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THE STATE UNIVERSITY OF NEW JERSEY

Transfer reaction experiments with fission fragment beams

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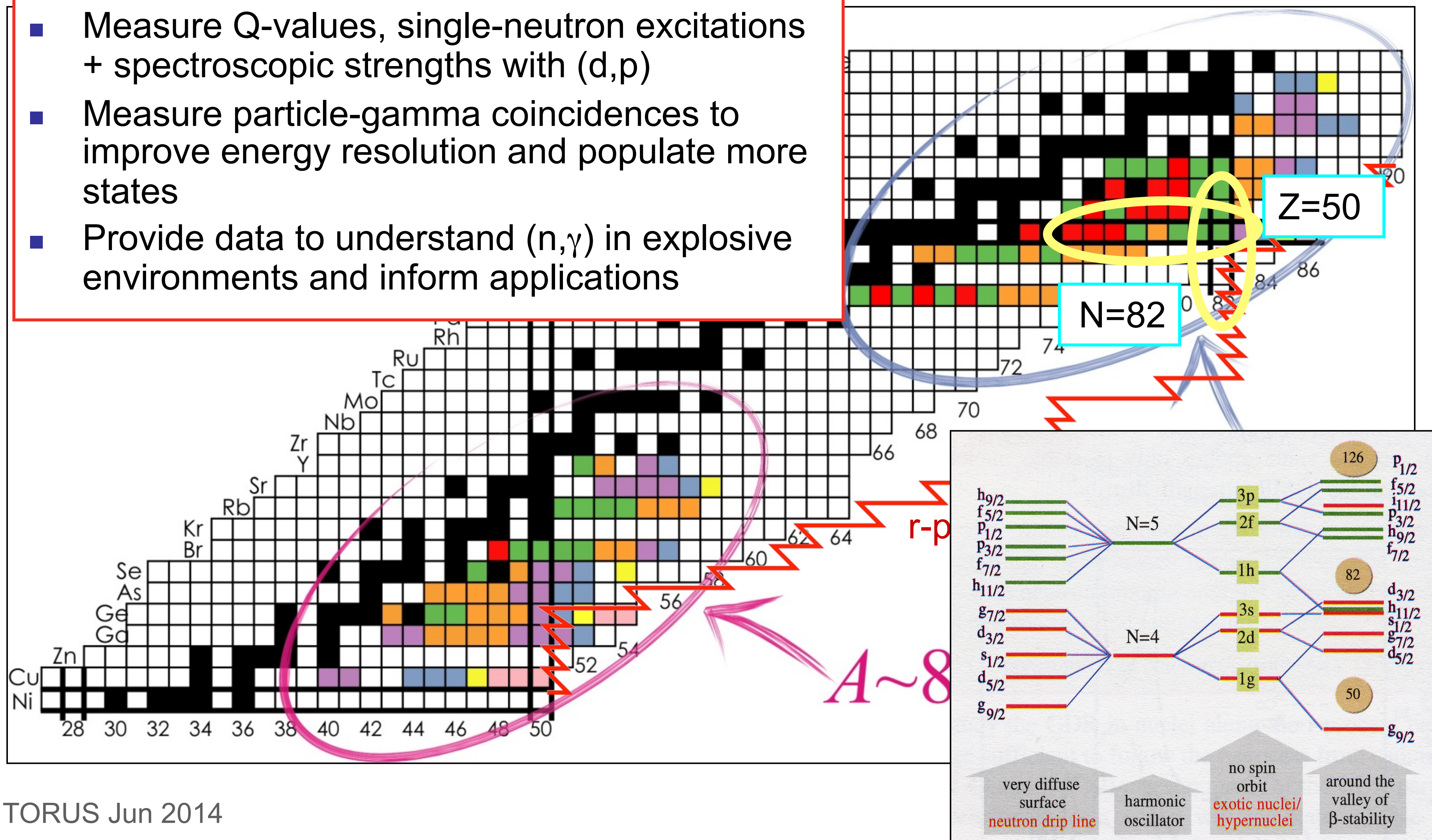
TORUS Collaboration Meeting

Michigan State University, June 2014

Neutron transfer reactions with neutron-rich nuclei

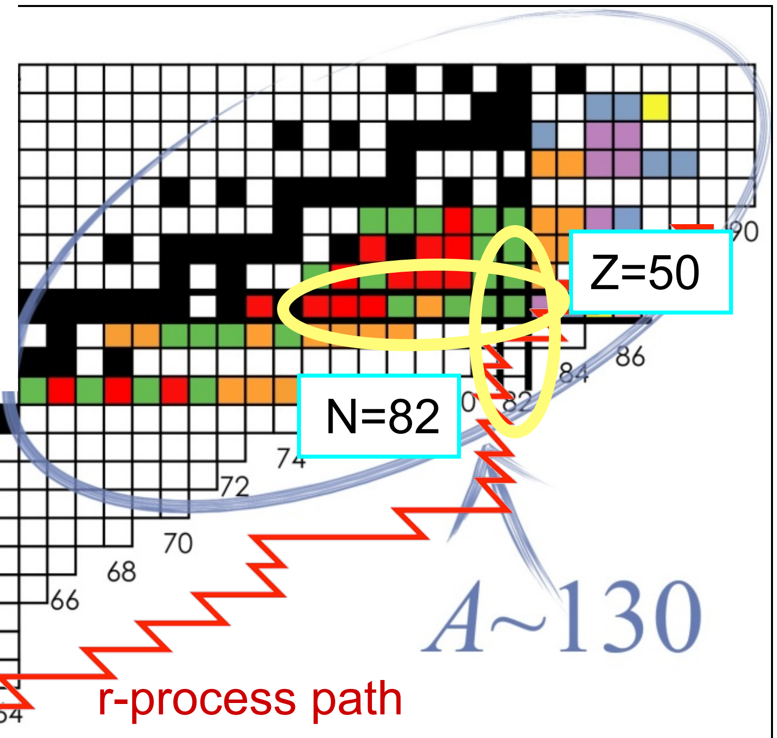
Measure (d,p) reactions with neutron-rich beams

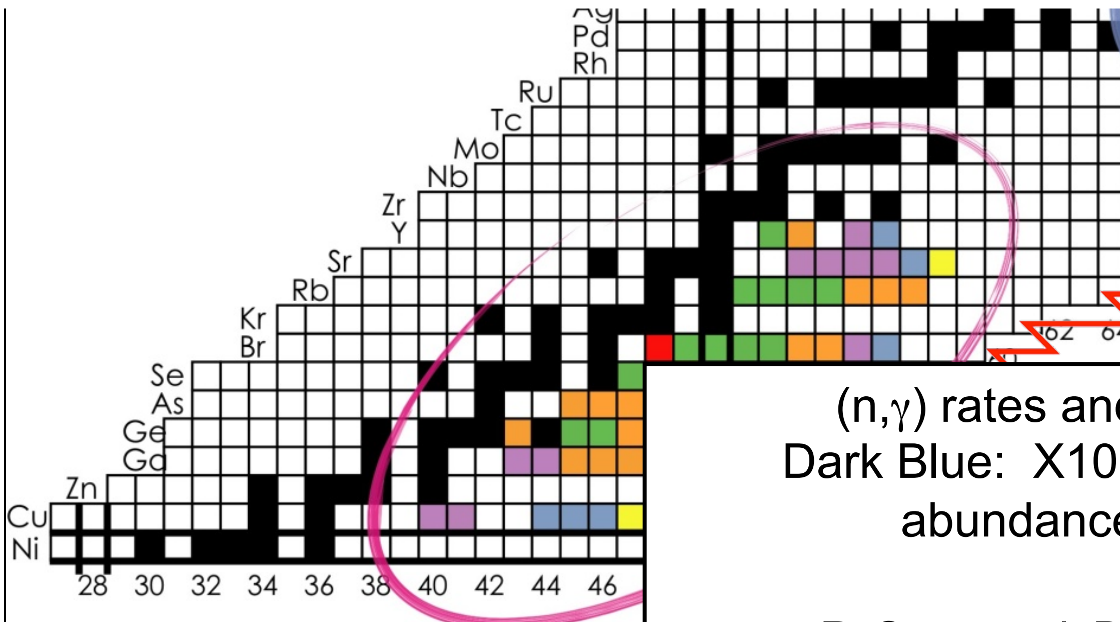
- Measure Q-values, single-neutron excitations + spectroscopic strengths with (d,p)
- Measure particle-gamma coincidences to improve energy resolution and populate more states
- Provide data to understand (n,γ) in explosive environments and inform applications



Neutron transfer reactions with neutron-rich nuclei

Z \ N	78	79	80	81	82	83	84	85	86	87
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





(n,γ) rates and r process nucleosynthesis
Dark Blue: X10 increase in (n,γ) rates change abundance patterns by at least 5%

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

A≈130 (d,p) Collaborations

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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

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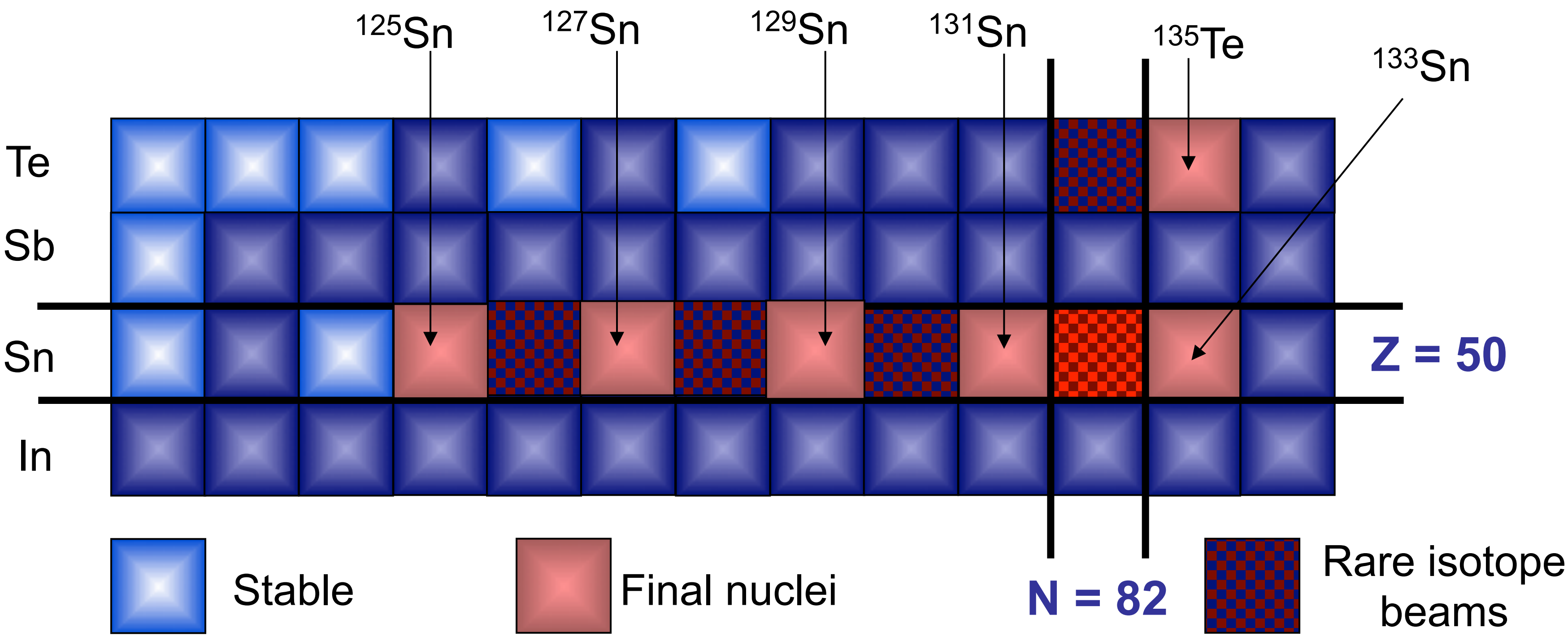
*GODDESS

