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THE STATE UNIVERSITY OF NEW JERSEY

Sn (d,p) and r-process nucleosynthesis

Jolie A. Cizewski
Rutgers University

Workshop on r-process nucleosynthesis

Cairns, Australia

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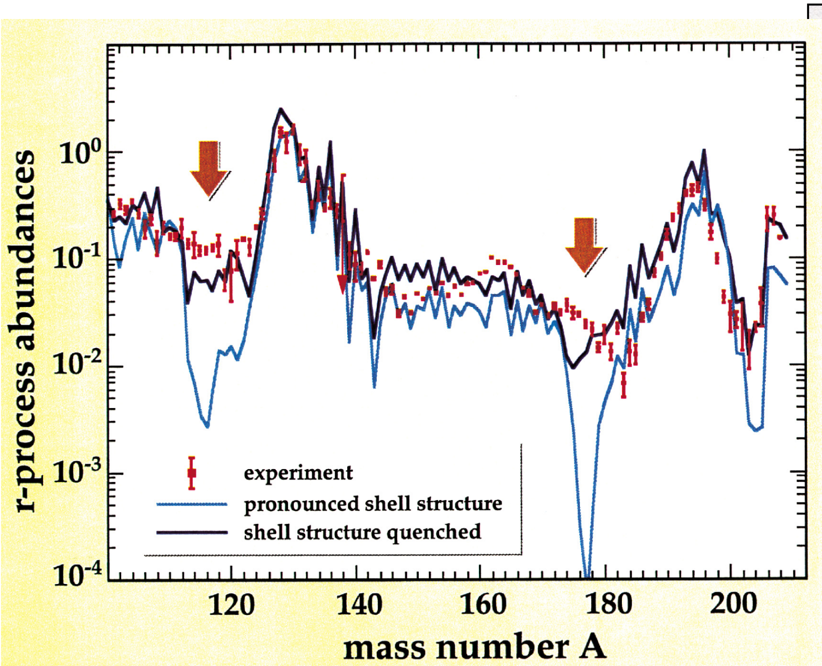
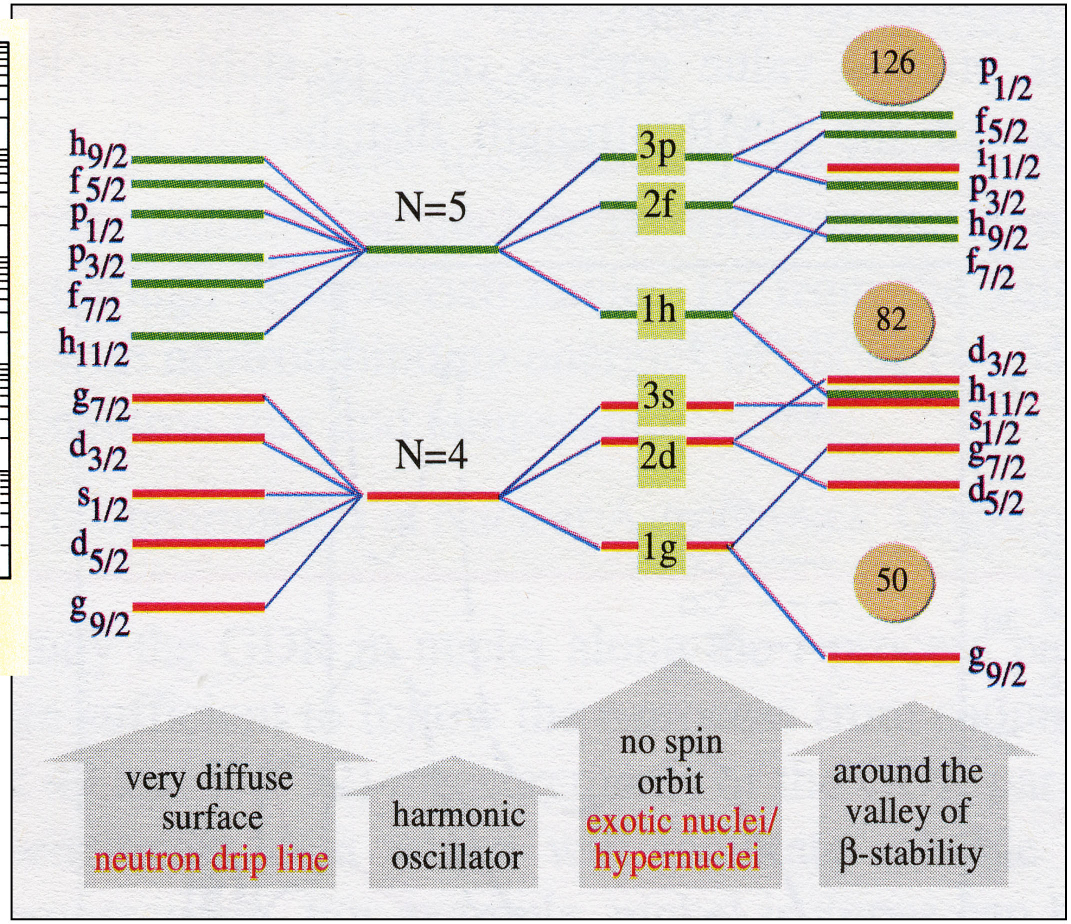
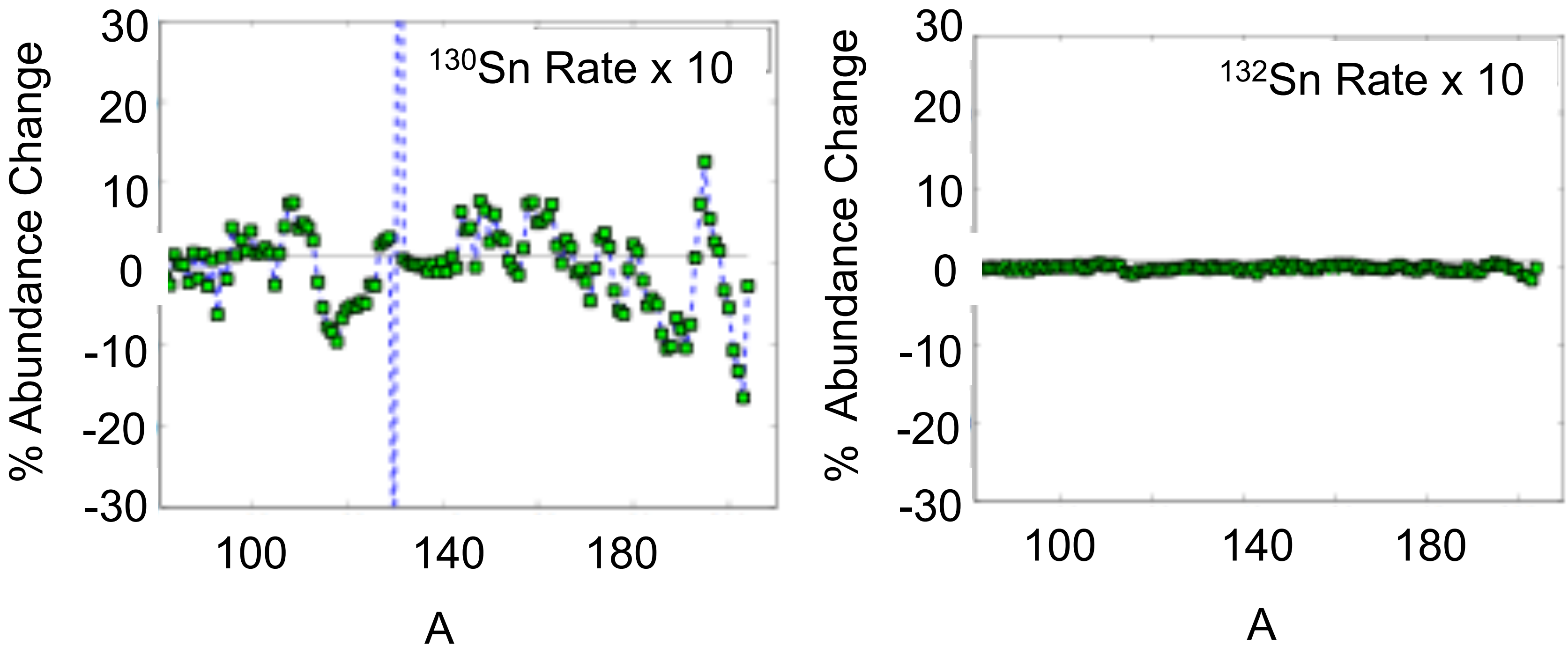
r-process abundances and evolution of nuclear shell structure?





Probe neutron-rich nuclei with beams of rare isotopes

r-process sensitivity studies

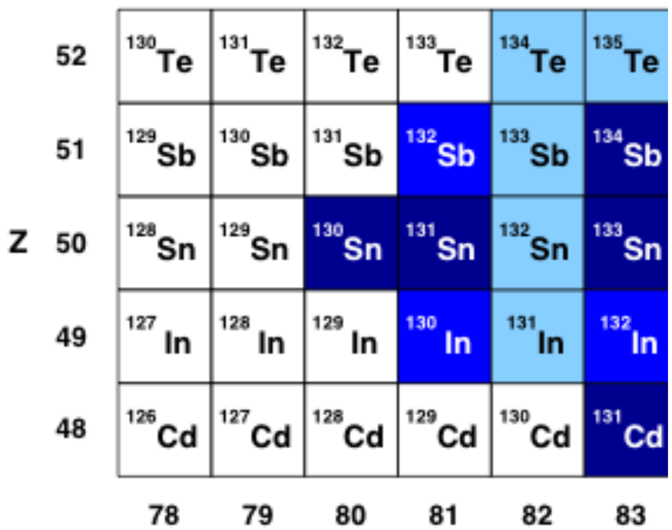


Simulations of the r-process show huge, **global** sensitivity to the ^{130}Sn(n,γ) rate, in contrast to the ^{132}Sn(n,γ) rate.

