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Neutron transfer reactions with exotic tin beams and neutron capture

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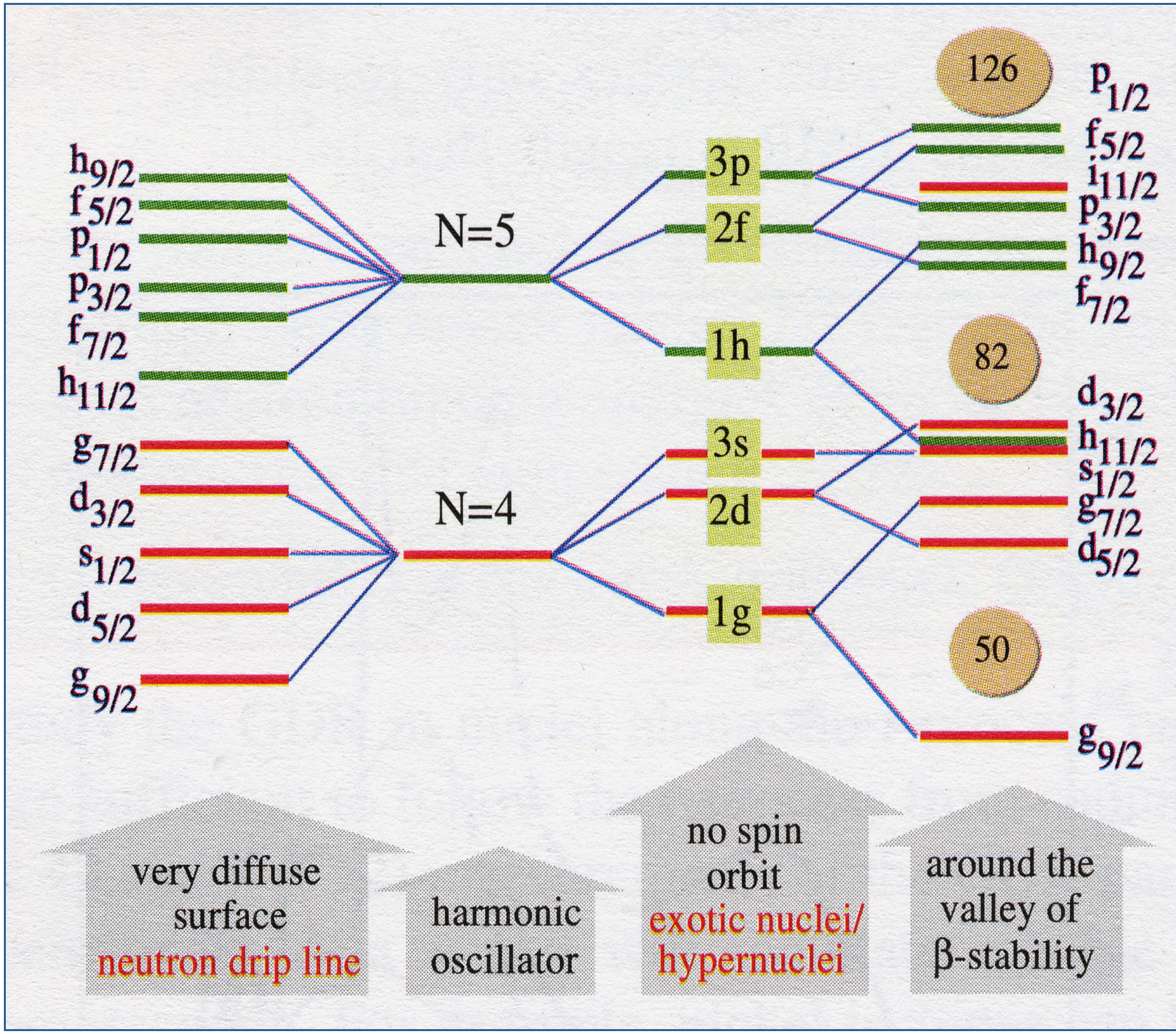
Rutgers University

DREB 2016, July 11-16, 2016

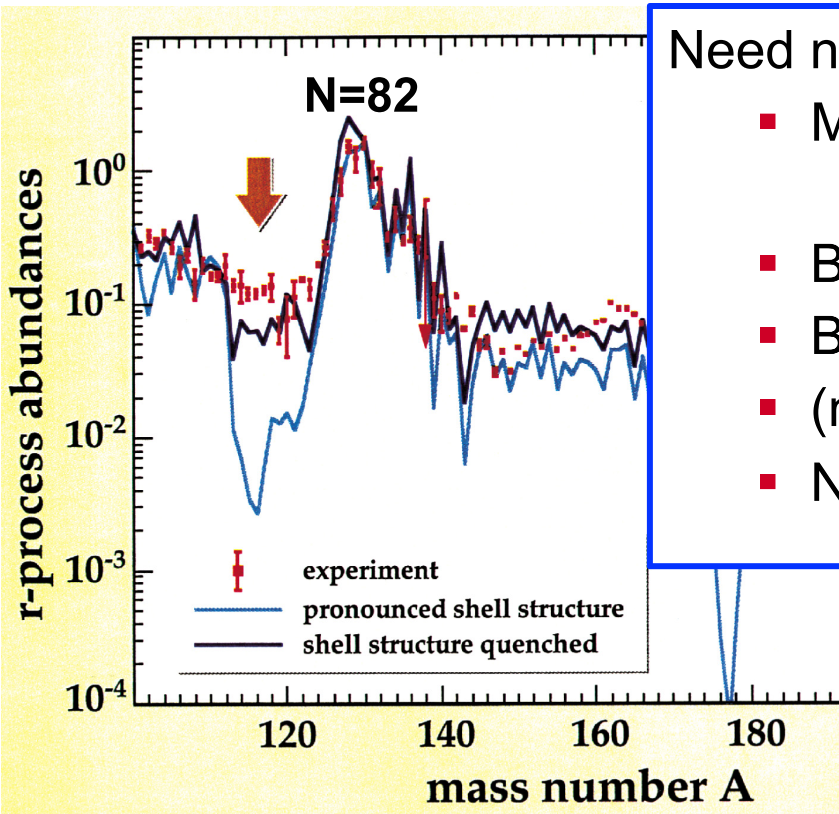
Halifax, Nova Scotia, Canada

Shell structure predicted to evolve as surface more diffuse



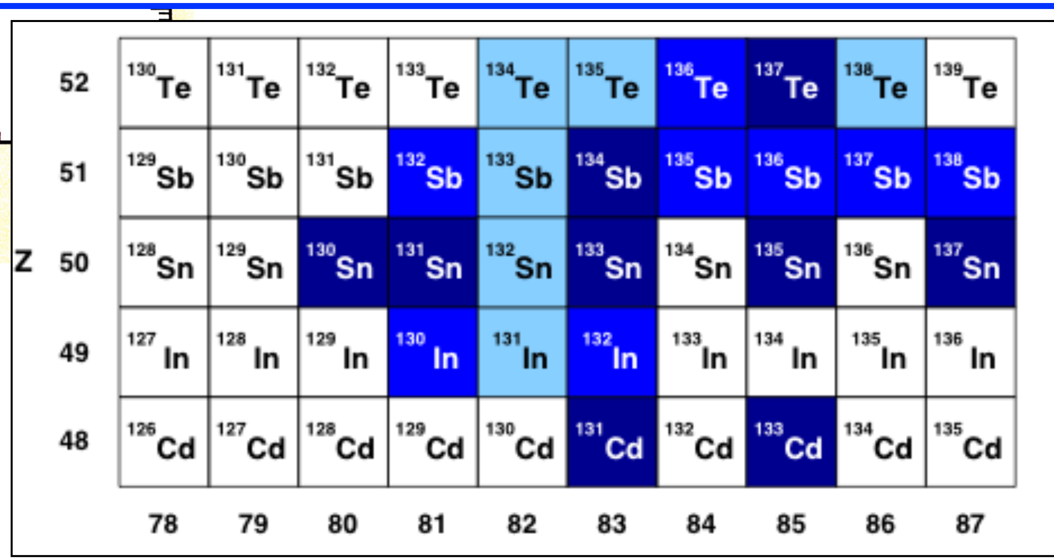
J. Dobaczewski, W. Nazarewicz, T. R. Werner, J. F. Berger, C. R. Chinn, and J. Decharge, Phys. Rev. C **53**, 2809 (1996)

r process abundances, freeze-out & (n,γ)



