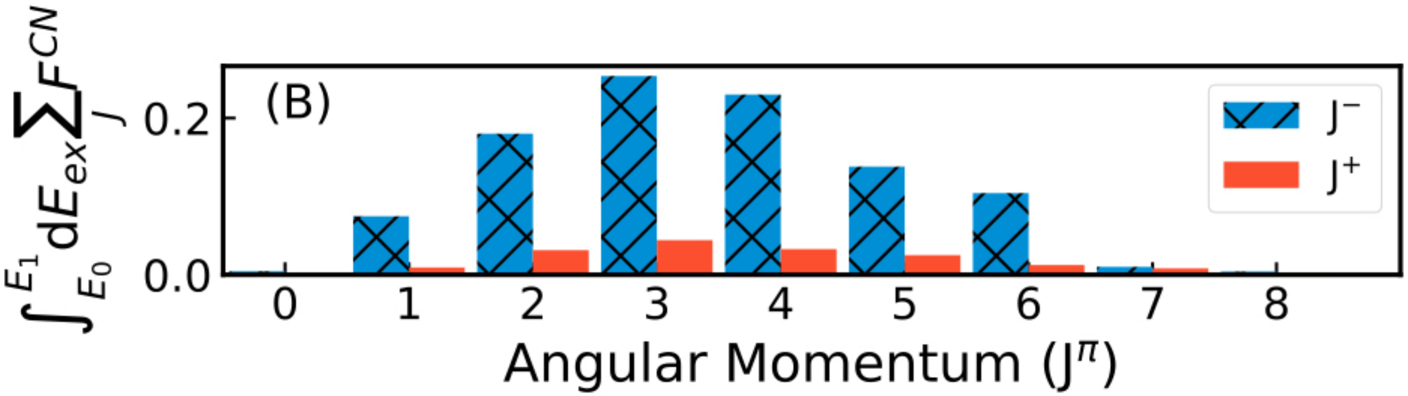
Potel d breakup calculations





^{95}Mo(g.s)=$5/2^+$

$\ell=0 \Rightarrow 2^+,3^+$ entry states



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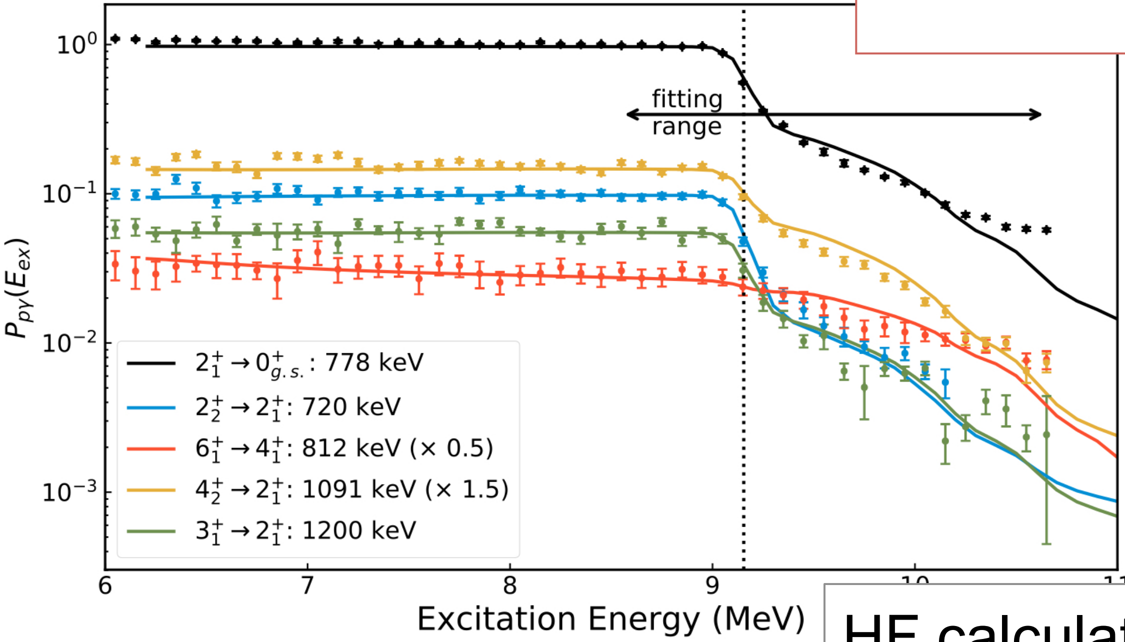
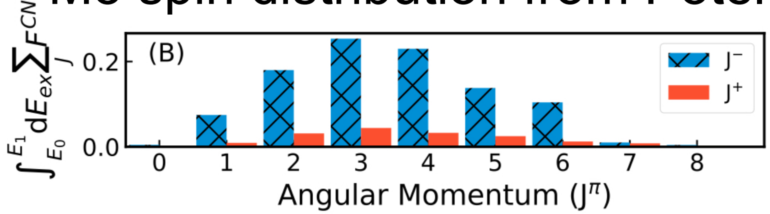
^{95}Mo(d,pγ): Input for $G^{CN}(E_x,J,\pi)$

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



Surrogate (d,pγ) data

^{96}Mo spin distribution from Potel



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

HF calculations (Jutta Escher)

- F^{CN} from Potel
- Bayesian fit to observed P(d,pγ)
  - Simple level density: Gilbert & Cameron
    - No norm to n resonance spacings
  - Simple Lorentzian γ strength function
    - No <Γ(γ)>

➢ $G^{CN}(E_x,J,\pi)$

Calculating σ(n,γ)

