Nuclear reaction experiments with rare isotopes: Probing nuclear structure, reactions and nucleosynthesis

(with (d,p) reactions)

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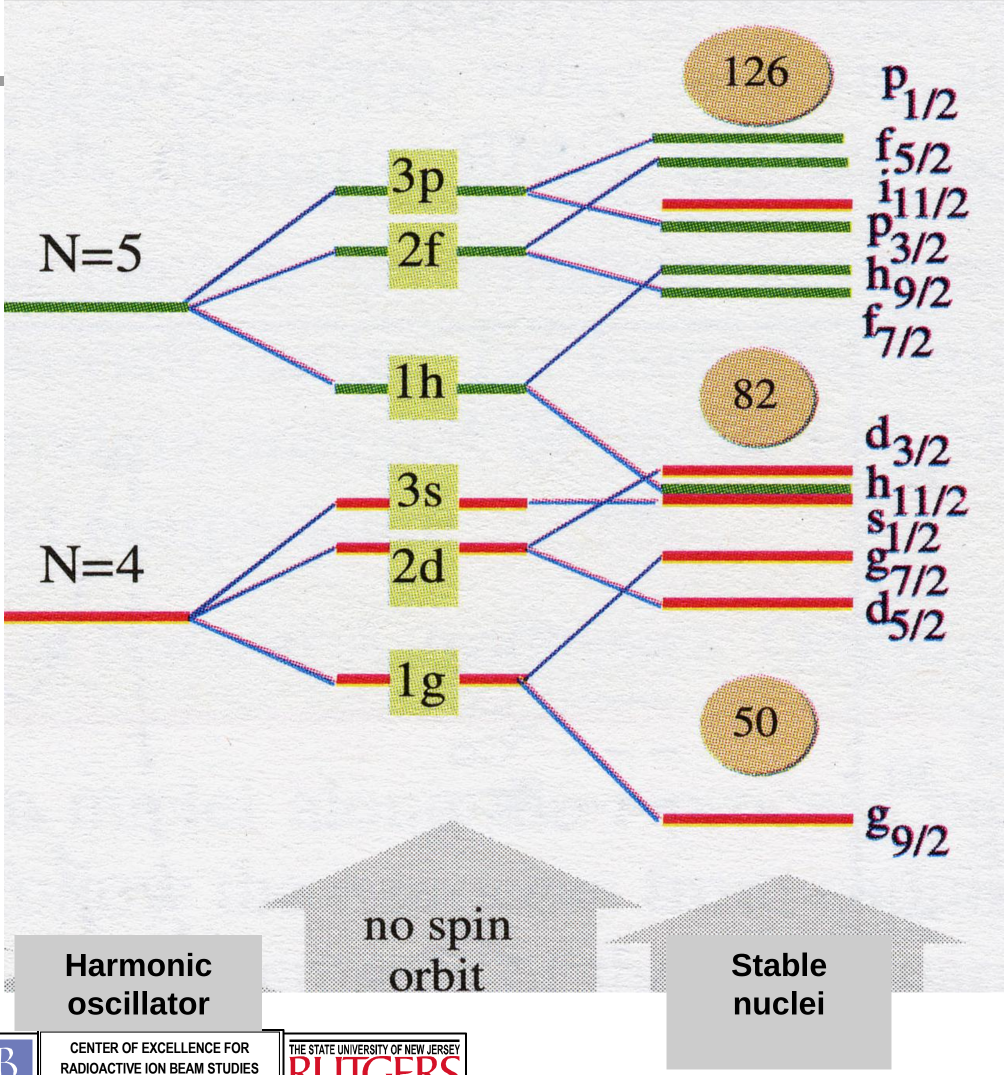
Verifying nuclear shell model

"Flat" harmonic oscillator potential with positive spin-orbit interaction



Harmonic oscillator

Stable nuclei

Confirming single-particle structure via (d,p) reactions at N=82

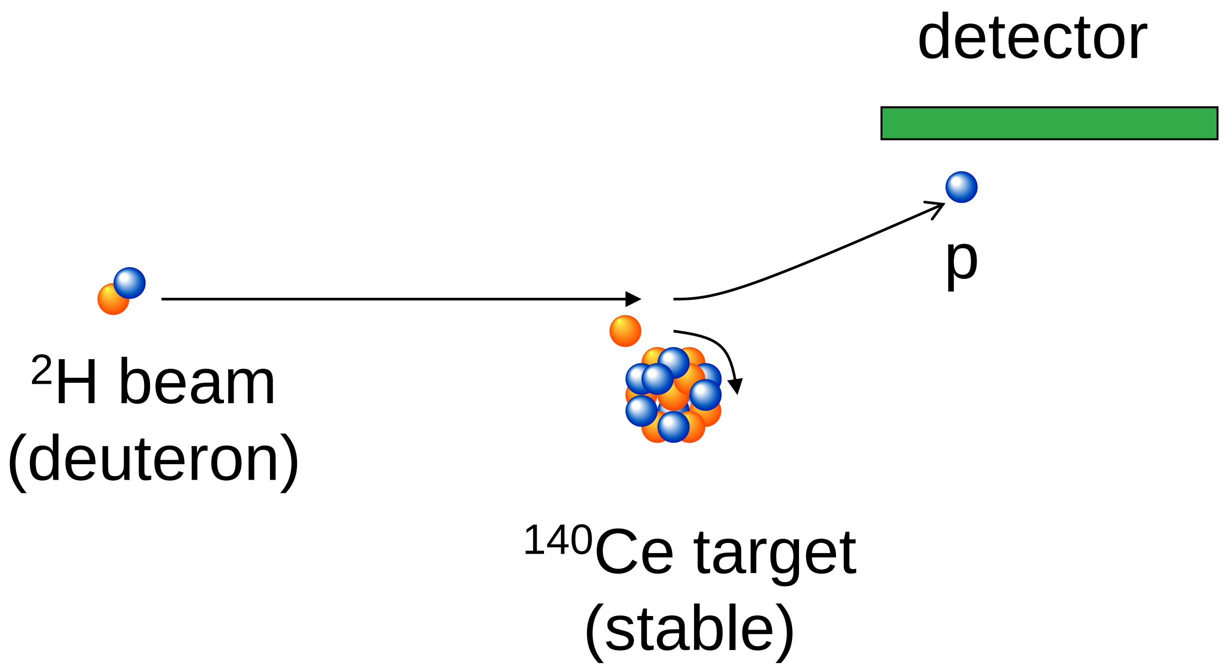
- Measure nuclear reaction in which ADD neutron to initial nucleus

$$ {}^{N+Z}_{Z}X_{N}({}^{2}_{1}H_{1},{}^{1}_{1}H_{0}){}^{N+1+Z}_{Z}X_{N+1} $$

$$ {}^{140}_{58}Ce_{82}(d,p){}^{141}_{58}Ce_{83} $$

- Energy of proton ⇒ Excitation energy in final nucleus
- Intensity of protons as function of angle ⇒ angular momentum transferred

Neutron transfer
(d,p) Reactions in Normal Kinematics

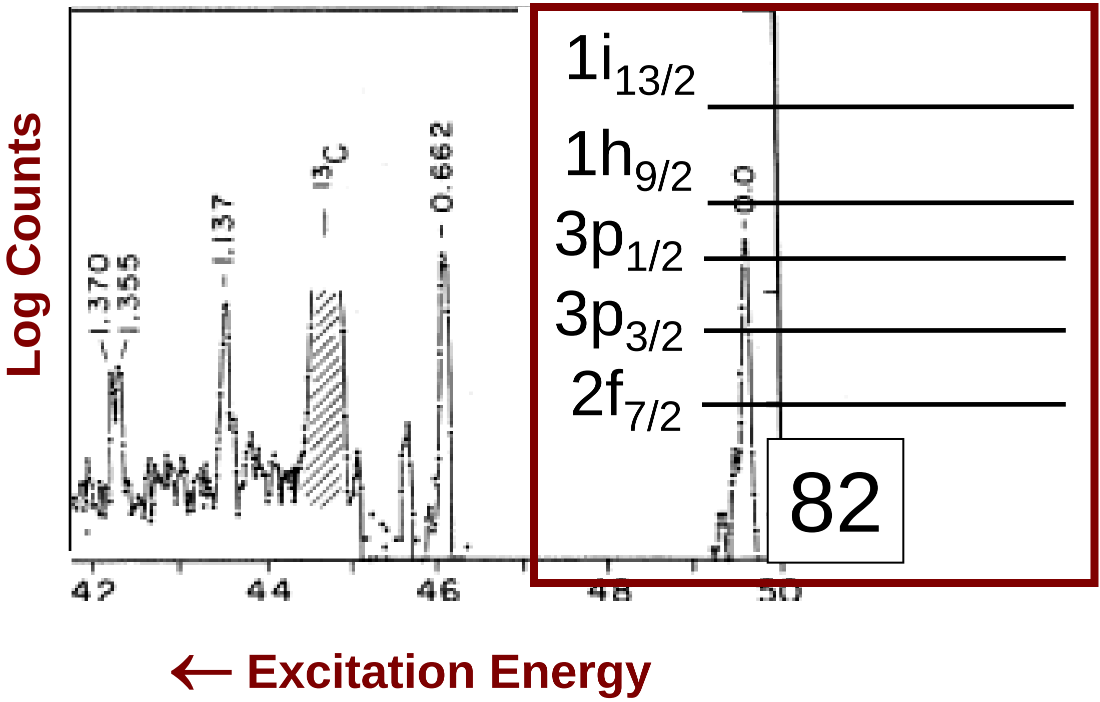


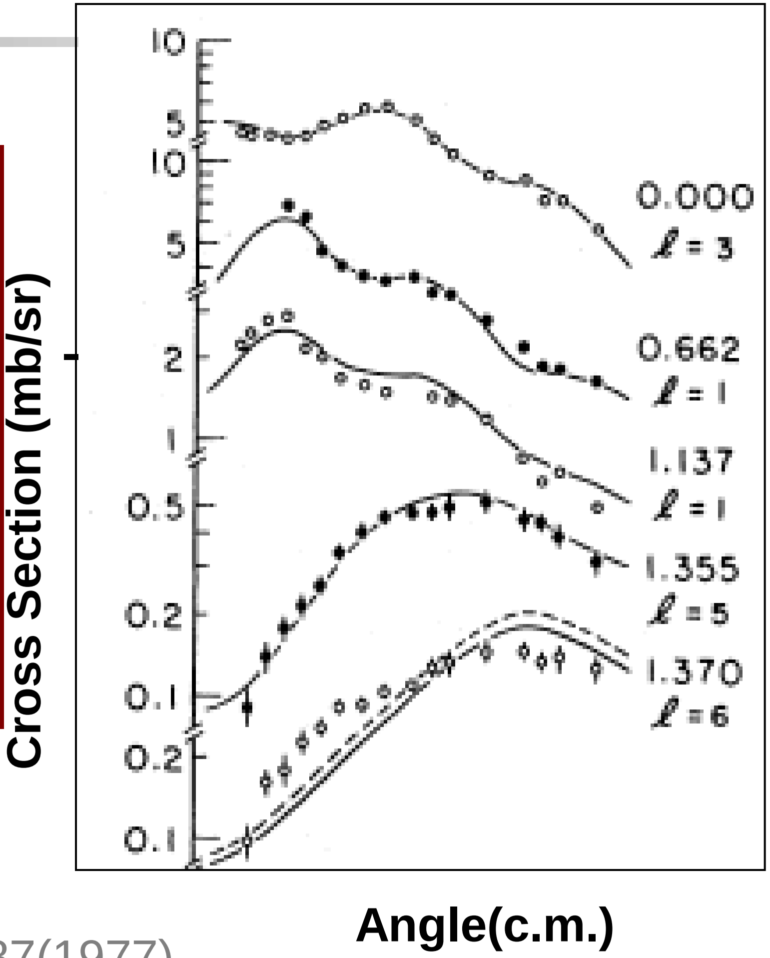
- Favorable kinematics → Good Q-value Resolution
- Deuteron beams are easy and cheap to produce
- **Only applicable to stable targets**

N=82 neutron transfer data

$$^{140}_{58}Ce_{82}(d,p)^{141}_{58}Ce_{83}$$

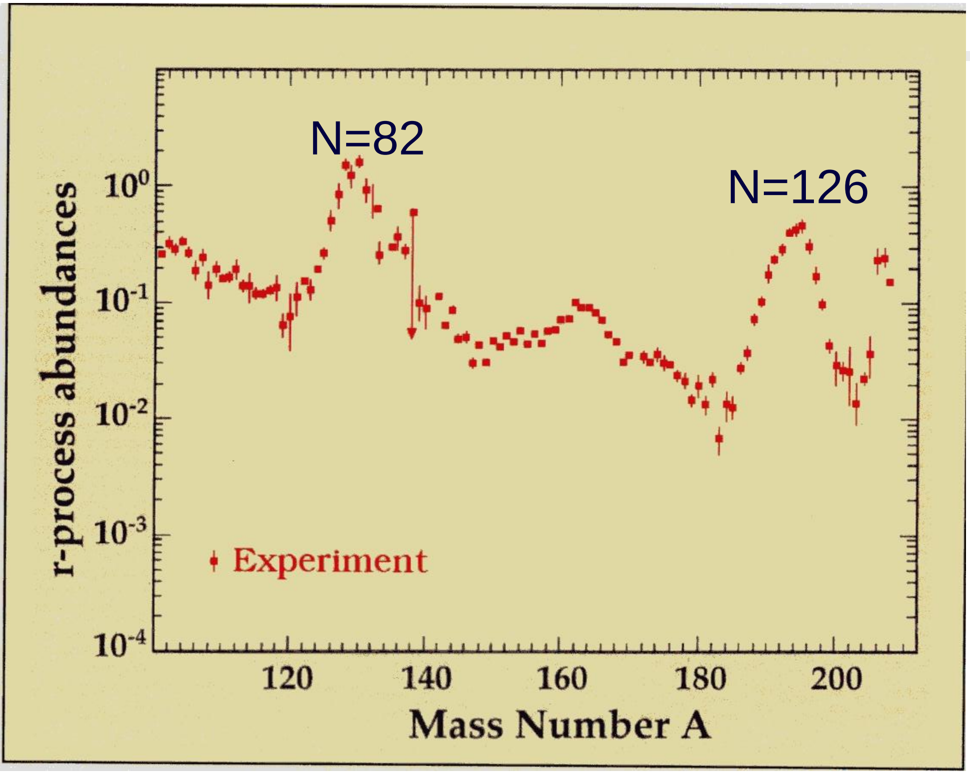
$$E(d)=17\,MeV$$





J.E. Park, W.W. Daehnick, M.J. Spisak, PRC 15, 587(1977)

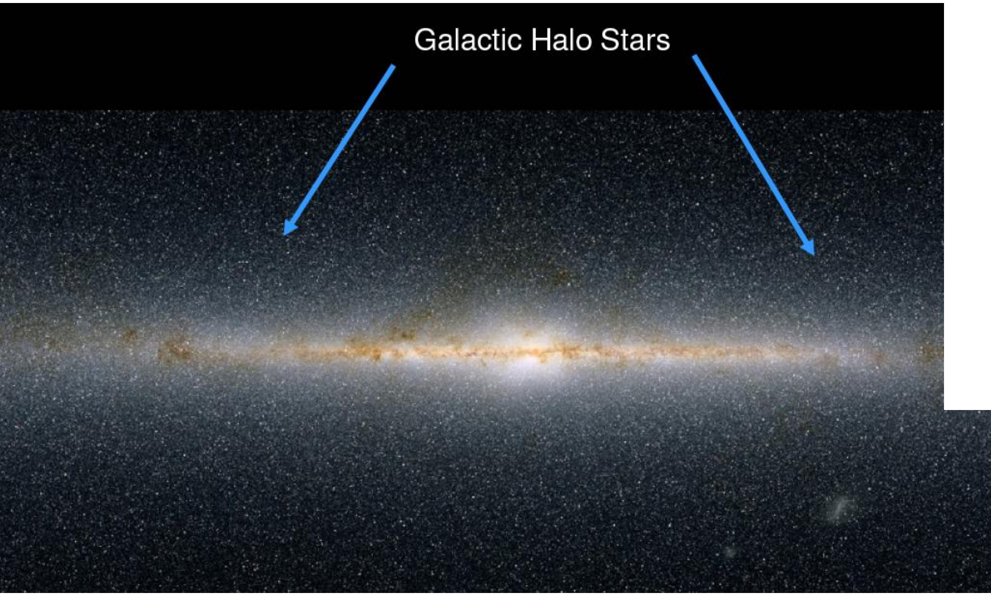
Evidence for Shell Structure: r process abundances of elements

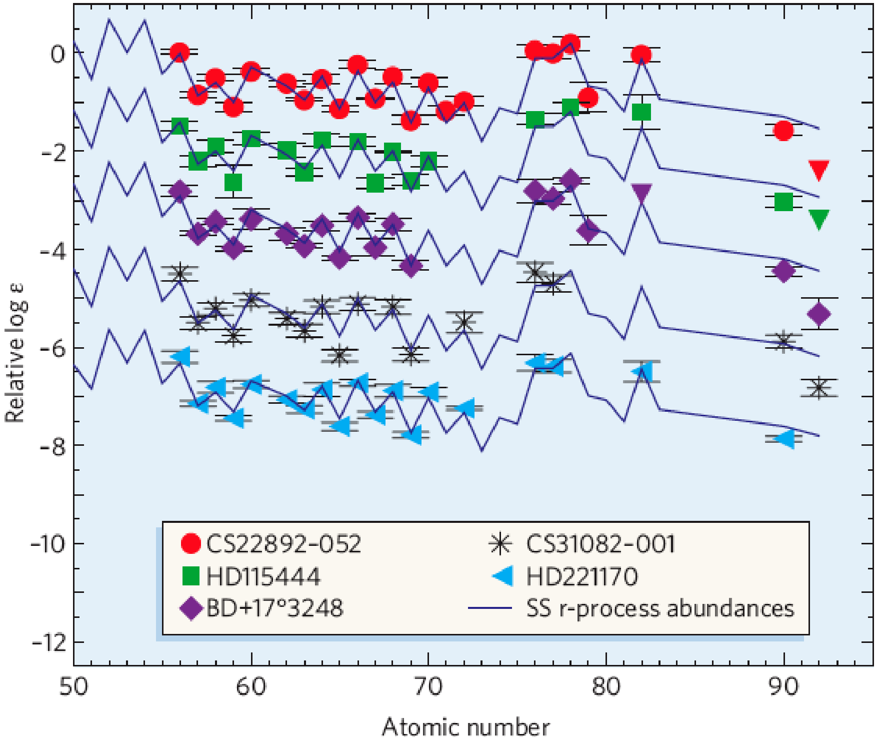


Solar abundances of r-process elements as function of mass

Peaks at isotopes with neutron numbers 82 and 126

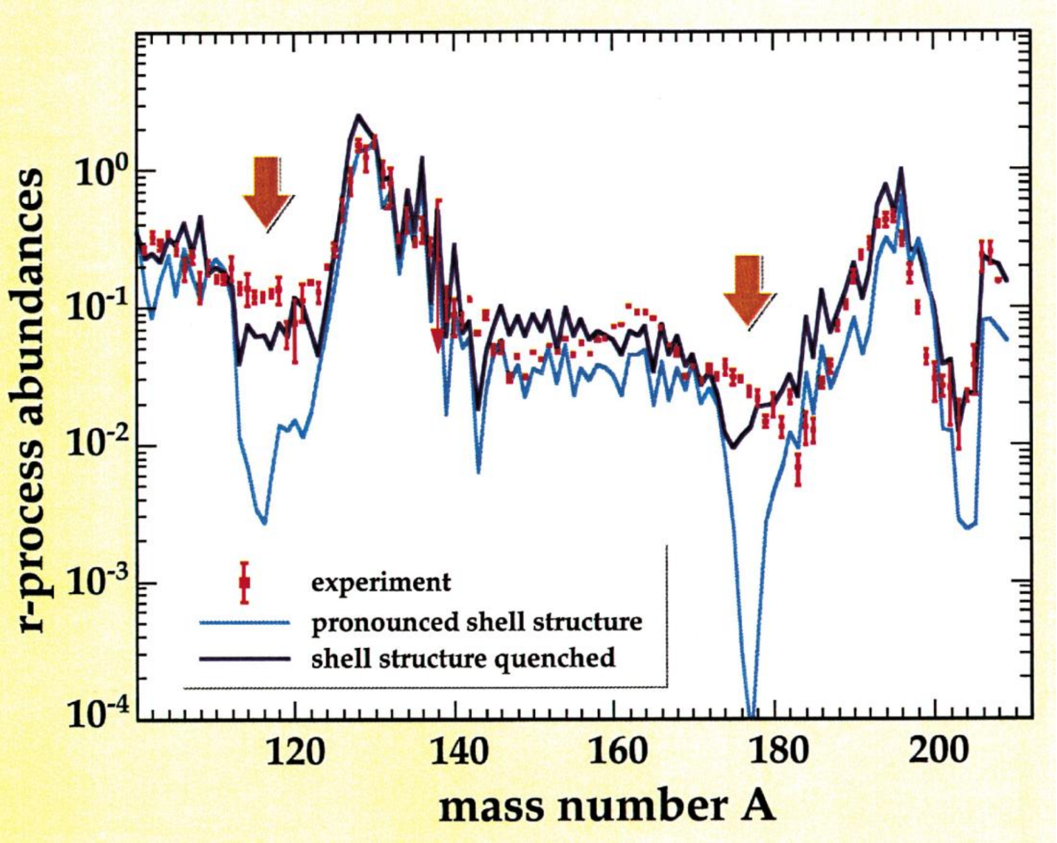
r process is robust, even oldest stars

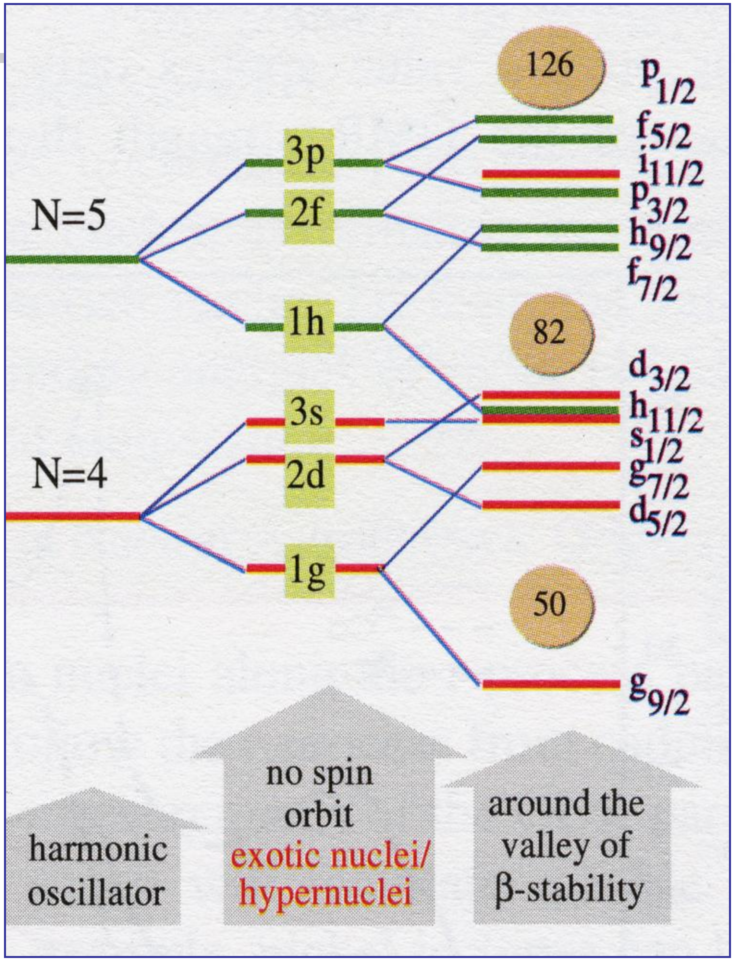




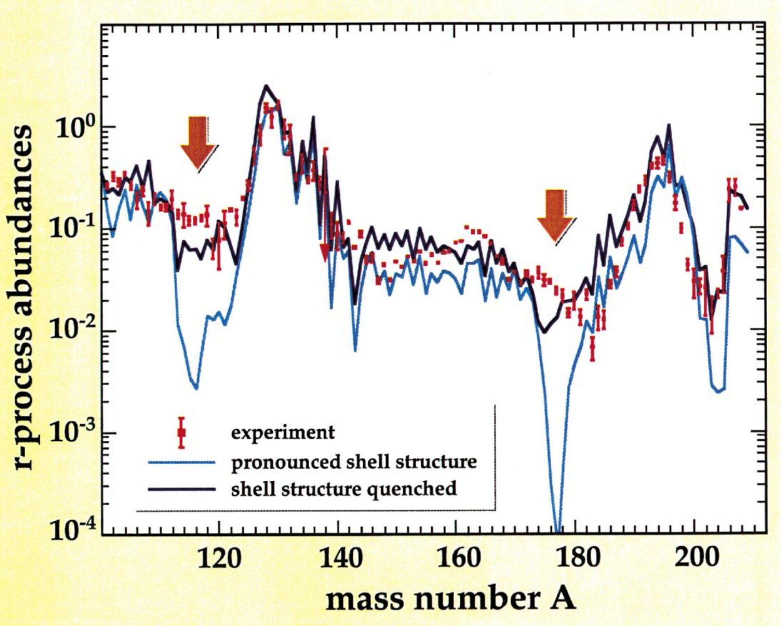
http://www.int.washington.edu/talks/WorkShops/int_06_2a/People/Cowan_J/cowan_int.pdf

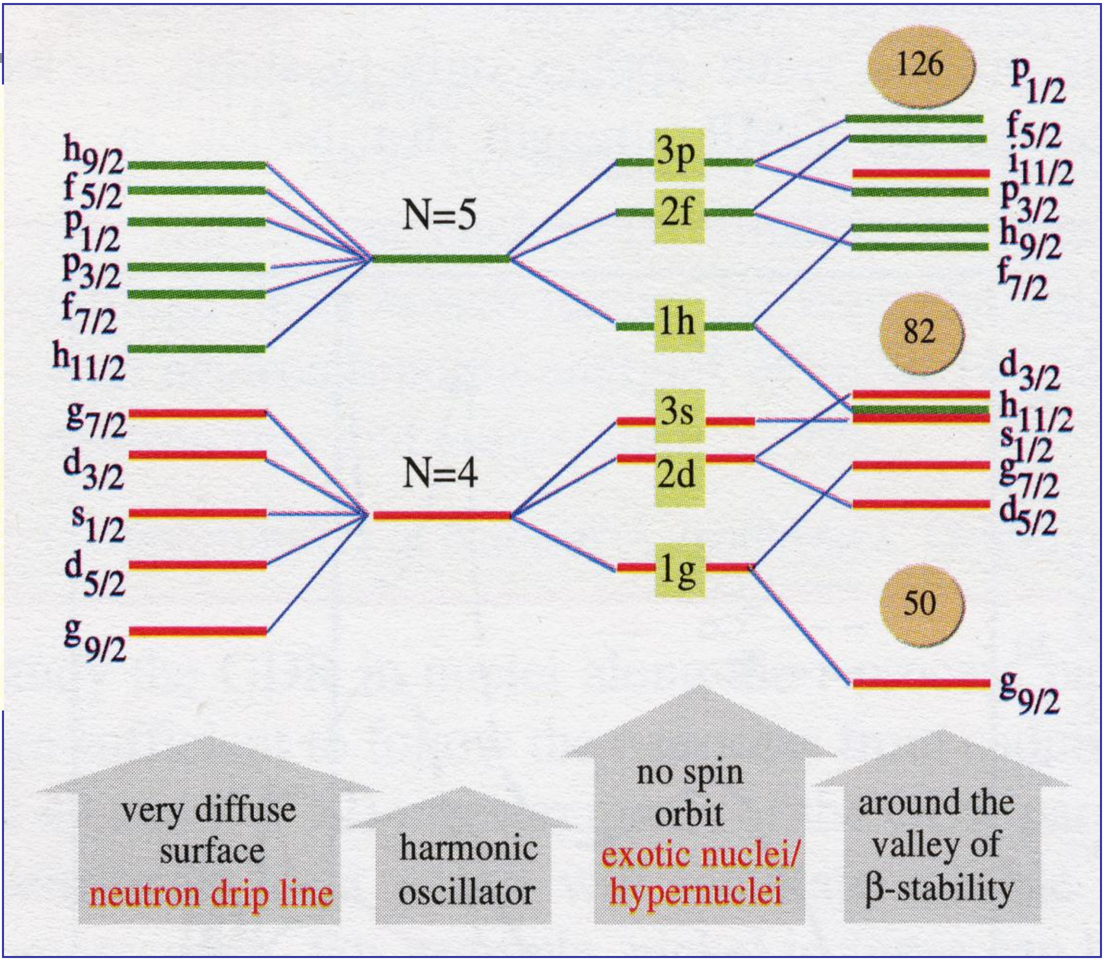
Evolution of nuclear shell structure?





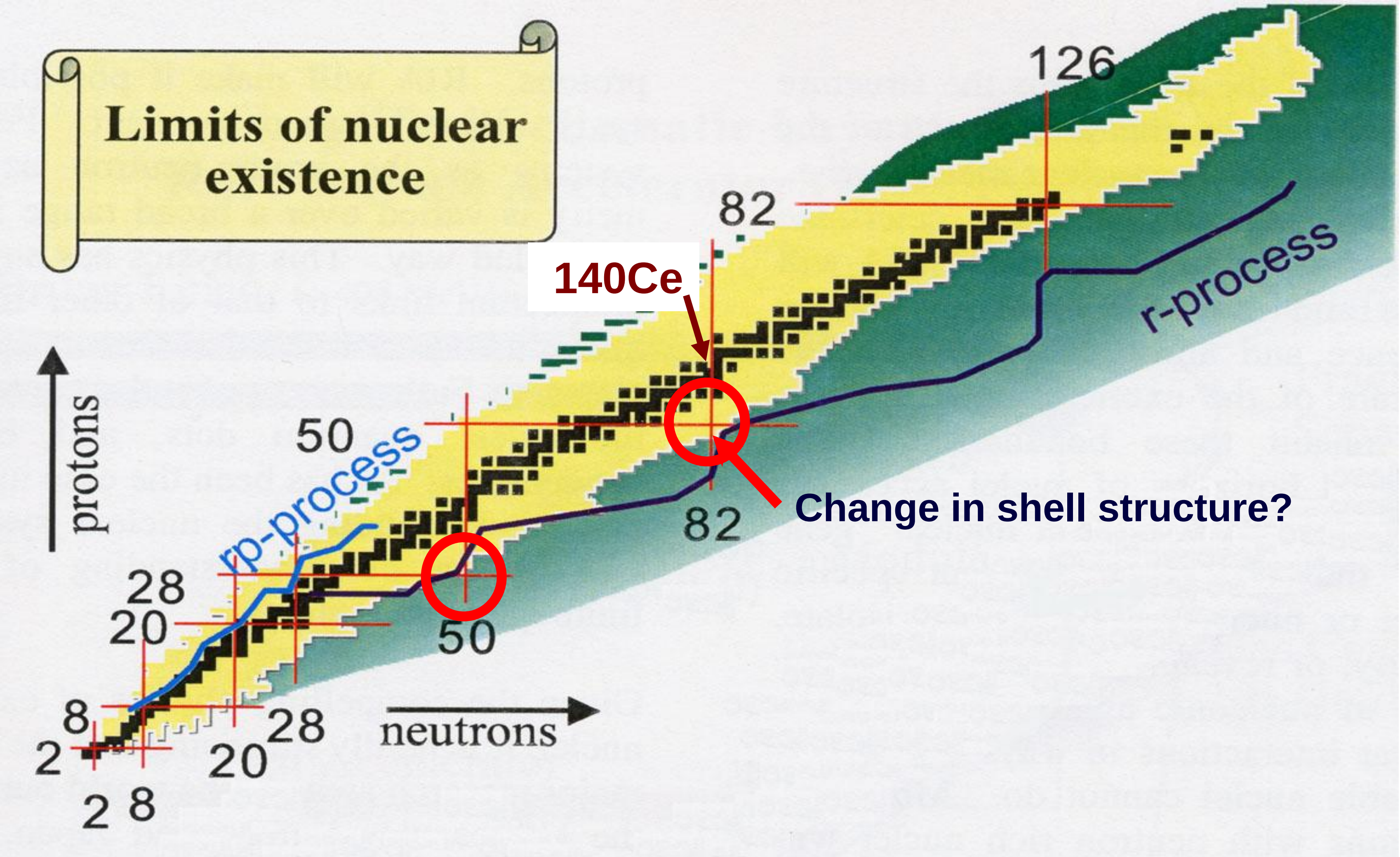
Evolution of nuclear shell structure?



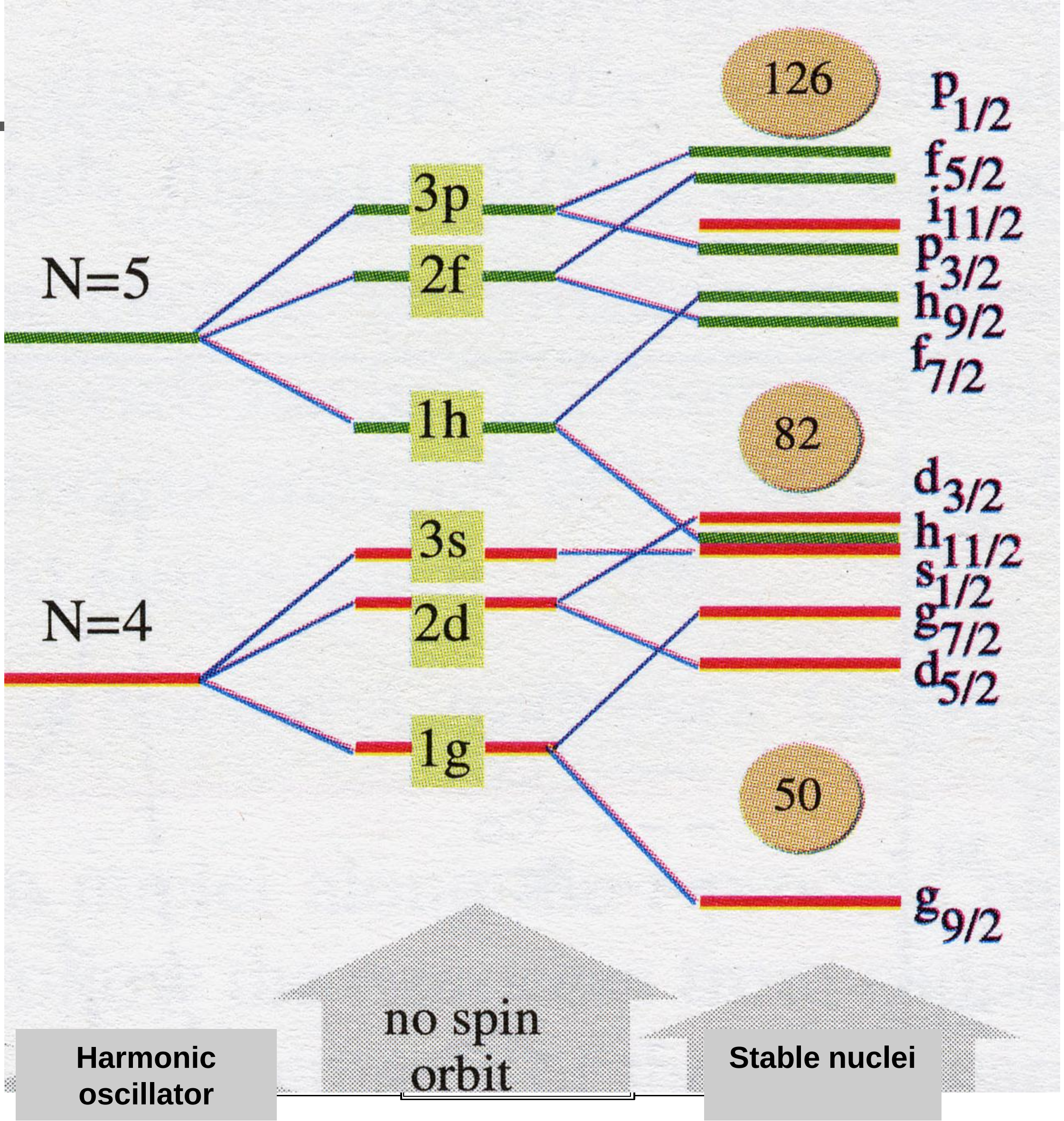


J. Dobaczewski, et al. PRC 53, 2809 (1996)
B. Pfeiffer, et al., NPA 693, 282 (2001).

Neutron-rich nuclei & shell closures



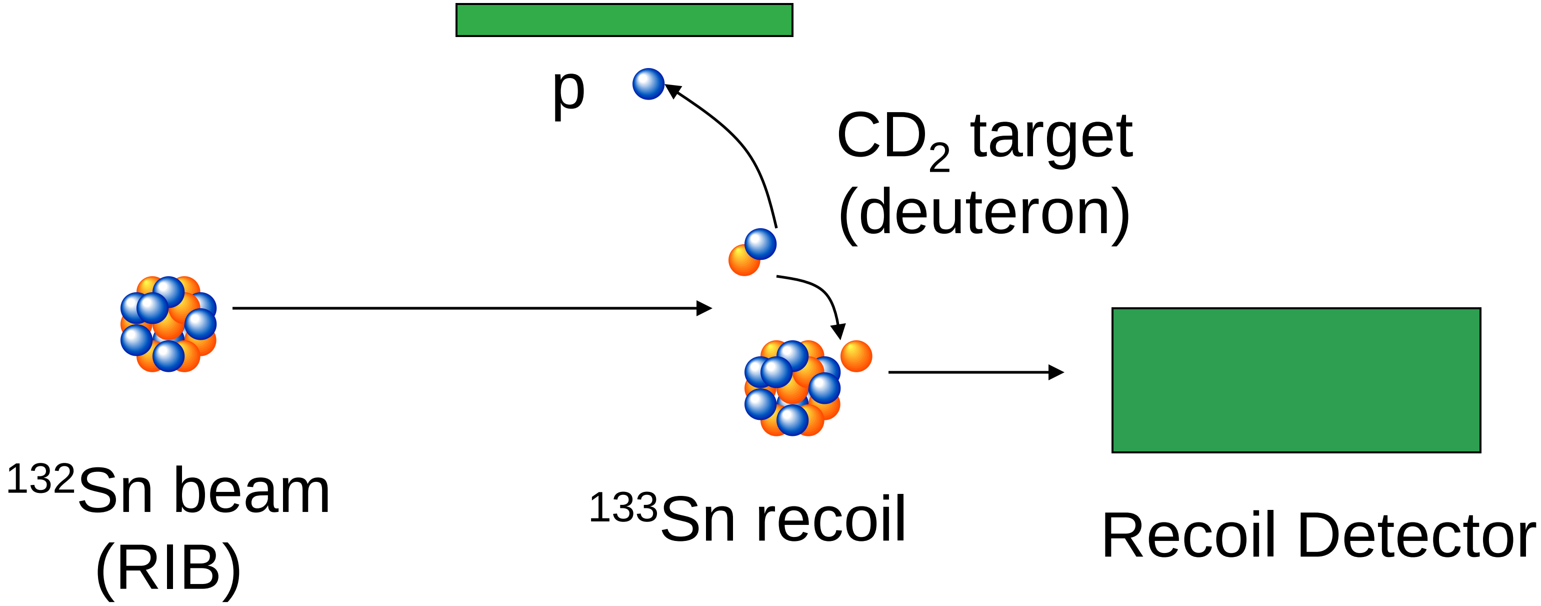
What are neutron orbitals N>82, Z=50?



