Informing neutron capture via surrogate(d,pγ) measurements

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Informing (n,γ) via surrogate (d,pγ)

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Steve Pain[(3)] Gregory Potel[(4)],
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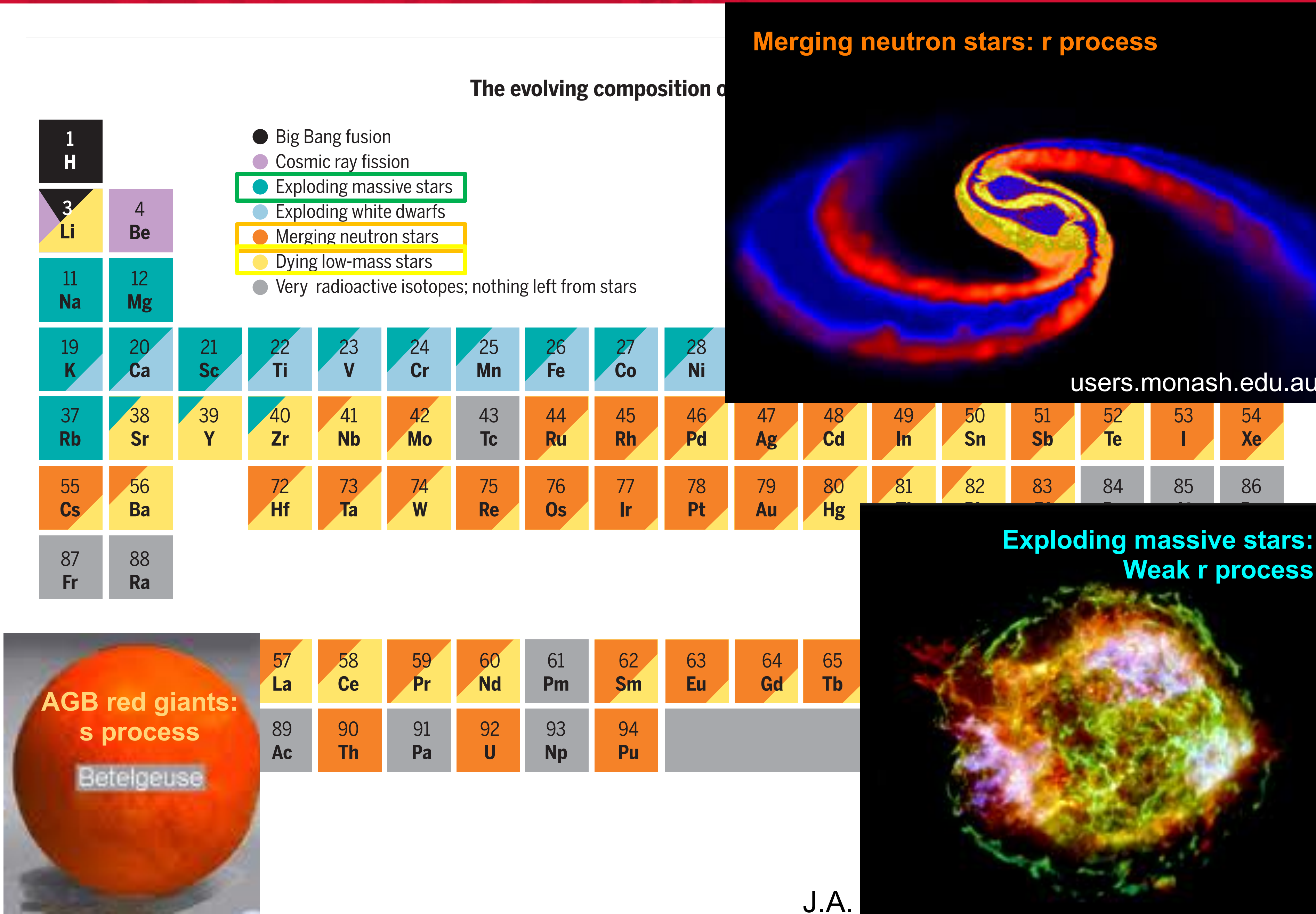
(2) Lawrence Livermore National Laboratory
(3) Oak Ridge National Laboratory
(4) Michigan State University & FRIB

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

Synthesis of Z>28 elements: neutron capture



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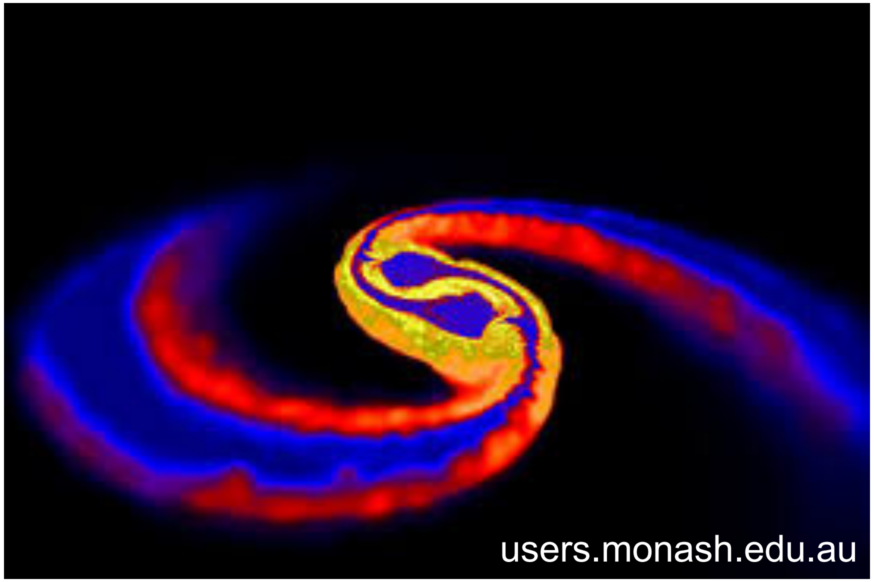
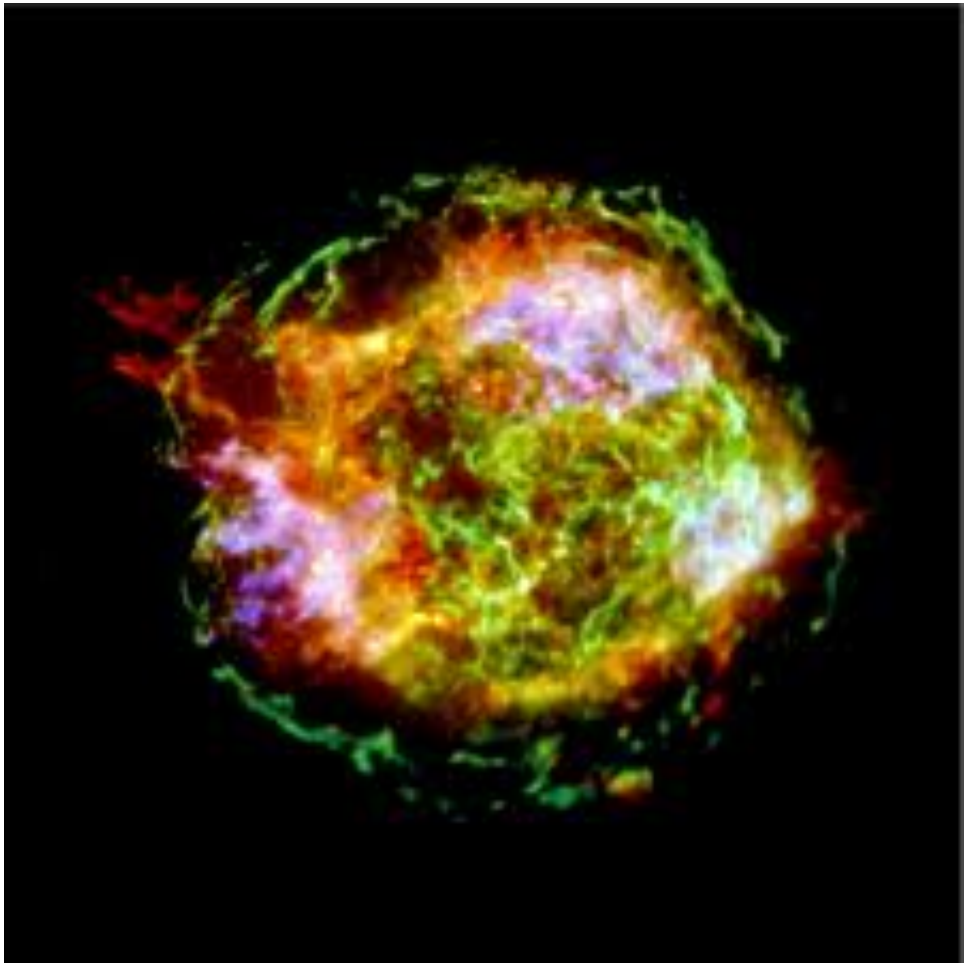
Neutron induced reactions in stars & r-process nucleosynthesis

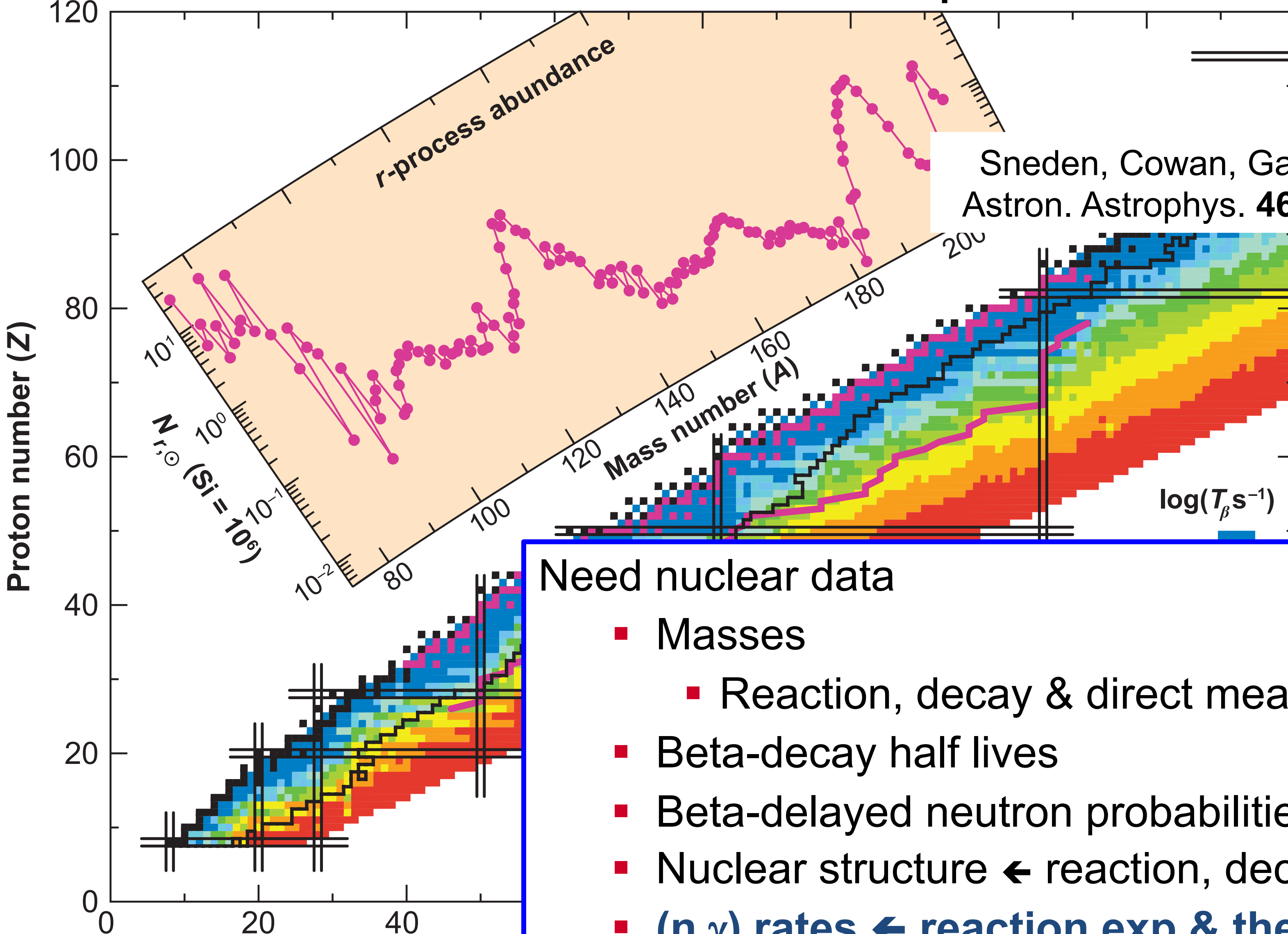




- Rapid neutron capture
  - Believed to take place in supernovae explosions and/or binary neutron star mergers
  - r process nucleosynthesis
  - Far from stability

http://www.nasa.gov/centers/marshall/multimedia/photos/2004/photos04-222.html_prt.htm

Understanding r-process nucleosynthesis depends on nuclear data



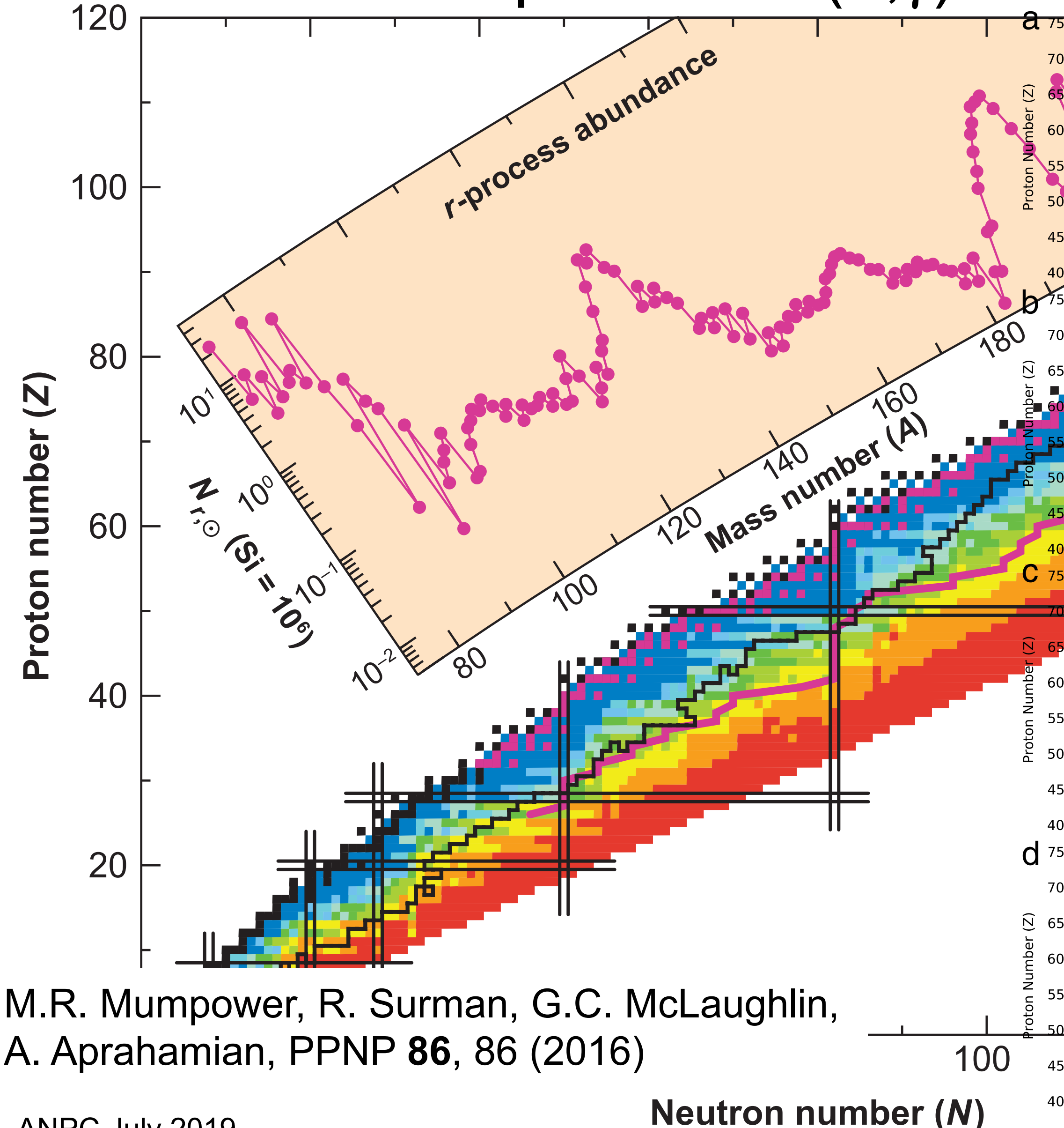
Sneden, Cowan, Gallino, Annu. Rev. Astron. Astrophys. **46**:241-288 (2008)