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

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

A≈^{130}Sn σ(n,γ) and sensitivities

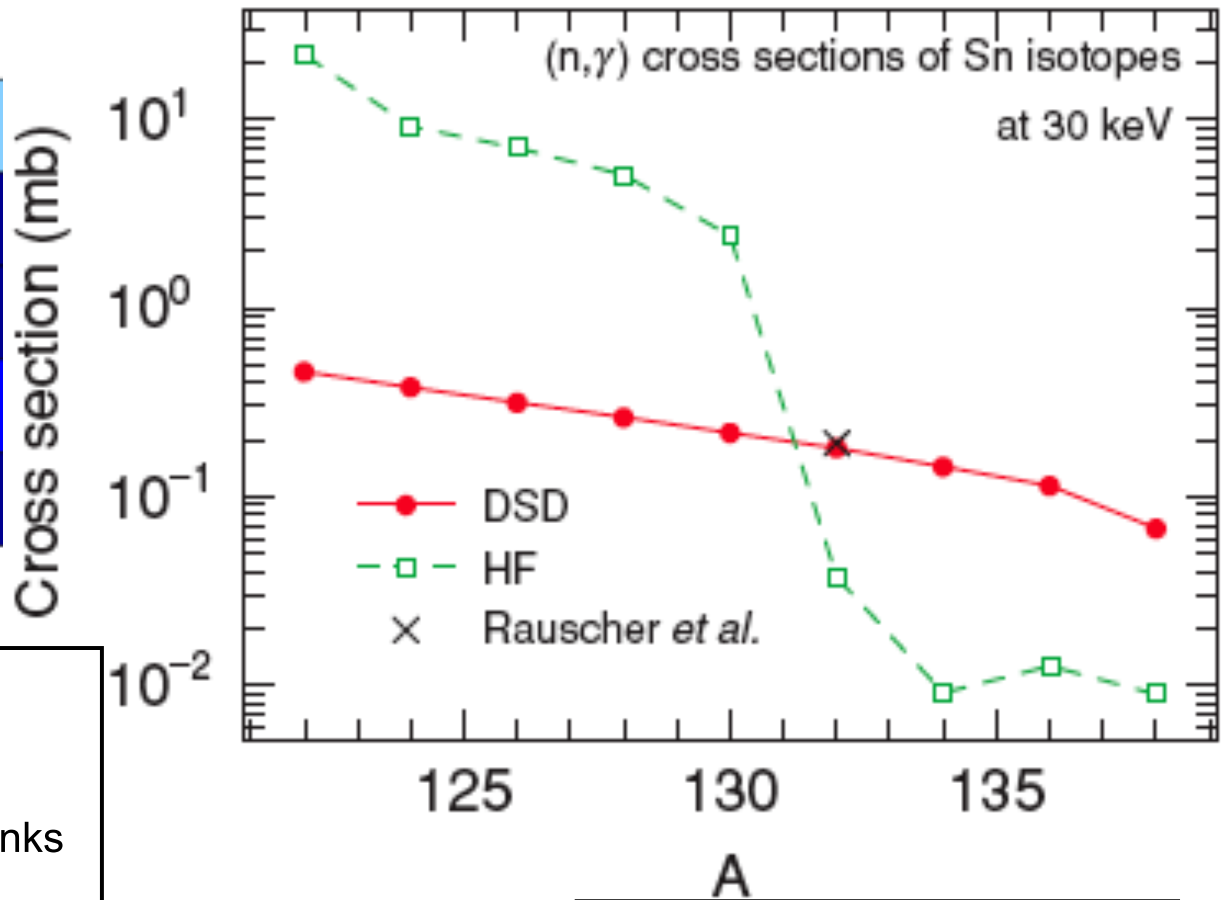


Changes in (n,γ) rates that change abundance patterns by at least 5%

Change factors:

Dark blue: x10; become neutron sinks

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

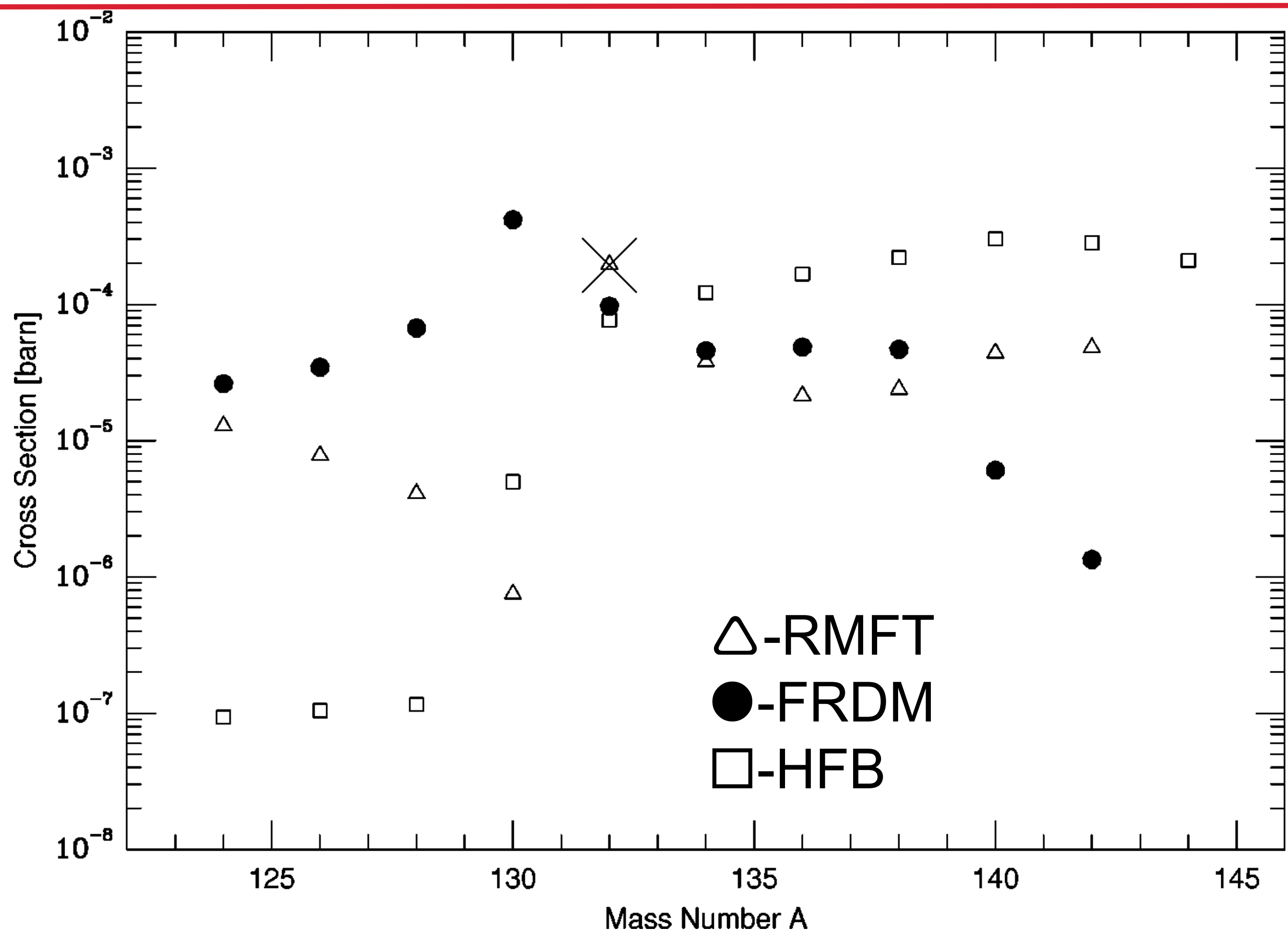


Sn(n,γ) vs A

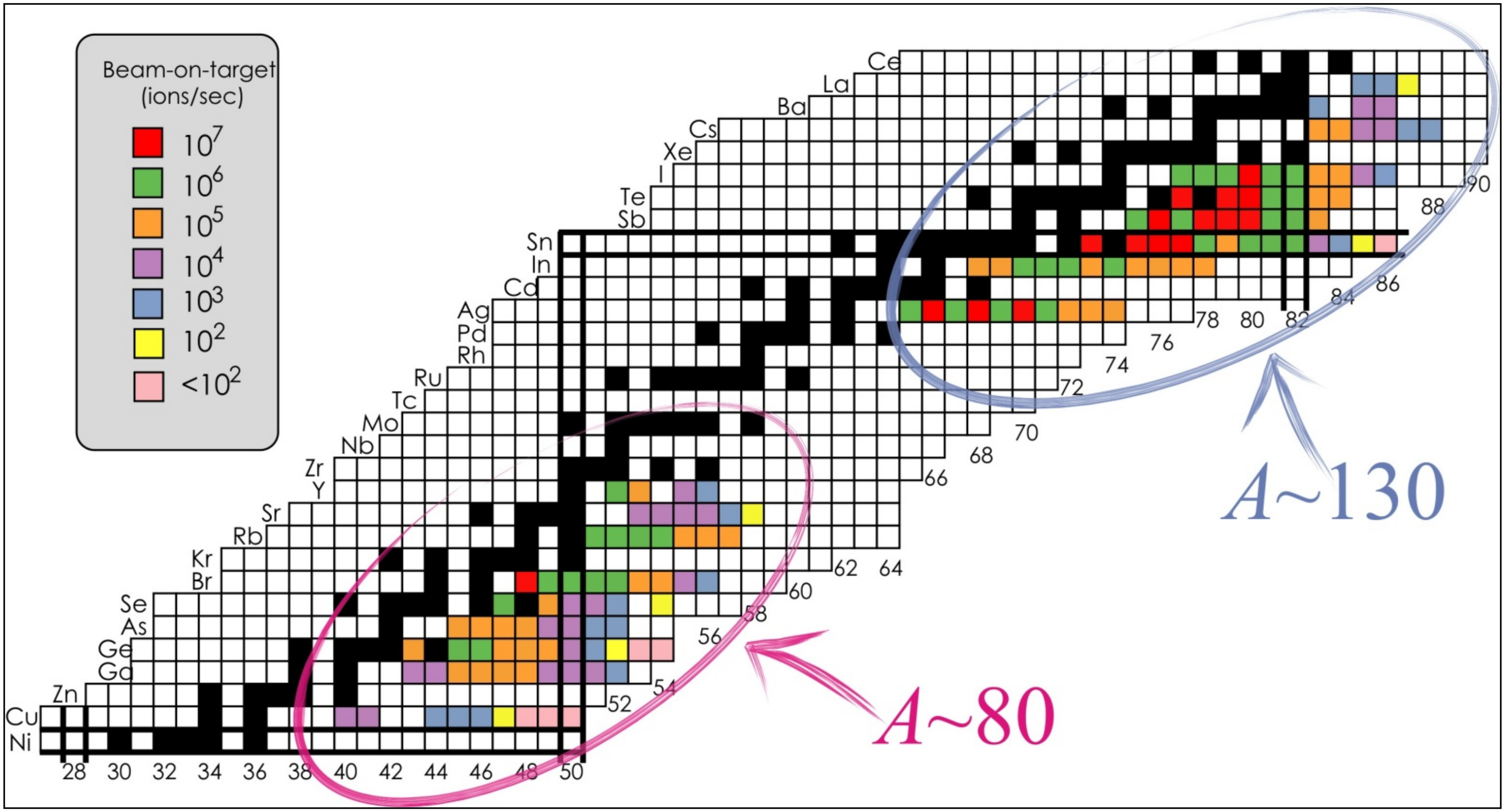
Chiba, et al. PRC **77**, 015809 (2008)

Rauscher et al., direct (n,γ) cross sections

PRC **57** 2031 (1998)



