Developing a surrogate for the (n,γ) reaction on short-lived nuclei

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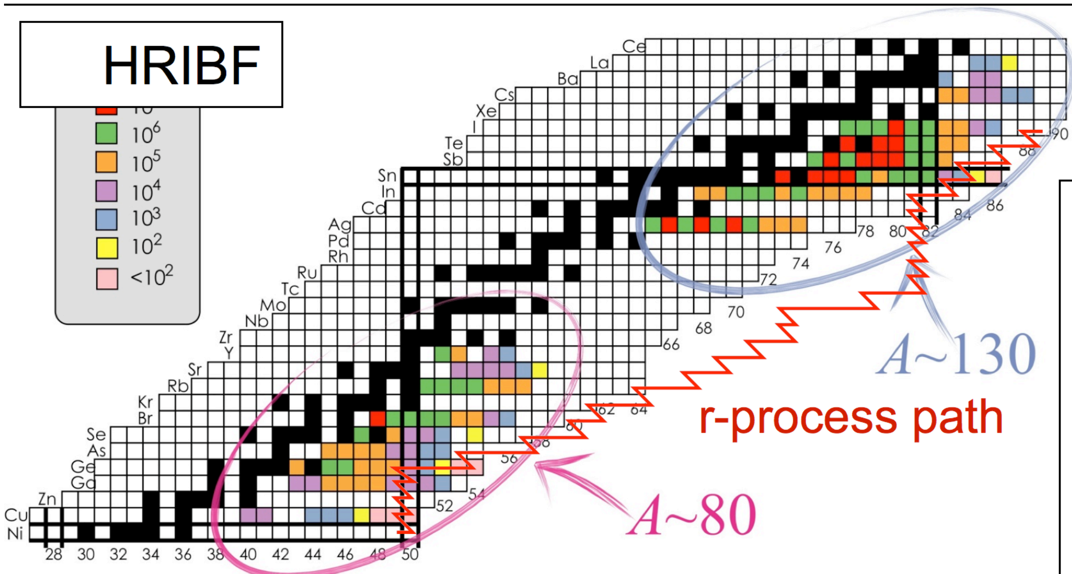
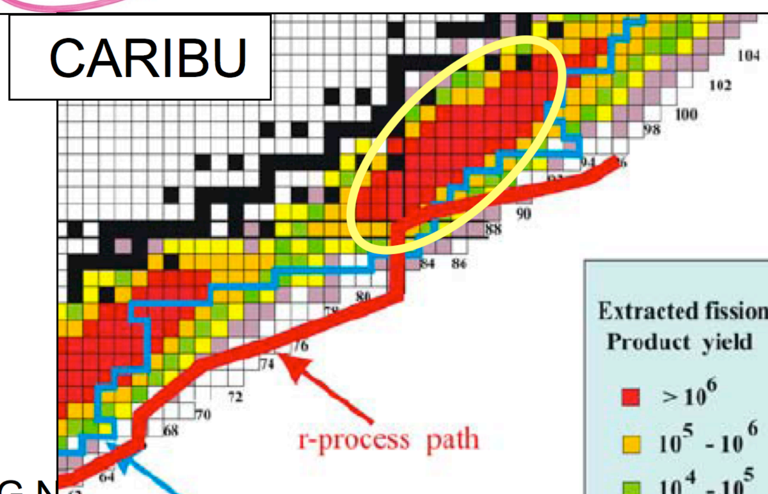
Neutron Capture
A(n,γ)A+1 Reactions

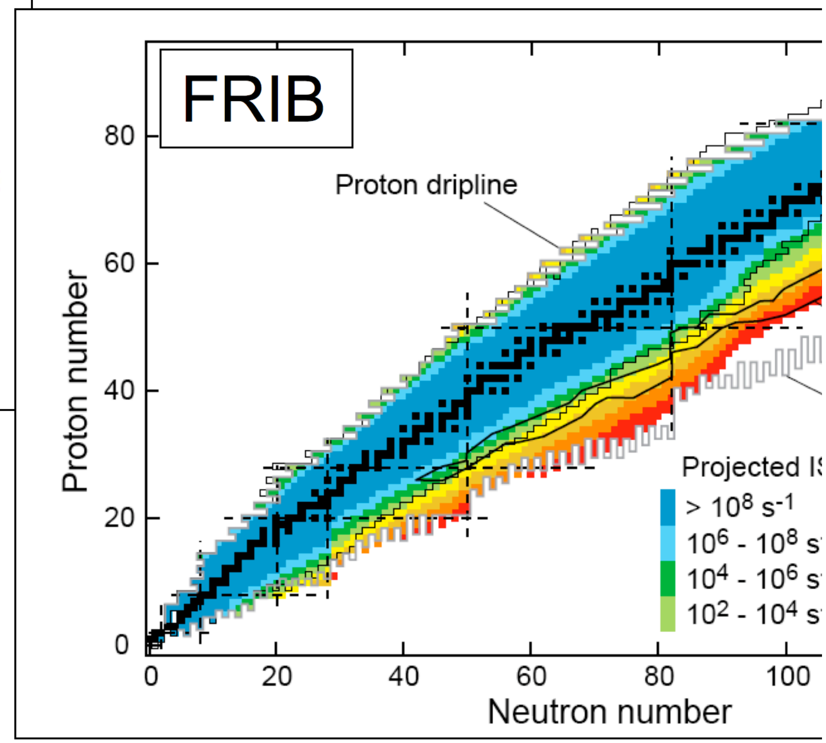
- Important for basic and applied nuclear science
  - Nucleosynthesis processes
    - s and r process responsible for elements heavier than iron
  - Nuclear reactors
    - Cross sections on fission fragments
  - Nuclear forensics, including weapons modeling
- On stable isotopes: well studied
- On rare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

Surrogate reactions with beams

Only way to get $\sigma(n,\gamma)$ when $t_{1/2}$ << 100 days

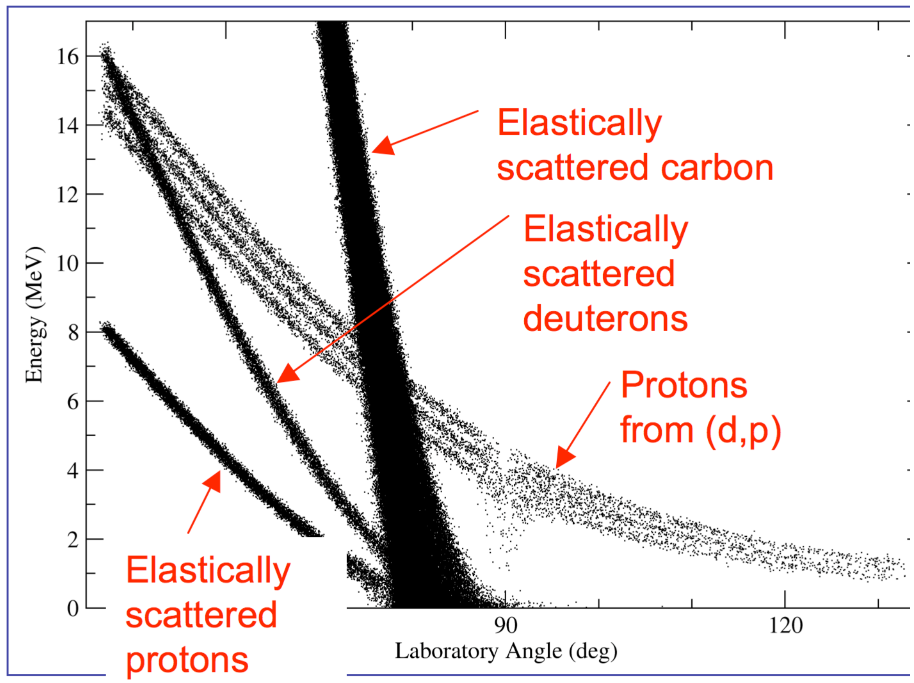






(d,pγ) good candidate for (n,γ) surrogate with beams

- Relatively good match with spin distribution in (n,γ) which is dominated by ℓ=0
- “Easy” to produce CD_2 targets
- “Lower” beam energies (than heavier targets) to get above neutron separation energy
- Kinematics favors cleaner reaction



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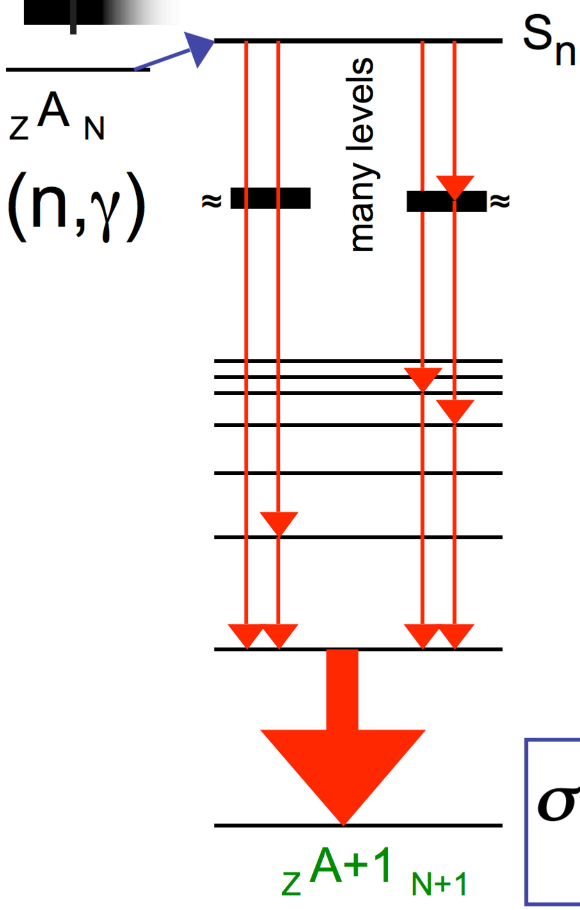
Outline