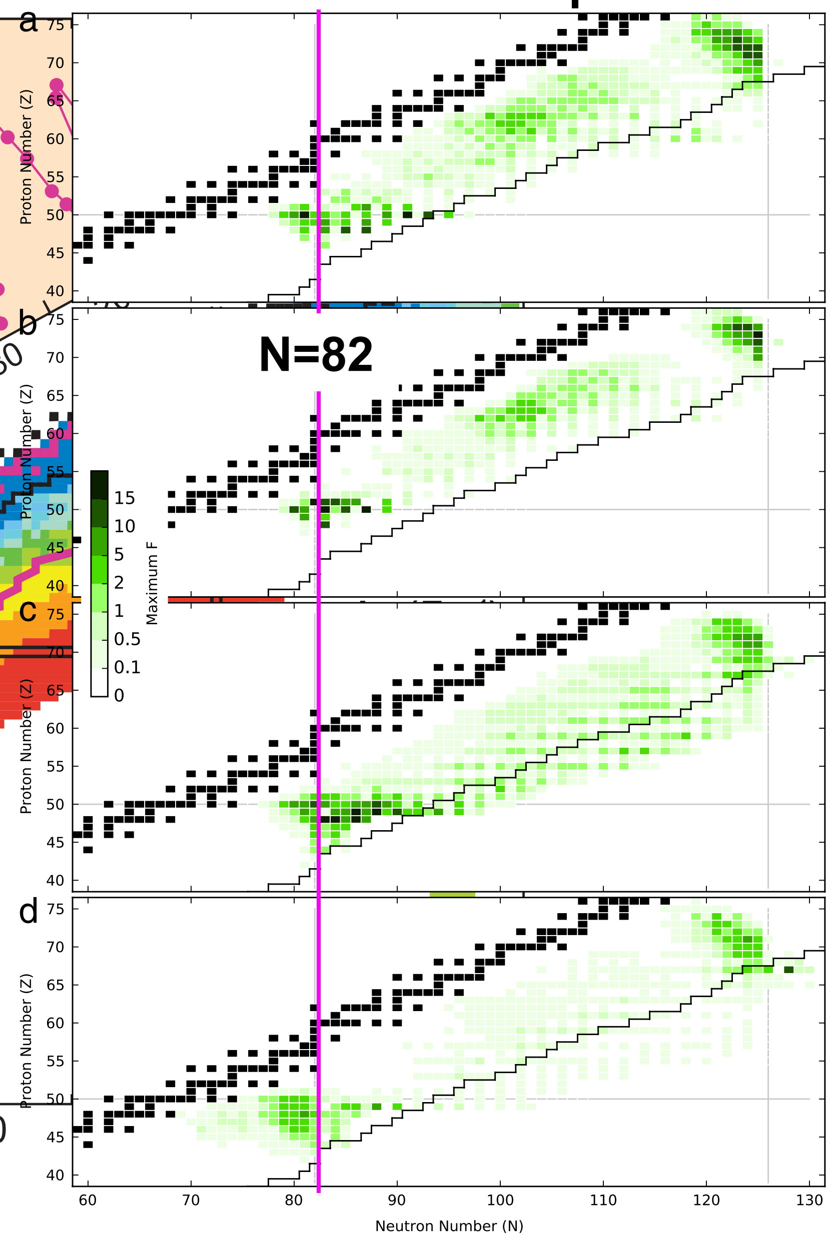
Need nuclear data

- 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

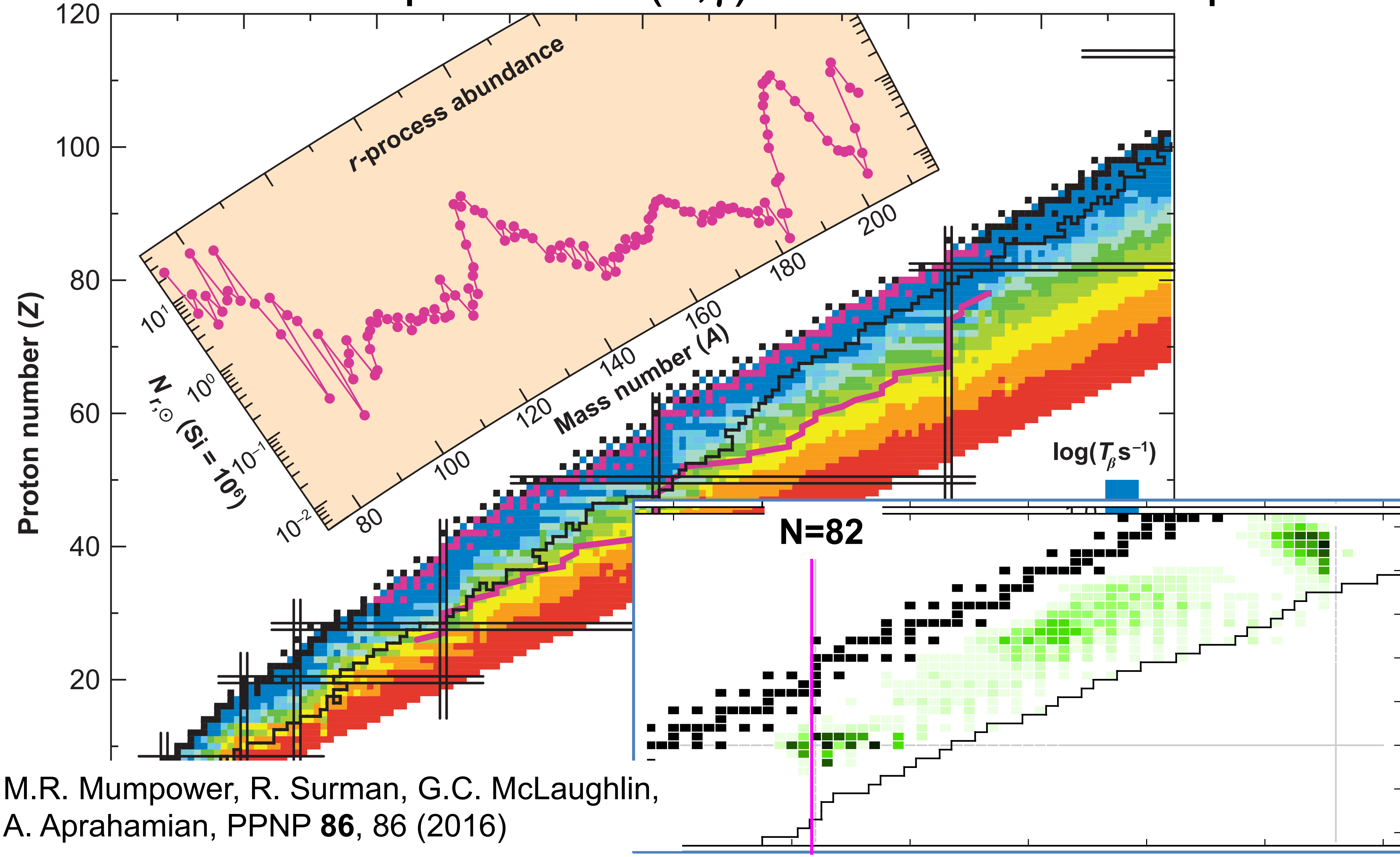




M.R. Mumpower, R. Surman, G.C. McLaughlin, A. Aprahamian, PPNP **86**, 86 (2016)

r-process nucleosynthesis

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

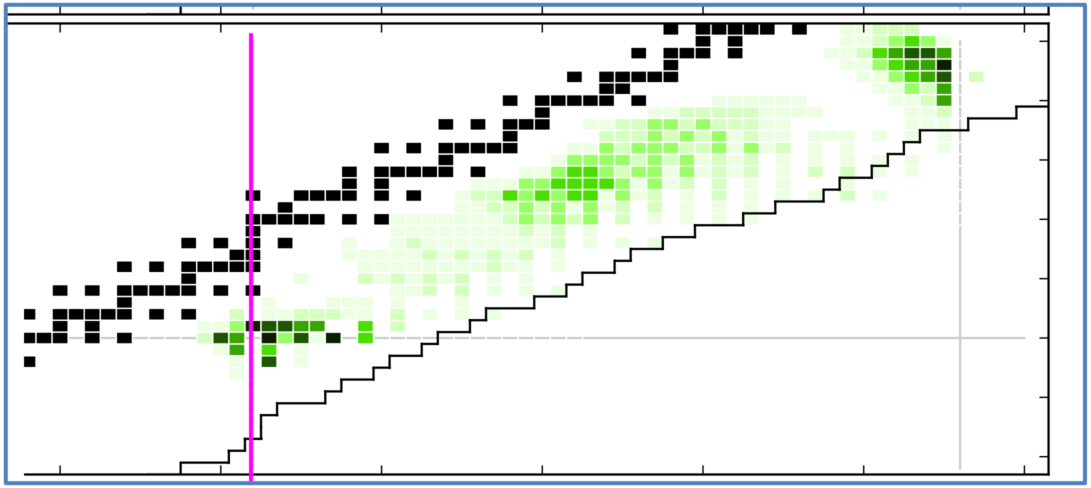


M.R. Mumpower, R. Surman, G.C. McLaughlin, A. Aprahamian, PPNP **86**, 86 (2016)

(freeze out) high entropy, hot wind

Near shell closure

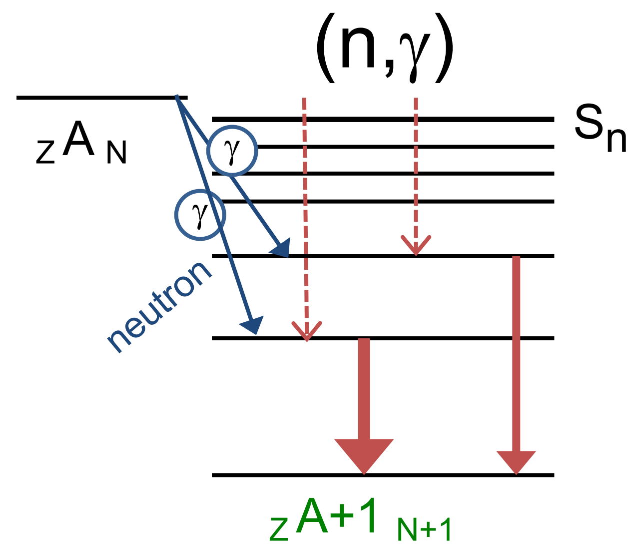
neutron capture dominated by direct capture



Z=50 isotopes high entropy hot site

Mumpower, et al. PPNP 2016

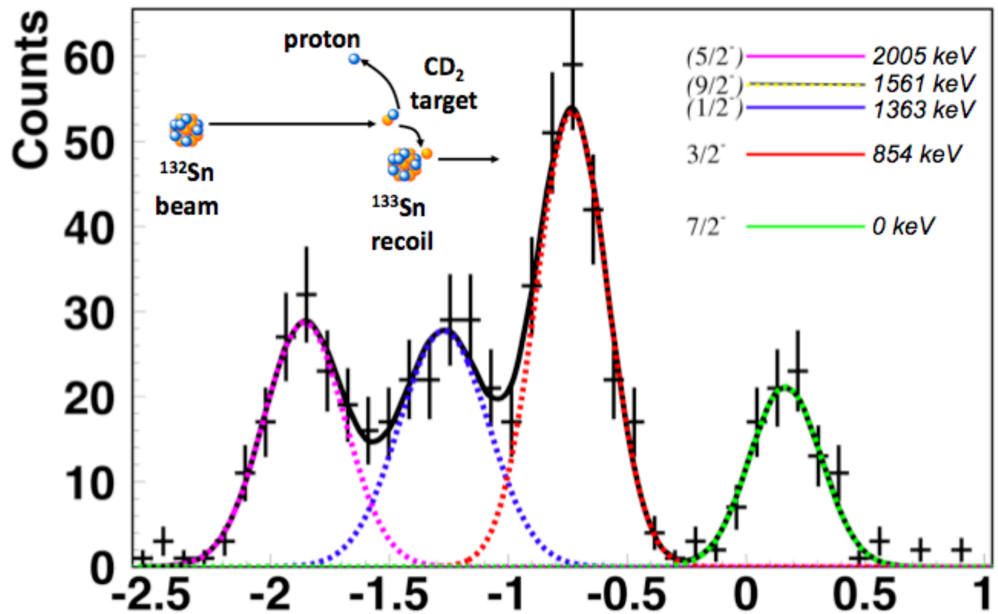
79	129	0.68
80	130	11.90
81	131	6.02
82	132	0.10
83	133	30.60
84	134	1.01
85	135	14.29



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

^{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

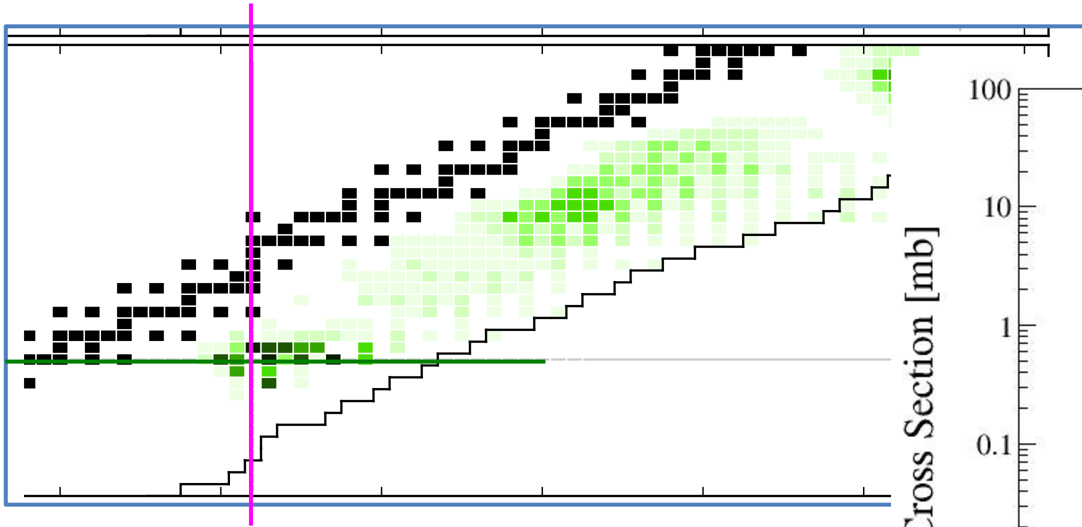


K.L. Jones et al.
Nature, **465**,454 (2010)
Phys. Rev. C **84**, 034601 (2011)