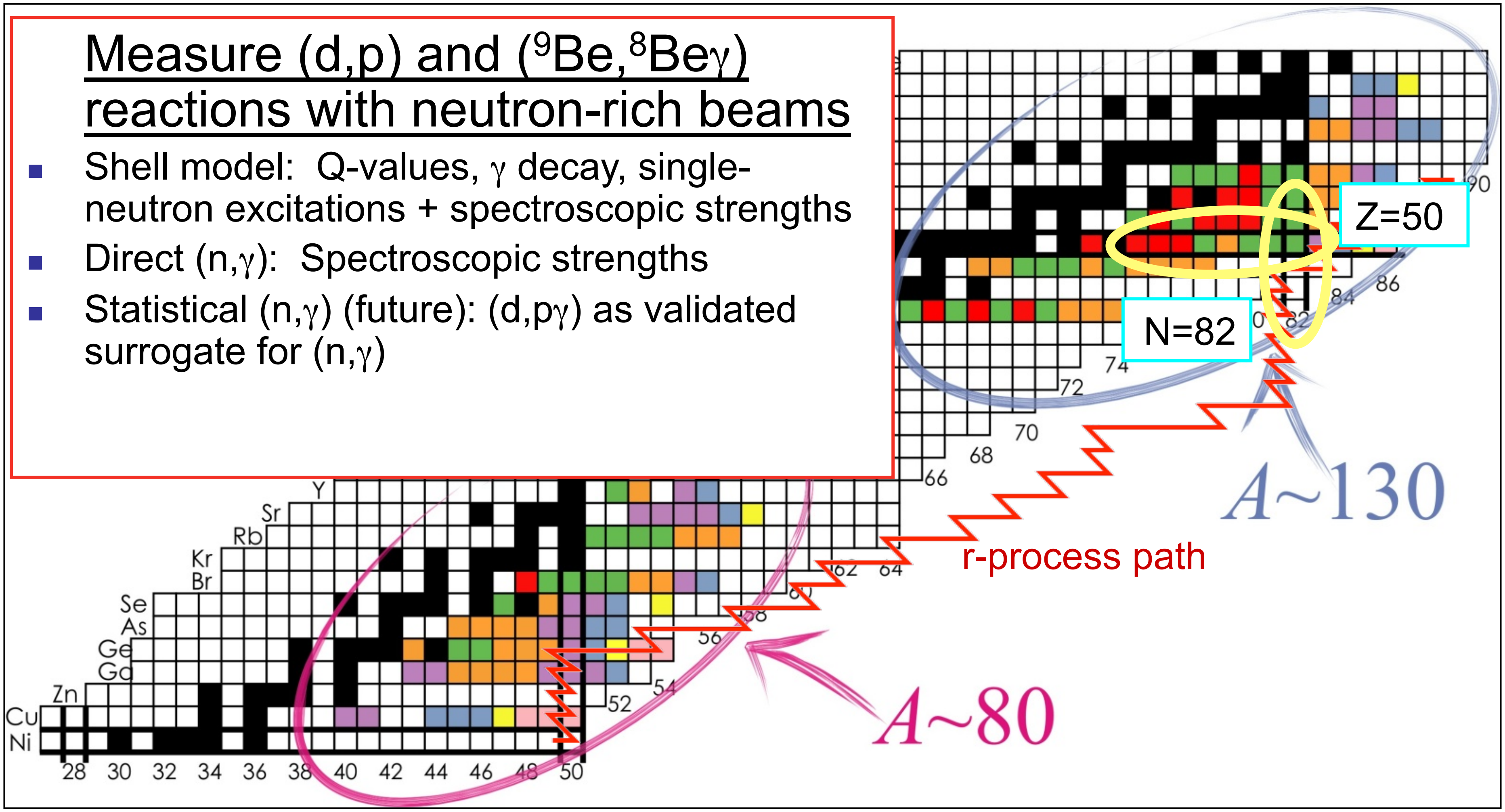
Neutron transfer (d,p) reactions near ^{132}Sn



Neutron transfer (d,p) reactions near ^{132}Sn

Measure (d,p) and (^{9}Be,$^{8}Be\gamma$) reactions with neutron-rich beams

- Shell model: Q-values, γ decay, single-neutron excitations + spectroscopic strengths
- Direct (n,γ): Spectroscopic strengths
- Statistical (n,γ) (future): (d,pγ) as validated surrogate for (n,γ)



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A≈130 (d,p) and (^{9}Be,^{8}Beγ) Collaboration

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ORNL: G. Arbanas, J.M. Allmond, D.W. Bardayan, J.R. Beene, A. Galindo-Uribarri, J.F. Liang, C.D. Nesaraja, Steve D. Pain, D.C. Radford, D. Shapira, M.S. Smith

Univ. Tennessee: S. Ahn, A. Bey, K.Y. Chae, R. Kapler, Kate L. Jones, B.H. Moazen, S.T. Pittman, K.T. Schmitt

Tennessee Tech: Ray L. Kozub

Michigan State Univ: Filomena Nunes **ORAU:** W. A. Peters

Louisiana State University: J.C. Blackmon, M. Matos

Univ. of Surrey: S. Hardy, C. Shand, T.P. Swan, J.S. Thomas, G.L. Wilson

Colorado School of Mines: K.A. Chipps, L. Erikson, R. Livesay

Ohio University: A.S. Adekola **UNAM:** E. Padilla-Rodal

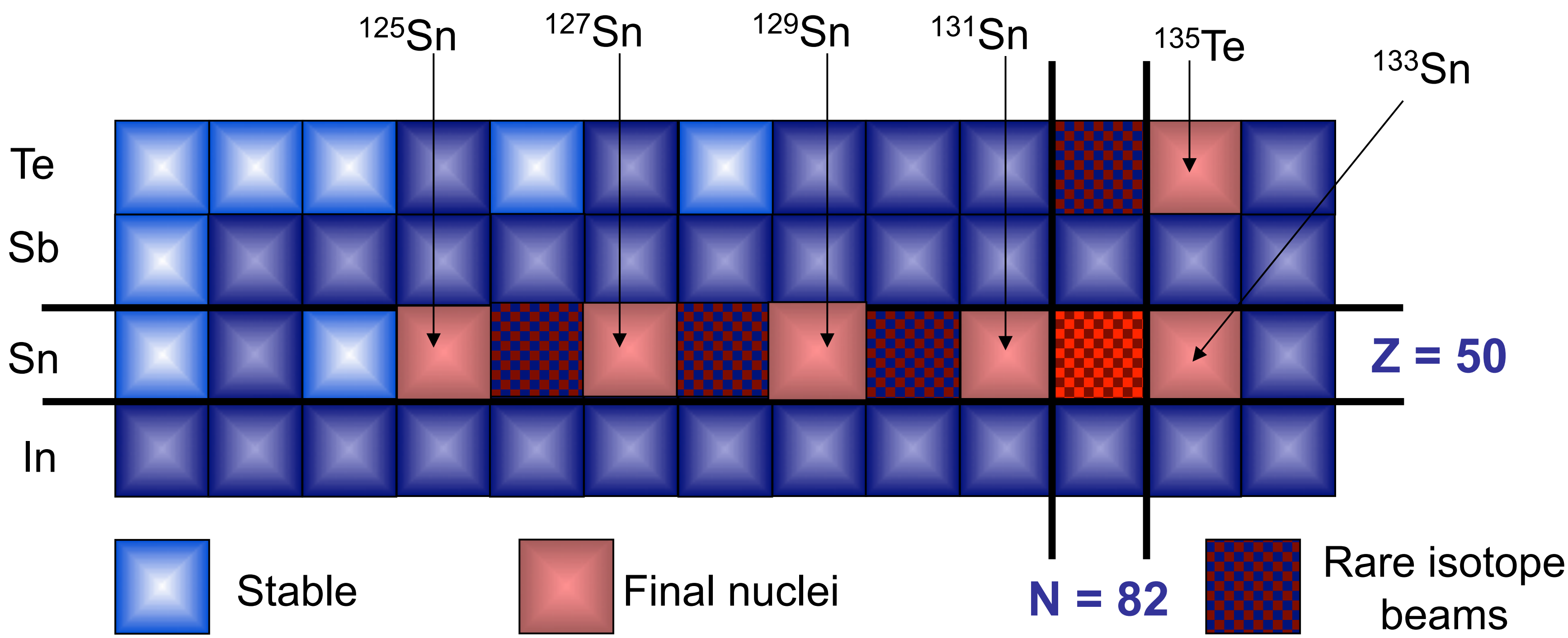
Funded in part by the

U.S. DOE Office of Science & NNSA/SSAA & National Science Foundation

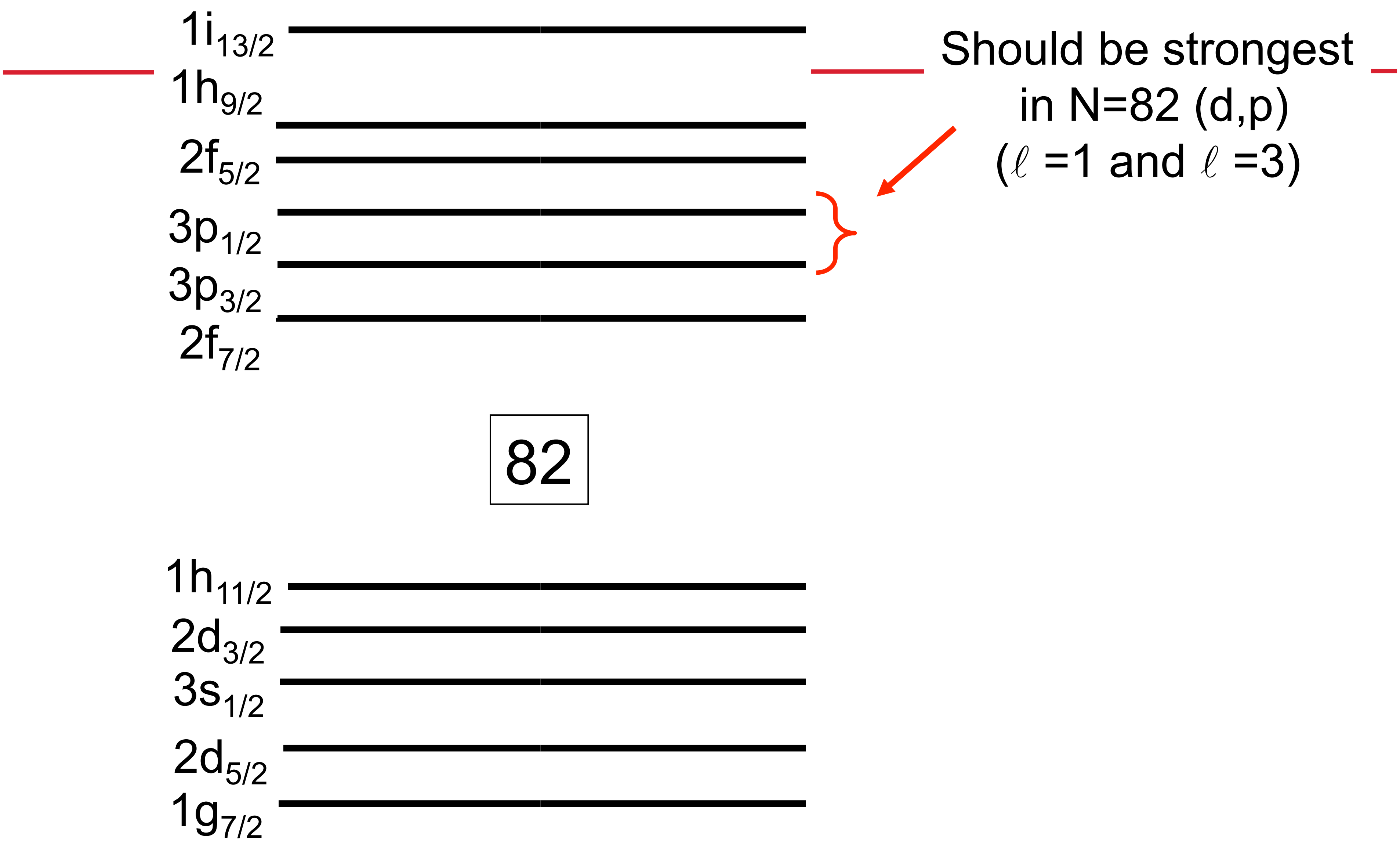
Near ^{132}Sn Z=50, N=82

Nuclear reaction & structure studies

Neutron transfer A(d,p)A+1 reactions
Neutron transfer A(d,t)A-1
Neutron transfer + gamma A(^{9}Be,$^{8}Be\gamma$)A-1