Harmonic oscillator

Stable nuclei

Neutron transfer
(d,p) Reactions in Inverse Kinematics



p

CD_2 target
(deuteron)

^{132}Sn beam
(RIB)

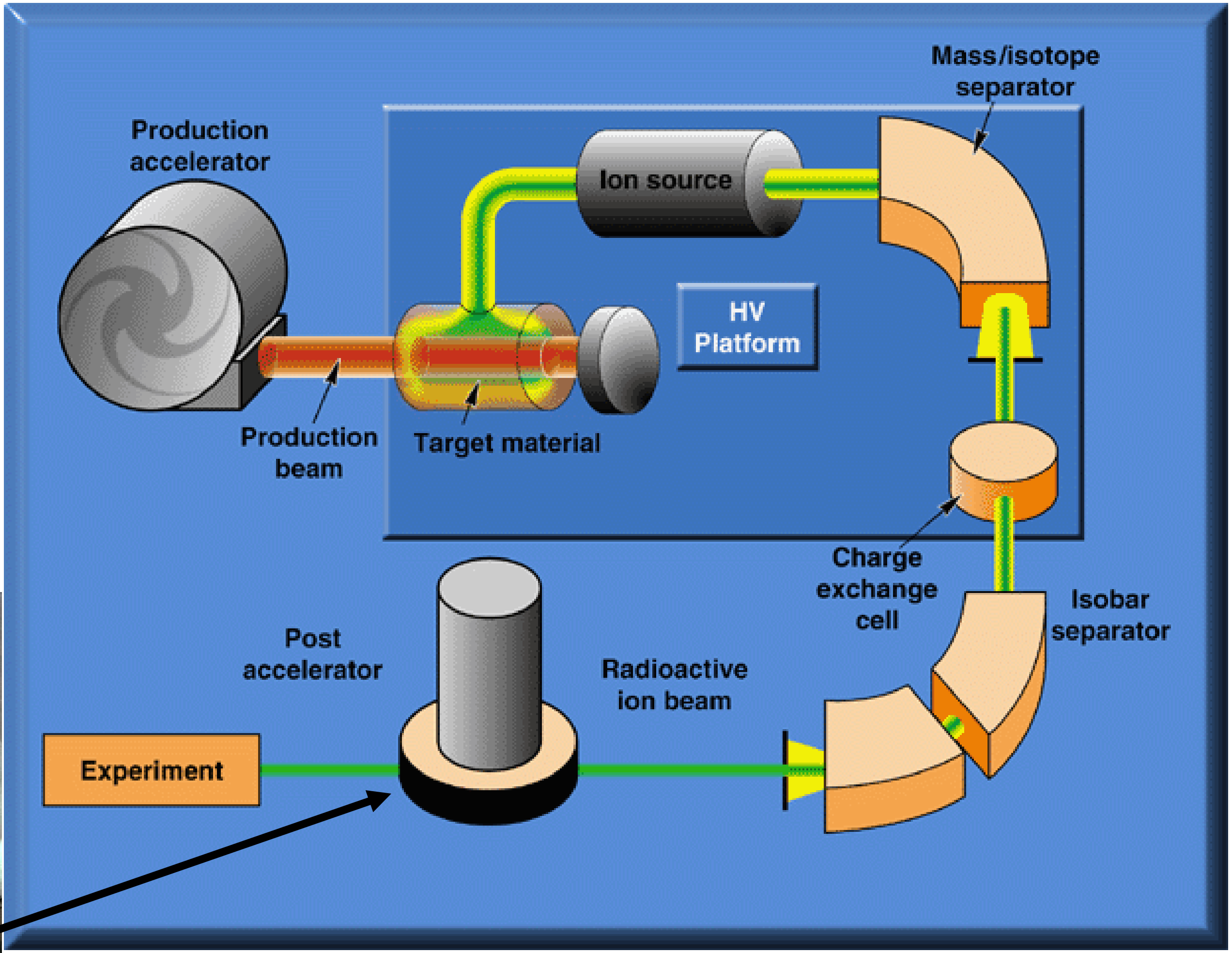
^{133}Sn recoil

Recoil Detector

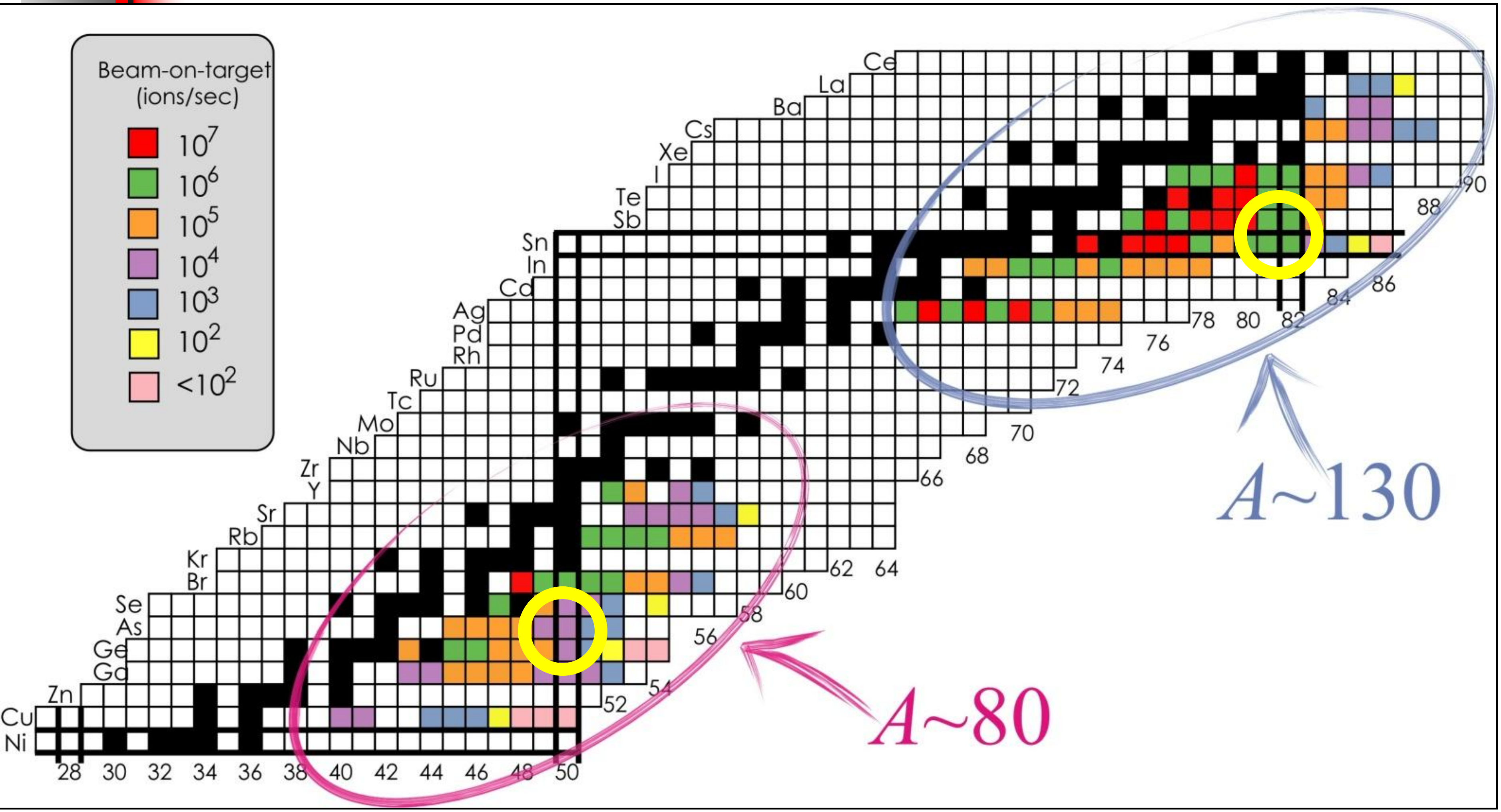
- Unfavorable kinematics → Reduced Q-value Resolution
- Rare Ion Beams (RIBs) are difficult and expensive to produce

Applicable to all isotopes which can be made into a beam; need ≈10^4 particles/second

Isotope Separator On Line for RIBs:
Holifield Radioactive Ion Beam Facility



HRIBF neutron-rich beams from p-induced fission of ^{238}U



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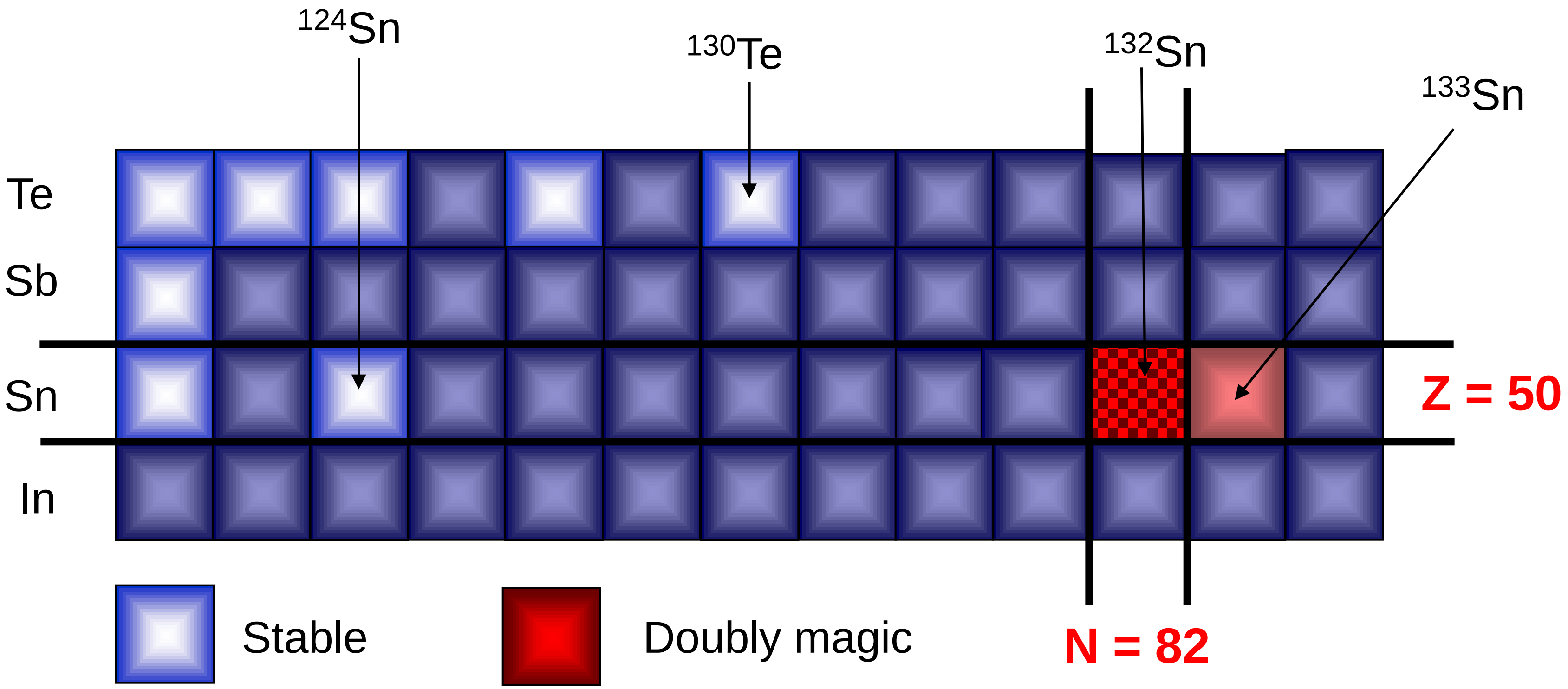
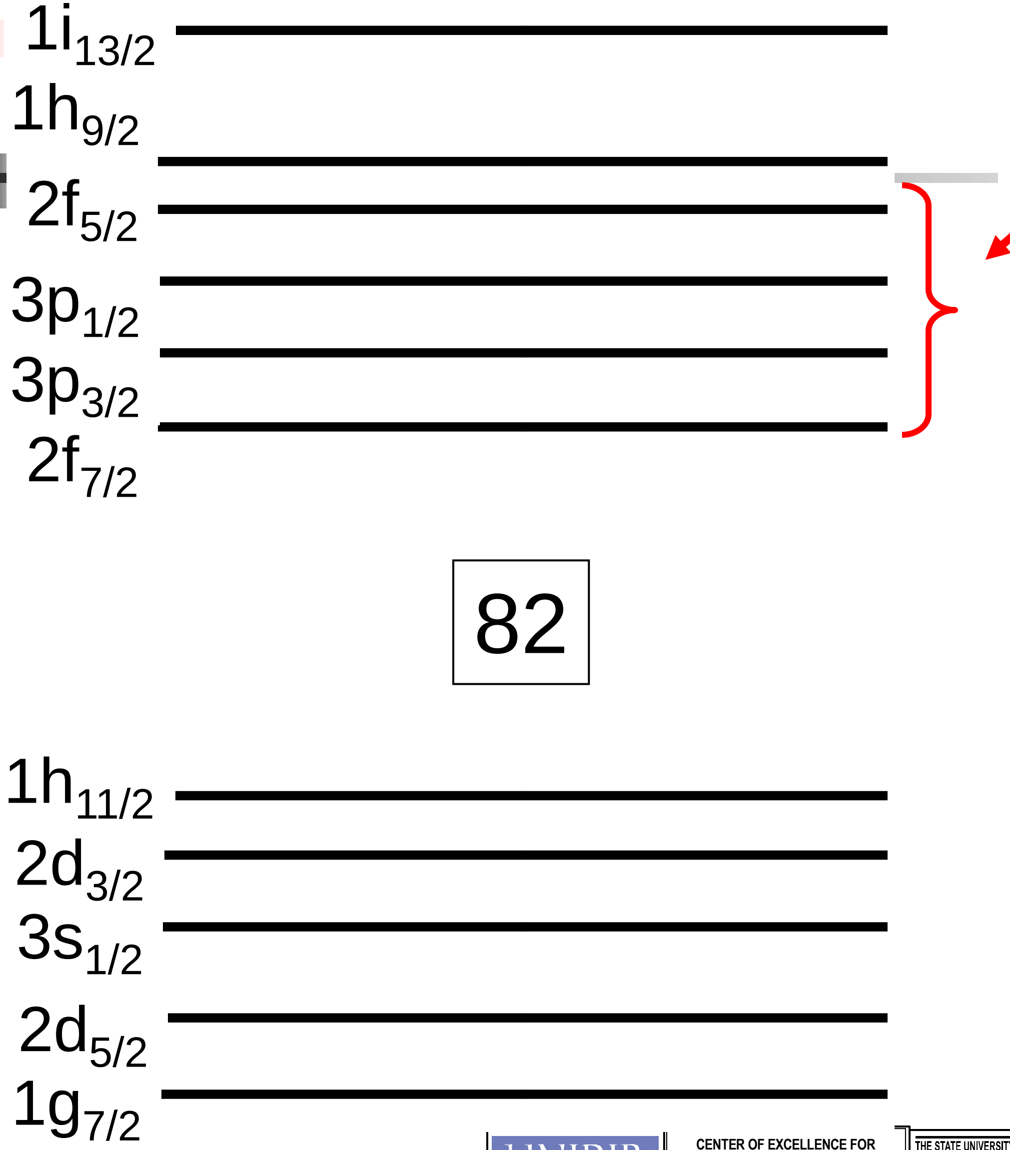
Transfer measurements with ^{132}Sn, Z=50, N=82



^{132}Sn(d,p) what should expect to see?



$1i_{13/2}$

$1h_{9/2}$

$2f_{5/2}$

$3p_{1/2}$

$3p_{3/2}$

$2f_{7/2}$

82

$1h_{11/2}$

$2d_{3/2}$

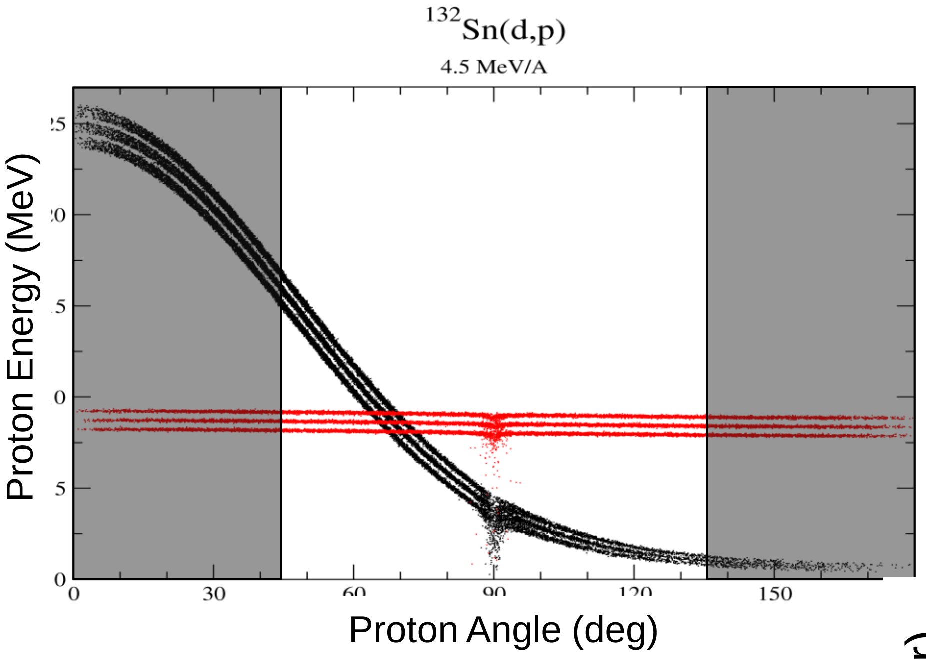
$3s_{1/2}$

$2d_{5/2}$

$1g_{7/2}$

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

^{132}Sn(d,p) kinematics @ 4.7 A-MeV



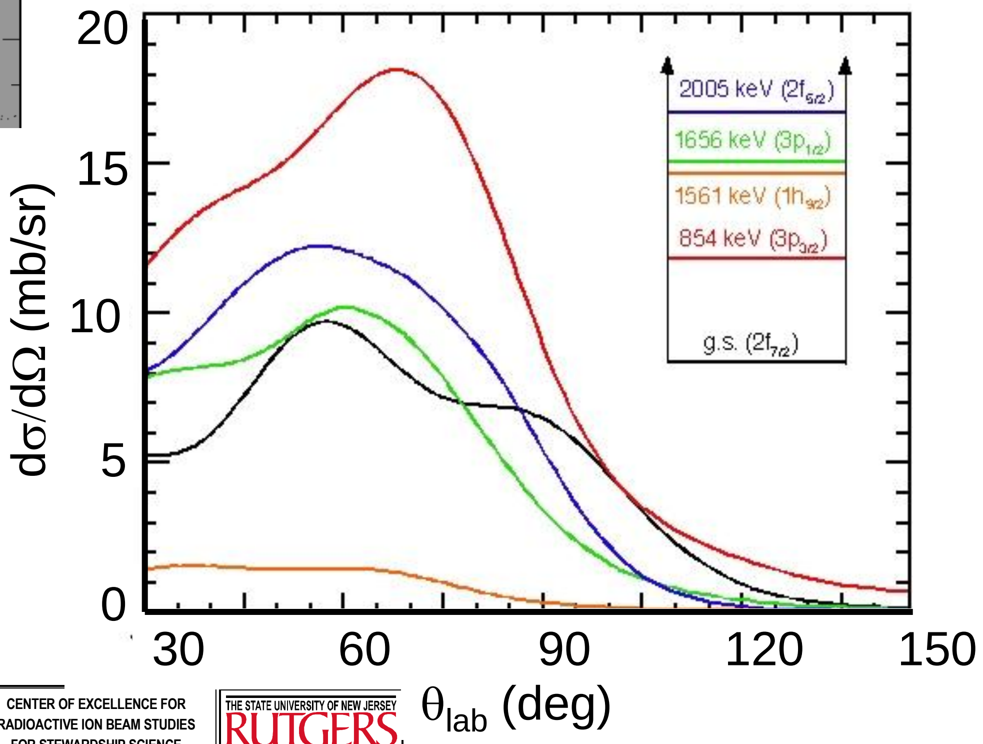
Forward $\theta_{c\text{-}o\text{-}m}$ ↔ backward θ_{lab}

At backward θ_{lab}: E_{proton} very small cross section very small.

At forward θ_{lab}: E_{proton} rises quickly with angle ($dE/d\theta$ is large).

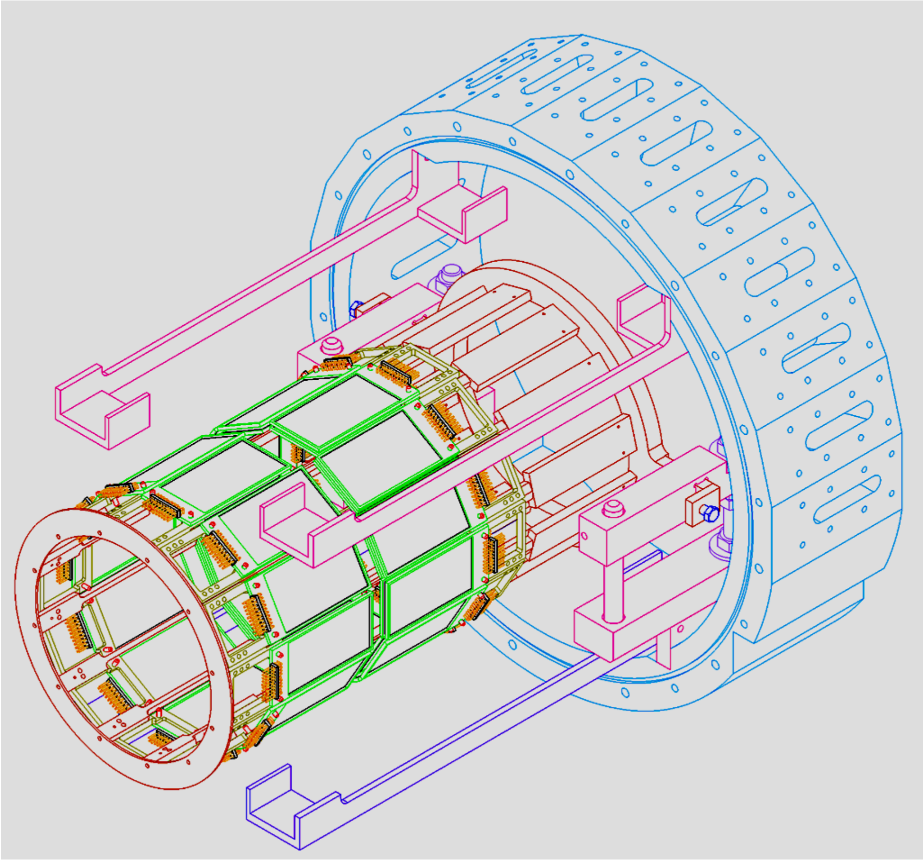
Want to measure around 90°

Good angle resolution



^{132}Sn(d,p) detectors

Oak Ridge Rutgers University Barrel Array (ORRUBA)



- Flexible design to measure light products from transfer reactions
- 2 rings of 12, resistive and non-resistive Si detectors (1000μm, 500μm and 65μm)
- ~80% ϕ coverage, angles 47° →132°
- 324 electronics channels

S.D. Pain (Rutgers & ORNL), et al. NIM **B261**, 1122 (2007)

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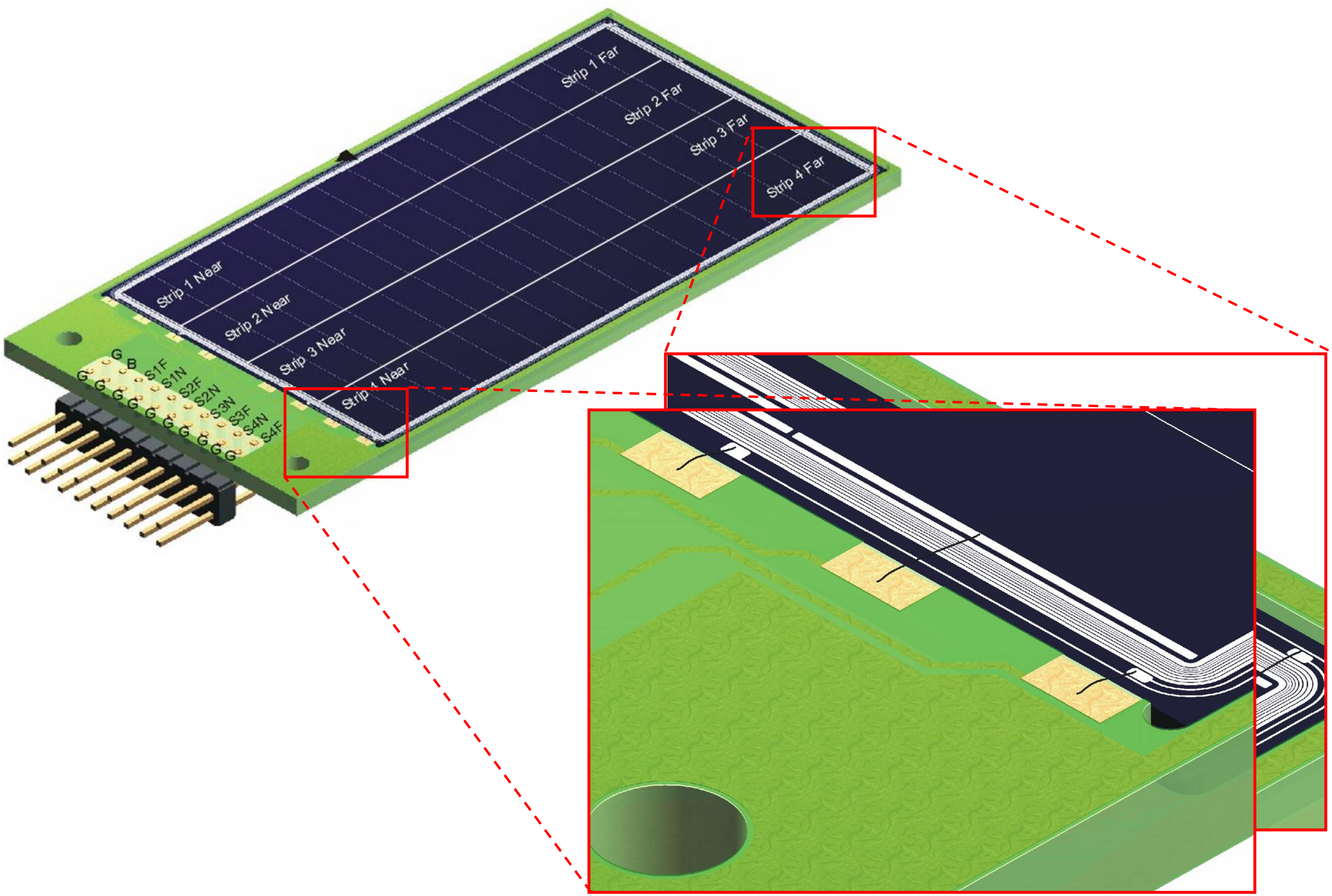
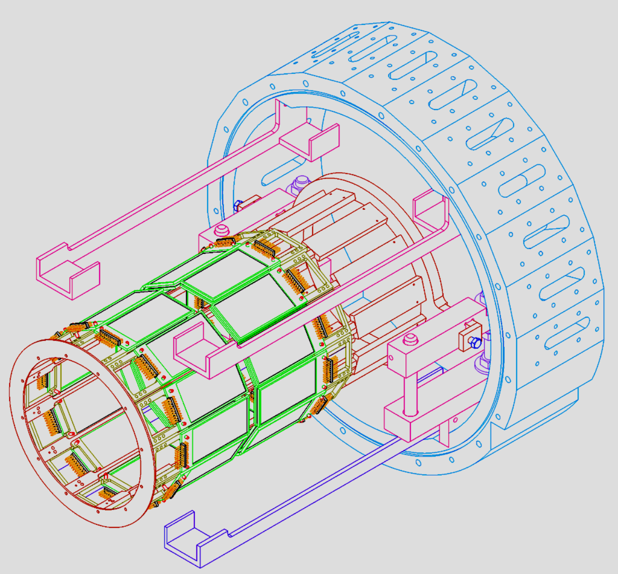
ORRUBA position-sensitive (resistive strip) detectors

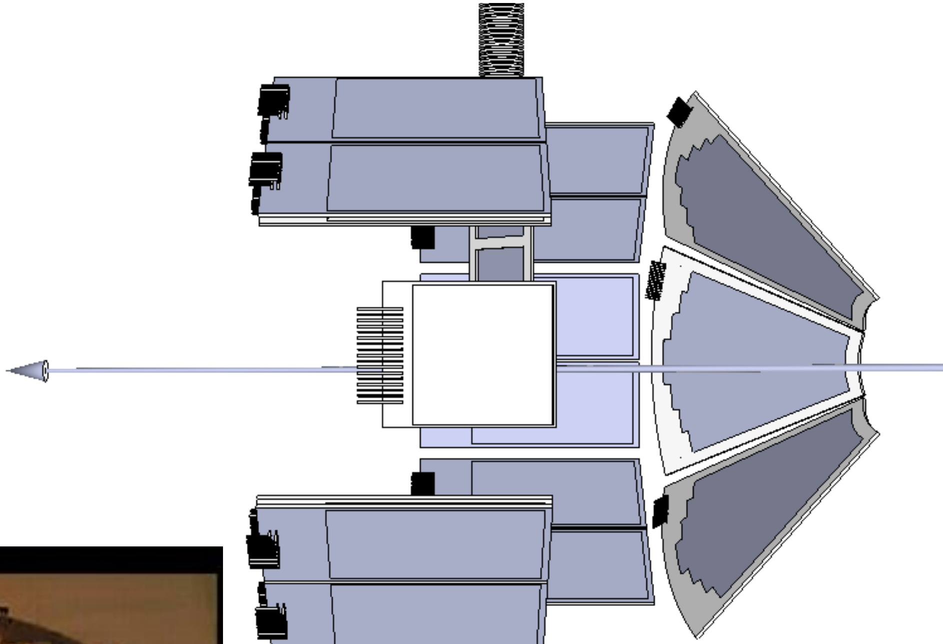


^{132}Sn(d,p) detectors

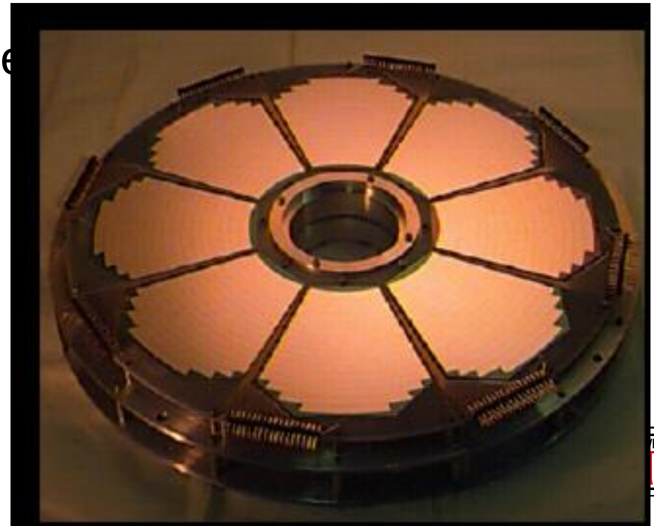
Oak Ridge Rutgers University Barrel Array (ORRUBA)



Early implementation of ORRUBA w/ SIDAR

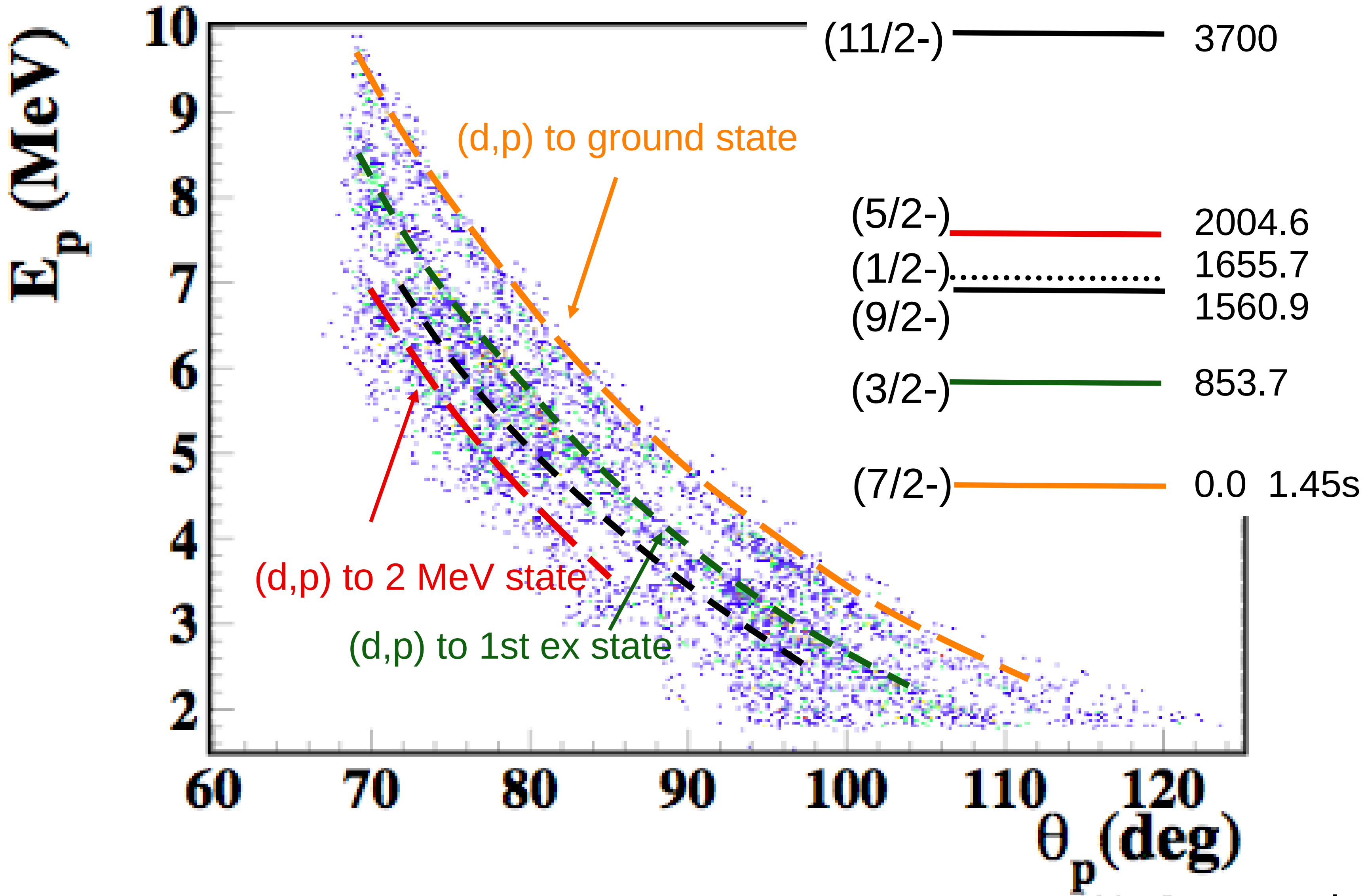


- 10 resistive strip Si dete
140µm and 65µm)
- Angles 47° →132°



SIDAR:
6 segments of 16-strip Si detectors in lampshade mode

^{132}Sn(d,p) data in lab



K.L. Jones et al.

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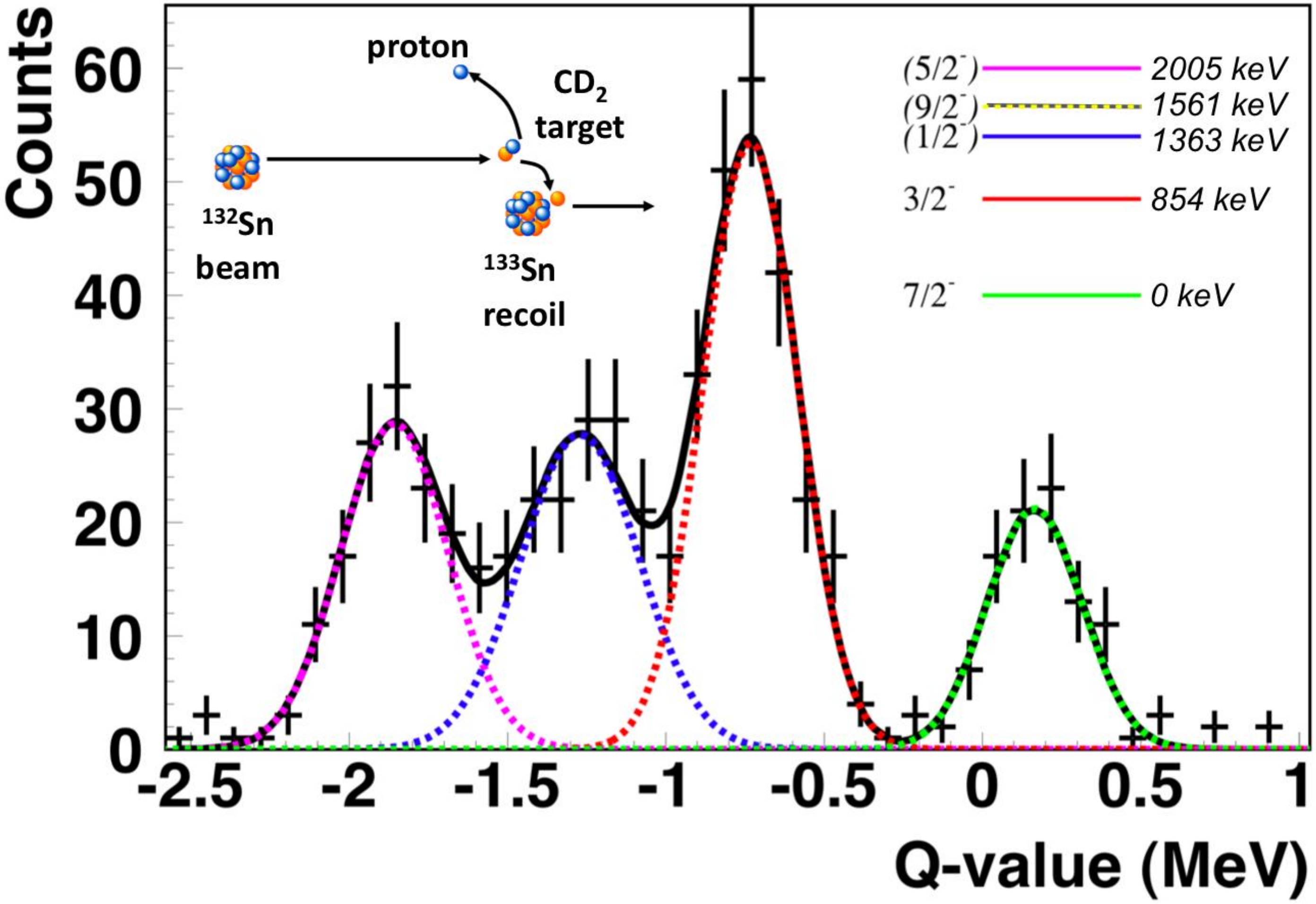
^{132}Sn(d,p) Q-value



K.L. Jones et al.
Nature, **465**,454 (2010)

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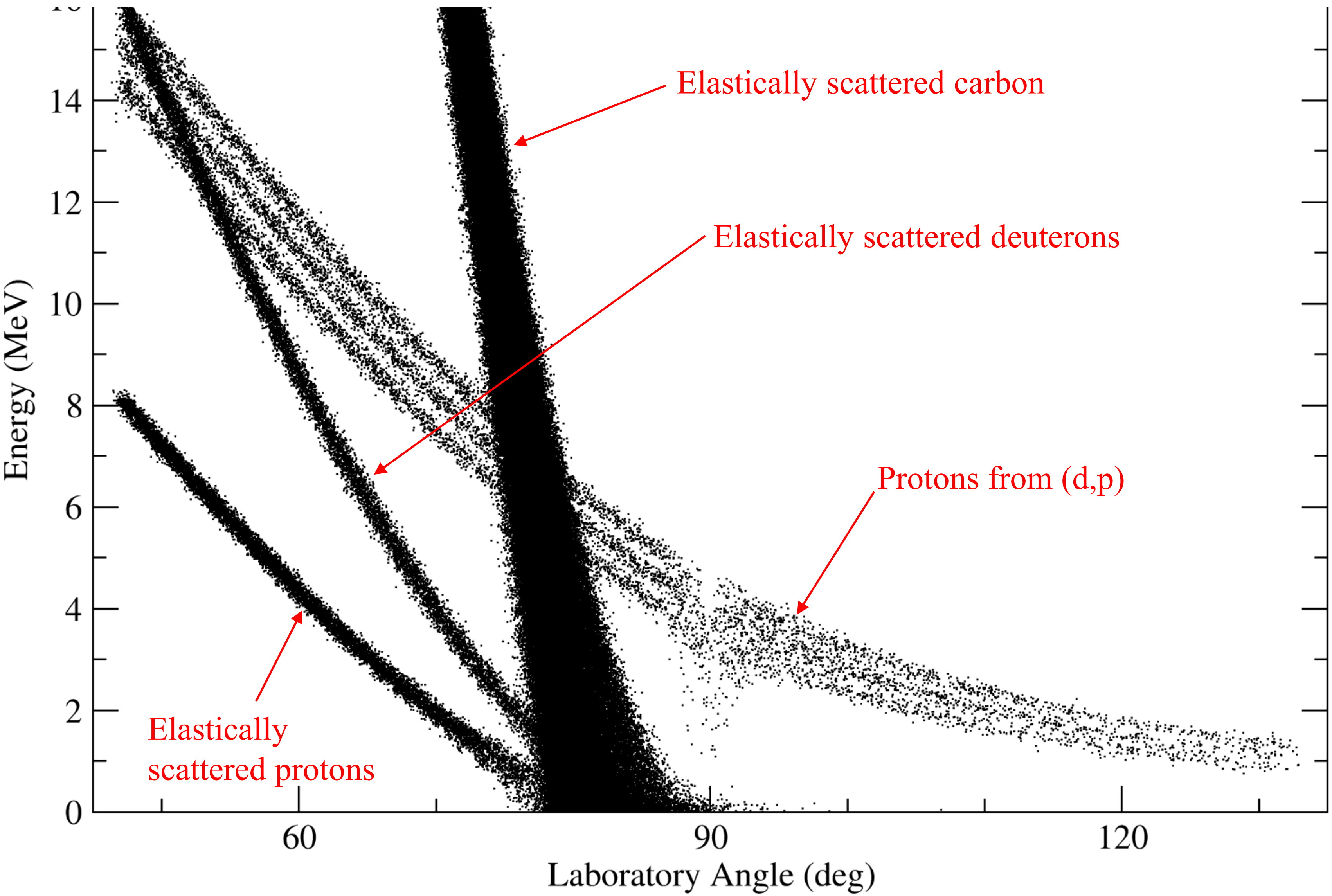
Getting the physics out

- (d,p) exp cross sections
  - Absolute exp cross sections ⇐ normalization of data from elastic scattering of deuterons