Need nuclear data

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

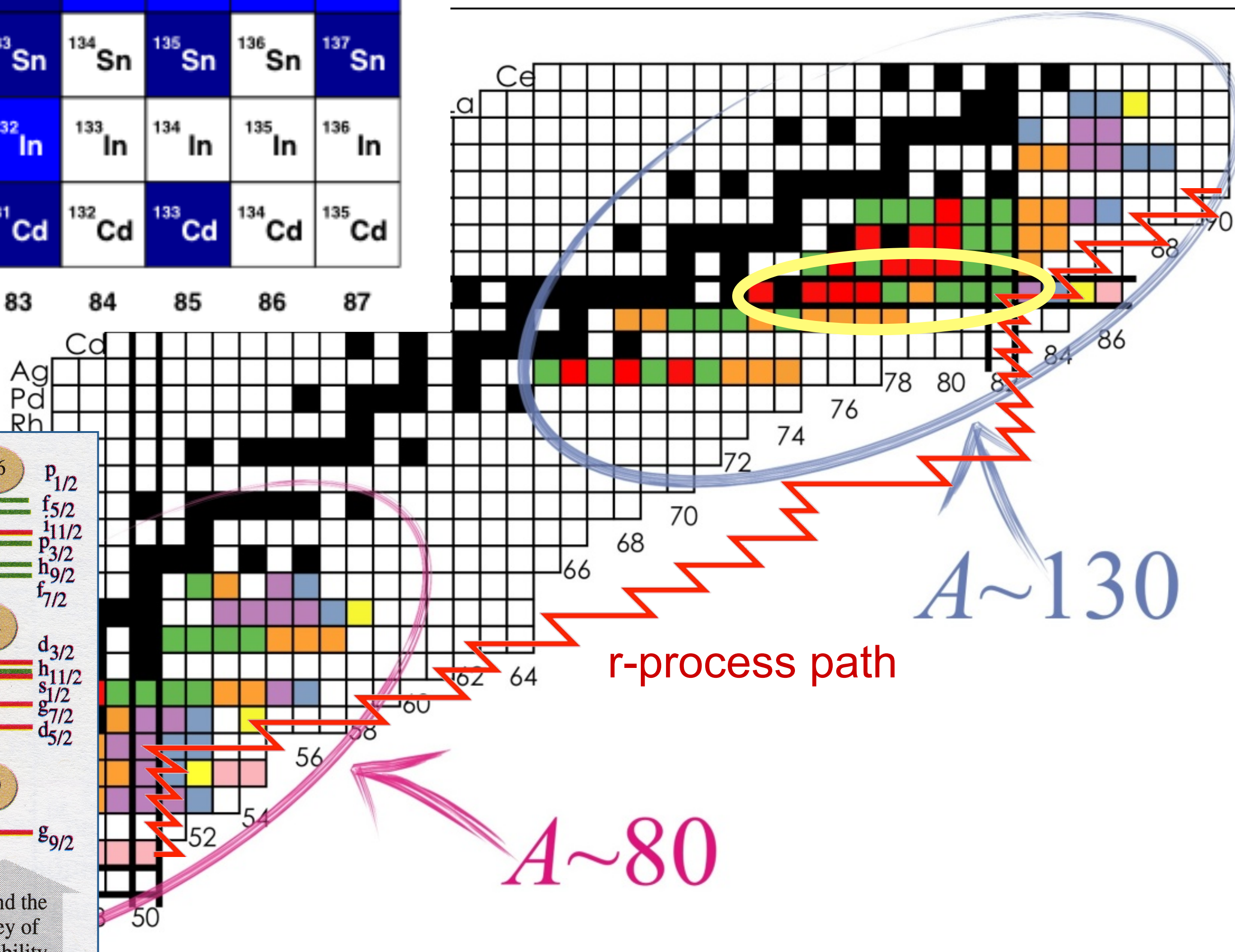


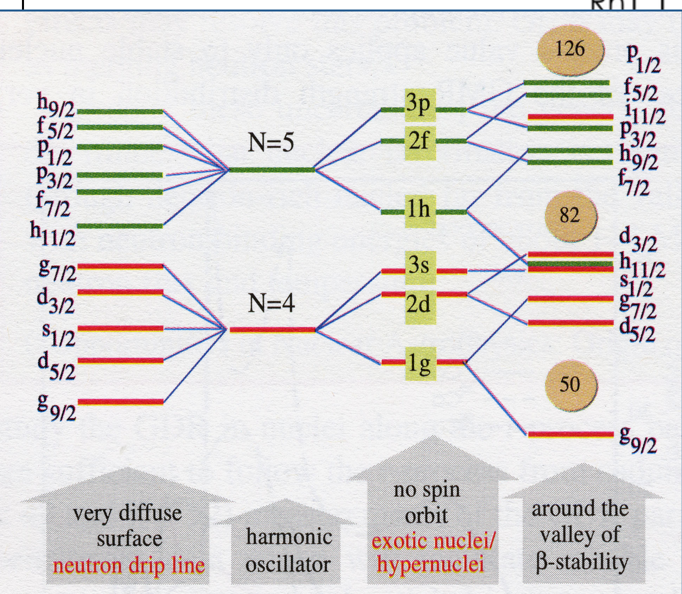
Dark Blue: X10 increase in (n,γ) rates change abundance patterns by >5%

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

Sn(d,p) studies at HRIBF

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





RADIOACTIVE ION BEAM STUDIES FOR STEWARDSHIP SCIENCE

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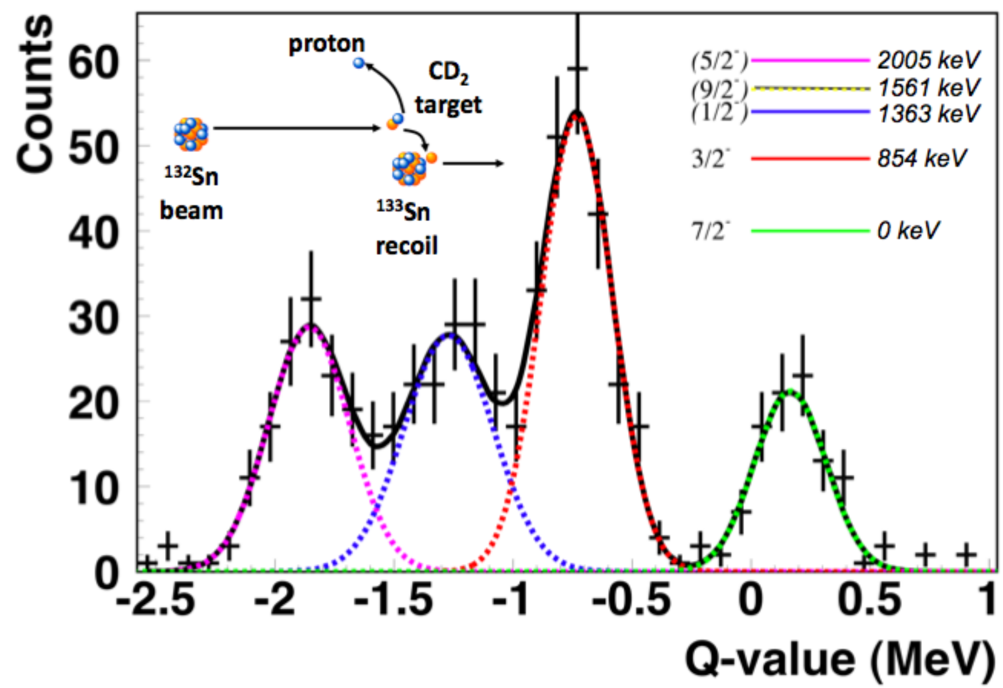
^{132}Sn(d,p): N=83 single neutron states

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)

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

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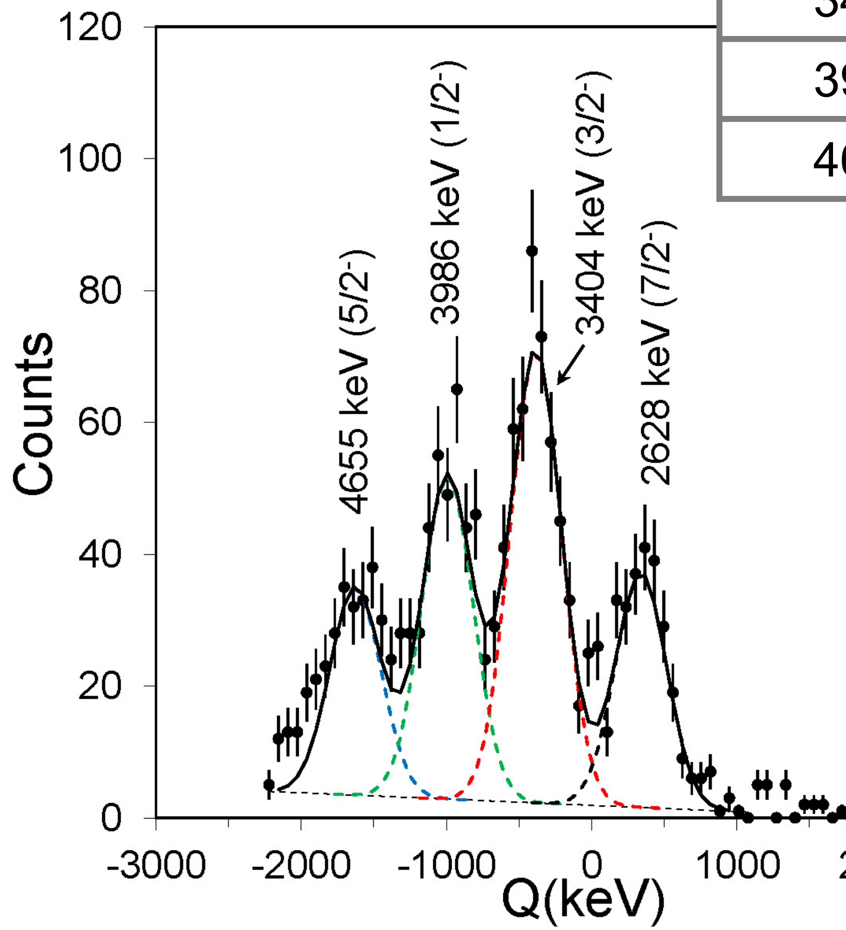
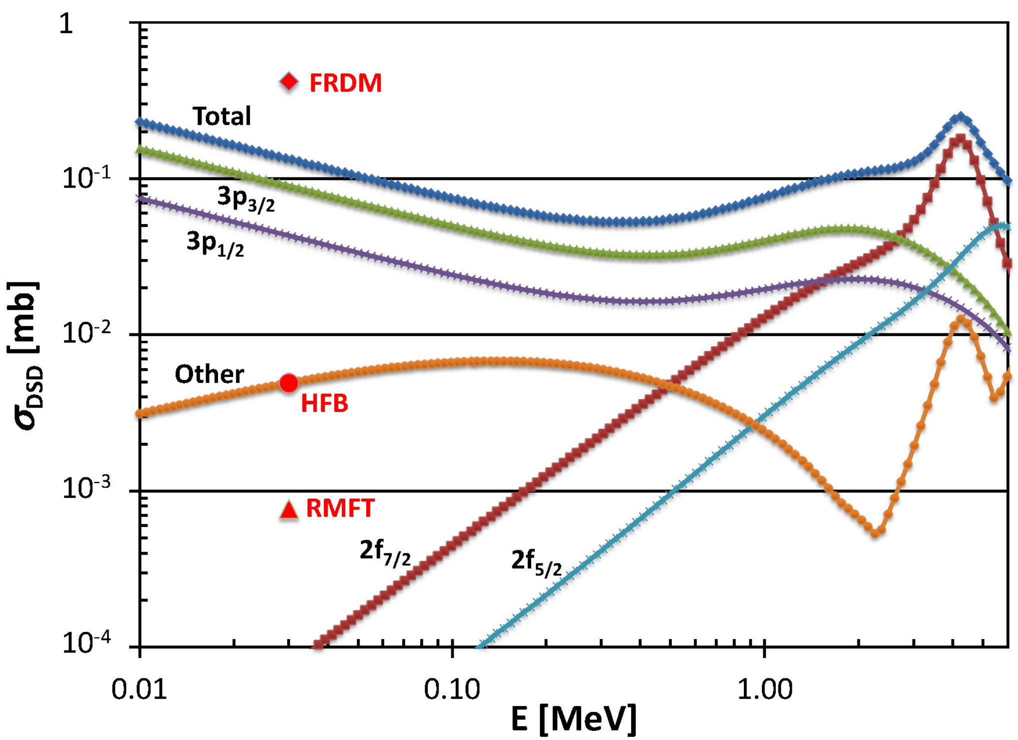
E_x(keV)	J^π	Config	SF (DWBA)
2628	$(7/2)^-$	$2f_{7/2}$	0.70(21)
3404	$(3/2)^-$	$3p_{3/2}$	0.70(21)
3986	$(1/2)^-$	$3p_{1/2}$	1.0(3)
4655	$(5/2)^-$	$2f_{5/2}$	0.75(23)