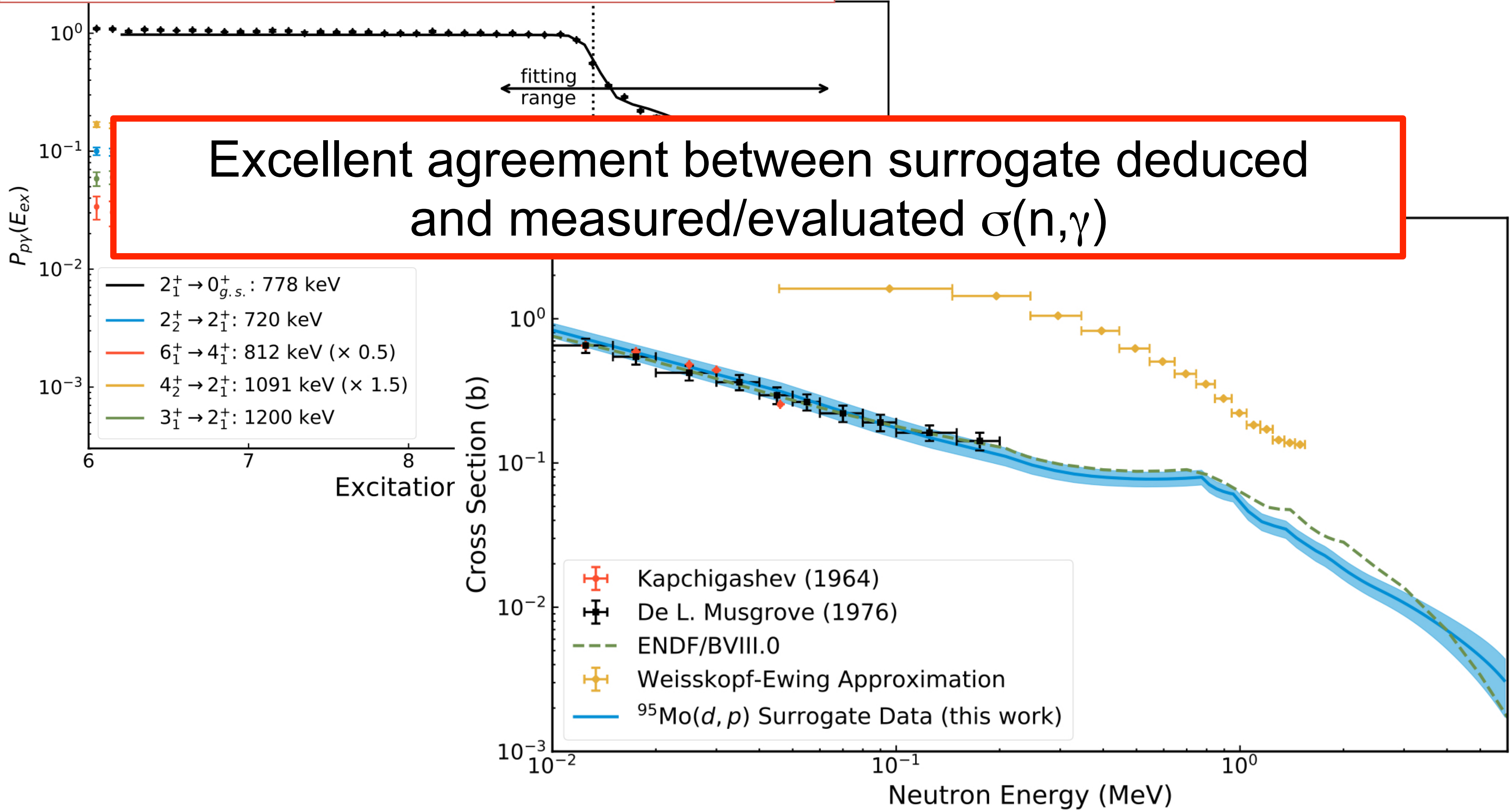
$$P_{p\gamma}(E_x,\theta)=\sum_{J,\pi}F_{dp}^{CN}(E_x,J,\pi,\theta)G_{\gamma}^{CN}(E_x,J,\pi)$$

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

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

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

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



Excellent agreement between surrogate deduced and measured/evaluated σ(n,γ)