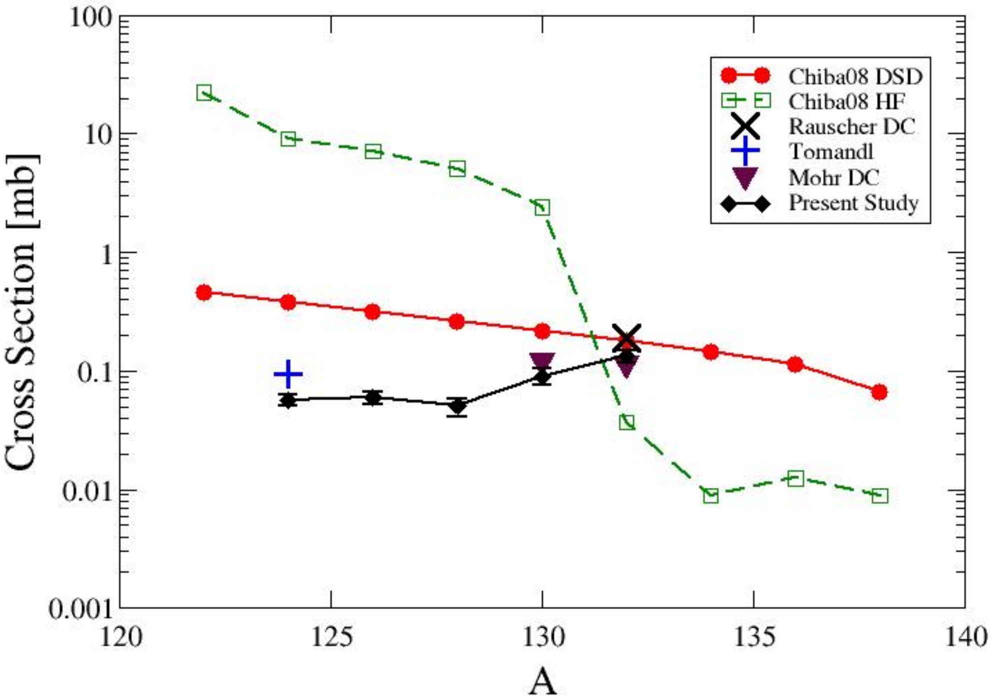
$$S_{lj} = \frac{d\sigma_{exp}}{d\sigma_{DW}} = \left|A_{lj}\right|^2$$

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)

^{132,130,128,126,124}Sn DSD (n,γ)



	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)

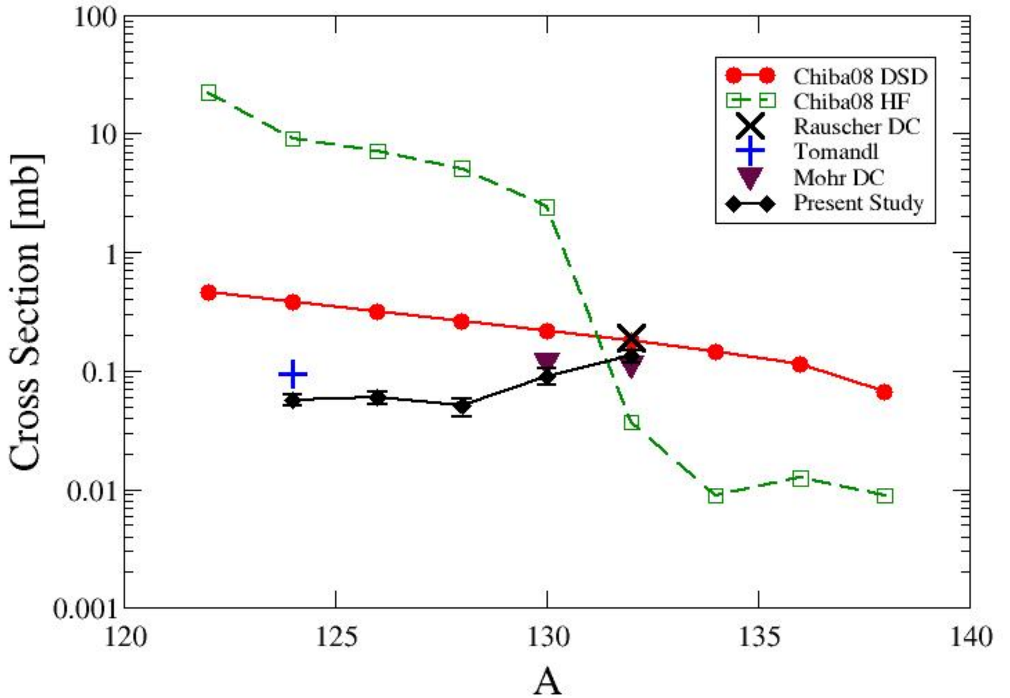


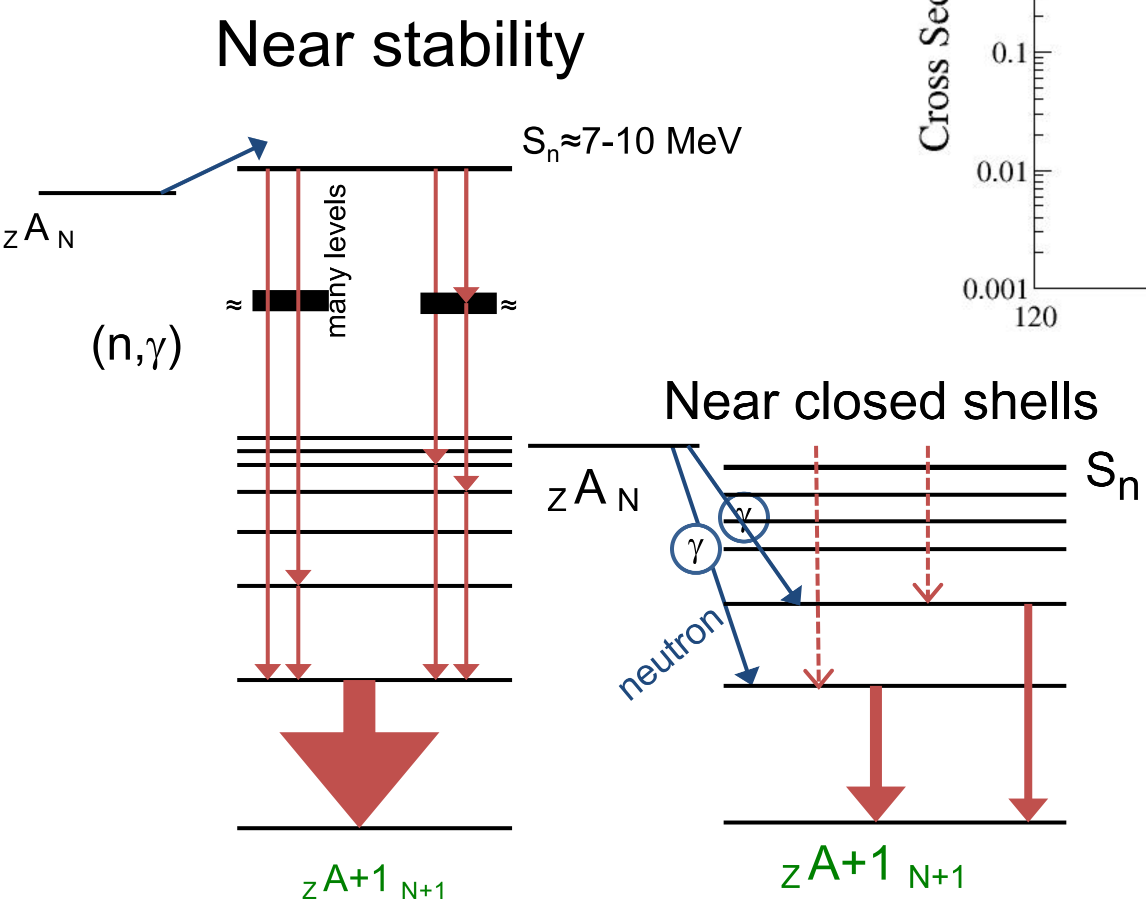
Sn(n,γ) vs A

Theory: Chiba, et al. PRC **77**, 015809 (2008)
Exp DSD: B. Manning, PRC **99**, 041202(R) (2019)

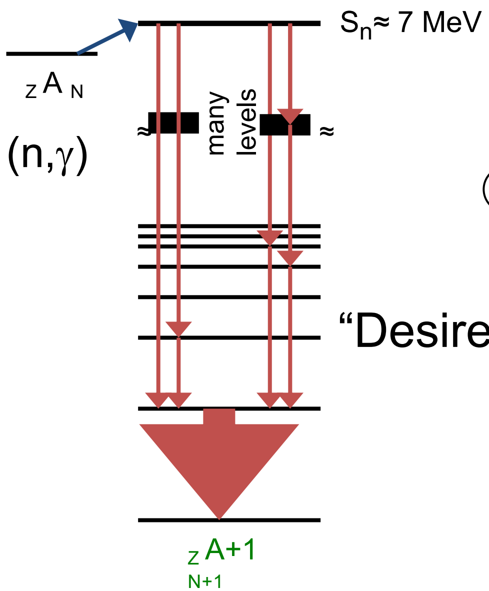
^{132,130,128,126,124}Sn statistical (n,γ)?

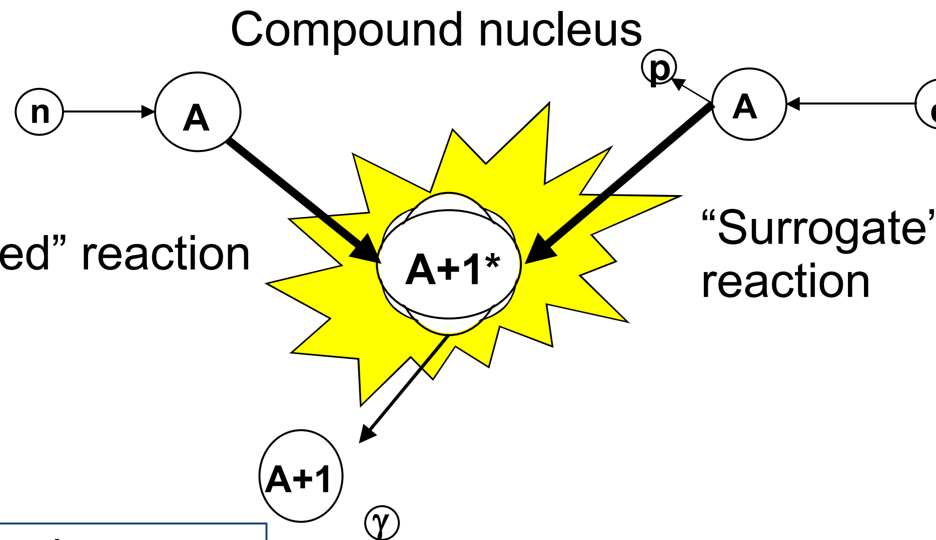
Statistical (n,γ) dominates σ when $N<N_{magic}$

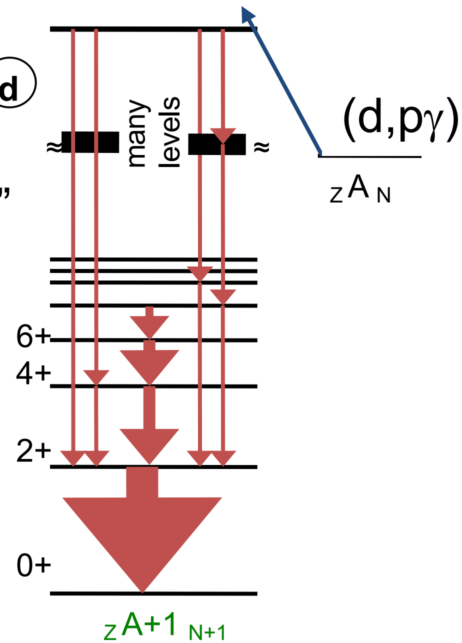




Surrogate reaction concept & Hauser-Feshbach formalism







(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:

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

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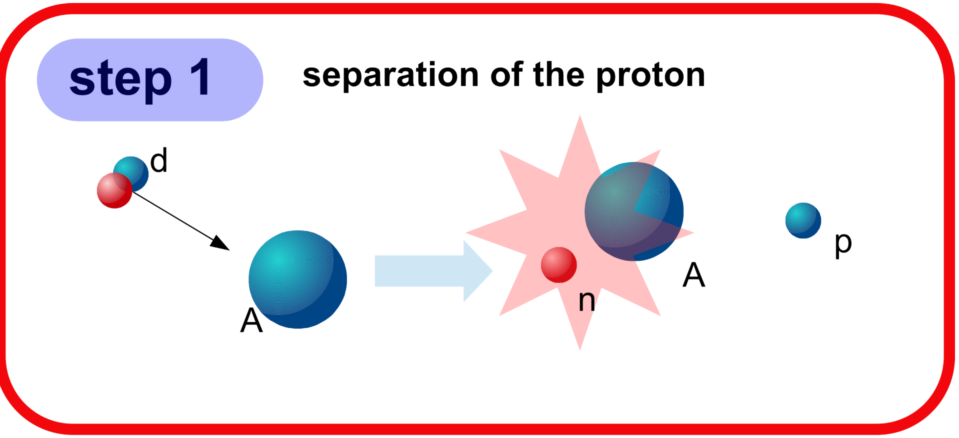
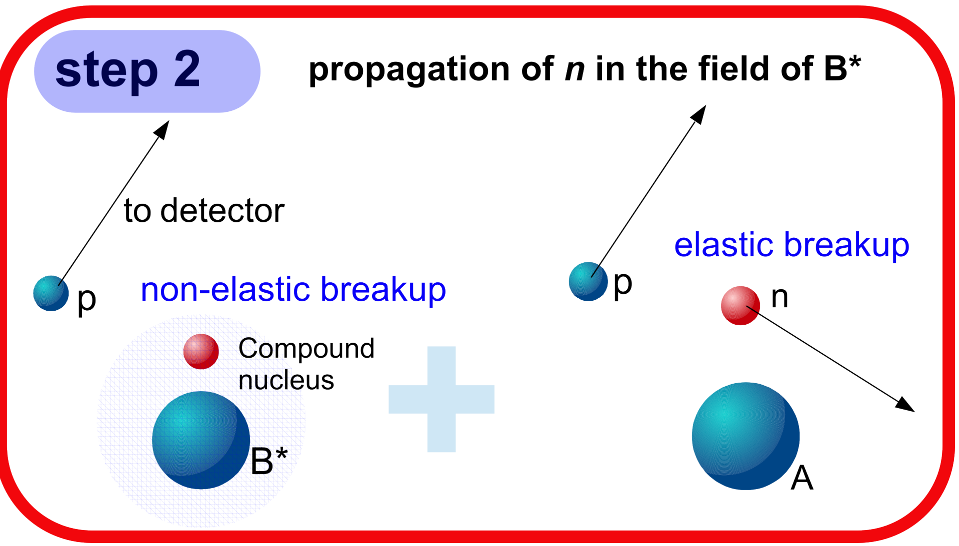
Forming compound nucleus in (d,p)