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



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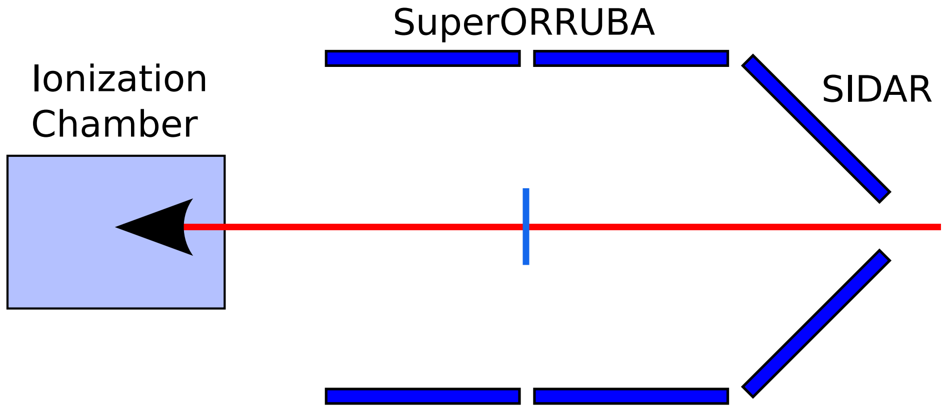
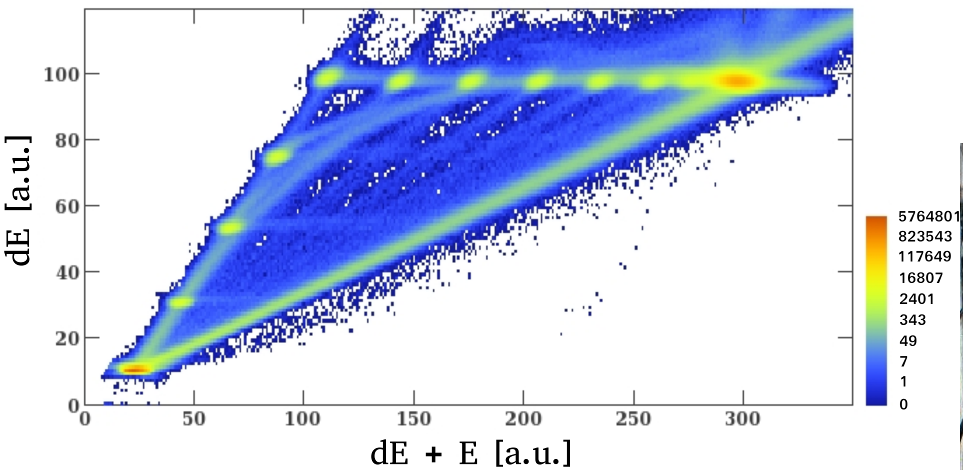
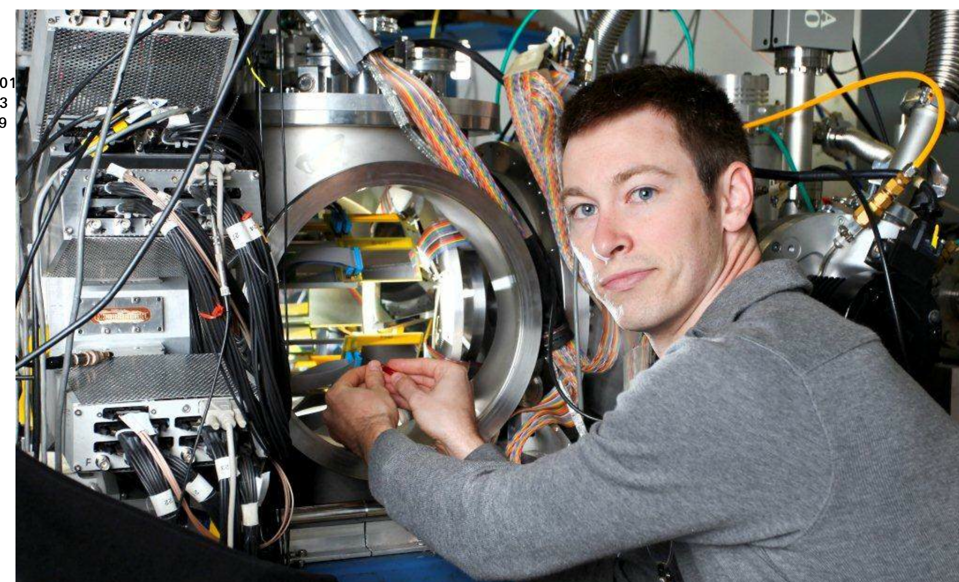
^{124,126,128}Sn(d,p) with SuperORRUBA + Ion chamber





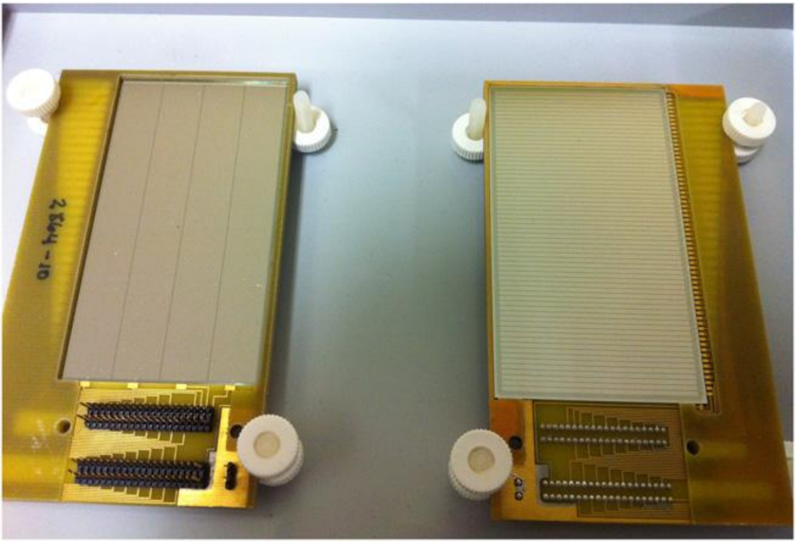
Ion chamber: K. Y. Chae et al., Nucl. Instrum. Meth. A **751**, 6 (2014)

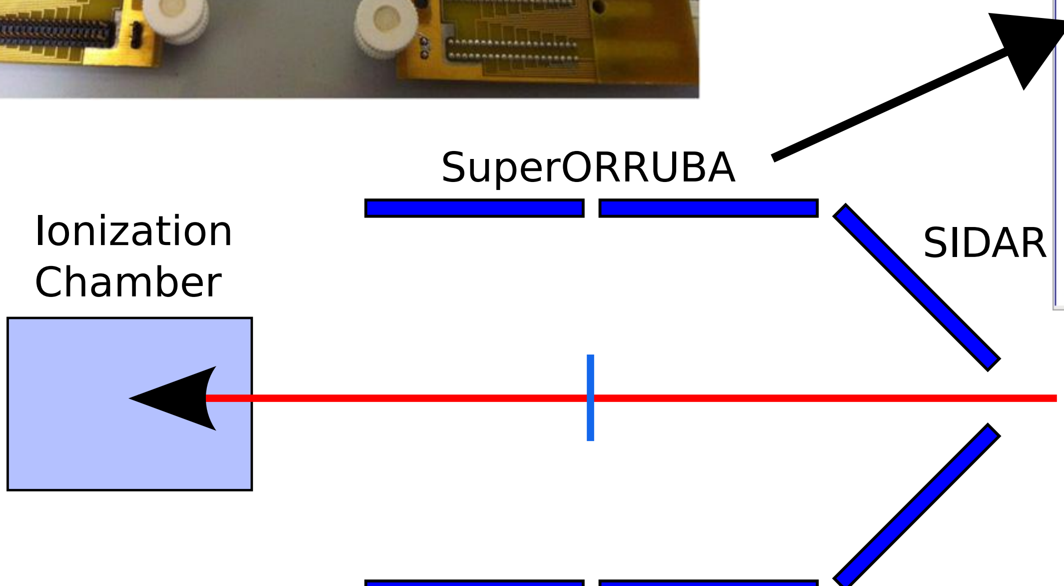
Original design: K. Kimura, et al., Nucl. Instrum. Meth. A **538,** 608 (2005).