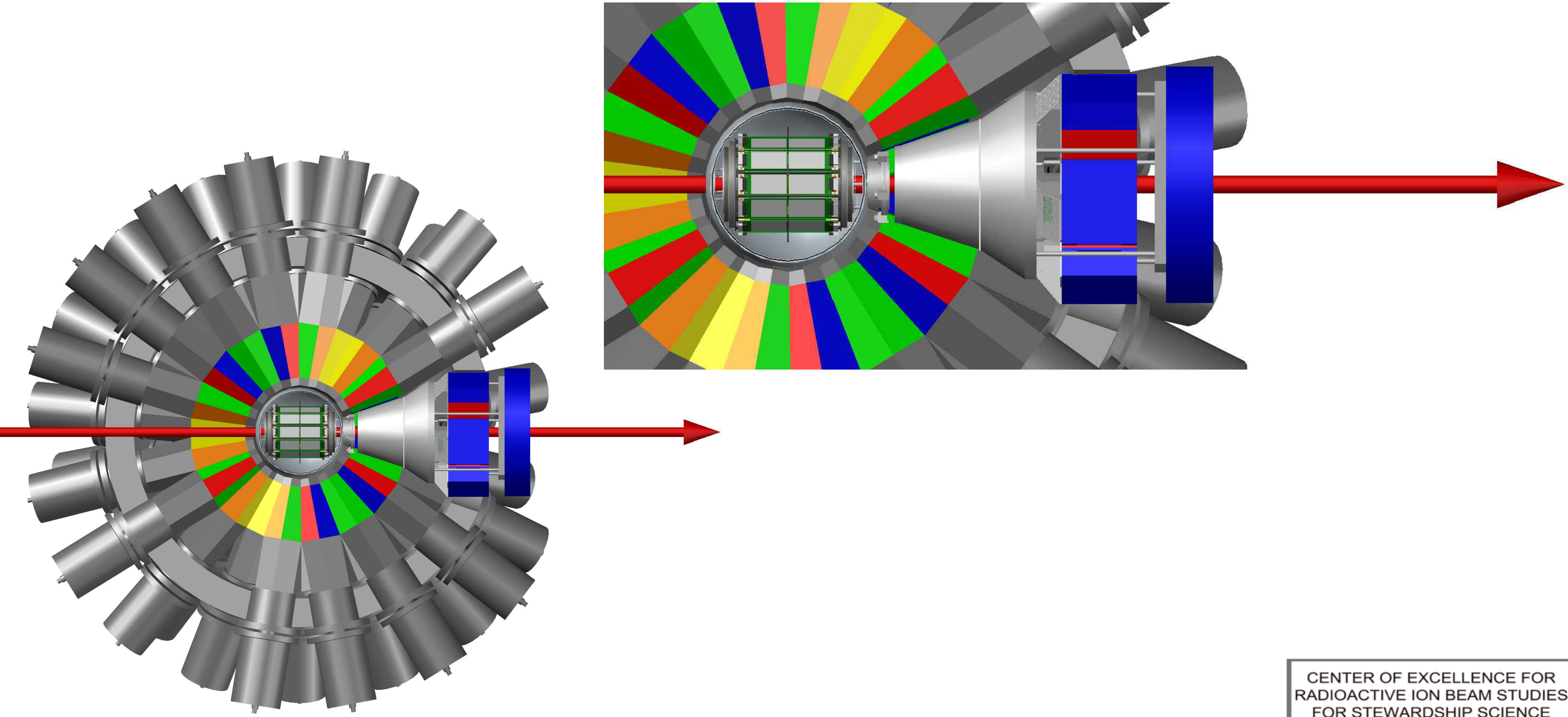
A. Ratkiewicz et al., submitted to PRL

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

Measuring (d,pγ) with radioactive beams

Coupling charged particle & gamma detector arrays

GODDESS: Gammasphere ORRUBA
Dual Detectors for Experimental Structure Studies



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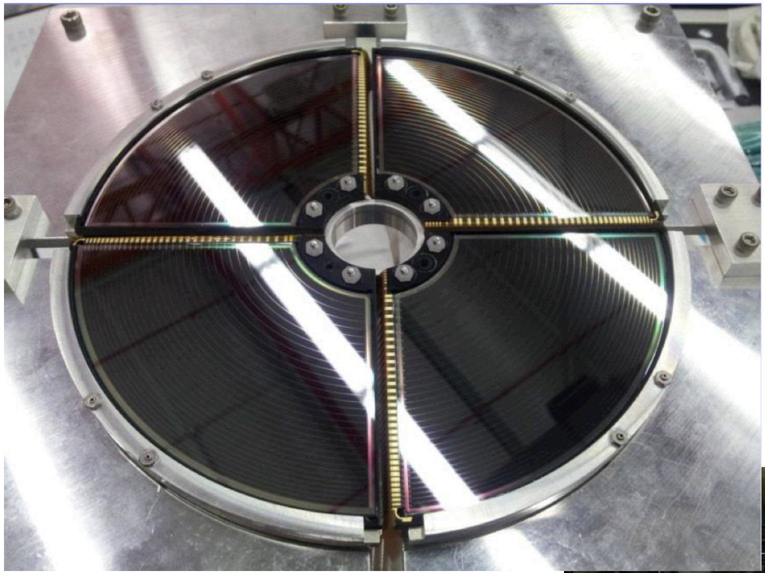
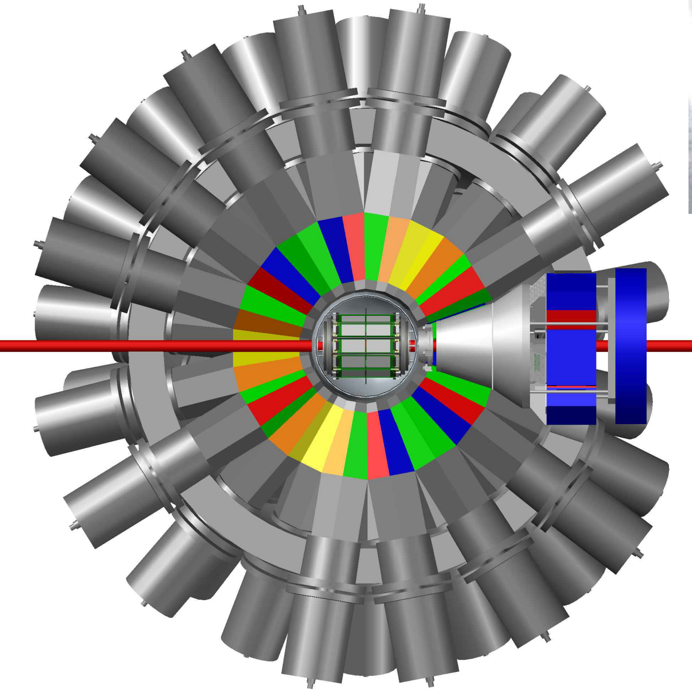
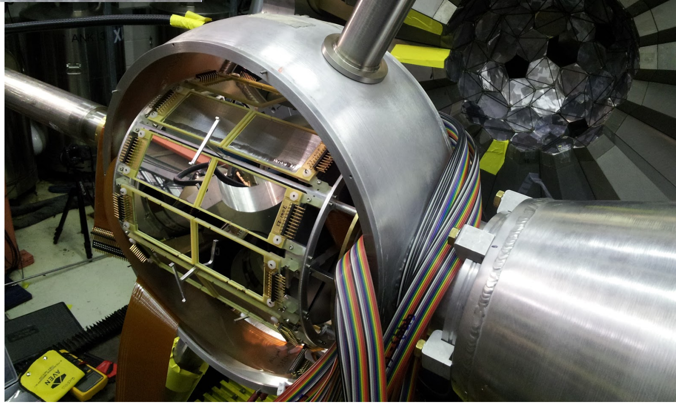
GODDESS: Gammasphere ORRUBA Dual Detectors for Experimental Structure Studies







Oak Ridge Rutgers University Barrel Array + endcaps

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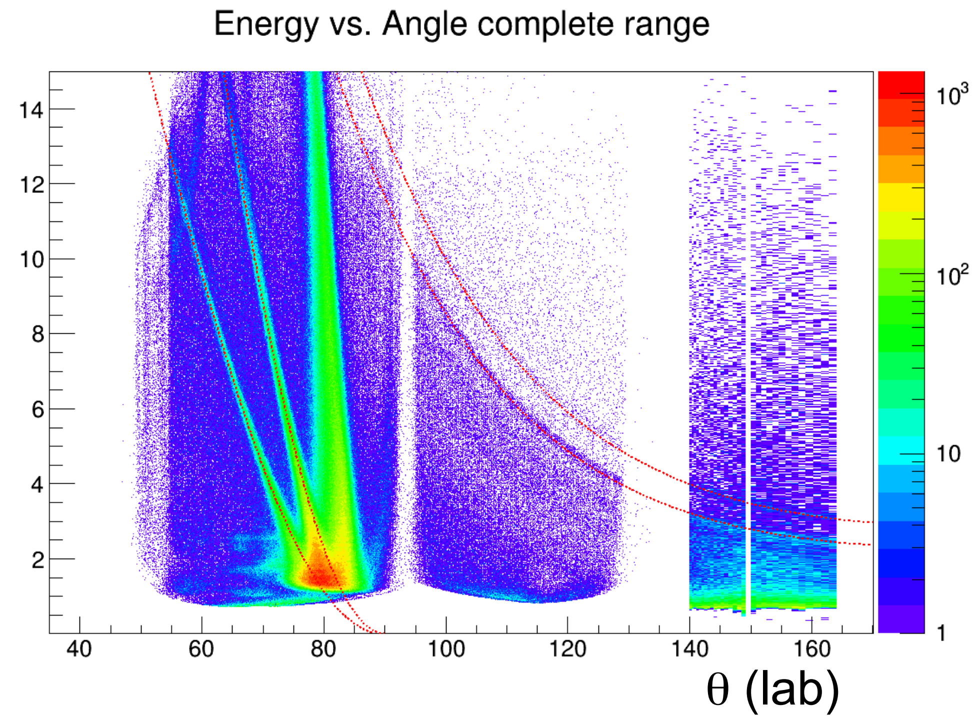
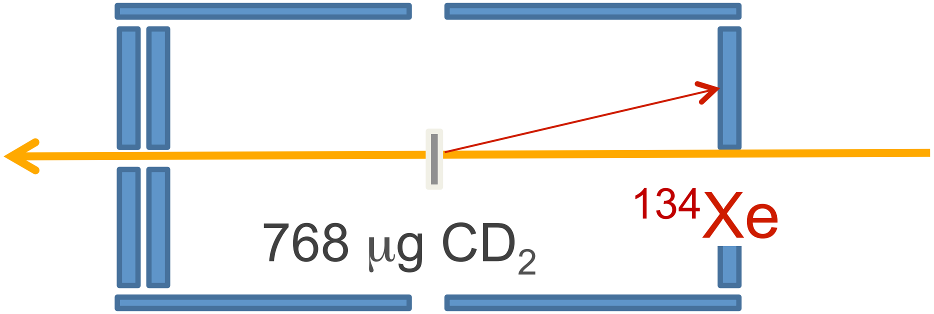
^{134}Xe(d,pγ) with GODDESS: levels+SF

