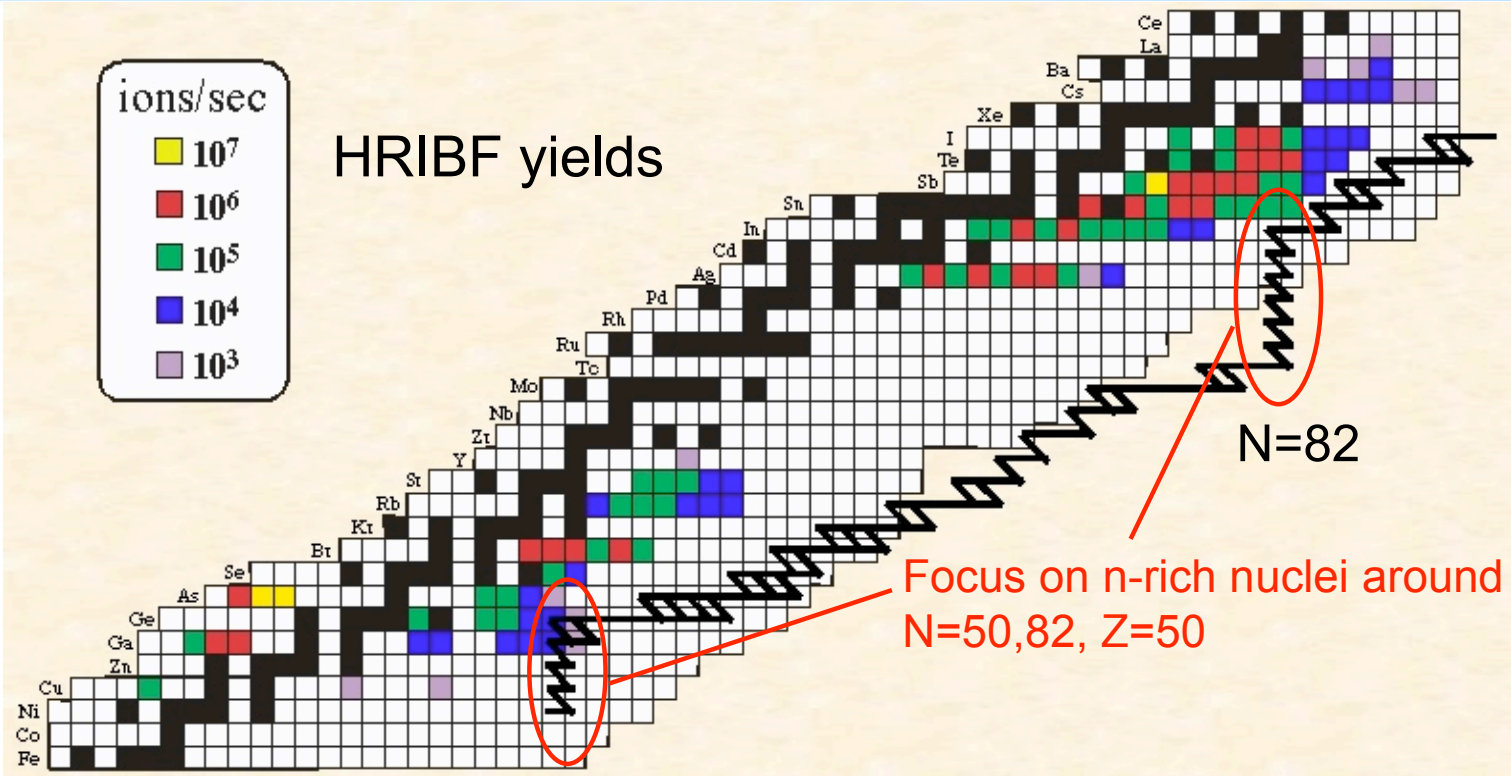
Neutron-transfer reactions using neutron-rich beams at the HRIBF

Kate Jones

University of Tennessee

- N=50 and N=82 shell closures and the r-process
- ^{83}Ge and ^{85}Se: crossing the N=50 shell closure
- Shell model calculations for N=51 isotones
- Status of data from transfer reactions around ^{132}Sn

HRIBF beams and the shell closures at N=50,82



Fission fragment beams

Production via p-induced fission on U gives access to n-rich nuclei close to N=50,82 (not well produced by other methods e.g. fragmentation, fusion evaporation)

r-process close to shell closure

Low Q value for (n,γ)