- Surrogate reaction and surrogate ratio methods
- What we have learned:
  - Is there a promising surrogate for (n,γ)?
- Where we are going: Measuring spin distributions

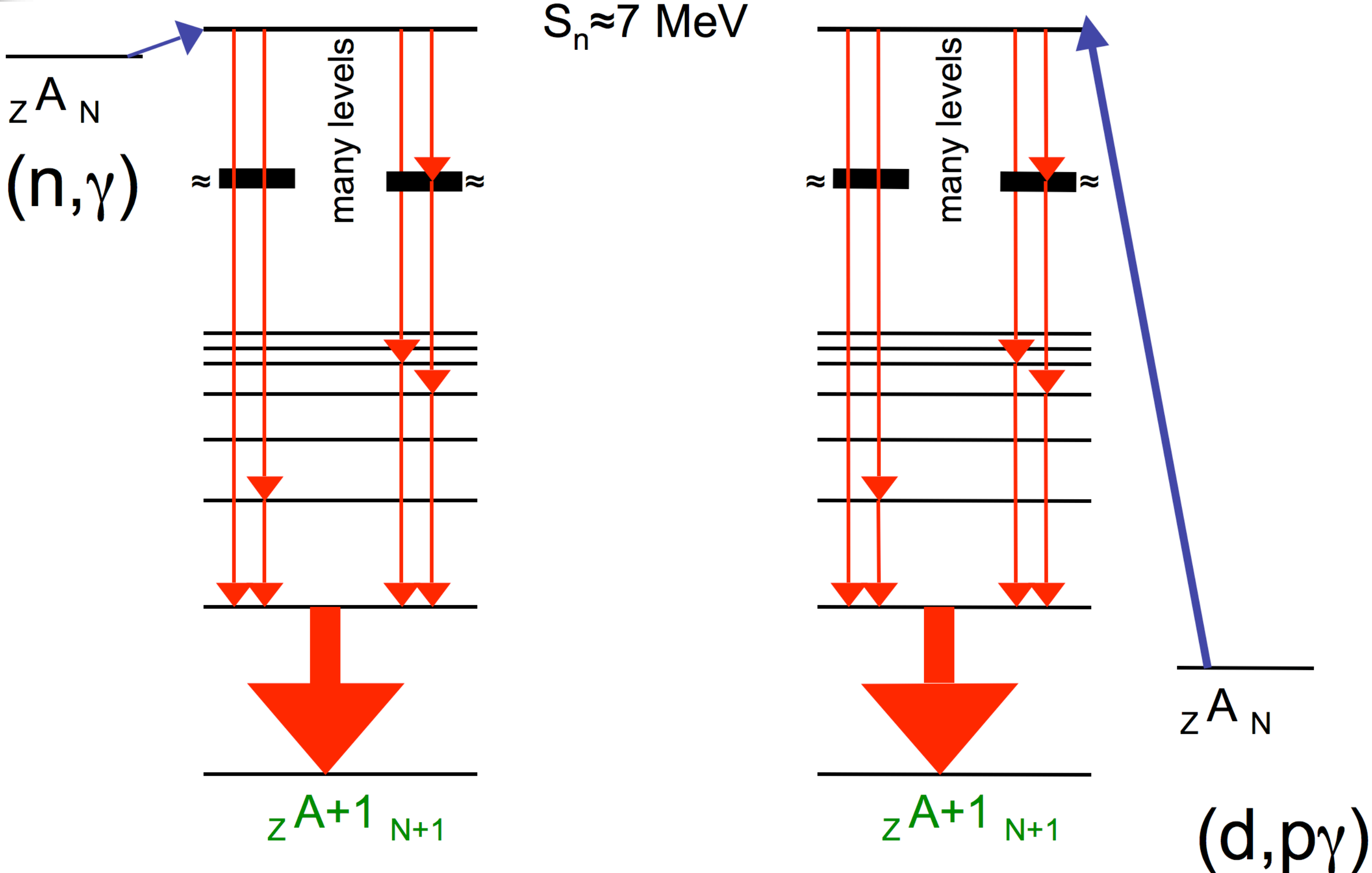
A(n,γ)(A+1)



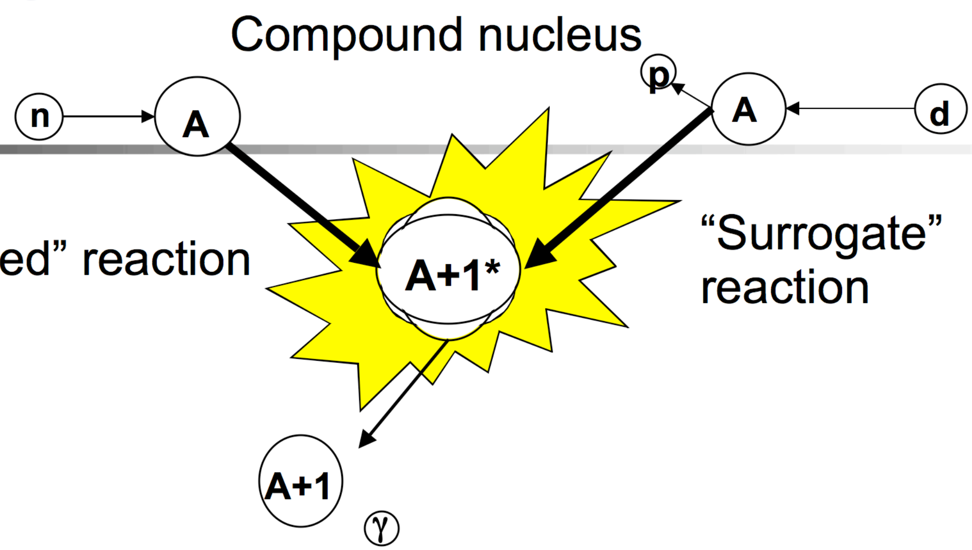
- Target of material A
- Beam of neutrons
- Cross section vs neutron energy depends upon product of cross section of formation of compound nucleus AND decay of the compound nucleus
  - In principle for each spin,parity
- Can calculate formation; difficult to calculate decay

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

A(n,γ)(A+1) ↔ A(d,p)(A+1)
Surrogate for (n,γ)?



Surrogate reaction concept



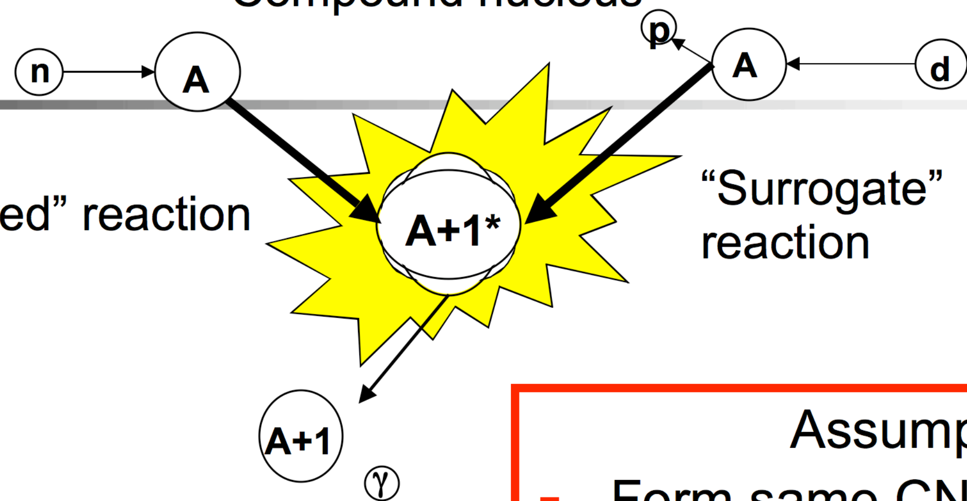
(n,γ) cross section can be written as product of compound nucleus formation and decay for every spin and parity:

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

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

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

Surrogate reaction W-E Limit



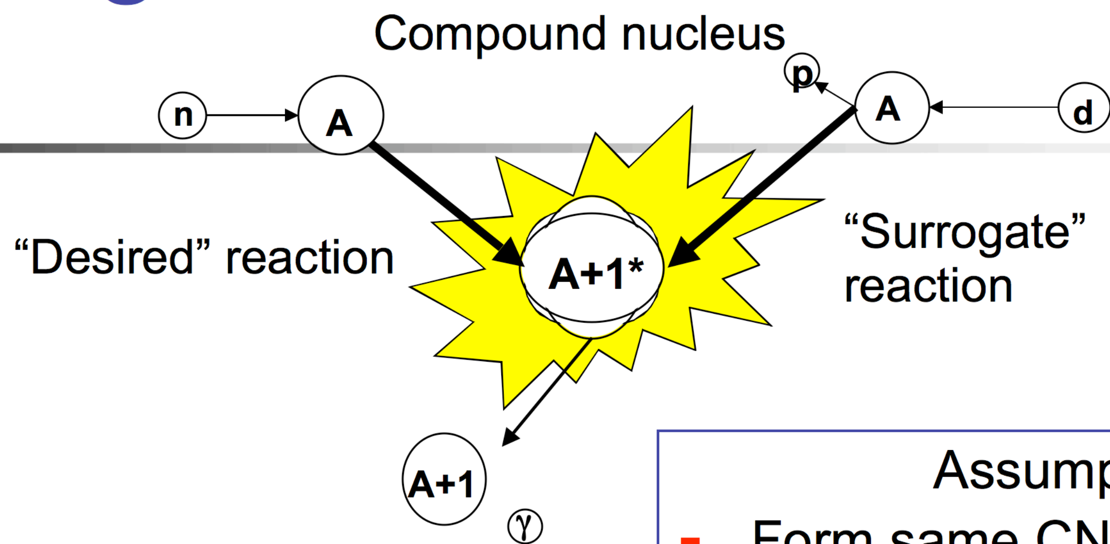
Assumptions:

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

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

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

Surrogate reaction W-E Limit



Assumptions:

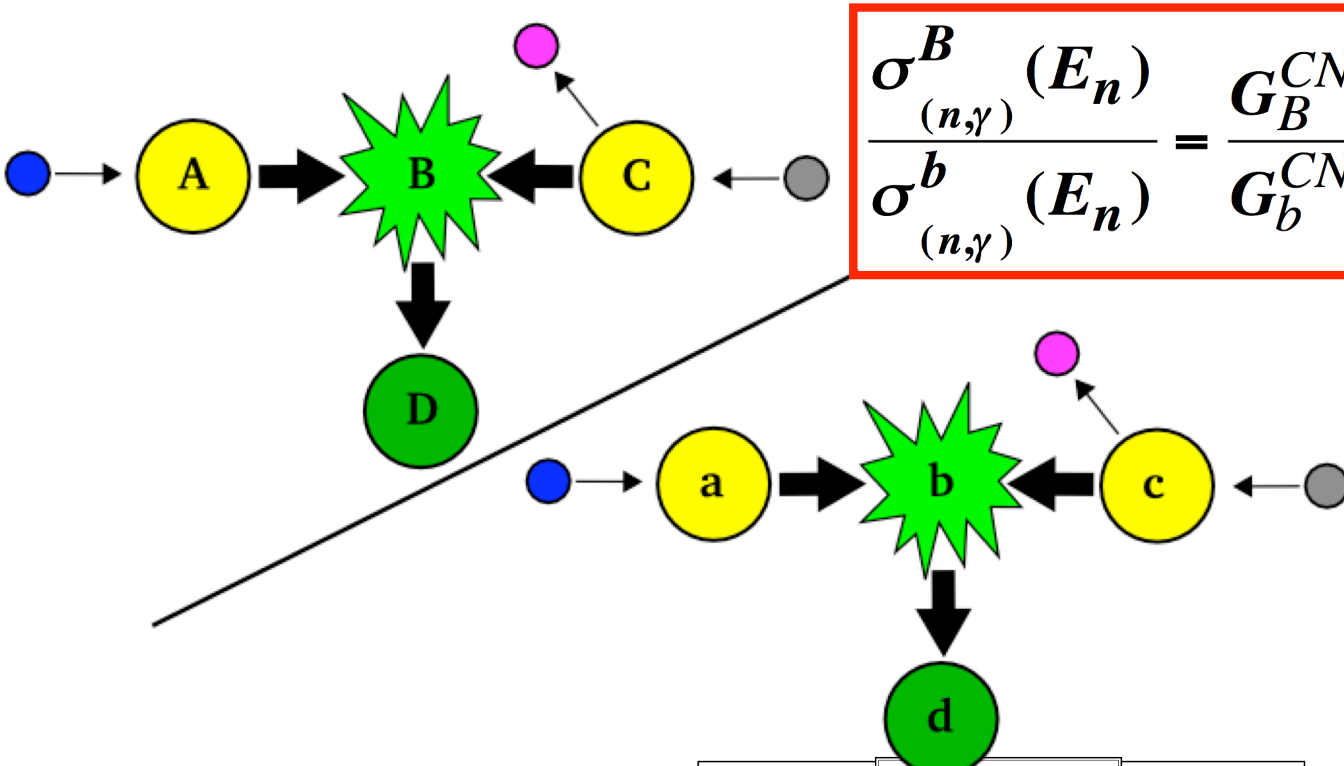
- Form same CN with surrogate and F=1
- Weisskopf-Ewing limit: CN pop & decay indep of spin, parity

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

Surrogate ratio technique

- Ratio of experimental yields can reduce systematic uncertainties
- Assume similar compound nuclear cross sections
- Know one cross section ⇒ ratio gives the unknown

$$\frac{\sigma^{B}_{(n,\gamma)}(E_n)}{\sigma^{b}_{(n,\gamma)}(E_n)} = \frac{G_B^{CN}(E_n)}{G_b^{CN}(E_n)} = \frac{\varepsilon_b N^{B}_{p\gamma}(E_n}{\varepsilon_B N^{b}_{p\gamma}(E_n}$$



Can demonstrate that (d,pγ) is (n,γ) surrogate?

- Choose pair of nuclei where (n,γ) has been measured vs E(neutron)
  - ^{171,173}Yb(n,γ)^{172,174}Yb by Wisshak et al.

- Measure (d,pγ) reaction in normal kinematics with
  - ≈18 MeV beam of deuterons
  - Detect gamma rays in coincidence with reaction protons
  - Energy of protons ⇔ excitation energy in nucleus (above neutron separation energy)

- Analysis: Surrogate Ratios: ratios of intensities of collecting gamma rays = ratio of reaction cross sections

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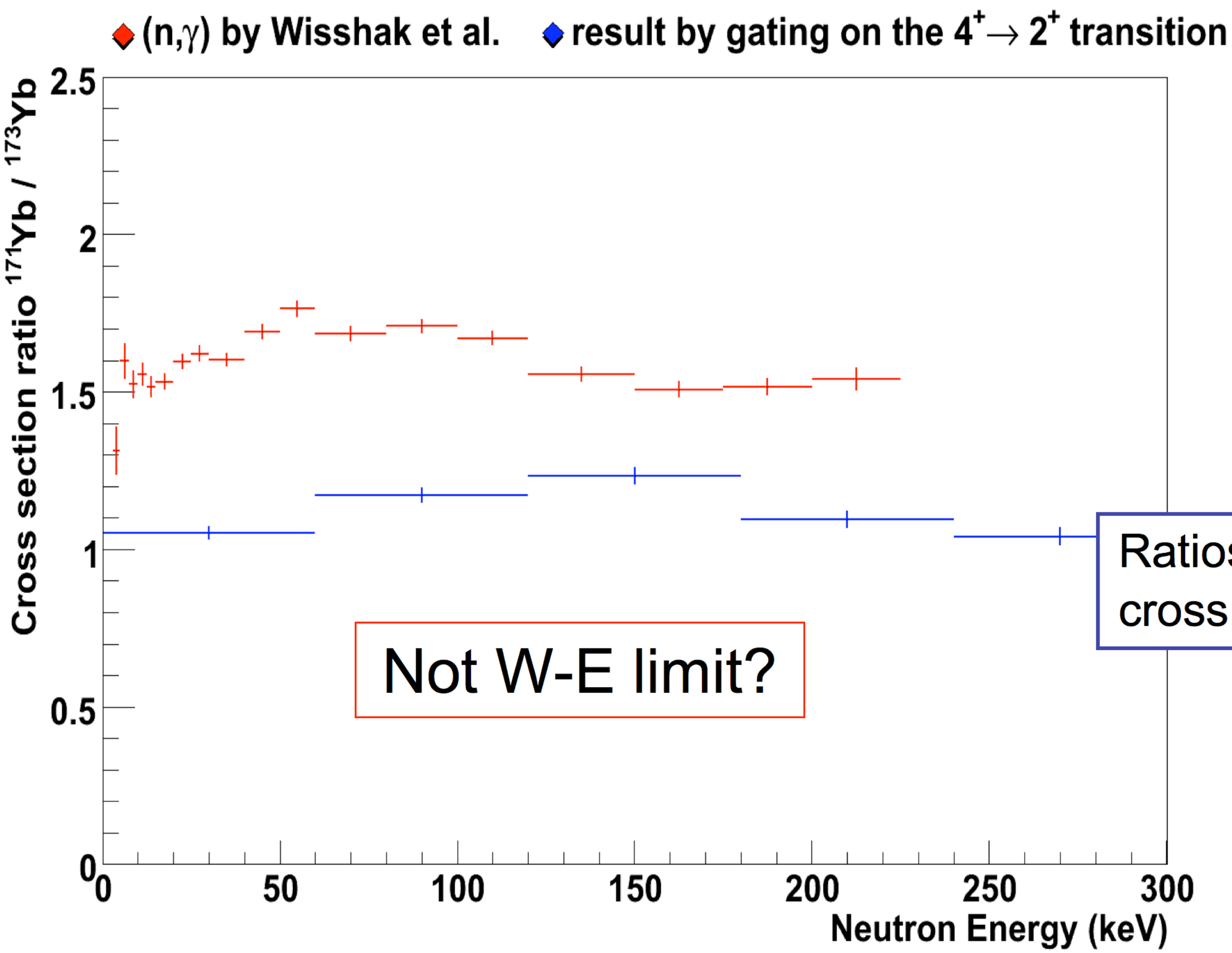
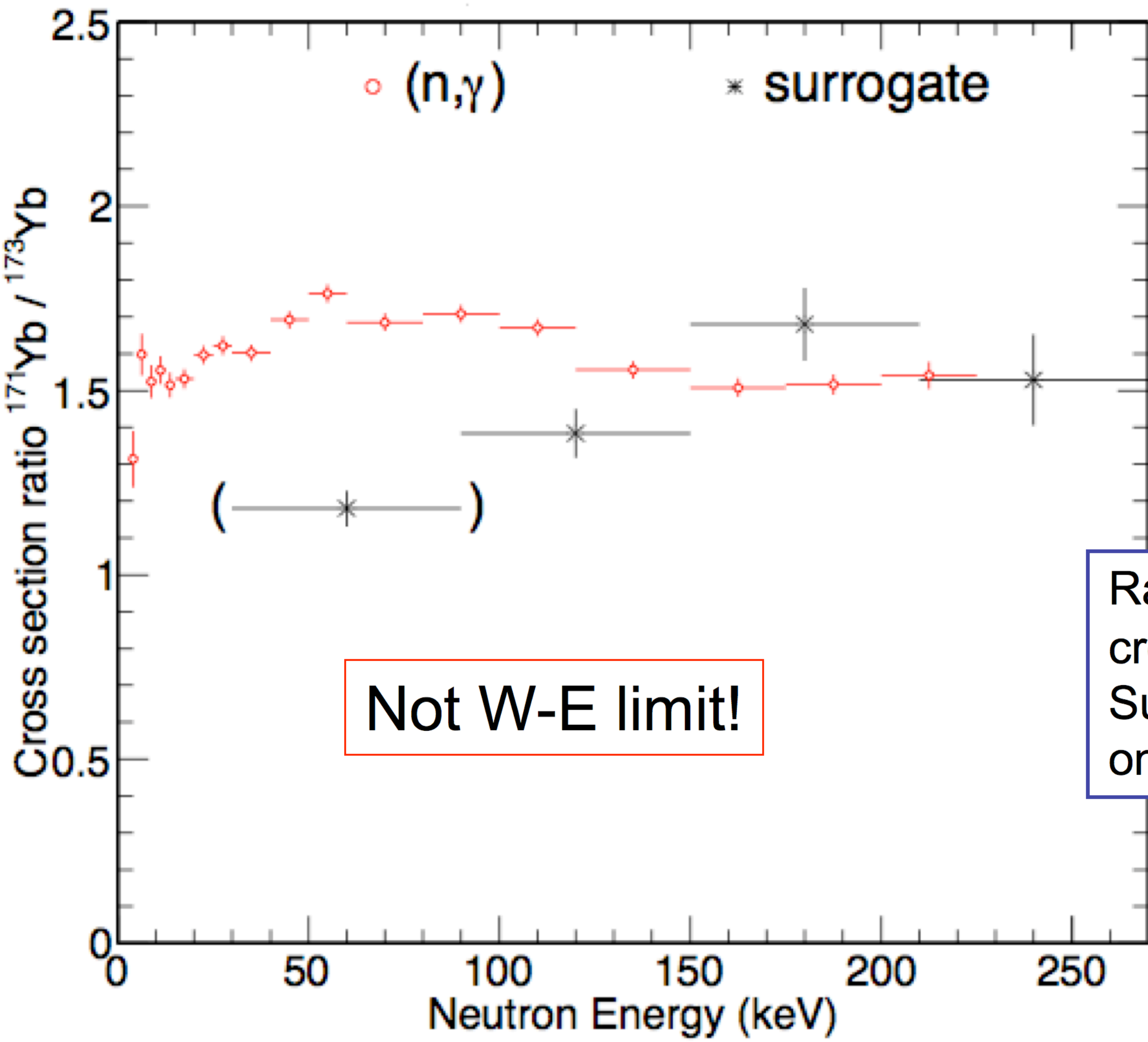
Known σ(n,γ) vs σ(n,γ) from ^{171,173}Yb(d,pγ)