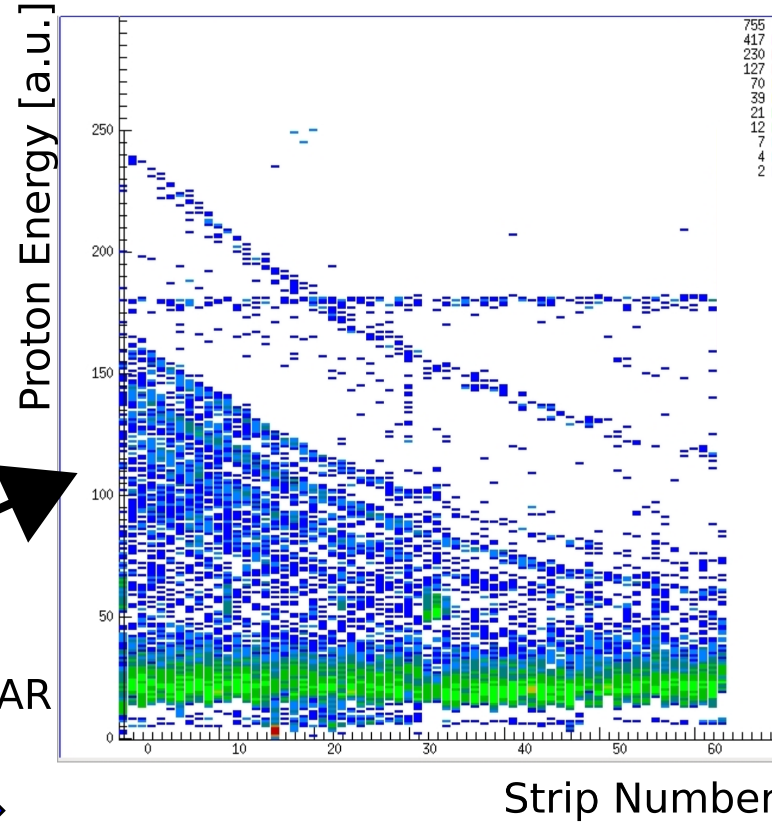


B. Manning, Rutgers PhD dissertation & to be published

IC gated back angle SuperORRUBA

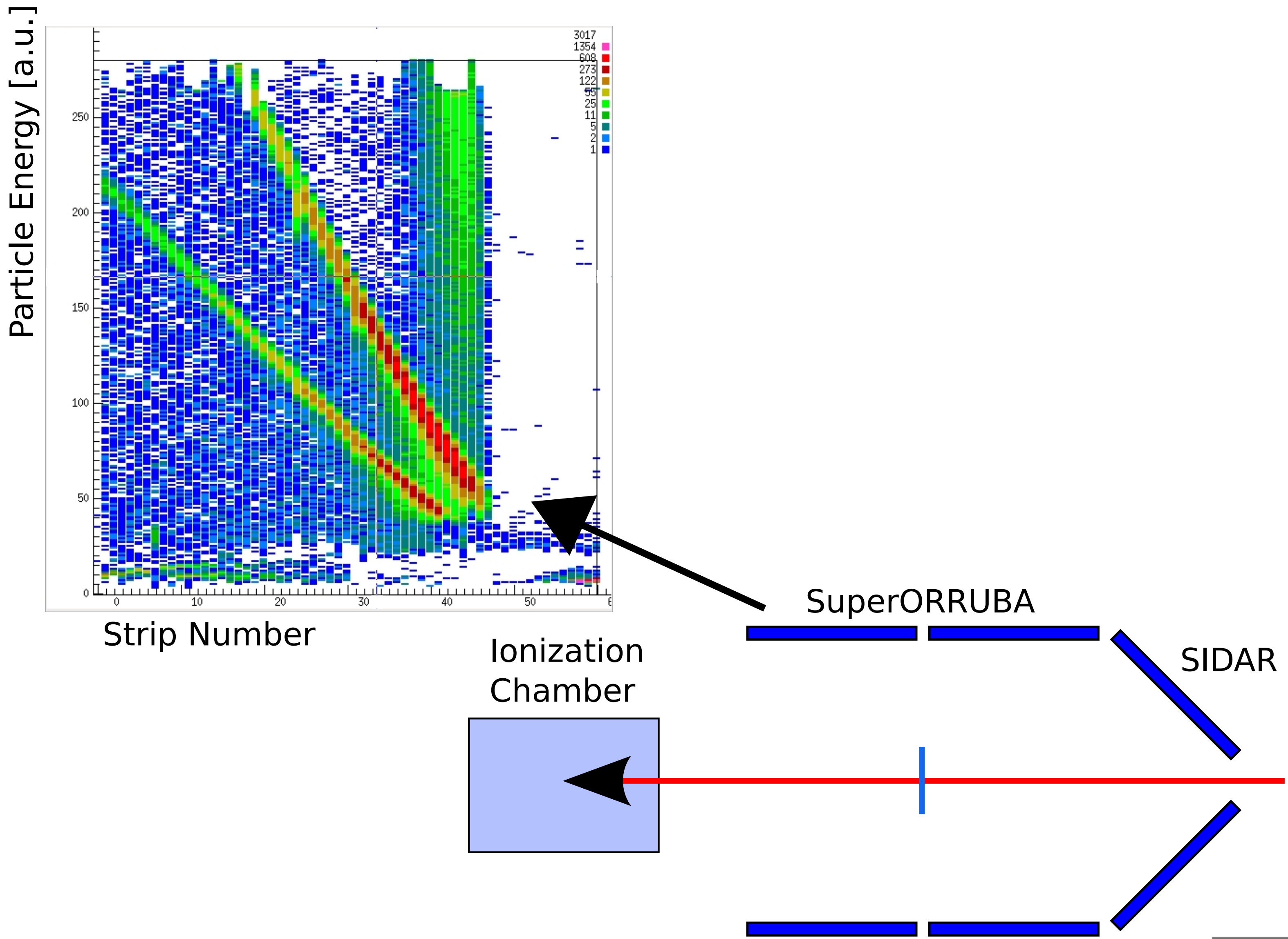




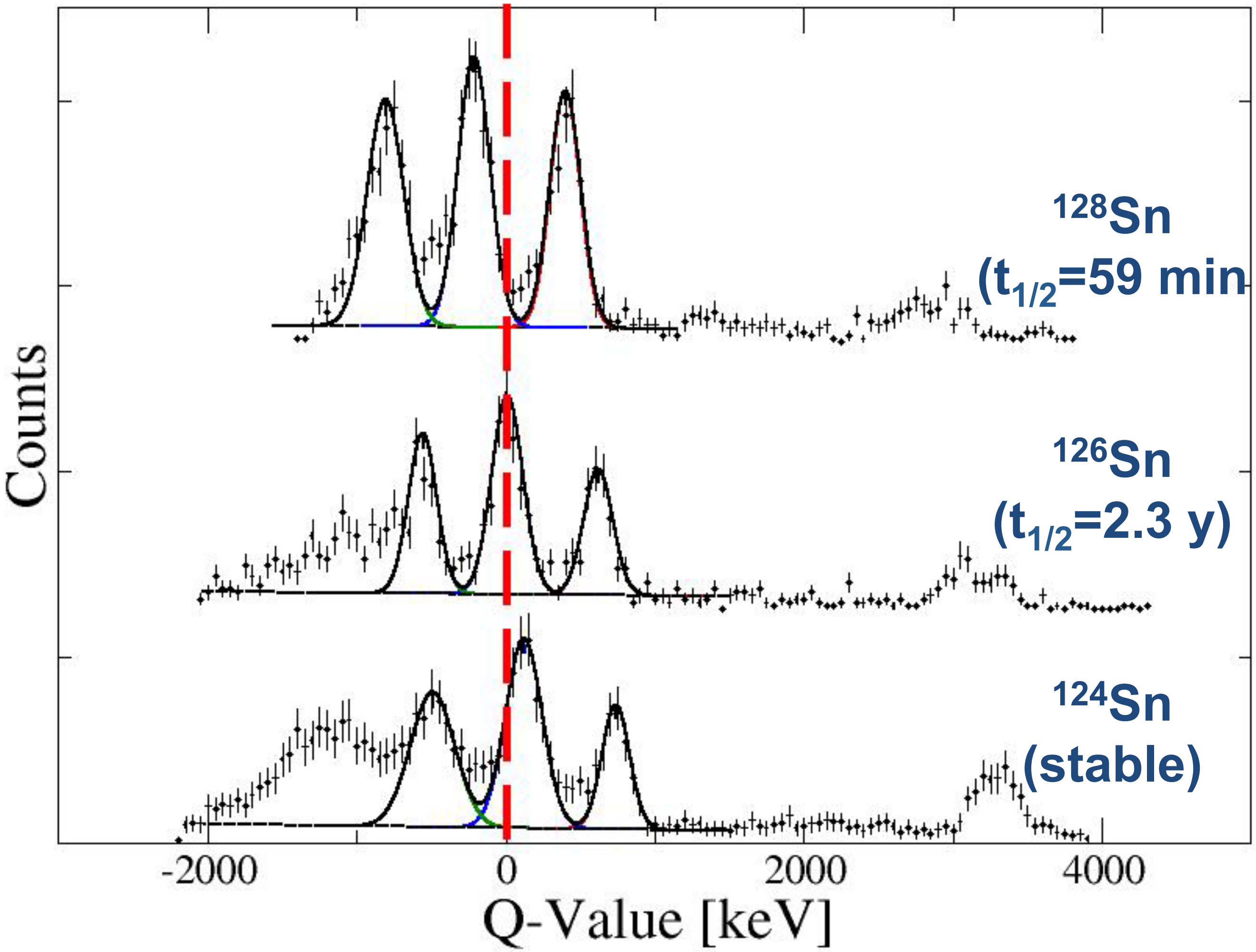


SuperORRUBA: D. W. Bardayan et al.,
Nucl. Instrum. Meth. A **711**, 160 (2013).