- Spectroscopic factors

Simulation of ^{132}Sn+ CD_2 targets: Measure elastics for normalization



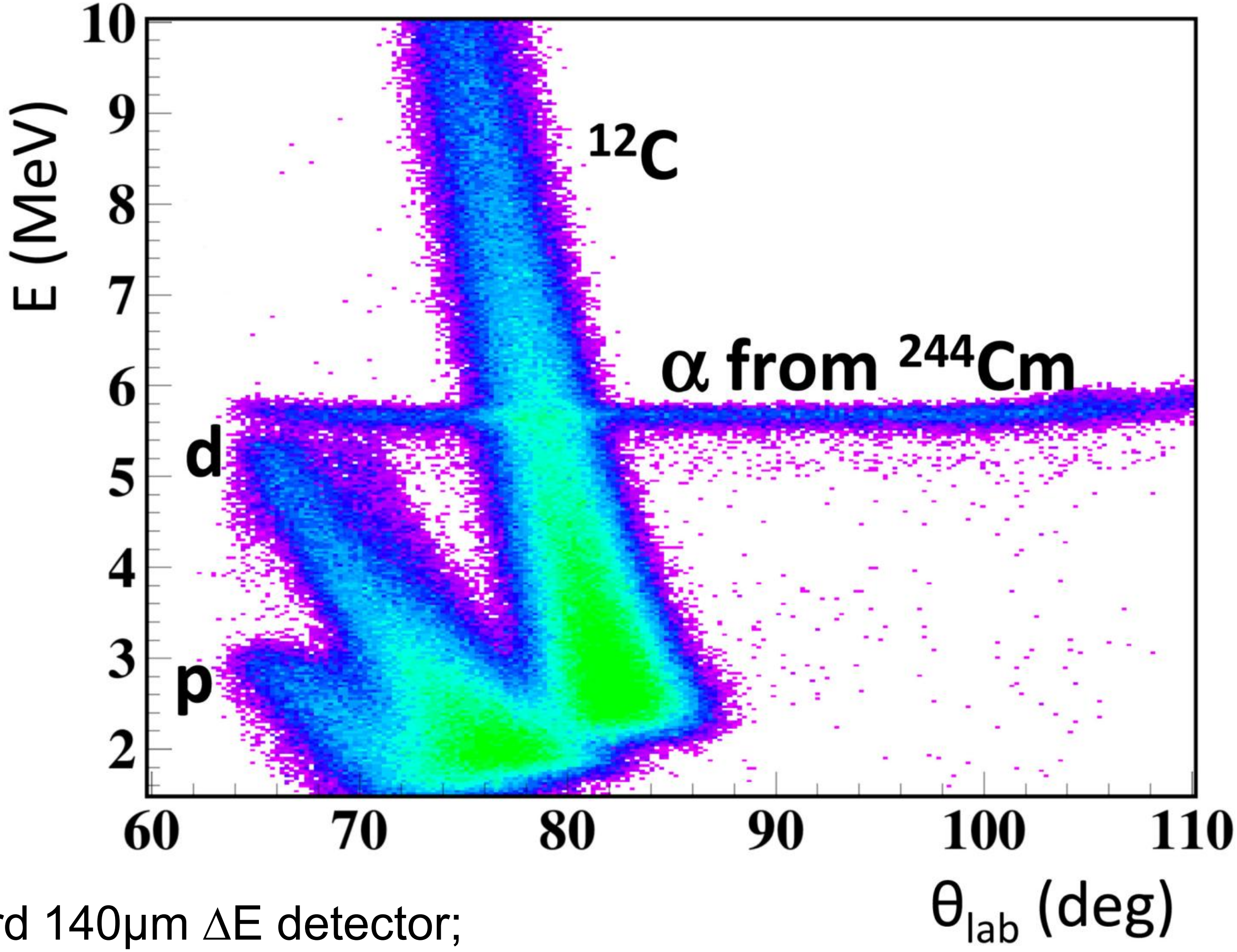
Elastically scattered carbon

Elastically scattered deuterons

Protons from (d,p)

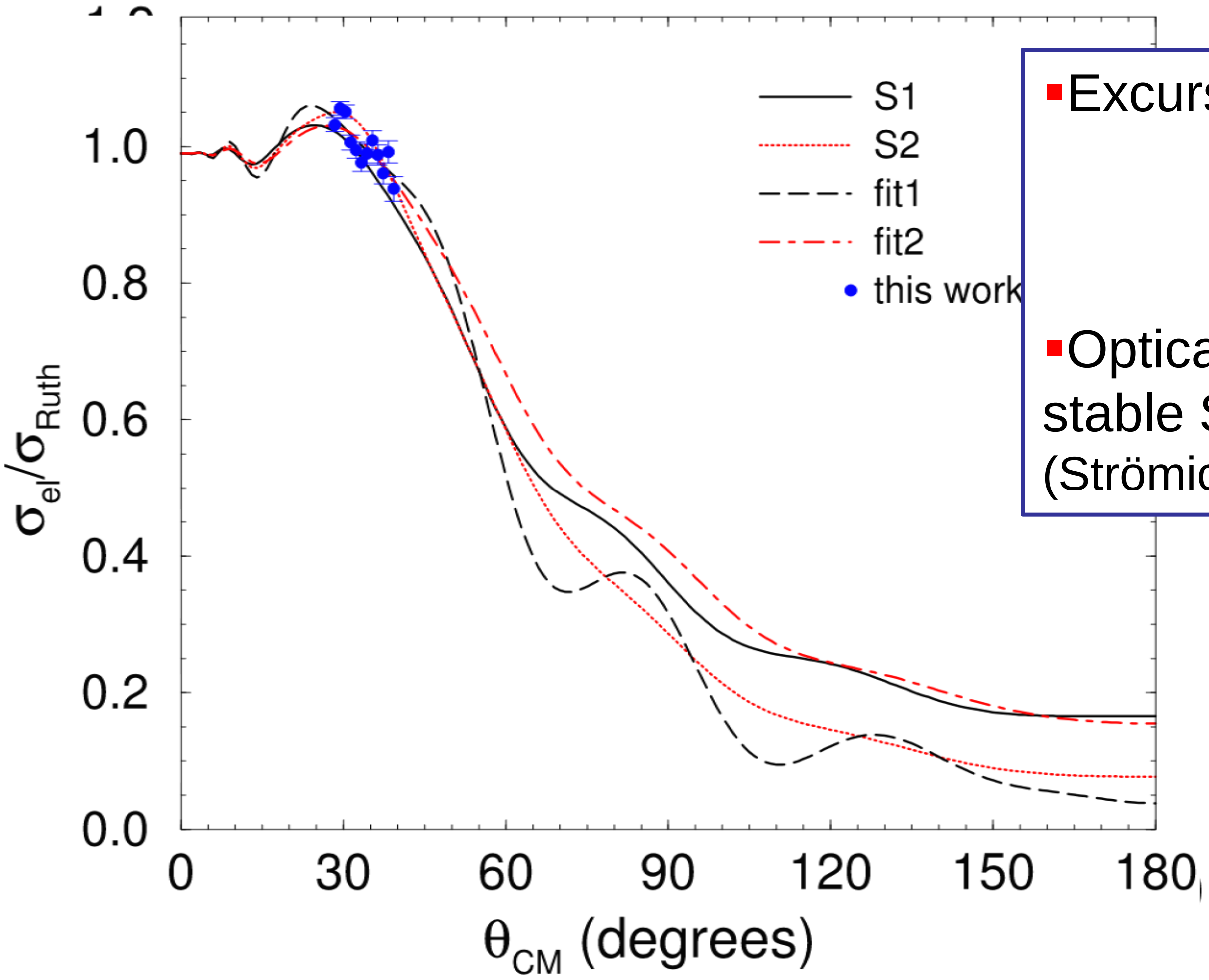
Elastically scattered protons

Elastic scattering of ^{132}Sn on CD$_2$ target



Forward 140μm ΔE detector;
Most forward θ_{cm} ⇔ lowest E deuterons

Elastic scattering of ^{132}Sn on deuterons



- Excursion from Rutherford <8%

  ≈70° $<\theta_{lab}<$≈76° ;

  ≈28° $<\theta_{cm}<$≈38°

- Optical model parameters from stable Sn nuclei

  (Strömich et al., PRC 16, 2193 (1977)

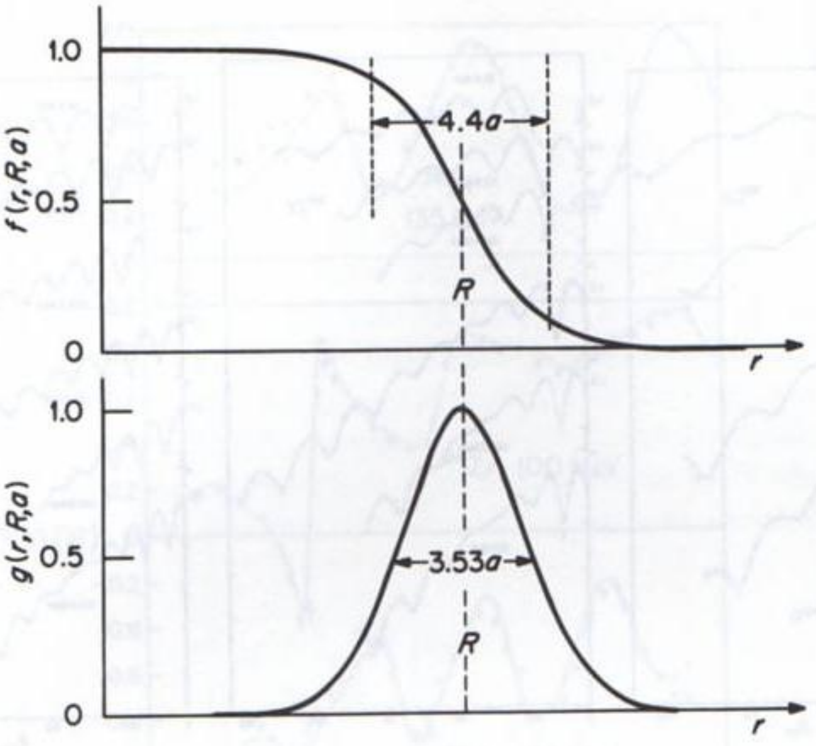
K.L. Jones et al.,
PRC (in press 2011)

(d,p) spectroscopic factors

- Input for theoretical cross sections DWBA
  - Potentials (optical model)
    - Incoming deuteron, outgoing proton, neutron bound state

$$\boxed{S = \left(\frac{d\sigma}{d\Omega}\right)_{\exp} \Big/ \left(\frac{d\sigma}{d\Omega}\right)_{DWBA}}$$

(d,p) optical model parameters



Woods Saxon potential

- Radius: $R=r_oA^{1/3}$
- Diffuseness: a
- Volume term
- Surface absorption term (derivative of W-S)
- Spin-orbit term (Thomas shape)

Deuteron & proton

Neutron: to fit the binding energy

$$U(r) = -Vf(r,R,a) - iW_D g(r,R'a') - V_{SO} r^{-1}(d/dr)f(r,R_{SO},a_{SO})$$

Satchler, Intro to Nuclear Reactions

A(d,p)B spectroscopic factors

- Input for theoretical cross sections DWBA
  - Potentials (optical model)
    - Incoming deuteron, outgoing proton, neutron bound state
  - Wave function of transferred particle, e.g., $2f_{7/2}$ neutron

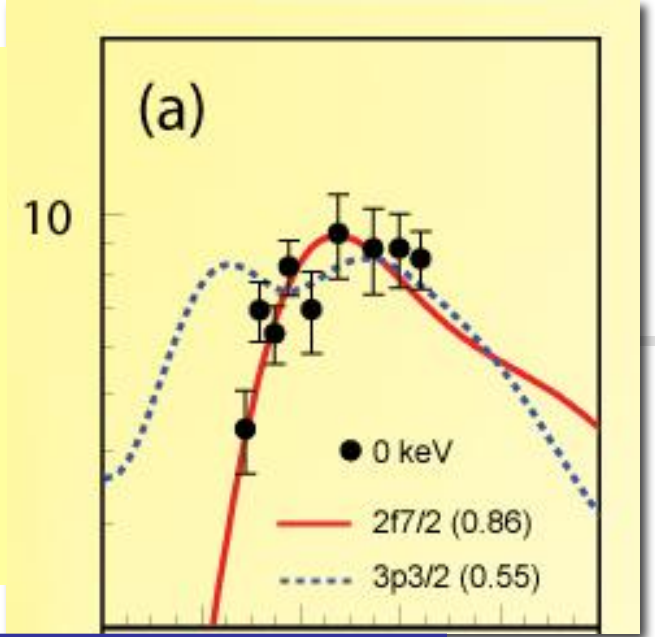
$$I_{An}^{B} = A_{\ell sj}\varphi_{\ell sj}(r) \qquad S_{\ell sj} = \left|A_{\ell sj}\right|^2$$

$$\boxed{S = \left(\frac{d\sigma}{d\Omega}\right)_{\exp} \Bigg/ \left(\frac{d\sigma}{d\Omega}\right)_{DWBA}}$$

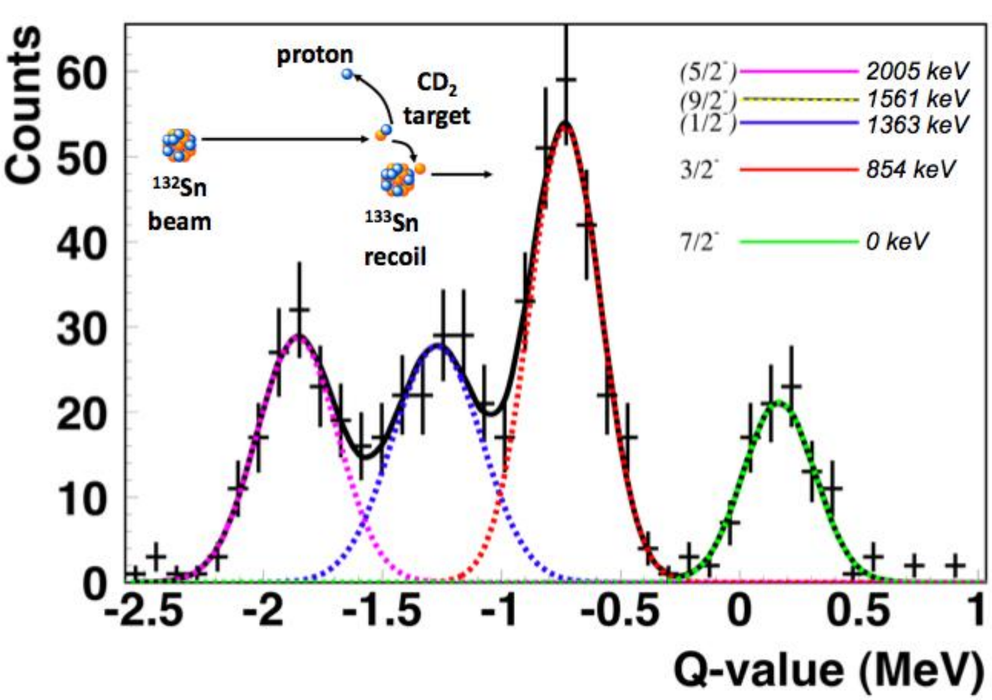
  - S≈1 ⬄ essentially pure single-particle wave functions

Angular Distributions

$d\sigma/d\Omega$ (mb/sr)



θ(cm) degrees

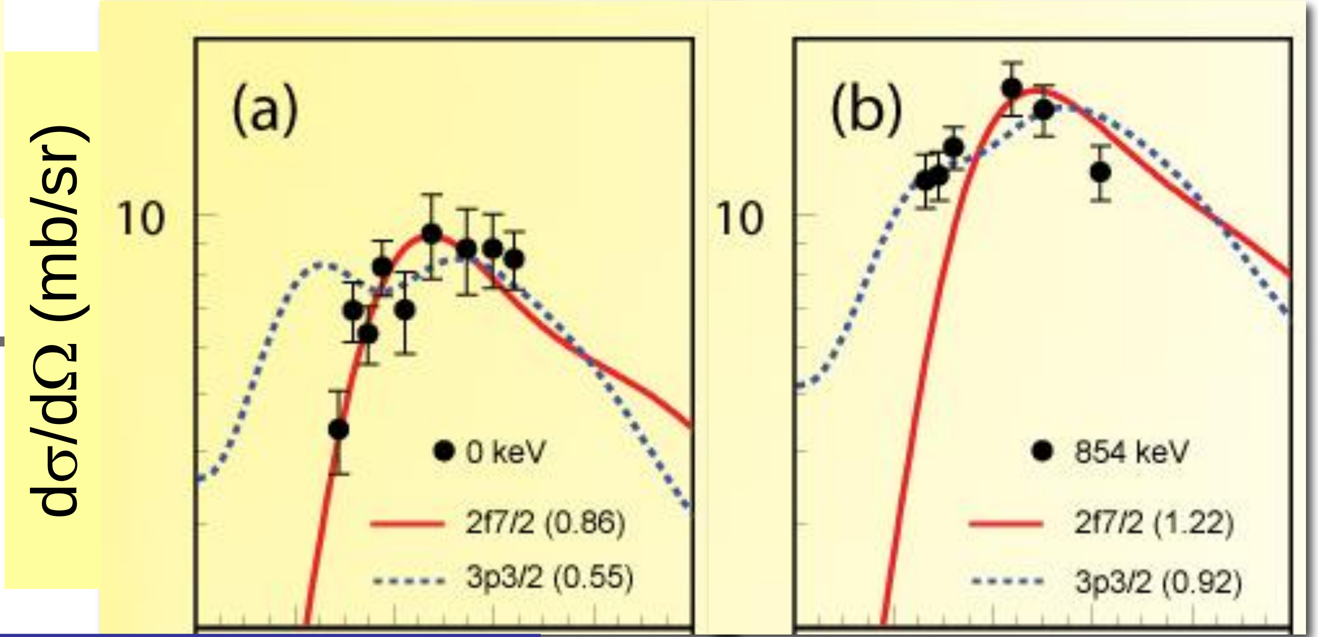


^{133}Sn

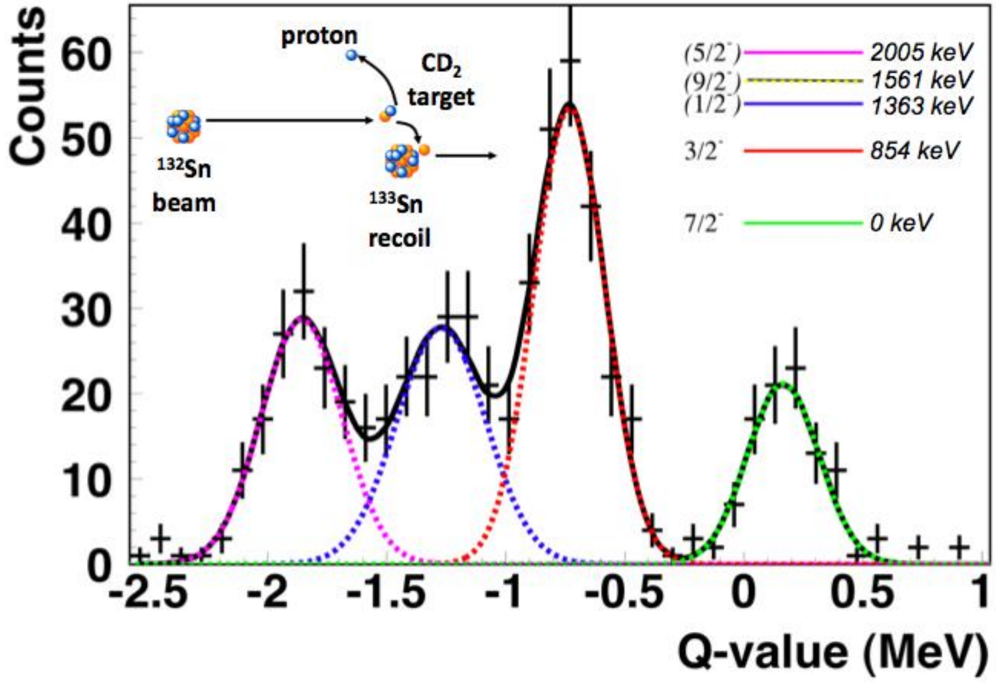
ground state

K.L. Jones et al.
Nature, **465**,454 (2010)

Angular Distributions



θ(cm) degrees

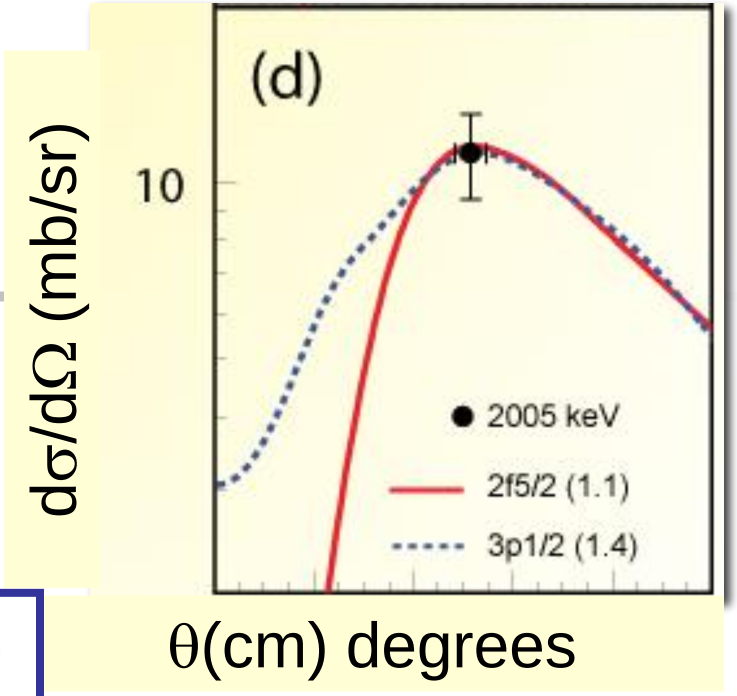


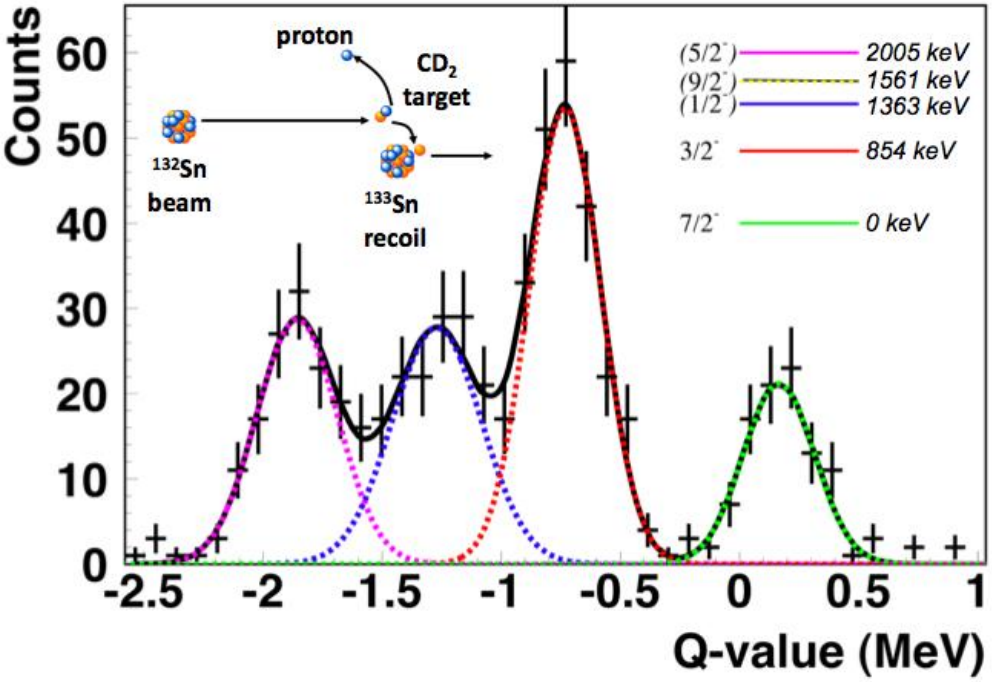
^{133}Sn

ground & 854 keV

K.L. Jones et al.
Nature, **465**,454 (2010)

Angular Distributions



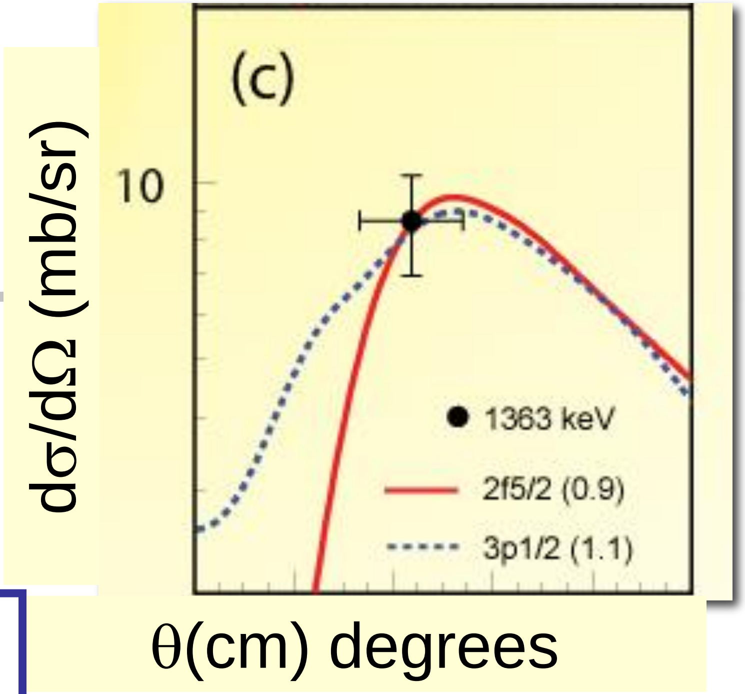


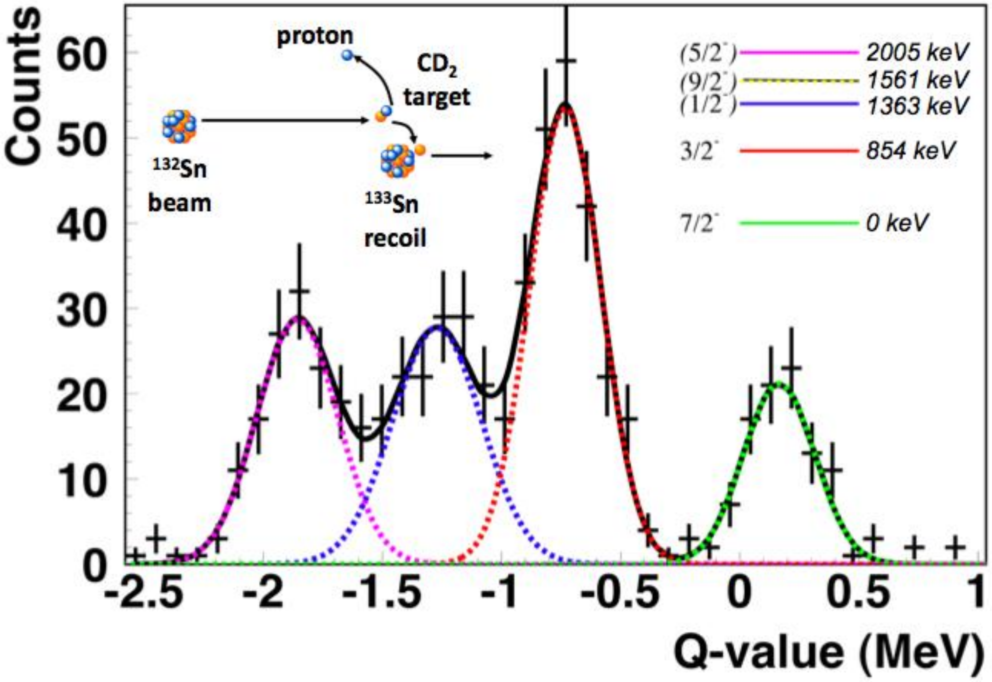
^{133}Sn

2005 keV

K.L. Jones et al.
Nature, **465**,454 (2010)

Angular Distributions



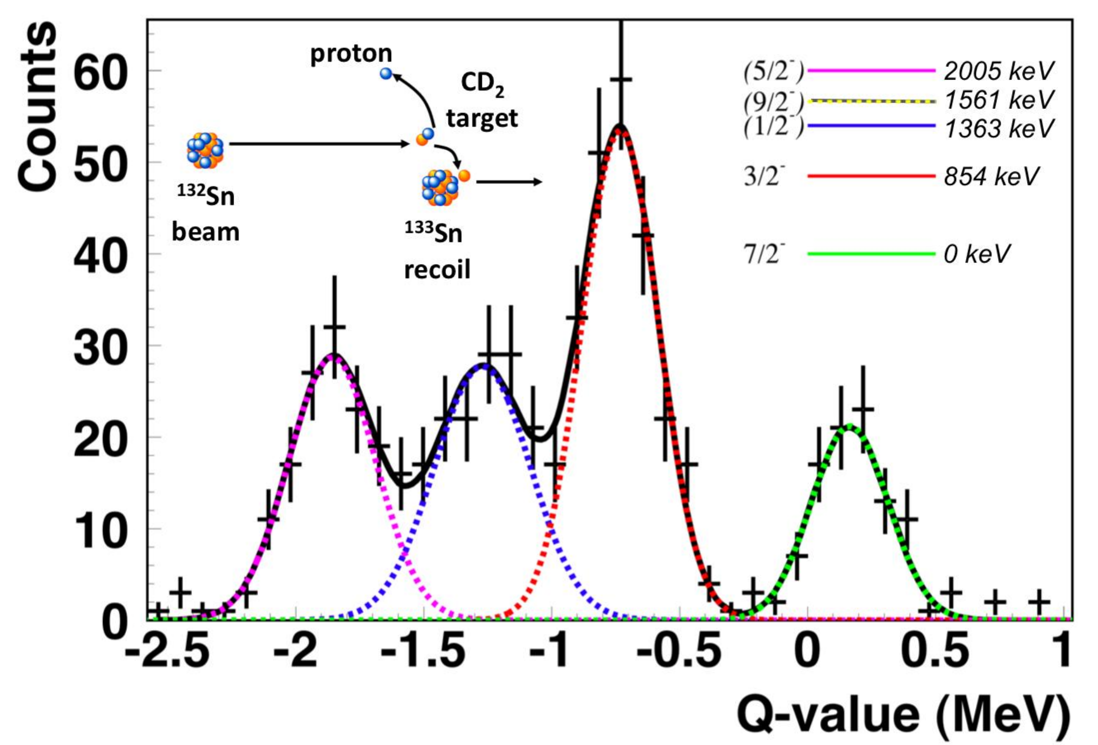


^{133}Sn

1363 keV

K.L. Jones et al.
Nature, **465**,454 (2010)

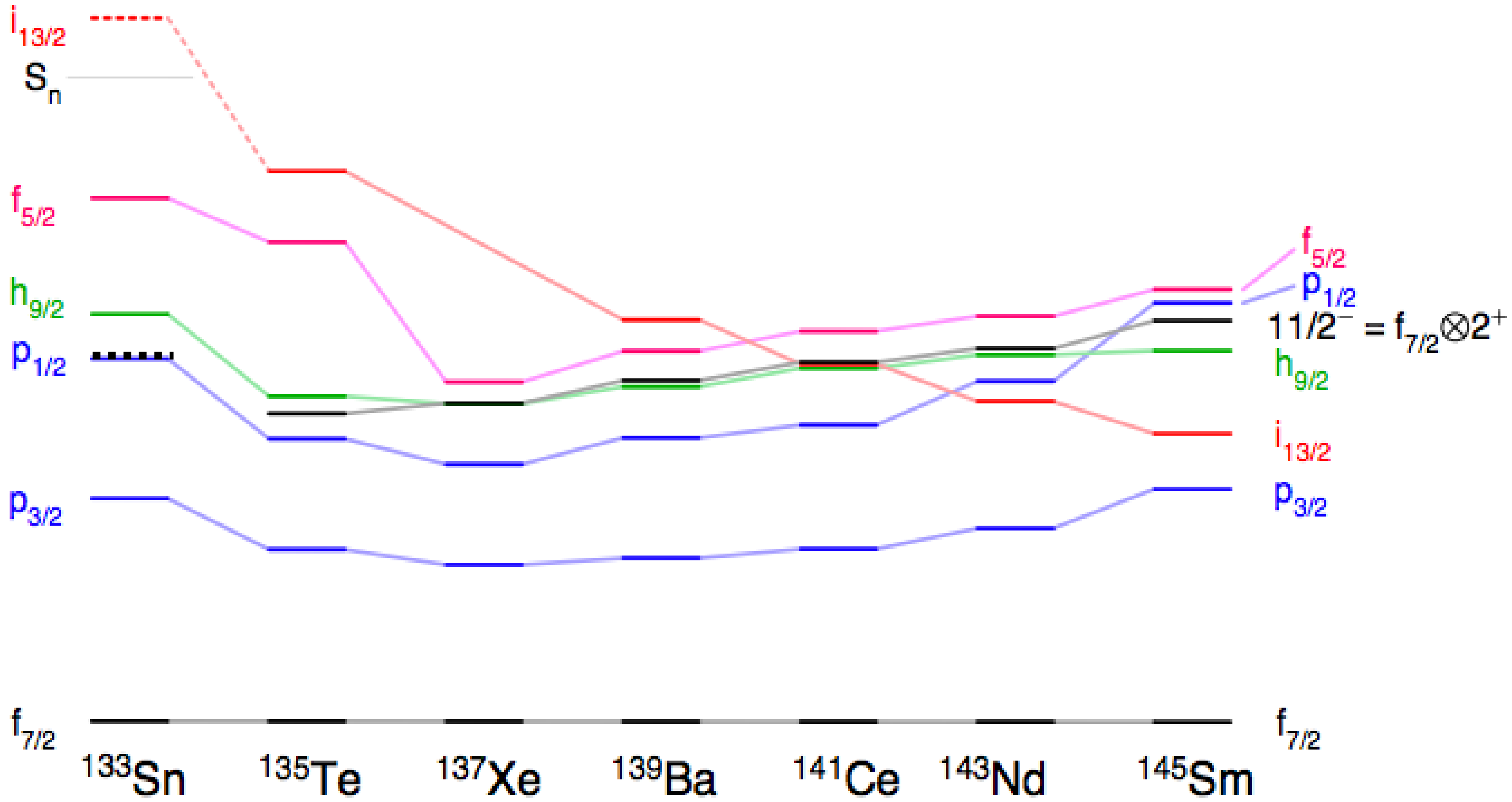
Identified $2f_{7/2}$, $3p_{3/2}$, ($3p_{1/2}$), $2f_{5/2}$ neutron strength in ^{133}Sn



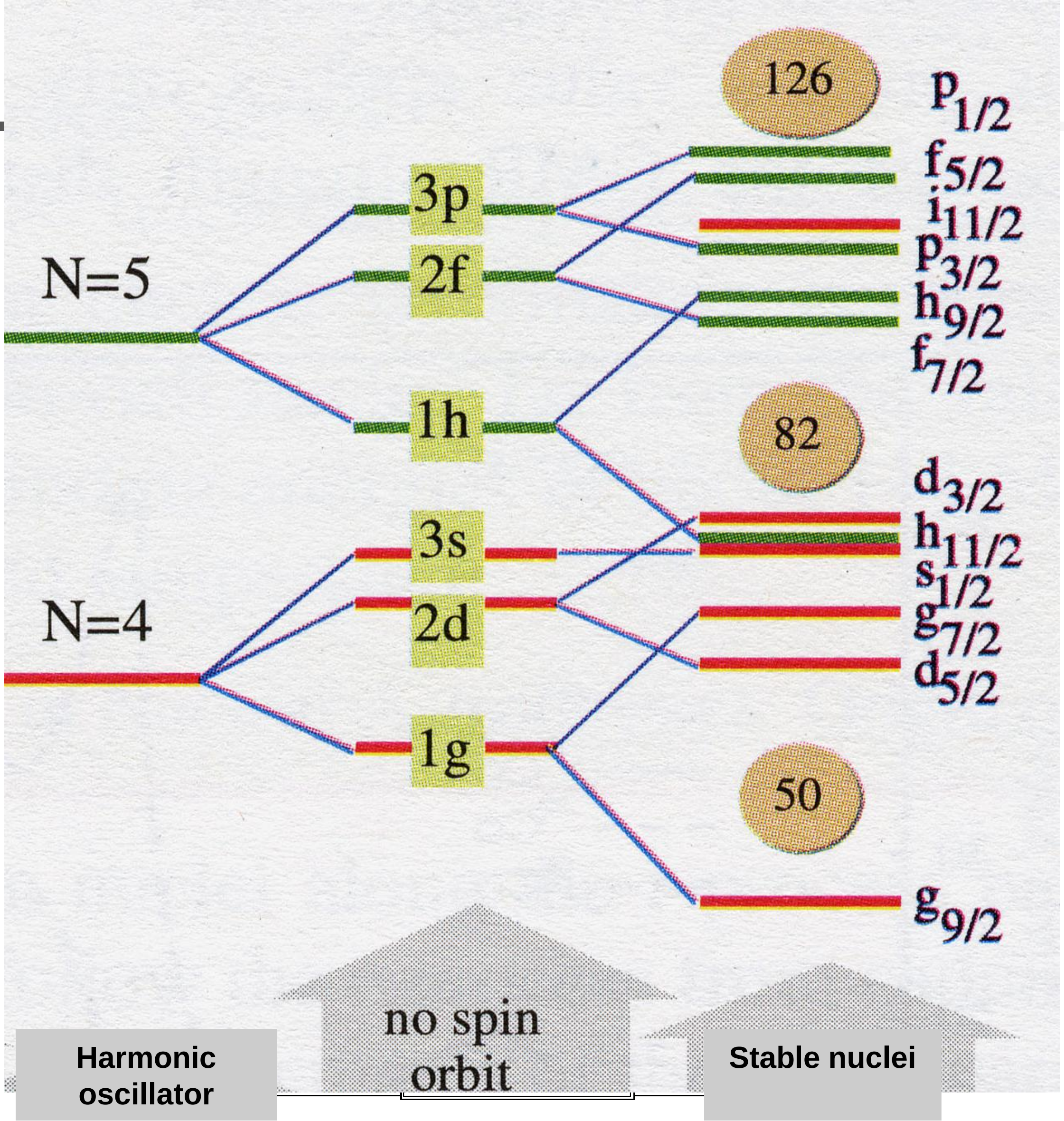
E_x(keV)	J^π	Config	SF
0	$7/2^-$	$2f_{7/2}$	0.86(16)
854	$3/2^-$	$3p_{3/2}$	0.92(18)
1363(31)	($1/2^-$)	$3p_{1/2}$	1.1(3)
2005	($5/2^-$)	$2f_{5/2}$	1.1(2)

K.L. Jones et al.
Nature, **465**,454
(2010)

N=83 systematics



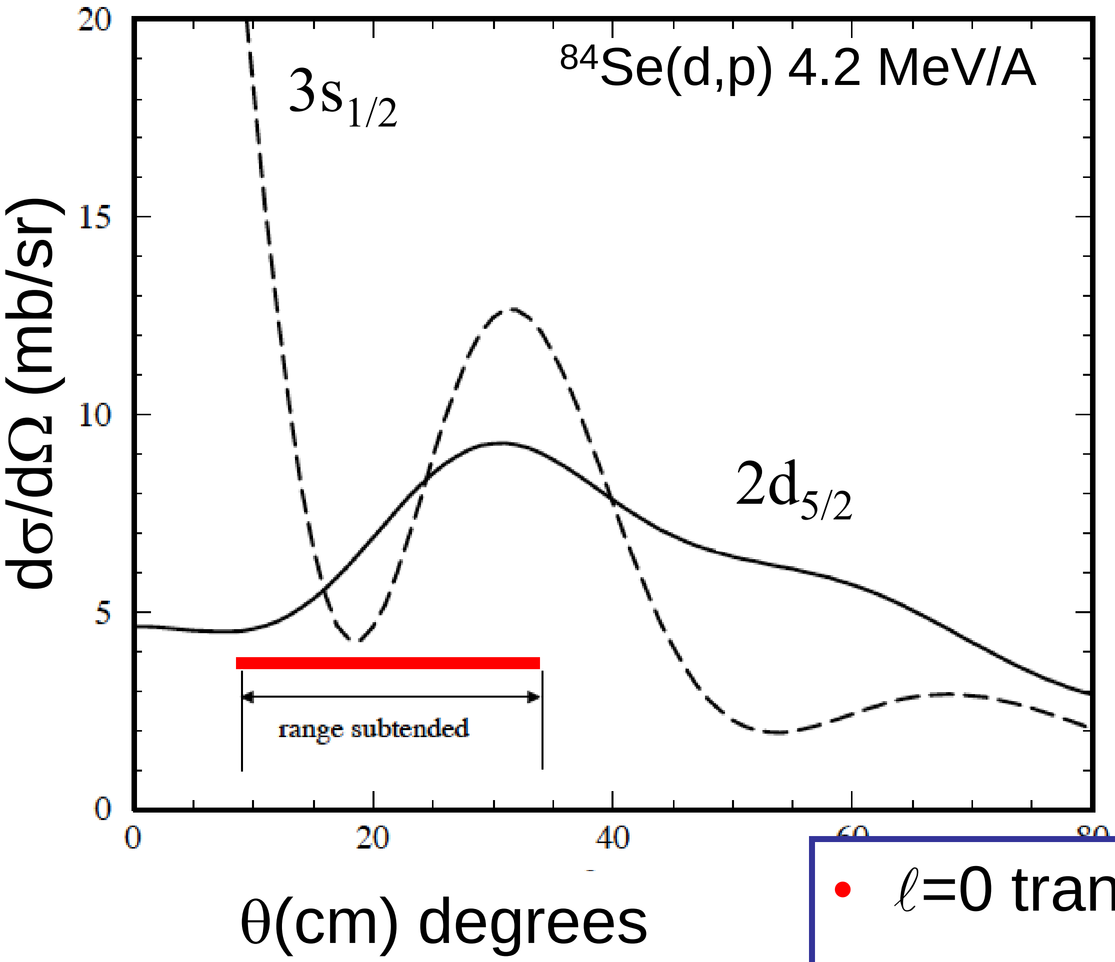
What are neutron orbitals N>50, Z≈28?