RADIOACTIVE ION BEAM STUDIES FOR STEWARDSHIP SCIENCE

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}Beγ)A-1



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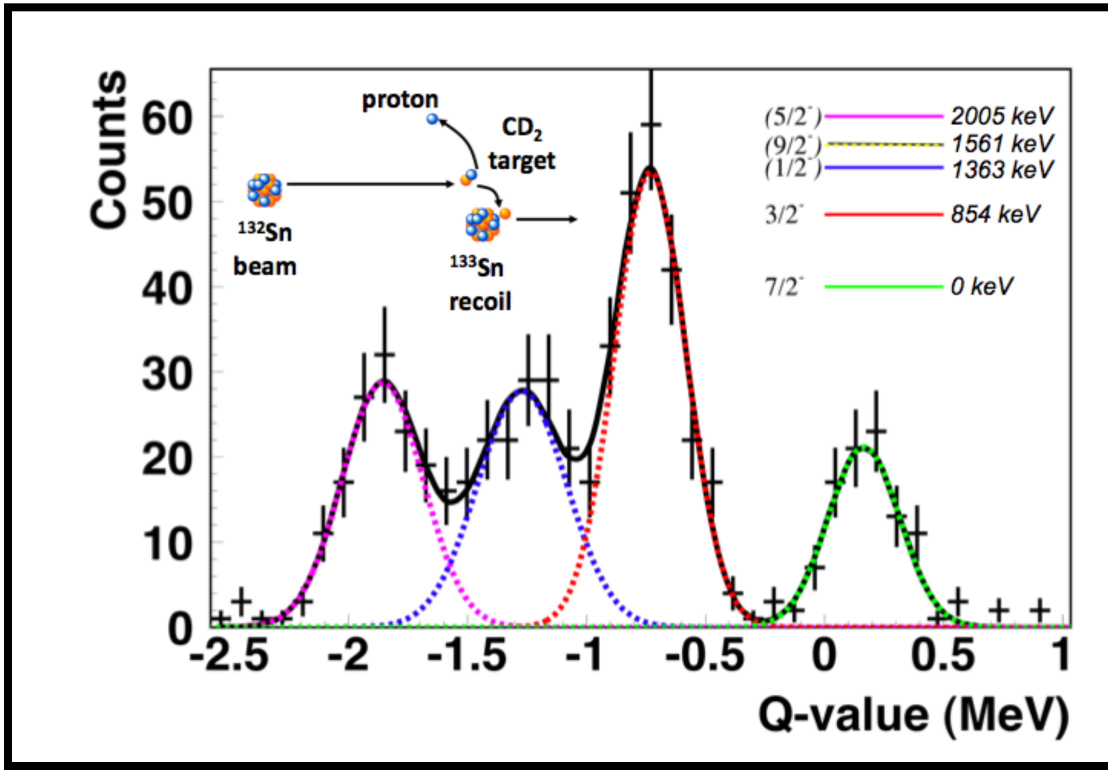
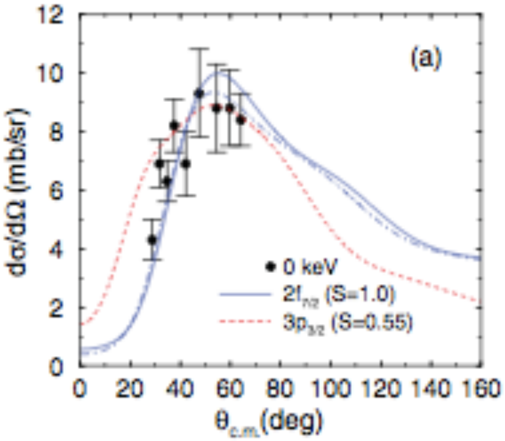
Identified $2f_{7/2}$, $3p_{3/2}$, $(3p_{1/2})$, $2f_{5/2}$ neutron strength in ^{133}Sn

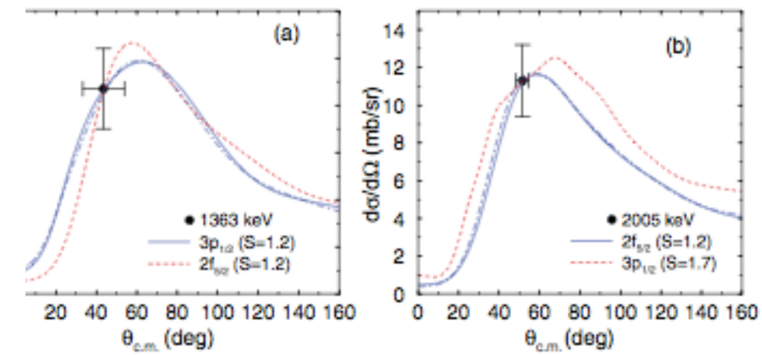
K.L. Jones et al.
Nature, **465**,454 (2010)
Phys. Rev. C **84**, 034601 (2011)



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)	$9(2)\times10^{-4}$

^{132}Sn(d,p) FR-ADWA-CH calculations





K.L. Jones, F. Nunes et al.
Phys. Rev. C **84**, 034601 (2011)

Finite-Range Adiabatic Wave Approximation

- Includes d breakup and finite range
- d from nucleon optical models
- CH (modern, global) optical model parameters

E_x(keV)	J^π	SF (DWBA)	C^2 (fm^{-1})	SF (FR-ADWA)	C^2 (fm^{-1})
0	$7/2^-$	0.86(14)	0.64(10)	1.00(8)	0.82(7)
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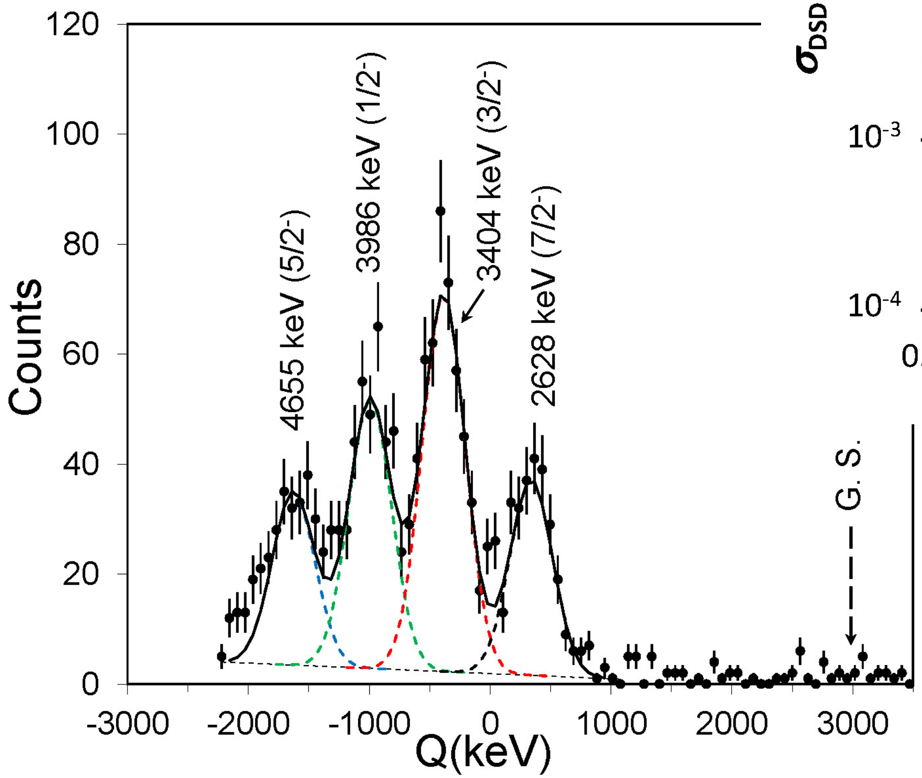
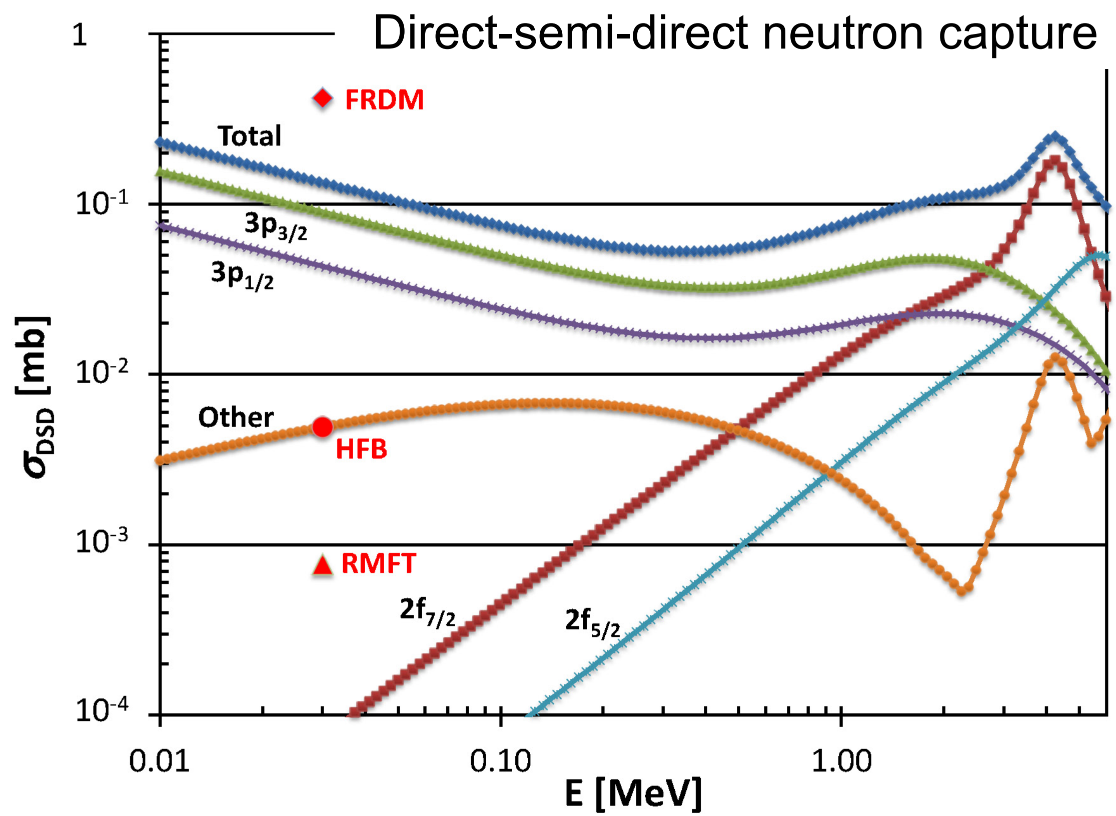
1363(31)	$(1/2^-)$	1.1(3)	2.6(4)	1.2(2)	2.9(6)
2005	$(5/2^-)$	1.1(2)	$9(2)\times10^{-4}$	1.2(3)	$1.2(3)\times10^{-4}$

$^{130}Sn(d,p)$ and direct-semi-direct neutron capture





R.L. Kozub, G. Arbanas et al. PRL **109**, 172501 (2012)

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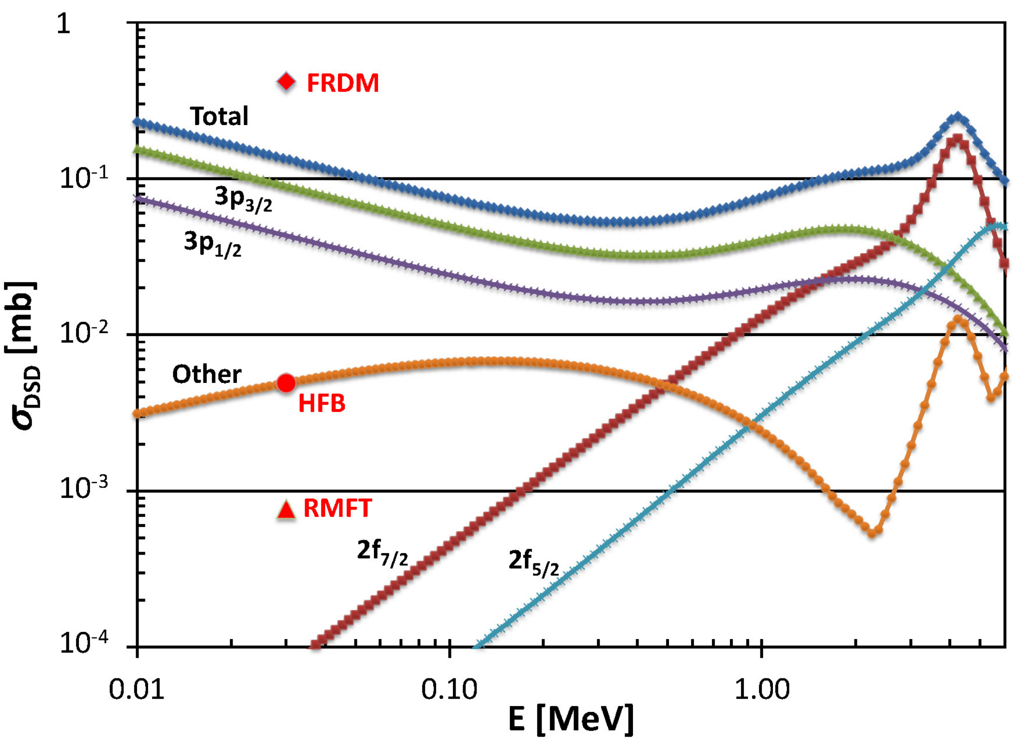
Direct-semi-direct neutron capture calculations