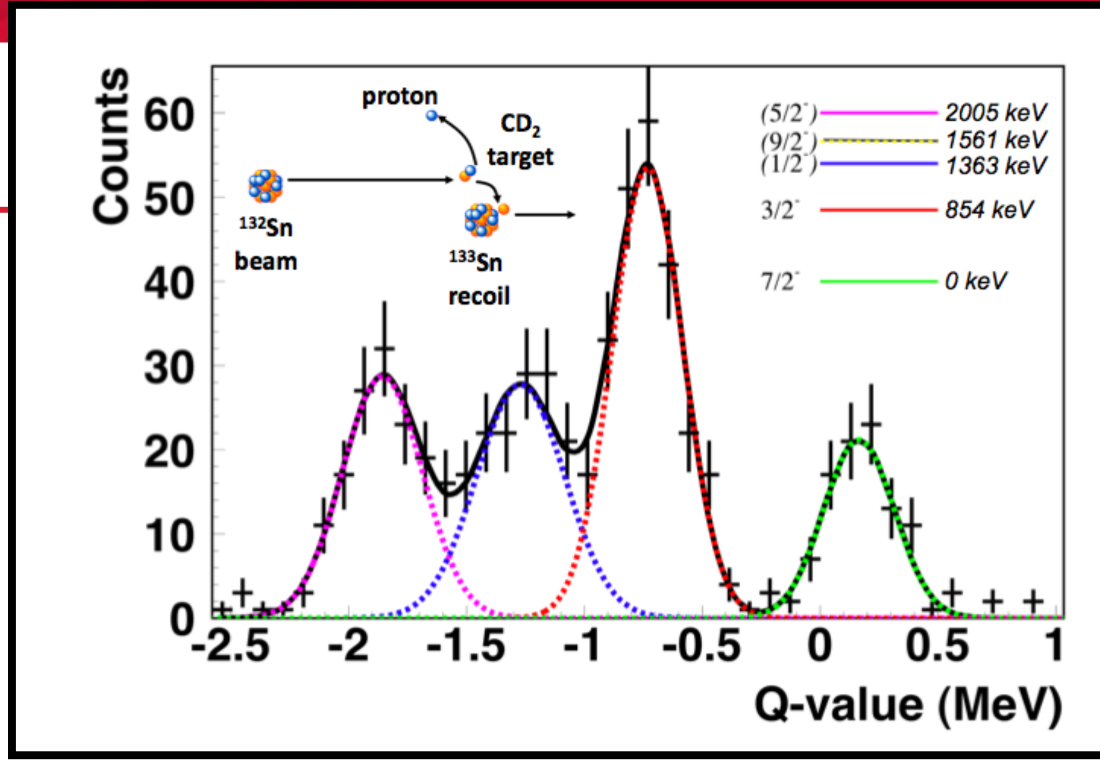


Sn (d,p): what should expect to see?



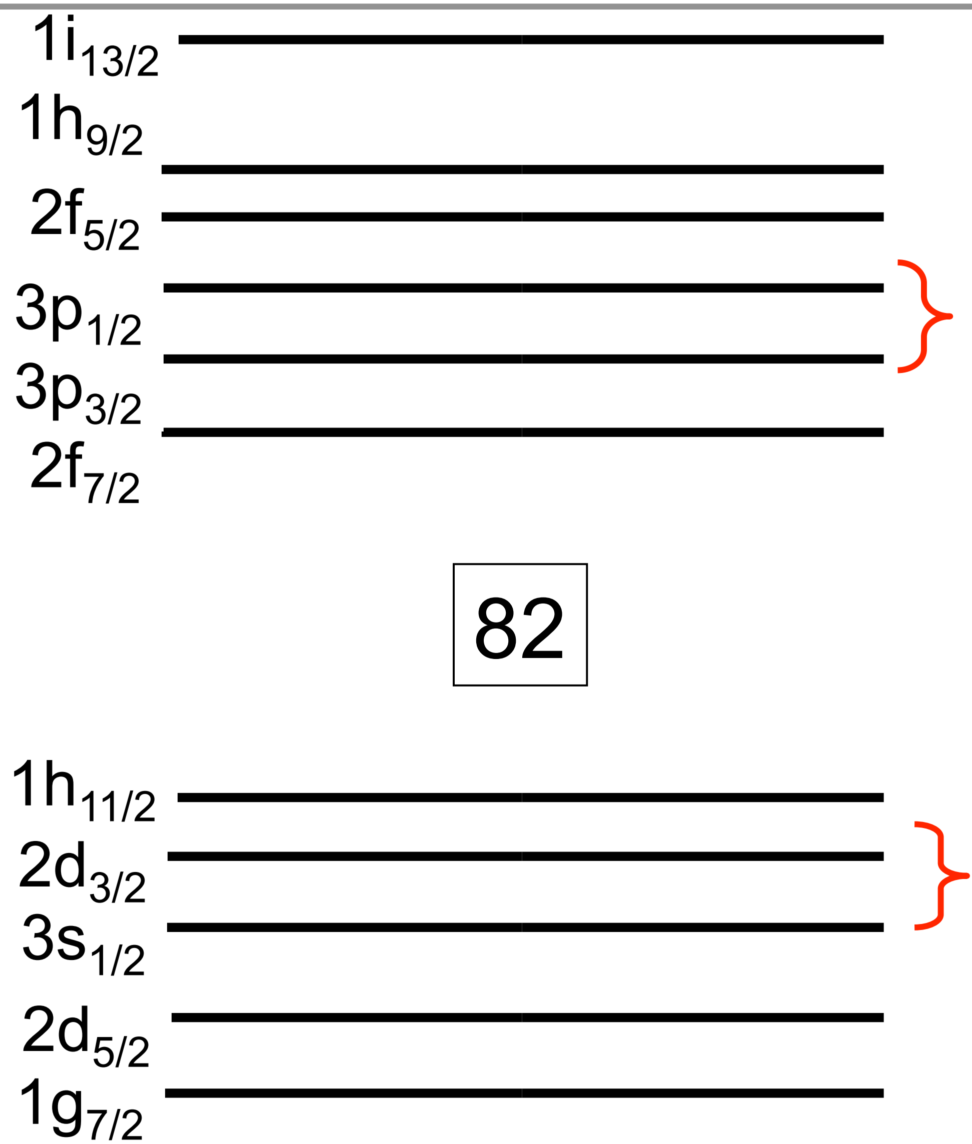
Identified $2f_{7/2}$, $3p_{3/2}$, $(3p_{1/2})$, $2f_{5/2}$ neutron strength in ^{133}Sn

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



E_x(keV)	J^π	Config	SF (DWBA)	SF (FR-ADWA)	C^2 (fm^{-1})
0	$7/2^-$	$2f_{7/2}$	0.86(14)	1.00(8)	0.64(10)
854	$3/2^-$	$3p_{3/2}$	0.92(14)	0.92(7)	5.6(9)
1363(31)	$(1/2^-)$	$3p_{1/2}$	1.1(3)	1.2(2)	2.6(4)
2005	$(5/2^-)$	$2f_{5/2}$	1.1(2)	1.2(3)	$9(2)\times10^{-4}$

N<82 (d,p) what should expect to see?



Should be strongest across N=82 (d,p) (ℓ =1 and ℓ =3)

ℓ=1 important in direct (n,γ)

N<82 neutron holes

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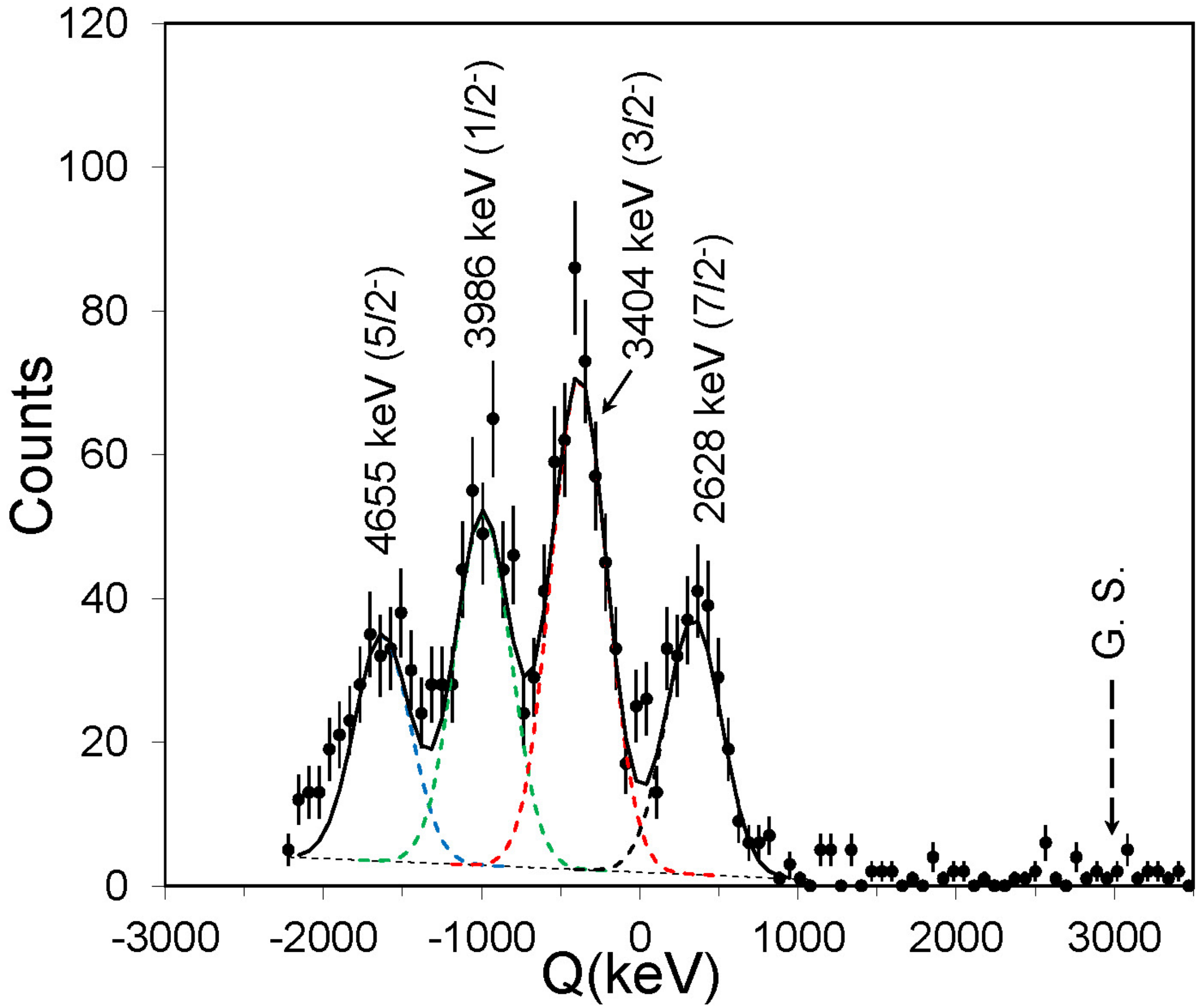
$^{130}Sn(d,p)$



R.L. Kozub, et al.