Harmonic oscillator

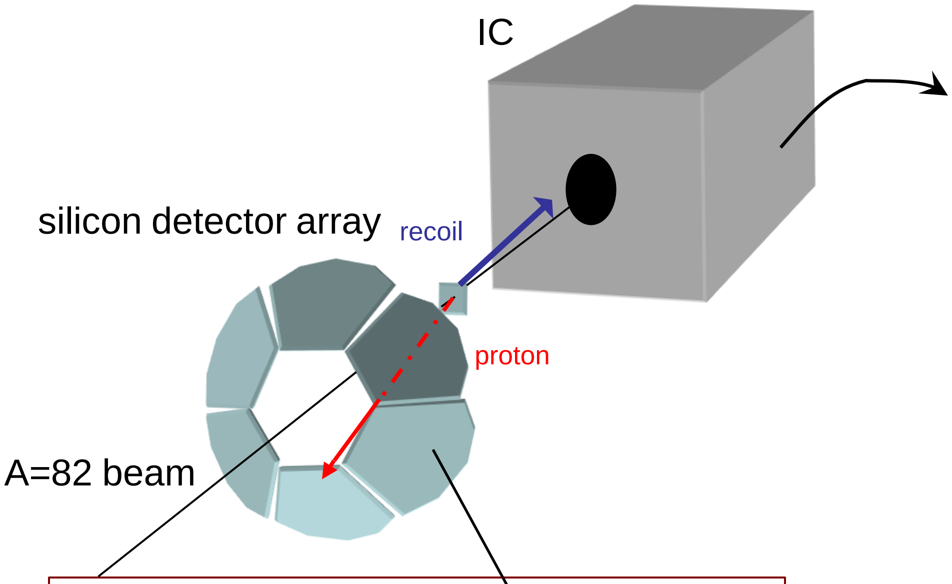
Stable nuclei

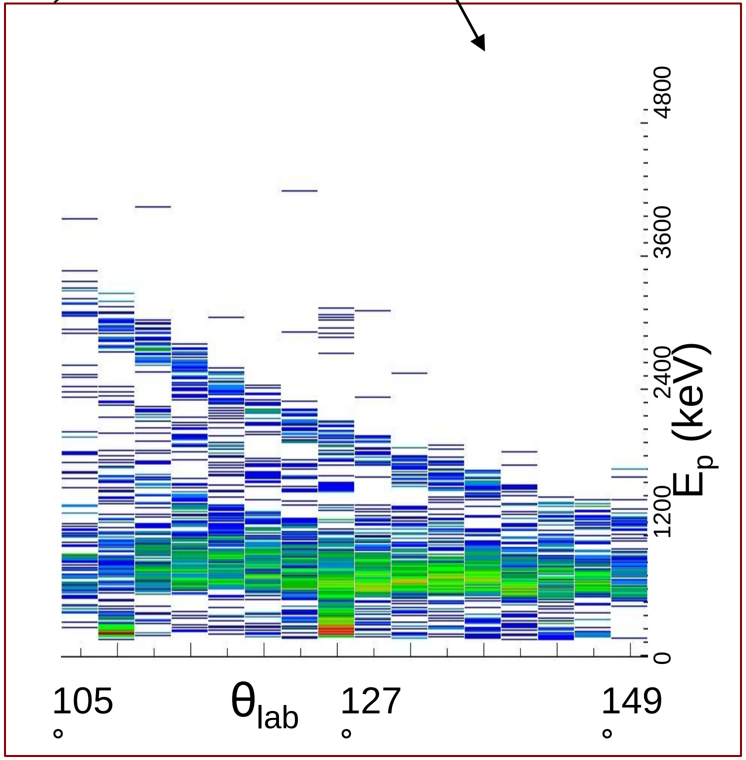
N>51: $3s_{1/2}$ & $2d_{5/2}$ neutron transfer

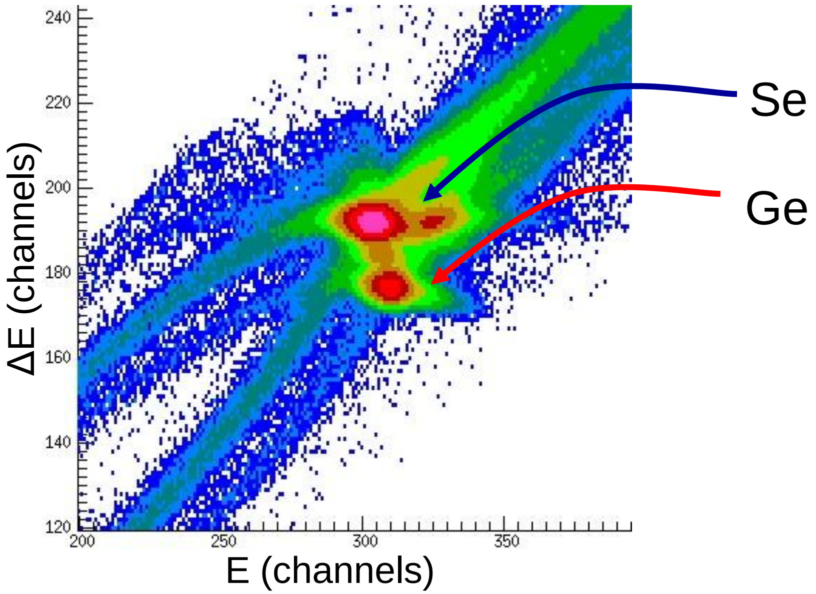


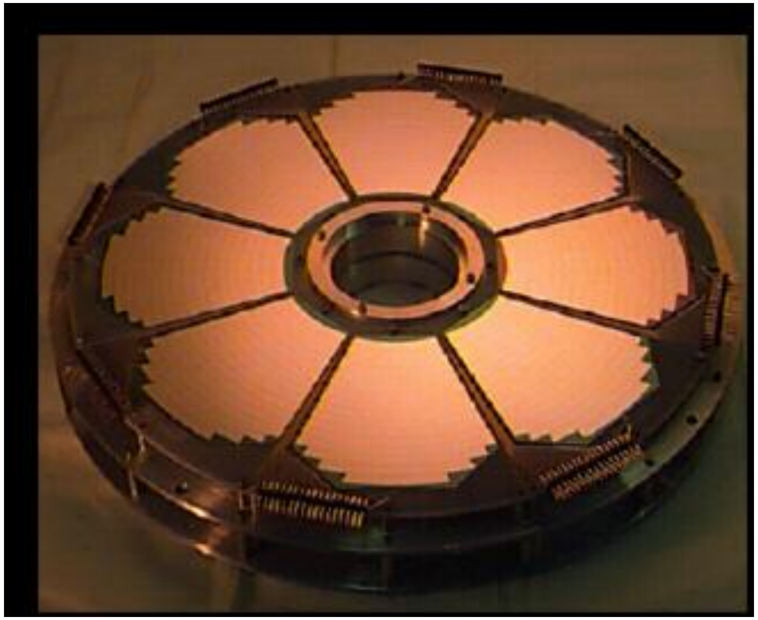
- ℓ=0 transfer peaks at $\theta_{cm}=0°$
- θ_{cm}(forward) ⇔ θ_{lab}(back)
- Measure $\theta_{lab} > 90°$

$^{2}H(^{82}Ge,p)^{83}Ge$

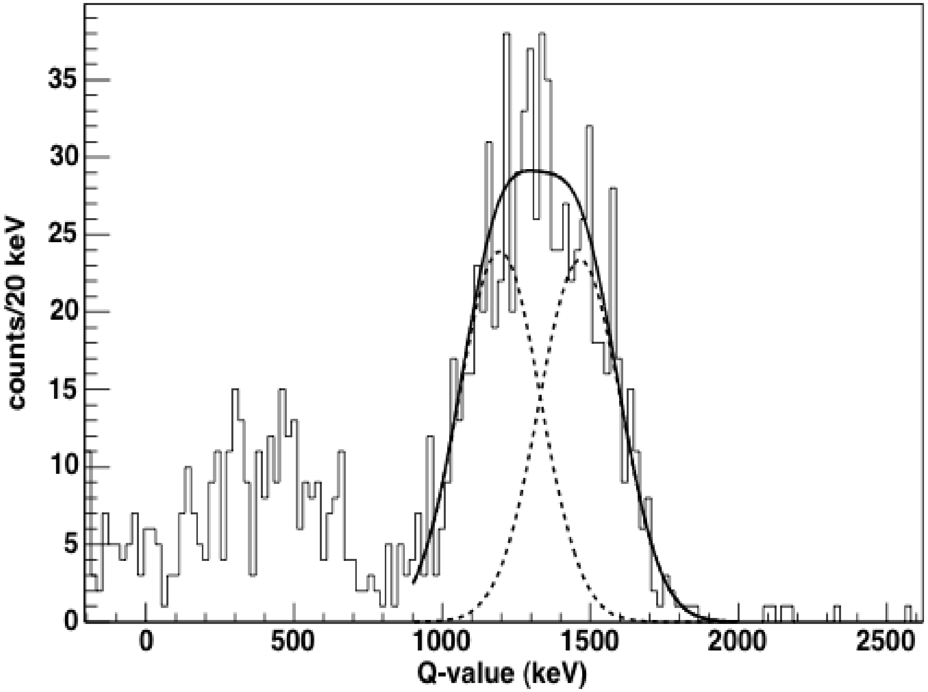


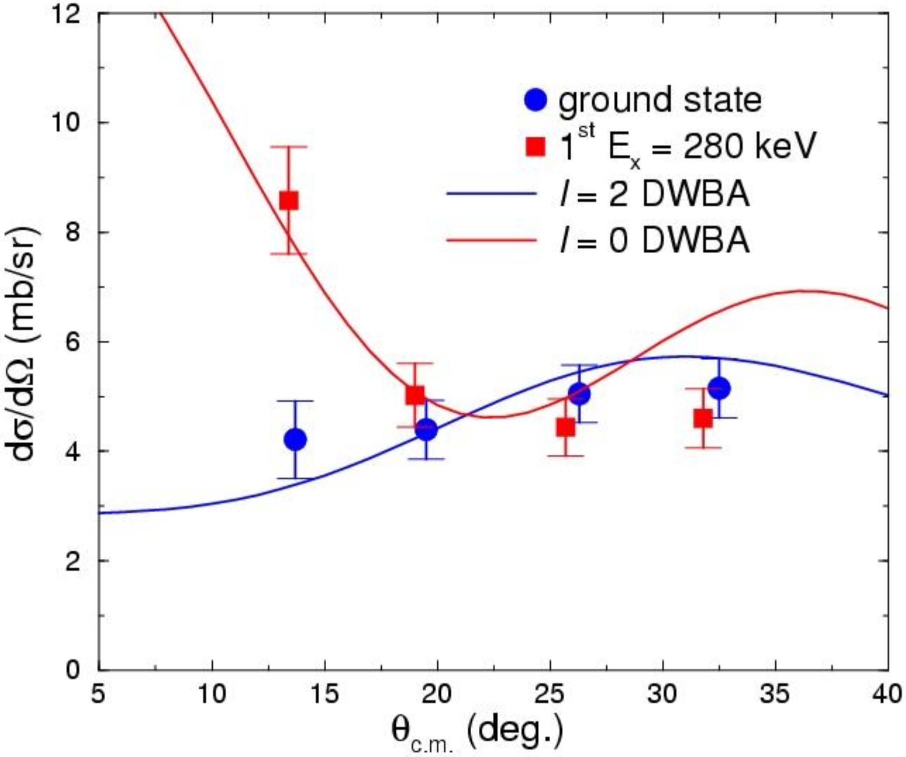






^{83}Ge Results





Q = 1.47 (±0.02 stat. ±0.07 sys.) MeV

1^{st} E_x = 280 (± 20 stat.) keV

$S_n(^{83}\text{Ge})$ = 3.69 ± 0.07 MeV

$\Delta(^{83}\text{Ge})$ = – 61.25 ± 0.26 MeV

J.S. Thomas et al., PRC **71**, 021302R (2005)

Results are consistent with:

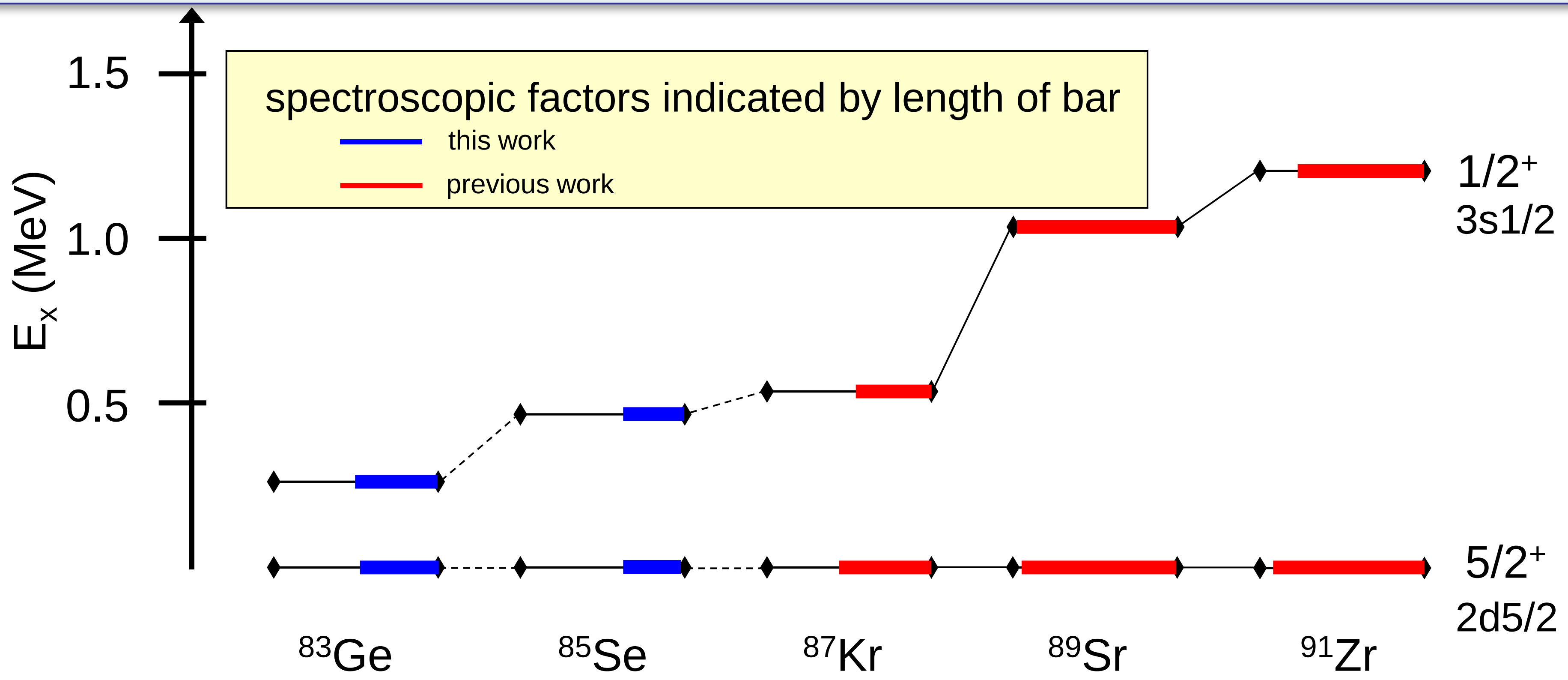
ℓ = 2 ground state ($d_{5/2}$)

ℓ = 0 1^{st} excited ($s_{1/2}$) at E_x=280 keV

g.s. S = 0.48 ± 0.14

1^{st} S = 0.50 ± 0.15

Comparison of Even Z ≤ 40, N = 51 Isotones



^{83}Ge Exp			**^{83}Ge Thy**	
E_x(MeV)	**J^π**	**$S_{\ell j}$**	**E_x(MeV)**	**$S_{\ell j}$**
0.0	(5/2)+	0.48(12)	0.0	0.73
0.28(7)*	1/2+	0.50(13)	0.47	0.38

J.S. Thomas, D. Dean et al., PRC 76, 044302 (2007)

*247 keV from beta decay, Winger et al.

Summary of N=82, N=50 (d,p)

- Developed techniques to measure (d,p) in inverse kinematics
- Measured single-neutron excitations in ^{133}Sn
  - Expected $2f_{7/2}$, $3p_{3/2}$, $3p_{1/2}$, $2f_{5/2}$ states identified with $S \approx 1$
  - ^{132}Sn is one of best candidates for doubly magic nucleus
  - To see change in shell structure need to go more n-rich
- Measured single-neutron excitations in N=51 ^{83}Ge
  - $3s_{1/2}$ excitation comes down in energy vs $2d_{5/2}$
  - Fragmentation of single-particle strengths
  - Open question: how strong is double magic shell closure at ^{78}Ni with N=50 and Z=28?

Is everything so straightforward?

- Ambiguities in spectroscopic factors?
- Wave function of the deuteron?
- Can we improve energy resolution?
- Can neutron transfer inform astrophysical neutron capture (s and r) processes on rare isotopes?

(d,p) spectroscopic factors

- Output from theoretical cross sections compared to exp
- (relative) S≈1 ⇒ full spectroscopic strength
- Ambiguities in S?

$$\boxed{S = \left(\frac{d\sigma}{d\Omega}\right)_{\exp} \Big/ \left(\frac{d\sigma}{d\Omega}\right)_{DWBA}}$$

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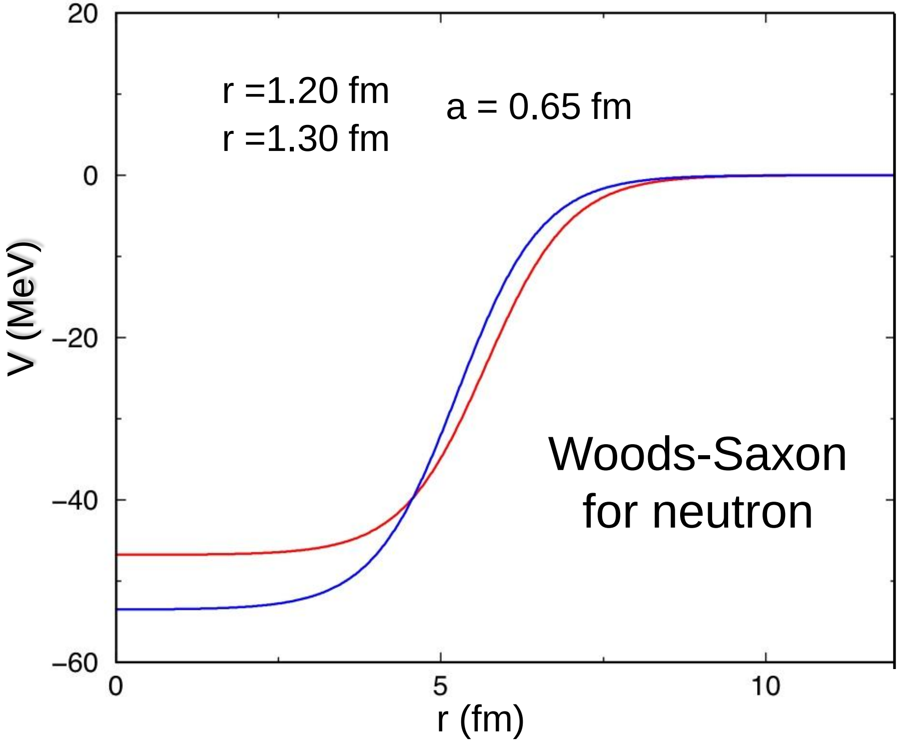
CENTER OF EXCELLENCE FOR RADIOACTIVE ION BEAM STUDIES FOR STEWARDSHIP SCIENCE

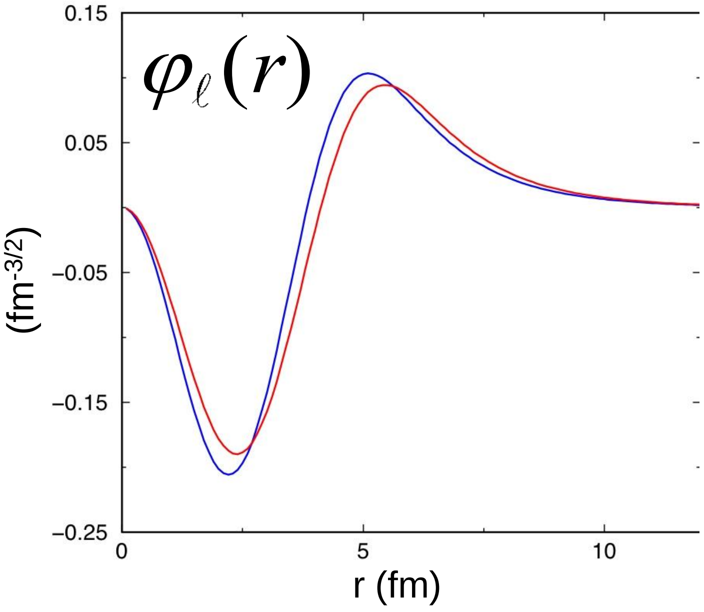
THE STATE UNIVERSITY OF NEW JERSEY RUTGERS

Ambiguity in Single-Particle WF

Only constraint on potential is that correct
binding energy of neutron (well depth) must be reproduced

Geometrical parameters not well-determined (radius, diffuseness)



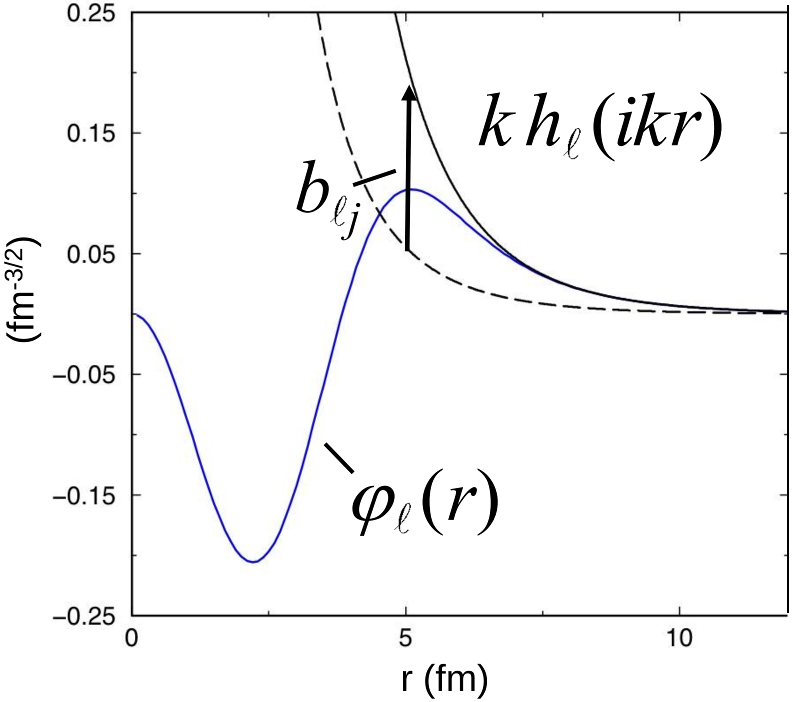


Single-particle wavefunction (and SF) ambiguities

Ambiguity in Single-Particle WF

Only constraint on potential is that correct binding energy of neutron (well depth) must be reproduced

Geometrical parameters not well-determined (radius, diffuseness)



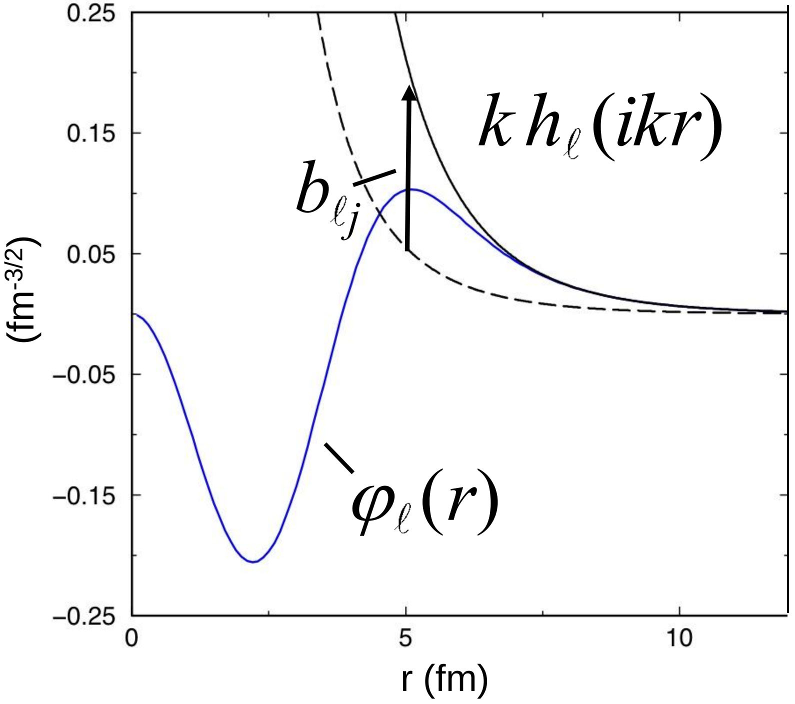
<u>Peripheral reaction</u>: only probe tail of WF
Shape of asymptotic part of WF determined by binding energy (through k)

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

b=Single particle Asymptotic Normalization Coefficient, ANC

Ambiguity in Single-Particle WF

Geometrical parameters not well-determined (radius, diffuseness)



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 (r_0,a) is change in $b_{\ell j}$

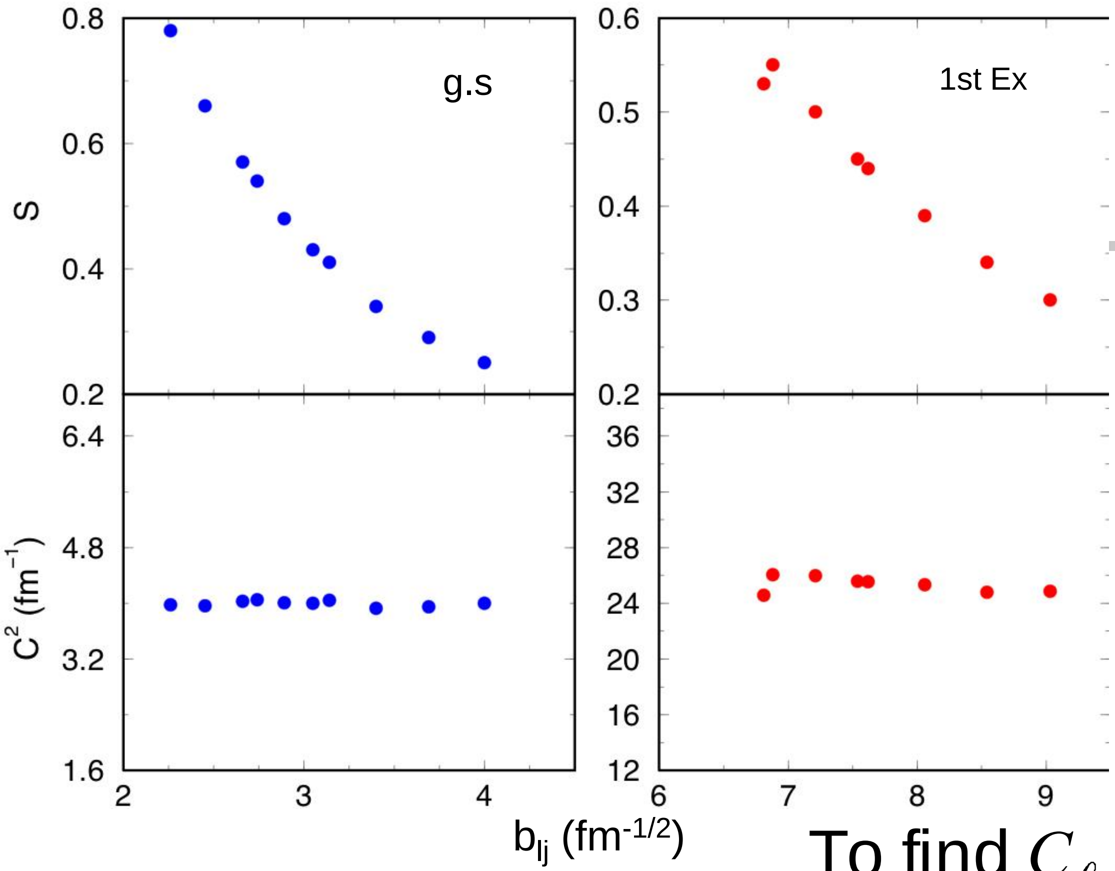
Asymptotically:

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

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

For peripheral reactions, ANC C^2 is probed

Peripheral reactions: Model Independence of C^2



^{82}Ge(d,p)^{83}Ge
4 MeV/u

$$\left(\frac{d\sigma}{d\Omega}\right)_{\exp} = S\left(\frac{d\sigma}{d\Omega}\right)_{DW}$$

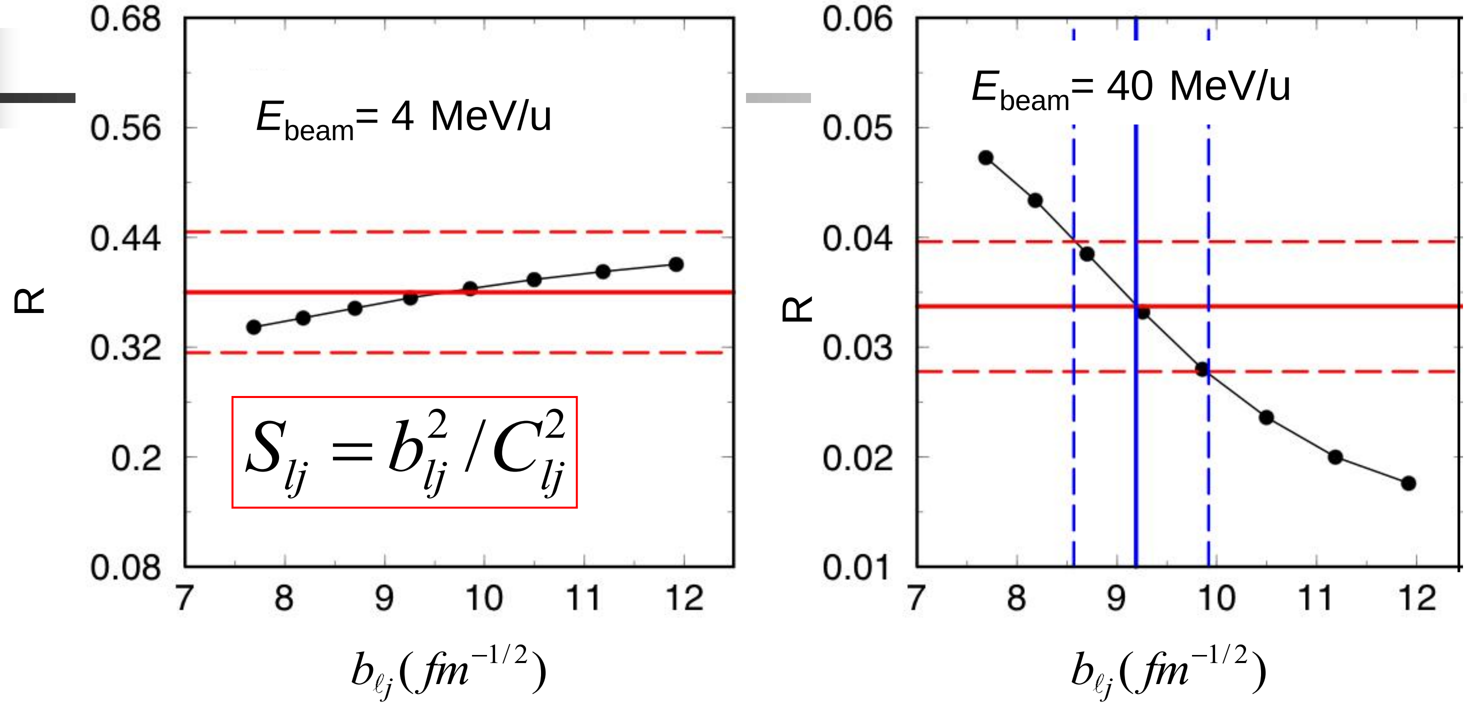
$$C_{\ell j}^2 = S_{\ell j} b_{\ell j}^2$$

To find $C_{\ell j}$ for different bound state geometries ($b_{\ell j}$), normalize σ_{DW} to exp

ANC C is independent of bound-state properties
But how limit uncertainties in spectroscopic factors?

Reducing s.p. uncertainties by constraining bound state parameters

A.M. Mukhamedzhanov and F.M. Nunes, Phys. Rev. C 72 (2005) 017602.



$$R = [d\sigma / d\Omega]^{\exp} / C_{lj}^2 = [d\sigma / d\Omega]^{DW} / b_{lj}^2$$

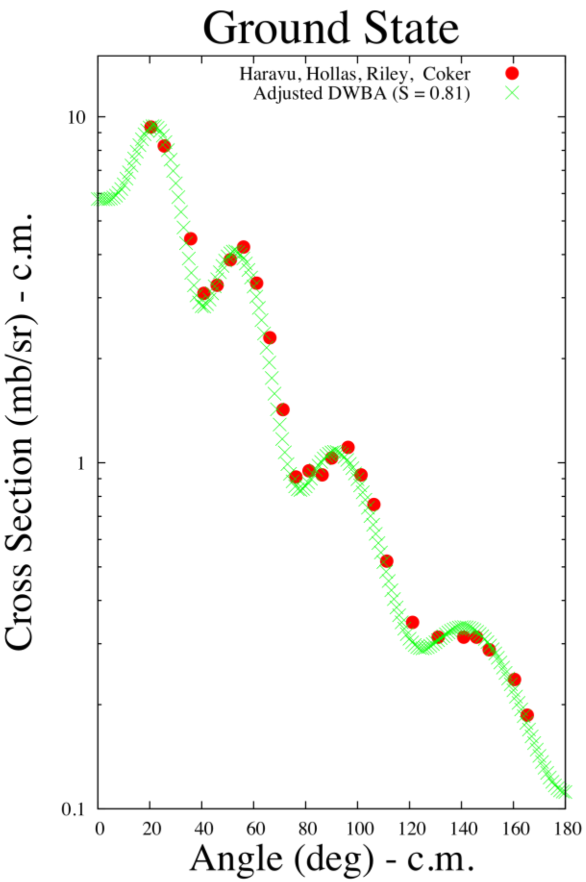
E≈4 MeV/u (peripheral)

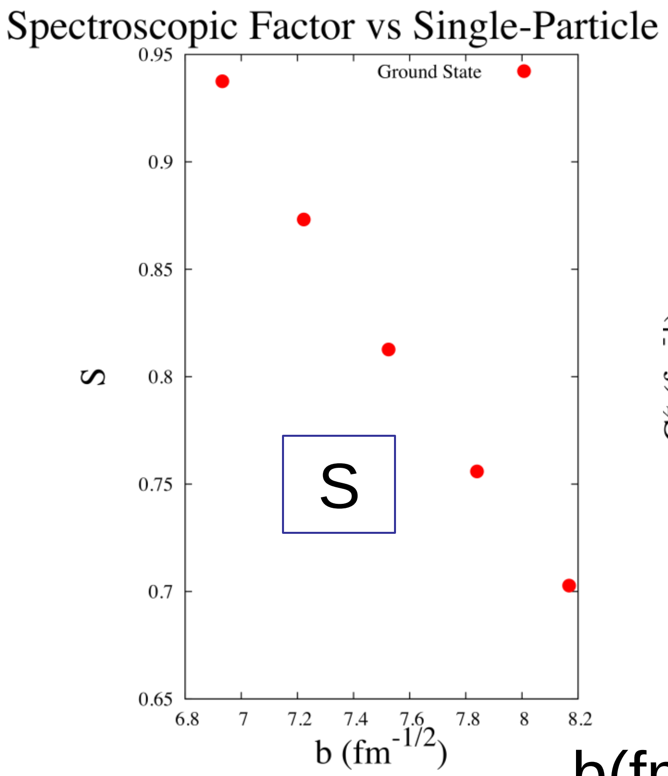
- Constrain C, exp uncertainties
- No constraint on b

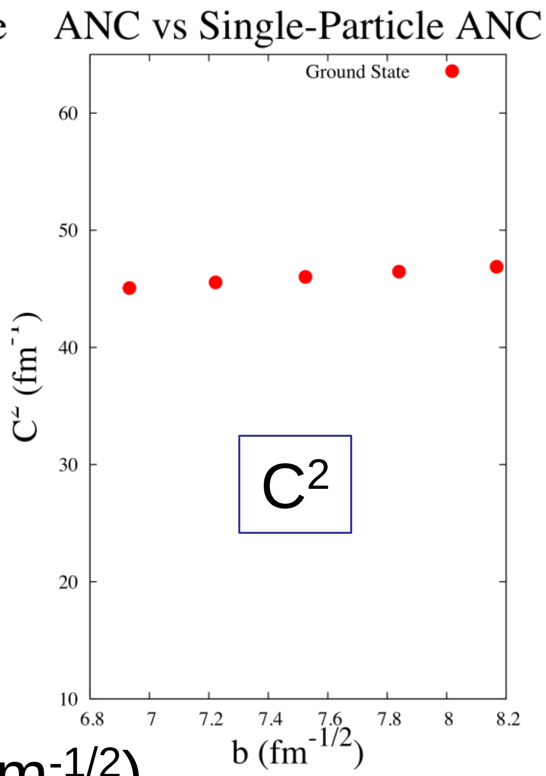
E≈40 MeV/u (less peripheral)

- R strong dependence on b
- Combine w/ low-E, constrain b
- Reduce ambiguities on spec factor

^{86}Kr(d,p) at ≈5 and ≈40 MeV/u: reducing ambiguities in spec factors







b(fm$^{-1/2}$)

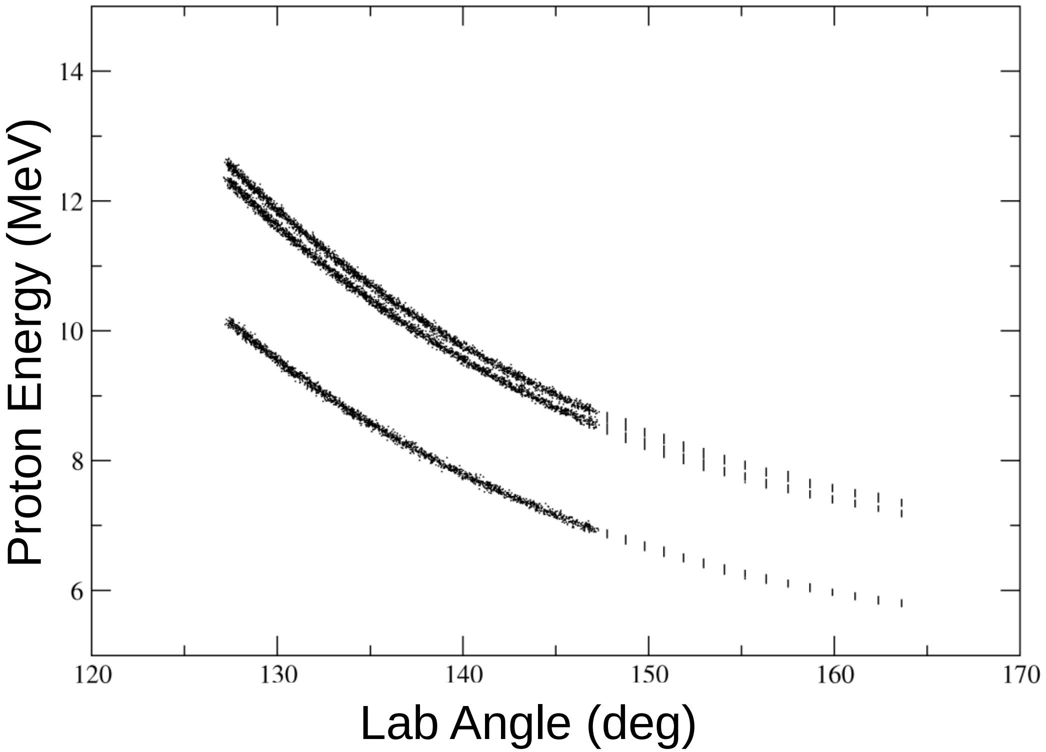
^{86}Kr(d,p) measured w/ 11 MeV deuterons.

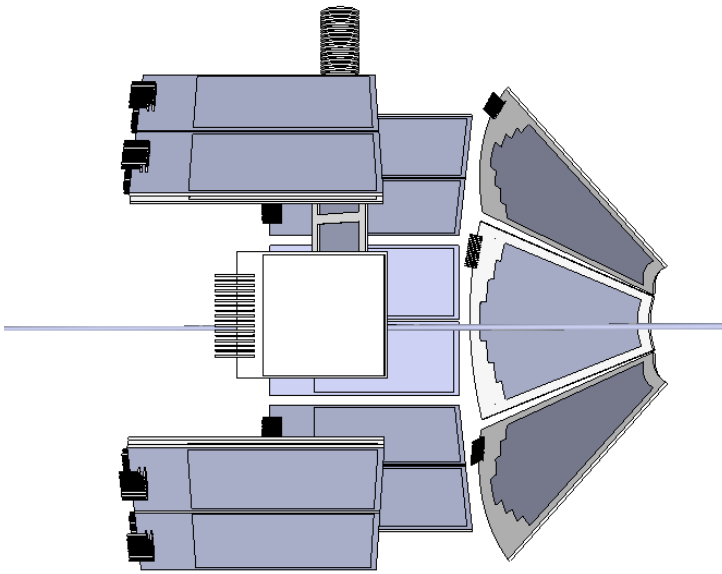
Extracted spectroscopic factor and ANC C^2 vs single-particle ANC b

EBSS July 2011

K. Haravu et al. PRC 1, 938 (1970)

^{86}Kr(d,p) at ≈5 and ≈35 MeV/u: reducing ambiguities in spec factors





Proposal: Measure ^{86}Kr(d,p) w/ ≈35 MeV/u ^{86}Kr beam, SIDAR+ORRUBA

- Extract spectroscopic factors vs single-particle ANC b.
- Compare to ANCs C^2 constrained by low-E (d,p)

Is everything so straightforward?