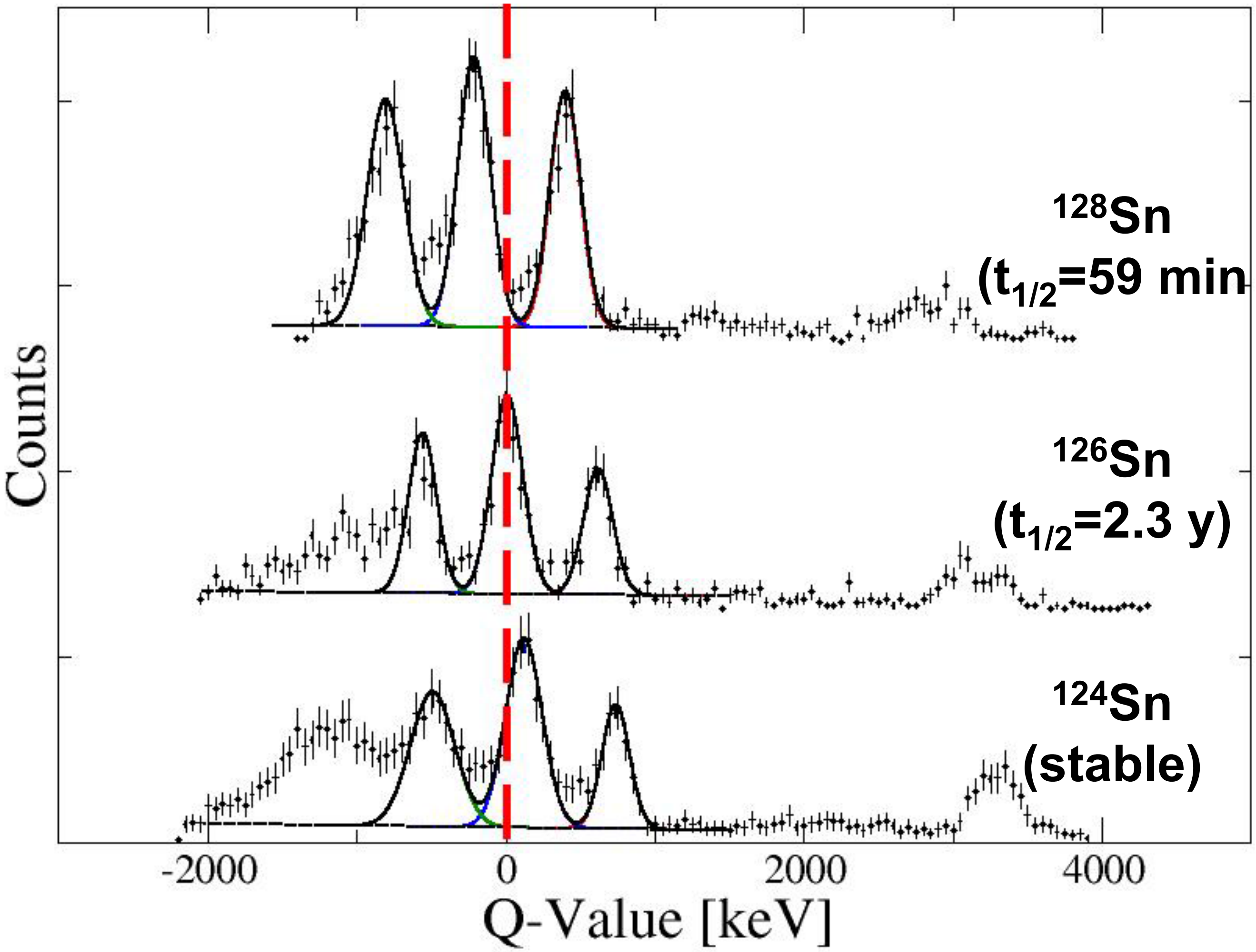
Direct semi-direct direct capture with CUPIDO

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

R.L. Kozub, G. Arbanas et al. PRL **109**, 172501 (2012)



$^{124,126,128}Sn(d,p)$



B. Manning, in preparation

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$^{132,130,128,126,124}Sn(d,p)$ systematics

!!! Preliminary !!!

	$2f_{7/2}$ E_x (MeV)	SF	$3p_{3/2}$ E_x (MeV)	SF	$3p_{1/2}$ E_x (MeV)	SF
$^{132}Sn(d,p)$	0.00	1.00	0.854	0.92	1.36	1.3
$^{130}Sn(d,p)$	2.63	0.95	3.40	0.55	3.99	0.85
$^{128}Sn(d,p)$	2.67	0.68	3.29	0.26	3.84	0.42
$^{126}Sn(d,p)$	2.65	0.54	3.30	0.27	3.89	0.49
$^{124}Sn(d,p)$	2.76	0.39	3.39	0.29	4.10	0.42

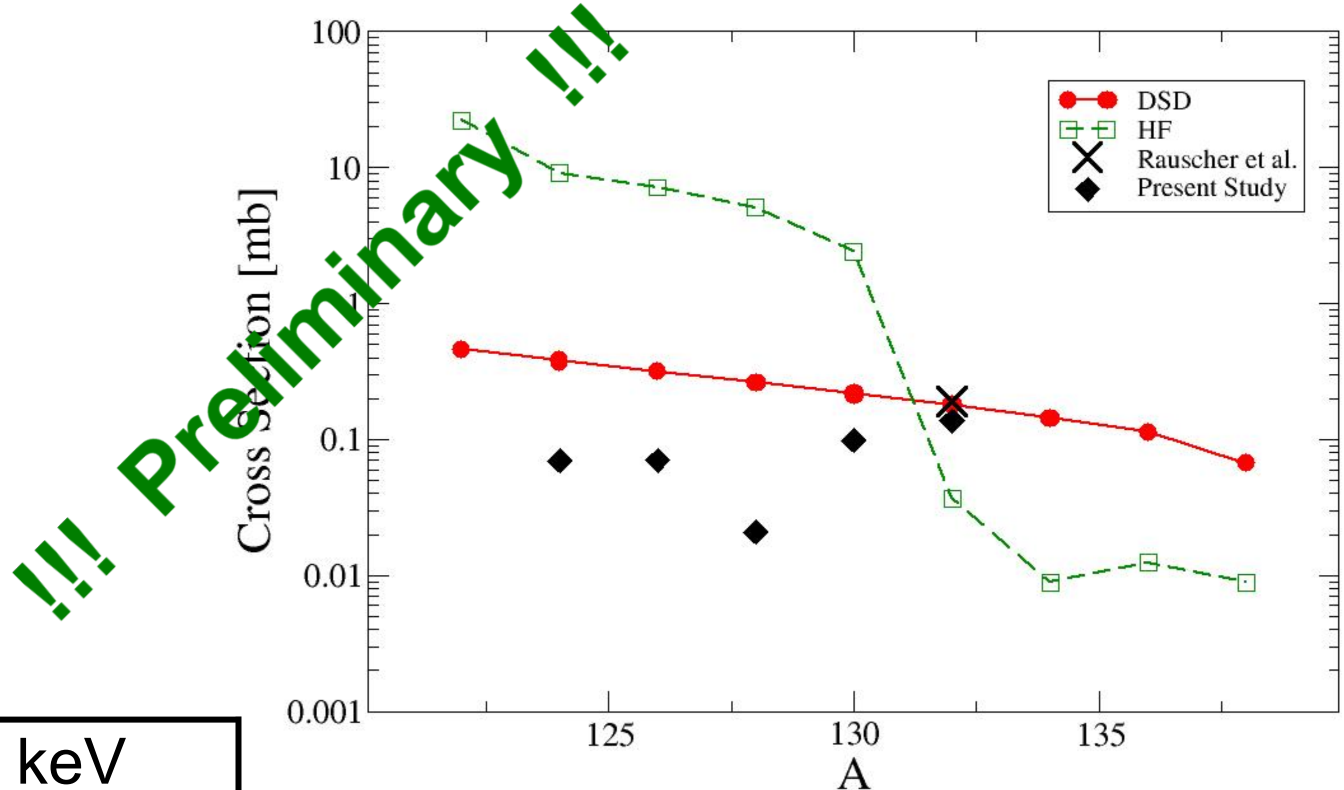
Uncertainties ≈ 30% for all spectroscopic factors

Same reaction theory & Optical Model:

- Finite-Range Adiabatic Wave Approximation
- Chapel Hill 89 Optical Model Parameters

B. Manning, in preparation

^{132,130,128,126,124}Sn DSD (n,γ)



	30 keV σ(n,γ) (μb)
^{132}Sn(d,p)	137
^{130}Sn(d,p)	98
^{128}Sn(d,p)	21
^{126}Sn(d,p)	70
^{124}Sn(d,p)	70

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

B. Manning, in preparation

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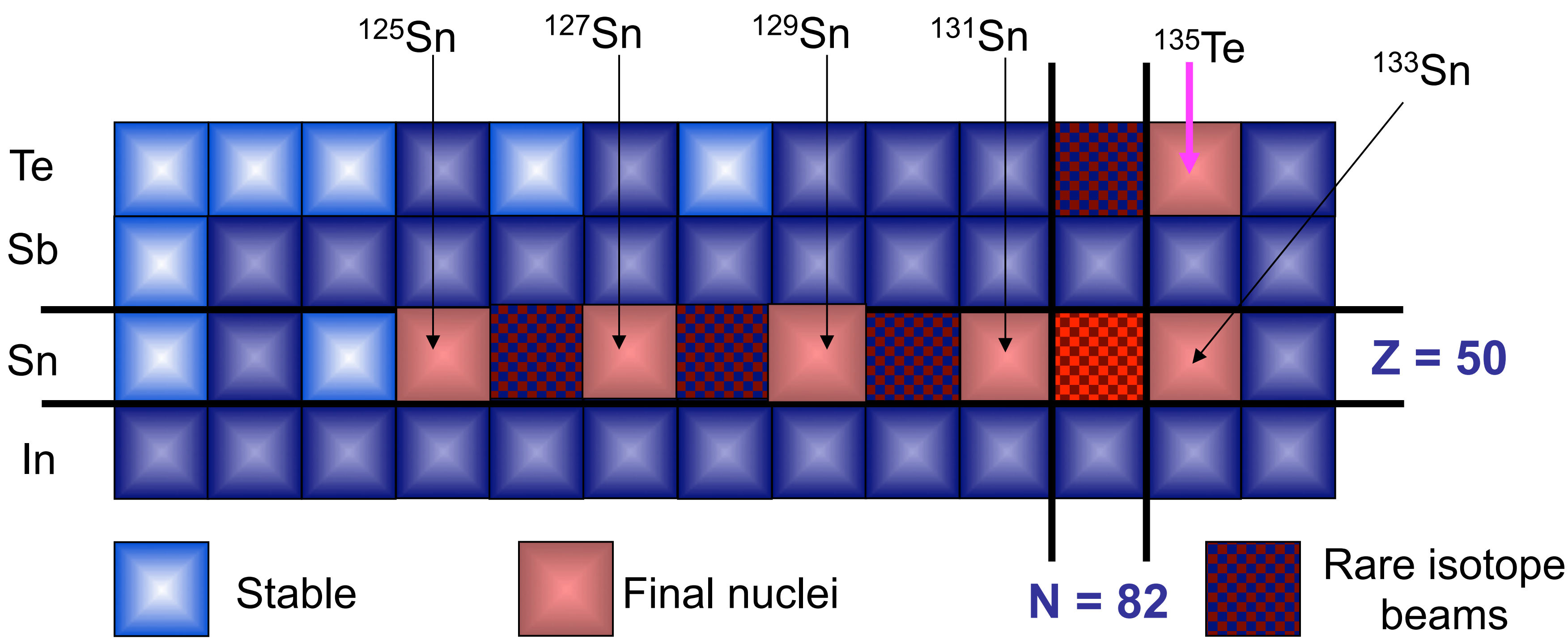
Summary of previous studies

- Measured (d,p) with Sn beams
  - Extracted E_x, spectroscopic factors, ANCs, DSD (n,γ)
    - "state of the art" FR-ADWA reaction model with global optical model parameters
    - CUPIDO to extract direct-semi-direct neutron capture cross sections
      - Incident channel: Koning Delaroche potential
      - Bound state: Bear Hodgson potential
      - Experimental SF and E_x constrained the model
  - Questions for theorists
    - How robust are reaction model(s)?
    - How robust are optical model parameterization (especially when weakly bound)?
    - How robust are DSD calculations?
    - How model fragmentation of s.p. strength?
- Next steps for experiment
  - Beyond ^{132}Sn
  - Surrogate for compound nucleus (n,γ)

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}Beγ)A-1



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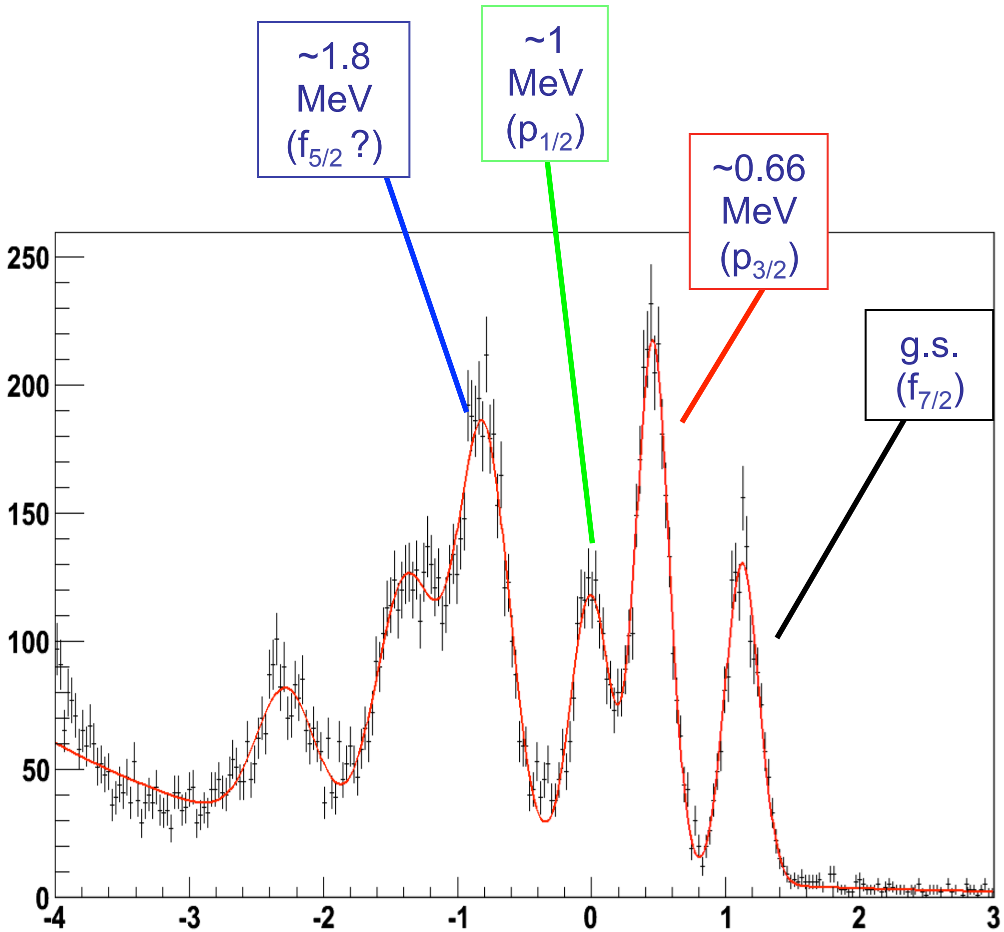
^{134}Te(d,p) to N=83 ^{135}Te

PRELIMINARY



S.D. Pain et al.