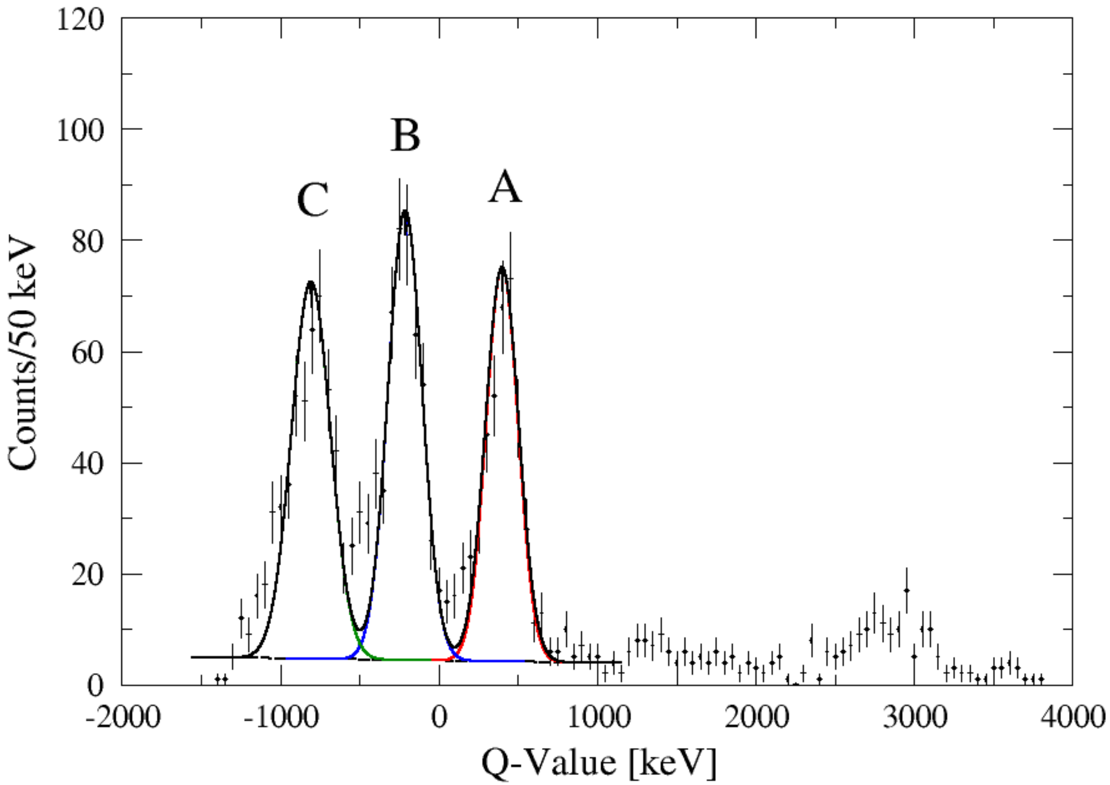
Forward Angle Elastics

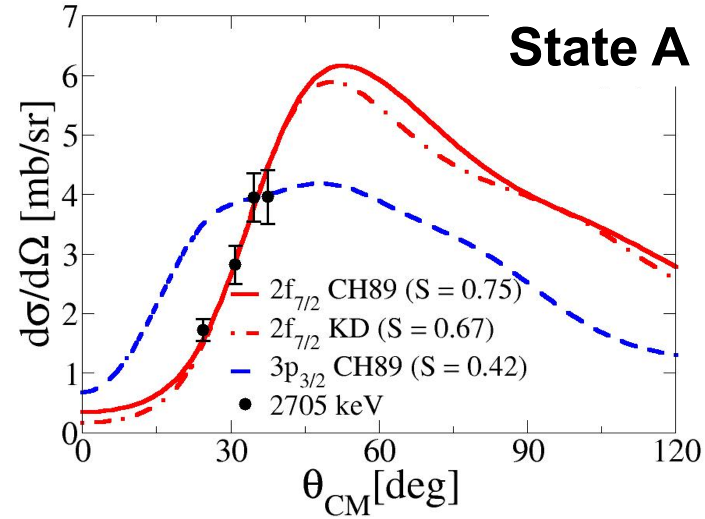


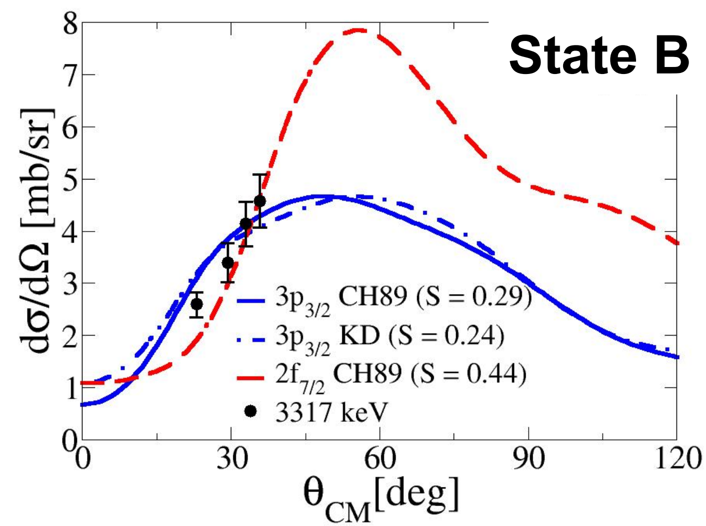
$^{124,126,128}Sn(d,p)$



^{128}Sn(d,p): Q value & angular distributions







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

	$2f_{7/2}$ 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(8)	0.85	0.92(7)	1.36	1.3(3)
^{130}Sn(d,p)	2.63	0.95(13)	3.40	0.55(8)	3.99	1.00(14)
^{128}Sn(d,p)	2.71	0.75(10)	3.32	0.29(4)	3.91	0.46(7)
^{126}Sn(d,p)	2.71	0.54(8)	3.33	0.27(3)	3.88	0.49(4)
^{124}Sn(d,p)	2.77	0.39(3)	3.39	0.29(3)	3.99	0.42(5)

Same reaction theory & Optical Model:

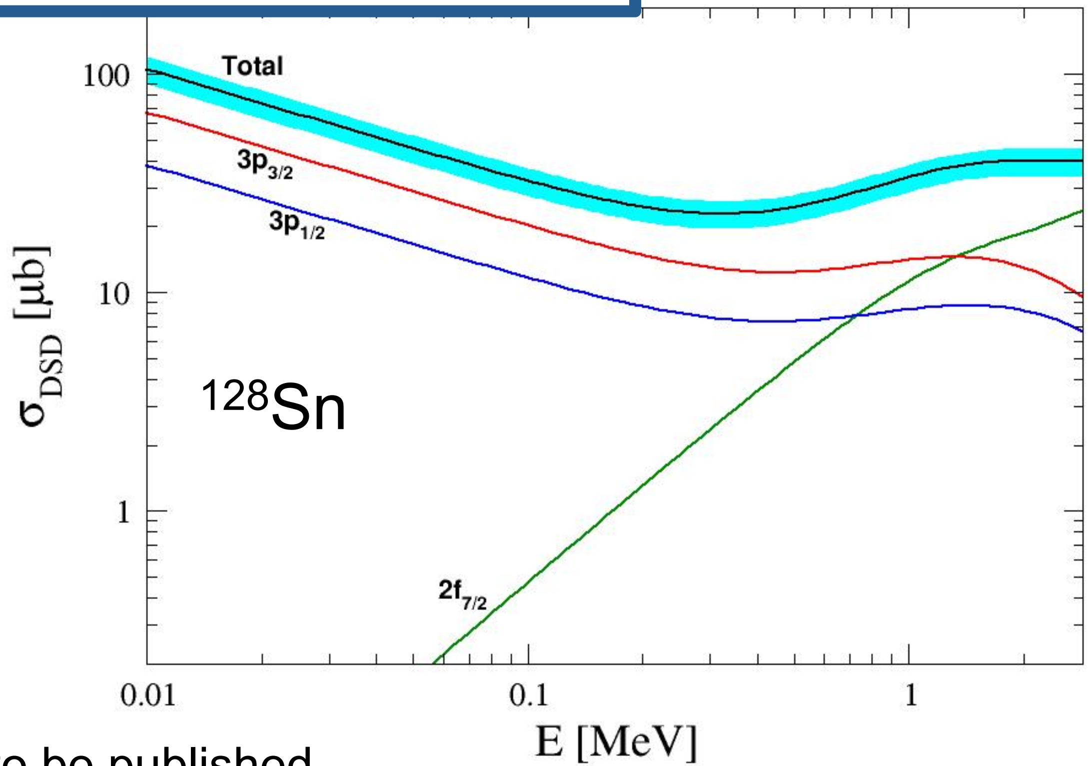
- Finite-Range Adiabatic Wave Approximation
- Chapel Hill 89 Optical Model Parameters

B. Manning et al., to be published
^{132}Sn(d,p) cross sections: K.L. Jones et al., PRC **84**, 034601 (2011)
^{130}Sn(d,p) cross sections: R.L. Kozub et al., PRL **109**, 172501 (2012)

Direct-semi-direct neutron capture calculations

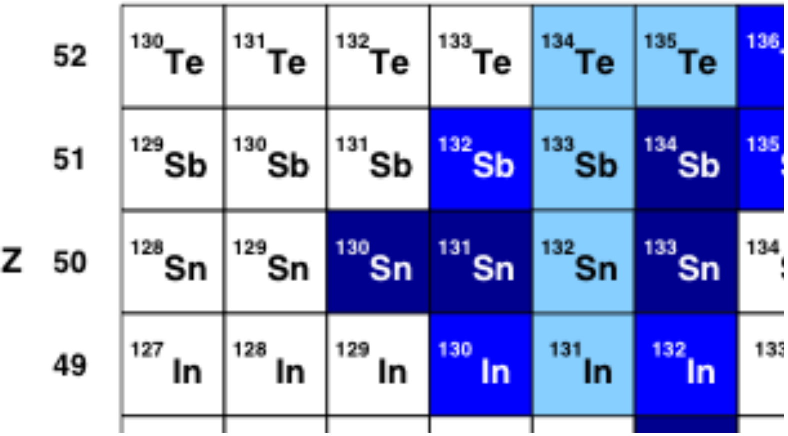
Direct semi-direct direct capture with CUPIDO

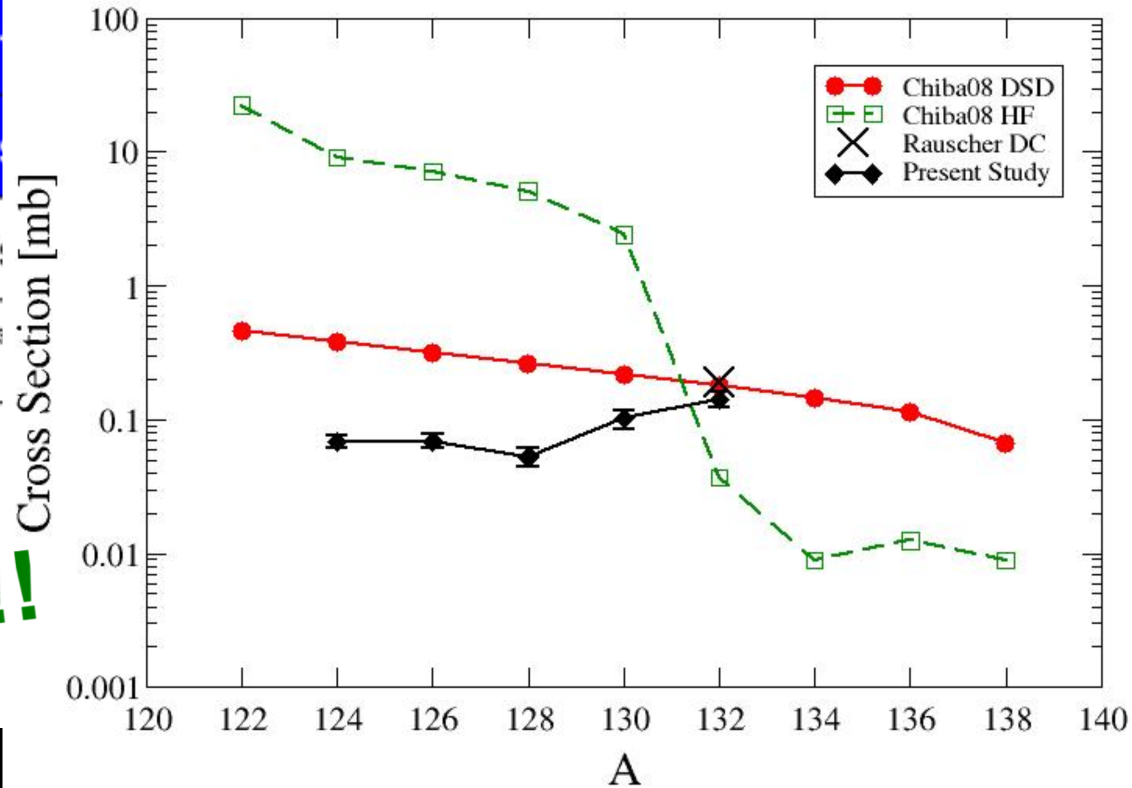
- Semi-direct capture via GDR
  - Add GDR to s.p. EM operator
- Incident n channel: Koning Delaroche potential
- Bound state: Bear Hodgson potential
- Used measured SF and Ex to constrain
- Uncertainties ≈ 20%



B. Manning, G. Arbanas et al. to be published

^{132,130,128,126,124}Sn DSD (n,γ)





!!! Preliminary !!!