R. Hatarik et al.
PRC **81**, 11602(R) (2010)

Ratios of (d,pγ) and (n,γ) cross sections for ^{171,173}Yb

Known $\sigma(n,\gamma)$ vs $\sigma(n,\gamma)$ from $^{171,173}Yb(d,p\gamma)$



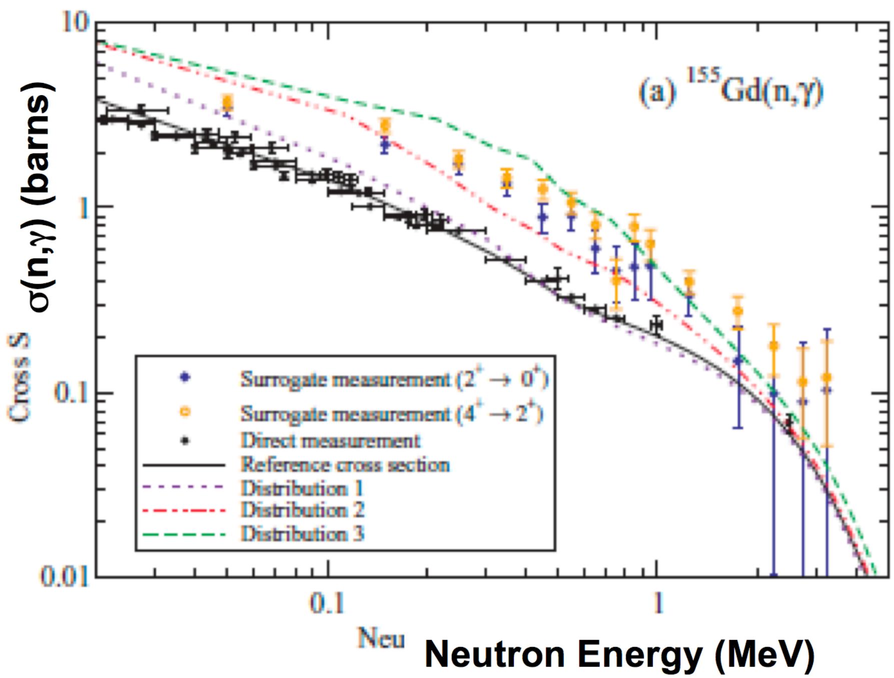
R. Hatarik et al.
PRC **81**, 11602(R) (2010)

Ratios of $(d,p\gamma)$ and (n,γ) cross sections for $^{171,173}Yb$
Subtract direct feeding of 4+; only sidefeeding of 4+

$(d,p\gamma)$ can be (n,γ) surrogate

Select $(d,p\gamma)$ spectra that most accurately reflect (n,γ) spin distribution

Surrogate-deduced σ(n,γ) vs measured σ(n,γ)



^{155}Gd(n,γ) vs ^{156}Gd(p,p'γ)

N.Scielzo, J. Escher et al PRC **81** (2010)

Black: measured and calculated σ(n,γ

Blue, yellow data

Surrogate-deduced σ(n,γ) from

2→0 & 4→2 transitions

Curves:

- Purple = (d) distribution; peak=1.5
- Red = (e) distribution; peak=4.5
- Green = (f) distribution; peak=7.5

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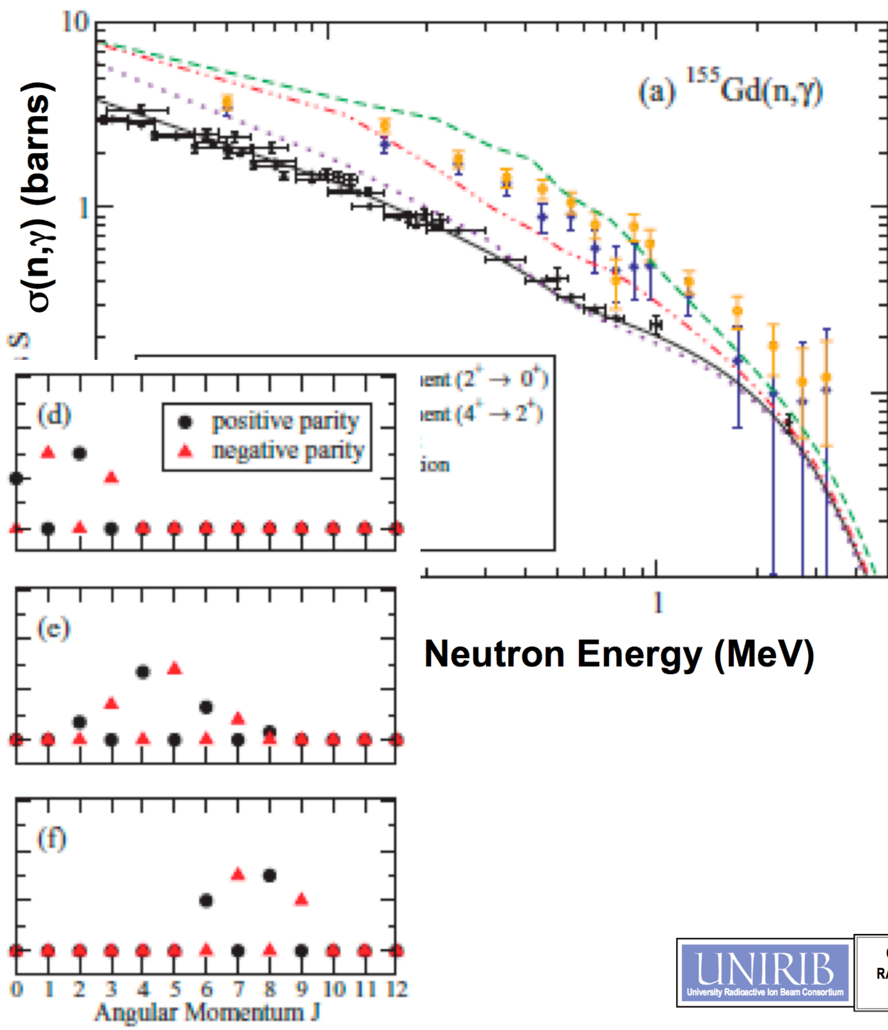

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Is there a valid surrogate for (n,γ)?