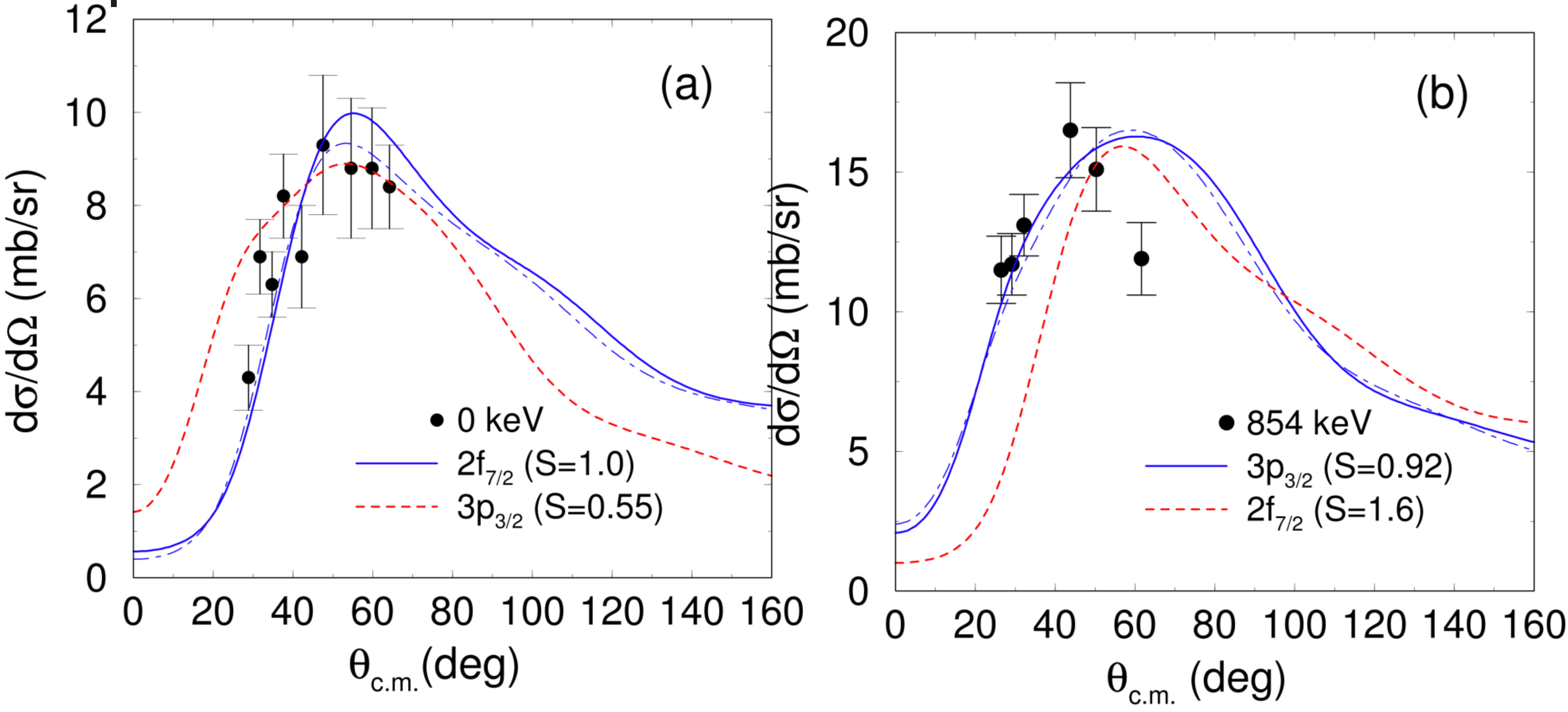
- Ambiguities in spectroscopic factors?
- Wave function of the deuteron?
- Quenching of spectroscopic factors?
- Can we improve energy resolution?
- Can neutron transfer inform astrophysical neutron capture (s and r) processes on rare isotopes?

Deuteron is weakly bound; how does this affect transfer?

- Need to account for breakup of the deuteron:
  - Johnson, Soper, Tandy Finite-Range
  - ADiabatic Wave Approximation (FR-ADWA)
- Construct deuteron adiabatic wave from realistic deuteron optical potential (e.g., Reid interaction)
- Global optical model parameters, e.g., CH89
- Application: ^{132}Sn(d,p)

- References:
  - R.C. Johnson & P.J.R. Soper, PRC 1, 976 (1970)
  - R.C. Johnson and P.C. Tandy, NPA 235, 56 (1974)

^{132}Sn(d,p) with FR-ADWA & CH89



^{132}Sn(d,p) with FR-ADWA & CH89

Spectroscopic factors extracted w/
FR-ADWA and CH89 optical model parameters

		Spectroscopic	Factor
Ex(keV)	**nlj**	**DWBA**	**FR-ADWA**
0	2f7/2	0.86 (7)	1.00 (8)
854	3p3/2	0.92 (7)	0.92 (7)
1363±31	(3p1/2)	1.1 (2)	1.2 (2)
2005	(2f5/2)	1.1 (2)	1.2 (3)

Is everything so straightforward?

- Ambiguities in spectroscopic factors?
- Wave function of the deuteron?
- Can we improve energy resolution?
- Can neutron transfer inform astrophysical neutron capture (s and r) processes on rare isotopes?

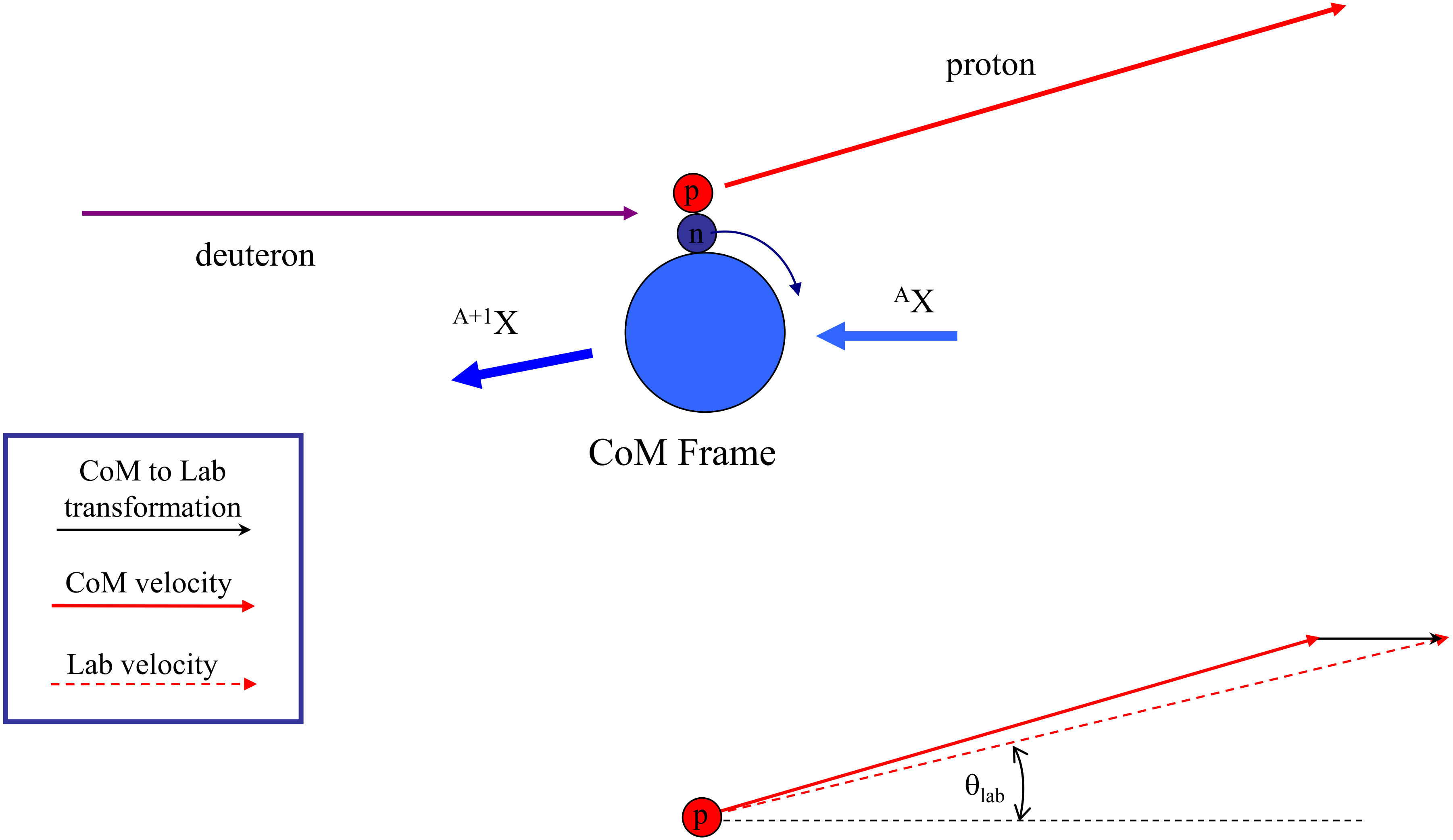
Summary of Part I

- Developed techniques to measure (d,p) in inverse kinematics
- Measured single-neutron excitations in ^{133}Sn
  - Expected $2f_{7/2}$, $3p_{3/2}$, $3p_{1/2}$, $2f_{5/2}$ states identified with $S \approx 1$
  - ^{132}Sn is one of best candidates for doubly magic nucleus
  - Conclusions robust when include realistic deuteron wave function AND global optical model parameters
- Measured single-neutron excitations in N=51 ^{83}Ge
  - $3s_{1/2}$ excitation comes down in energy vs $2d_{5/2}$
  - Fragmentation of single-particle strengths
- Need to reduce ambiguities in spectroscopic factors because of minimal probe of nuclear interior
  - Path forward: measure at 2 different beam energies

Thank you – Part I

Extra slides

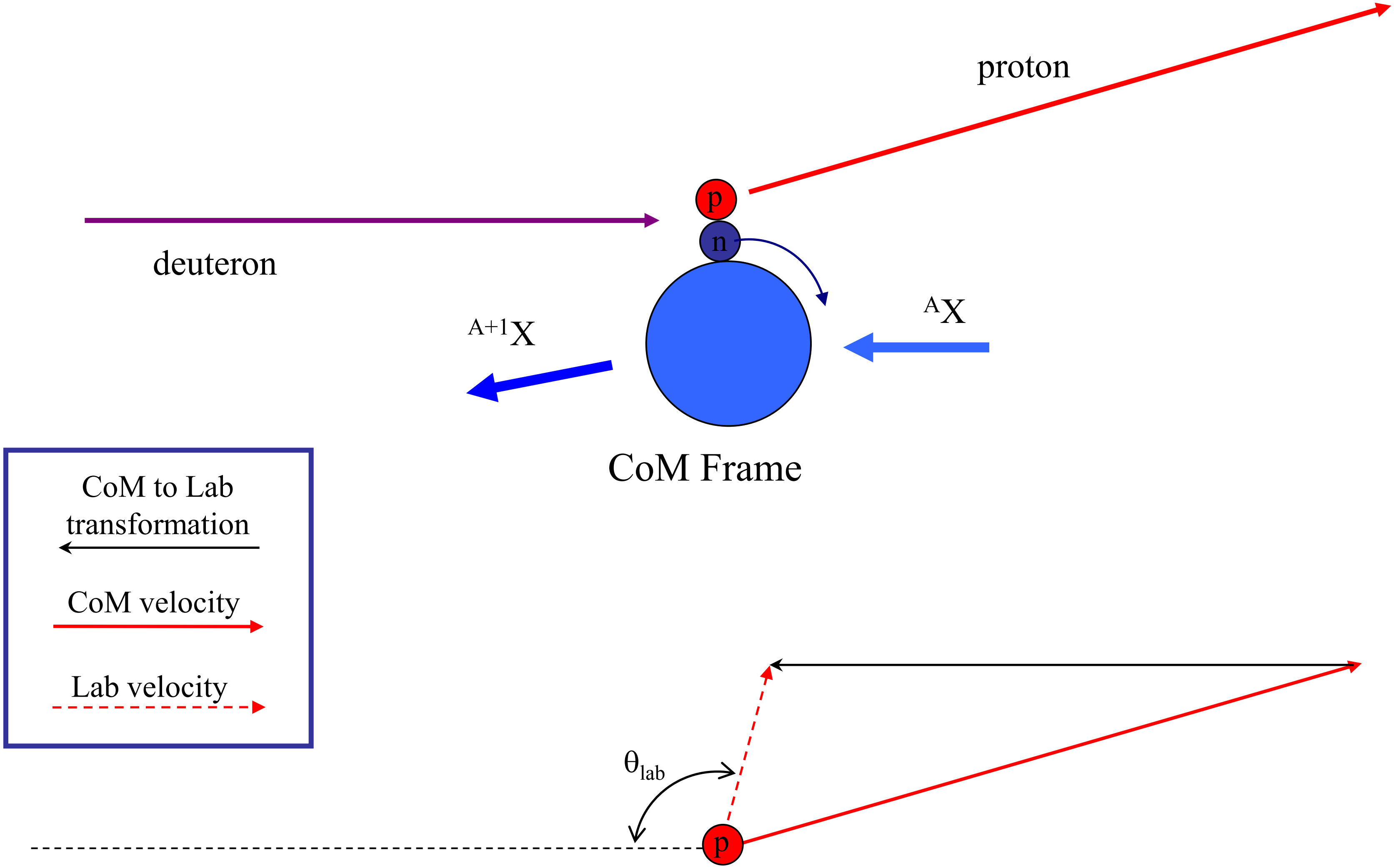
(d,p) Reactions



Normal Kinematics

S.D. Pain

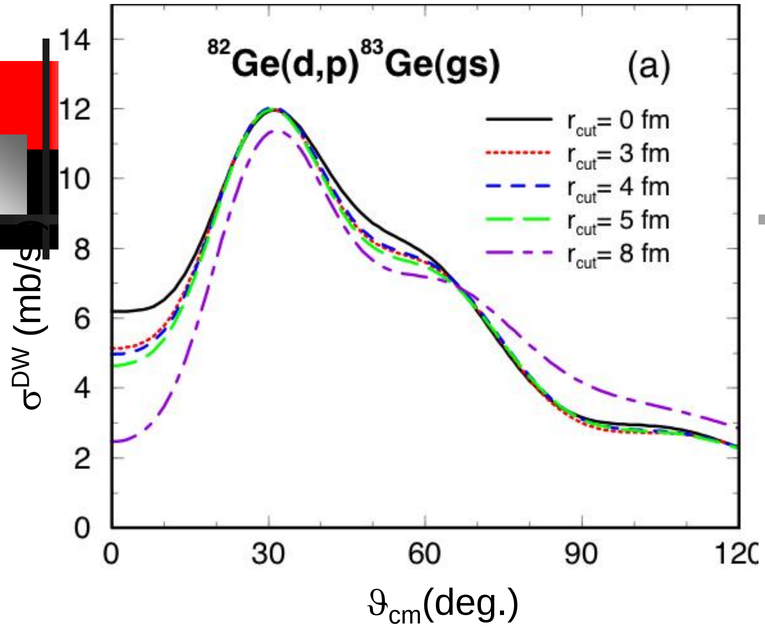
(d,p) Reactions

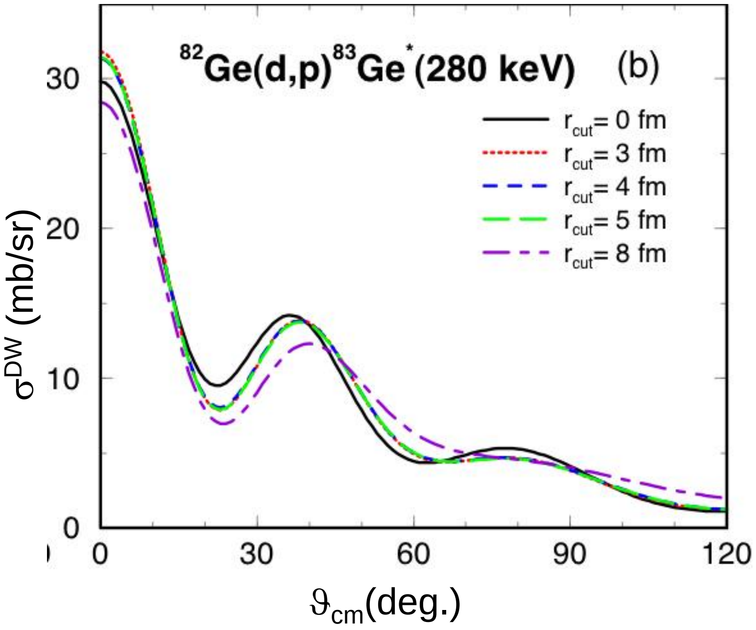


Inverse Kinematics

S.D. Pain

Peripheral Transfer Reactions





Reaction occurs at nuclear exterior

E ~ 1 MeV above Coulomb barrier

Single-particle SF determined from normalization to main peak

Distorted waves calculations performed with varying lower radial cutoffs

Peak magnitude nearly insensitive to cutoff out to r_{cut} ~ 8 fm

N=82, N=50 (d,p) Collaborations

Rutgers University J.A.C., R. Hatarik, B. Manning, P.D. O'Malley, T.P. Swan, Jeff Thomas
Univ. Tennessee K.Y. Chae, R. Kapler, Kate L. Jones, Z. Ma, B.H. Moazen
ORNL G. Arbanas, D.W. Bardayan, J.C. Blackmon, D. Dean, C.G. Gross, J.F. Liang, C.D. Nesaraja, Steve D. Pain, D. Shapira, M.S. Smith
Tennessee Tech Ray L. Kozub, J.F. Shriner Jr.
Michigan State Univ: Filomena Nunes
Univ. North Carolina-Chapel Hill: R.P. Fitzgerald, D.W. Visser
University of Surrey C. Harlin, N.P. Patterson, J.S. Thomas
Colorado School of Mines K.A. Chipps, L. Erikson, U. Greife, R. Livesay
Ohio University A.S. Adekola

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

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RUTGERS

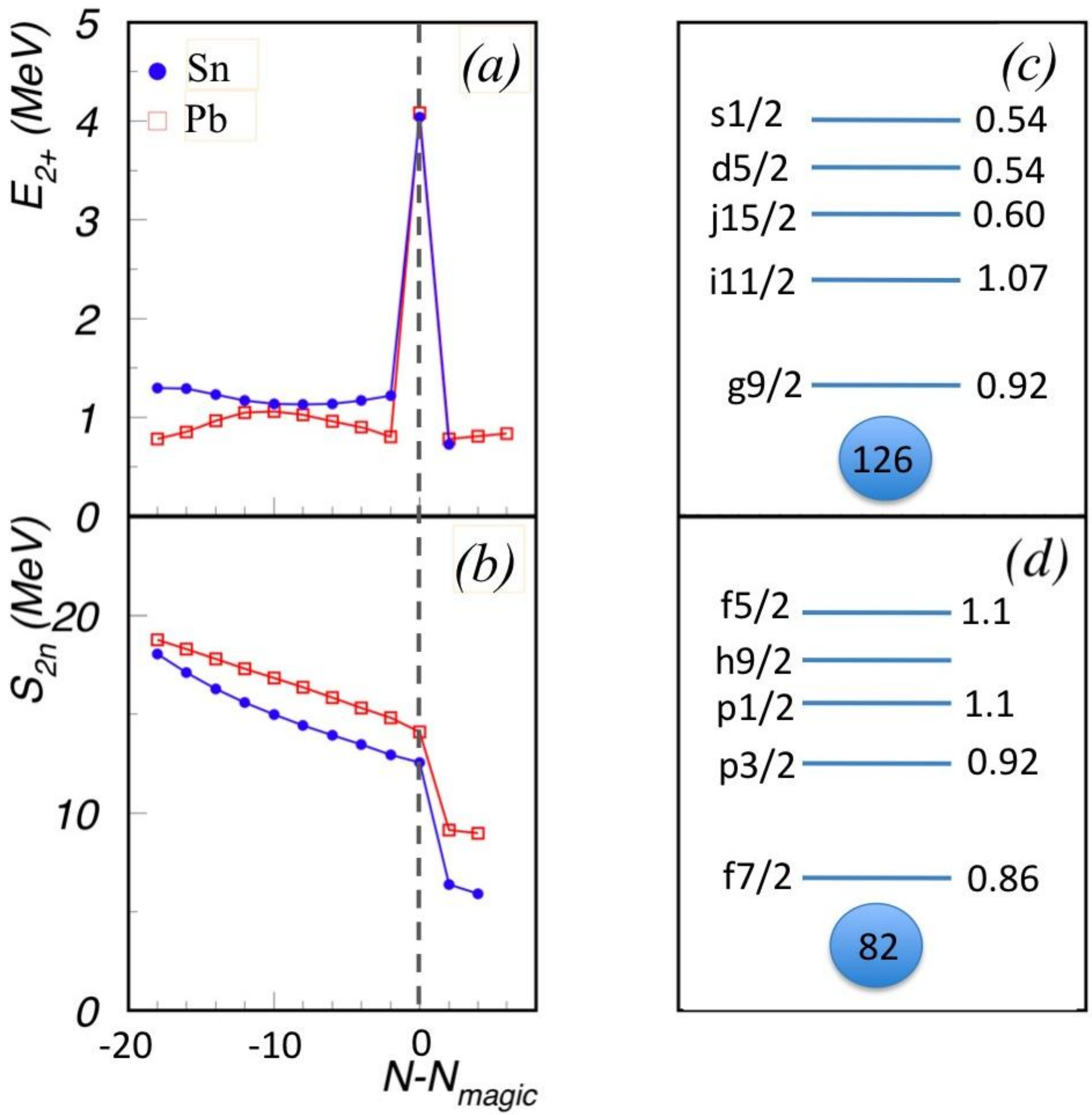
Optical Potential

- ✧Fitting the details of elastic scattering data requires more than simple diffraction from an opaque disk.
- ✧The most common model in fitting scattering data entails a complex potential and is called the optical model.
- ✧The optical potential has the form: **U(r) = V(r) + iW(r)**.
- ✧The real part of the optical potential explains the scattering.
- ✧The imaginary part provides ***absorption*** ; the removal of particles from the elastic scattering channel via nuclear reactions.

What is a Spectroscopic Factor?

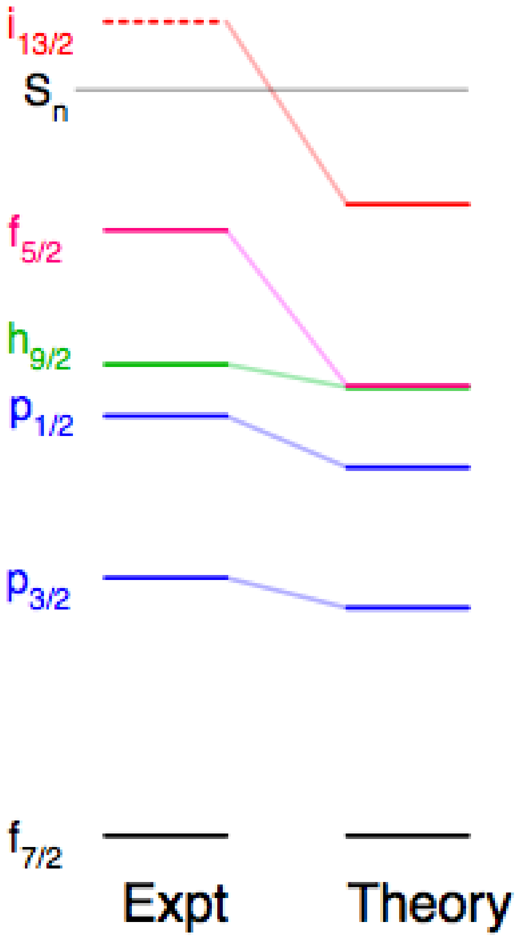
- It’s the norm of the overlap function between the initial state and the final state.
- Example for (d,p)
  - “How much does my recoiling nucleus look like my target nucleus plus a neutron in a given single particle state?”

^{132}Sn (N=82,Z=50) vs ^{208}Pb (N=126,Z=82):



K.L. Jones et al.
Nature, **465**,454 (2010)

N=83 Single Particle Energies



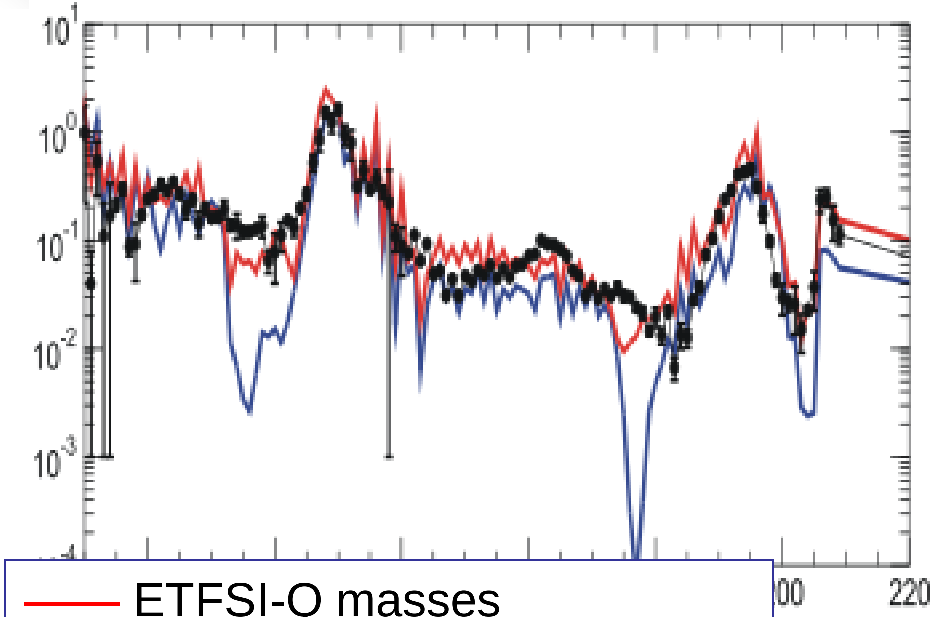
- Shell model theory, from states in other nuclei e.g. Z=54, 56 isotones

  Sakar and Sakar
  Phys. Rev. **C64** 014312 (2001).

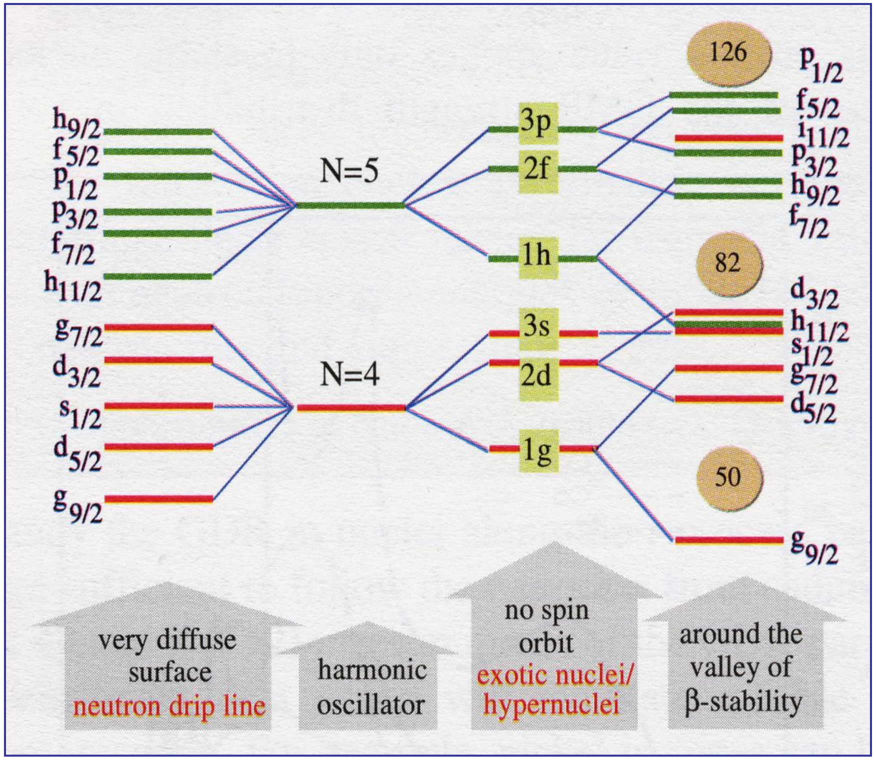
- Reproduces candidate $p_{1/2}$ state in ^{133}Sn

- Impact on masses, other nuclear properties, nuclear astrophysics

r-process abundances



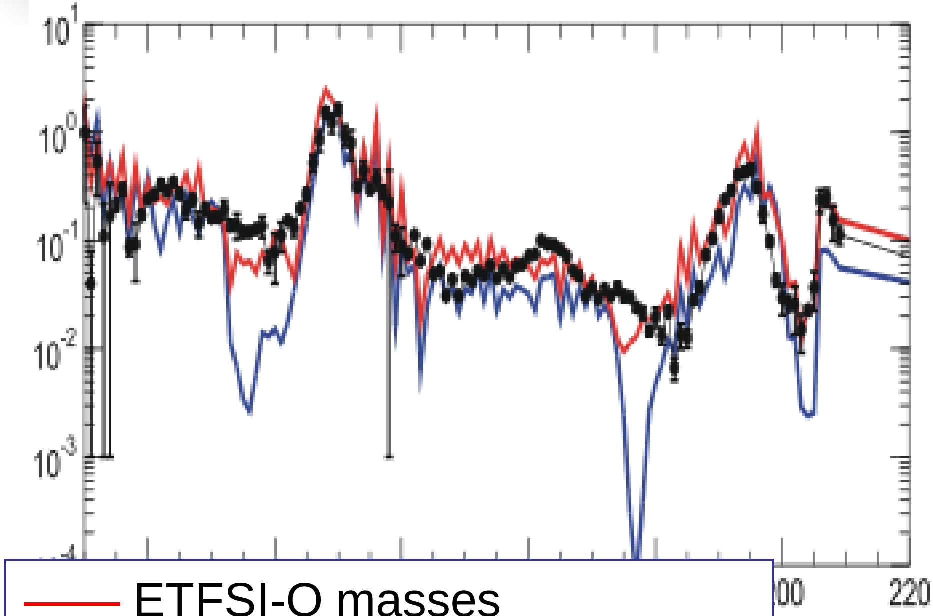
— ETFSI-Q masses
— ESTSI-1 masses
Classical r process astro model



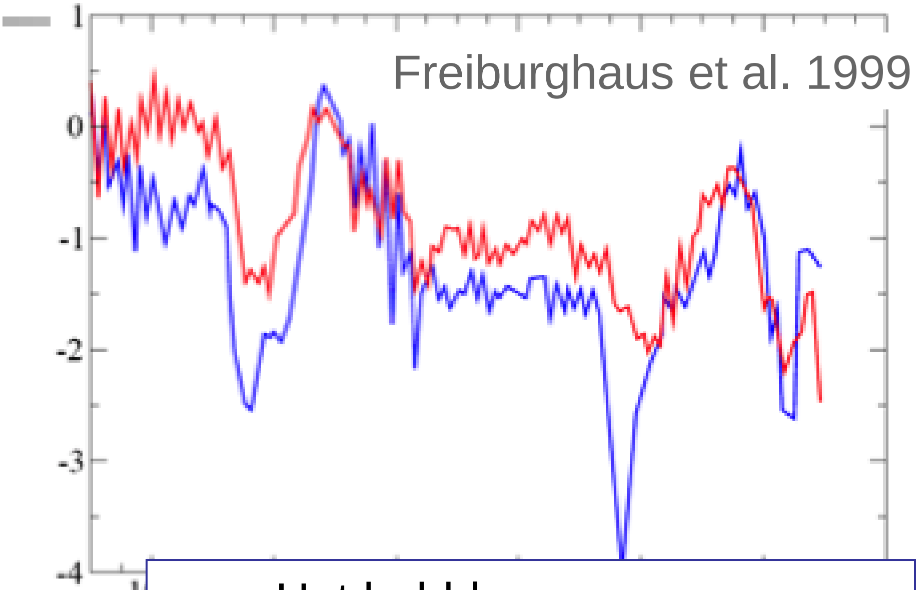
Peaks of r-process abundances near “magic numbers”, nuclear shell closures

BUT, models of nuclear structure from stability do not reproduce abundances
⇒ Change in nuclear structure far from stability?

r-process abundances



——— ETFSI-Q masses
——— ESTSI-1 masses
Classical r process astro model



Freiburghaus et al. 1999

——— Hot bubble
——— Classical r process model
ETFSI-1 masses

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 ??

Nuclear reaction experiments with rare isotopes: Probing nuclear structure, reactions and nucleosynthesis

(with (d,p) reactions)

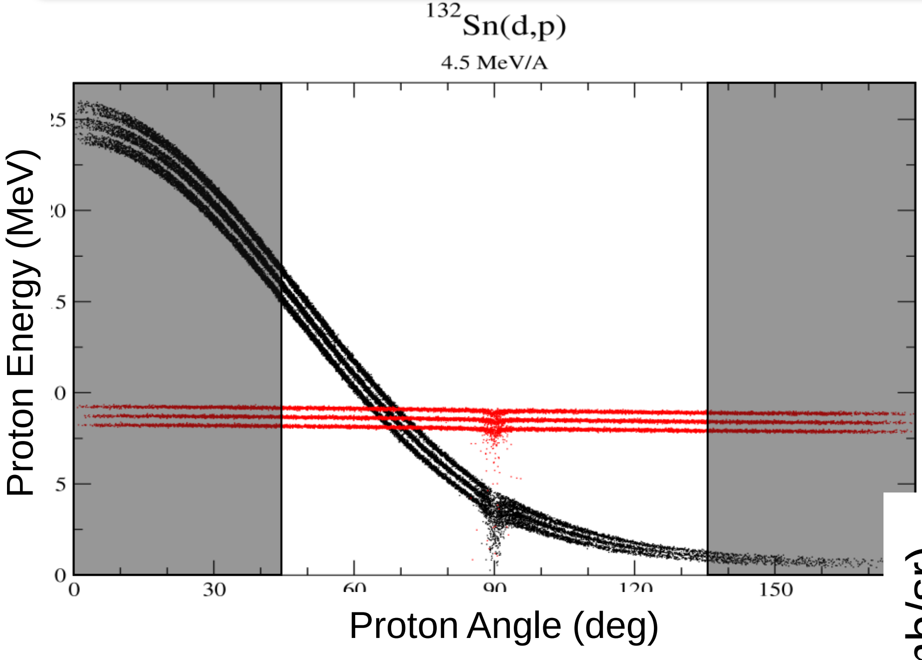
Jolie A. Cizewski
Rutgers University
cizewski@rutgers.edu

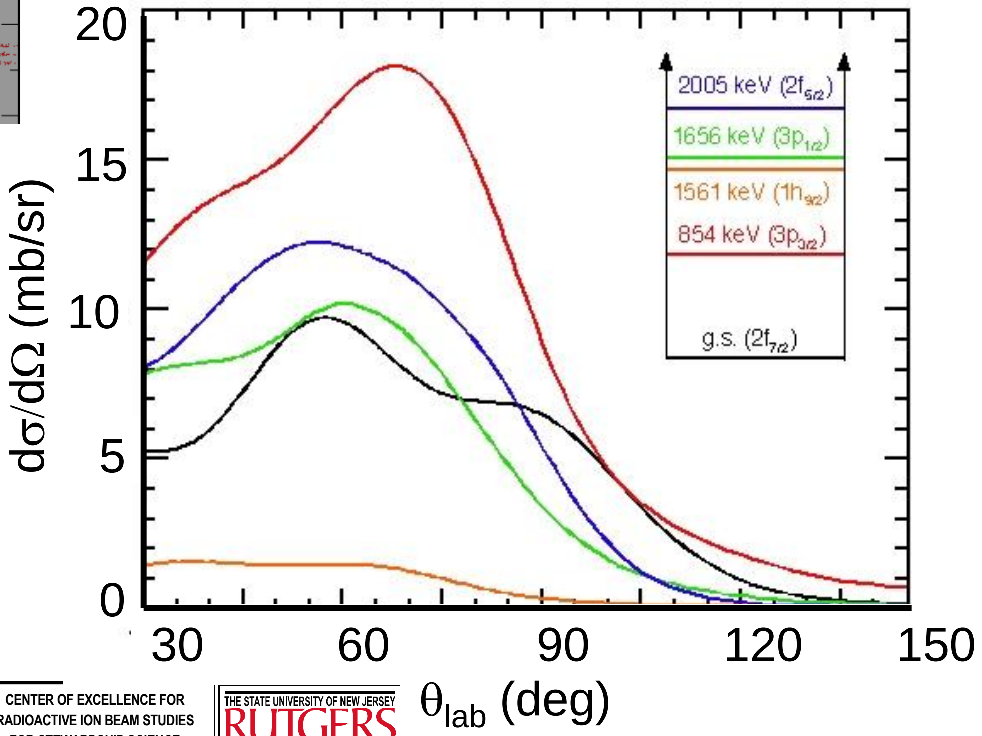
Review of part 1

- Goal: understanding single-particle character of nuclei far from stability
  - Important for nuclear structure
  - Important for synthesis of heavy elements in the cosmos
- Introduction to (d,p) reactions with RIBs
- Challenges with inverse kinematics
  - New instruments to detect light ions and heavy recoils
- Challenges with extracting the physics, e.g., spectroscopic factors

(d,p) in inverse kinematics

Where do you put your detectors?





Forward $\theta_{c\text{-}o\text{-}m}$ ↔ backward θ_{lab}

At backward θ_{lab}: E_{proton} very small cross section very small.

At forward θ_{lab}: E_{proton} rises quickly with angle ($dE/d\theta$ is large).

Getting the physics out

- Elastic scattering
  - To normalize the data
  - Future: elastic scattering to inform optical model
- (d,p) exp absolute differential cross sections
- Spectroscopic factors

$$\boxed{S = \left(\frac{d\sigma}{d\Omega}\right)_{\exp} \Big/ \left(\frac{d\sigma}{d\Omega}\right)_{DWBA}}$$

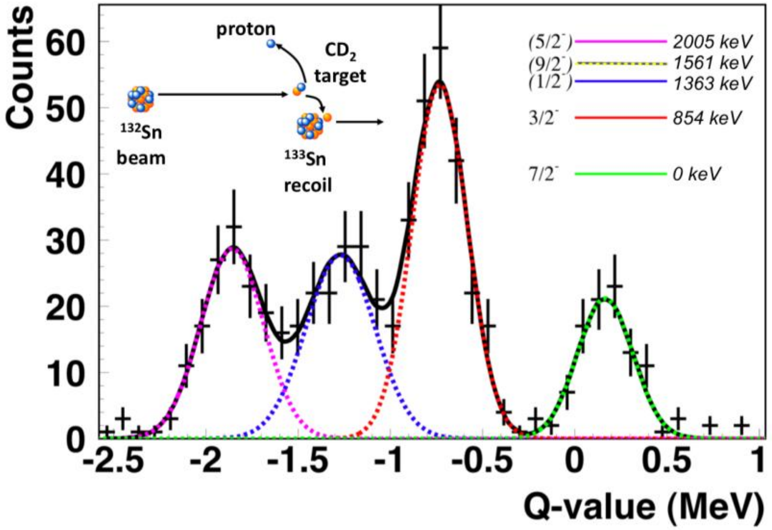
Is everything so straightforward?

- Wave function of the deuteron?
- Can we improve energy resolution?
- Can neutron transfer inform astrophysical neutron capture (s and r) processes on rare isotopes?