$^{130}Sn(d,p)$ & $^{132}Sn(d,p)$

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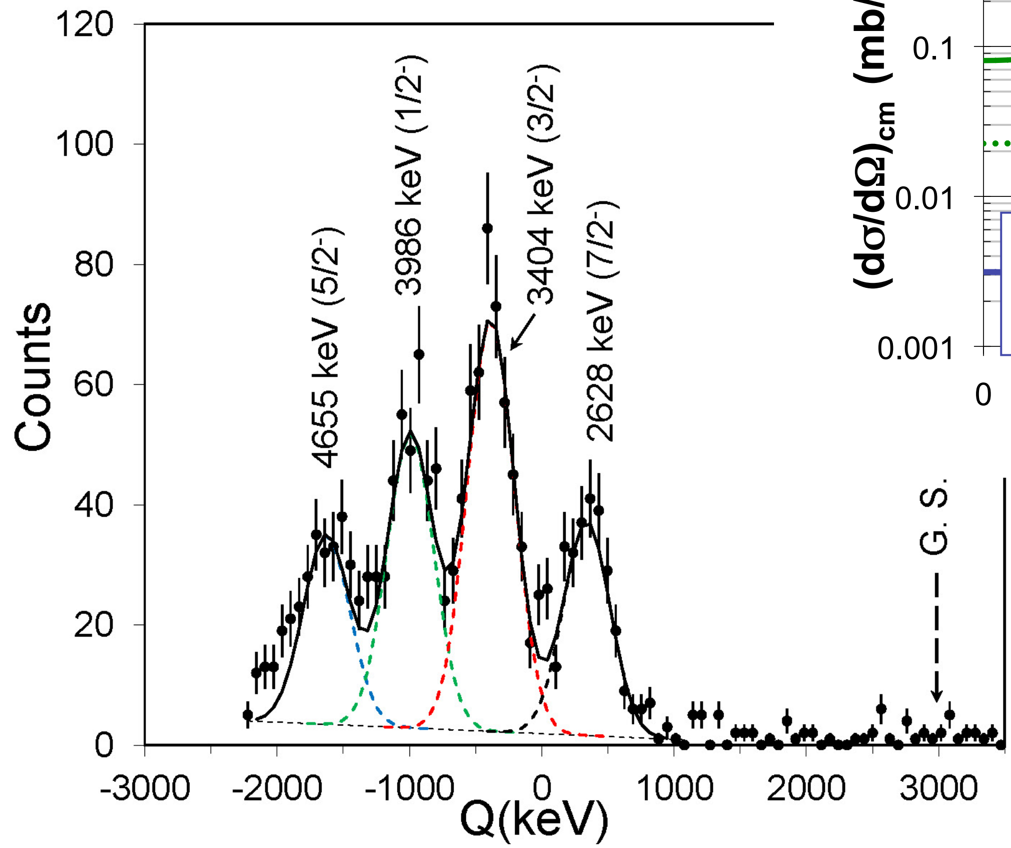

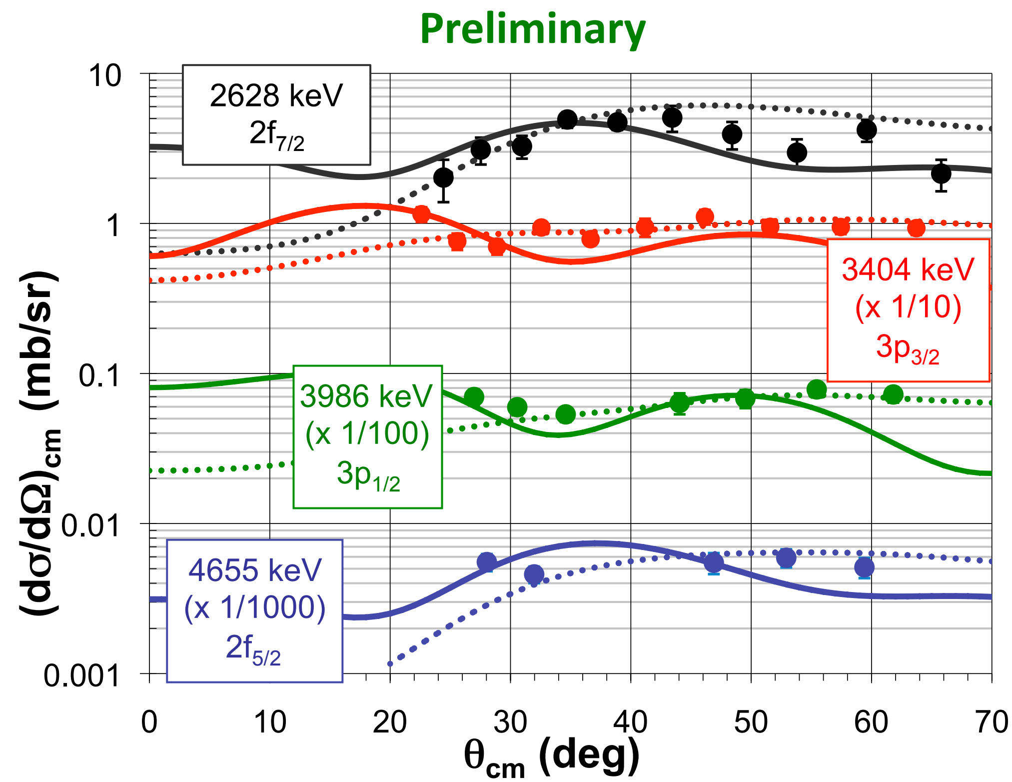

R.L. Kozub, et al.

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Many more nuclei can be studied in next few years

Changes in (n,γ) rates that change abundance patterns by at least 5%
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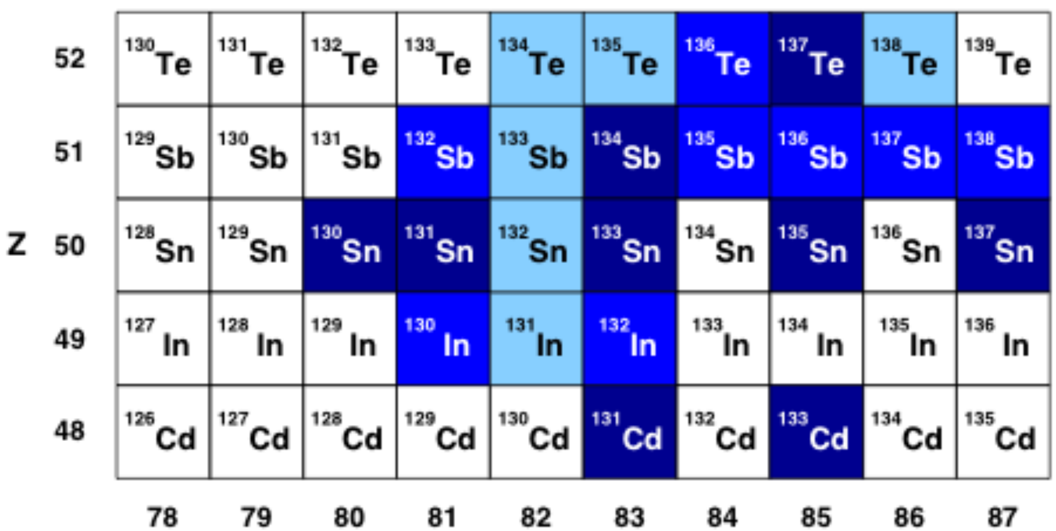
R. Surman, J. Beun, G.C. Mclaughlin, W.R. Hix, PRC **79**, 045809 (2009)



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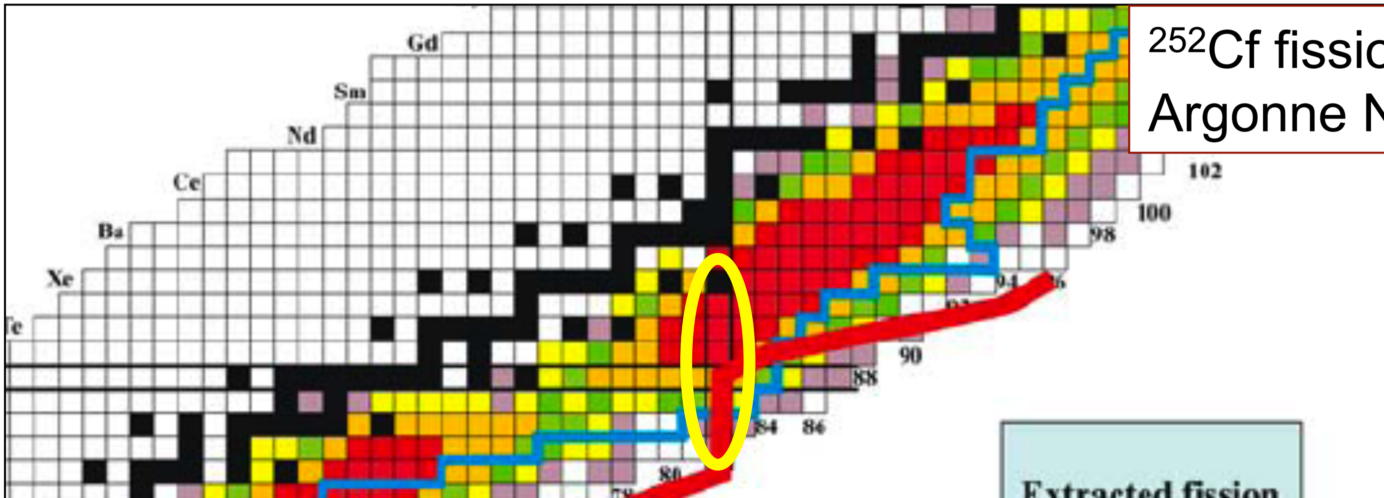
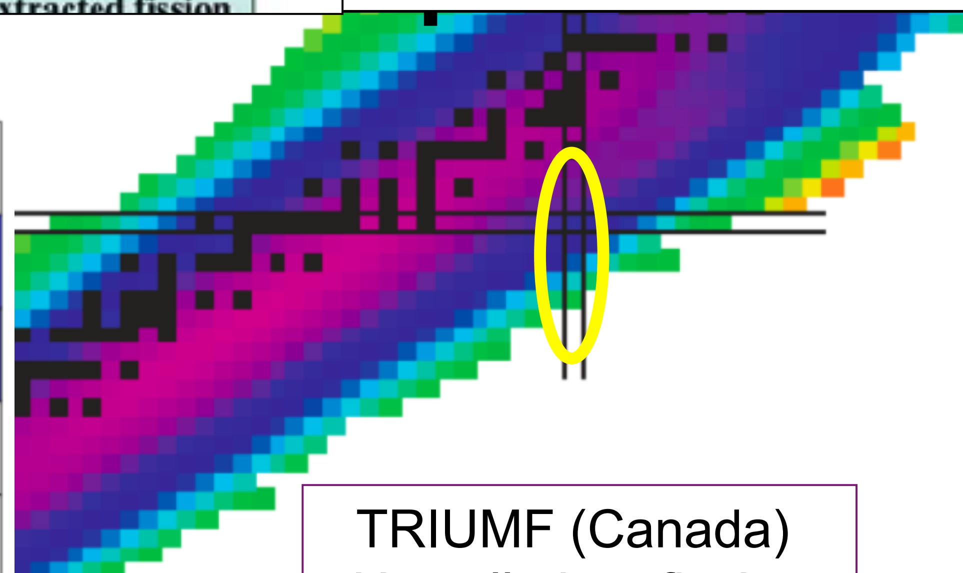