- Important: want $\sigma(n,\gamma)$ for unstable species ($t_{1/2}$<100 days)
  - Near stability surrogate "normal" kinematics: Light beam + heavy target
  - Far from stability surrogate "inverse" kinematics: Rare isotope beam + light target
- WE limit is not valid: decay probabilities <u>not</u> indep of spin
  - (n,γ) cross sections dominate at low E_n, $\ell \approx 0$
  - Surrogate reactions (e.g., $(d,p\gamma)$) bring in finite angular momentum $\ell > 0$
- To validate: Compare <u>measured</u> spin distributions in (n,γ) with $(d,p\gamma)$ surrogate measurements
- Goal: develop prescription to take surrogate decay probabilities to inform (n,γ) decay probabilities to get $\sigma(n,\gamma)$

^{95}Mo(n,γ) and ^{95}Mo(d,pγ) spin distributions

- What is known
  - ^{95}Mo(n,γ) cross sections $E_n \leq 200$ keV
  - FP12 neutron flux vs E_n (extrapolated)
- (n,γ) measured at FP12
  - Two HpGe detectors in close geometry
  - ^{96}Mo yrast intensities vs E_n to deduce spin distribution of CN in (n,γ)
- Surrogate measurements at LBNL and HRIBF
  - ^{95}Mo(d,pγ) in normal and inverse kinematics
  - ^{96}Mo yrast intensities vs E_n(effective) to deduce spin distribution of CN formed in (d,p)

^{95}Mo(n,γ) at FP12 LANSCE

$^{95}Mo(n,\gamma)$ at FP12 LANSCE

Preliminary results: A. Adekola, GG7, Friday am

CSEWG Nov 2010

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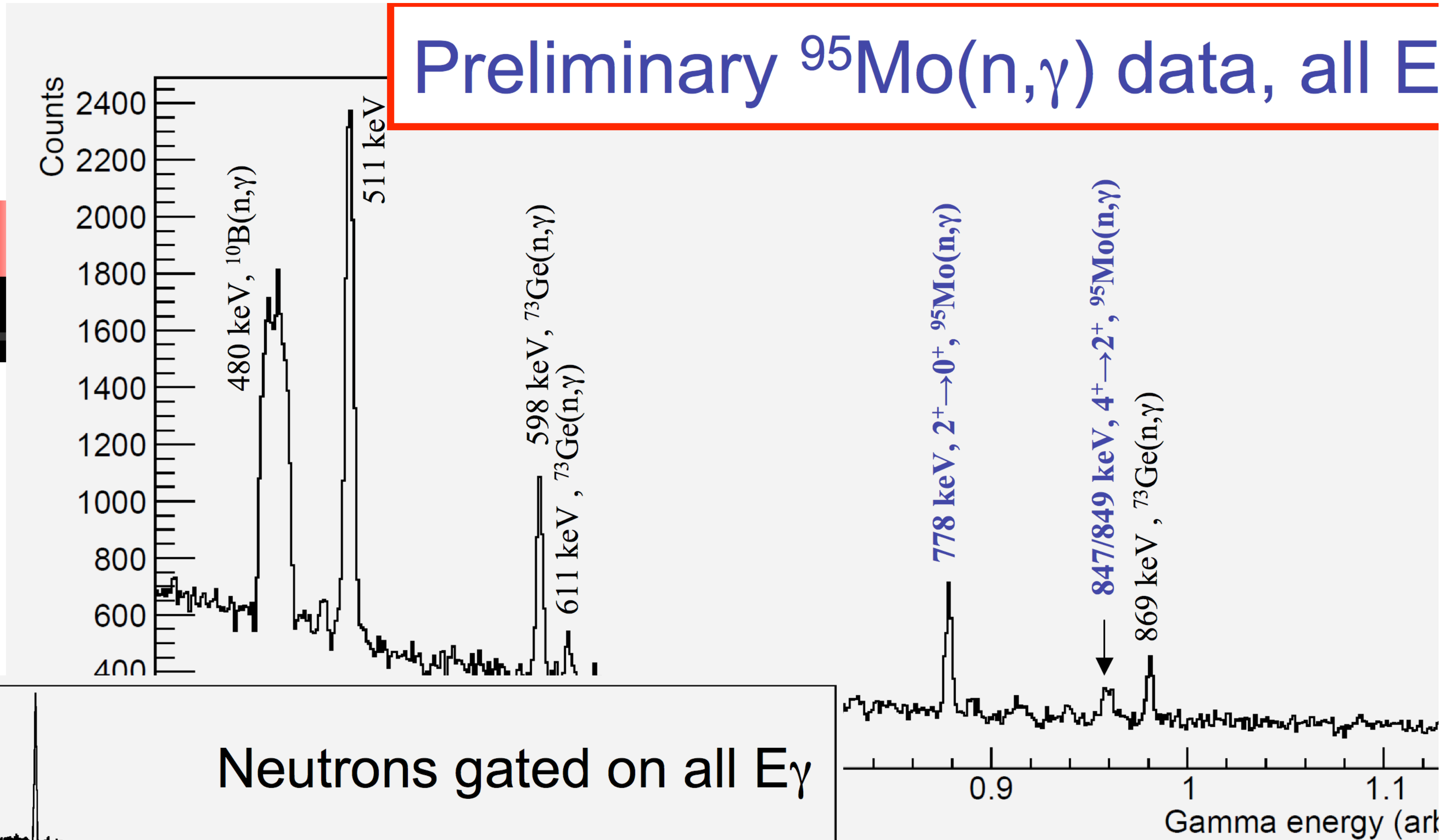
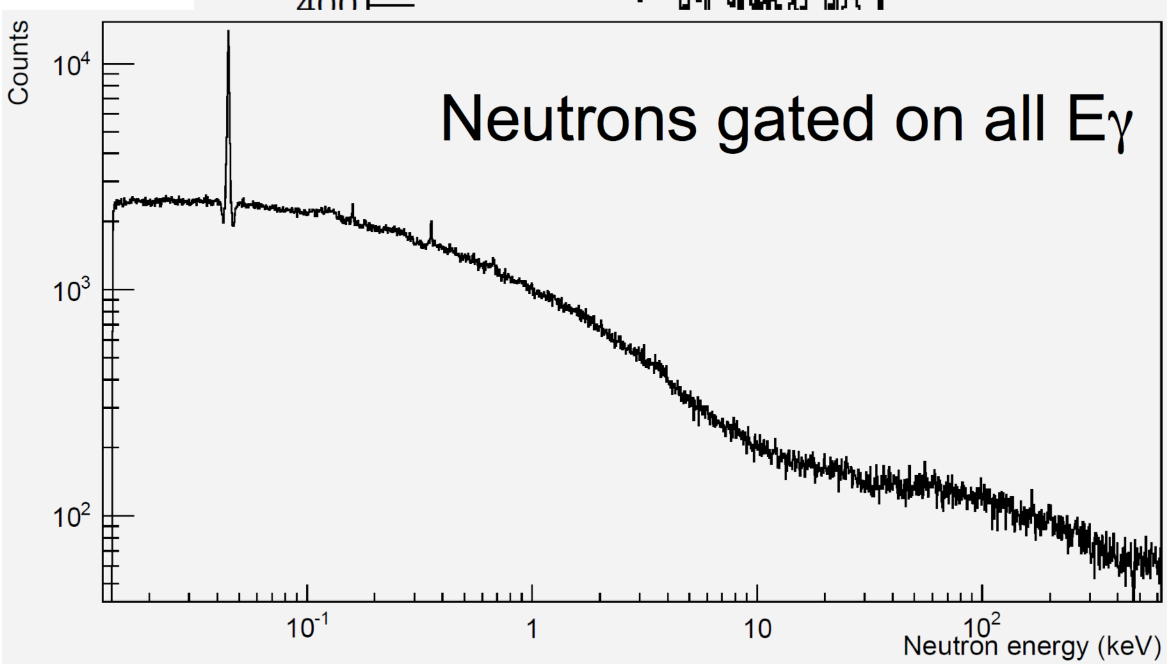
Preliminary ^{95}Mo(n,γ) data, all E