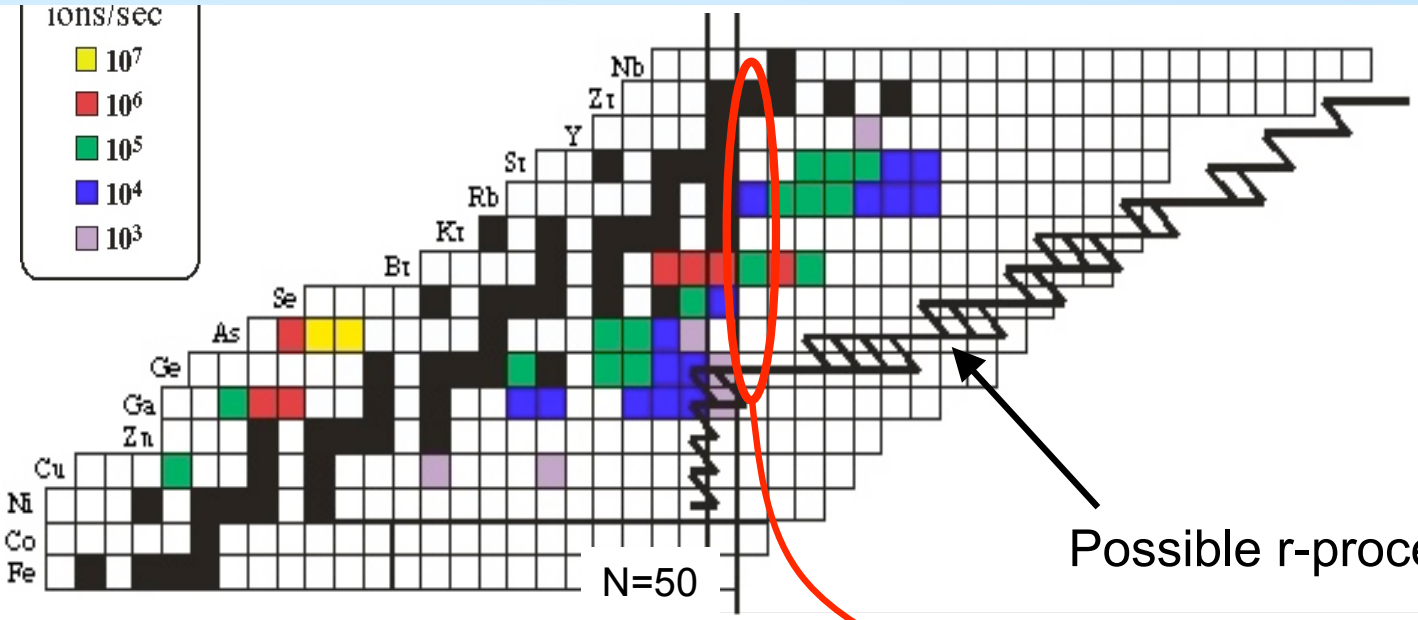
Low level density

Small capture cross section

Statistical model not reliable

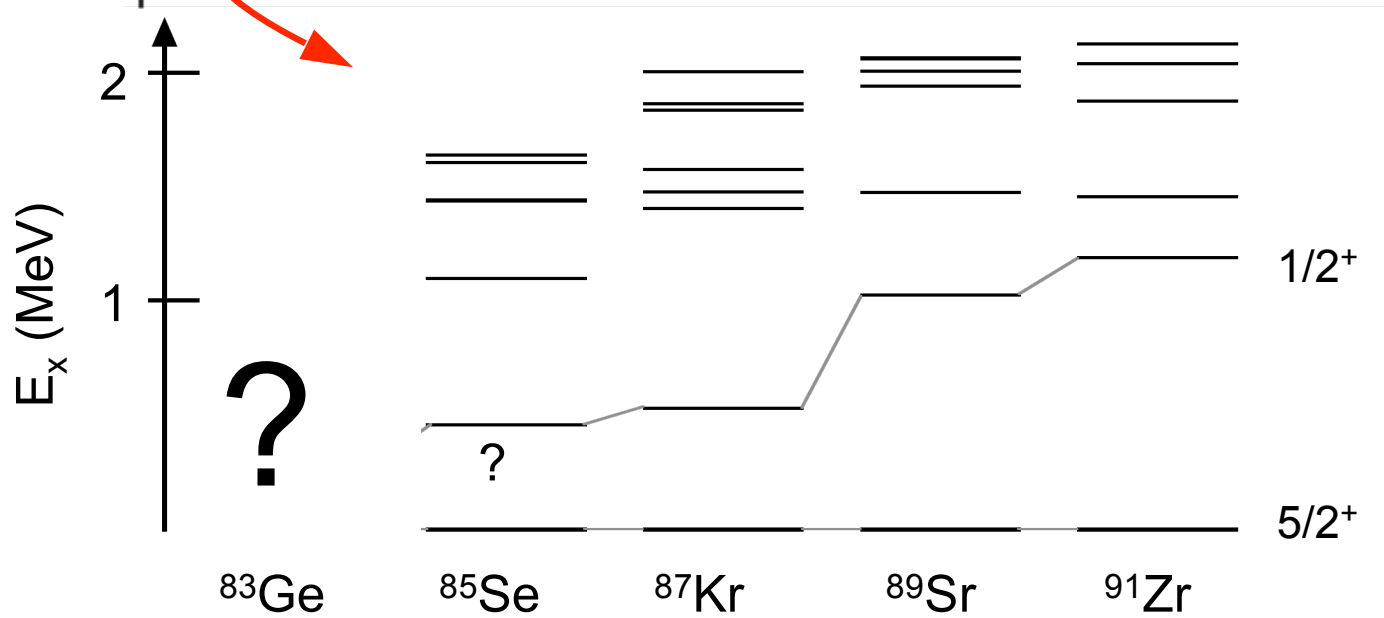
Direct capture important

Crossing N=50: ^{83}Ge and ^{85}Se