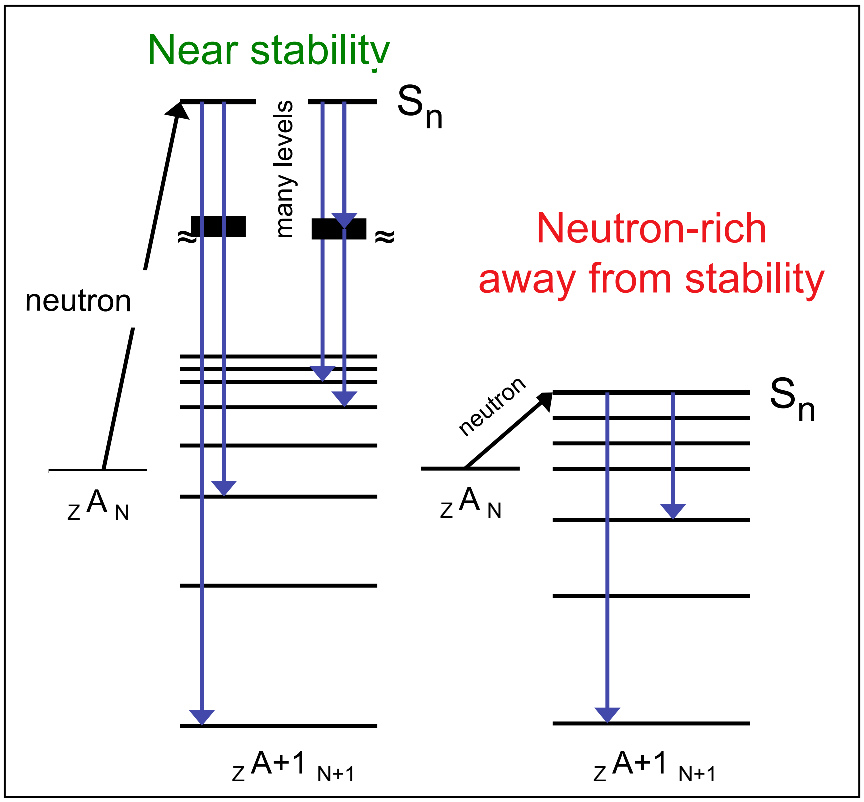
^{252}Cf fission fragments at Argonne National Lab

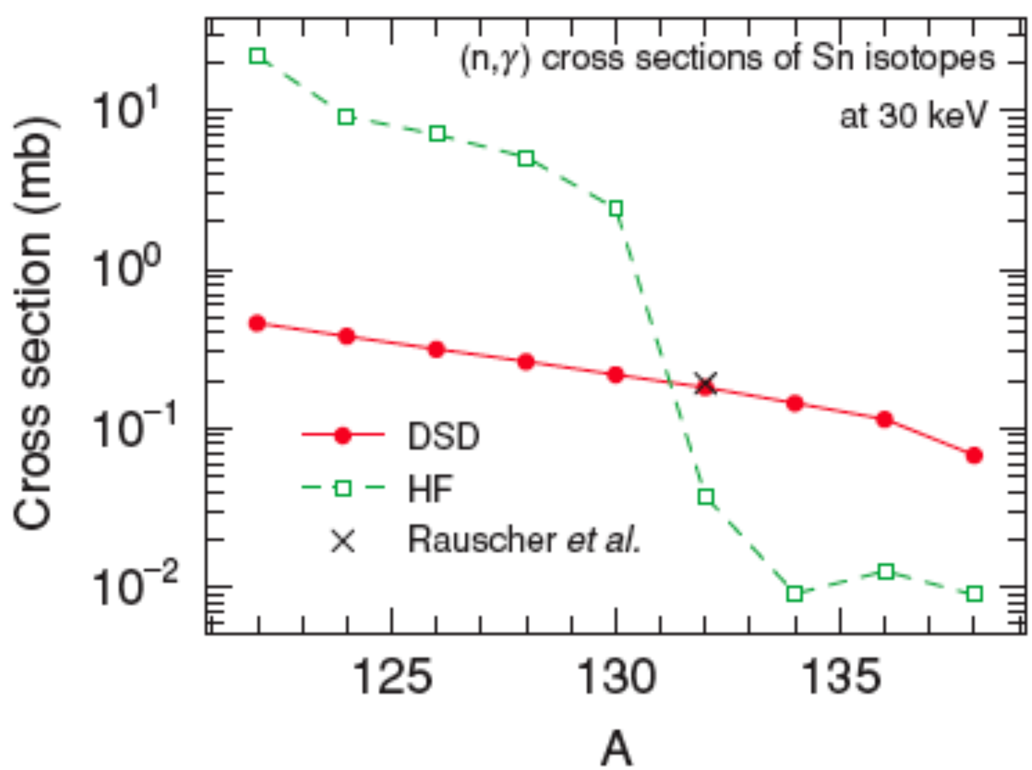
Z										
52	^{130}Te	^{131}Te	^{132}Te	^{133}Te	^{134}Te	^{135}Te	^{136}Te	^{137}Te	^{138}Te	^{139}Te
51	^{129}Sb	^{130}Sb	^{131}Sb	^{132}Sb	^{133}Sb	^{134}Sb	^{135}Sb	^{136}Sb	^{137}Sb	^{138}Sb
50	^{128}Sn	^{129}Sn	^{130}Sn	^{131}Sn	^{132}Sn	^{133}Sn	^{134}Sn	^{135}Sn	^{136}Sn	^{137}Sn
49	^{127}In	^{128}In	^{129}In	^{130}In	^{131}In	^{132}In	^{133}In	^{134}In	^{135}In	^{136}In
48	^{126}Cd	^{127}Cd	^{128}Cd	^{129}Cd	^{130}Cd	^{131}Cd	^{132}Cd	^{133}Cd	^{134}Cd	^{135}Cd
	78	79	80	81	82	83	84	85	86	87



TRIUMF (Canada)
U spallation+fission

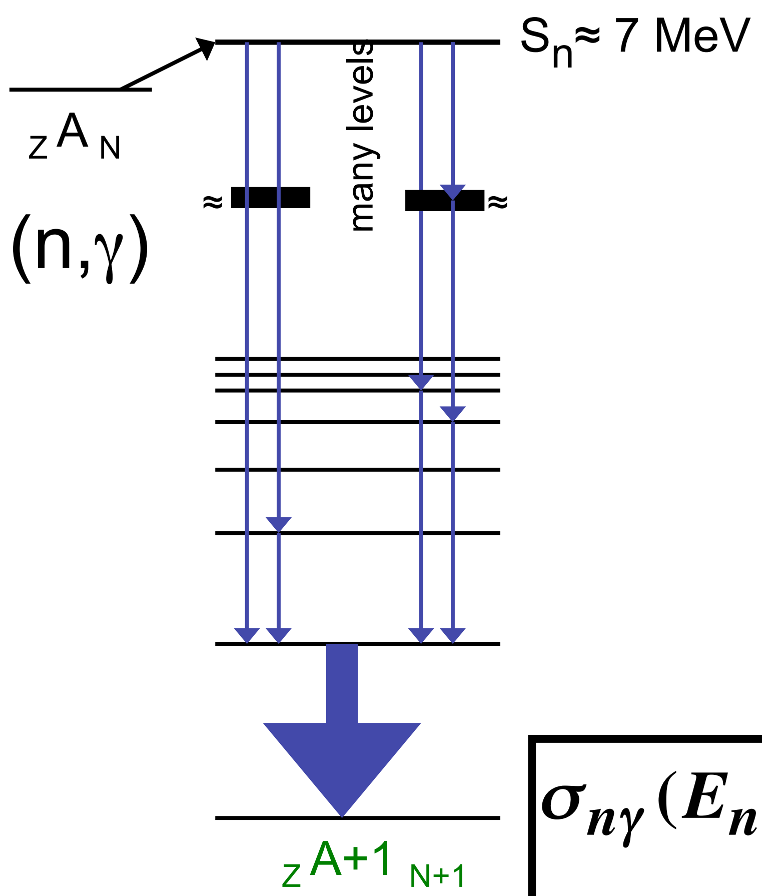
A≈130 Sn σ(n,γ) and sensitivities





Sn(n,γ) vs A
Chiba, et al. PRC **77**, 015809 (2008)

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

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

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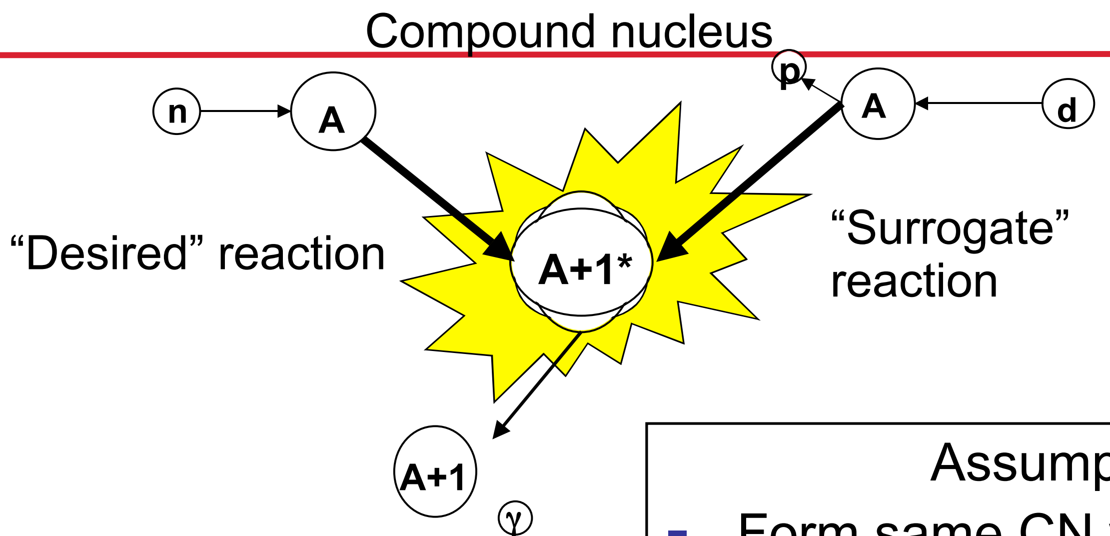
Surrogate reaction W-E Limit