A. Adekola, GG7, Friday a

^{95}Mo(n,γ) and ^{95}Mo(d,pγ) spin distributions

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  - ^{95}Mo(d,pγ) in normal and inverse kinematics
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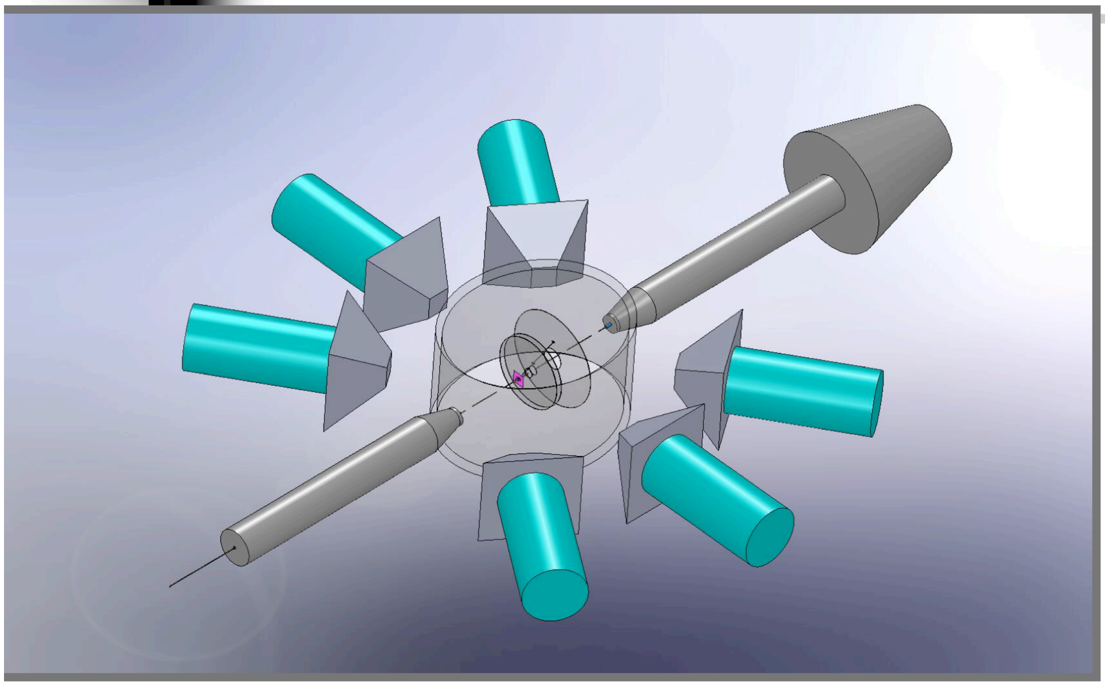
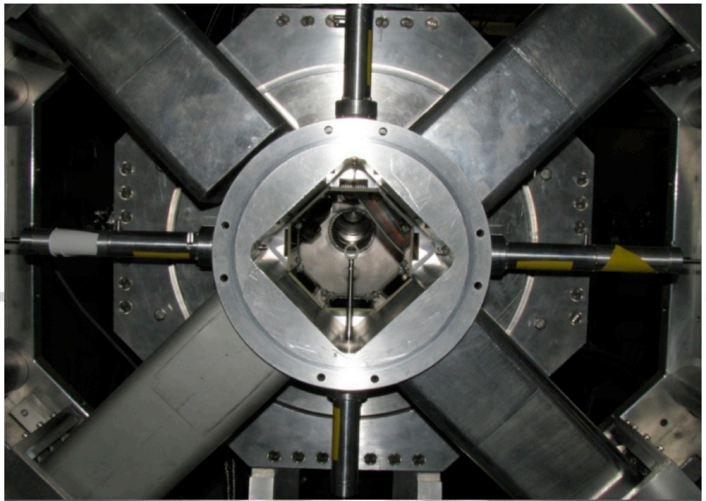
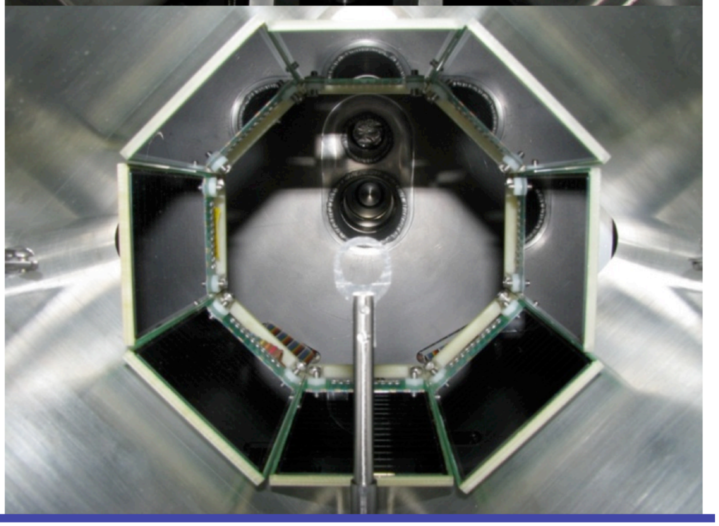
^{95}Mo(d,pγ) Normal & Inverse Kinematics







At LBNL

- LIBERACE: 6 Clover Ge γ-ray detectors STARS
- ΔE-E double-sided silicon strip detectors

At HRIBF

- 4 Clover Ge γ-ray detectors, close packed @ 90°
- 8 ORRUBA-type PSD Si strip detectors at θ>90°

Summary:(d,pγ) as (n,γ) surrogate?

- (n,γ) cross sections on unstable nuclei important for basic and applied nuclear science
- (n,γ) is not W-E limit and does surrogate populate same CN as (n,γ)?
  - Differences in entry spin distributions
  - Have developed (one case) prescription for deducing σ(n,γ) ratios
- Path forward
  - Measure spin distributions (n,γ)
  - Measure spin distributions in (d,pγ) surrogate, normal & inverse kinematics
  - Move forward techniques to measure surrogates in inverse kinematics
  - Develop robust prescription to deduce σ(n,γ) from surrogates
- Prospects are promising

Thank you and my Collaborators

(d,pγ) benchmarking

J.A.C., A. Adekola, A. M. Hatarik, R. Hatarik, M.E. Howard, P. D. O'Malley, T. Swan, **Rutgers University**
L. A. Bernstein, D. L. Bleuel, J. T. Burke, S. R. Lesher , N. Scielzo, J. E. Escher, **Lawrence Livermore National Laboratory**
J. Gibelin, L. W. Phair, **Lawrence Berkeley National Laboratory**
Milan Krticka, **Charles University, Prague**

(n,γ) spin distributions

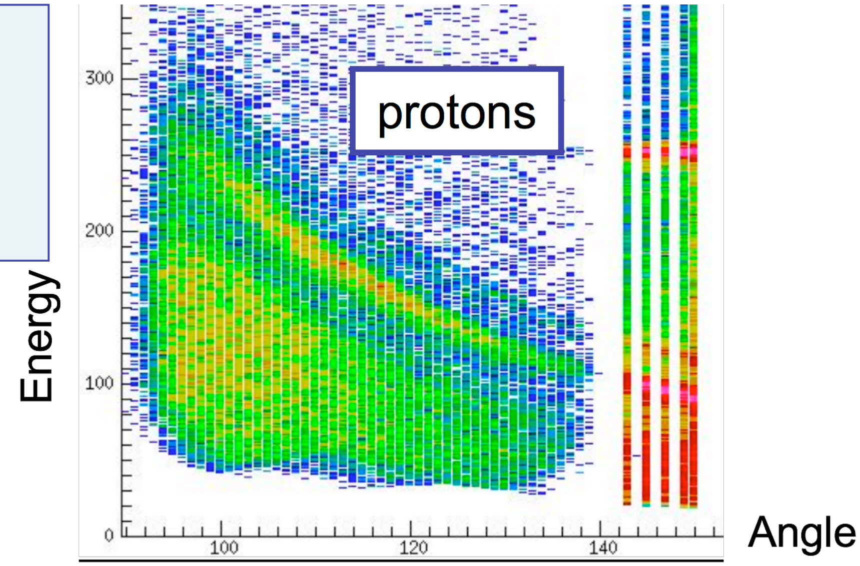
J.A.C., A. Adekola, M.E. Howard,B. Manning, **Rutgers University**
M. Devlin, M. Jandel, A. Couture, N. Fotiades, D. Vieira, S. Wender, **LANL**
W.A. Peters, **ORAU**
J. Burke, J.E. Escher, N. Scielzo, **LLNL**
R. Hatarik, **UCB**

(d,pγ) in inverse kinematics

J.A.C., W.A. Peters, R. Hatarik, P.D. O'Malley, J.S. Thomas, **Rutgers University**
M.S. Johnson, C. Matei, **Oak Ridge Associated Universities**
D.W. Bardayan, S.D. Pain, M.S. Smith, **Oak Ridge National Laboratory**
R.L. Kozub, J. Shriner, **Tennessee Technological University**
D.J. Vieira, M. Jandel, J.B. Wilhelmy, **Los Alamos National Laboratory**
B.J. Moazen, K.Y. Chae, K.L. Jones, **University of Tennessee**
J.C. Blackmon, **Louisiana State University**

$^{80}Se(d,p\gamma)$

stable ^{80}Se beam test



J.A.C., M.S. Johnson et al.
NIM **B261**, 938 (2007)

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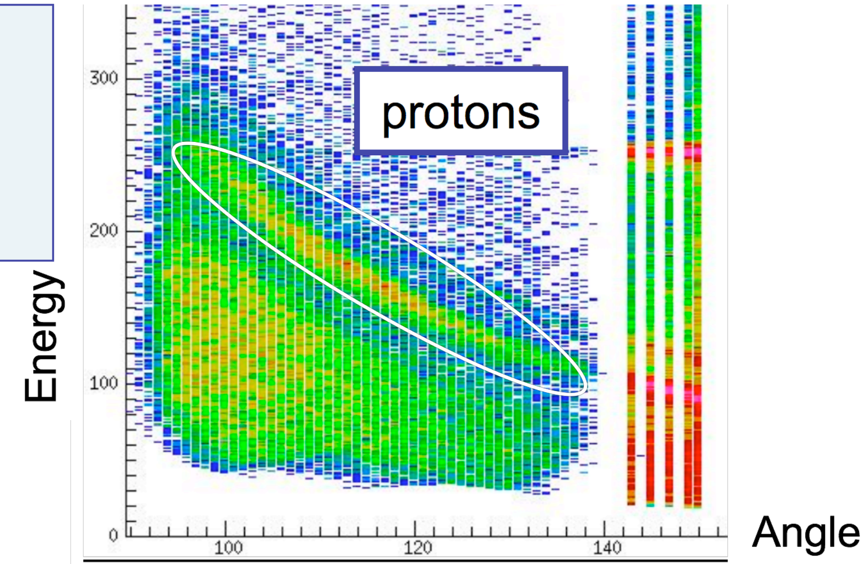