	30 keV σ(n,γ) (μb)
^{132}Sn(d,p)	142
^{130}Sn(d,p)	101
^{128}Sn(d,p)	53
^{126}Sn(d,p)	69
^{124}Sn(d,p)	69

Sn(n,γ) vs A

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

DSD from exp: G. Arbanas, B. Manning

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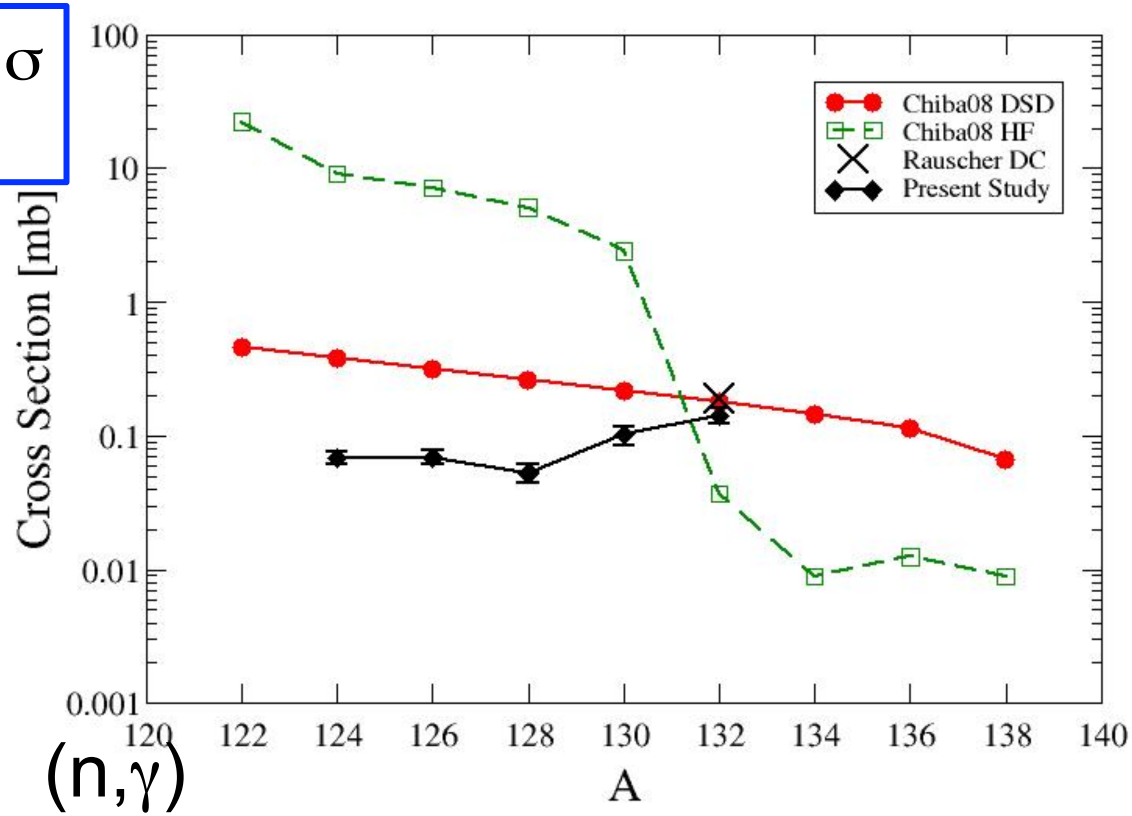
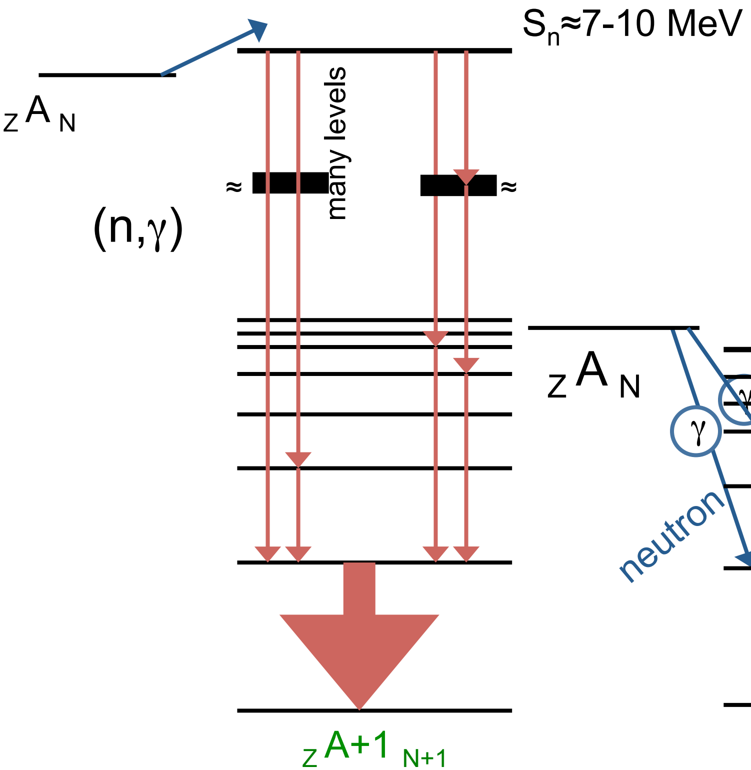
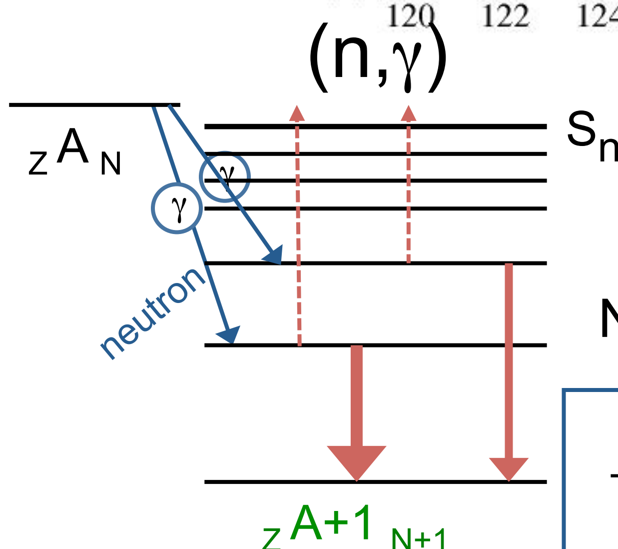
^{132,130,128,126,124}Sn statistical (n,γ)?

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



Near stability





Near waiting points

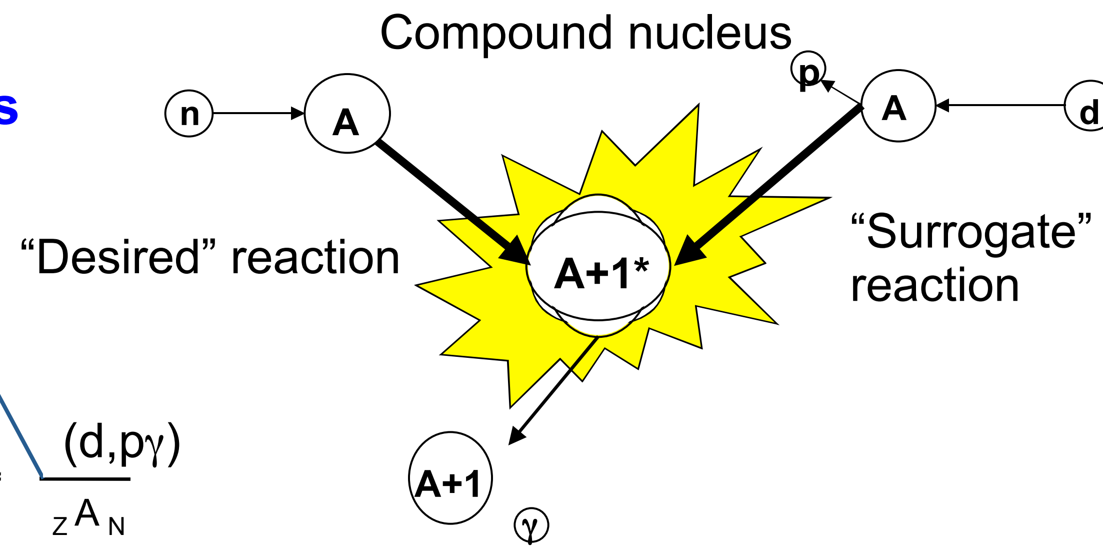
Sn(n,γ) vs A

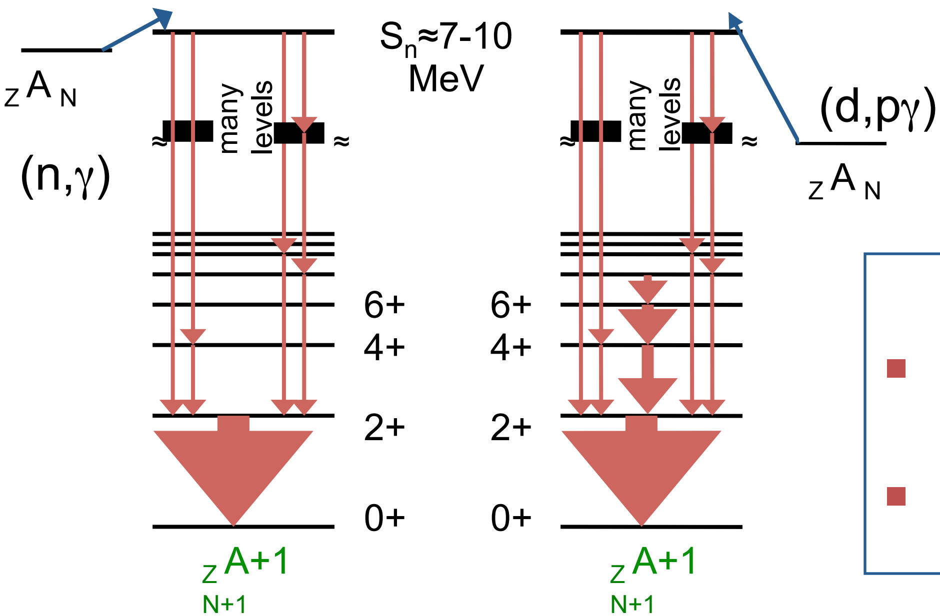
Theory: Chiba, et al. PRC **77**, 015809 (2008)

DSD from exp: G. Arbanas, B. Manning

Surrogate for (n,γ) and (d,pγ)?