Possible r-process line

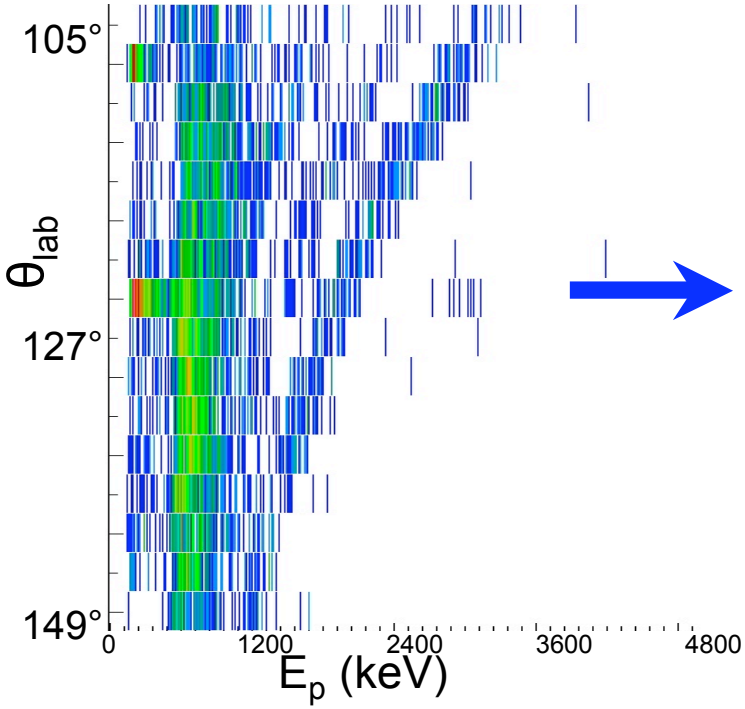
Only known property of ^{83}Ge is $t_{1/2}$ *

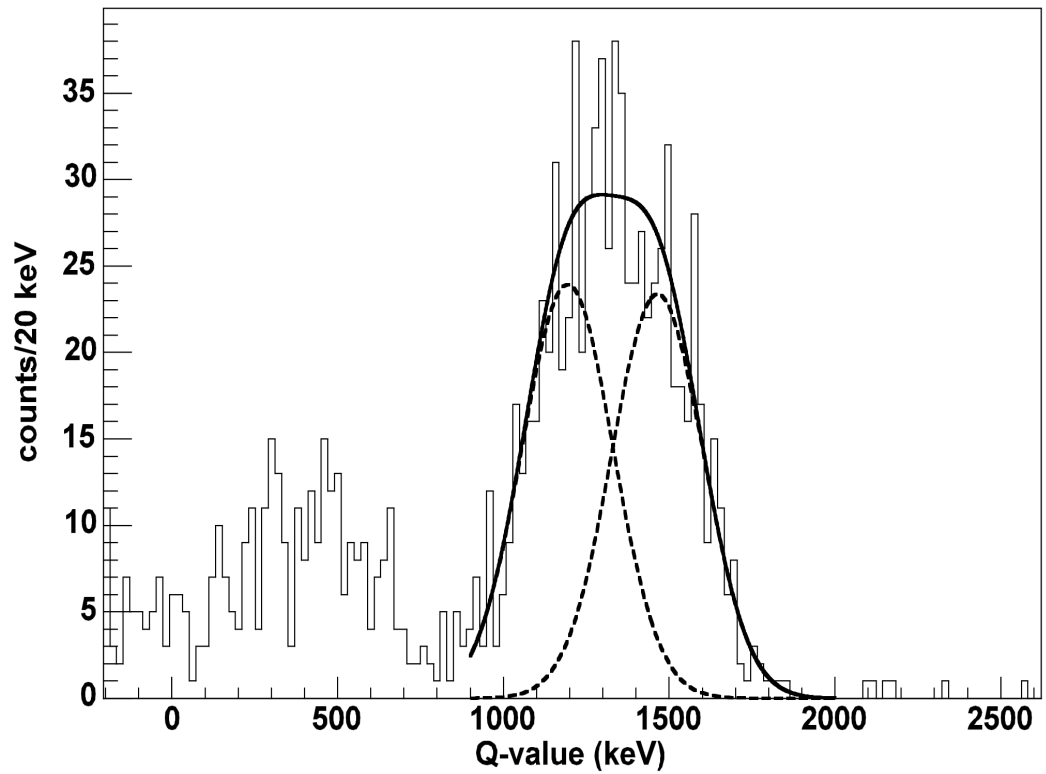


from ENSDF www.nndc.bnl.gov

* Winger, J.A. *et al.*, Phys. Rev. C 38, 285 (1988)