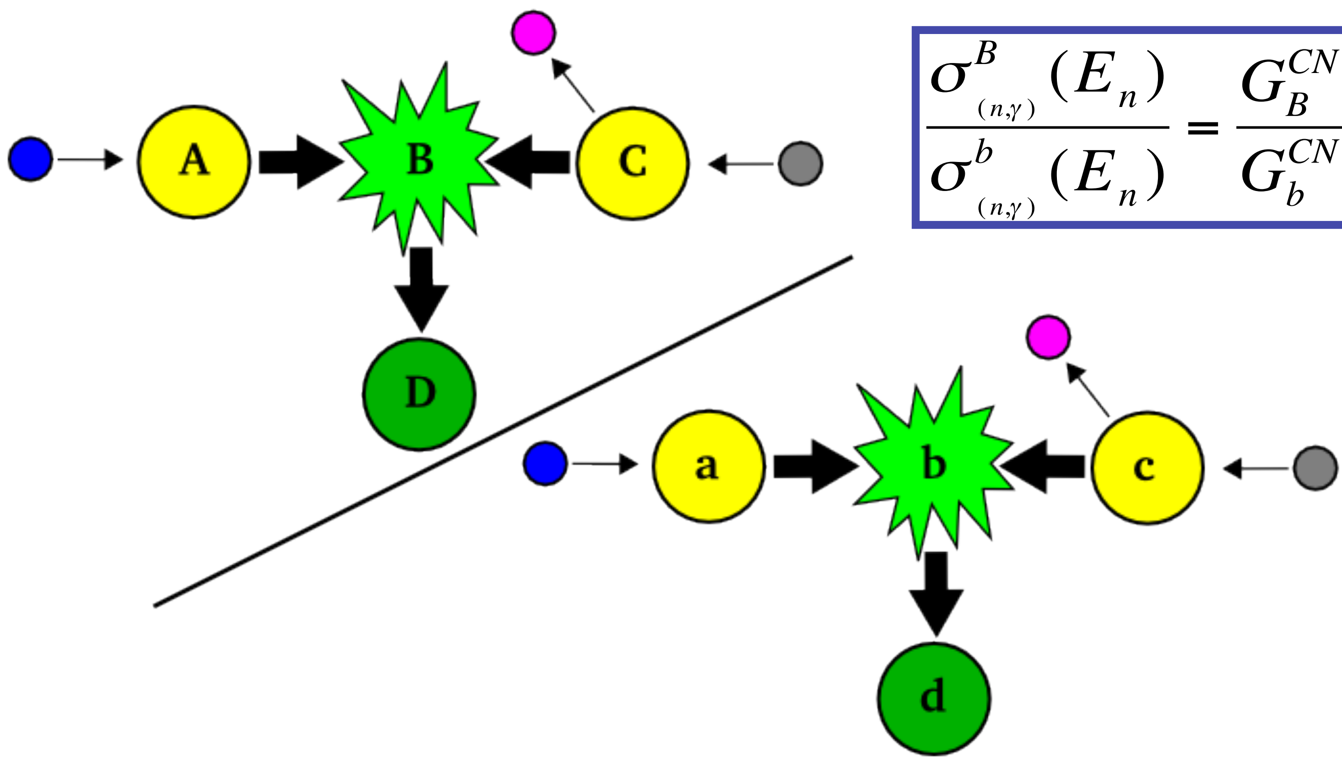
Assumptions:

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

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

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



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

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

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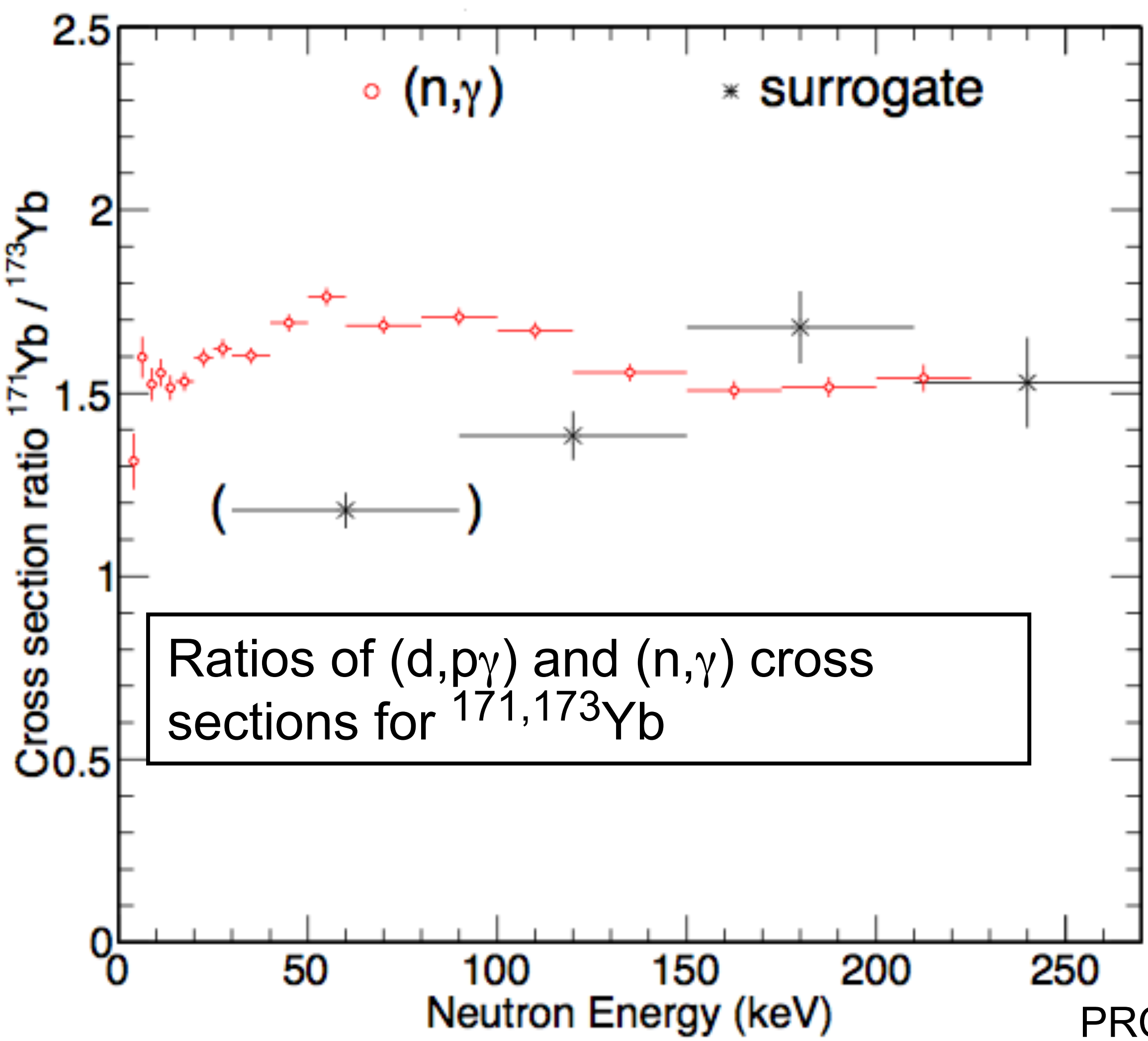


R. Hatarik et al.
PRC **81**, 011602 (R)(2010)

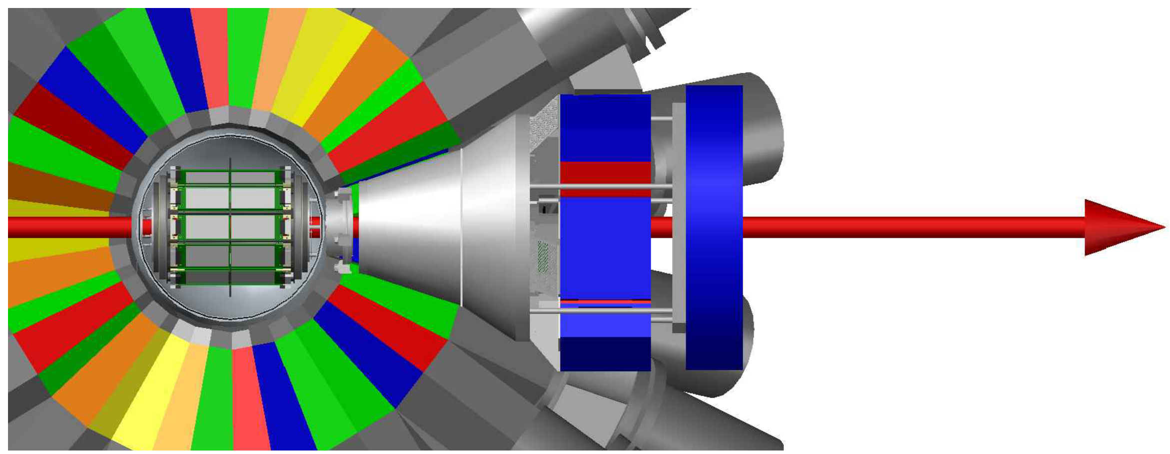
(d,pγ) can be (n,γ) surrogate

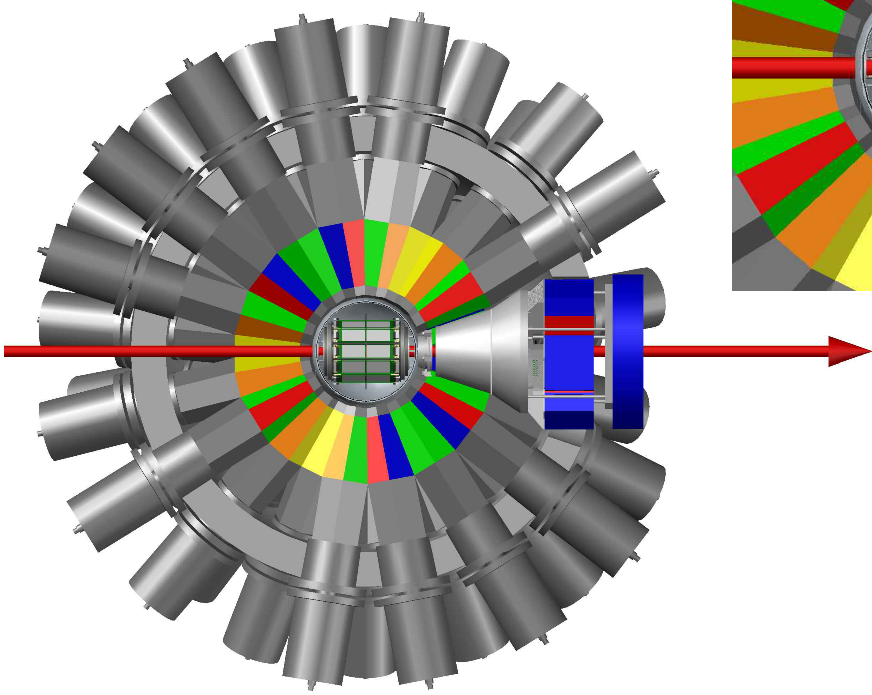
Select (d,pγ) spectra that most accurately reflect (n,γ) spin distribution

Validating (d,pγ) as (n,γ) surrogate

With ^{95}Mo target

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





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Validating (d,pγ) as (n,γ) surrogate