N=80 isotone





A. Lepailleur, private communication

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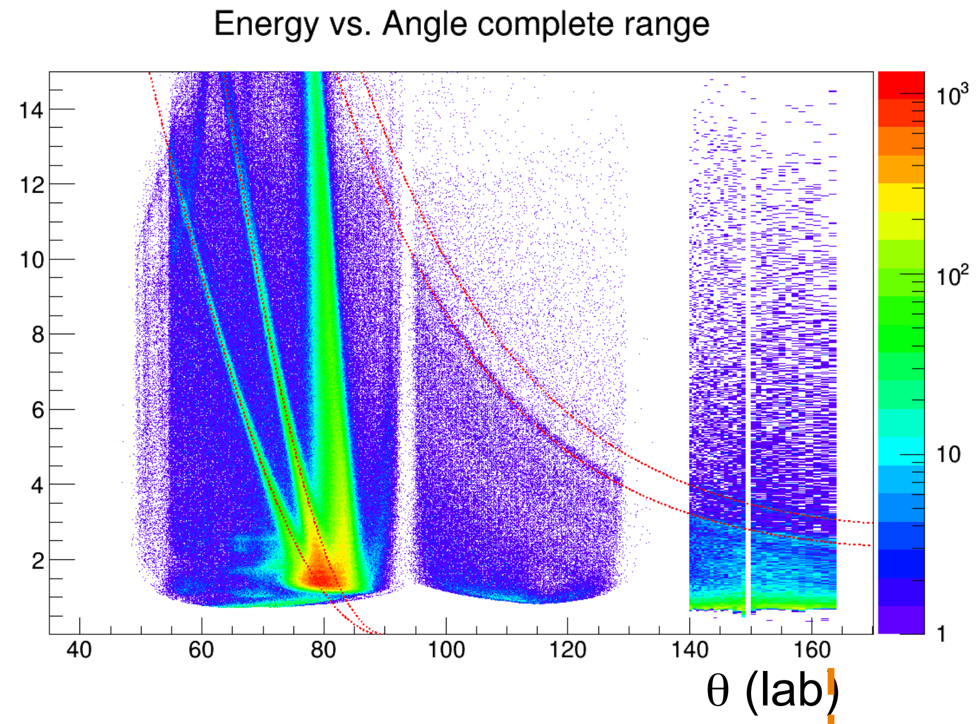
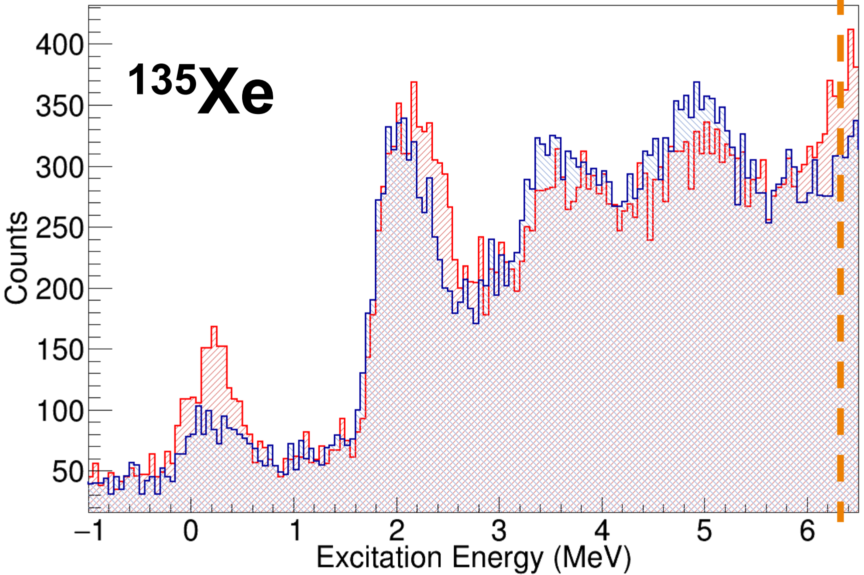
^{134}Xe(d,pγ) with GODDESS: levels+SF

N=80 isotone





^{135}Xe E_x spectrum

Red: QQQ5 (large θ)

Low-ℓ transfer important for DSD

Blue: SX3 (90°<θ<135°)

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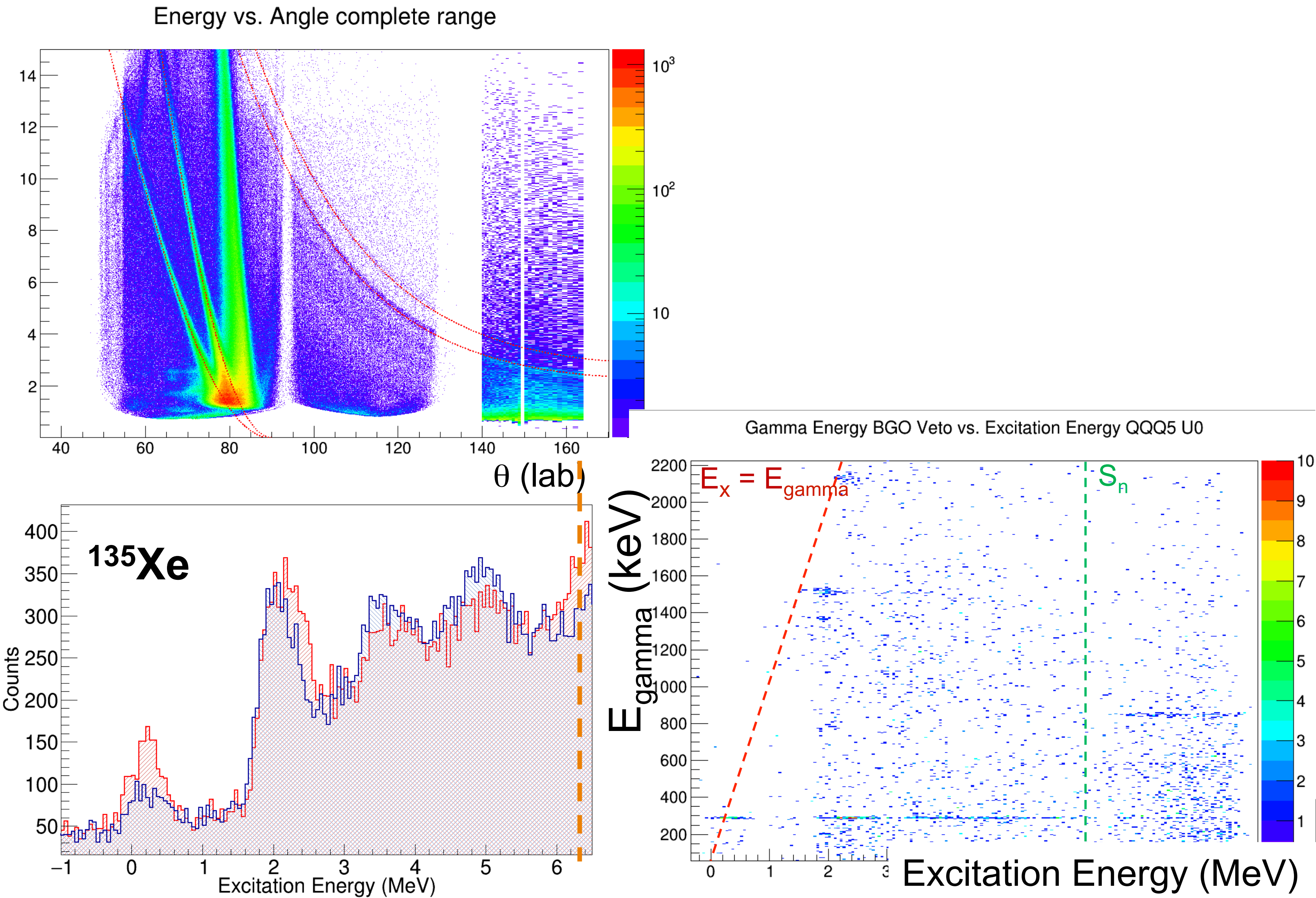
^{134}Xe(d,pγ) with GODDESS: levels+SF