Considerable fragmentation of strength E_x>1.8 MeV

RUTGERS Particle-gamma coincidence studies are powerful

- Improved energy resolution
  - Use particle-gamma gating techniques to improve energy resolution of excitations
  - Gamma-ray energy resolution 6-10 keV at 1 MeV (after Doppler correction)
- Additional spectroscopy
  - Levels populated in gamma decay not directly populated in (d,p)
- Surrogate (n,γ) reactions – require gamma-ray measurements in coincidence with reaction particles
- (Lifetime measurements – backed targets)

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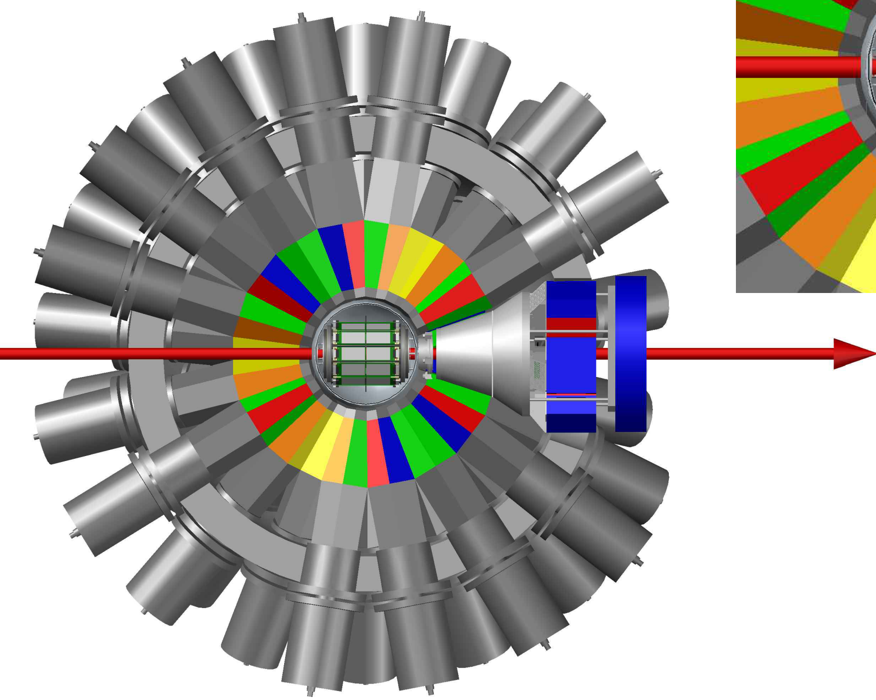
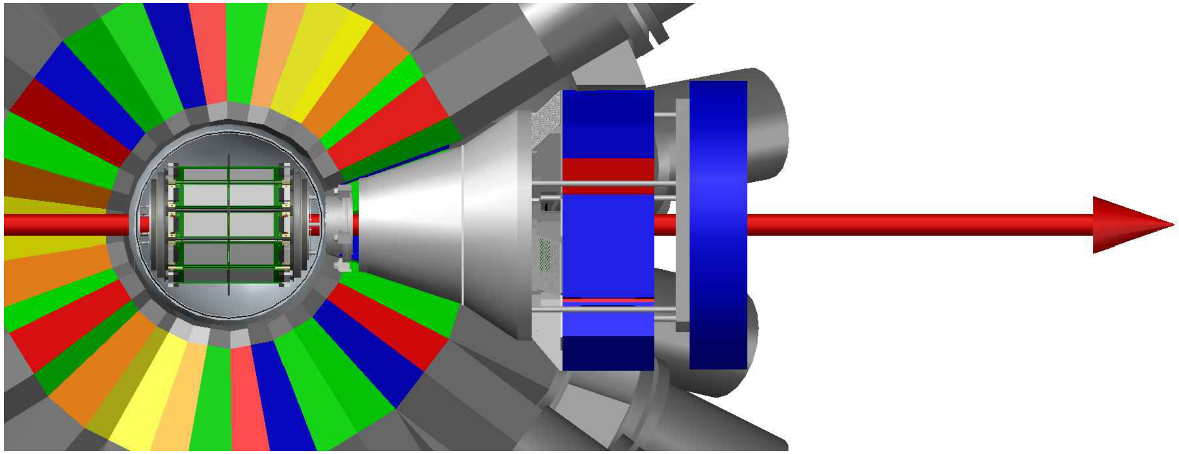
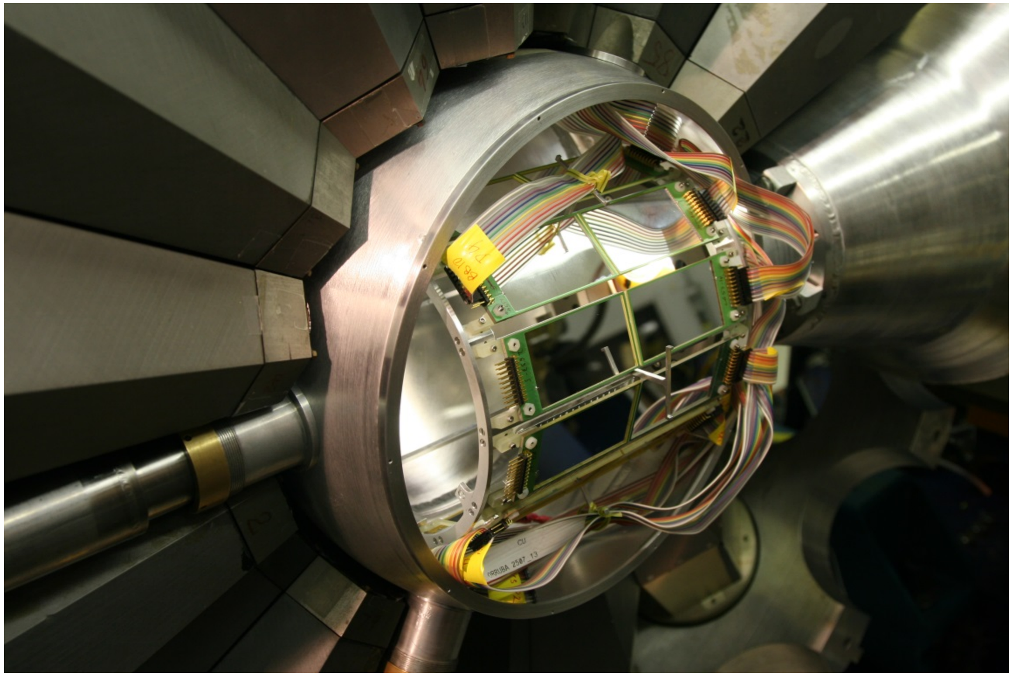
Particle-gamma coincidences
With Gammasphere and ORRUBA

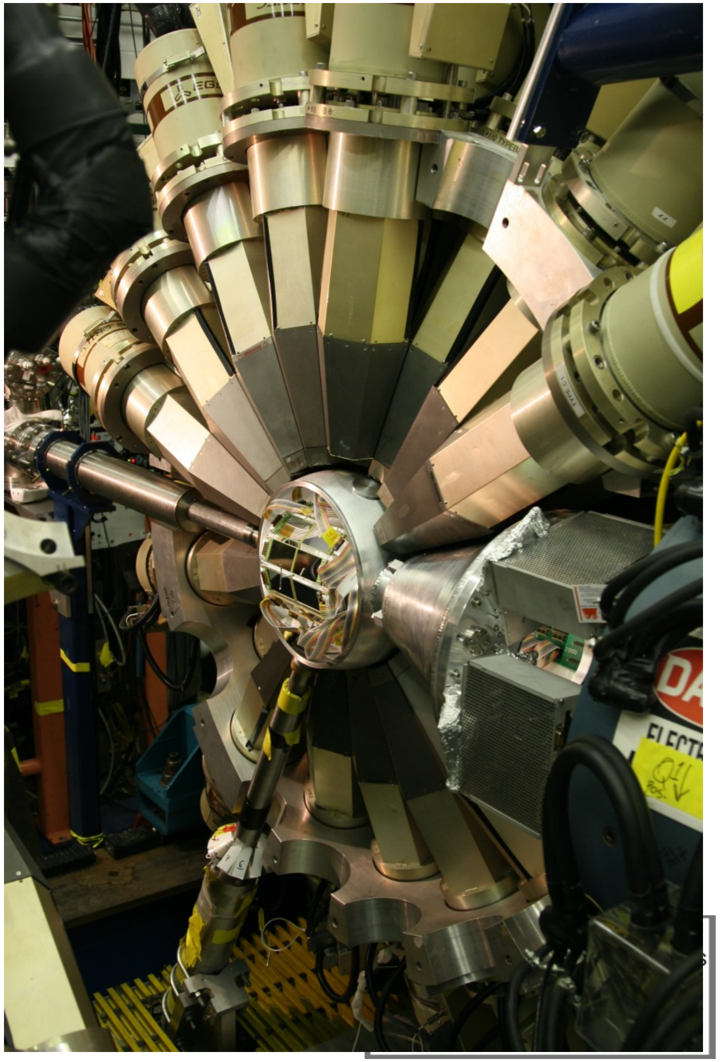
- Development of (d,pγ) in inverse kinematics (with RIBs)
  - Coupling Si strip detector array ORRUBA + endcaps to Gammasphere





GODDESS: Gammasphere ORRUBA Dual Detectors for Experimental Structure Studies

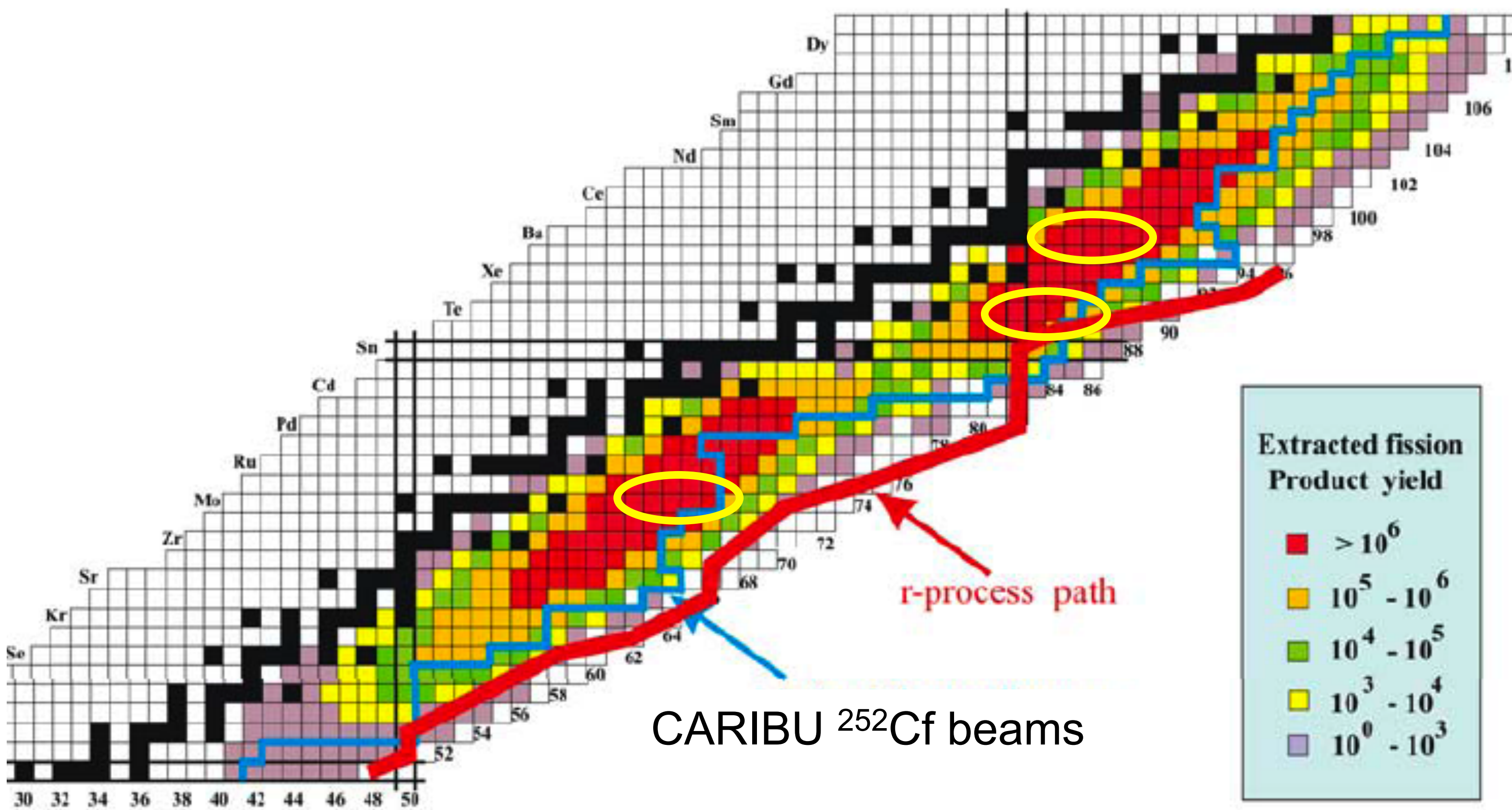




S.D. Pain, A. Ratkiewicz, et al.