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

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





<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

Surrogate (n,γ) with (d,pγ)

(d,p) reaction forms compound nucleus

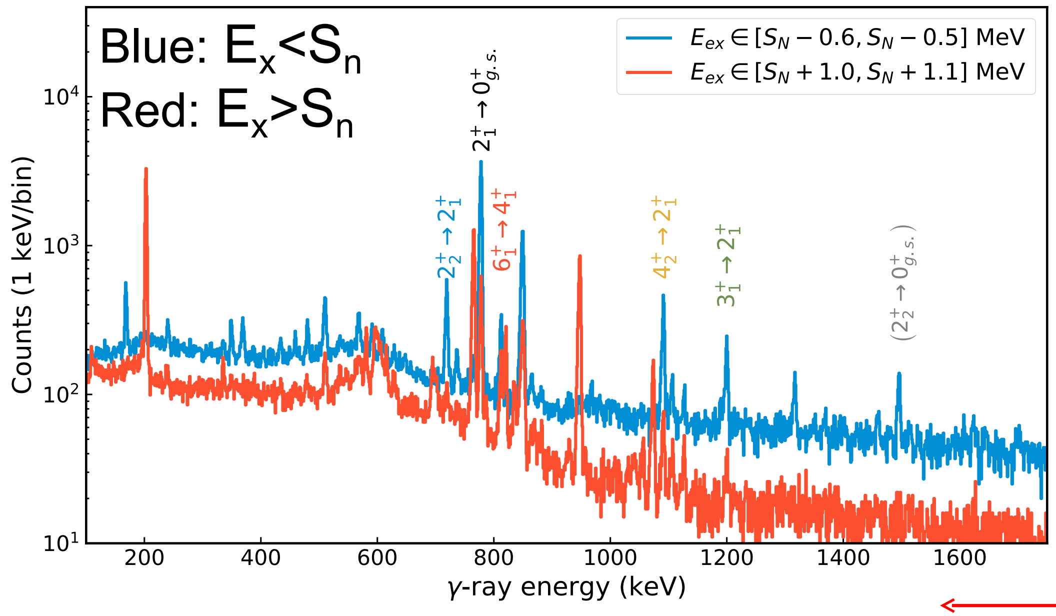
- Need to measure P(d,pγ)
- Need theory to calculate F^{CN}
- Need to deduce G^{CN} by fit to P(d,pγ) accounting for F^{CN}

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

Validate with $^{95}Mo(d,p\gamma)^{96}Mo$ reaction

σ(n,γ) was measured and evaluated

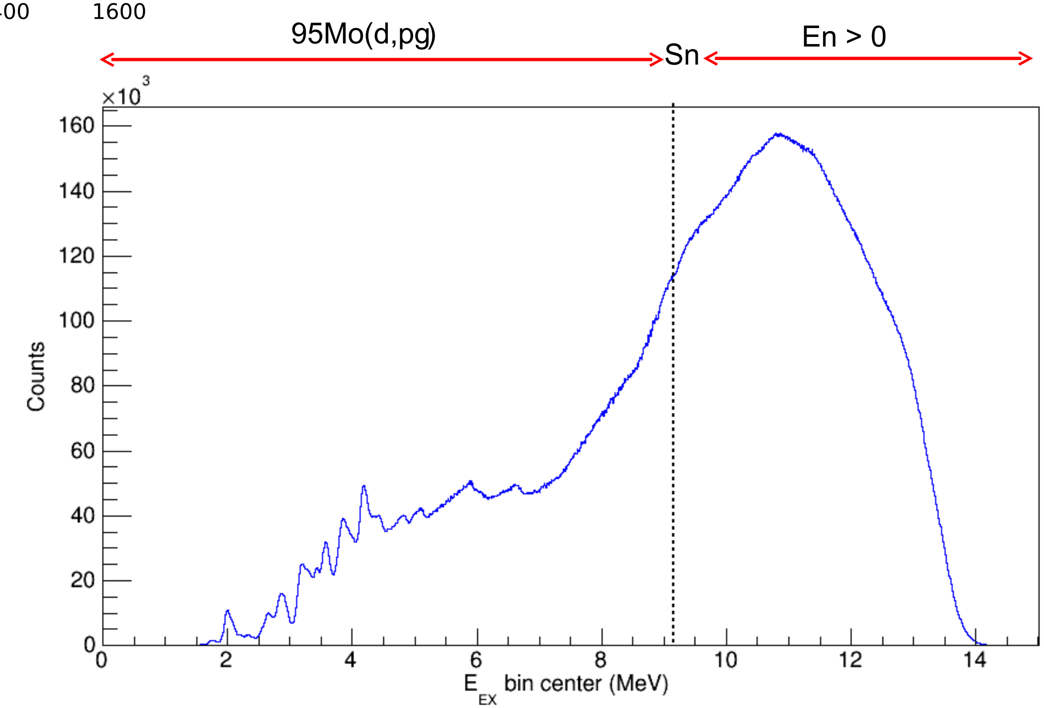
Gamma-ray Emission Probability



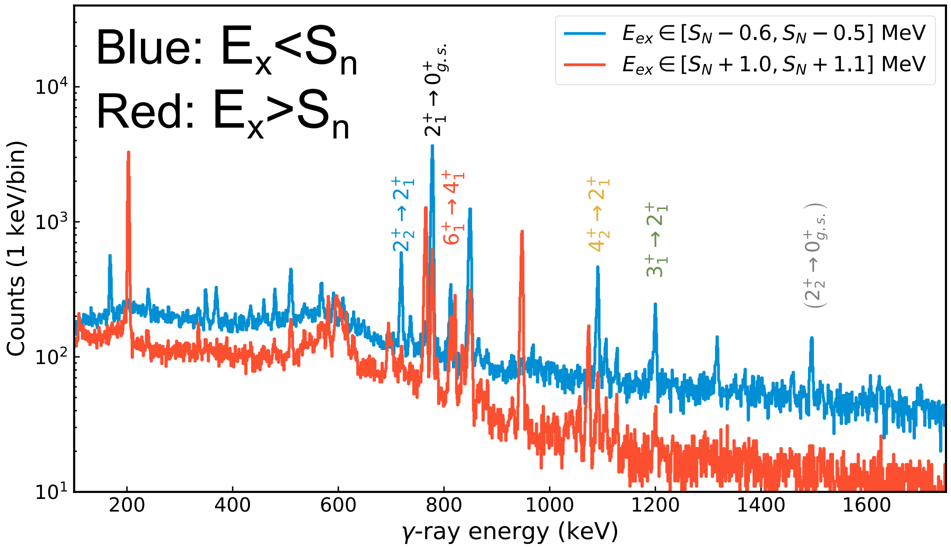
Measure p-γ coincidences

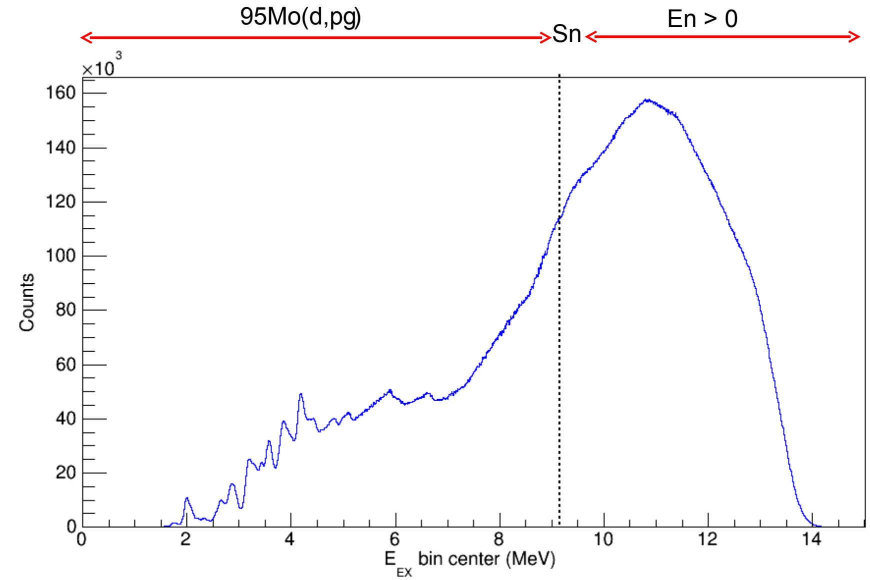
$$P(d, p\gamma) = \frac{N_{p-\gamma}}{N_p \varepsilon}$$

Norm to p singles



Gamma-ray Emission Probability





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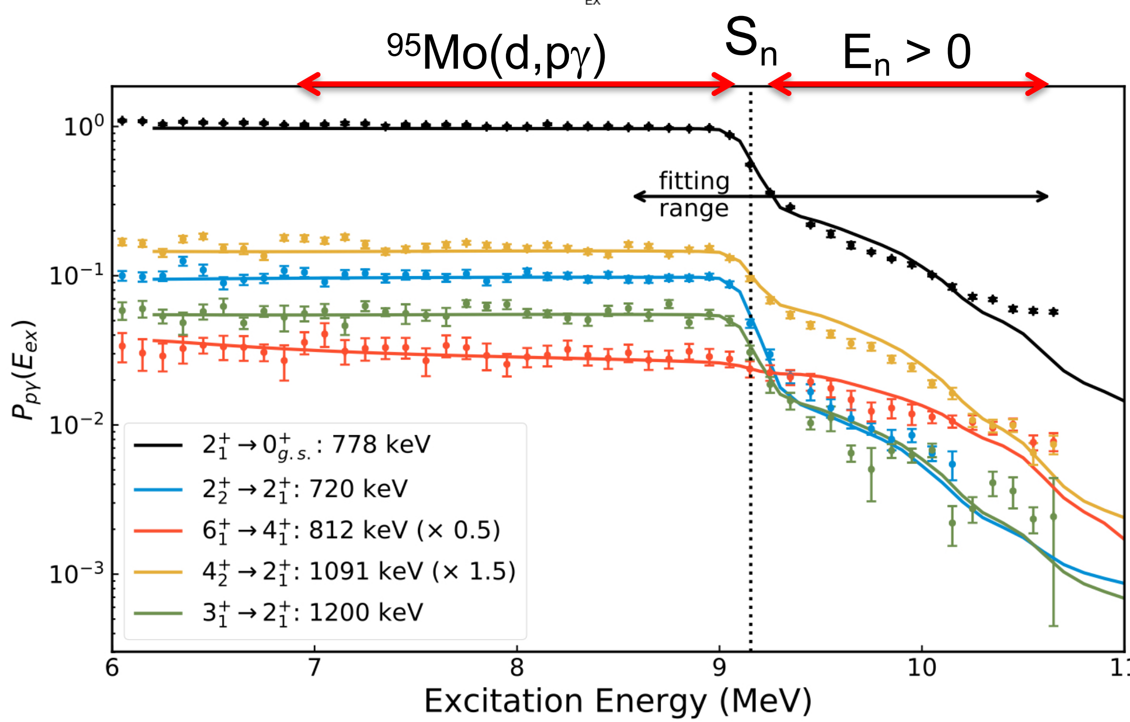
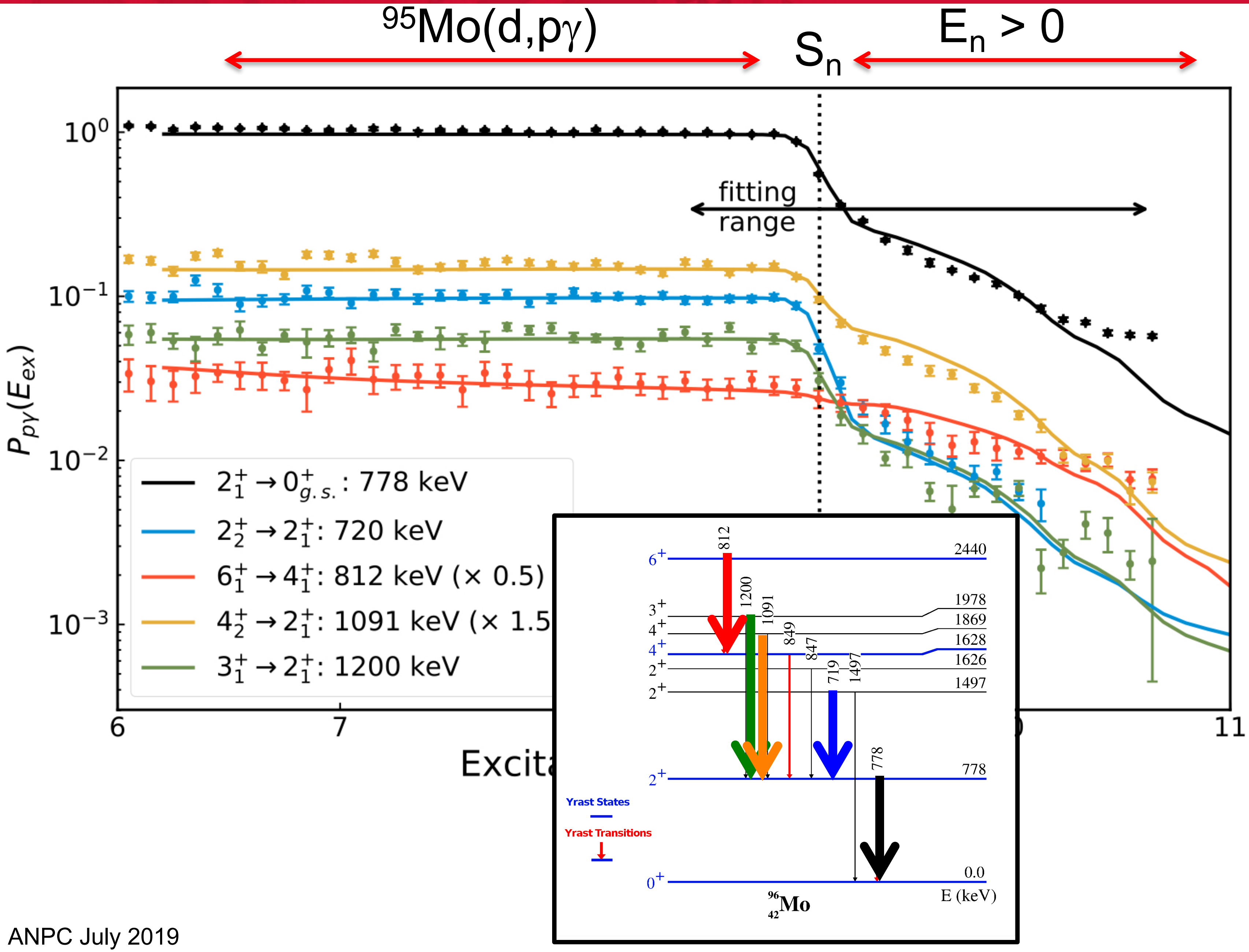


Gamma-ray Emission Probability



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

Measured P(d,pγ)