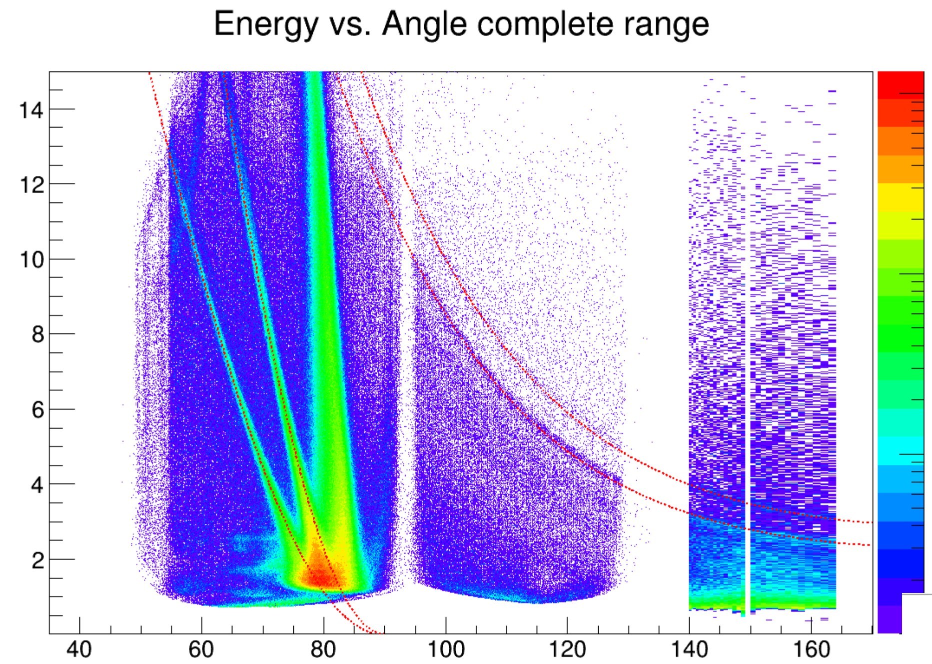


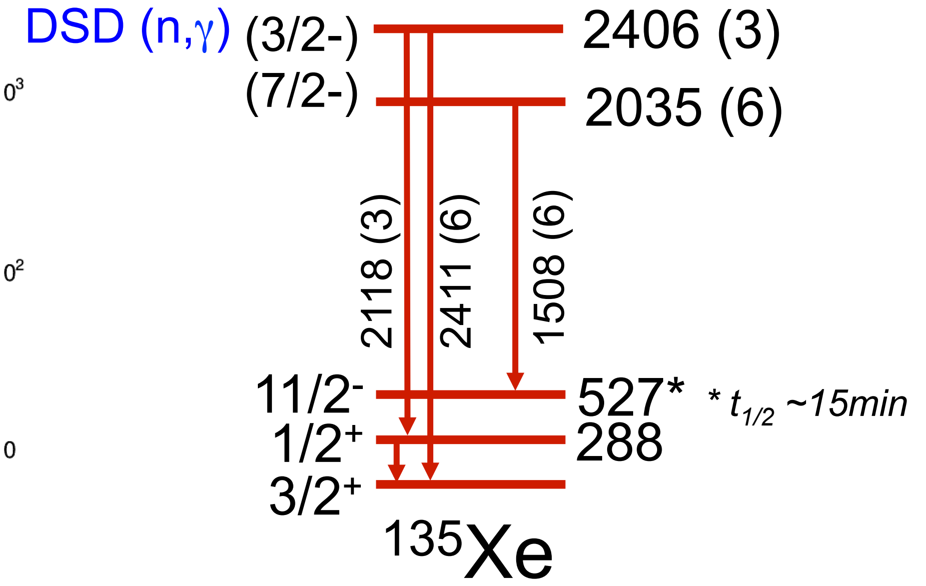
Energy vs. Angle complete range

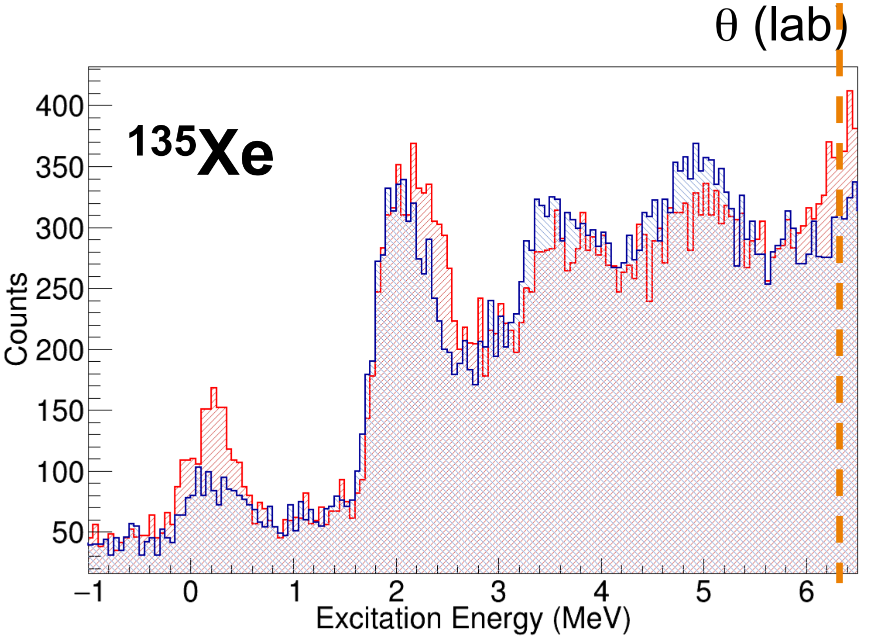
Gamma Energy BGO Veto vs. Excitation Energy QQQ5 U0