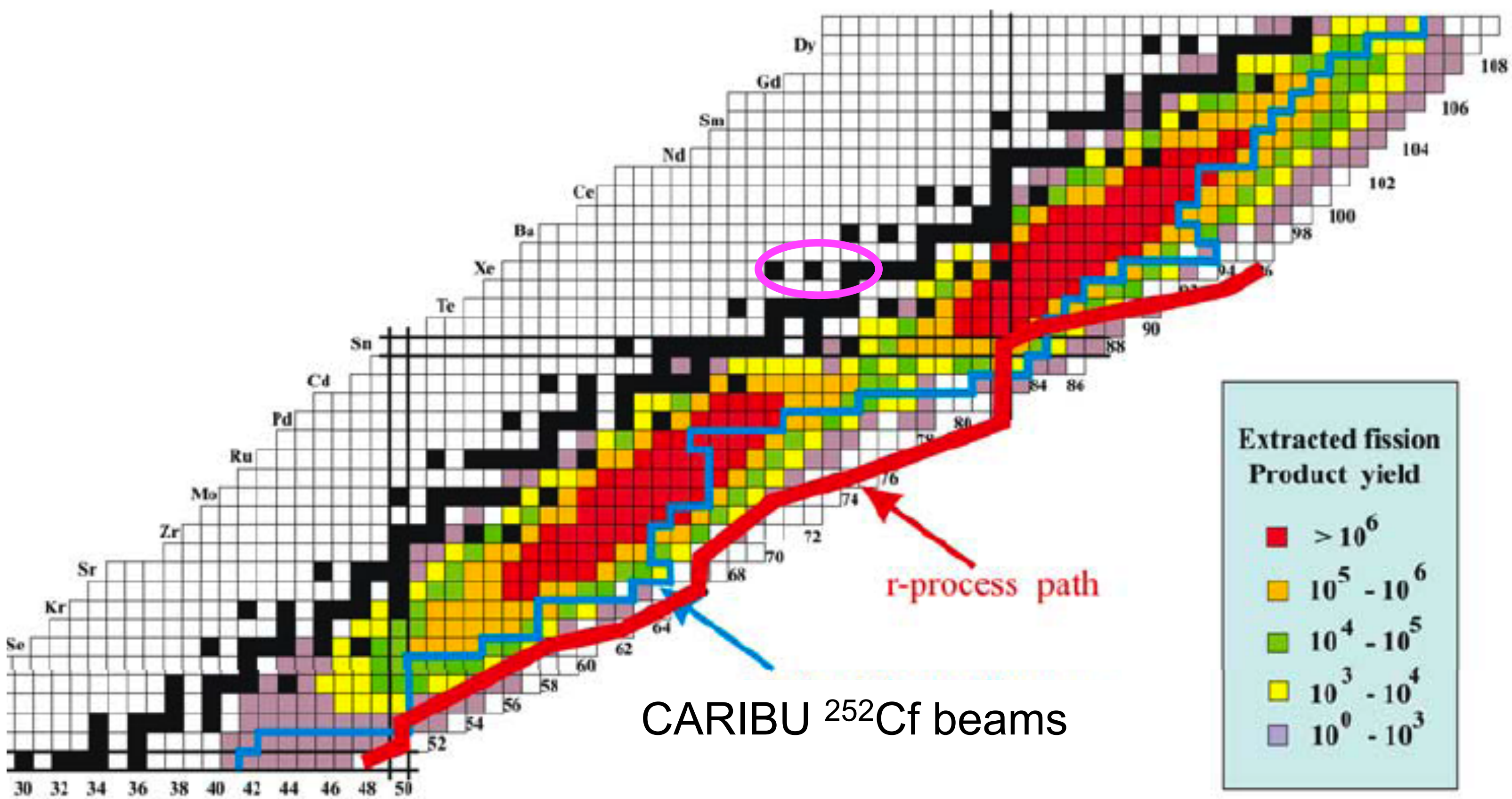
Future ATLAS beams & ORRUBA + Gammasphere

- Heavy and light ^{252}Cf fission fragments
  - ^{134}Te(d,pγ) N=82 fragmentation of s.p. strength - approved
  - ^{137}Te(d,pγ) to test (n,γ) rates for r-process nucleosynthesis
  - $^{142-144}$Ba(d,pγ) to study microscopic components of octupole collectivity
  - $^{104-106}$Mo(d,pγ) to study microscopic components of non-axial collectivity

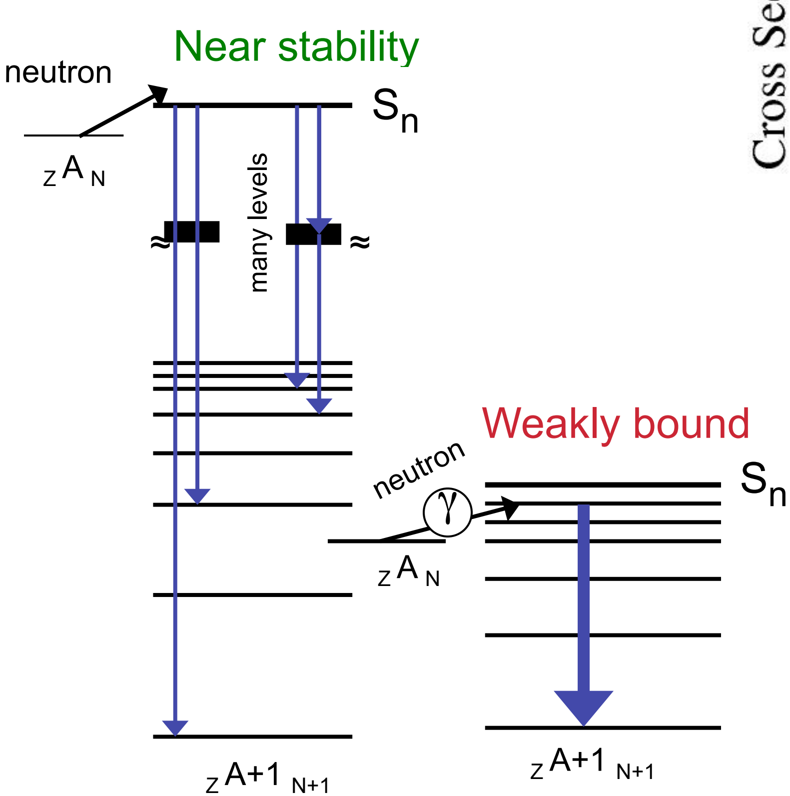


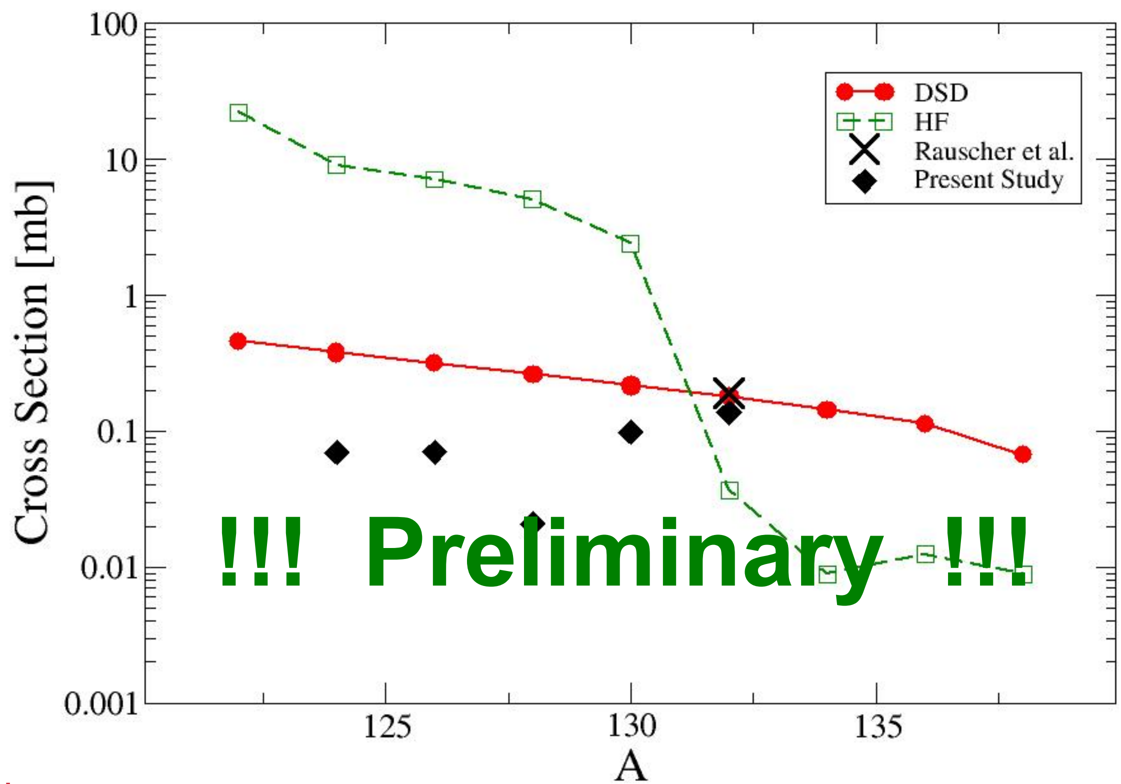
Future ATLAS beams & ORRUBA + Gammasphere

- Nuclear structure studies with noble gas beams
  - $^{124-128}$Xe(d,pγ) nature of collectivity in transitional nuclei



^{132,130,128,126,124}Sn (n,γ)?





Sn(n,γ) vs A

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

DSD from exp: G. Arbanas, B. Manning

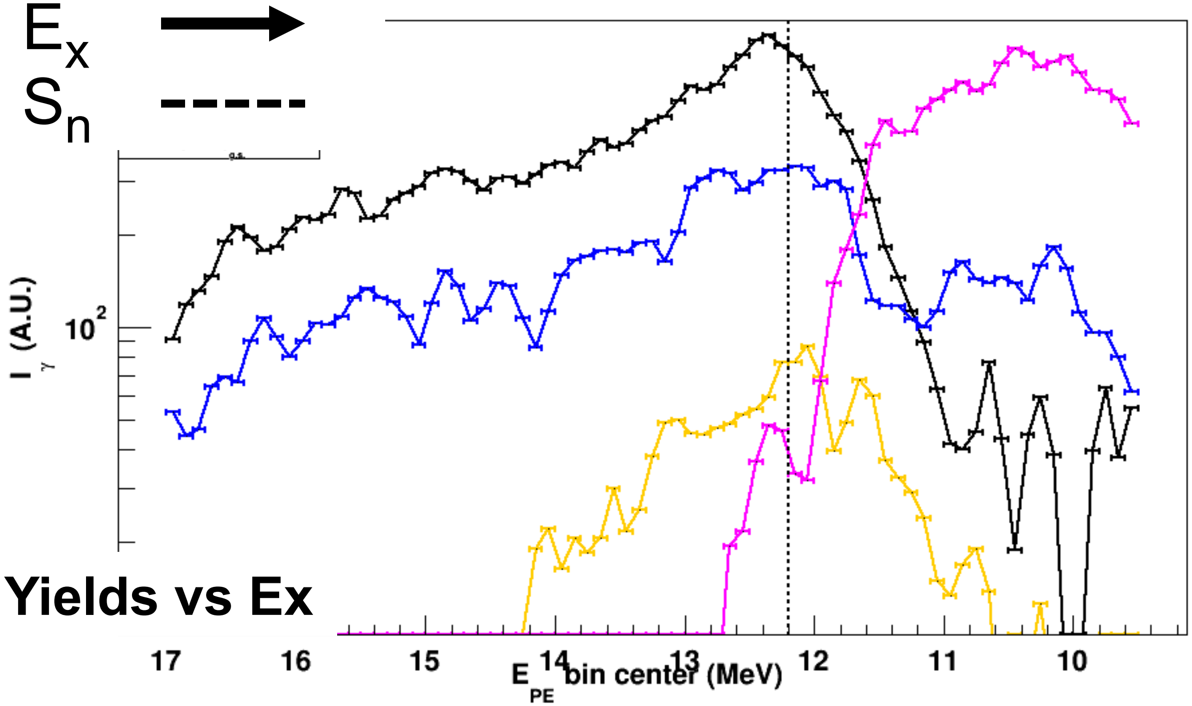
Validating (d,pγ) as (n,γ) surrogate

- Chose nucleus where σ(n,γ) is known to E_n≈200 keV
  - Odd-N, even-Z => final is even-even & collective (but not deformed)
- Validating surrogate method for σ(n,γ) on ^{95}Mo
  - σ(n,γ) measured by Musgrove et al., NPA **270**, 109 (1976)
- Understand ^{95}Mo(d,p) reaction mechanism: (d,p) to low-lying excitations
- Intensity of discrete ^{96}Mo lines vs E_n to deduce surrogate cross sections
  - Measure (n,γ) – analysis in progress
  - Measure (d,pγ) normal kinematics – analysis in progress
  - Measure (d,pγ) inverse kinematics – experiment approved
- Calculate σ(n,γ) from (n,γ) and (d,pγ) surrogate studies
- Multiplicity of γ transitions OR statistical γ's in ^{96}Mo vs E_n
  - DANCE ^{95}Mo(n,γ) archival data – analysis in progress
  - Gammasphere w/out hevimet collimators (d,pγ)
  - Calculate σ(n,γ) using multiplicity?
  - Calculate σ(n,γ) from pattern of statistical transitions?