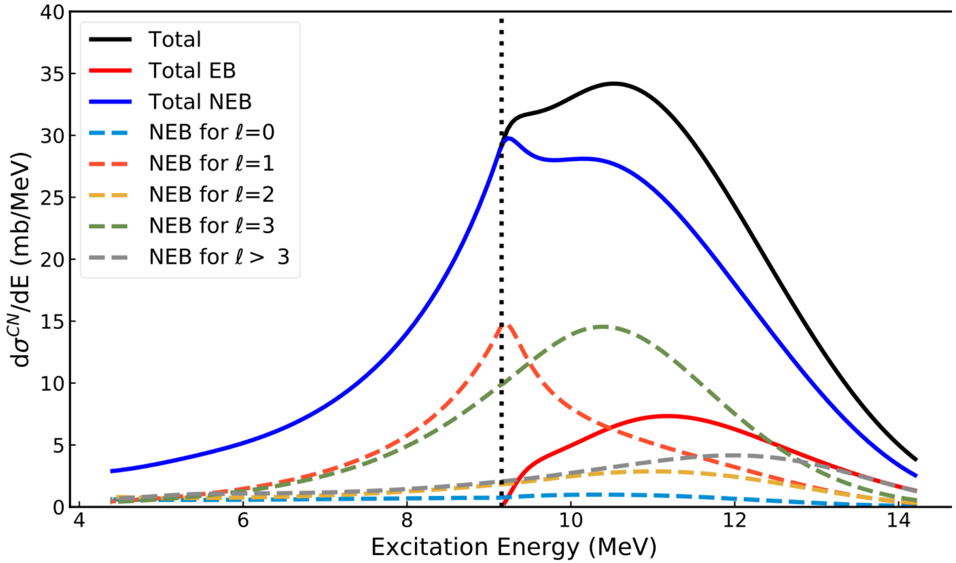
Calculate how (d,p) forms compound nucleus (E_x,J,π)

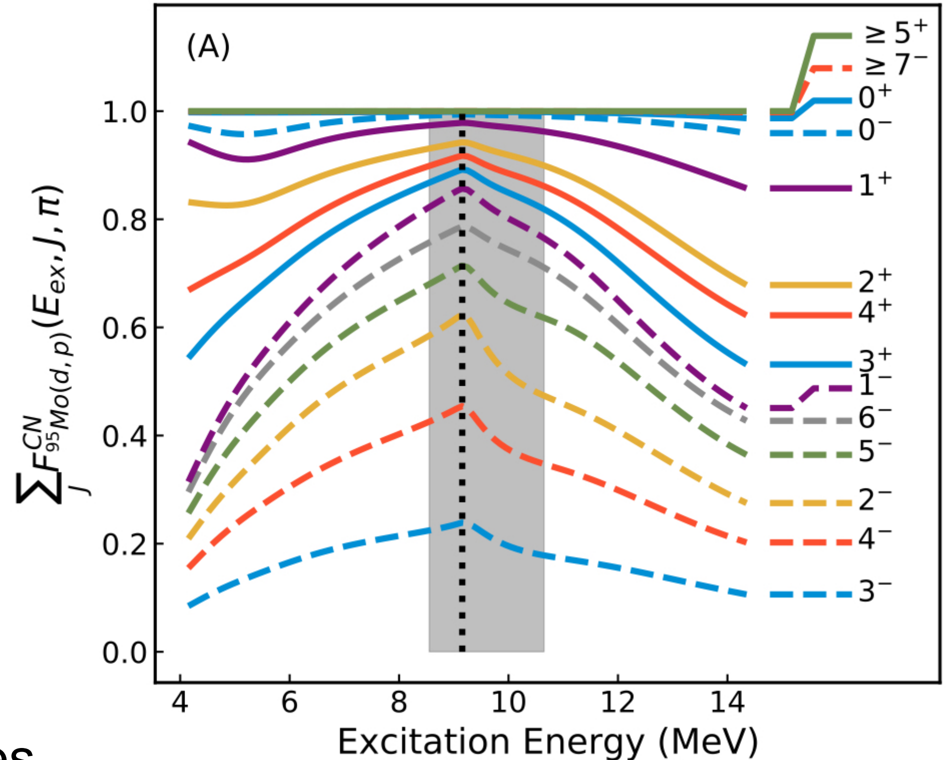
- Deduce G^{CN} by fit to P(d,pγ) accounting for F^{CN}

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

Potel model for d breakup and J^{π} distributions

Potel d breakup calculations

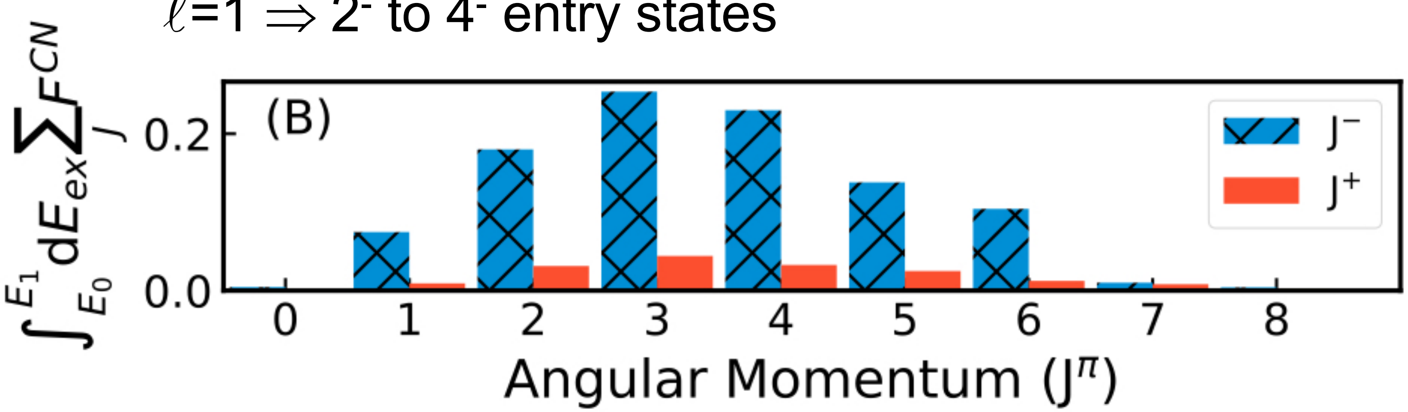




^{95}Mo(g.s)=$5/2^{+}$

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

$\ell=1 \Rightarrow 2^{-}$ to 4^{-} entry states



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

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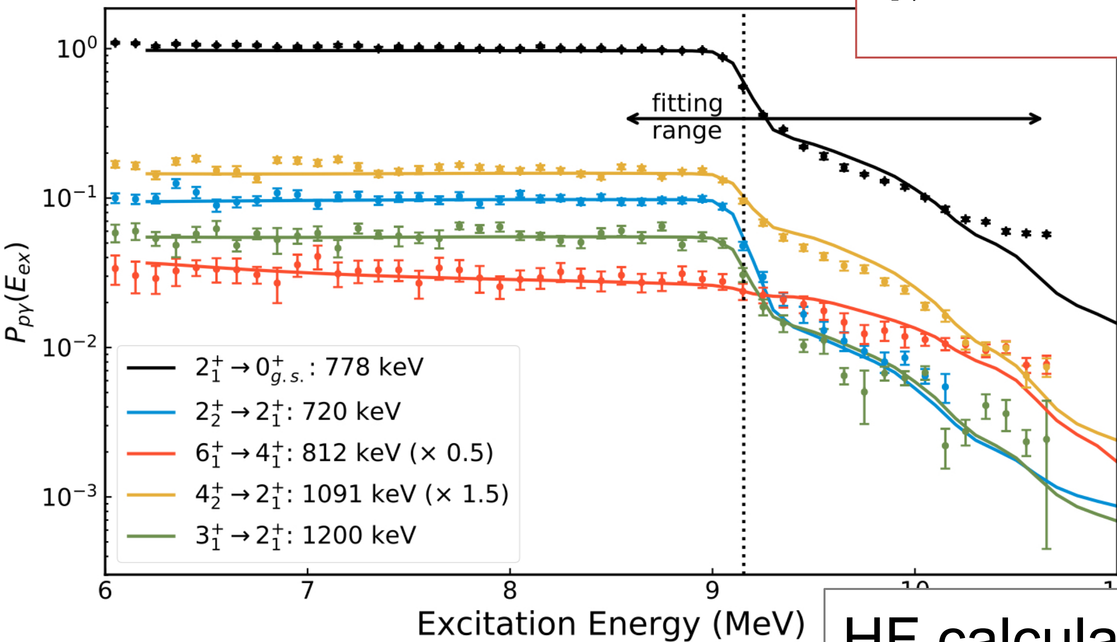
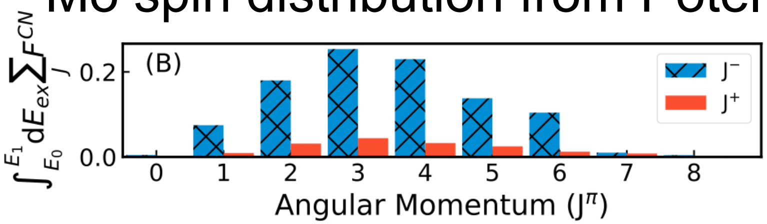
$$P_{p\gamma}(E_x,\theta) = \sum_{J,\pi} F_{dp}^{CN}(E_x,J,\pi,\theta)\, G_{\gamma}^{CN}(E_x,J,\pi)$$



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 $\sigma(n,\gamma)$

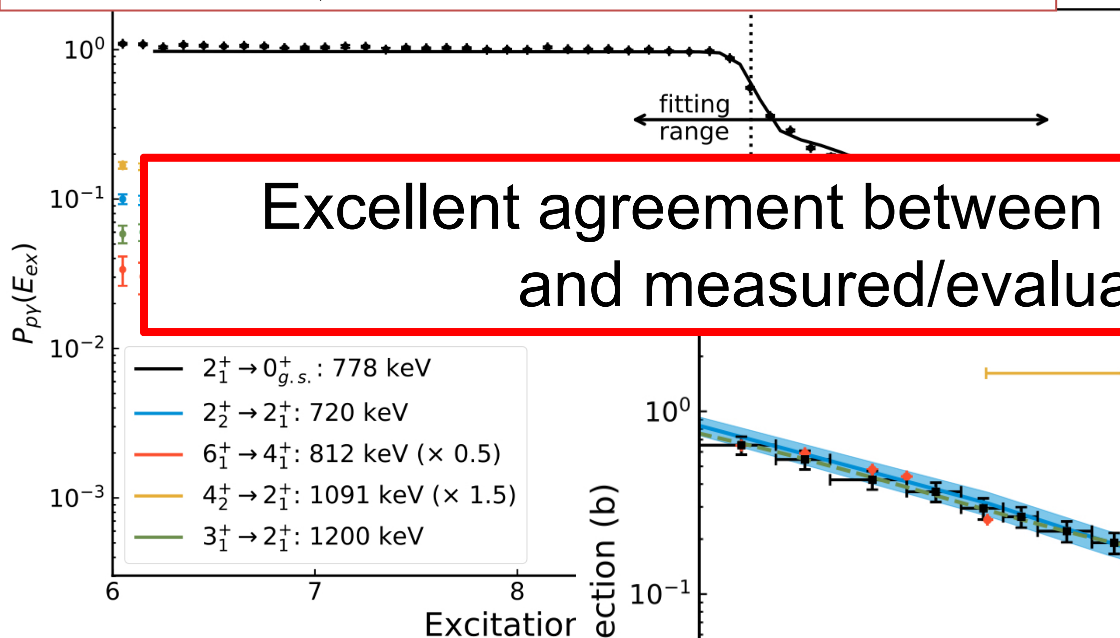
$$P_{p\gamma}(E_x,\theta) = \sum_{J,\pi} F_{dp}^{CN}(E_x,J,\pi,\theta) G_{\gamma}^{CN}(E_x,J,\pi)$$

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

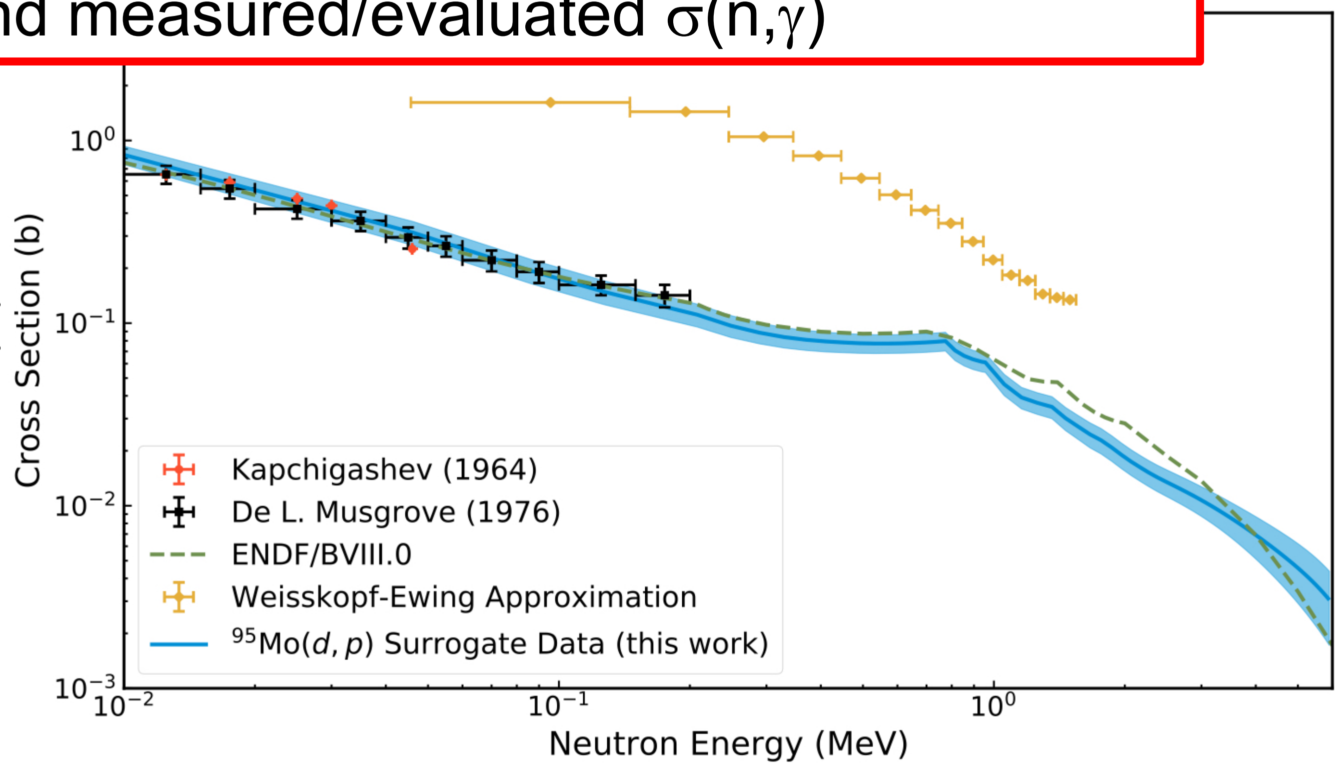
- Deduce $G^{CN}(E_x,J,\pi)$ from fit to data
- Calculate σ^{CN} w/ Koning-Delaroche optical potentials
- Deduce $\sigma(n,\gamma)$ vs E_x