^{134}Xe(d,pγ) with GODDESS: levels+SF

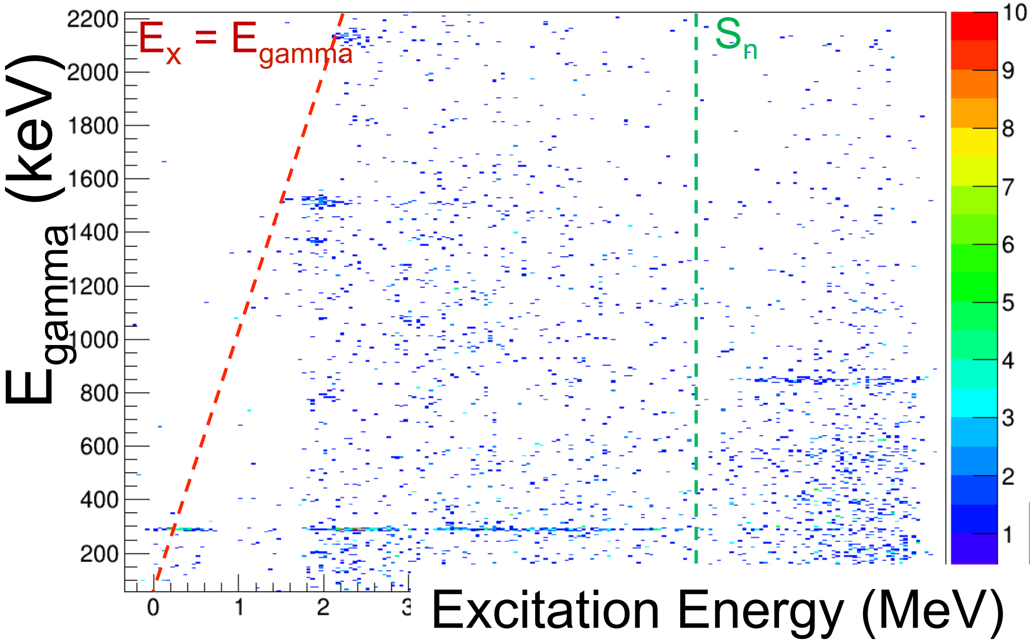
Energy vs. Angle complete range







Gamma Energy BGO Veto vs. Excitation Energy QQQ5 U0



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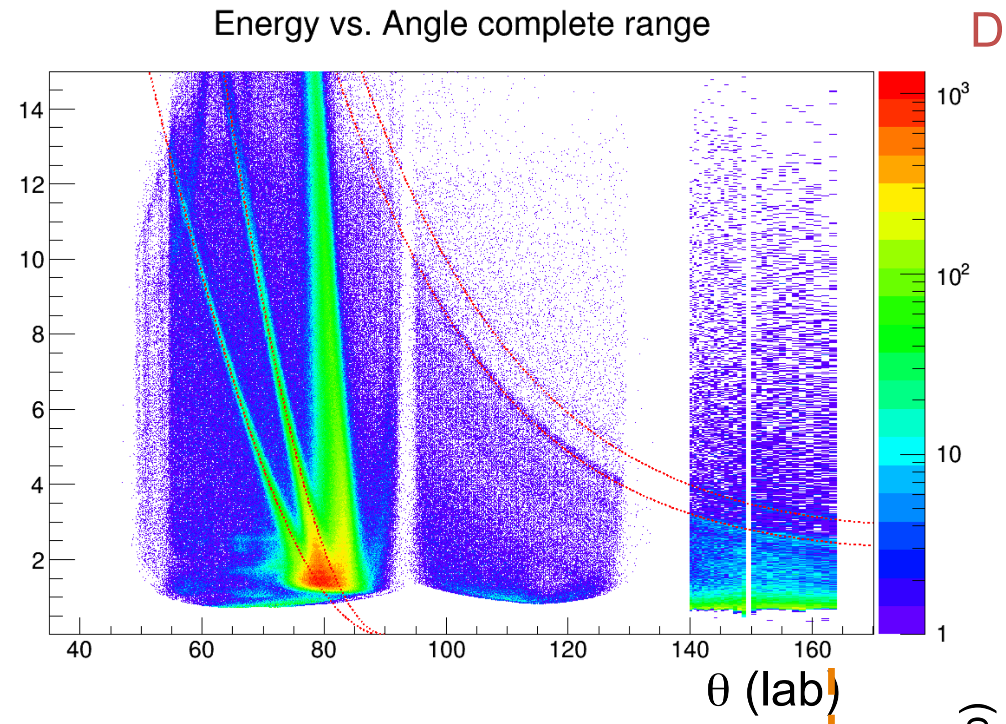
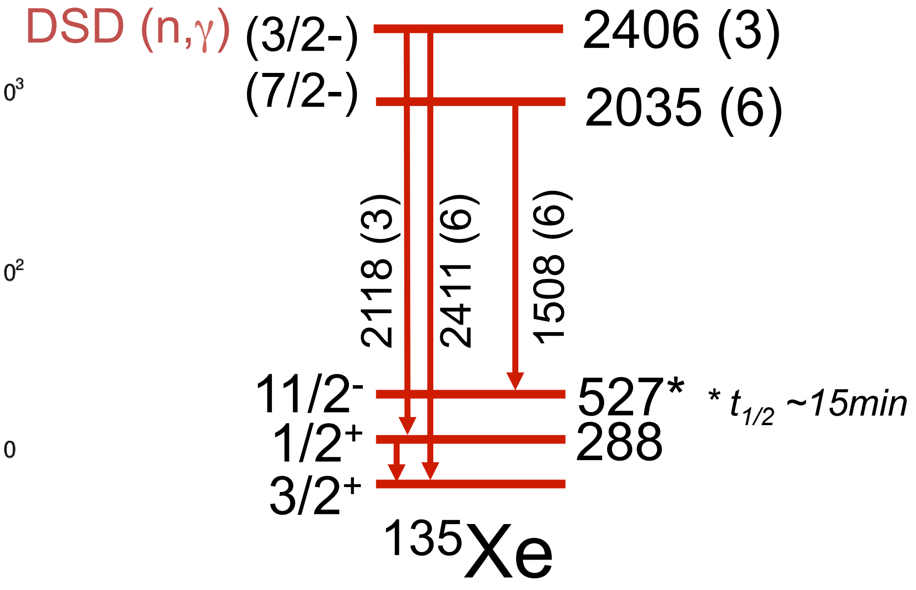
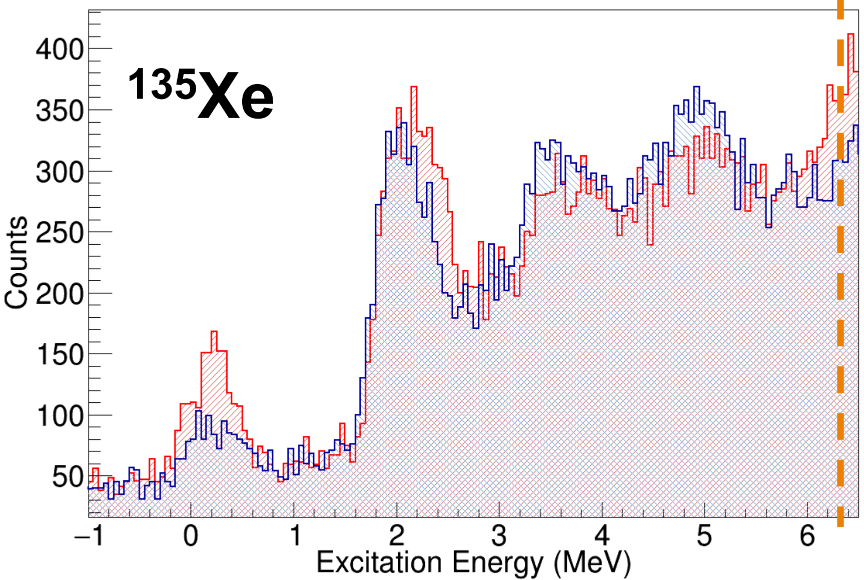
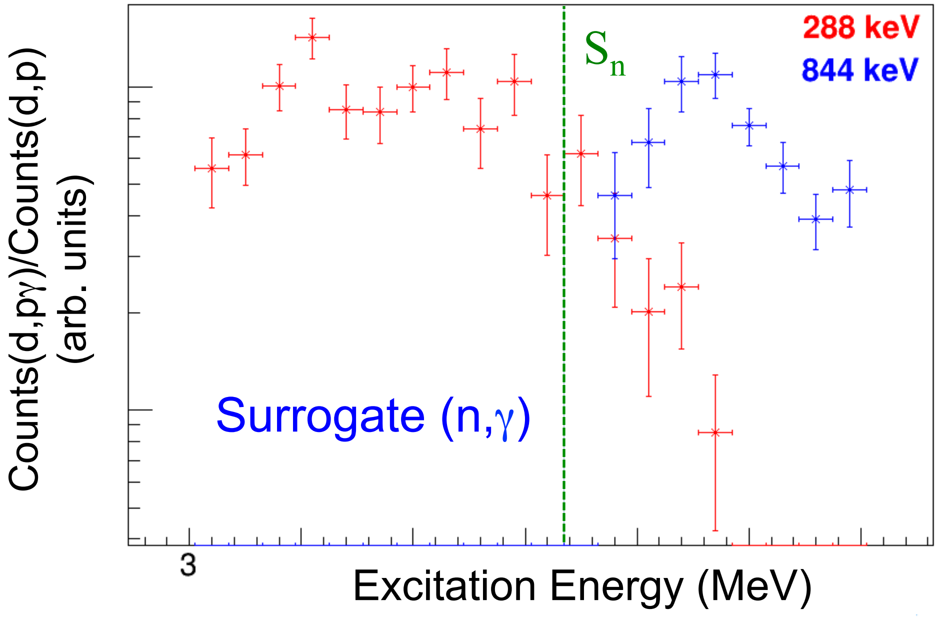