^{95}Mo(d,pγ) - preliminary results

E_x →

S_n - - - - -



Surrogates

^{95}Mo(n,γ)^{96}Mo

— $2^+ \rightarrow 0^+$

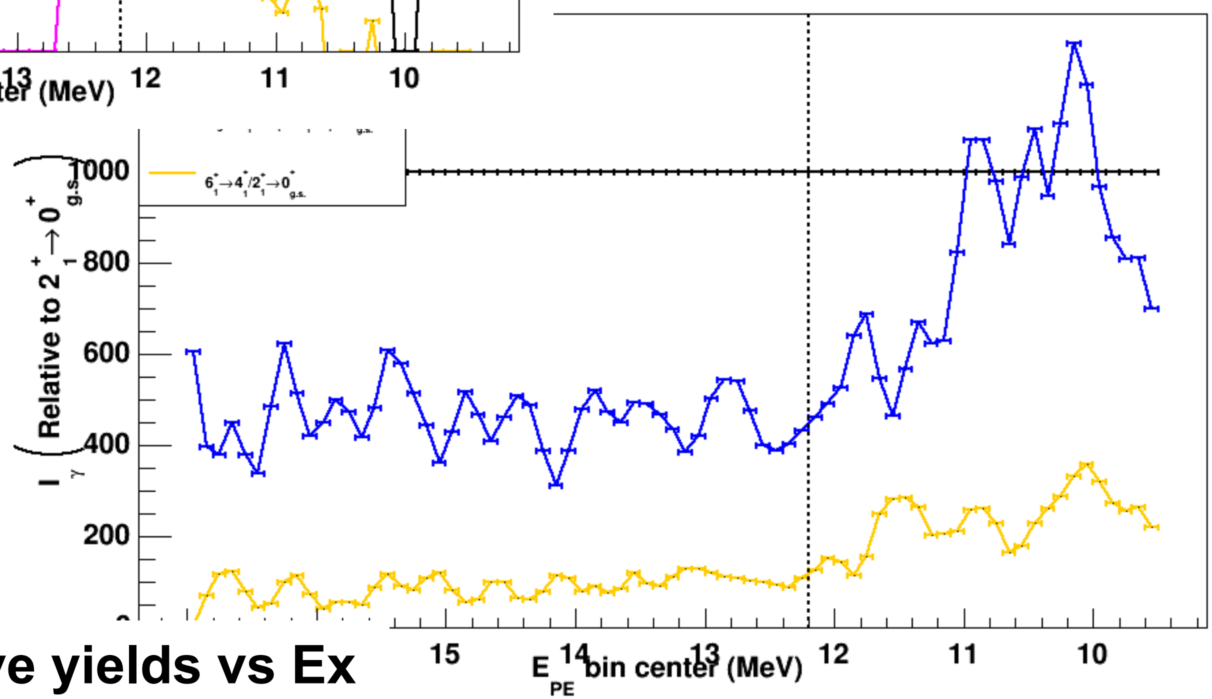
— $4^+ \rightarrow 2^+$ & $2_{(3)}^+ \rightarrow 2^+$

— $6^+ \rightarrow 4^+$

^{95}Mo(n,n')^{95}Mo

— $1/2^+ \rightarrow 5/2^+$ (gs)

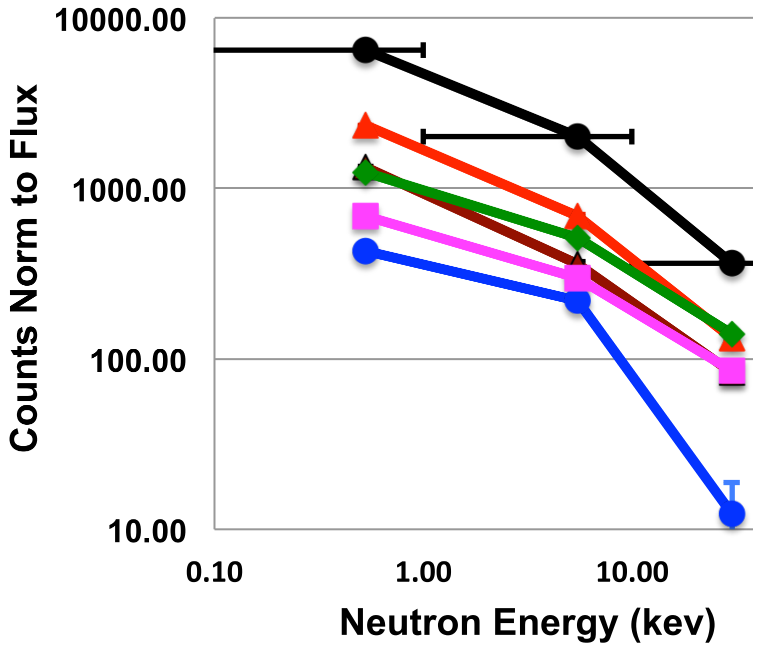
Yields vs Ex



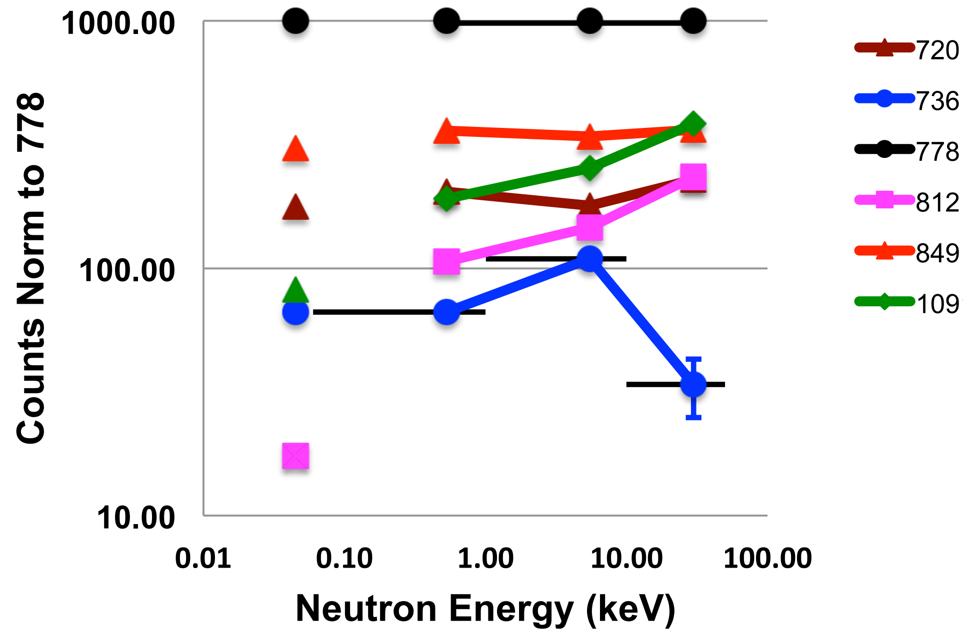
Relative yields vs Ex

^{95}Mo(n,γ) - preliminary results

Absolute yields



Yields relative to 778 keV



^{95}Mo(n,γ)^{96}Mo

- $2^+ \rightarrow 0^+$ (black)
- $4^+ \rightarrow 2^+$ & $2_{(3)}^+ \rightarrow 2^+$ (red)
- $6^+ \rightarrow 4^+$ (magenta)

Preliminary results

- ^{95}Mo(n,γ) E_n<100 keV

In progress

- ^{95}Mo+n E_n>150 keV

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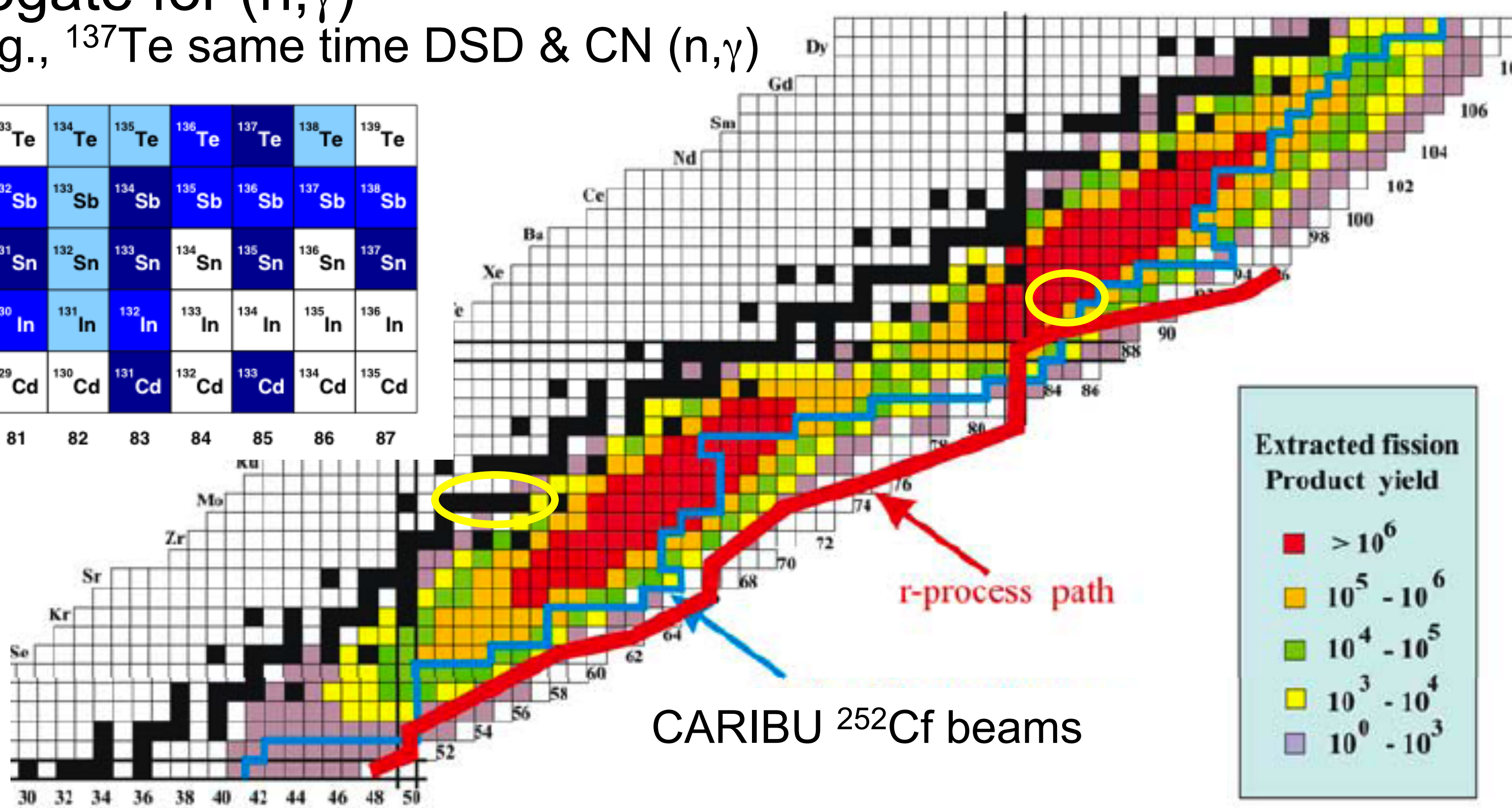
Future ATLAS beams & ORRUBA + Gammasphere

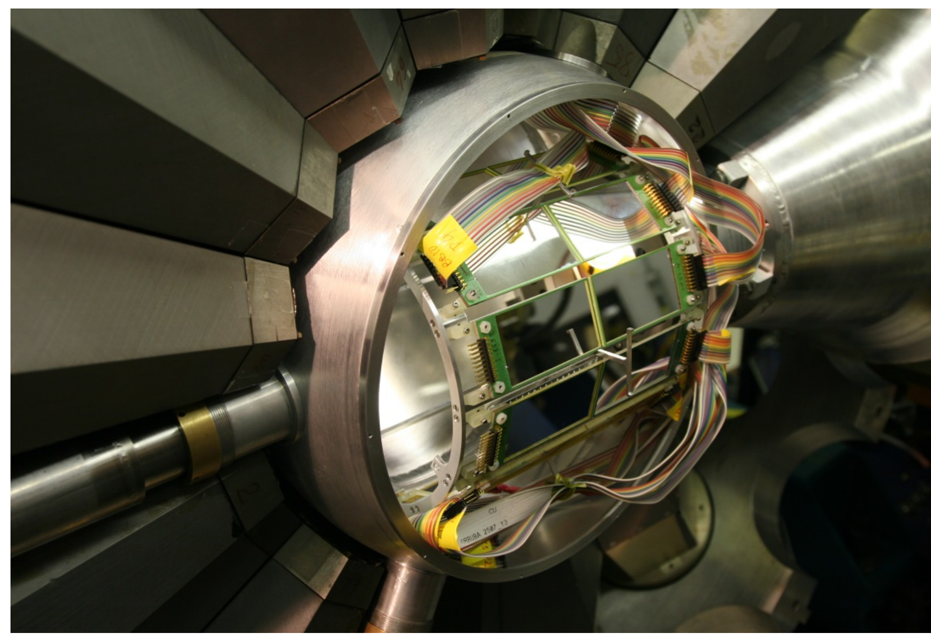
- Validating (d,pγ) as surrogate for (n,γ)
  - ^{95}Mo(d,pγ) inverse kinematics & compared to actual 95Mo(n,γ)
- Future: any (d,pγ) measurement w/ GODDESS will provide surrogate for (n,γ)
  - E.g., ^{137}Te same time DSD & CN (n,γ)

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



Summary of (d,p) future studies

- Extracting spectroscopic factors
  - Requires state of the art nuclear reaction theory
    - Deuteron breakup
    - Optical model parameters
  - Measuring elastic scattering as well as transfer
  - Constrains direct-semi-direct capture cross sections
- Surrogate for (n,γ)
  - Complete validation
    - Discrete, statistical, multiplicity γ
  - (n,γ) cross sections
    - r-process nucleosynthesis
    - Nuclear energy applications
    - National security applications
- Nuclear structure studies
  - Near closed shells
  - Transitional nuclei
  - Triaxial nuclei
  - Octupole collectivity