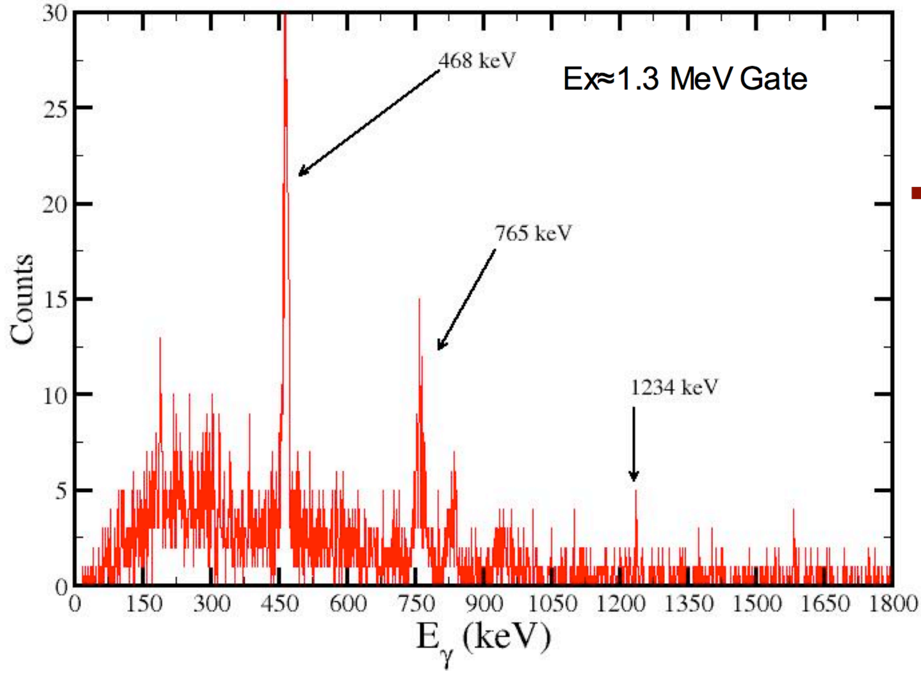

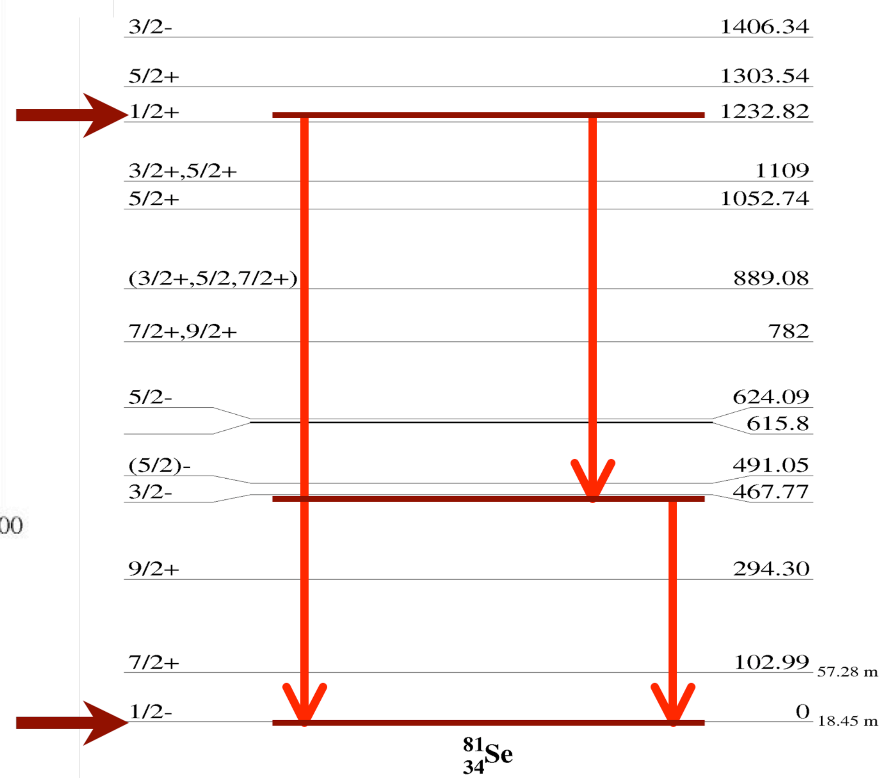

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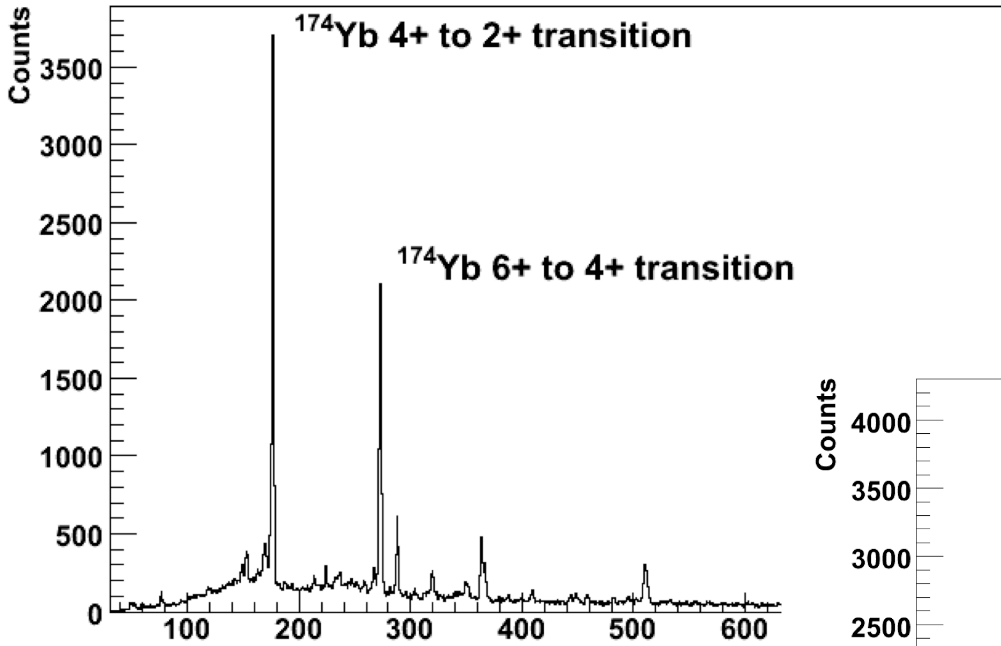
DICEBOX / experiment comparison

Intensity ratios of the $4^+ \Rightarrow 2^+$ and $6^+ \Rightarrow 4^+$
(ground state spins: ^{171}Yb $1/2^-$, ^{173}Yb $5/2^-$):

	Intensity ratio: $I(4^+ \text{ to } 2^+) / I(6^+ \text{ to } 4^+)$	
Target	(d,pγ) experiment	DICEBOX (n,γ)
^{171}Yb	3	J^π = 0- or 1-, Ex = 8.2 MeV 6+ to 4+ insignificant
^{173}Yb	1.8	J^π = 2- or 3-, Ex = 7.5 MeV 10

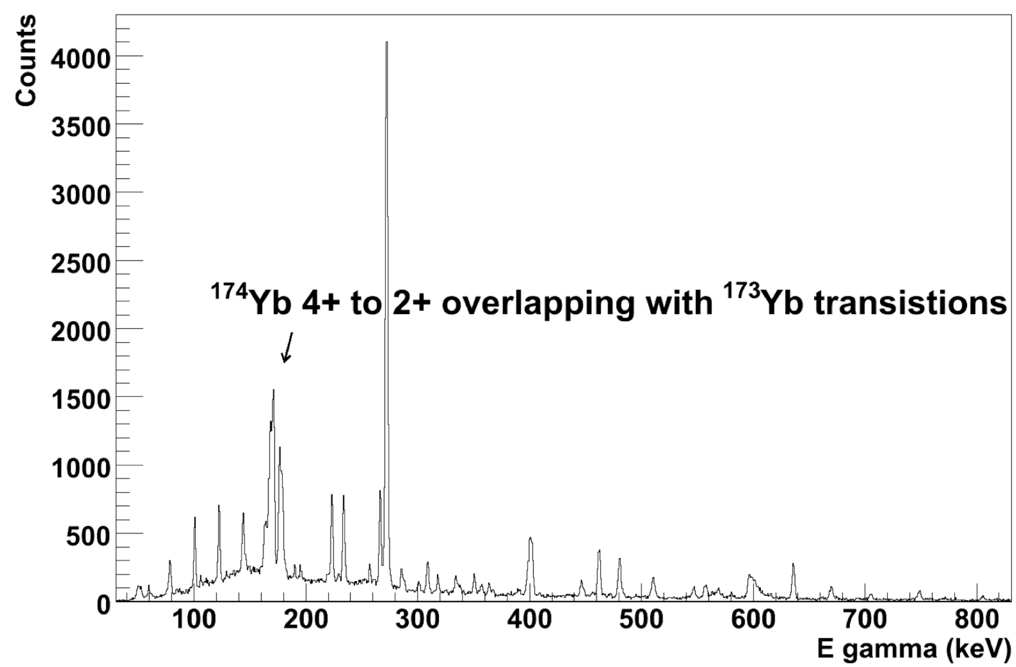
→ subtract 6^+ feeding of 4^+
to get spin distribution closer to (n,γ)