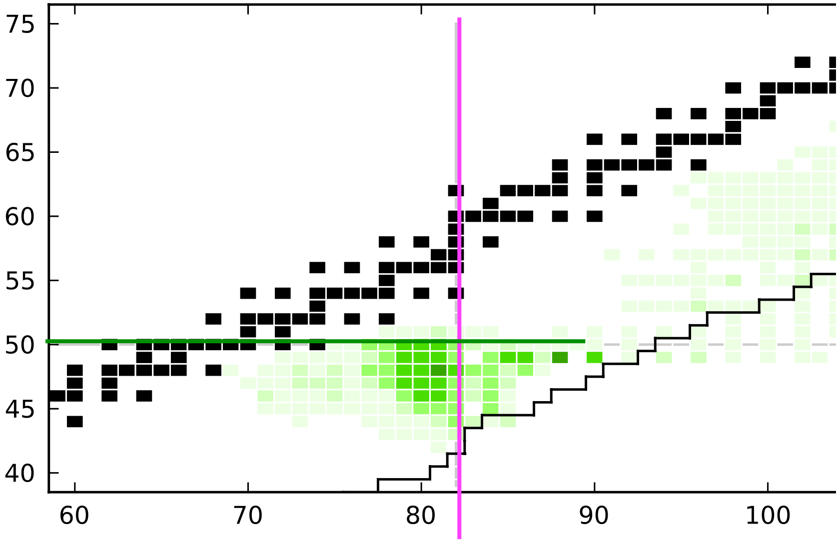


RUTGERS

Prepared to measure surrogate (n,γ) w/ RIBs & (d,pγ)

Goal: ≈^{132}Sn isotopes important for n-star mergers

Will have to wait for FRIB

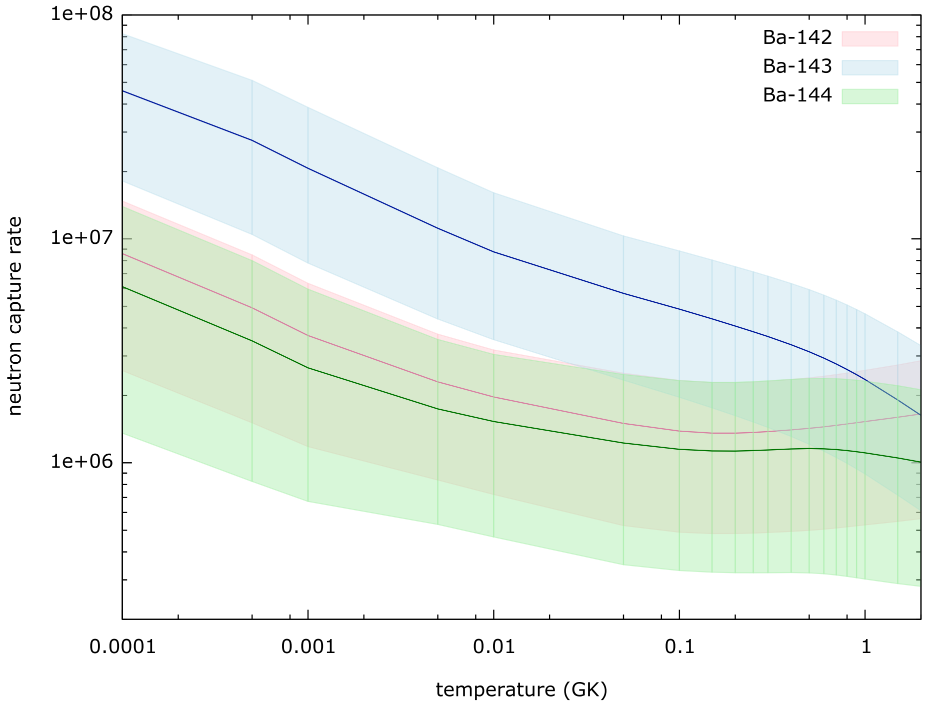


What can we do “now”?