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Transfer reaction experiments with fission fragment beams

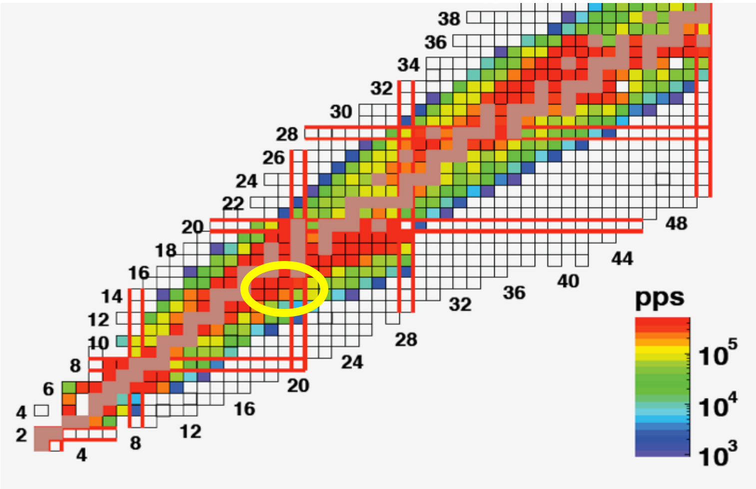
THANK YOU

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

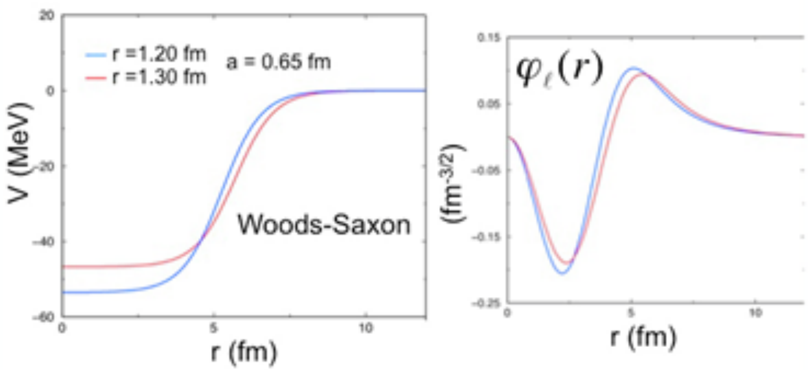
Extra Slides

Other reaction studies

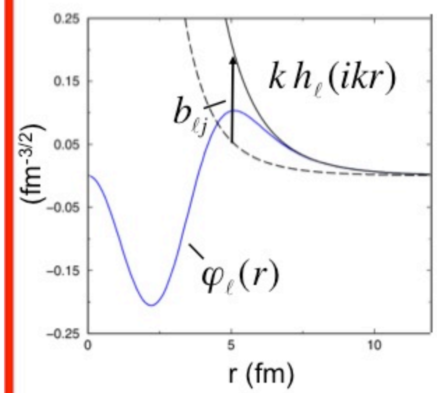
- Reducing ambiguities in spectroscopic factors
  - ^{86}Kr(d,p) at 35 MeV/u complete
  - ^{86}Kr(d,p) at 5.5 MeV/u extracting ANCs from published data
  - Propose to study ^{84}Se(d,p) at 35 MeV/u
  - ^{84}Se(d,p) at 4 MeV published and ANCs extracted
- Neutron detection studies near the Coulomb barrier
  - ^{7}Be(d,n) @ Notre Dame (Jones) May 2014
  - ^{17}F(d,n) @ Notre Dame (Bardayan) May 2014
  - ^{19}F(α,n) @ Notre Dame (Peters)
  - ^{19}F(α,n) @ ORNL (Peters) Summer 2014
  - ^{16}C(p,n) @ NSCL (Zegers) Summer 2014
- ^{56}Ni(d,n) with fast beams (Peters)
- (α,p), (^{3}He,d) studies
  with JENSA and ReA3 beams



Probing nuclear structure with (d,p) reactions



Left: Potential as a function of radius for 2 different values of radius.
Right: Wave function as a function of radius for different values of radius.



Peripheral reaction: only probe tail of WF
Shape of asymptotic part of WF determined by binding energy (through k)

$$\varphi_\ell(r) \to b_{\ell j}\, k\, h_\ell(ikr)$$

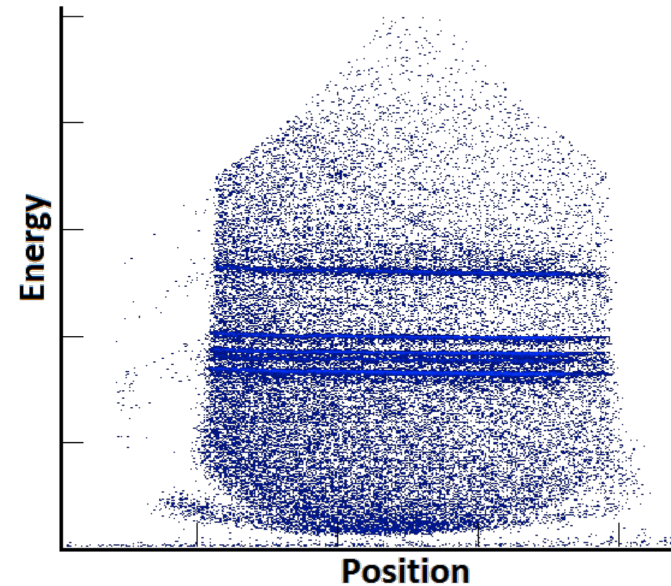
Change in geometry is change in $b_{\ell j}$

Asymptotically:

$$I^B_{An} \to C_{\ell j}\, k h_\ell(ikr) = S^{1/2}_{\ell j}\, b_{\ell j}\, k h_\ell(ikr)$$

$$C^2_{\ell j} = S_{\ell j}\, b^2_{\ell j}$$

- Use peripheral reactions at low beam energy to accurately determine asymptotic normalization coefficient (ANC), Clj – archival data
- Use higher energies to probe deeper into the nucleus and combine with low energy measurements (Clj) to provide constraints on single particle ANC, blj – under analysis
- Extract spectroscopic factor with uncertainties dominated by cross-section uncertainties from experimental statistics rather than uncertainties in the bound state wave function



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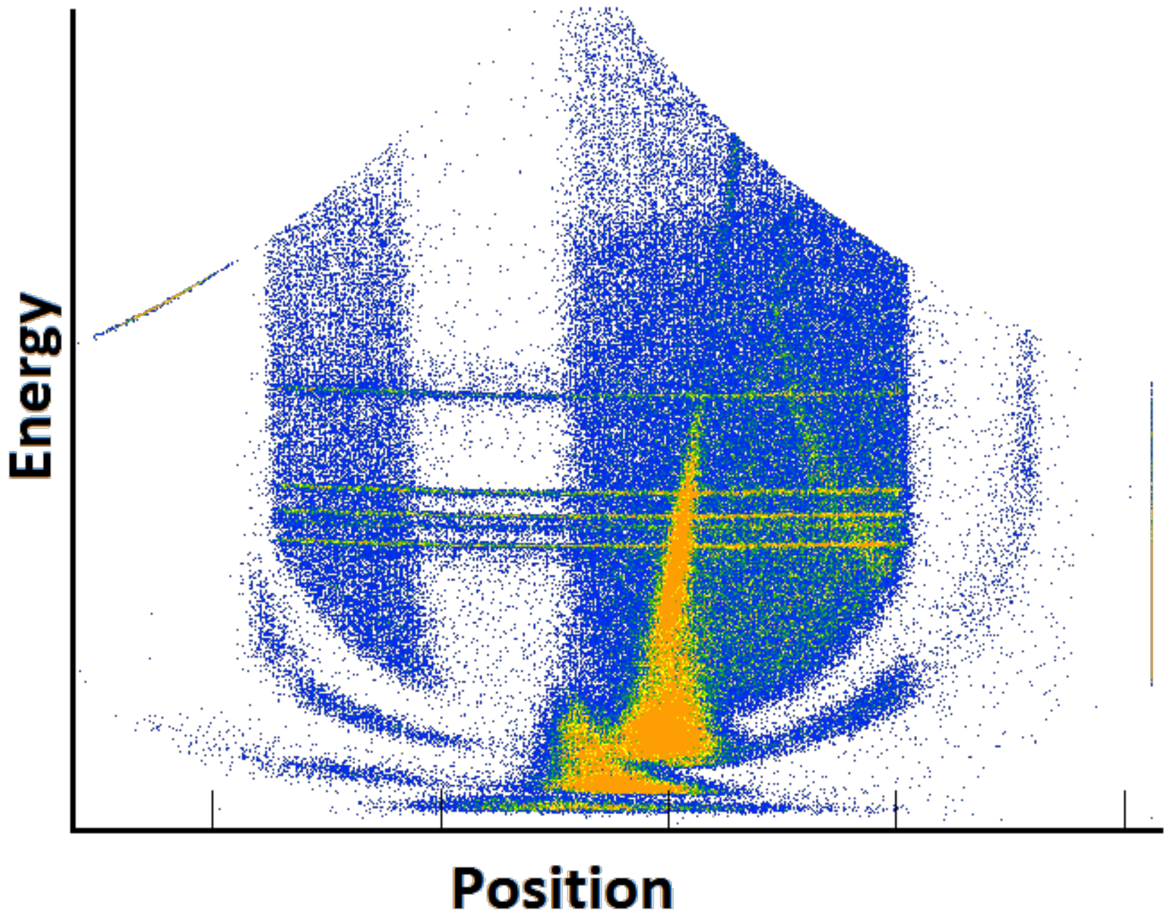
Preliminary Data

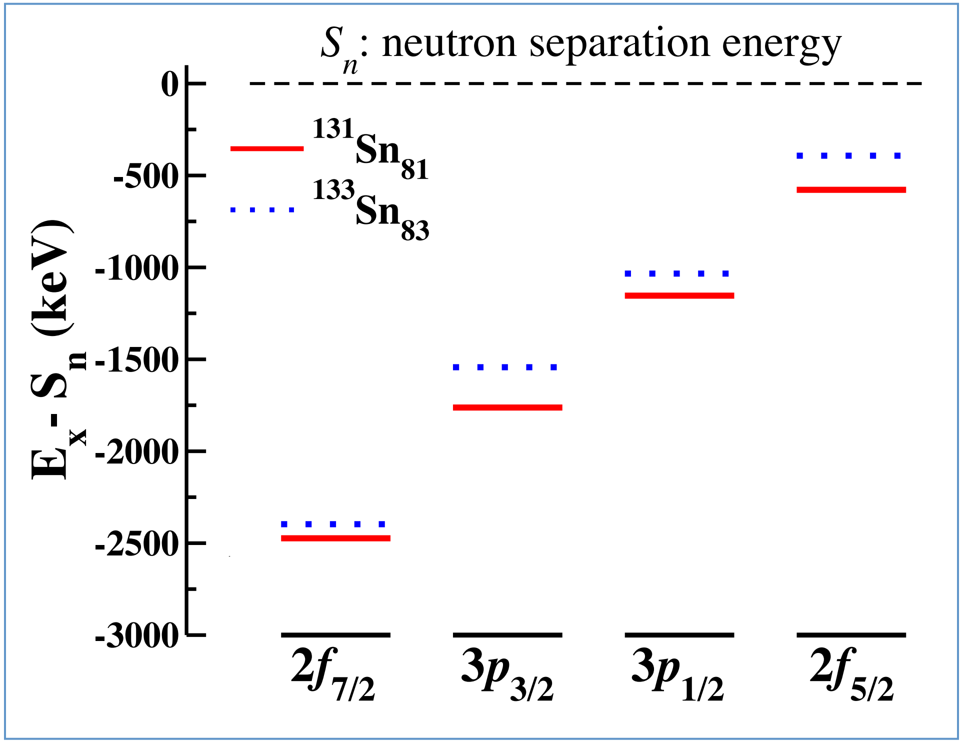
- Clear elastic scattering line from deuterons and a faint punch through line
- Gap in data caused by shadowing
- Alpha contamination from the ^{233}U source used for calibration

Data from a single strip of an ORRUBA detector at **forward** angles



$^{131,130}Sn(n,\gamma)$

- ^{131}Sn
  - Ground state = $3/2^+$
  - S_n=5.25 MeV
  - DSD via $3p_{3/2}$ and $3p_{1/2}$
    - $1^-,2^-,3^-$ states at $E_x \approx 4$ MeV
  - ℓ=0 capture
    - $1^+,2^+$ states above E_x=5.25 MeV
- ^{130}Sn
  - Ground state = 0^+
  - S_n=7.69 MeV
  - DSD via $3p_{3/2}$ and $3p_{1/2}$
    - $1/2^-,3/2^-$ states in ^{131}Sn; $E_x \approx$ 4.0 and 3.4 MeV
  - ℓ=0 capture
    - $1/2^+$ states in ^{131}Sn above E_x=7.69 MeV