(n,γ) important for nucleosynthesis & applications





Assumptions:

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

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

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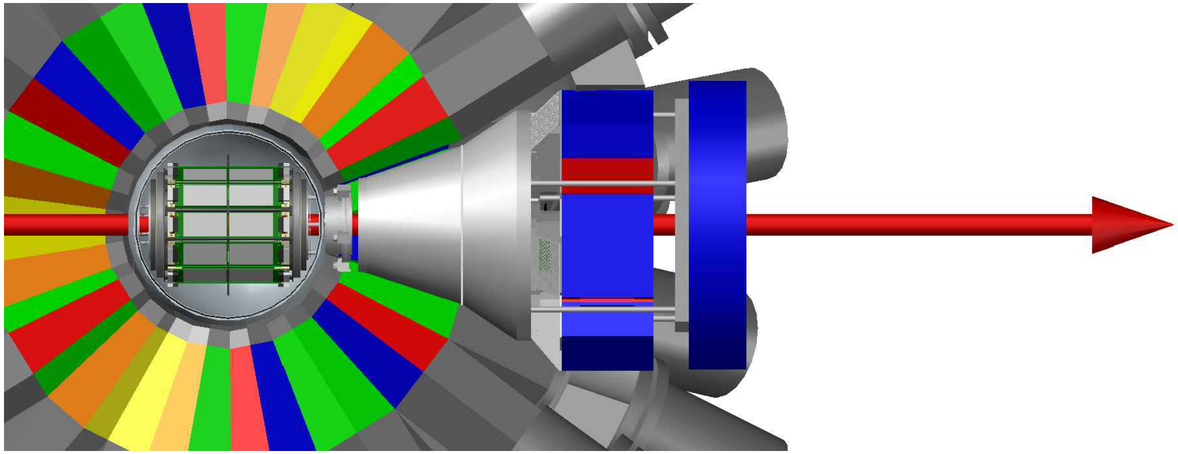
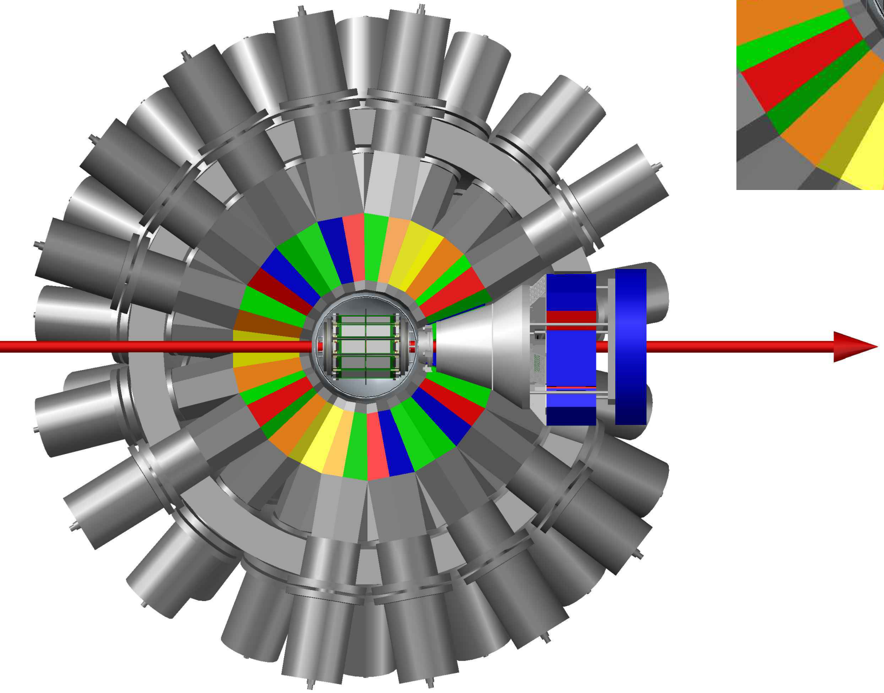
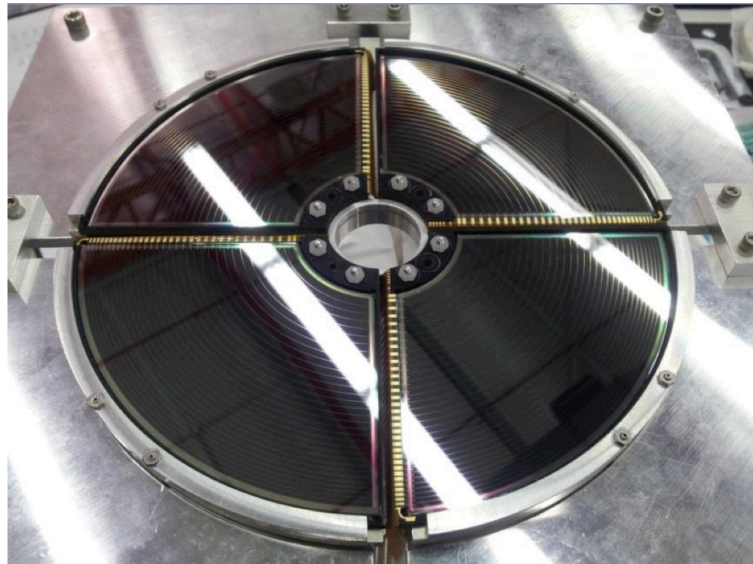
GODDESS: Gammasphere ORRUBA Dual Detectors for Experimental Structure Studies