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

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



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



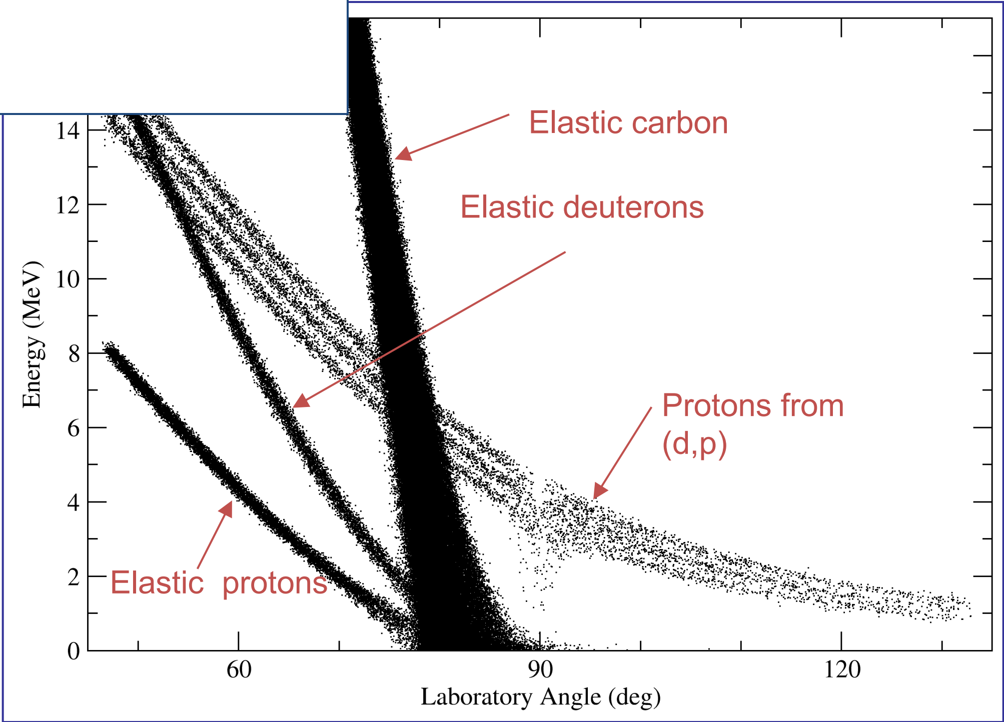
A. Ratkiewicz et al., PRL **122**, 052502 (2019)

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

(d,pγ)

Good candidate for (n,γ) surrogate with beams

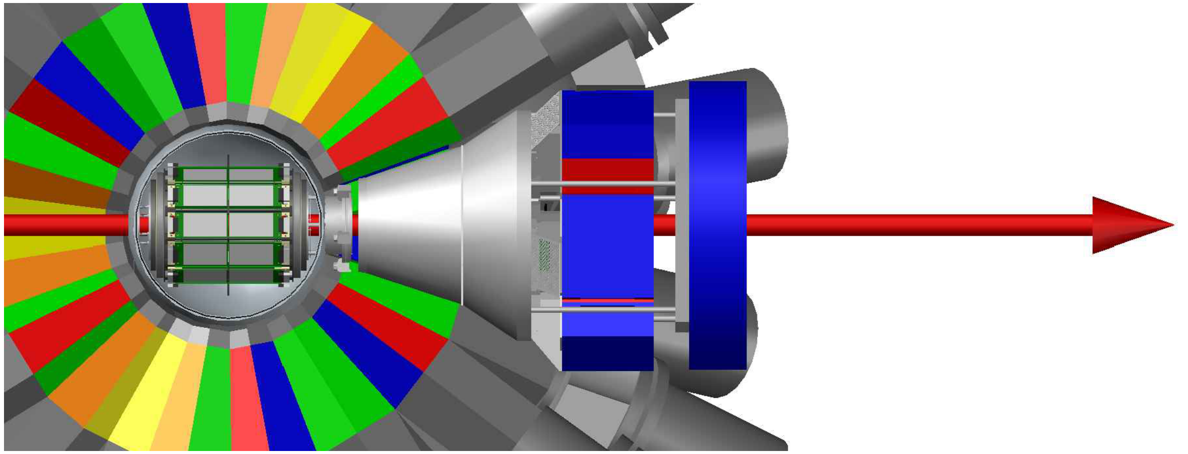
- Relatively good match with spin distribution in (n,γ) which is dominated by ℓ=0
- Reaction predominantly one-step transfer of $j=\ell\pm1/2$ neutron
- "Easy" to produce CD_2 targets
- "Lower" beam energies (than heavier targets) to get above neutron separation energy
- Kinematics favors cleaner reaction

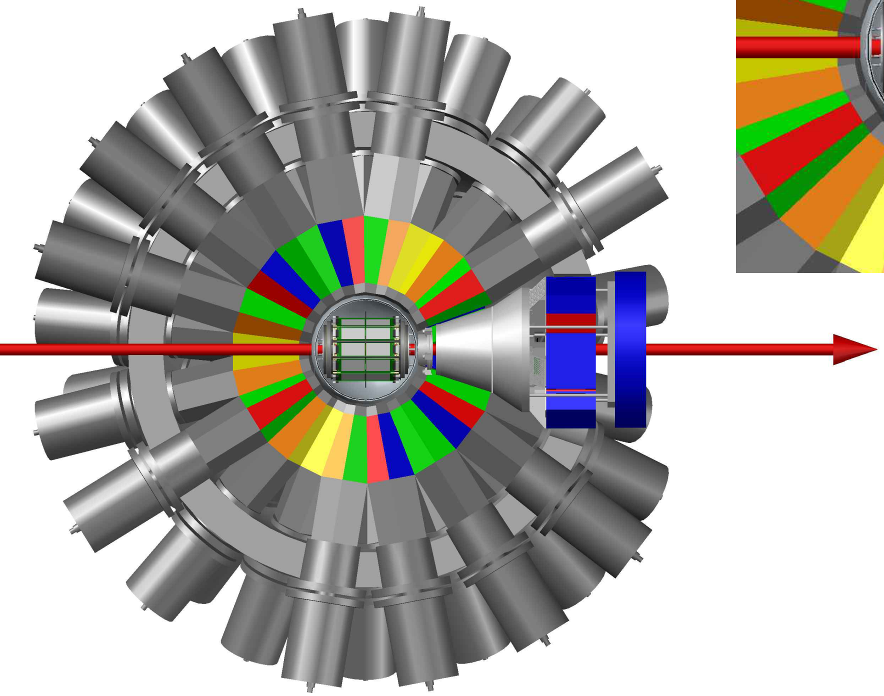


Measuring (d,pγ) with radioactive beams

Coupling charged particle & gamma detector arrays

GODDESS: Gammasphere ORRUBA
Dual Detectors for Experimental Structure Studies





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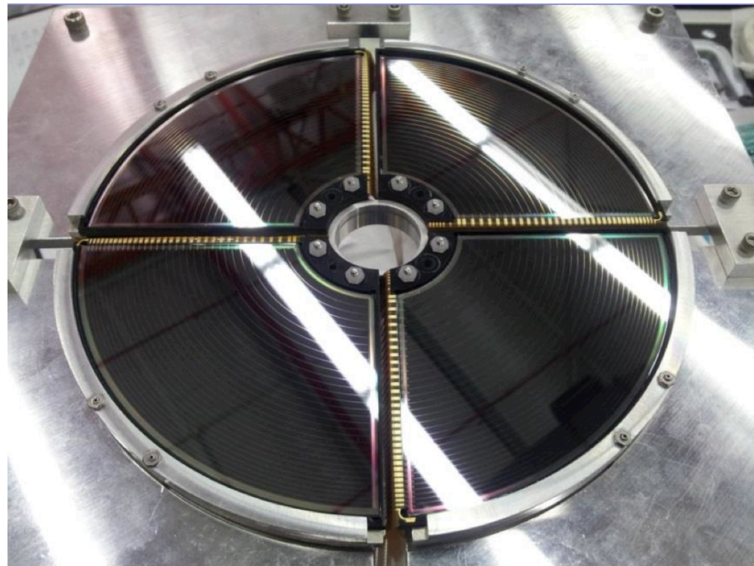
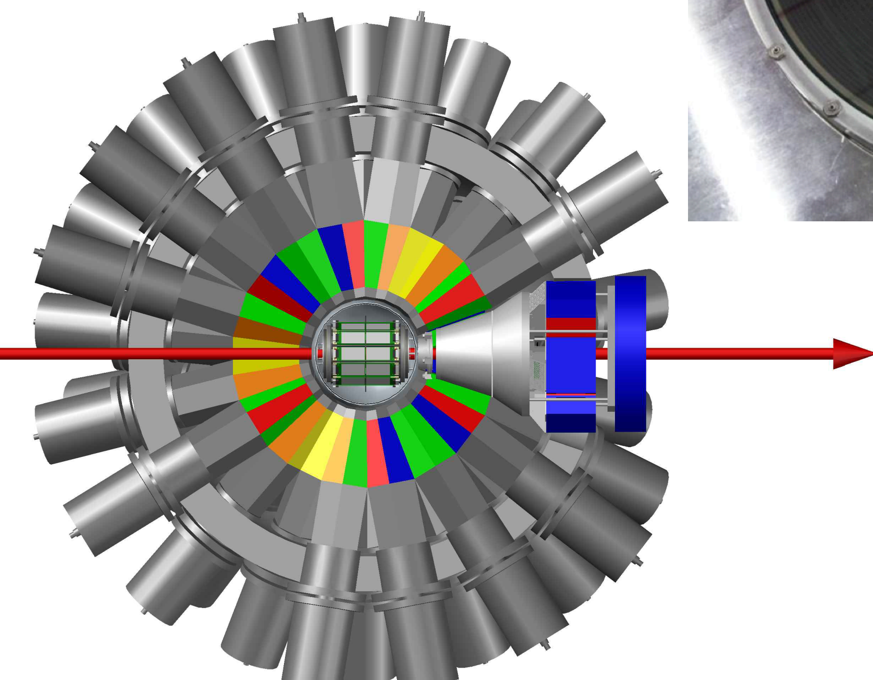
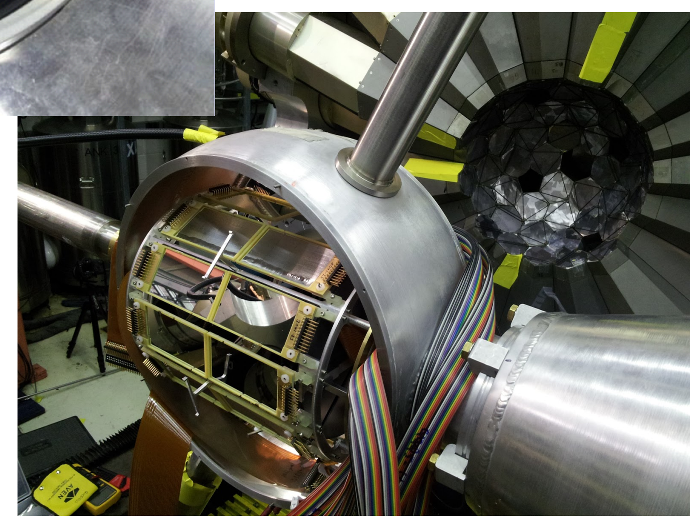