- CARIBU ^{252}Cf fragment beams
- Approved to measure ^{143}Ba(d,pγ) w/ GODDESS

Ba(n,γ) rates from [Mum16]

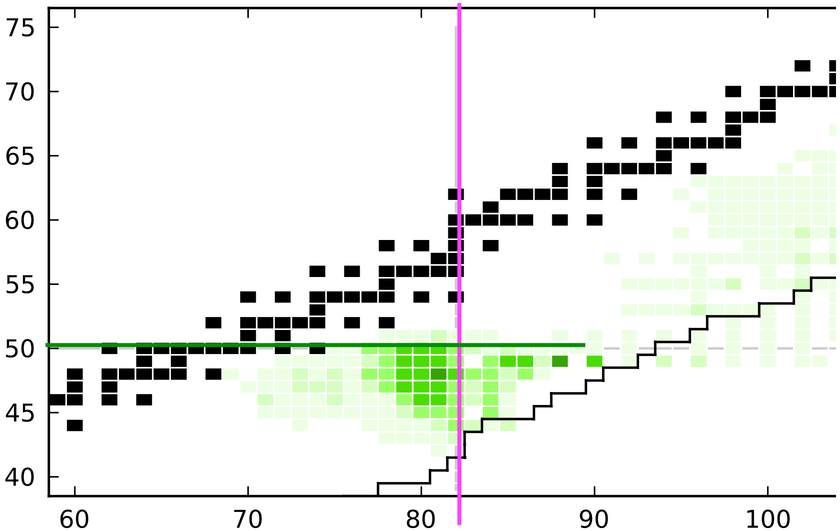
Would be first surrogate (n,γ) on fission fragment to constrain (n,γ) in this region



Prepared to measure surrogate (n,γ) w/ RIBs & $(d,p\gamma)$

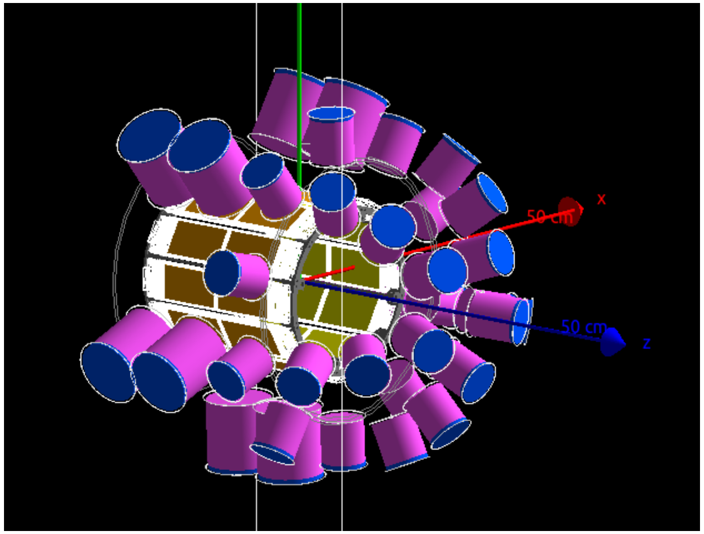
Goal: ≈^{132}Sn isotopes important for n-star mergers

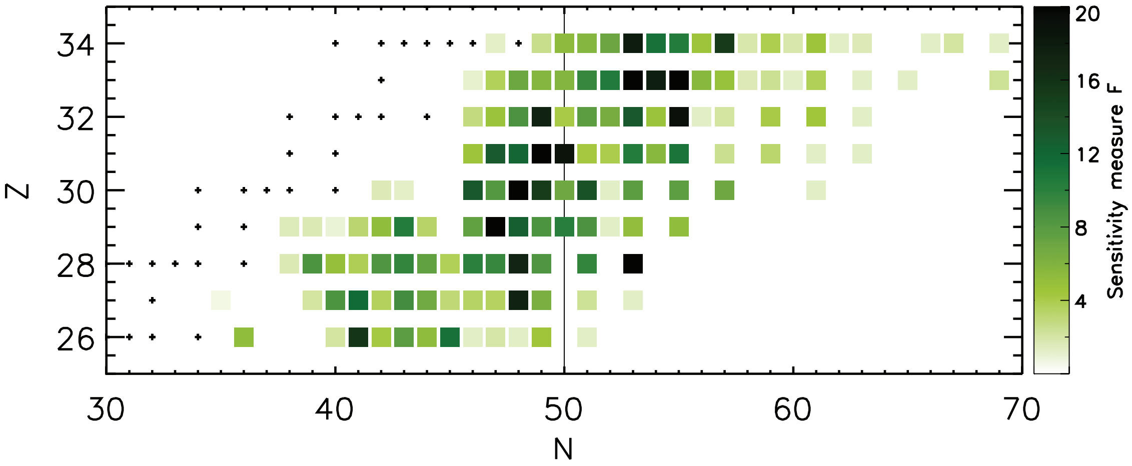
Will have to wait for FRIB



What can we do “now”?

- CARIBU ^{252}Cf fragment beams
- Approved to measure ^{143}Ba$(d,p\gamma)$ w/ GODDESS
- NSCL ≈80 fast beams
- Approved to measure ^{80}Ge$(d,p\gamma)$ w/ ORRUBA+HAGRiD



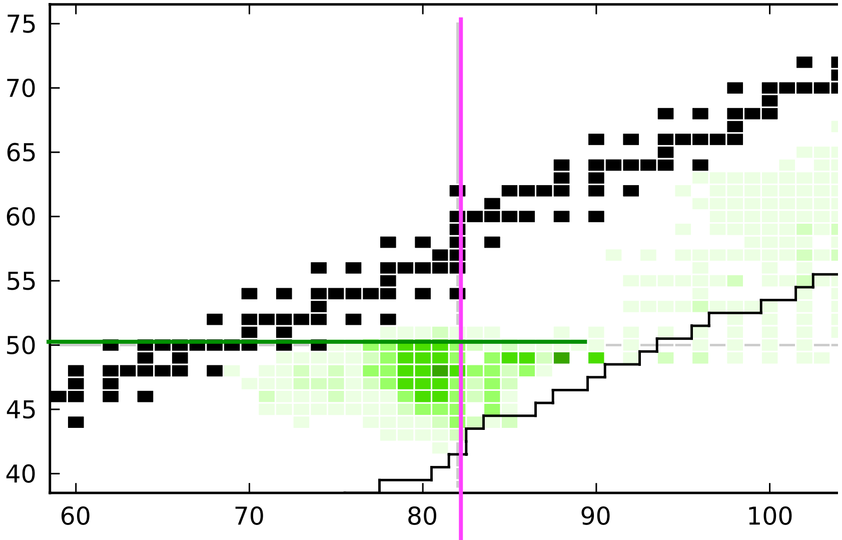


Surman et al. AIP Adv. **4**, 041008 (2014)

Thank you for your attention

- Understanding abundances from NSM r process is sensitive to (n,γ) rates, especially near shell closures, e.g., ^{130}Sn, and weakly bound nuclei with low level density
  - Need neutron transfer (d,p) to inform direct-semi-direct capture
- Unknown competition between DSD and CN (n,γ)
  - Need validated surrogate for (n,γ)
- Demonstrated that (d,pγ) is valid surrogate for (n,γ)
- Demonstrated ability to measure (d,p) protons in coincidence with gamma rays
- Near term
  - ^{143}Ba(d,pγ)
  - ^{80}Ge(d,pγ)
- Goal: FRIB (d,pγ)

e.g., with ^{130}Sn beams



EXTRA SLIDES

RUTGERS

Fitting $P(d,p\gamma)$ with FCN from Potel model

Hauser Feshbach code STAPRE (modified)

- Level Density
  - Use known discrete levels
  - Gilbert-Cameron level density
    - Fermi Gas model matched to Constant Temperature
- Gamma-ray strength function “usual” forms
  - E1, M1, E2, M2
  - E1 strength: modified, energy- and temperature-dependent Lorentzian
- Bayes’ method to obtain parameter constraints
- Monte-Carlo sampling of parameters to calculate cross sections

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