^{83}Ge results





$\Delta E_{cm} \approx$ 300 keV from the Se doublet

The large width of the first group ($\Delta E_{cm} \approx$ 460 keV) and the absence of other levels below E_x = 1 MeV suggest two states.

J.S.Thomas PRC **71** (2005) 021302

Q = 1.47 (±0.02 stat., ±0.07 sys.) MeV

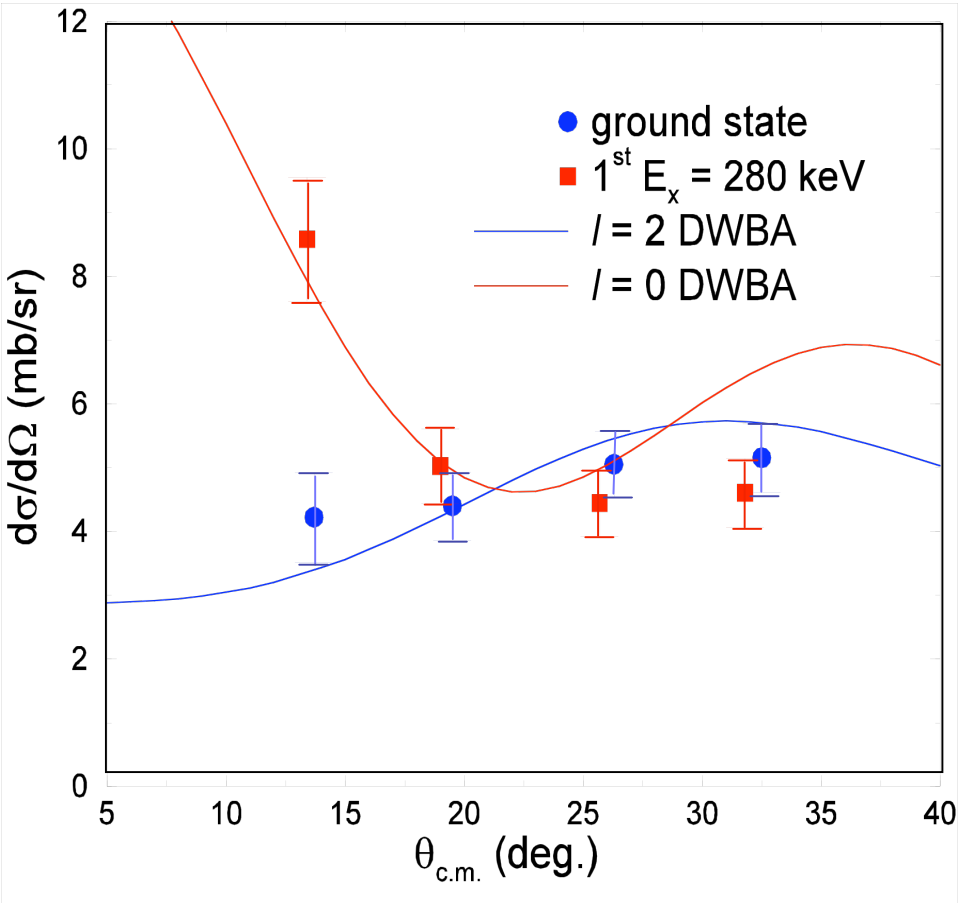
1st E_x = 280 (± 20 stat.) keV

$S_n(^{83}Ge)$ = 3.69 ± 0.07 MeV

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

^{83}Ge results cont: Angular distributions

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



Results are consistent with:

ℓ = 2 ground state ($d_{5/2}$)