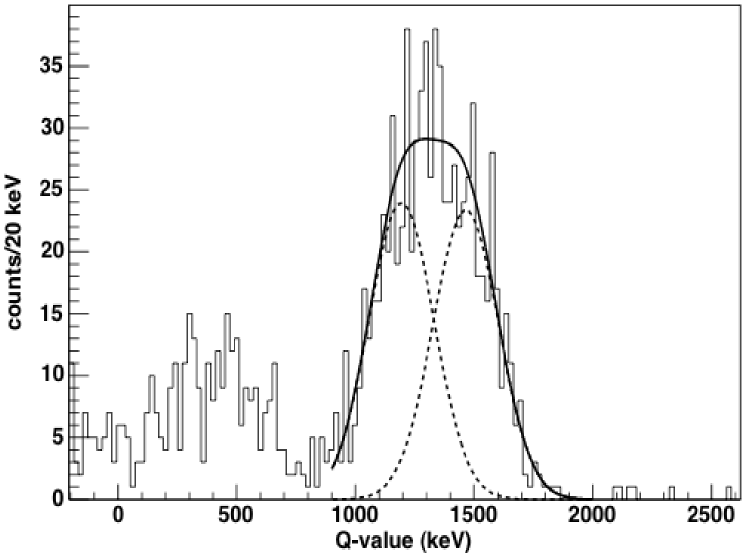
Need enhanced resolution

- Sources of “poor” resolution
  - Thickness of target
    - Heavy beam loses energy in target ⇔ doing reaction over range of energies
  - Energy and angle resolution of charged particle detectors
- Different approach to transfer: HELIOS
- Couple charged-particle and gamma-ray detectors

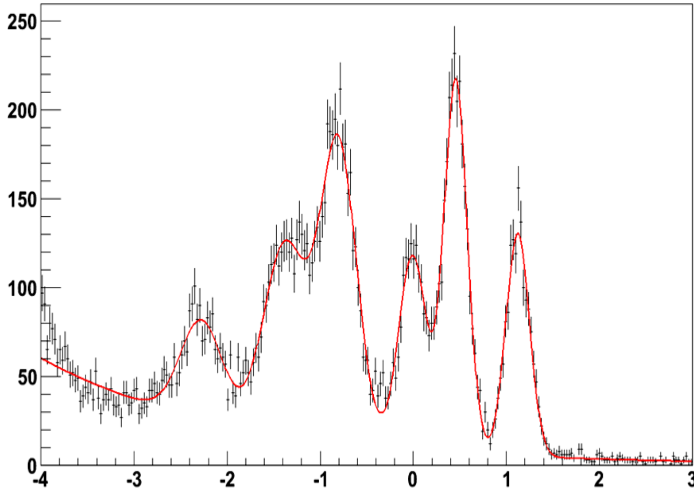
(d,p) reactions at ≈5 MeV/u



^{132}Sn + 80 μg/cm^2 CD$_2$ target at 30°
(160μg/cm^2 effective)



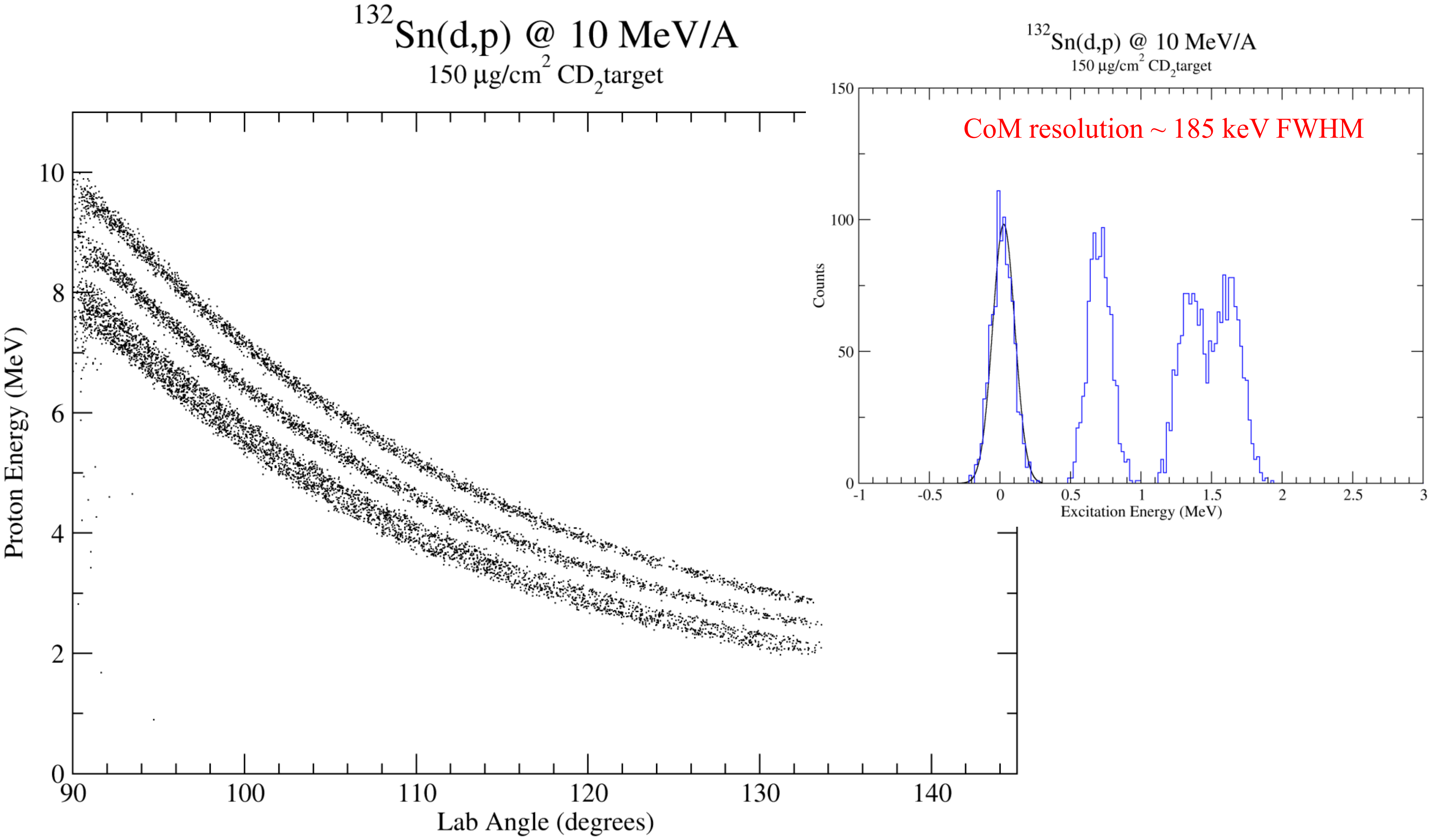
^{82}Ge + 430 μg/cm^2 CD$_2$ target at 90°



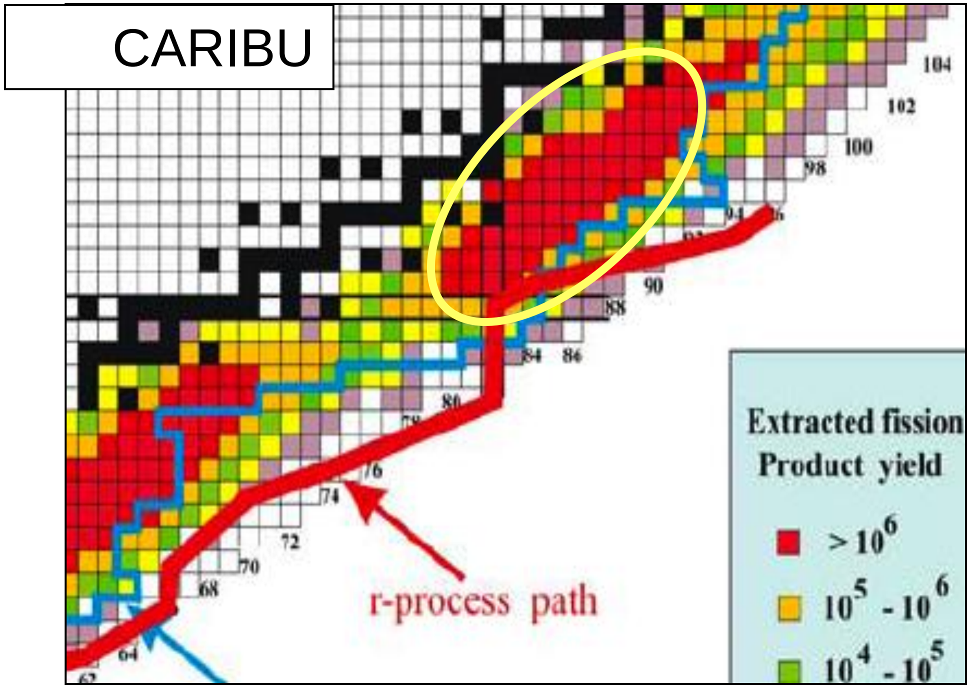
^{134}Te + 80 μg/cm^2 CD$_2$ target at 30°
(160μg/cm^2 effective)
Higher level density

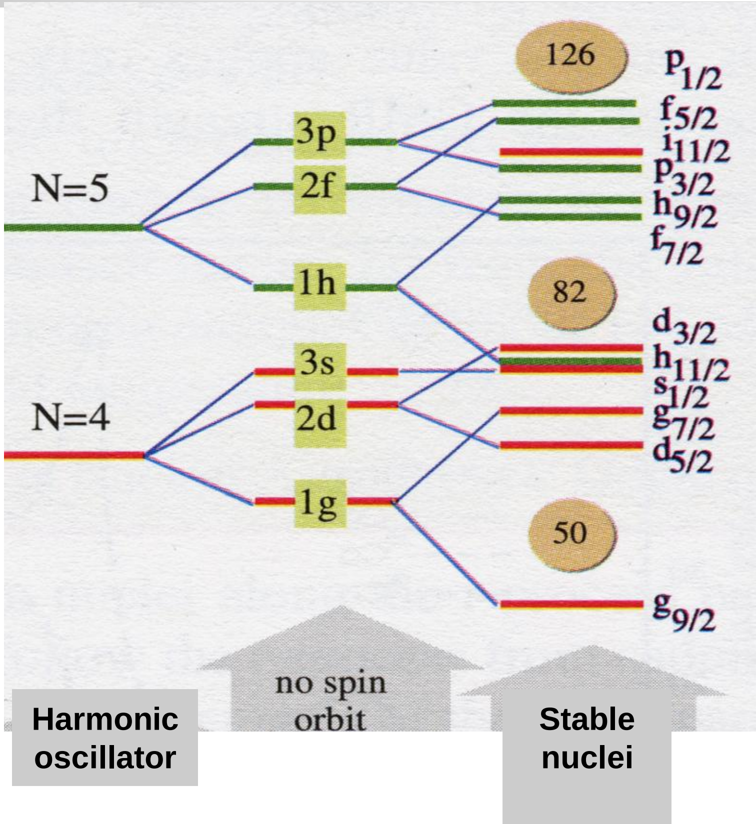
Solution 1: Run at higher beam energies

Simulation of ^{132}Sn(d,p) @ 10 MeV/A – ORRUBA response



Probing N≈82,Z≈50 at 8-10 MeV/u with CARIBU at ATLAS



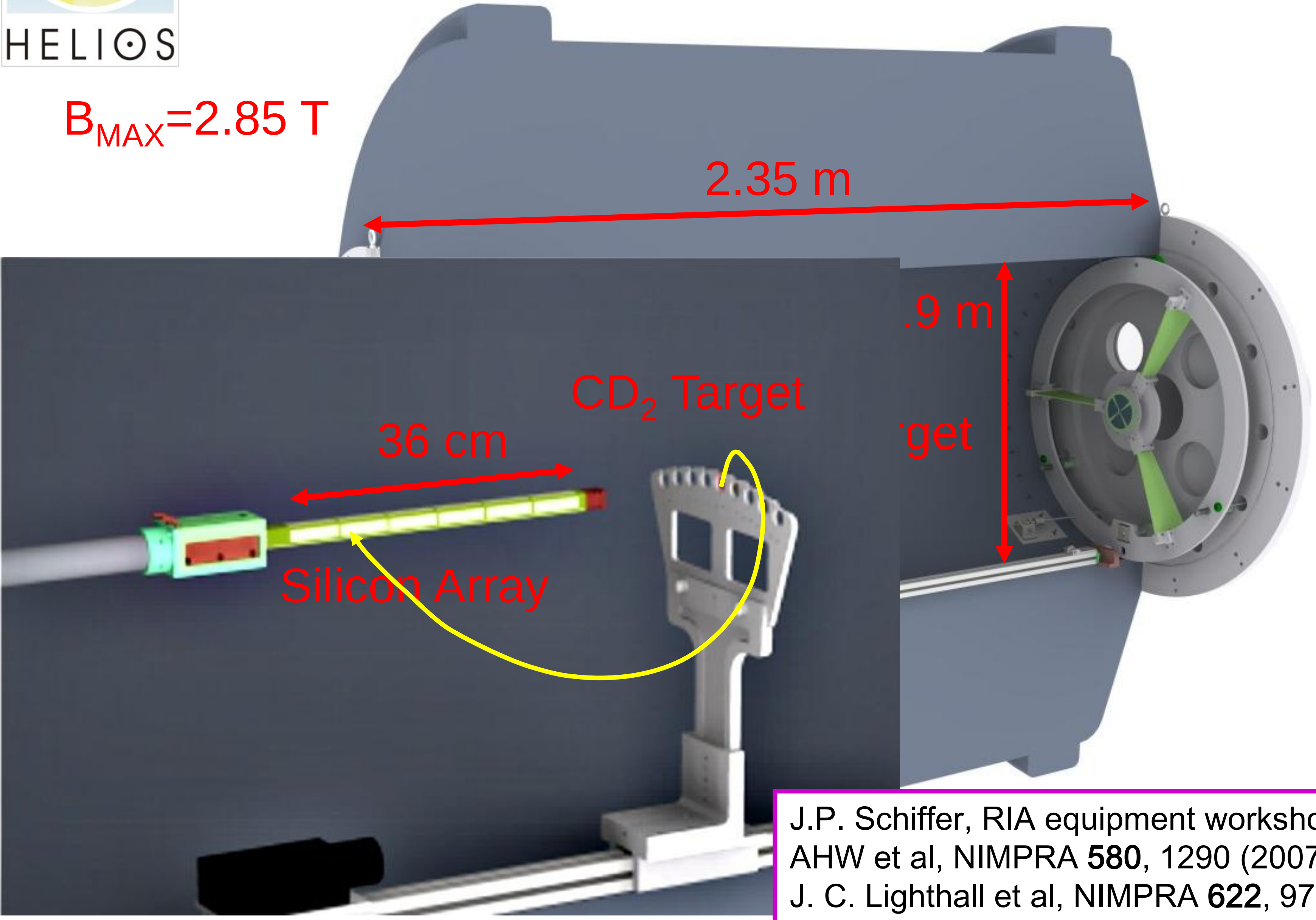


^{252}Cf fission fragments: stopped & re-accelerated to 8-10 MeV/u

Solution 2:
Different experimental technique

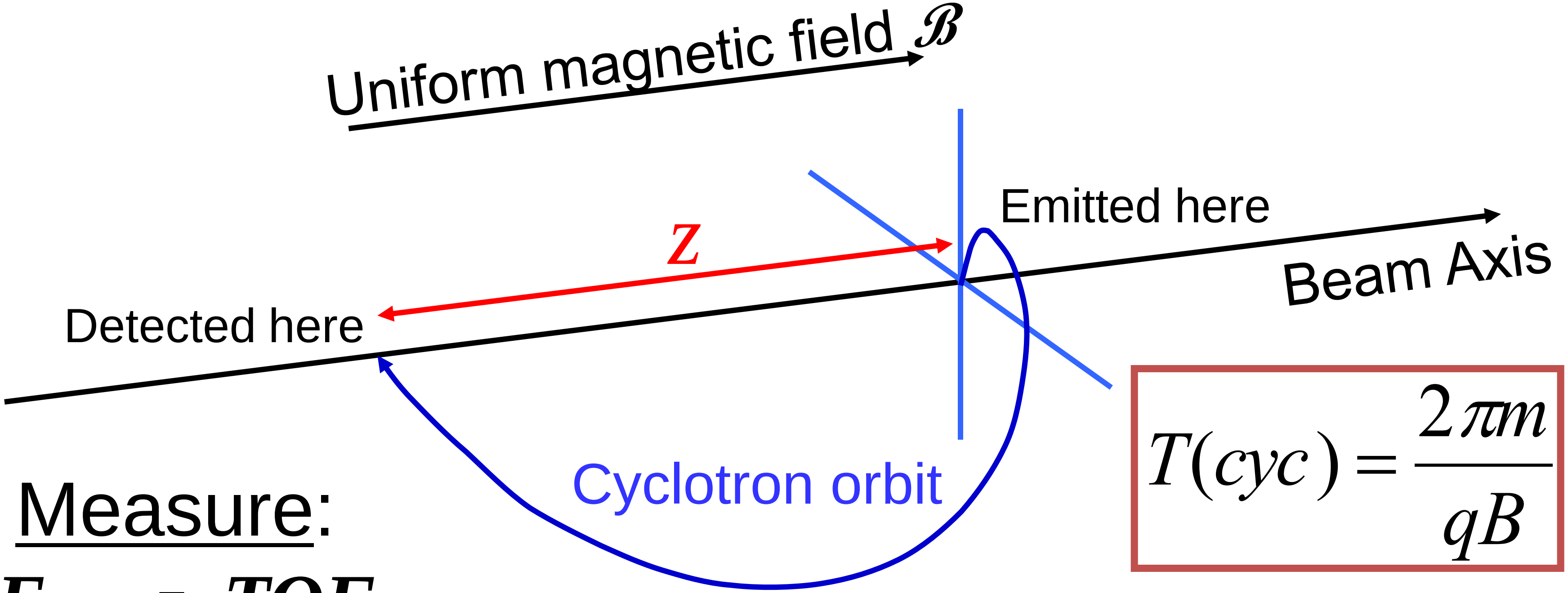
HELIcal Orbit Spectrometer -HELIOS

B_{MAX}=2.85 T



J.P. Schiffer, RIA equipment workshop 1999,
AHW et al, NIMPRA **580**, 1290 (2007)
J. C. Lighthall et al, NIMPRA **622**, 97 (2010)

In a magnetic field with HELIOS



$$\boxed{T(cyc) = \frac{2\pi m}{qB}}$$

Measure:

E_{lab}, z, TOF

Deduce:

E_{CM}, θ_{CM}

$$z \propto \cos\theta_{CM}$$

$$E_{lab} = E_{CM} - A + Bz$$

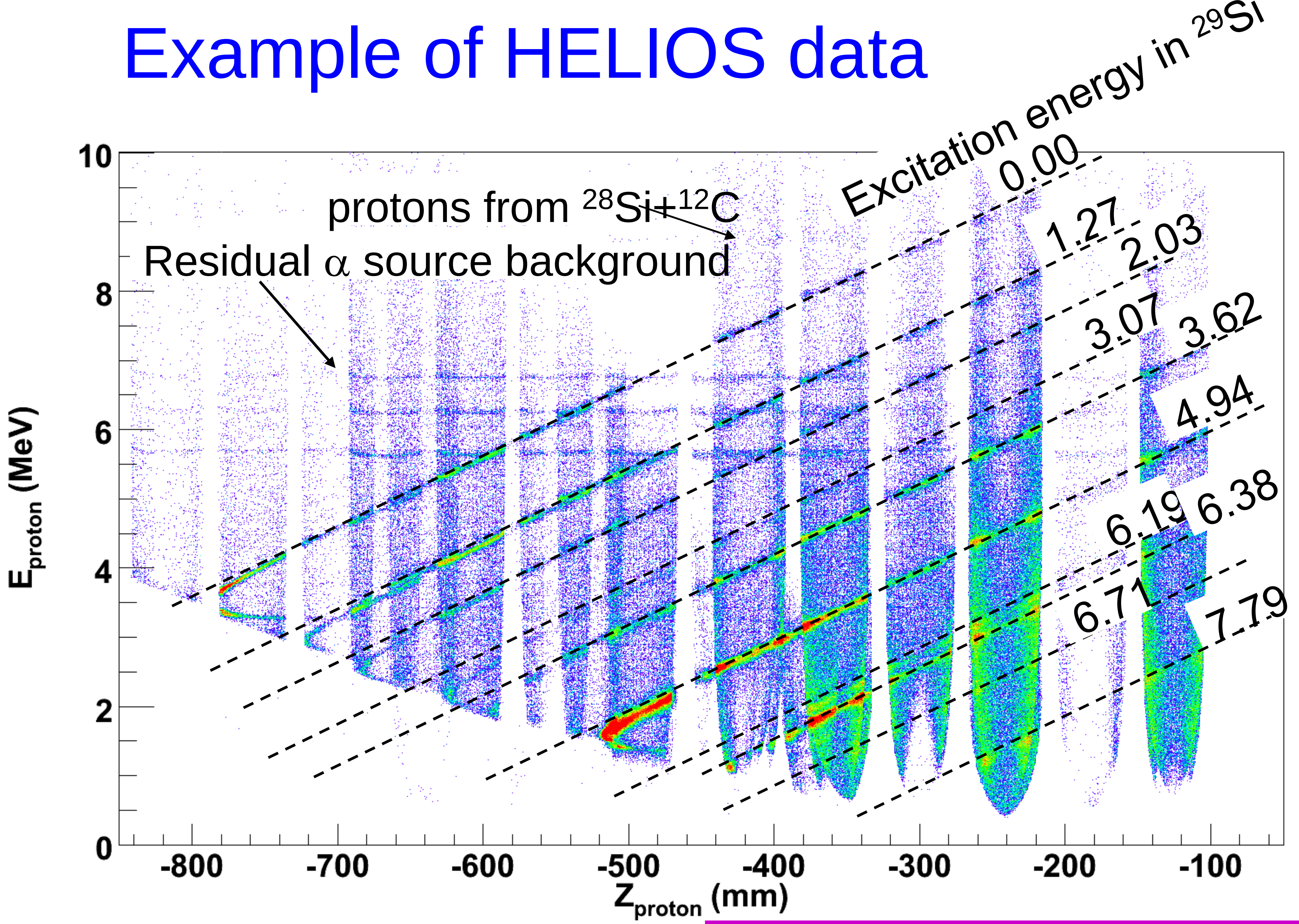
For a given state

$$\Delta E_{lab} = \Delta E_{CM}$$

For two states at fixed z

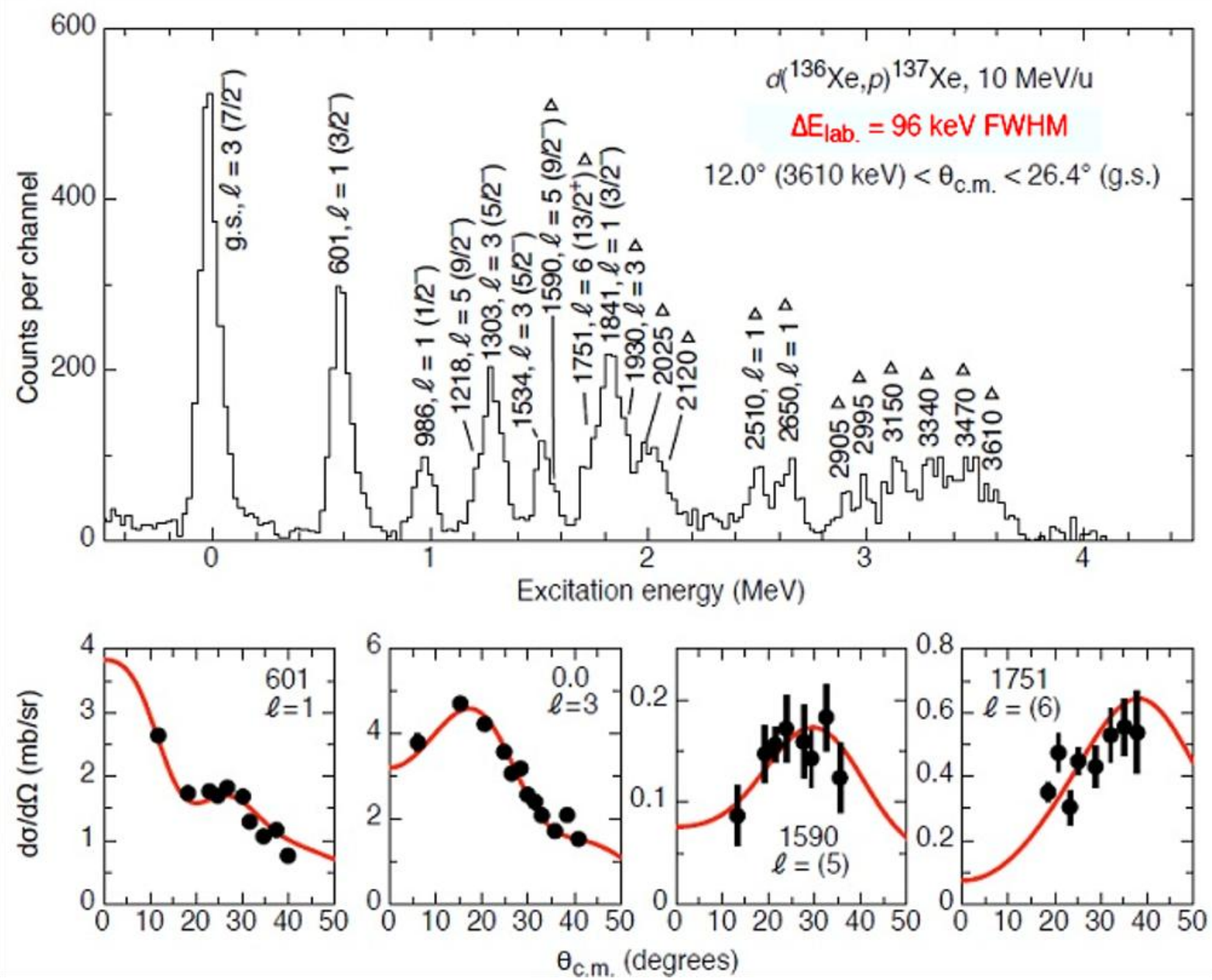
A. Wuosmaa

Example of HELIOS data



J. C. Lighthall et al, NIMPRA **622**, 97 (2010)

With heavy beams: ^{136}Xe(d,p)^{137}Xe



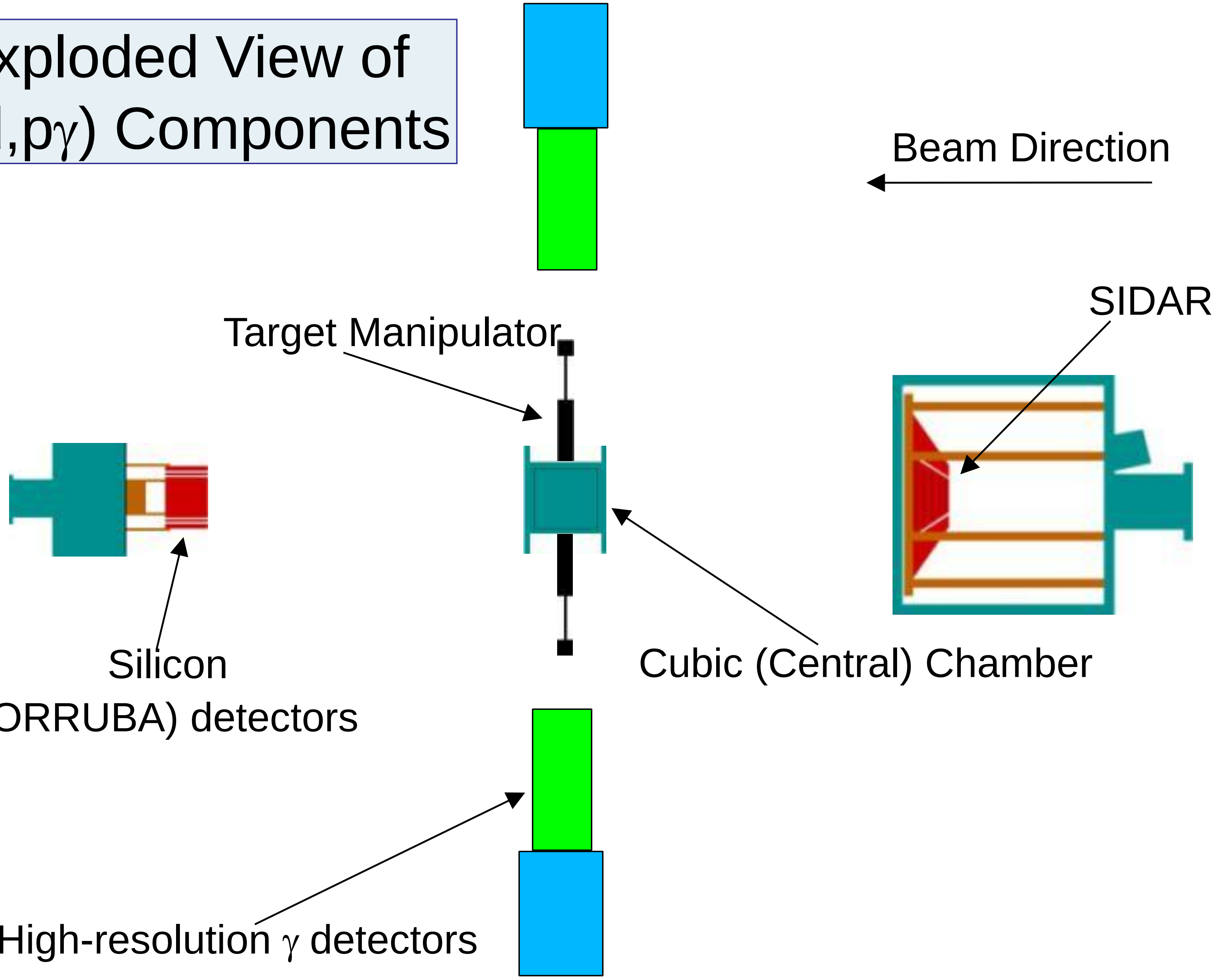
Anticipate ^{132}Sn(d,p)^{133}Sn with ^{132}Sn from CARIBU

B. P. Kay et al, in preparation

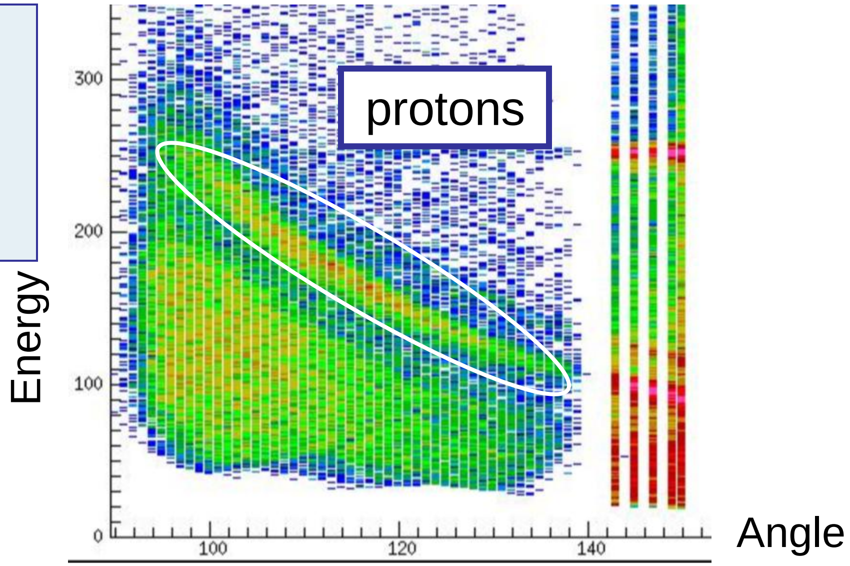
Need enhanced resolution

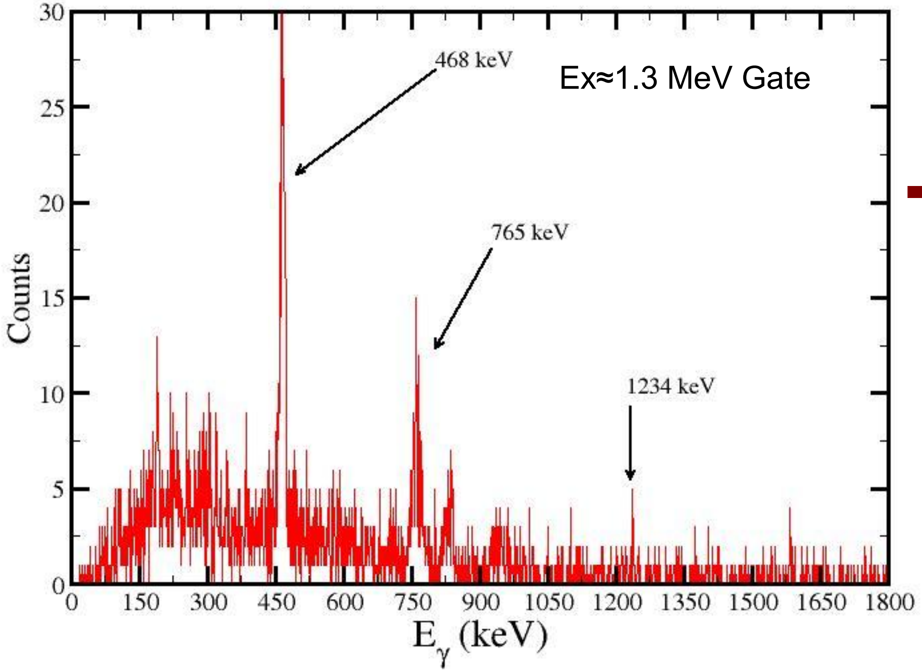
- Thinner targets, higher energy beams
- Different approach to transfer: HELIOS
  - <100 keV resolution with 10 MeV/u Xe beams on CD2 target
- Open shell nuclei: need even better resolution
- Couple charged-particle and gamma-ray detectors
  - Increase resolution
  - Populate additional states
  - (Surrogate for neutron-induced reactions)

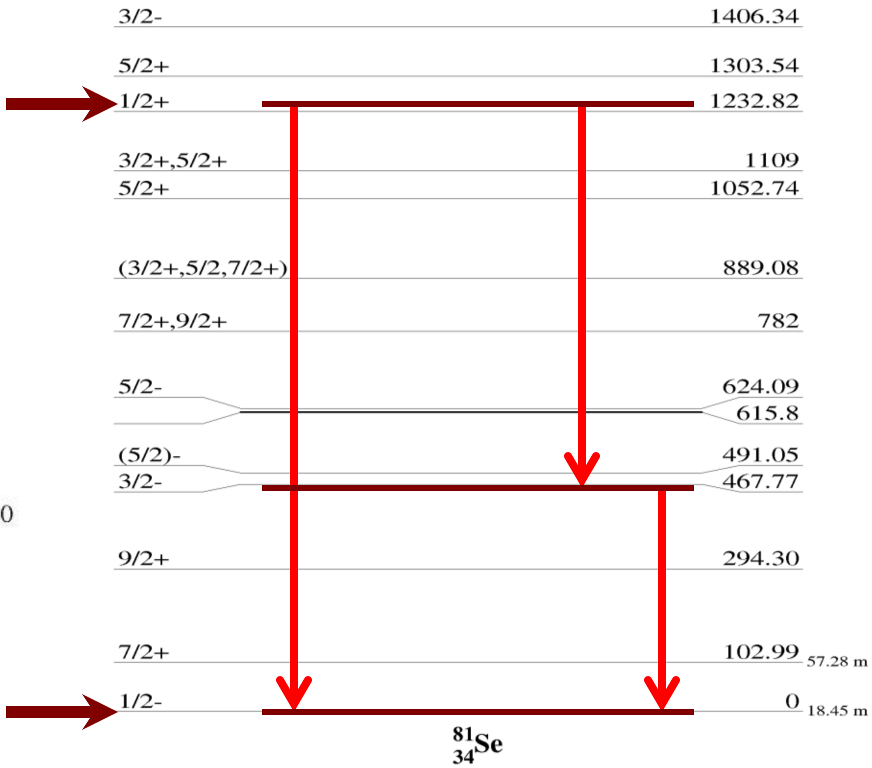
Exploded View of (d,pγ) Components



^{80}Se(d,pγ)
stable ^{80}Se beam test



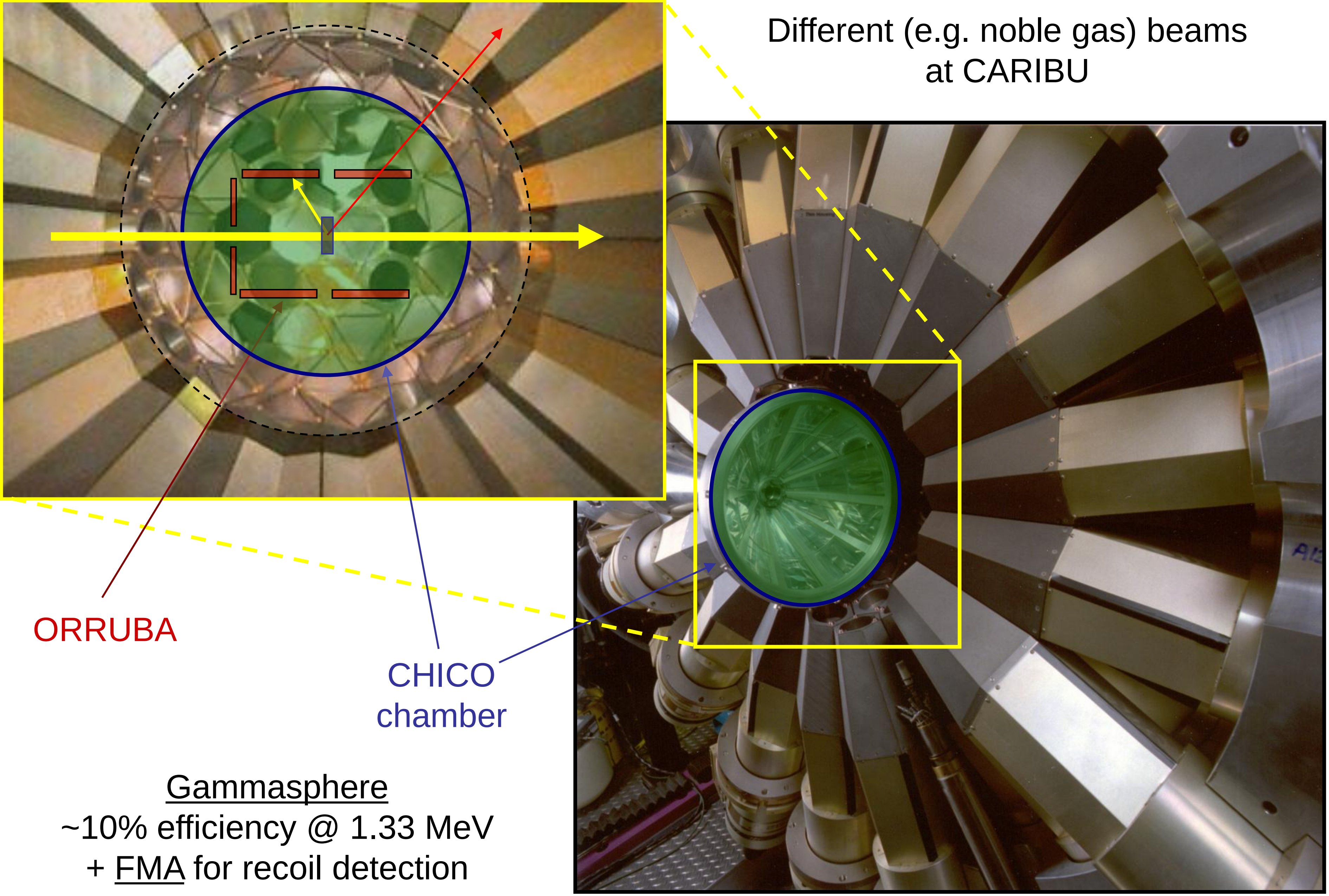




J.A.C., M.S. Johnson et al.
NIM **B261**, 938 (2007)

ORRUBA and Gammasphere and CARIBU

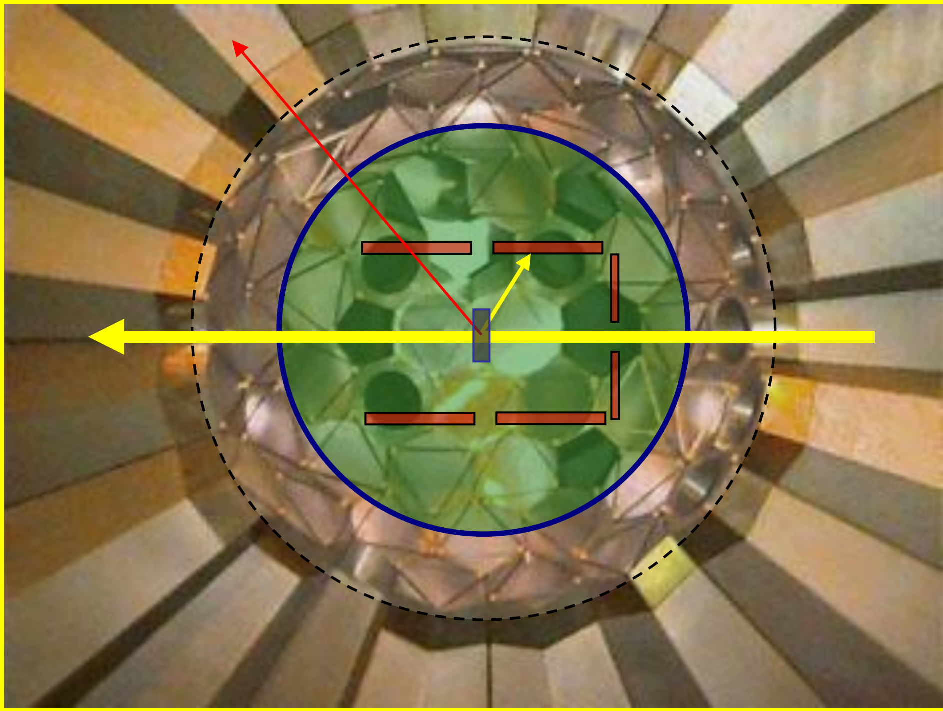
Different (e.g. noble gas) beams
at CARIBU