γ-ray spectrum
strength collected in “one” transition



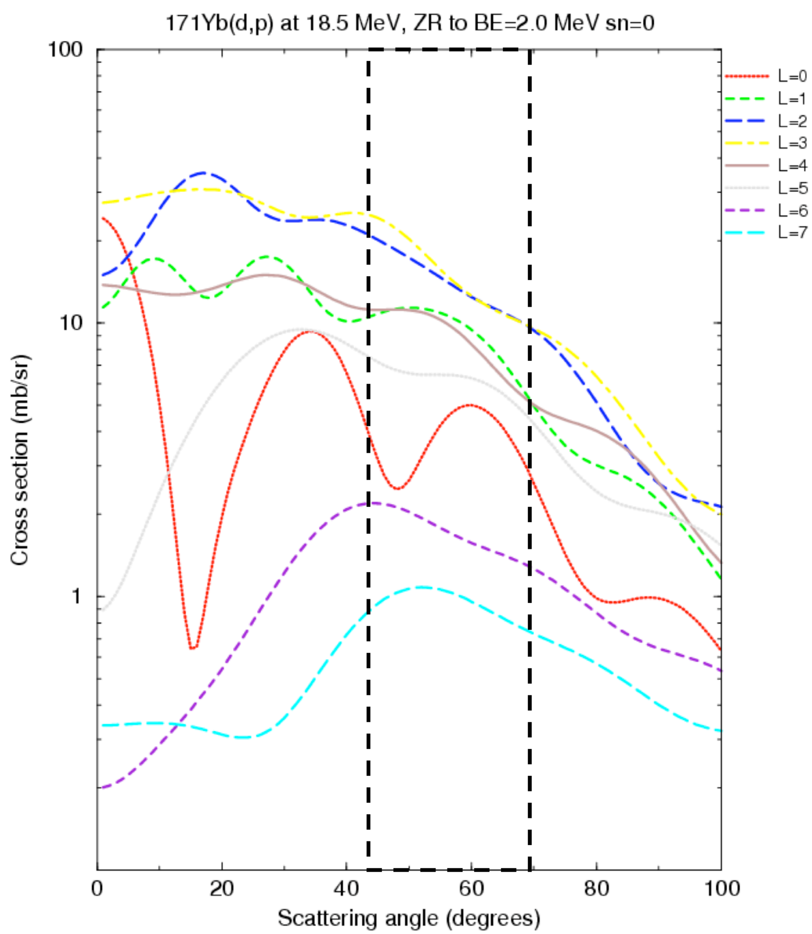
at neutron separation energy

at 1 MeV equivalent neutron energ

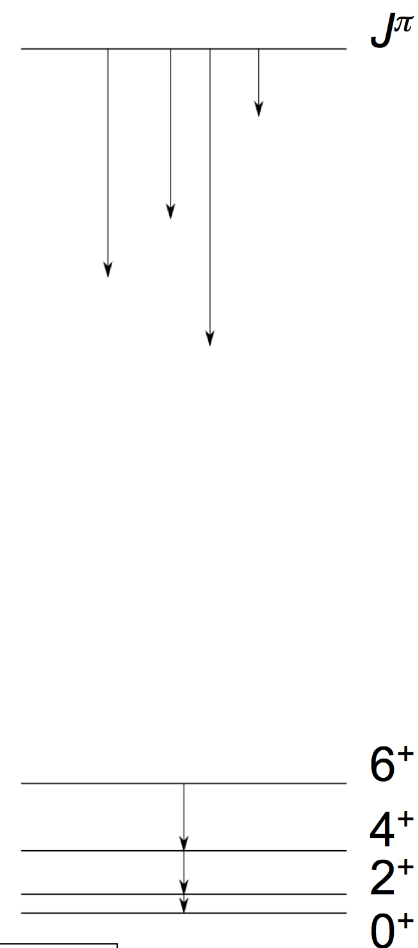


Spin distribution

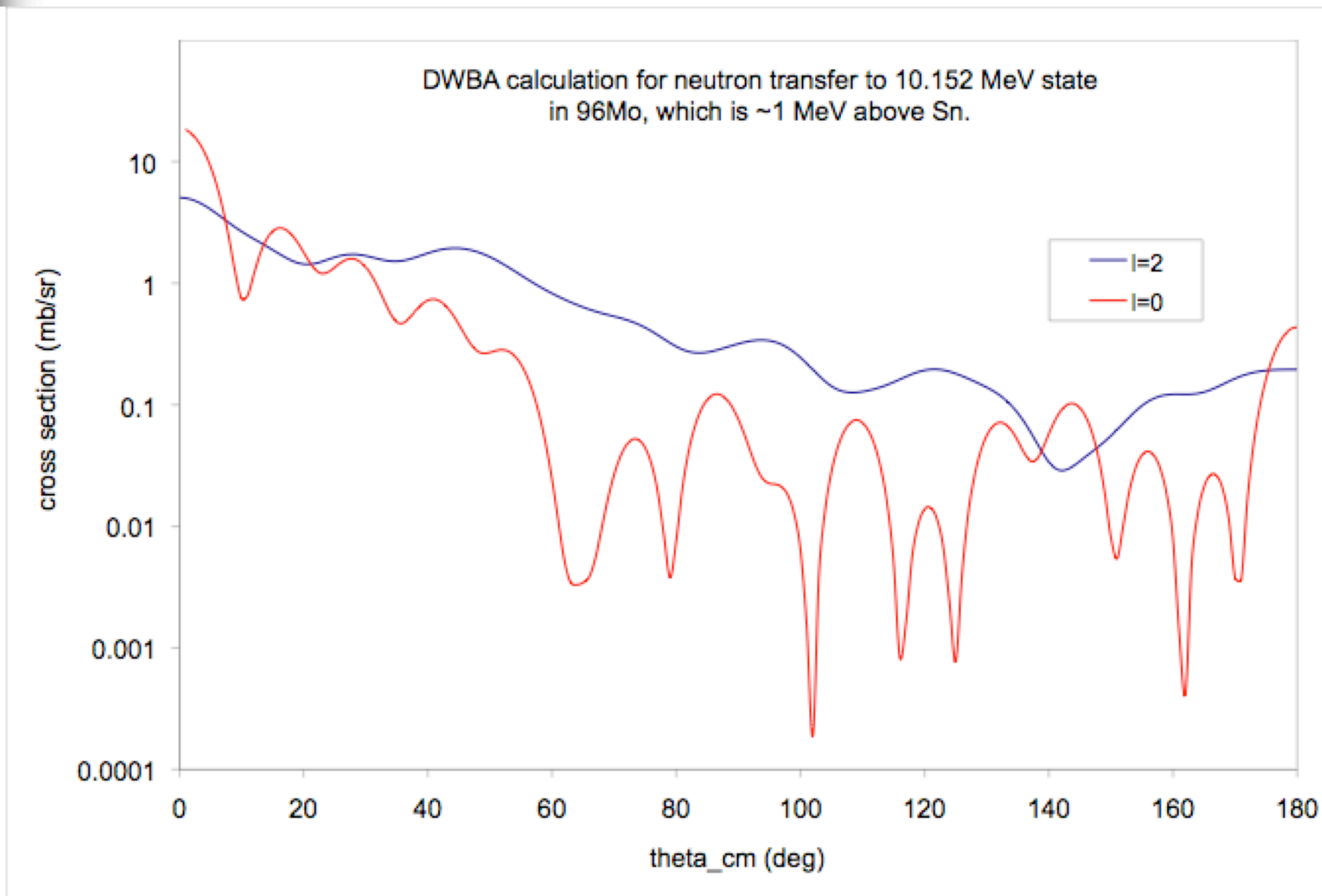
- angular dependence from proton



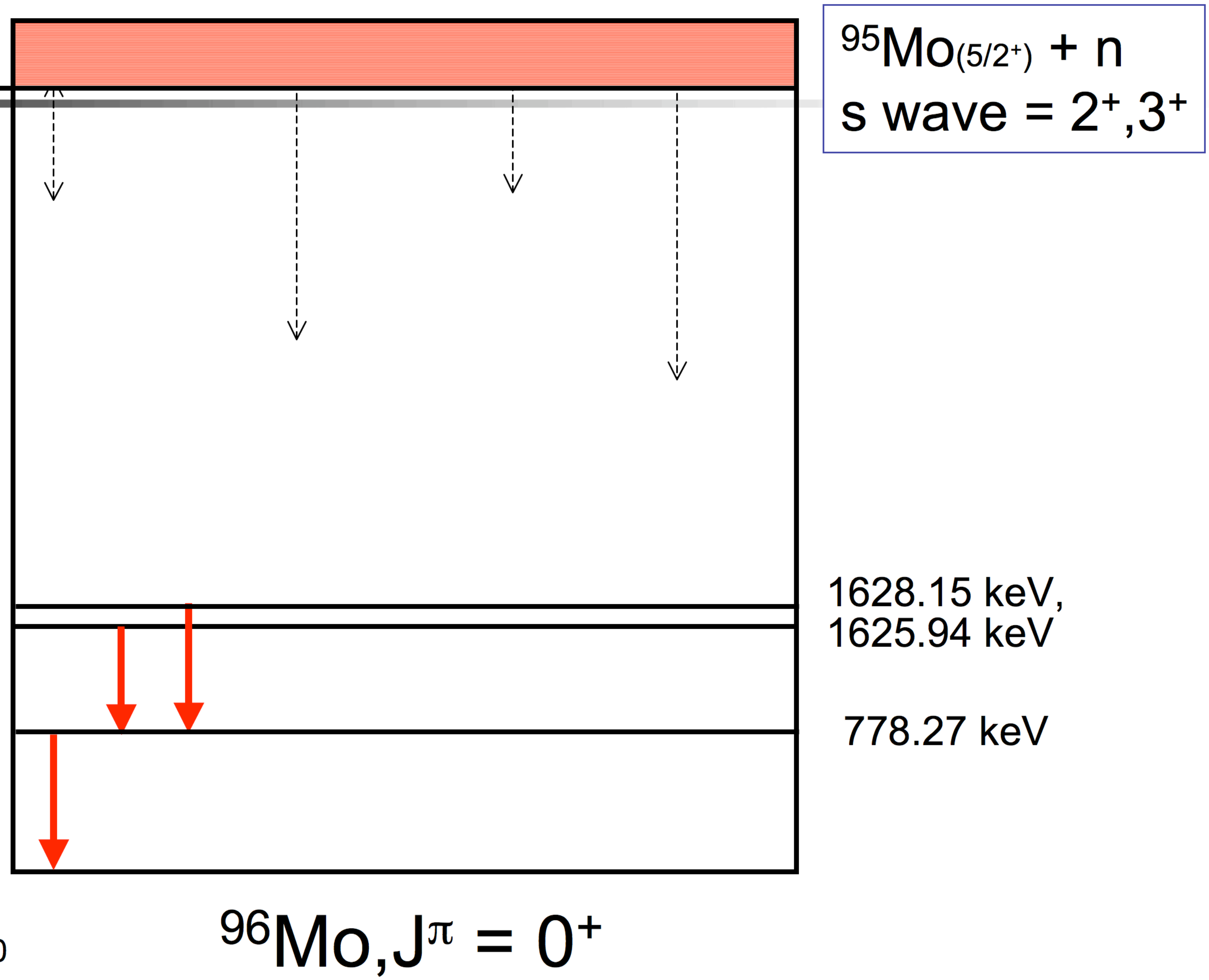
- looking at the γ-rays → DICEBOX



DWBA for 95Mo(d,p) Ex>Sn



Decay of ^{96}Mo CN



Partial ^{96}Mo level scheme