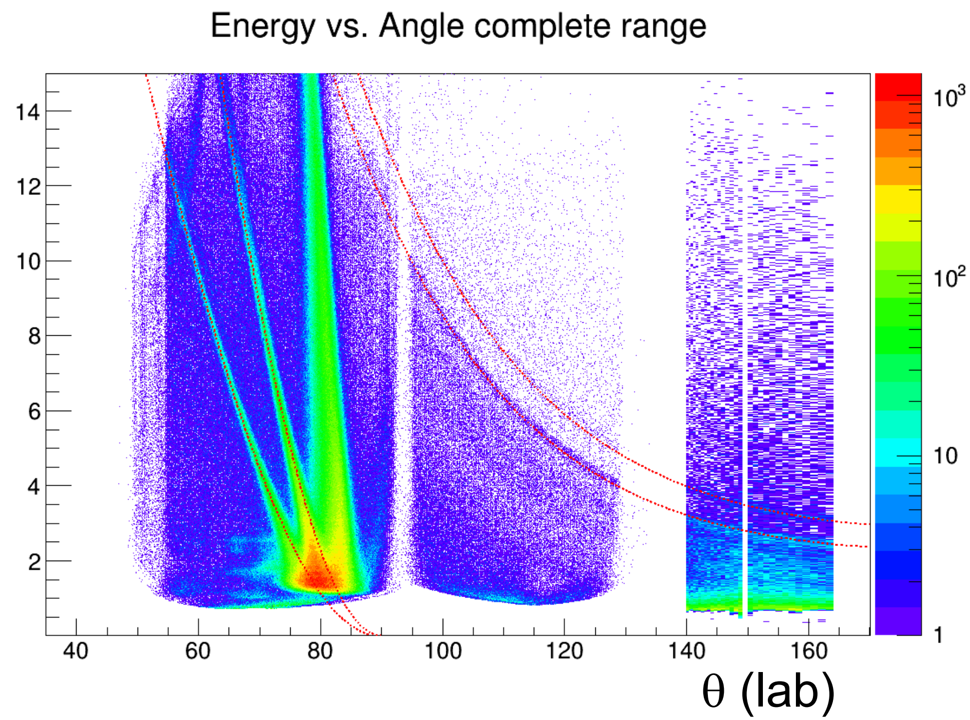


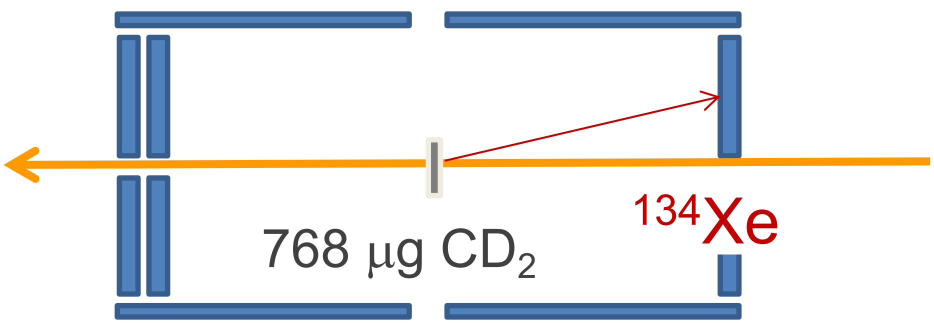


Oak Ridge Rutgers University Barrel Array + endcaps

$^{134}Xe(d,p\gamma)$ with GODDESS: levels+SF

N=80 isotone

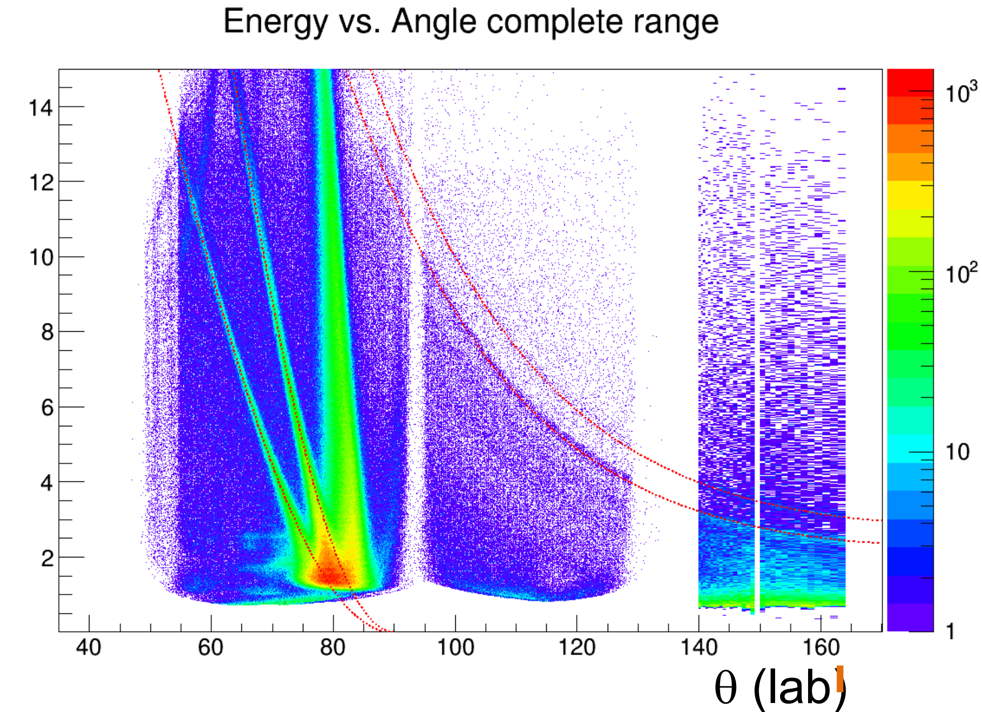


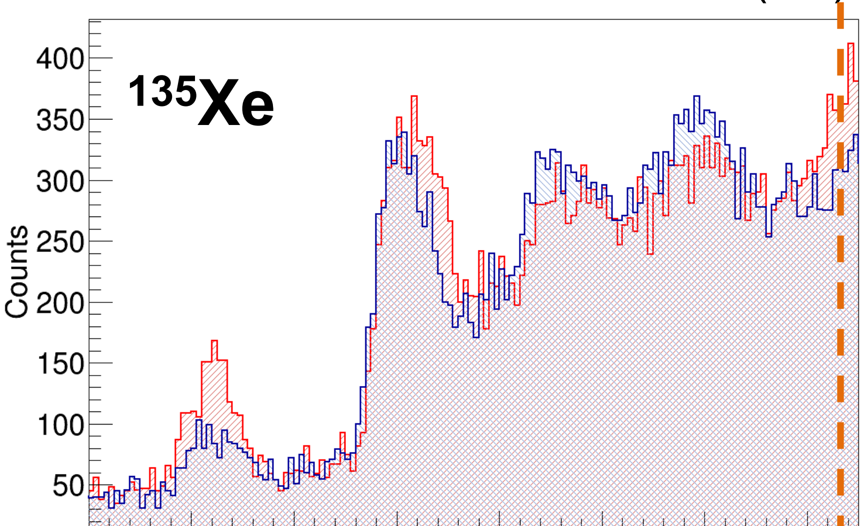


A. Lepailleur, private communication

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

N=80 isotone

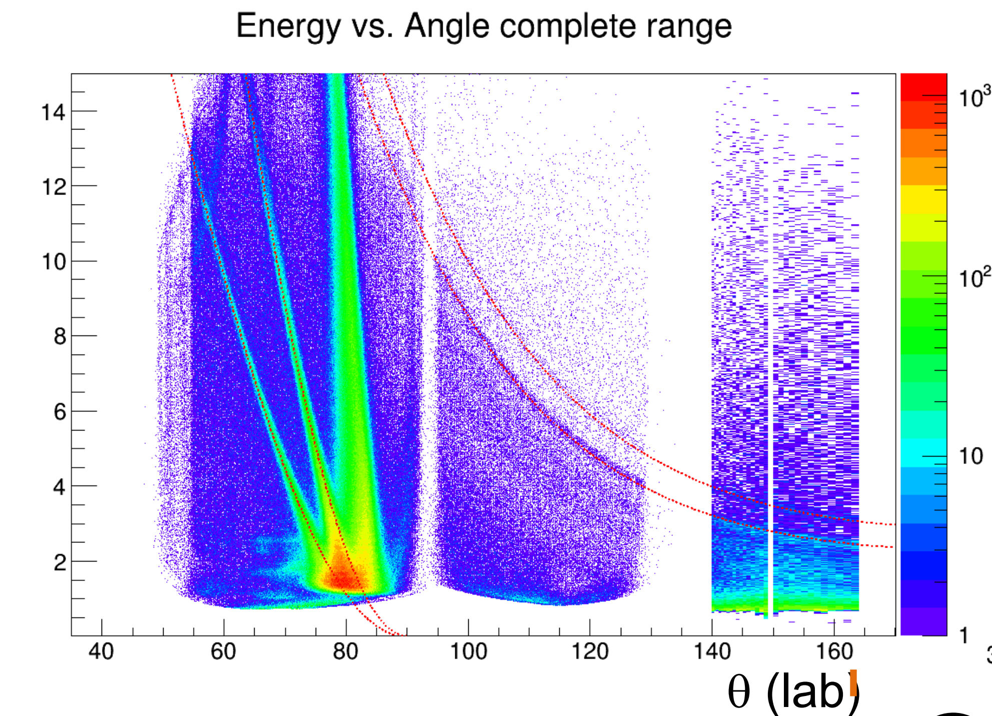


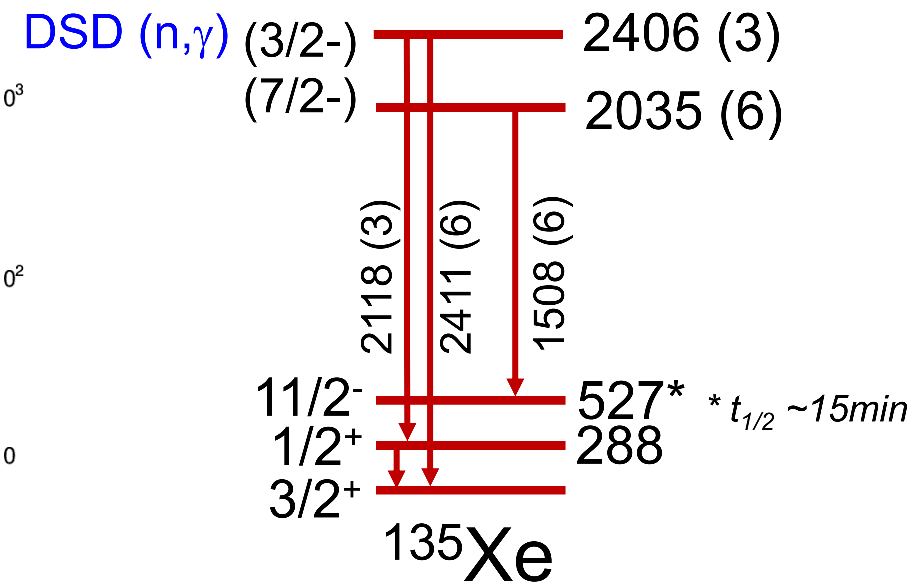


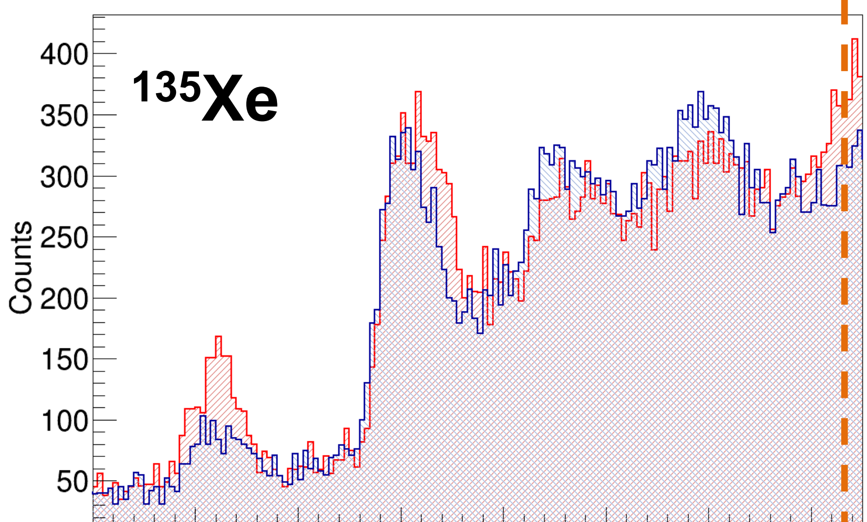
^{135}Xe E_x spectrum

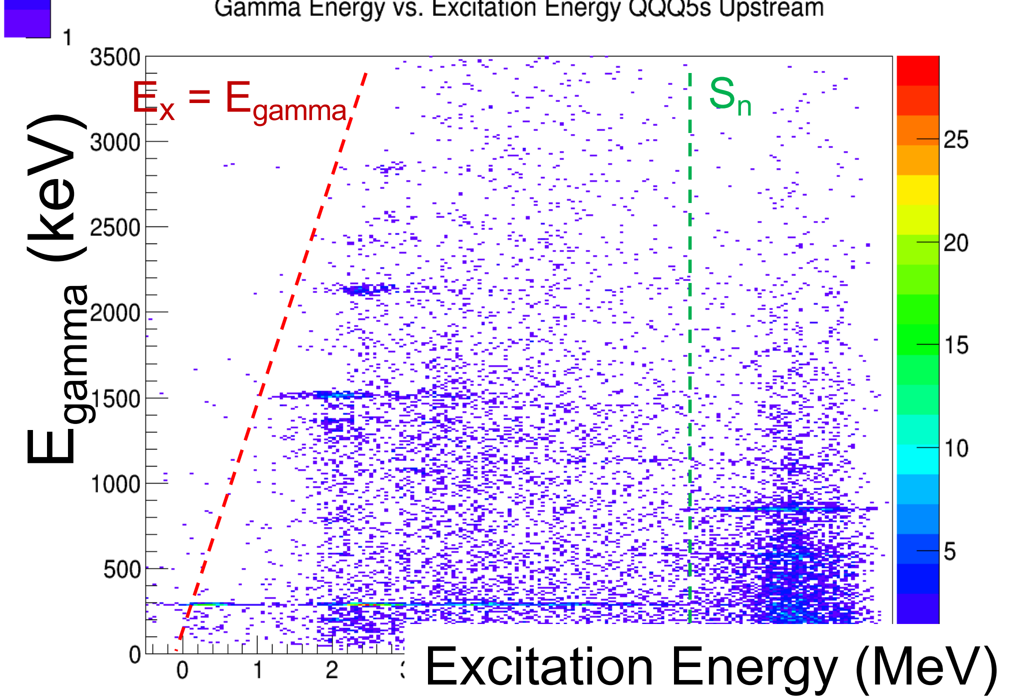
- Red: QQQ5 (large θ)
  - Low-ℓ transfer important for DSD
- Blue: SX3 (90° <θ<135°)