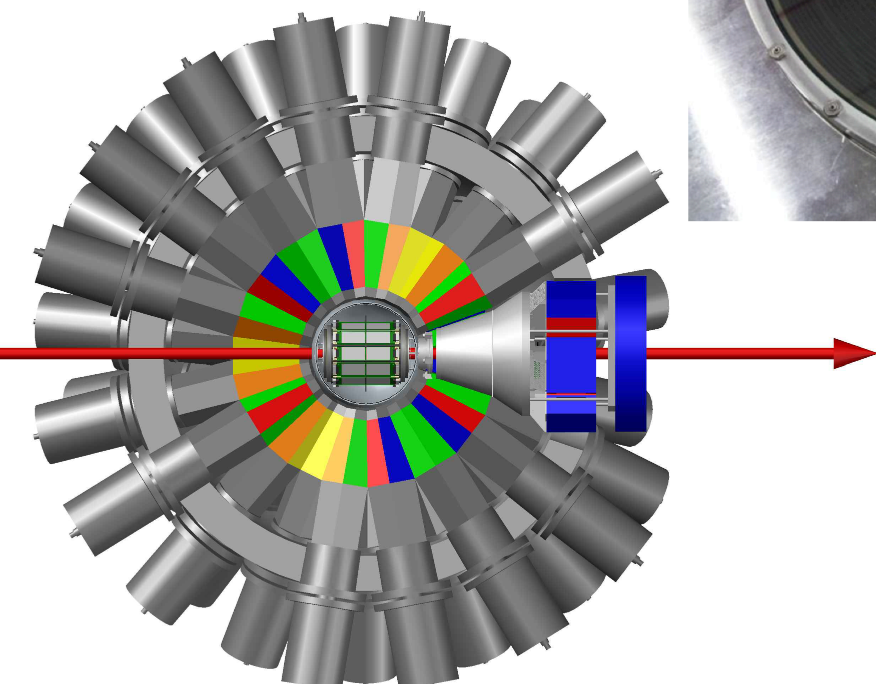


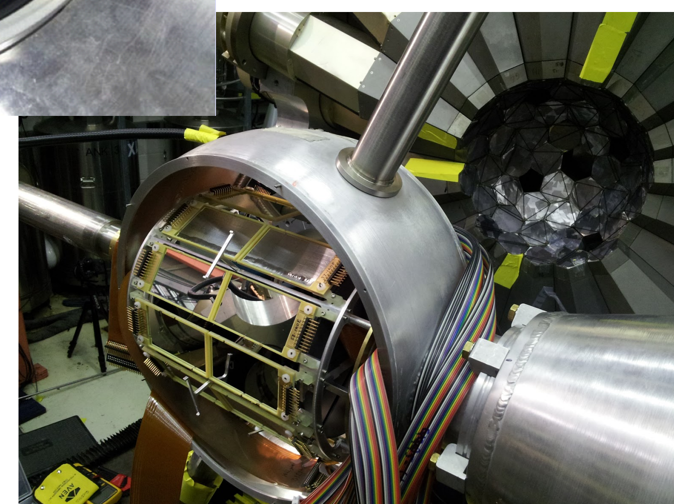


ORRUBA+ endcap annular detectors at back & forward angles

GODDESS: Gammasphere ORRUBA Dual Detectors for Experimental Structure Studies

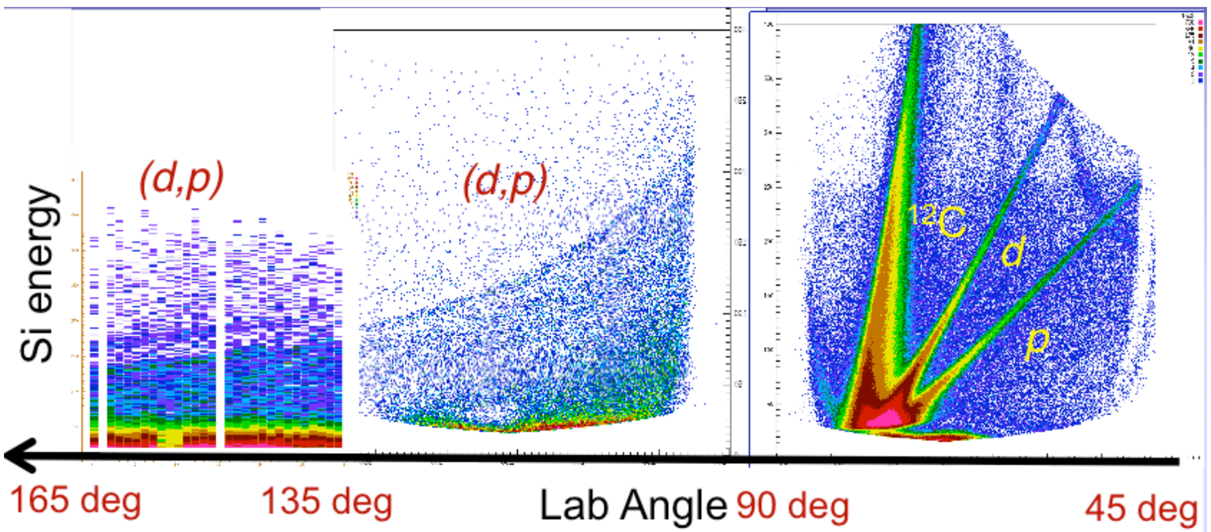


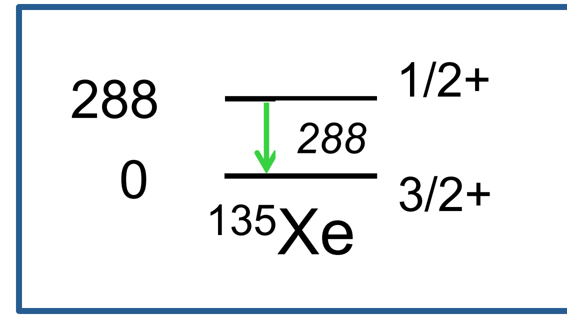


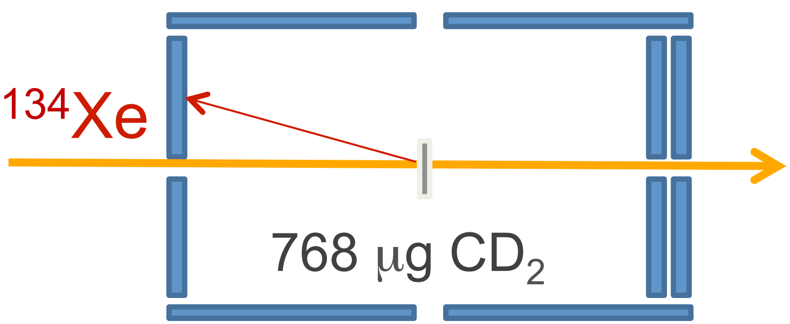


ORRUBA+ endcap annular detectors at back & forward angles

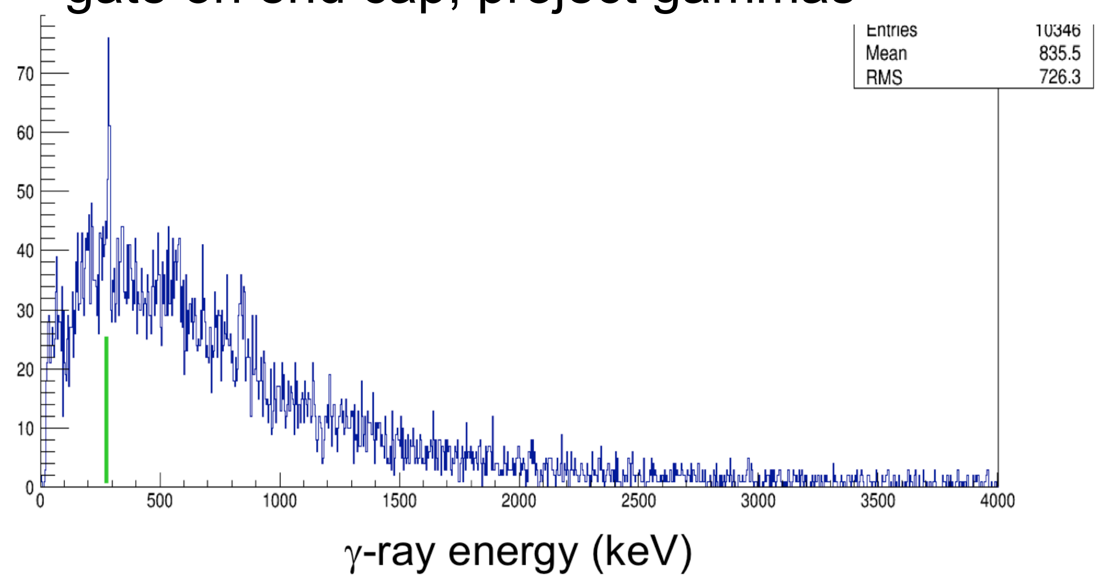
^{134}Xe(d,pγ) with GODDESS







Preliminary from one run:
gate on end cap, project gammas

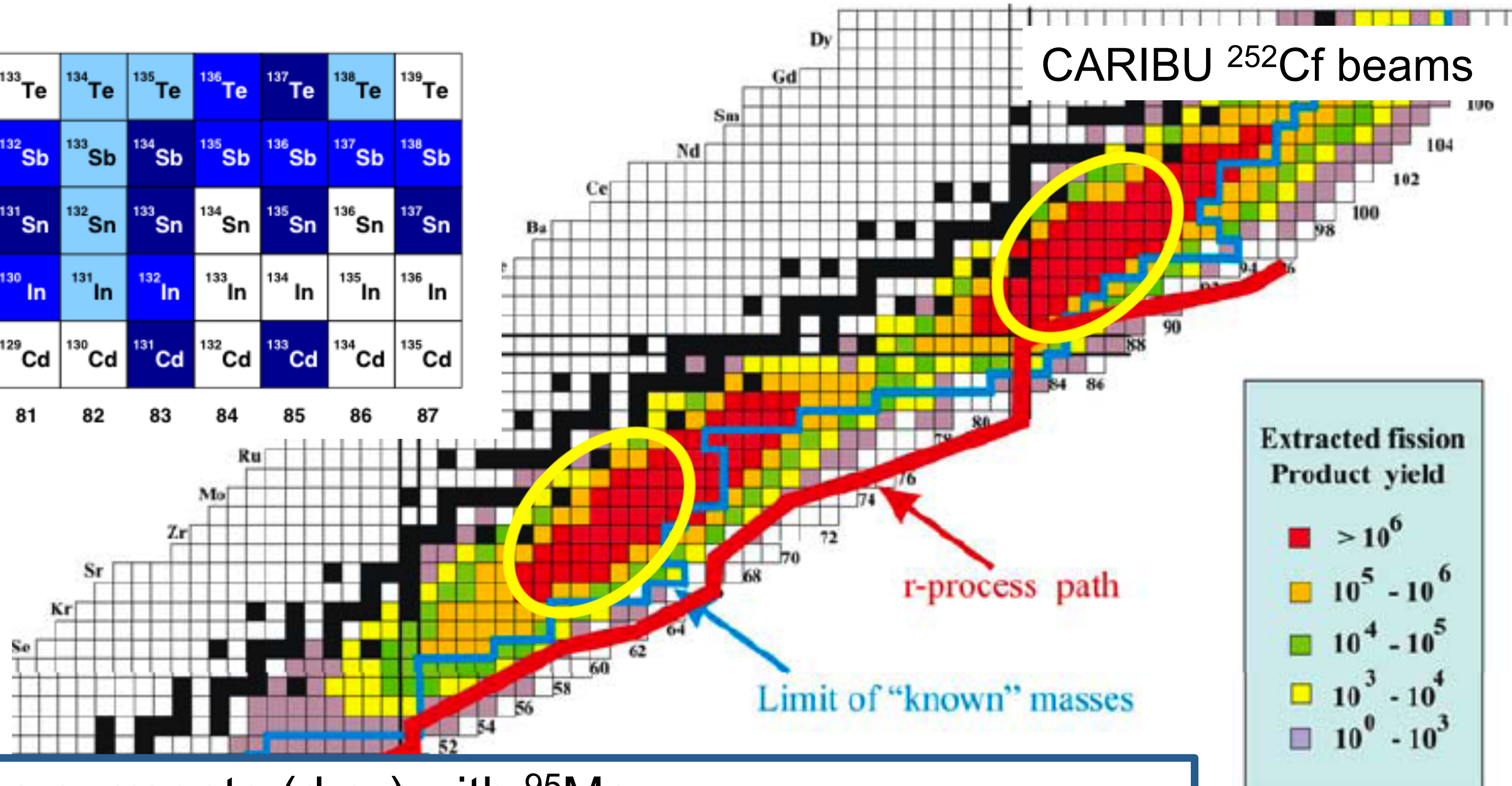


S.D. Pain, private communication

Experiments with GODDESS

^{252}Cf fission fragment ATLAS beams & ORRUBA + Gammasphere

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



- Validating surrogate (d,pγ) with ^{95}Mo
- Heavy and light ^{252}Cf fission fragments
  - ^{134}Te(d,pγ) ^{142,144}Ba(d,pγ) approved
  - ^{137,138}Xe(d,pγ) and others important to astrophysics

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Summary and prospects

- Sn(d,p) to probe nuclear structure away from stability
  - Transfer to states above N=82 gap dominate
- Direct (semi-direct) neutron capture cross sections near shell closures and weakly bound nuclei
  - Depend on spectroscopic factors that can be measured with (d,p)
  - Results: neutron-rich even Sn isotopes
- Compound nucleus neutron capture dominates in most nuclei
- Developing valid surrogate for (n,γ)
  - Developing techniques to measure (d,pγ) with radioactive beams
  - Poised to measure surrogate (n,γ) with ^{252}Cf fission fragments

Thank you
Neutron transfer reactions with exotic tin beams and neutron capture

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

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

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