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

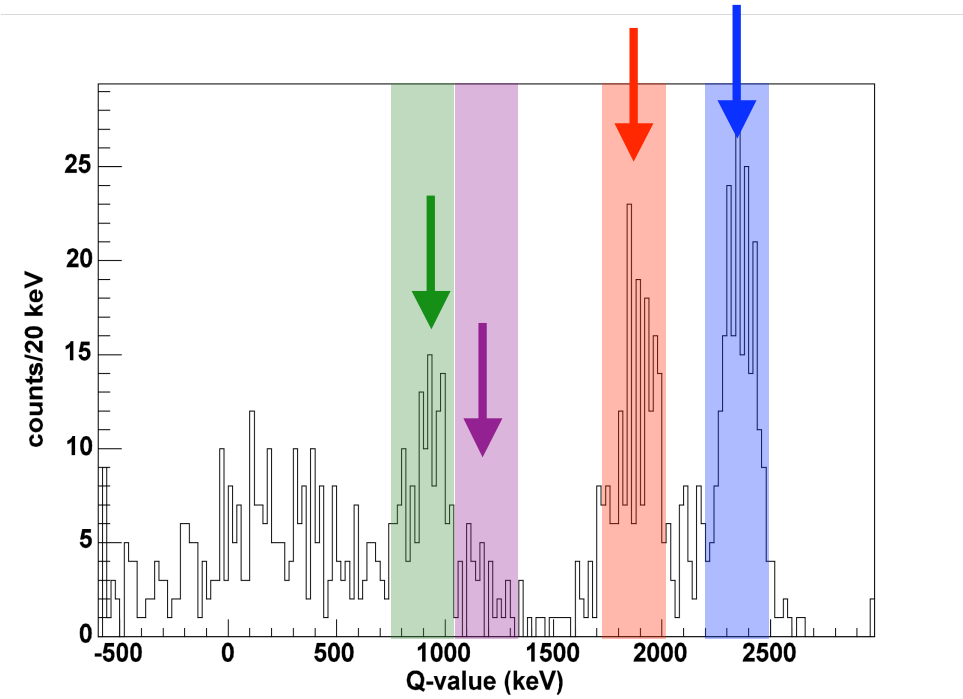
Spectroscopic Factors

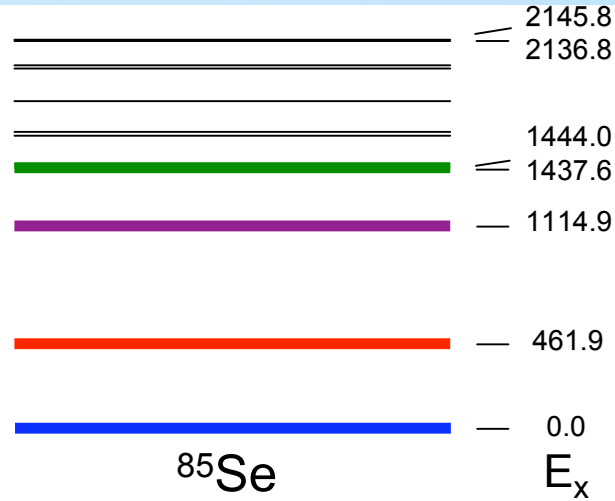
Measure single-particle nature of state

g.s. S = 0.48 ± 0.14

1st S = 0.50 ± 0.15

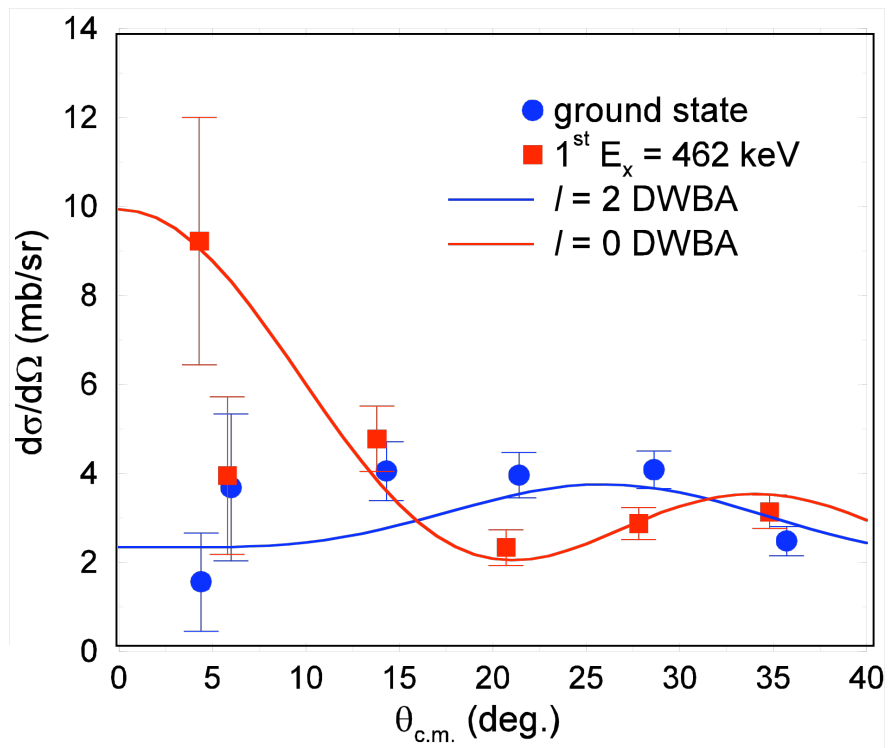
^{85}Se data





Energy levels from β⁻ decay

J.P. Omtvedt, *et al.*, Z. Phys. A **339**, 349 (1991).