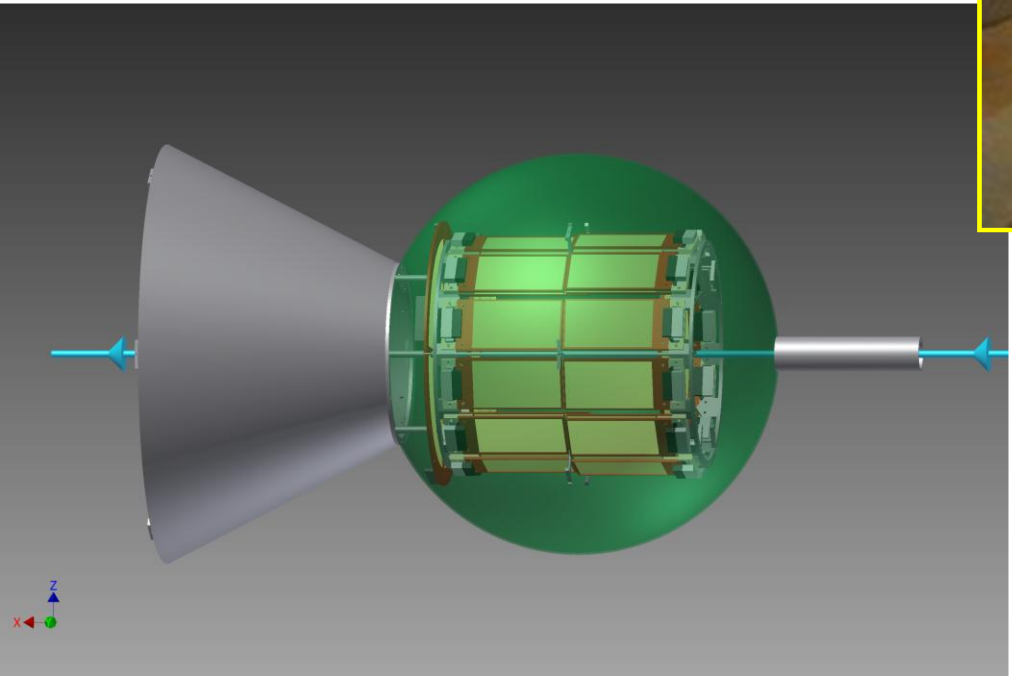


Gammasphere
~10% efficiency @ 1.33 MeV
+ FMA for recoil detection

Coupling ORRUBA + Gammasphere

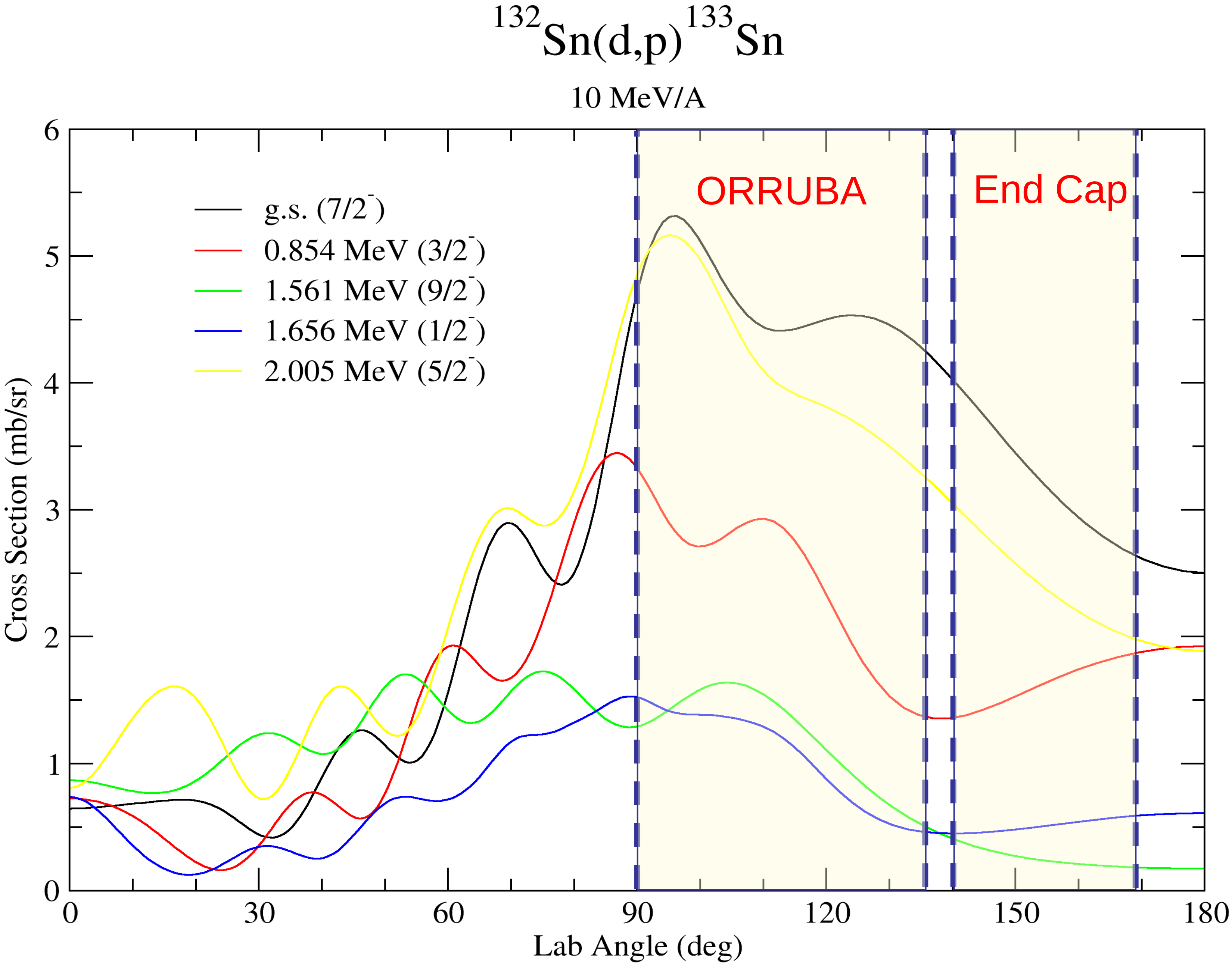
- Gammasphere + FMA (or other system) for heavy recoils
- Full ORRUBA + End cap





Experimental developments approved at ATLAS

Calculation of ^{132}Sn(d,p) @ 10 MeV/A



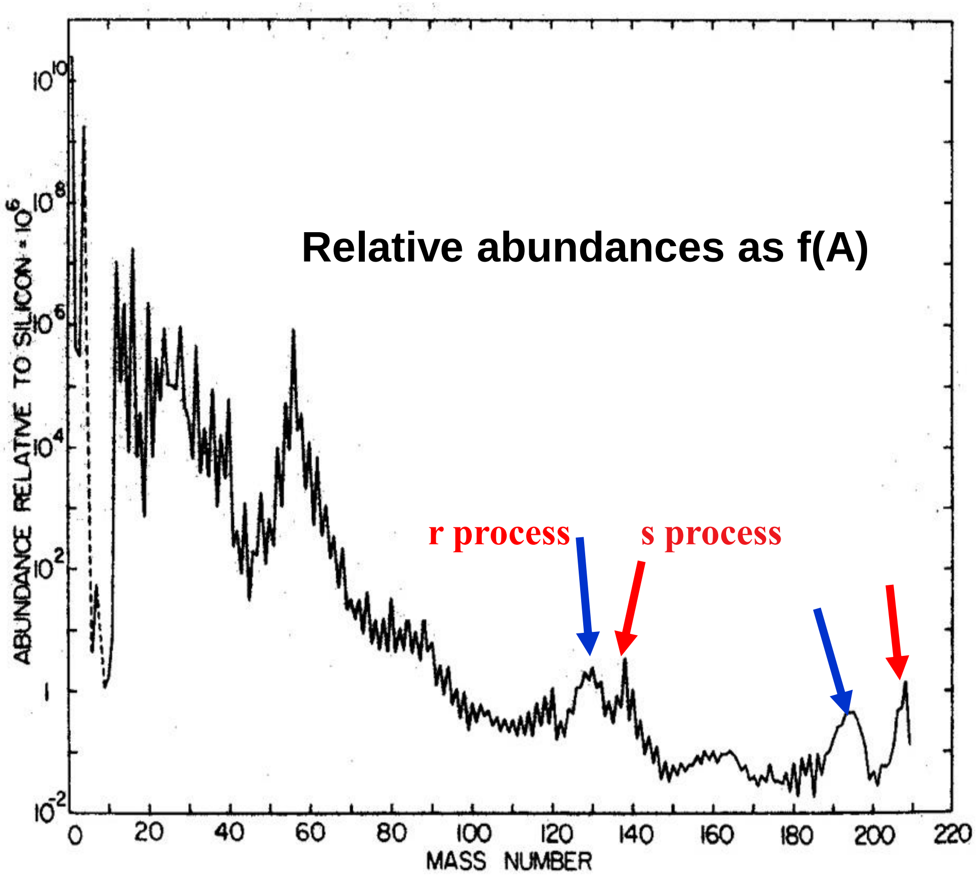
More physics with (d,pγ)

Surrogate for neutron capture?

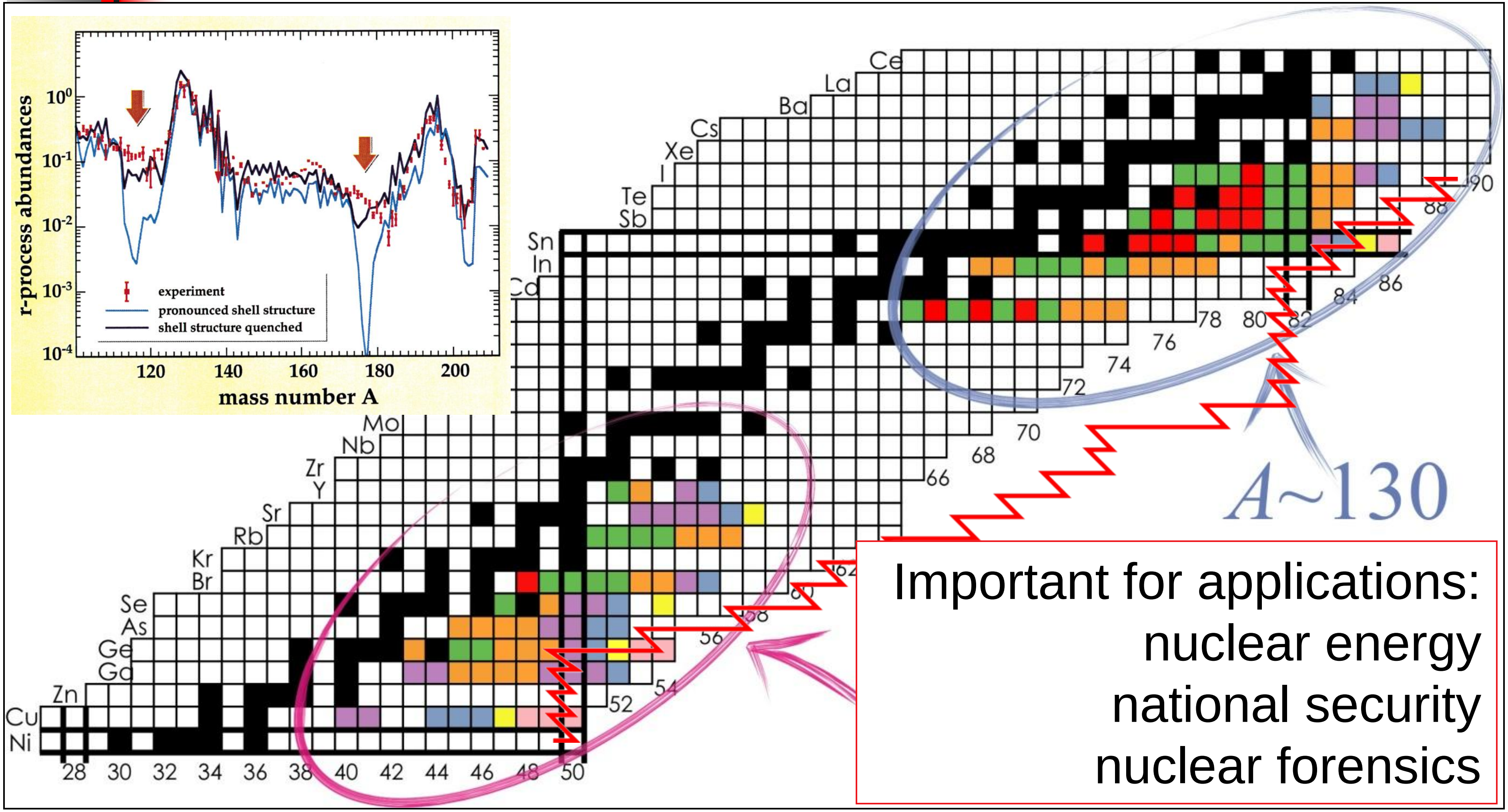
(n,γ) reactions & Nucleosynthesis

- Slow (s) and rapid (r) (n,γ) processes
- Unstable nuclei
- Can’t measure (n,γ) directly when

  $t_{1/2} < 100$ days

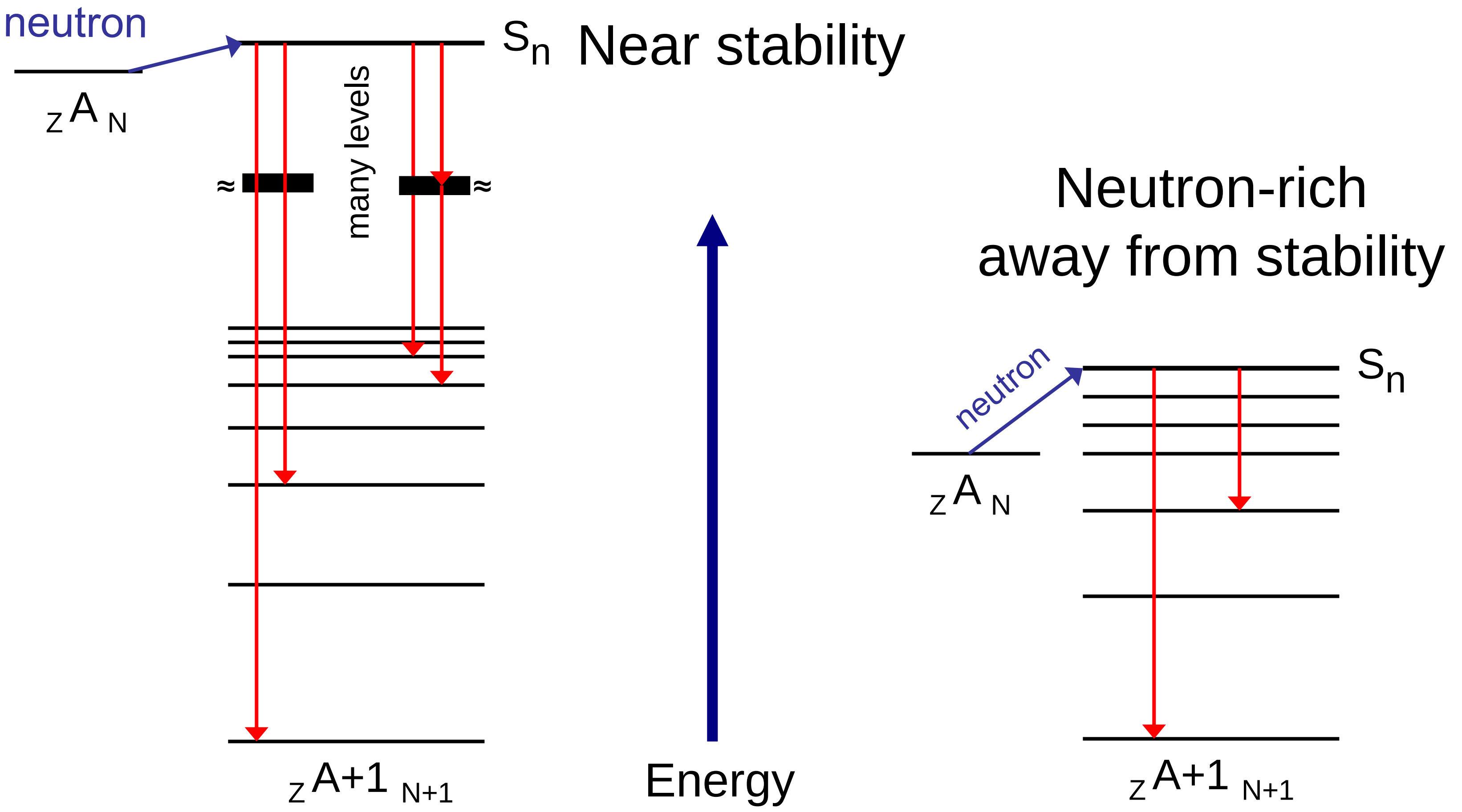


Neutron capture on fission fragments: r process nucleosynthesis & applications



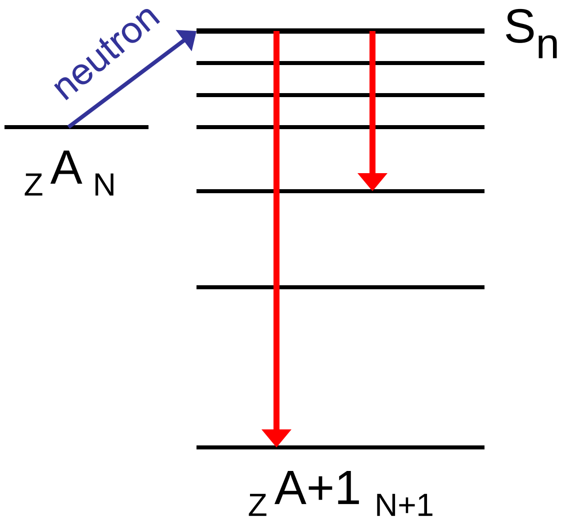
Important for applications:
nuclear energy
national security
nuclear forensics

Neutron Capture

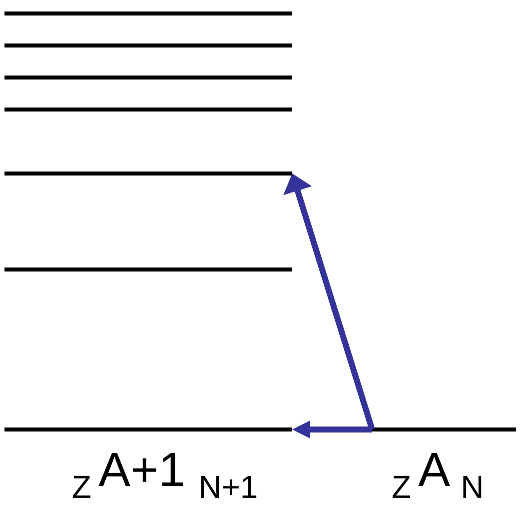


Neutron Capture Far From Stability

Neutron-rich (n,γ)

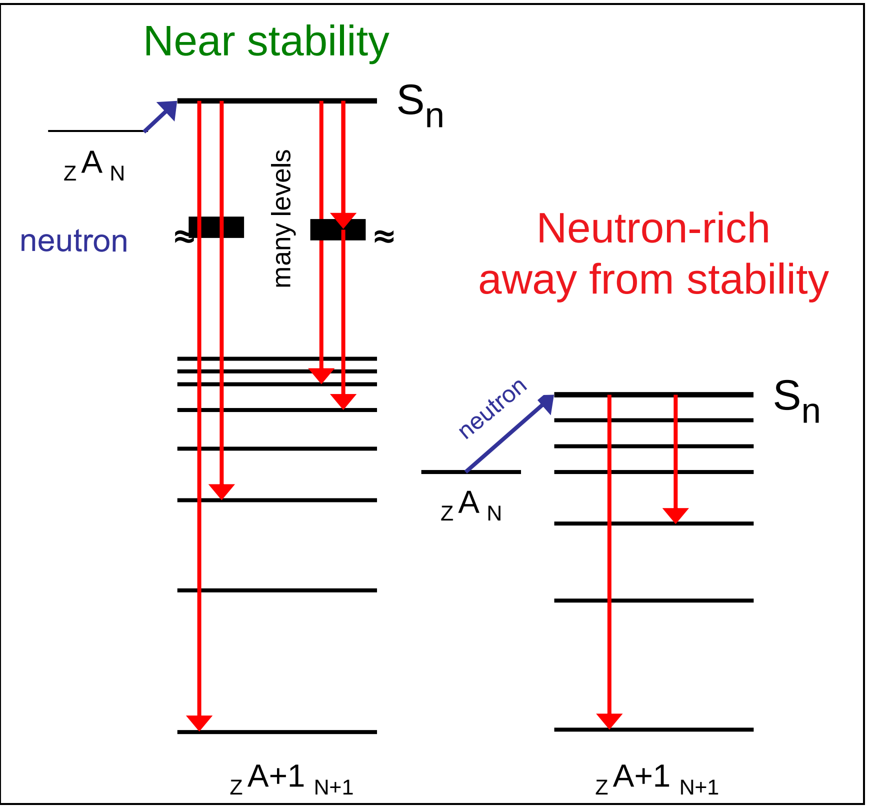


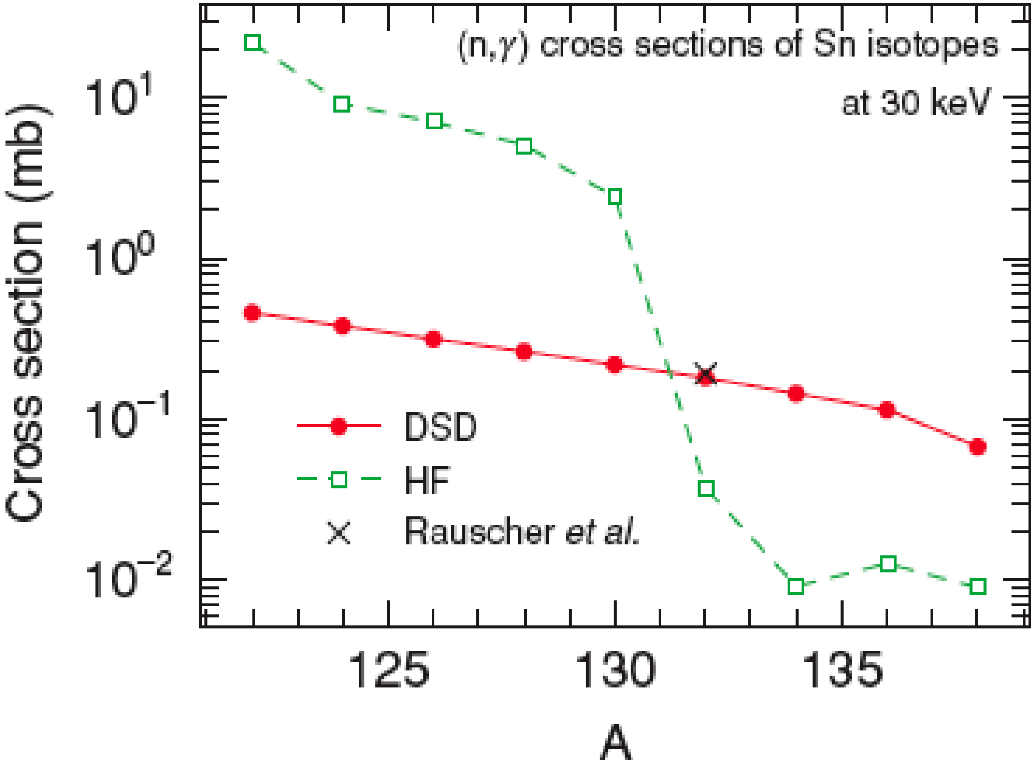
(d,p) Reaction



Direct capture especially important near neutron shell closures

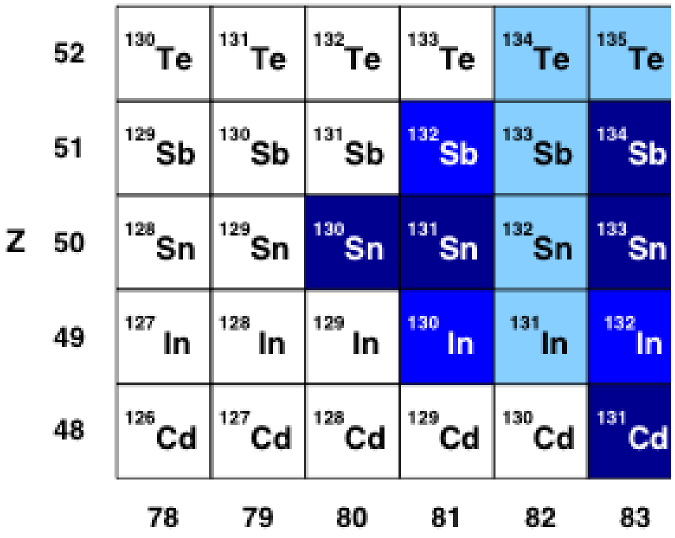
A≈^{130}Sn $\sigma(n,\gamma)$ and sensitivities



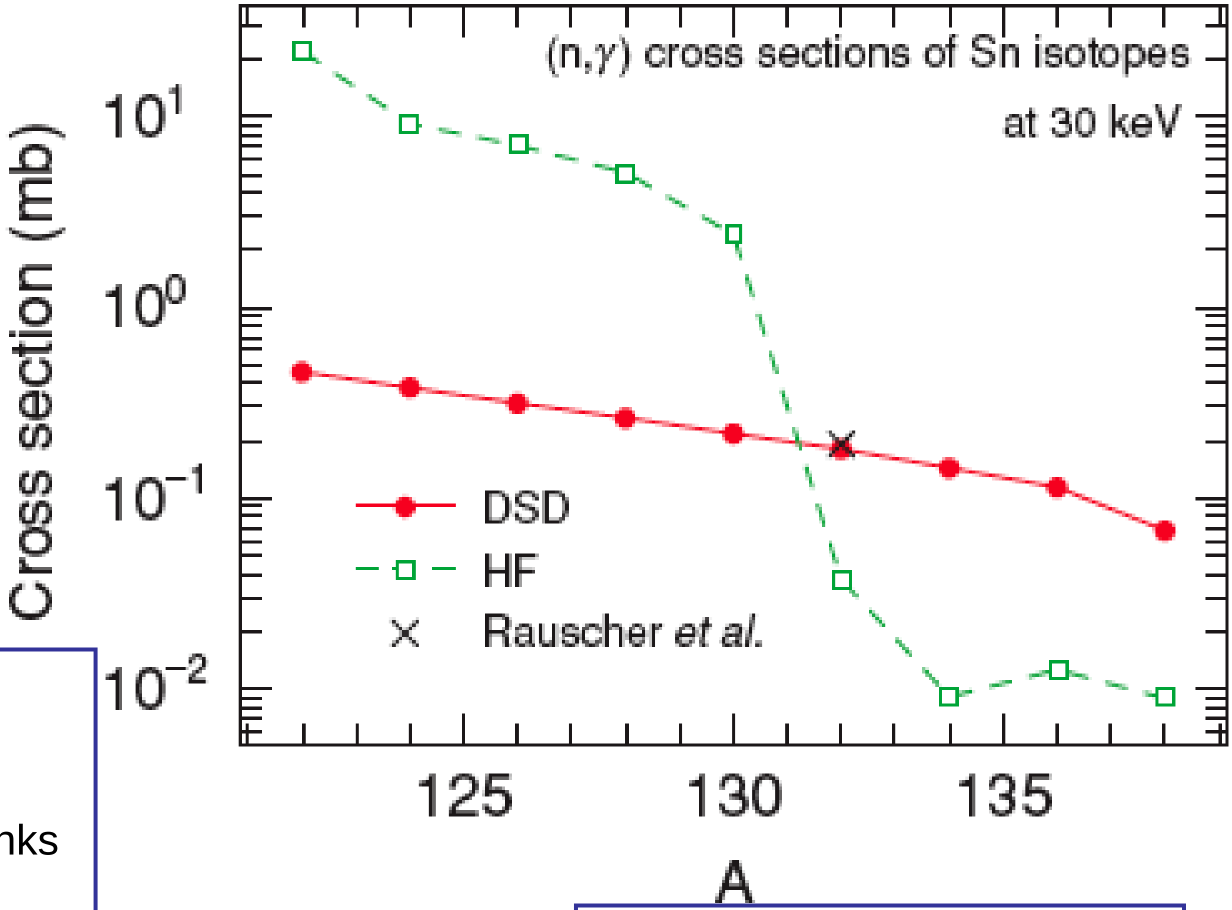


Sn(n,γ) vs A
Chiba, et al. PRC **77**, 015809 (2008)

A≈^{130}Sn σ(n,γ) and sensitivities



Z						
52	^{130}Te	^{131}Te	^{132}Te	^{133}Te	^{134}Te	^{135}Te
51	^{129}Sb	^{130}Sb	^{131}Sb	^{132}Sb	^{133}Sb	^{134}Sb
50	^{128}Sn	^{129}Sn	^{130}Sn	^{131}Sn	^{132}Sn	^{133}Sn
49	^{127}In	^{128}In	^{129}In	^{130}In	^{131}In	^{132}In
48	^{126}Cd	^{127}Cd	^{128}Cd	^{129}Cd	^{130}Cd	^{131}Cd
	78	79	80	81	82	83

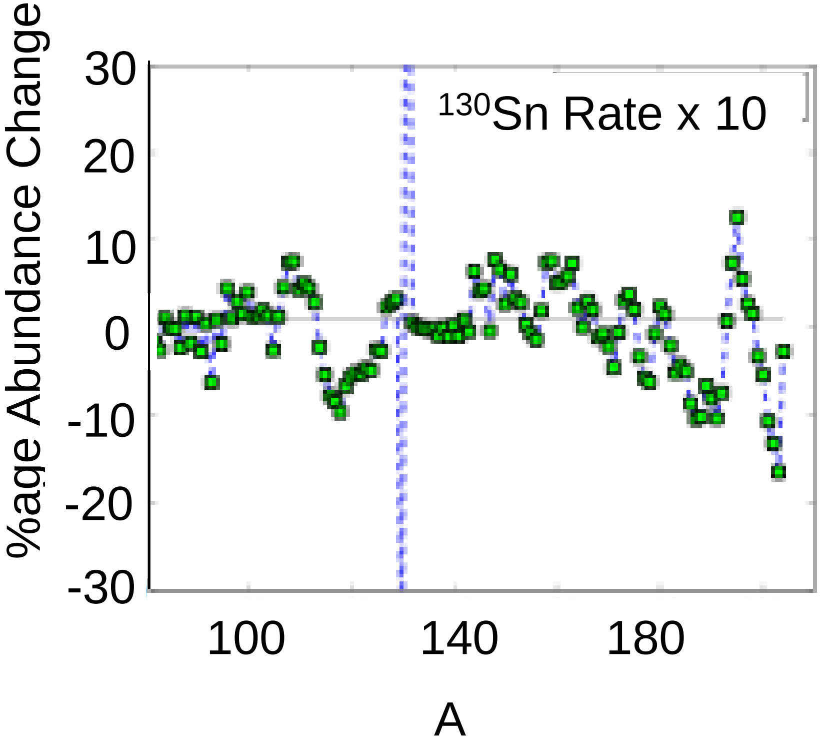


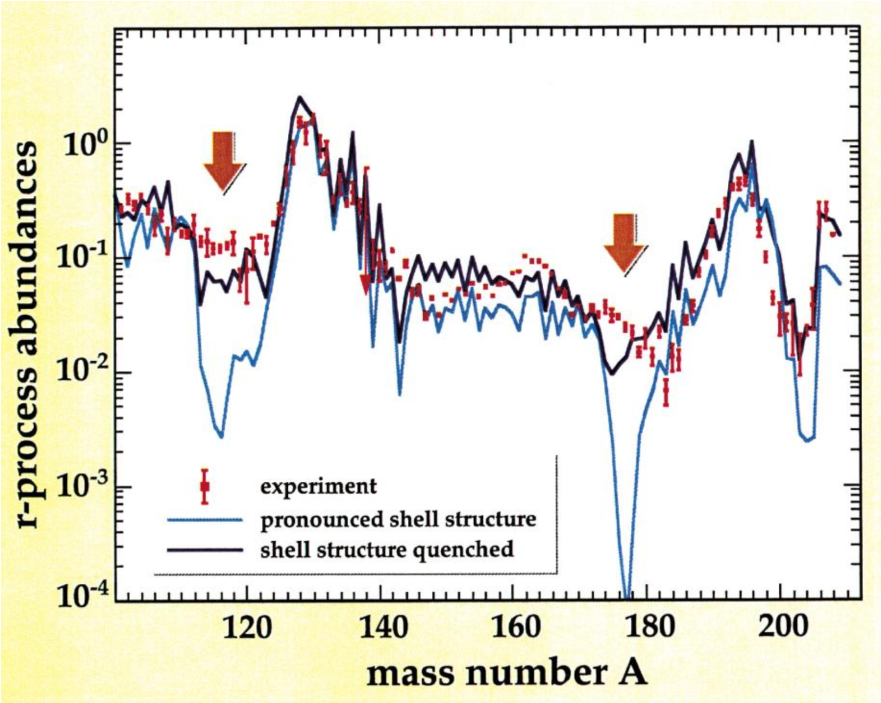
Changes in (n,γ) rates that change abundance patterns by at least 5%
Change factors:
Dark blue: x10; become neutron sinks

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)

r-process sensitivity studies





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

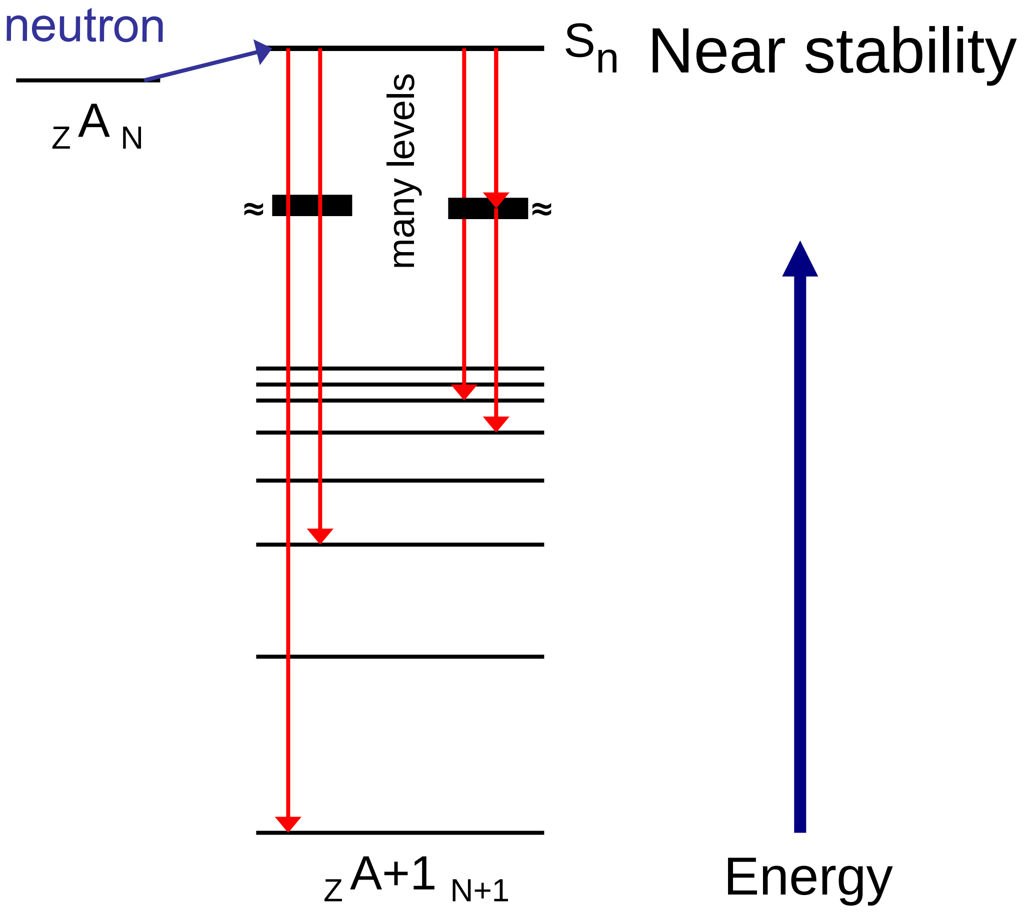
^{130}Sn(n,γ) direct capture rate uncertain by ≈10^3

(d,p) to ℓ=1⇔ direct (n,γ)

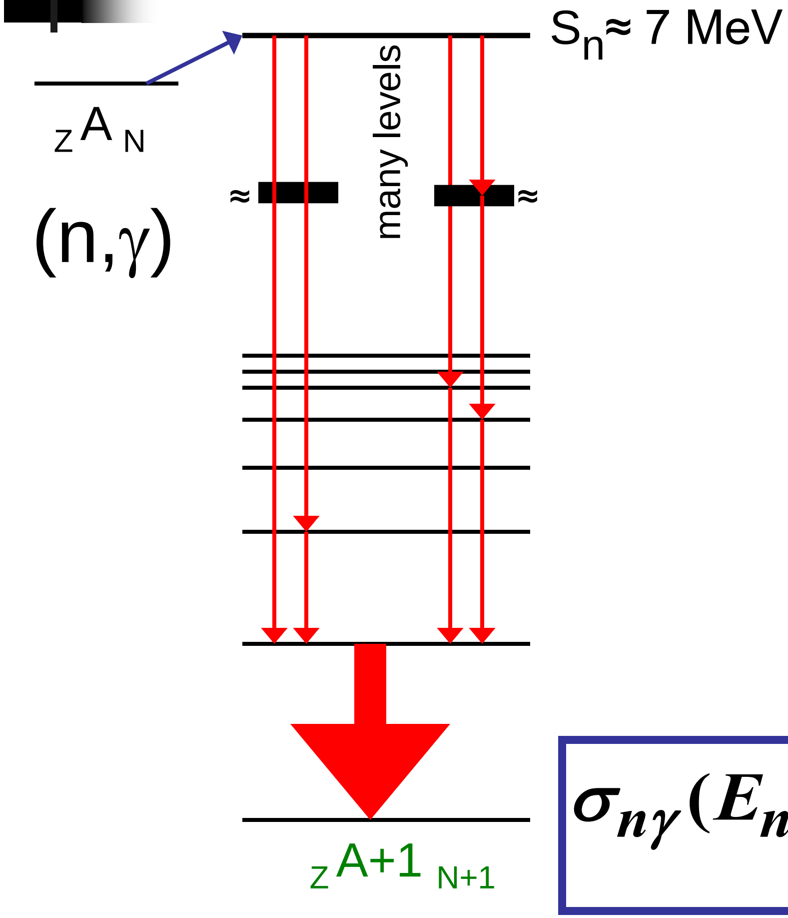
J. Beun, *et al.* J. Phys. G 36, 025201 (2009)

T. Rauscher, *et al.* PRC 57 2031 (1998)

Neutron Capture near stability and surrogate technique



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

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

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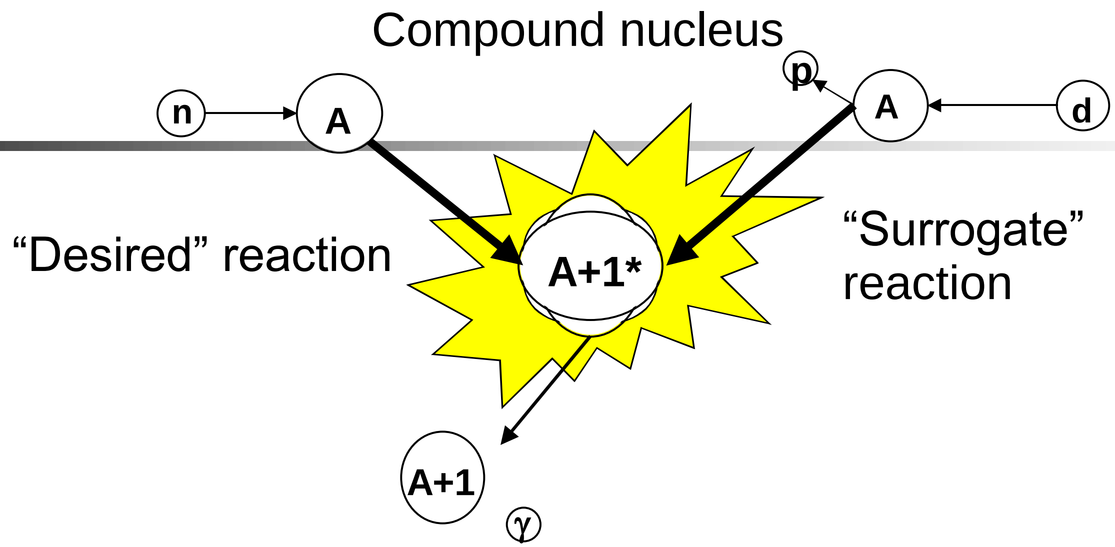
Surrogate reaction concept



Compound nucleus

“Desired” reaction

“Surrogate” reaction

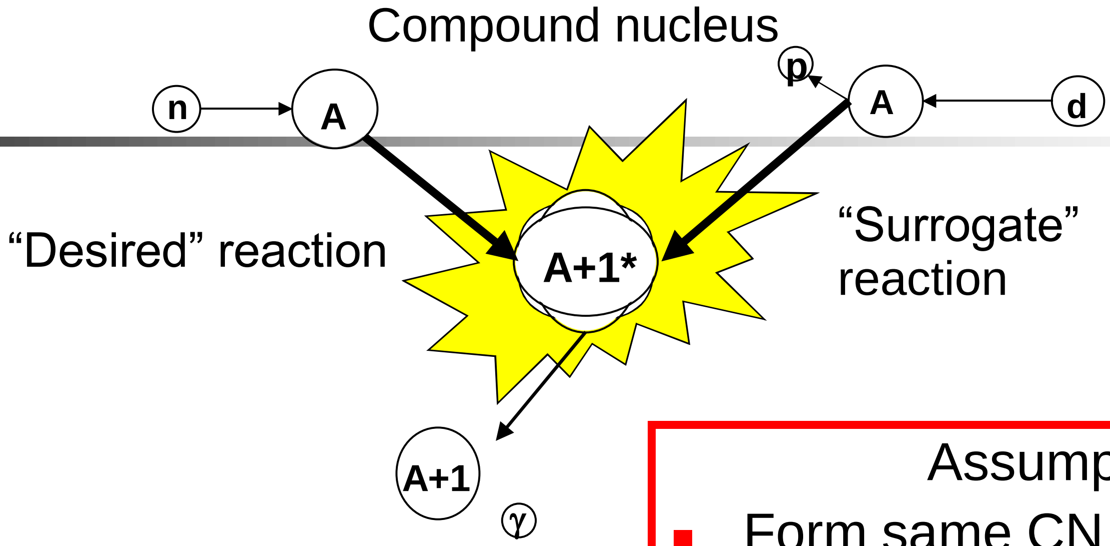
(n,γ) cross section can be written as product of compound nucleus formation and decay for every spin and parity:

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

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



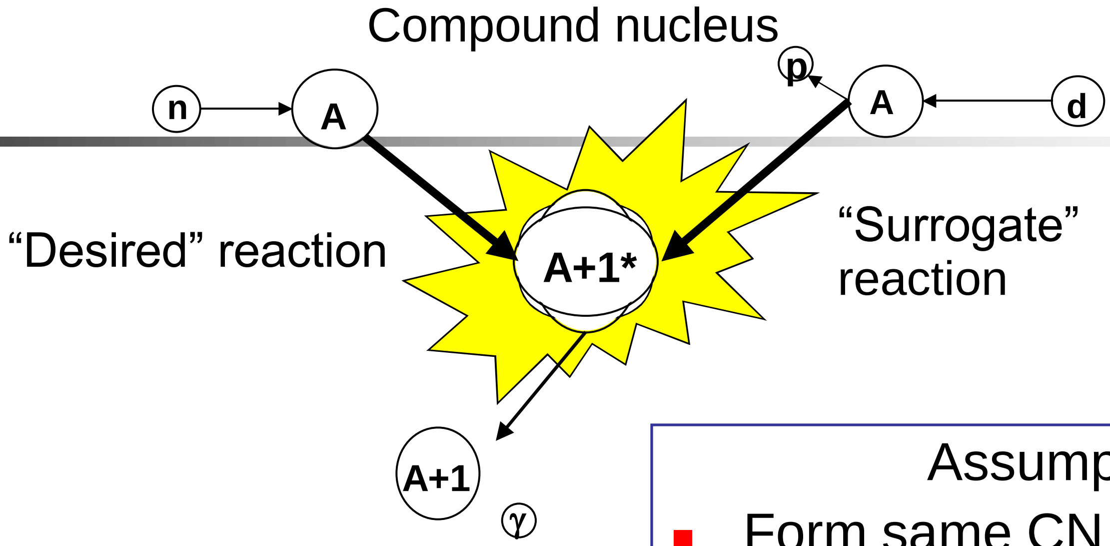
Assumptions:

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

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

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

Surrogate reaction W-E Limit


Compound nucleus

“Desired” reaction

“Surrogate” reaction

Assumptions:

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

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

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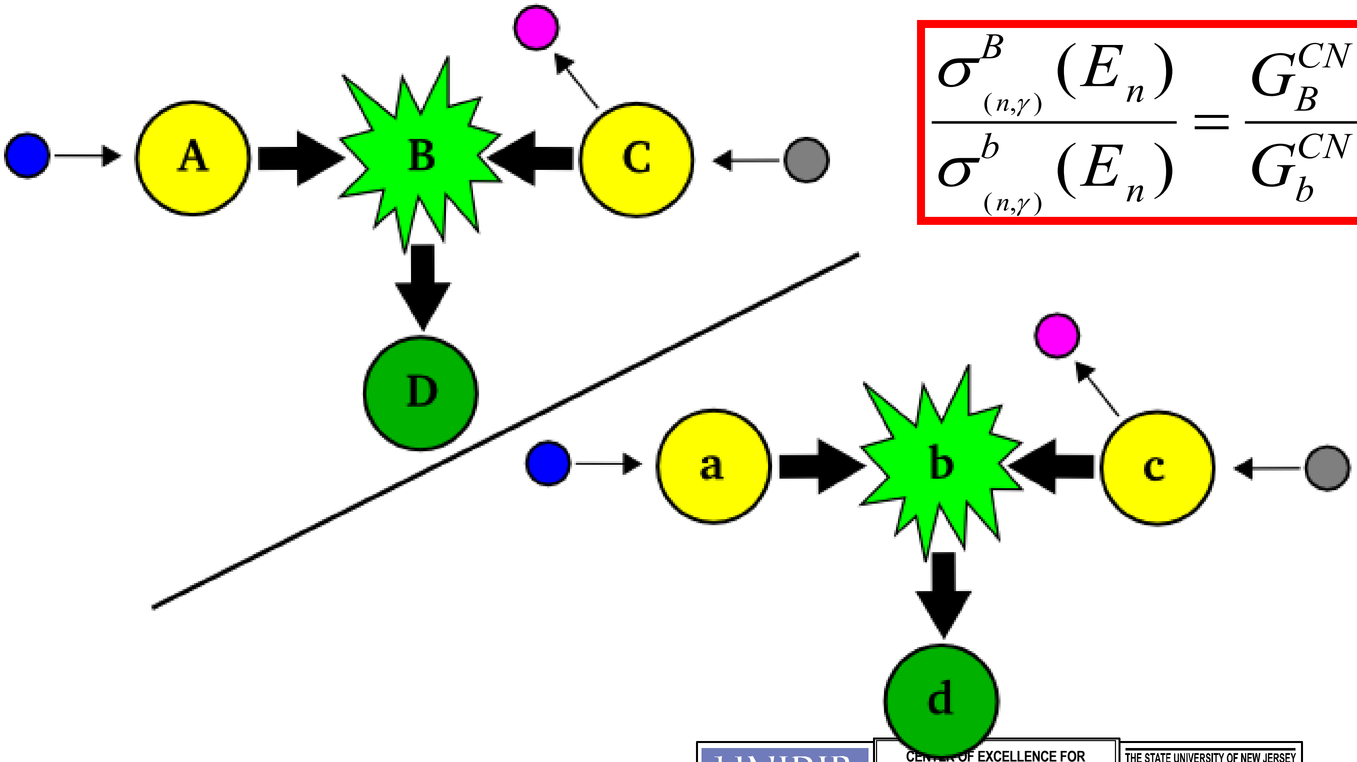
Surrogate ratio technique

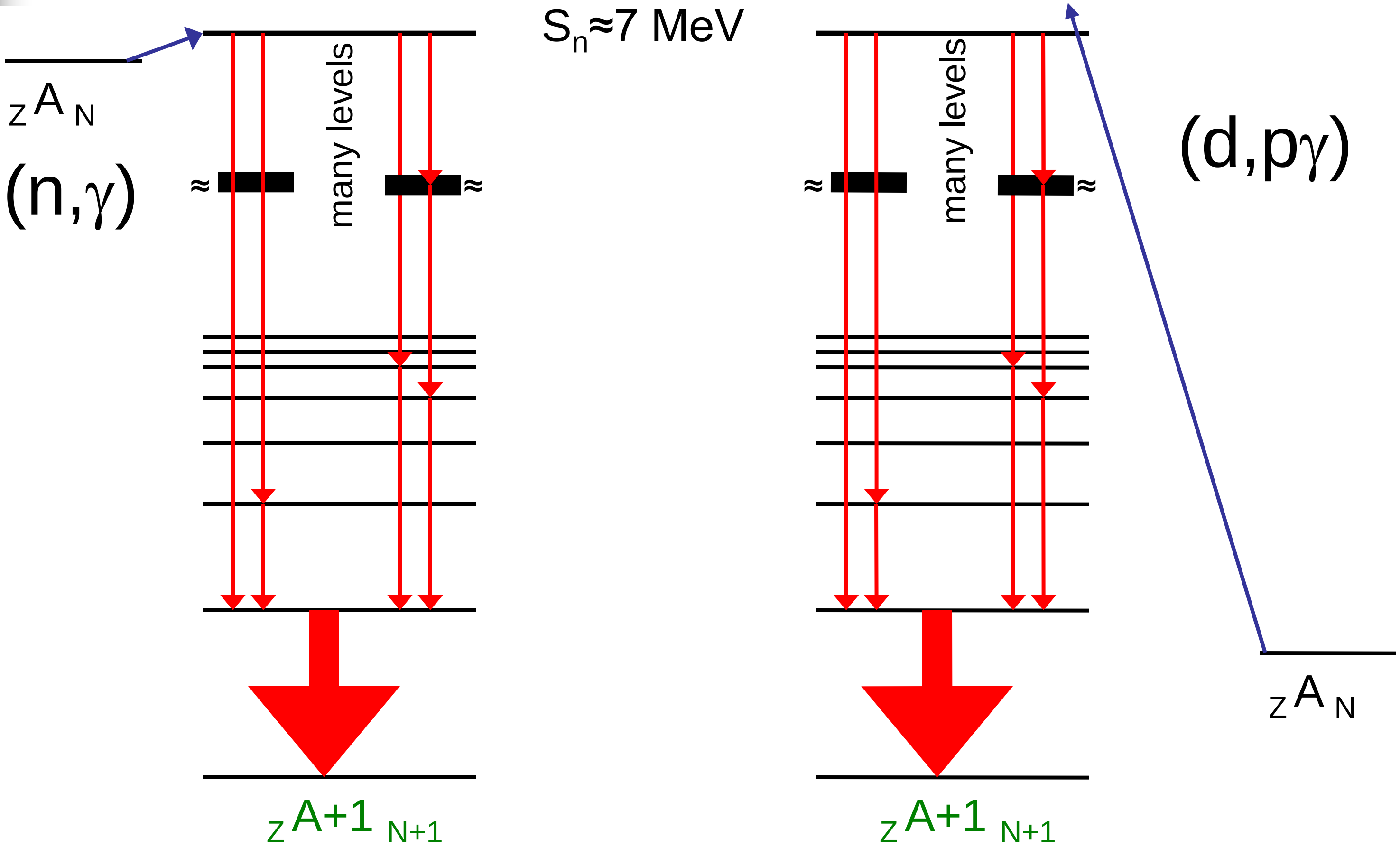
- Ratio of experimental yields can reduce systematic uncertainties
- Assume similar compound nuclear cross sections
- Know one cross section ⇒ ratio gives the unknown

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



$A(n,\gamma)(A+1) \leftrightarrow A(d,p)(A+1)$

Surrogate for (n,γ)?



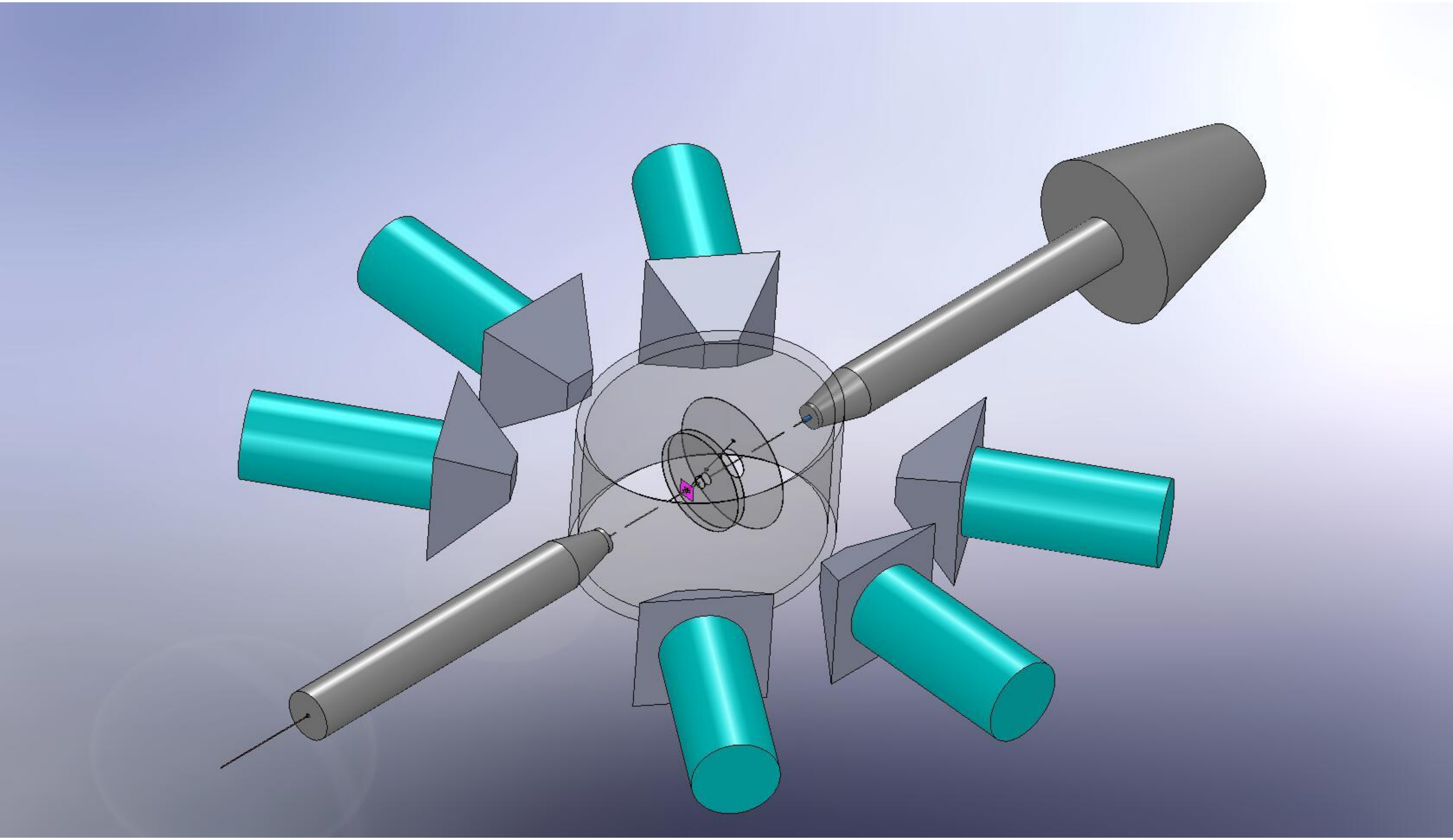
Can demonstrate that (d,pγ) is (n,γ) surrogate?

- 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)

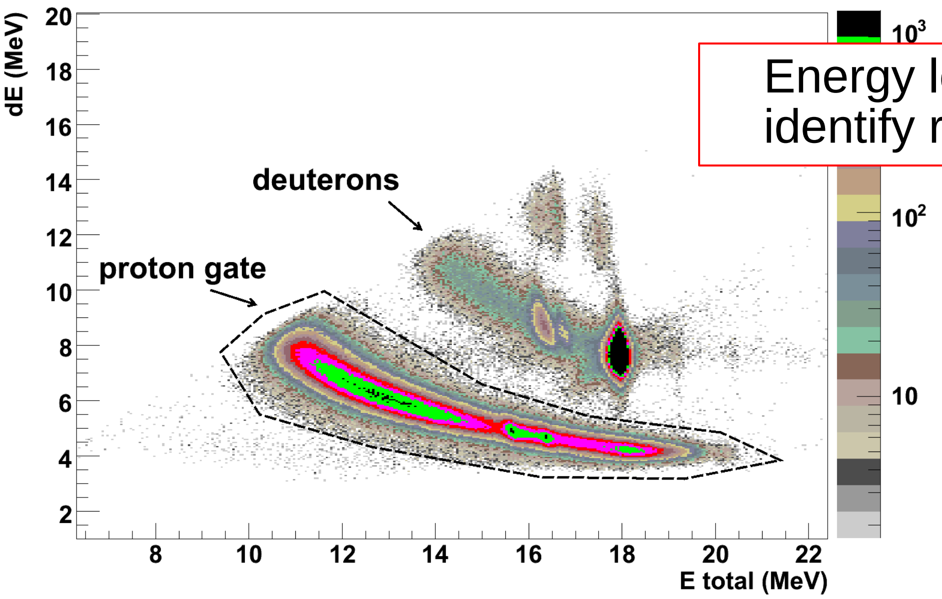
- Analysis: Surrogate Ratios: ratios of intensities of collecting gamma rays = ratio of reaction cross sections

^{171,173}Yb(d,pγ) Normal Kinematics



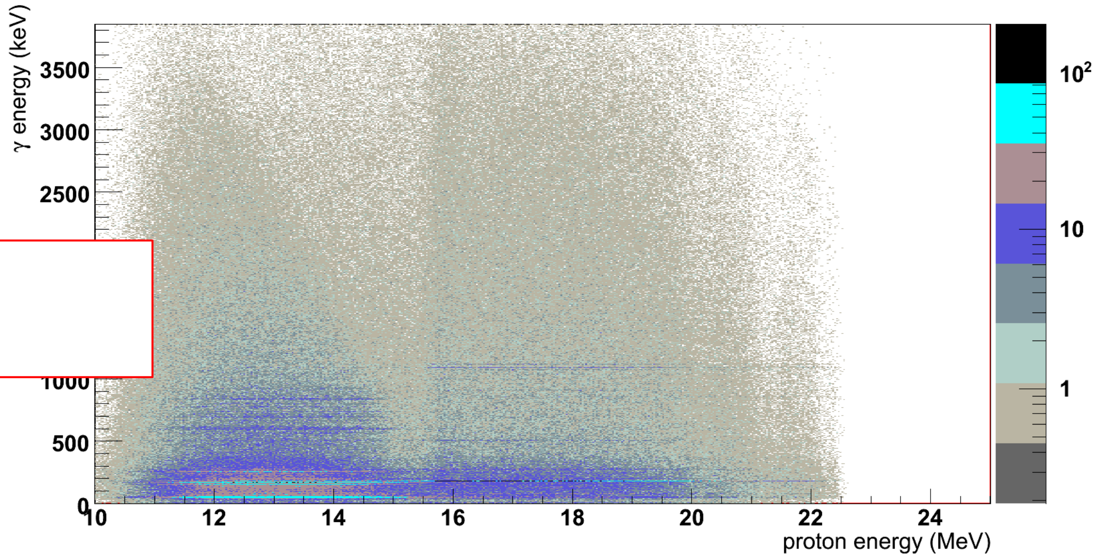
STARS + LIBERACE @ 88-Inch Cyclotron, LBNL
6 Compton-suppressed clover Ge detectors 18-MeV d beam

Particle-Gamma Coincidences



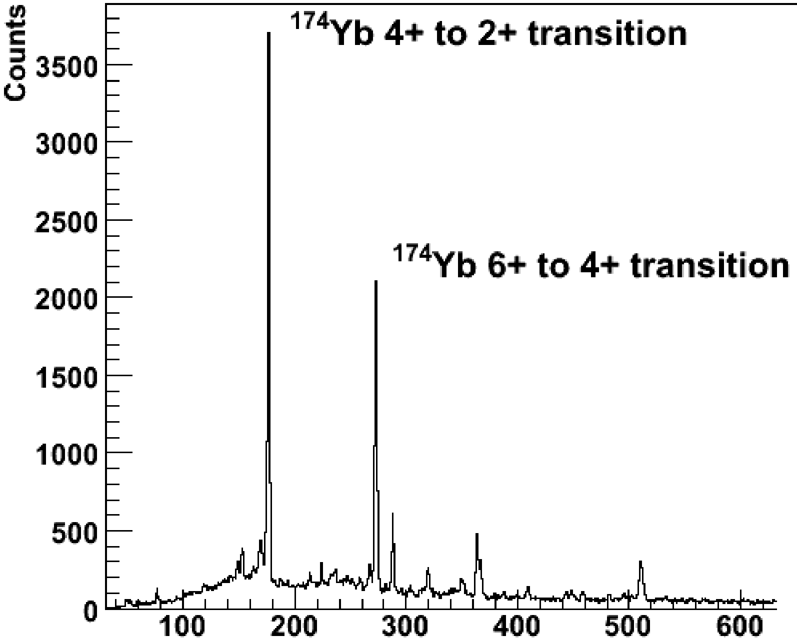
Energy loss vs energy to identify reaction protons

Proton energy region of interest:
15 to 16.2 MeV



□-energy vs proton energy gated on protons

□-ray spectrum
strength collected in “one” transition

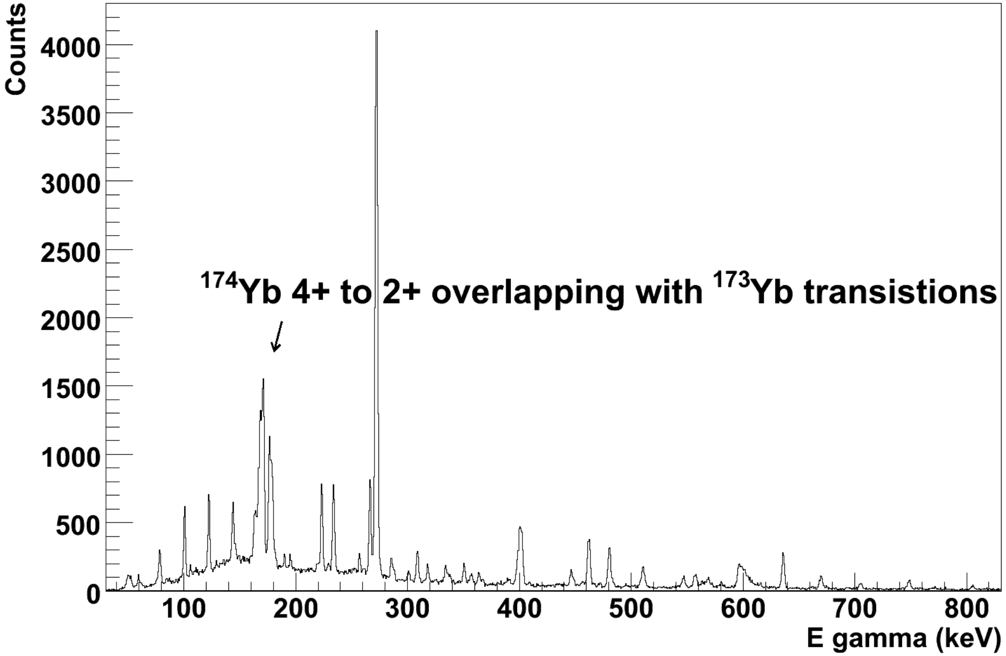


↑

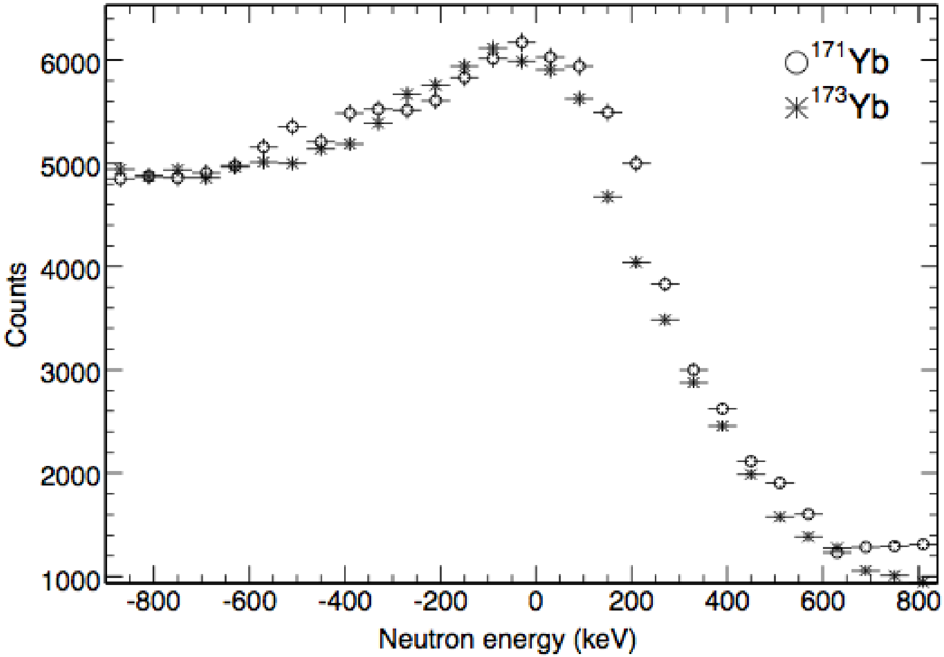
at neutron separation energy

at 1 MeV equivalent neutron energy

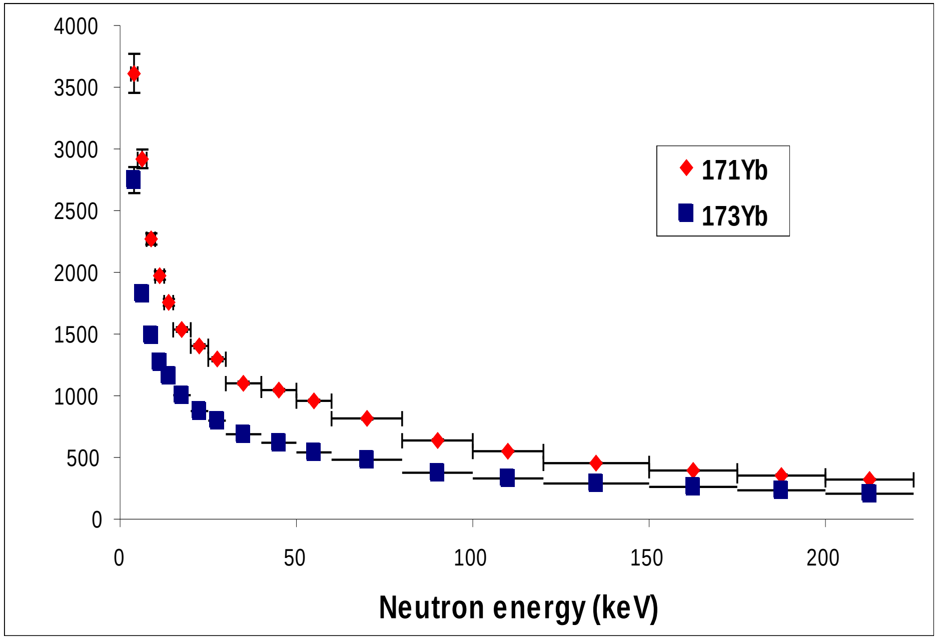
↓



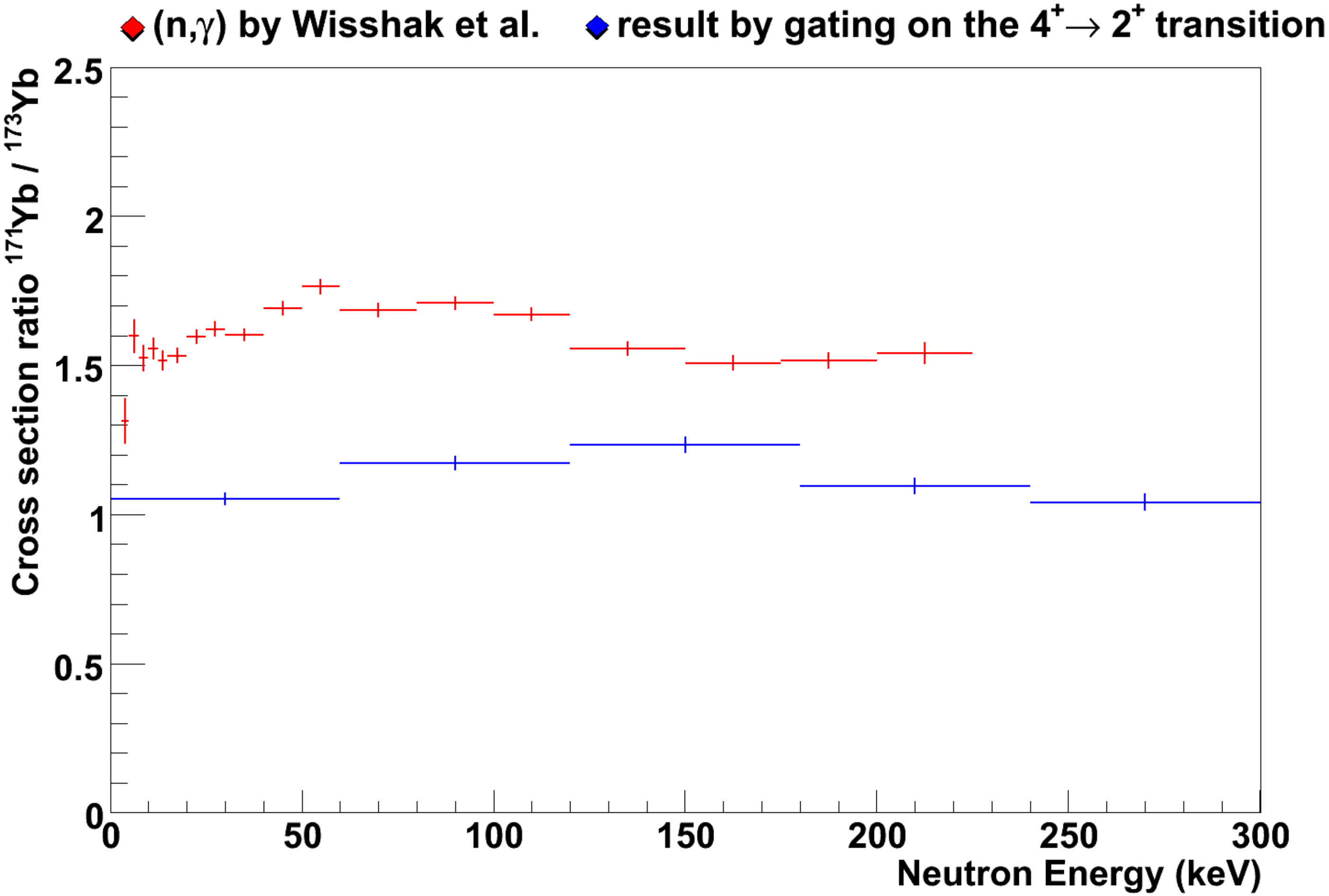
Count rate comparison



Known: Neutron capture cross sections for ^{171}Yb and ^{173}Yb from K. Wisshak et al, Phys Rev C **61**, (2000) 065801.



Cross section ratio 1



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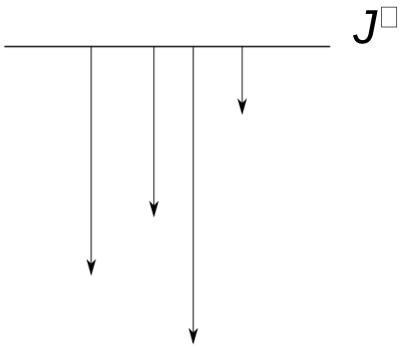
Are our assumptions valid?

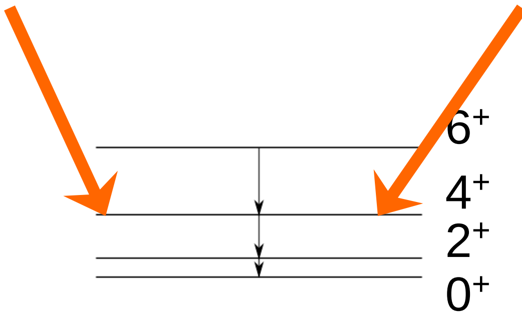
- Is the assumption that form same CN in (d,p) as (n,γ) valid?
    - Does (d,p) populate same spin distribution as (n,γ)?
- Are cross sections independent of spin?
    - Are we in Weisskopf-Ewing limit?

DICEBOX / experiment comparison

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

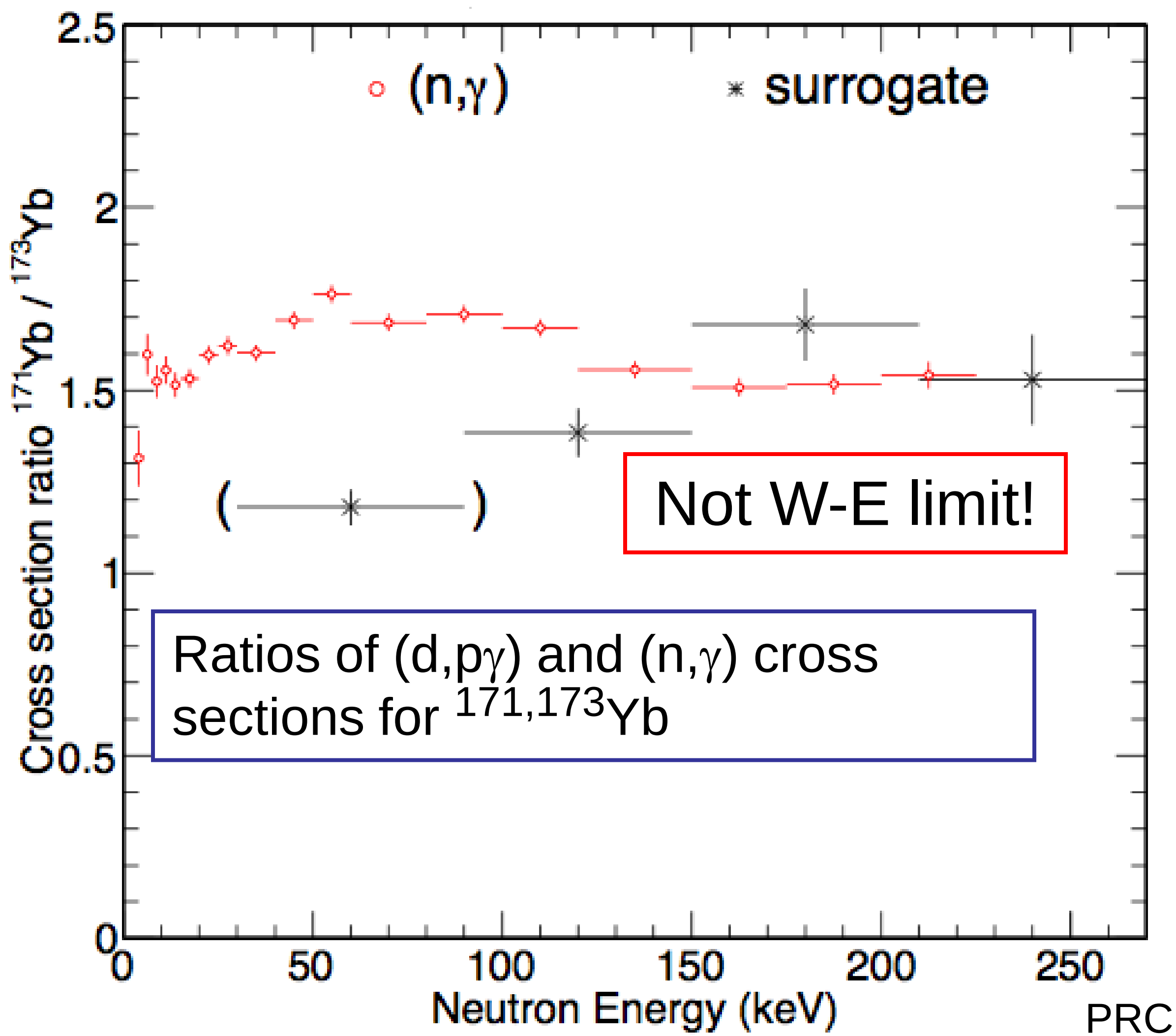


	Intensity ratio: I(4^+ to 2^+) / I(6^+ to 4^+)	
Target	(d,pγ) experiment	DICEBOX (n,γ)
^{171}Yb	3.0	J^π = 0- or 1-, Ex = 8.2 MeV 50
^{173}Yb	1.85	J^π = 2- or 3-, Ex = 7.5 MeV 10



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

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



Not W-E limit!

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

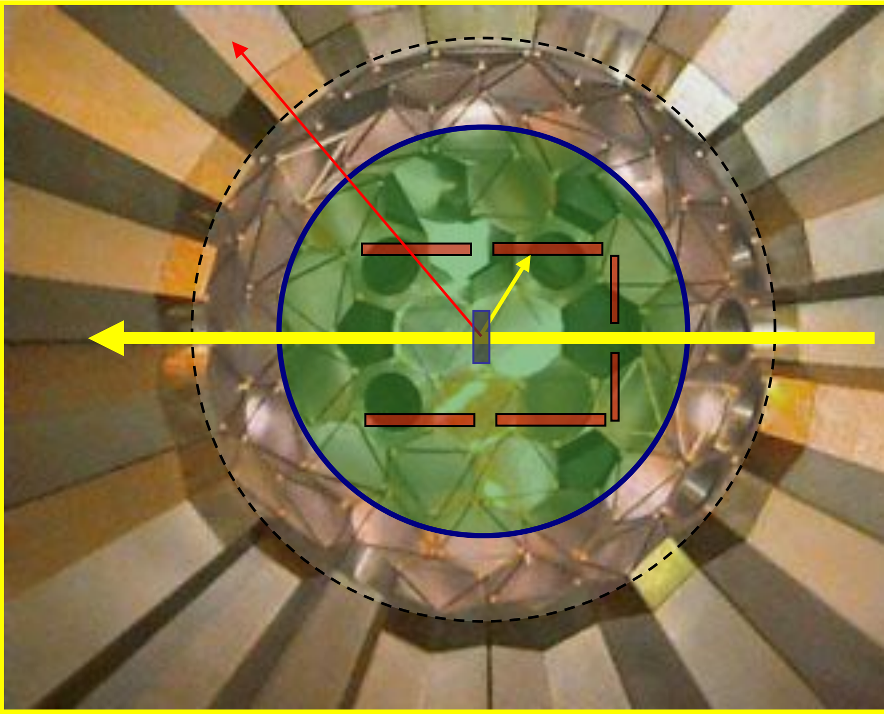
R. Hatarik et al.
PRC **81**, 011602 (R)(2010)

(d,pγ) can be (n,γ) surrogate

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

(n,γ) cross sections from surrogate reaction

- Demonstrated surrogate ratios may work.
- Ongoing efforts to validate cross sections from surrogate reaction
- For (n,γ) away from stability requires (d,pγ) with beams, e.g., ORRUBA + Gammasphere

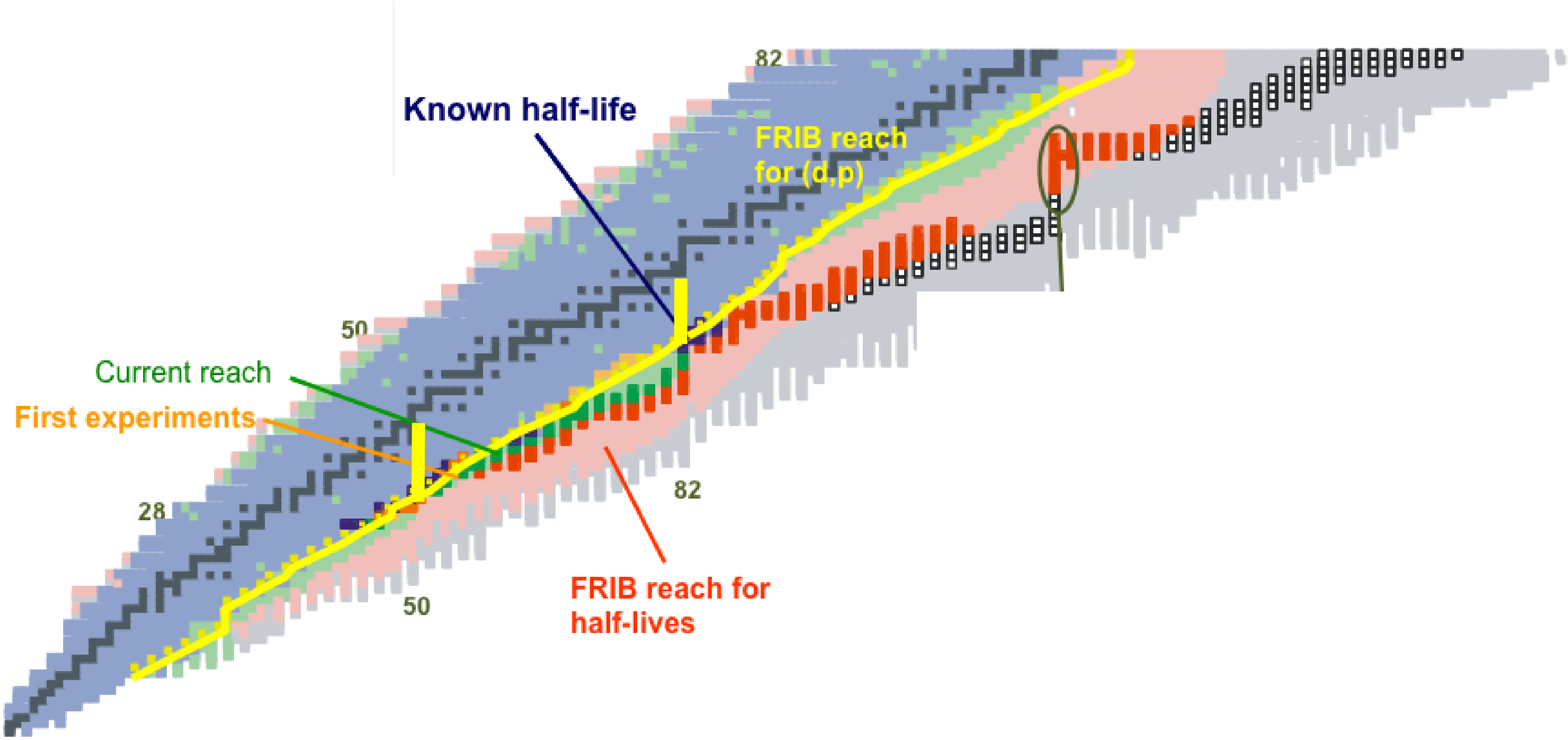


Summary lecture 2:

- Need to improve resolution in (d,p)
  - Run at higher energies
  - Use thin targets
  - Different approach: HELIOS
- Real improvements (<20 keV) requires (d,pγ)
  - E.g., Coupling ORRUBA to Gammasphere (GRETINA)

- Need to understand compound nucleus (n,γ), via validated surrogate technique, e.g., (d,pγ)
  - Important for nucleosynthesis of heavy elements
  - Important for applications (energy, forensics, security)

Prospects for (d,p) and measuring (d,pγ) surrogates for (n,γ) are bright



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B. Sherrill

Thank you – Part 2

Thanks go to:

K.L. Jones, S.D. Pain, J.S. Thomas, F. Nunes,
R. Kozub, R. Hatarik, A. Wuosmaa,
A. Adekola, M.E. Howard, B. Manning, P.D. O'Malley,

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