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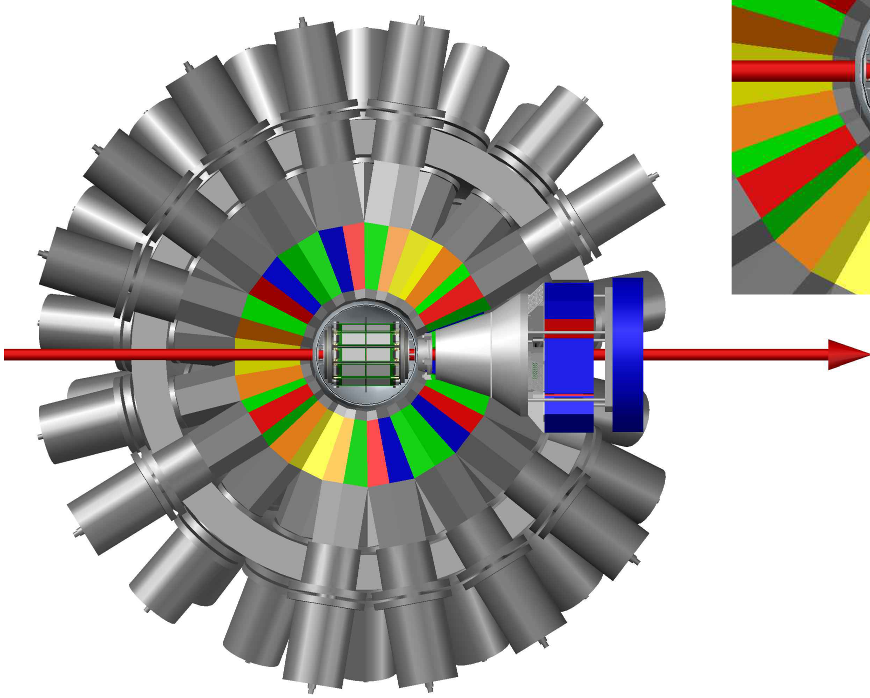
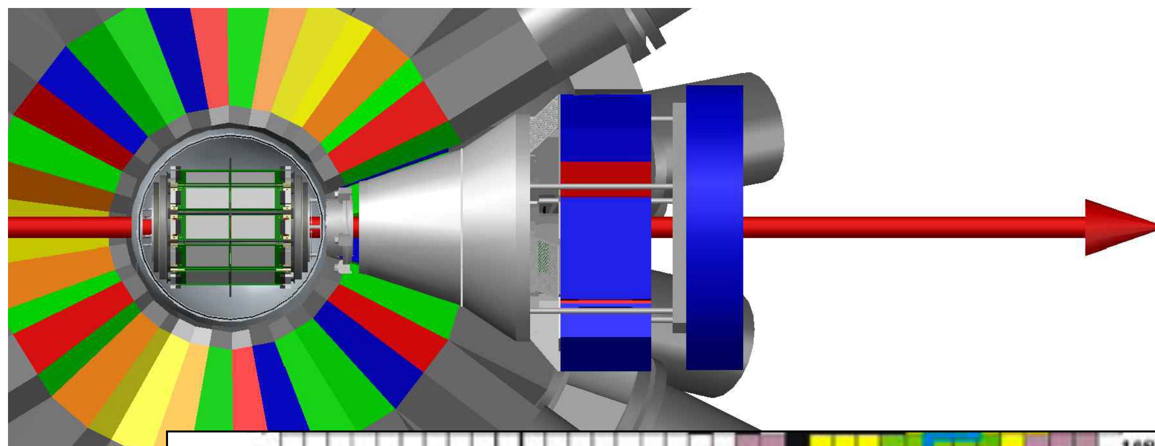
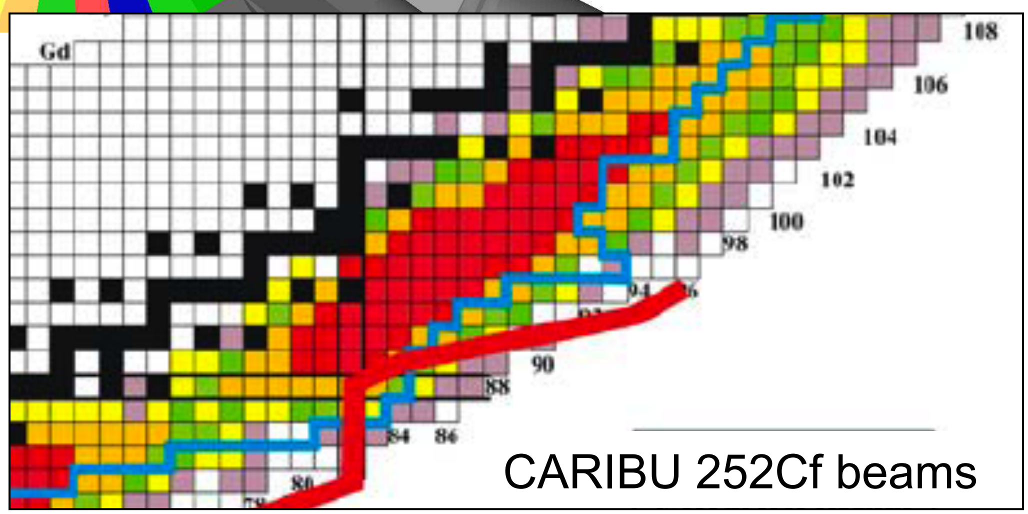
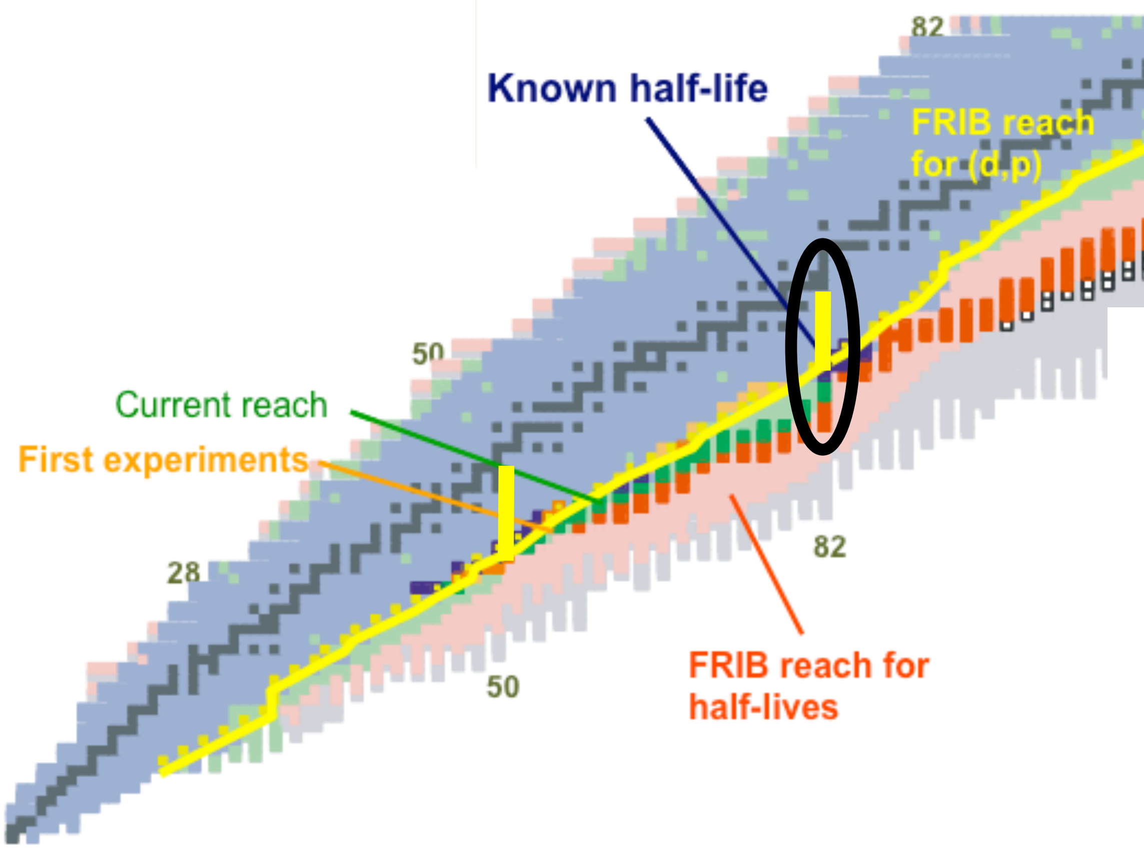




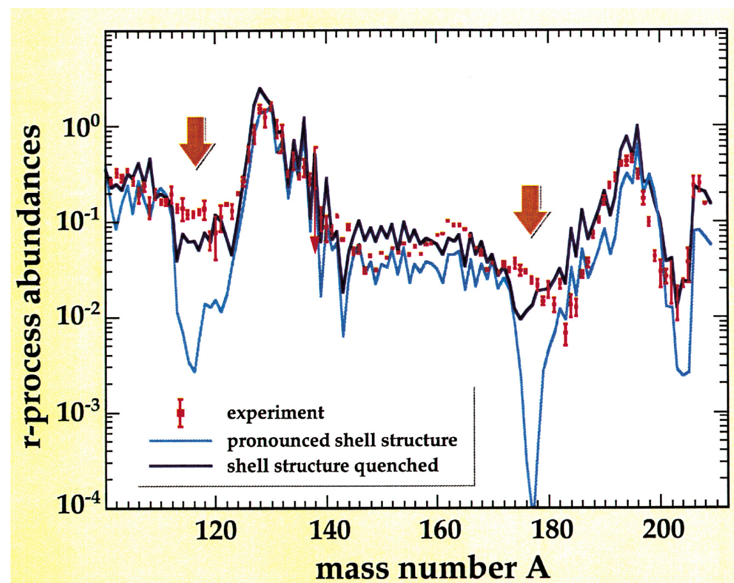


Long term prospects for probing neutron-rich nuclei near N=82 are bright

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



Neutron rich nuclei near N=82



Reference: B. Sherrill

Summary of A≈132 (d,p)

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- Measured single-neutron excitations in N=83 ^{133}Sn
  - Expected $2f_{7/2}$, $3p_{3/2}$, $3p_{1/2}$, $2f_{5/2}$ states identified with S≈1
  - ^{132}Sn is one of best examples of doubly magic nucleus
- Preliminary analysis of ^{130}Sn(d,p)
  - Sizeable, concentrated ℓ =1 strength at high excitation energies
  - Impact: direct neutron capture strength
- Recent measurements of ^{124,126,128,130,132}Sn (d,p) and (^{9}Be,^{8}Beγ)
  - Similar concentration of (tentative) ℓ=1 strength at high excitation energies
- Future
  - Additional direct (n,γ) rates via (d,p) reactions
  - Inform statistical (n,γ) components via (d,pγ) as a surrogate
- Provide nuclear physics input into r process nucleosynthesis
  - Shell structure N<50 N≈82
  - (n,γ) rates during freeze-out

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THANK YOU

Sn (d,p) and r-process nucleosynthesis

Supported by U.S. Department of Energy NNSA and Office of Nuclear Physics
and National Science Foundation

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