4 groups are populated, including g.s. and 1st excited

Angular distributions show ℓ = 2 ground state and ℓ = 0 1st excited state

g.s. S = 0.33 ± 0.09 ($d_{5/2}$)

1st S = 0.30 ± 0.08 ($s_{1/2}$)

JUS

Shell Model Calculations

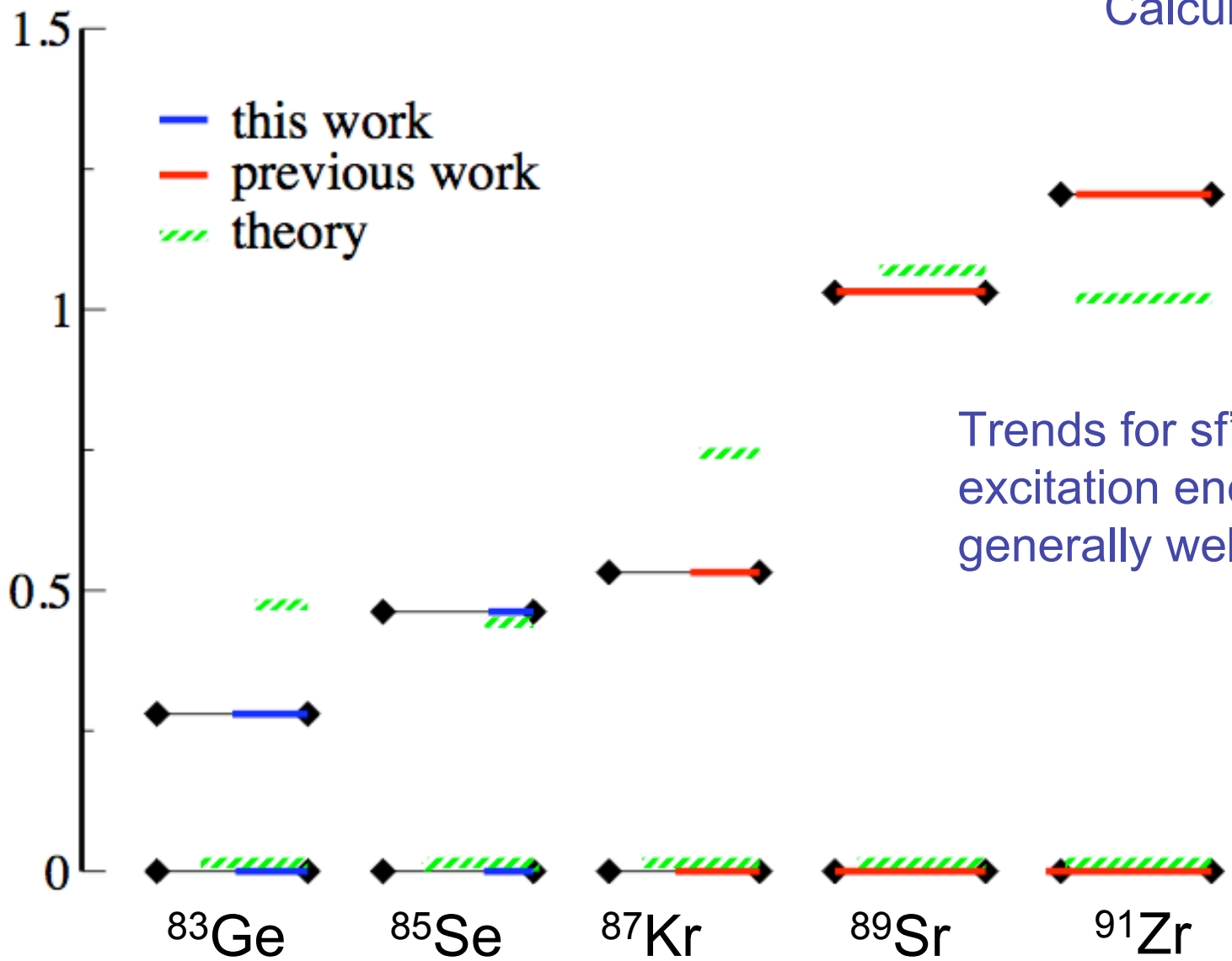
- Free N-N interaction ⇨ effective 2-body interaction
  - Start from charge-dependent Bonn potential
  - G-matrix to renormalize strongly repulsive core
  - Long-range effects included as core-polarization terms

  M. Hjorth-Jensen, T. T. S. Kuo, and E. Osnes, Phys. Rep. 261, 125 (1995).
- Model space
  - Protons: $0f_{5/2}$-1p-$0g_{9/2}$
  - Neutrons: $0g_{7/2}$-1d-2s-$0h_{11/2}$
  - Core ^{78}Ni: closed proton $0f_{7/2}$ orbital and closed neutron shell at N=50
- Code: ANTOINE
- Single particle energies from