A. Bey, private communication

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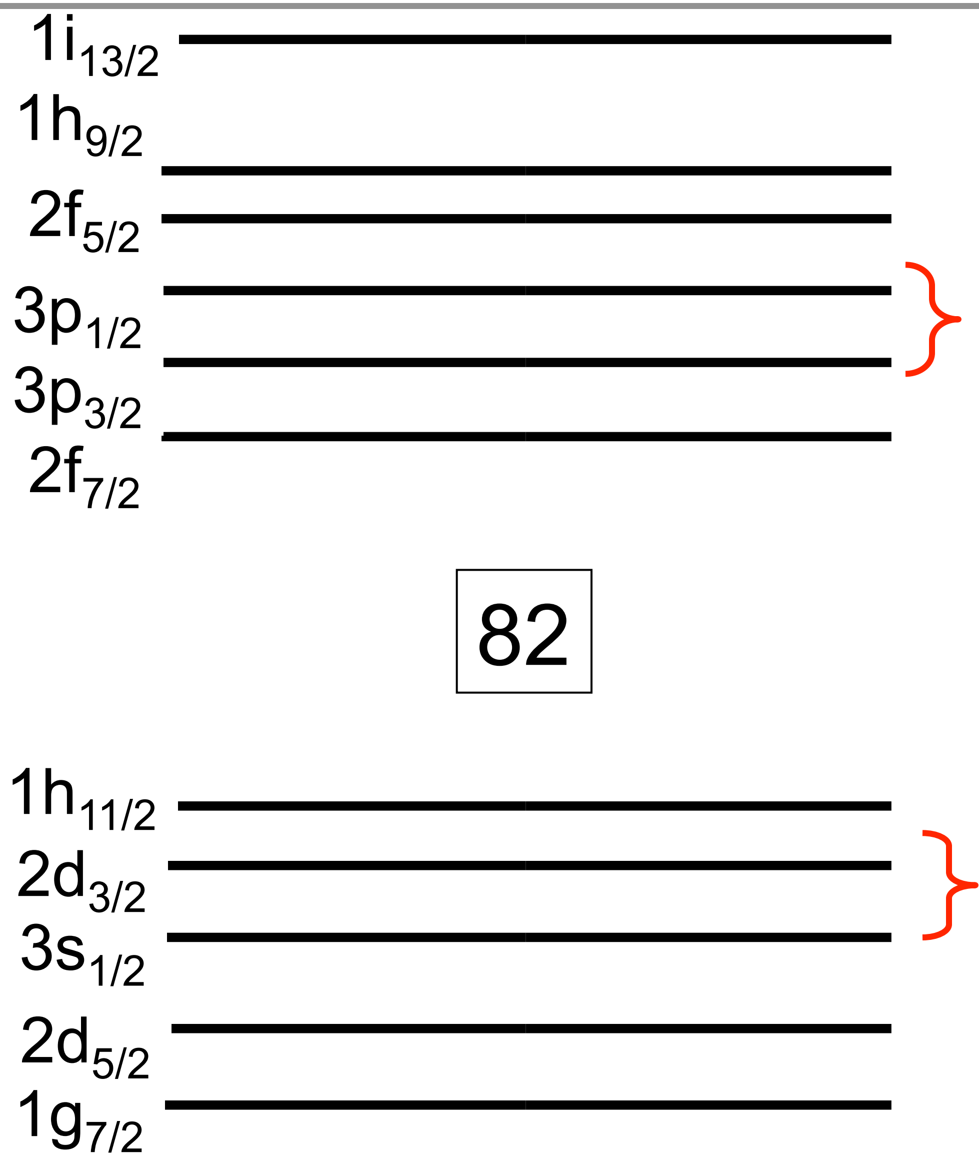
N<82 (d,p) what should expect to see?



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

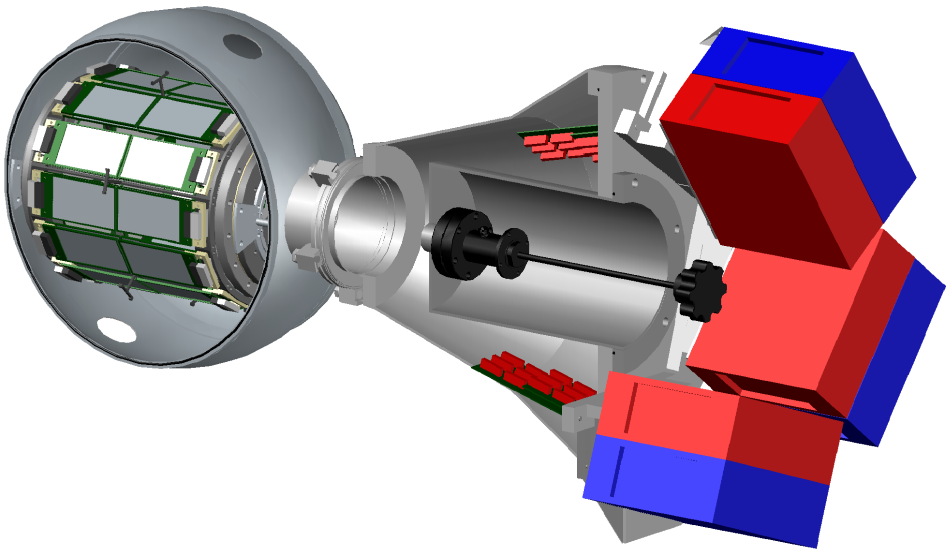
ℓ=1 important in direct (n,γ)

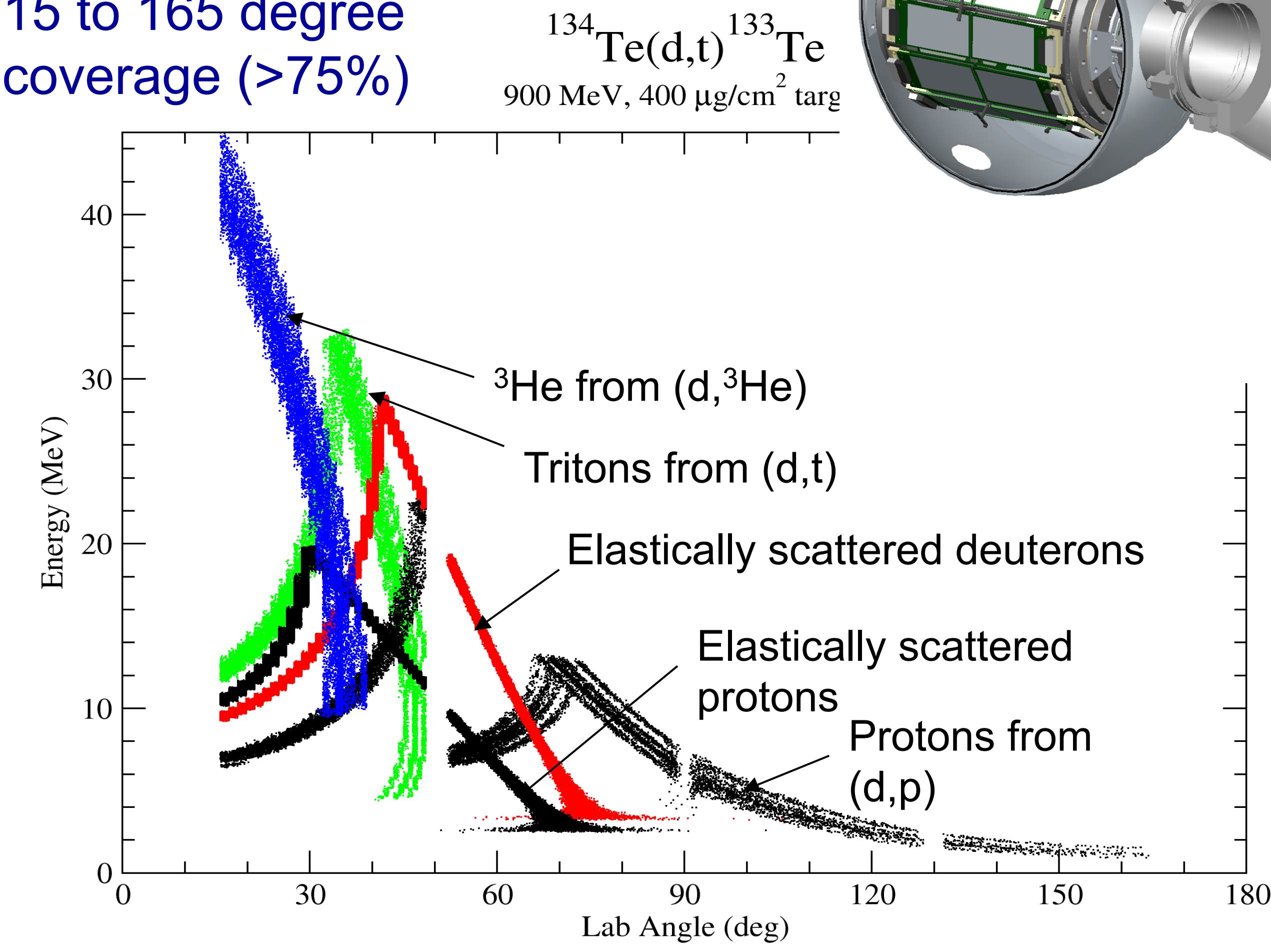
N<82 neutron holes

GODDESS is powerful

Polar angle coverage

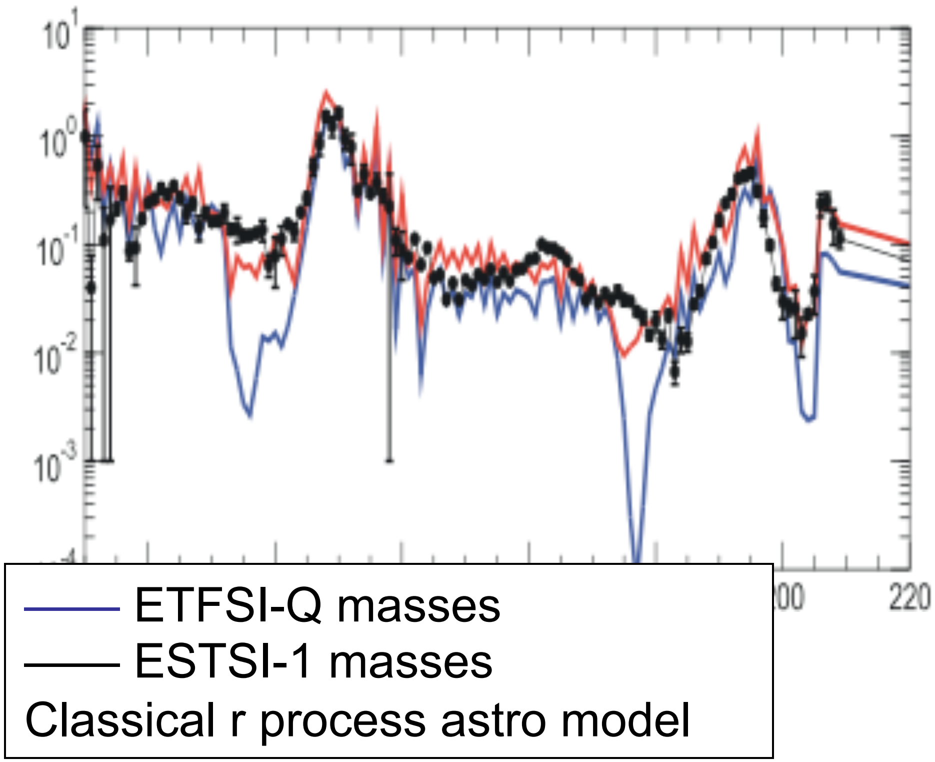
15 to 165 degree coverage (>75%)

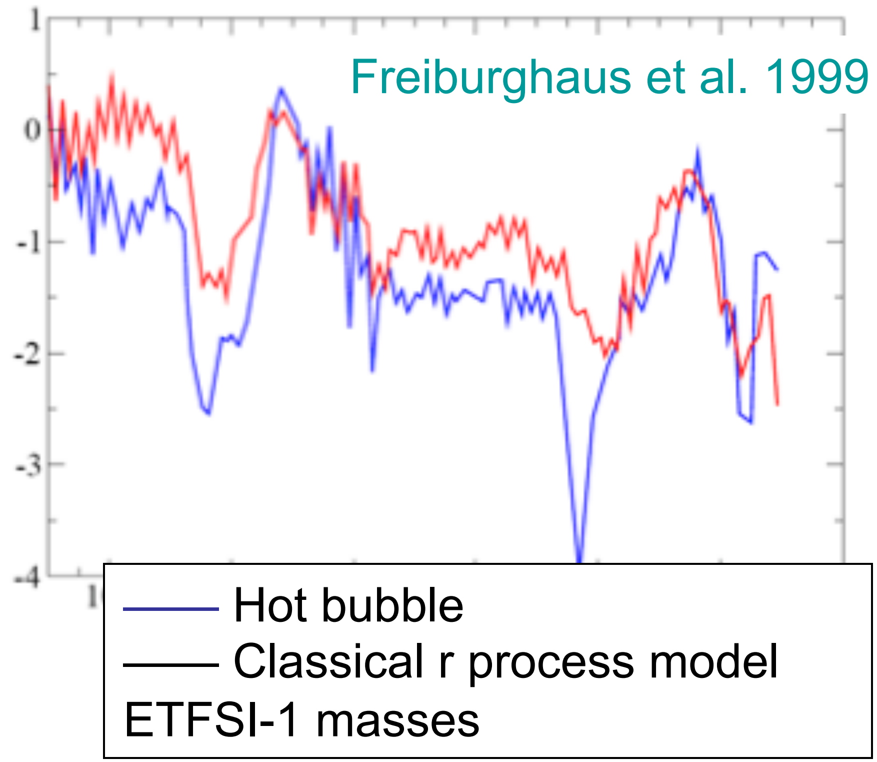




Forward endcap   Barrel   Backward endcap

r-process abundances





Peaks of r-process abundances near “magic numbers”, nuclear shell closures

BUT, different astrophysics models predict different abundances
⇒ Change in nuclear structure far from stability OR astrophysics OR ??