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



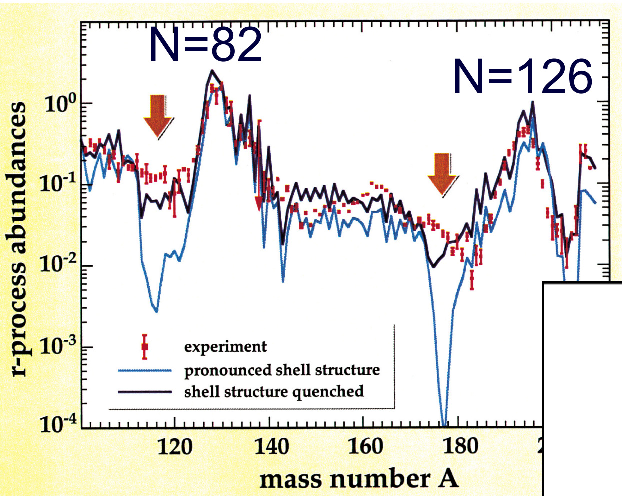






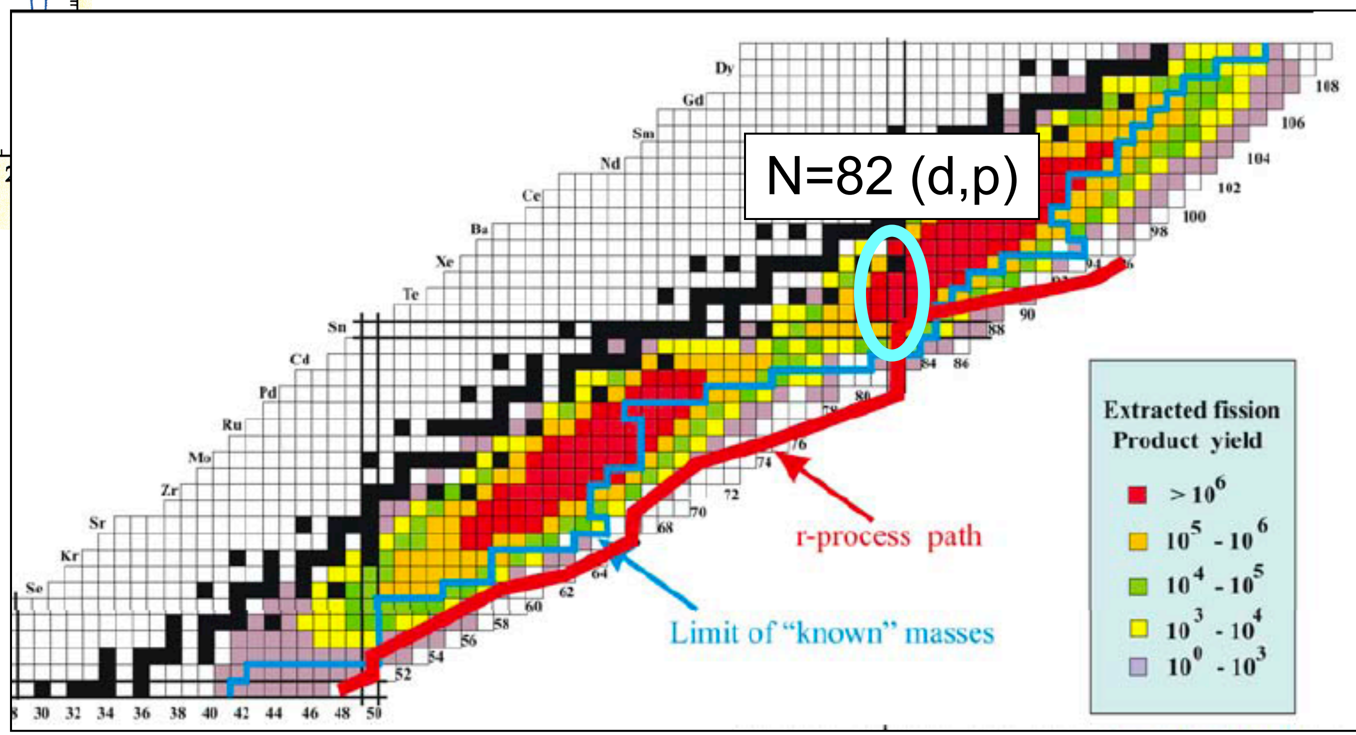
Many more nuclei can be studied

Gammasphere-ORRUBA GODDESS

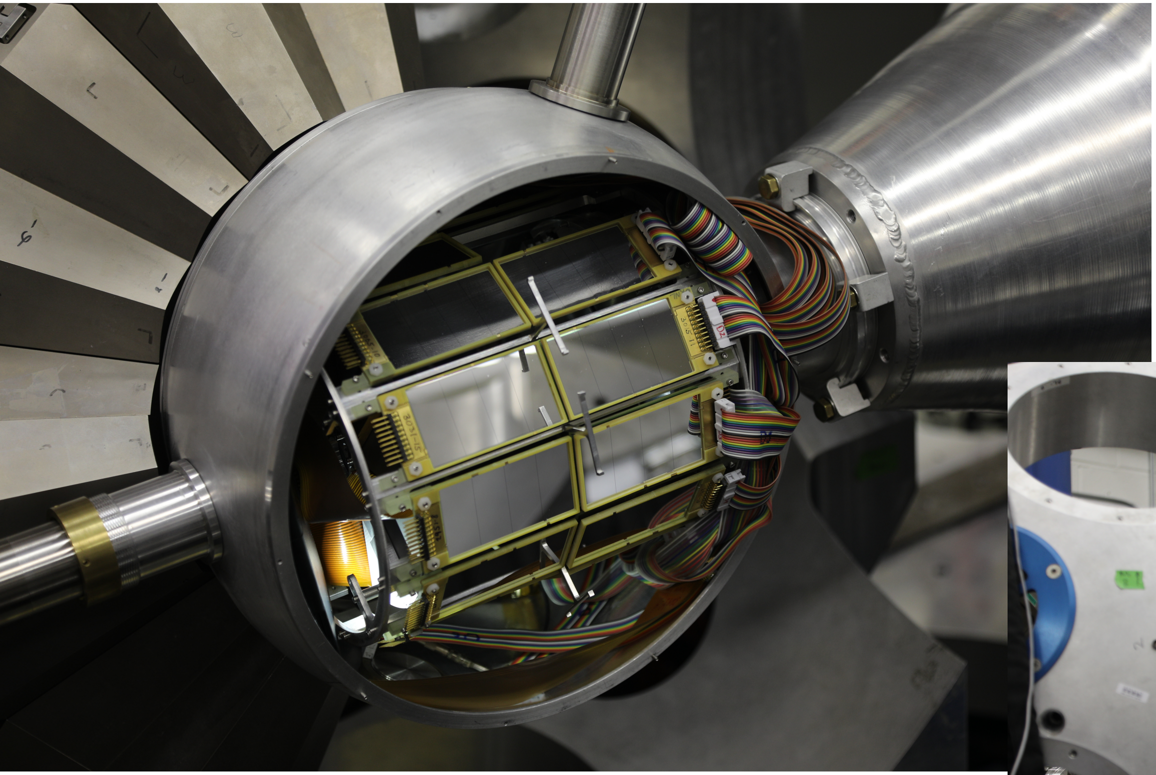


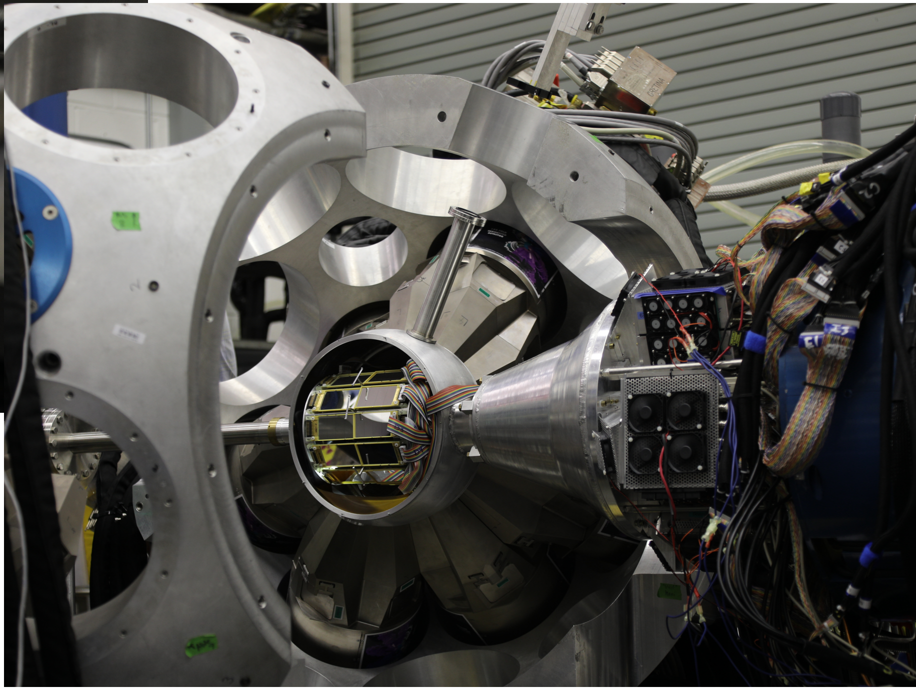
CARIBU

^{252}Cf fission fragments beams at ATLAS



GODDESS: GRETINA ORRUBA
Dual Detectors for Experimental Structure Studies





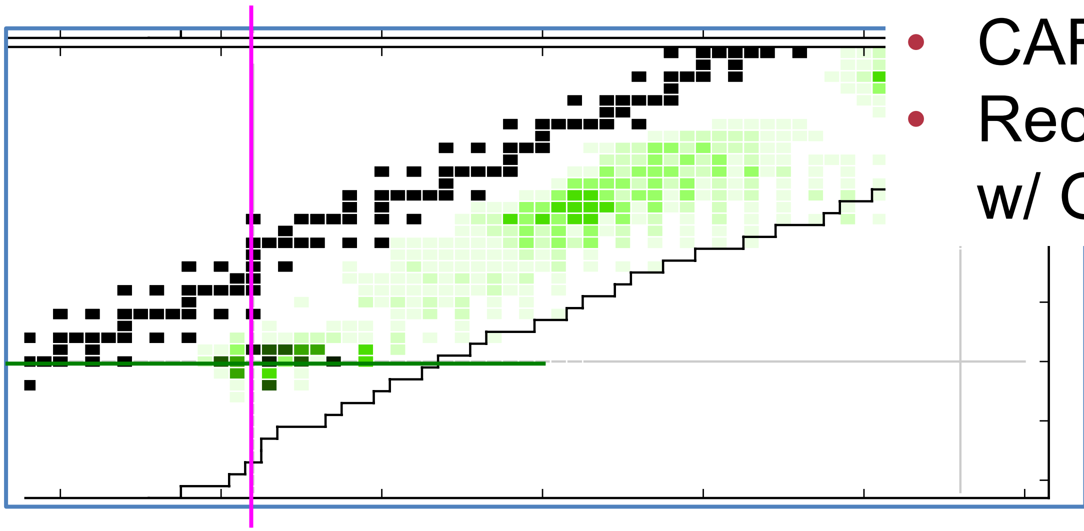
Gamma-Ray Energy Tracking In-Beam Nuclear Array

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

Goal: ≈^{132}Sn isotopes important for r process nucleosynthesis
Will have to wait for FRIB

What can we do "now"?

- CARIBU ^{252}Cf fragment beams
- Recently measured ^{134}Te(d,pγ) w/ GODDESS and GRETINA



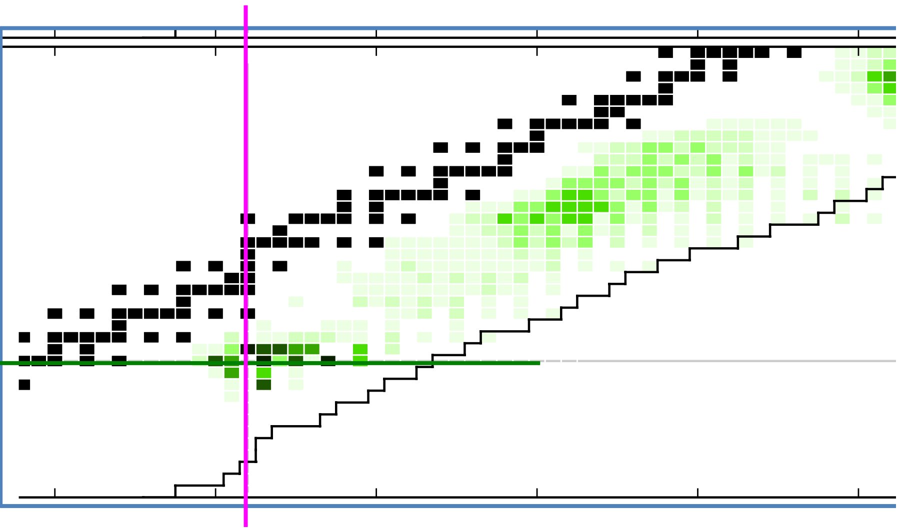
Understanding synthesis (and destruction of ^{134}Te during r process (and freeze-out) impacts observed Xe isotope ratios

- Could be first surrogate (n,γ) on fission fragment to constrain (n,γ) in this region
- Also approved to measure ^{143}Ba(d,pγ) as (n,γ) surrogate

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

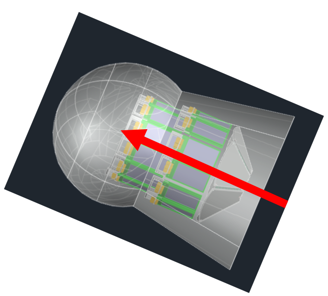
Goal: ≈^{132}Sn isotopes important for n-star mergers

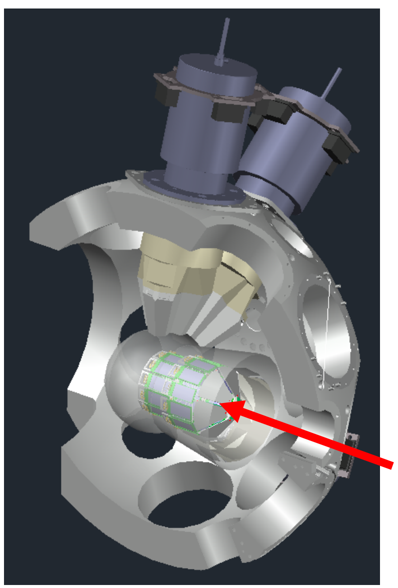
Will have to wait for FRIB

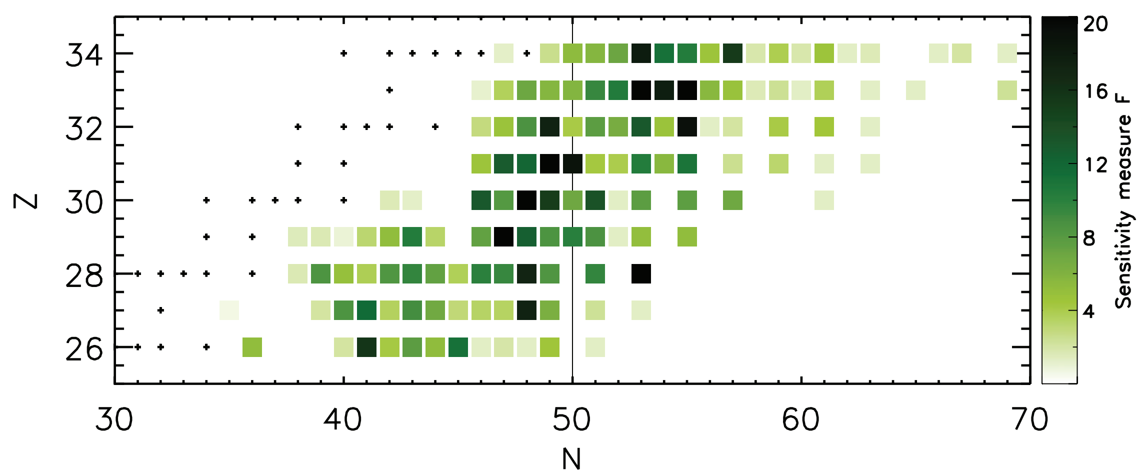


What can we do “now”?

- CARIBU ^{252}Cf fragment beams
- ^{134}Te(d,pg) and ^{143}Ba(d,pγ) w/ GODDESS
- NSCL ≈80 fast beams
- Approved to measure ^{80}Ge(d,pγ) w/ ORRUBA+GRETINA



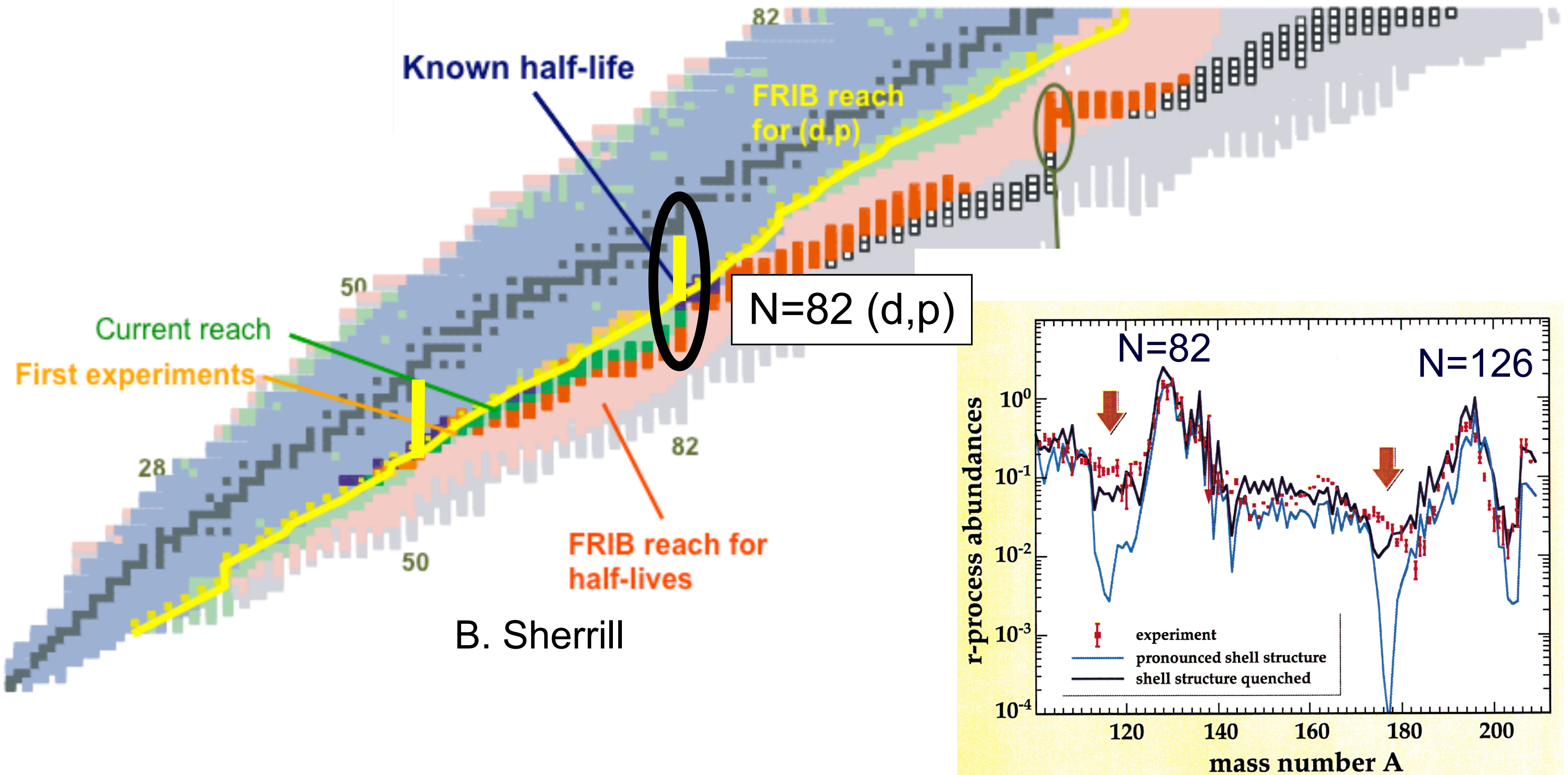




Surman et al. AIP Adv. **4**, 041008 (2014)

Many more nuclei can be studied GRETINA-ORRUBA GODDESS

Facility for Rare Isotope Beams (FRIB) under construction at MSU



Thank you for your attention

- Understanding abundances from 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
  - ^{134}Te(d,pγ), ^{143}Ba(d,pγ)
  - ^{80}Ge(d,pγ)
- Goal: FRIB (d,pγ)

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