  J. Duflo and A.P. Zuker, Phys. Rev. C 59, R2347 (1999).
  - changed $0g_{9/2}$SPE to 4.5 MeV (from 3.3 MeV) better agreement with 2^+ energies of N=50 isotones

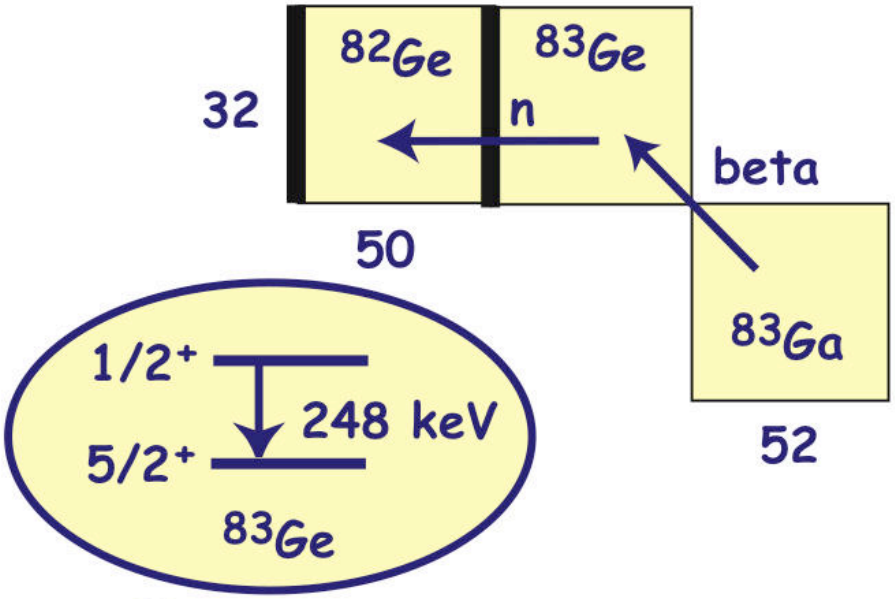
Shell model calculations: N=51

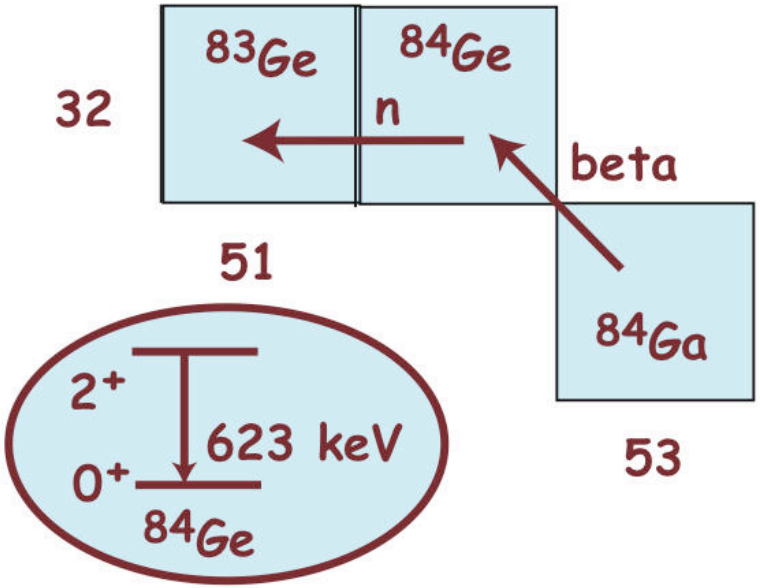
Calculations by D. Dean

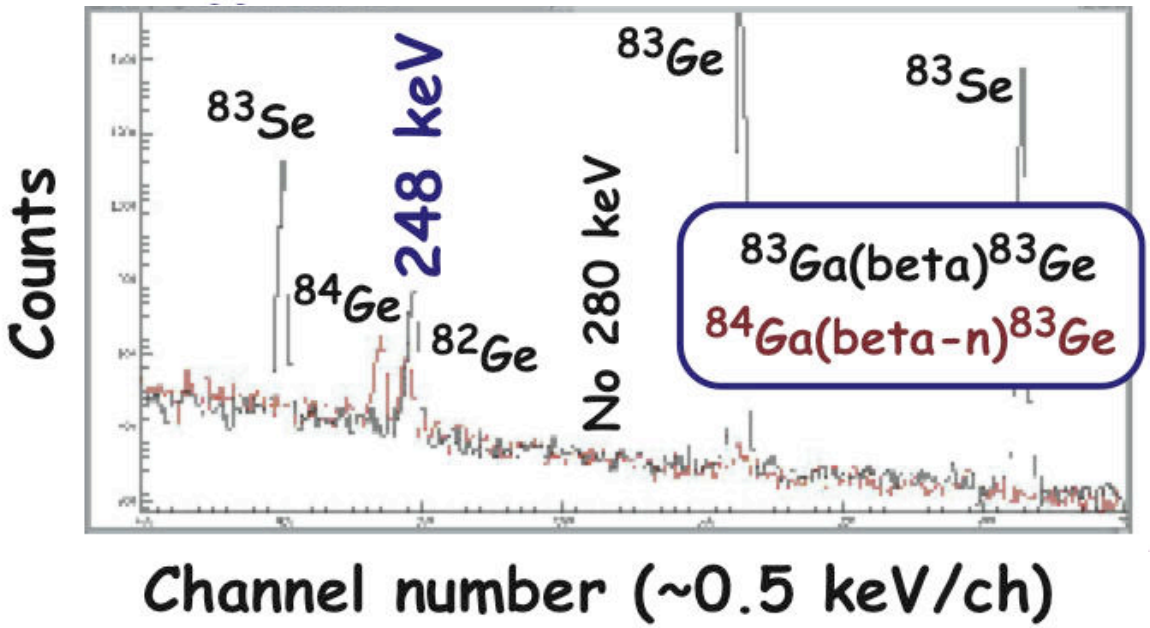


Trends for sf's and falling excitation energy of $1/2^+$ state generally well reproduced

1/2+ State in ^{83}Ge even lower!



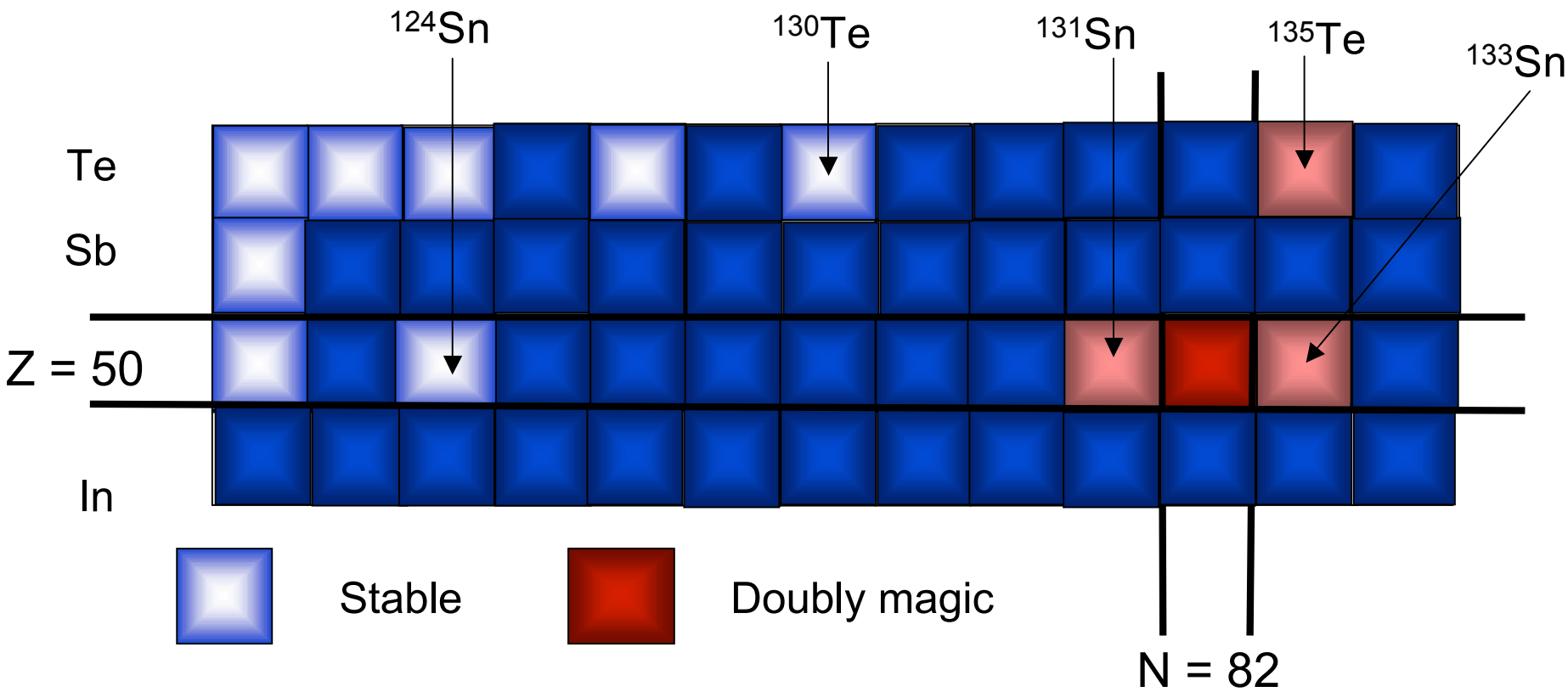




(Winger et al., Nov 2006)

Preliminary Results

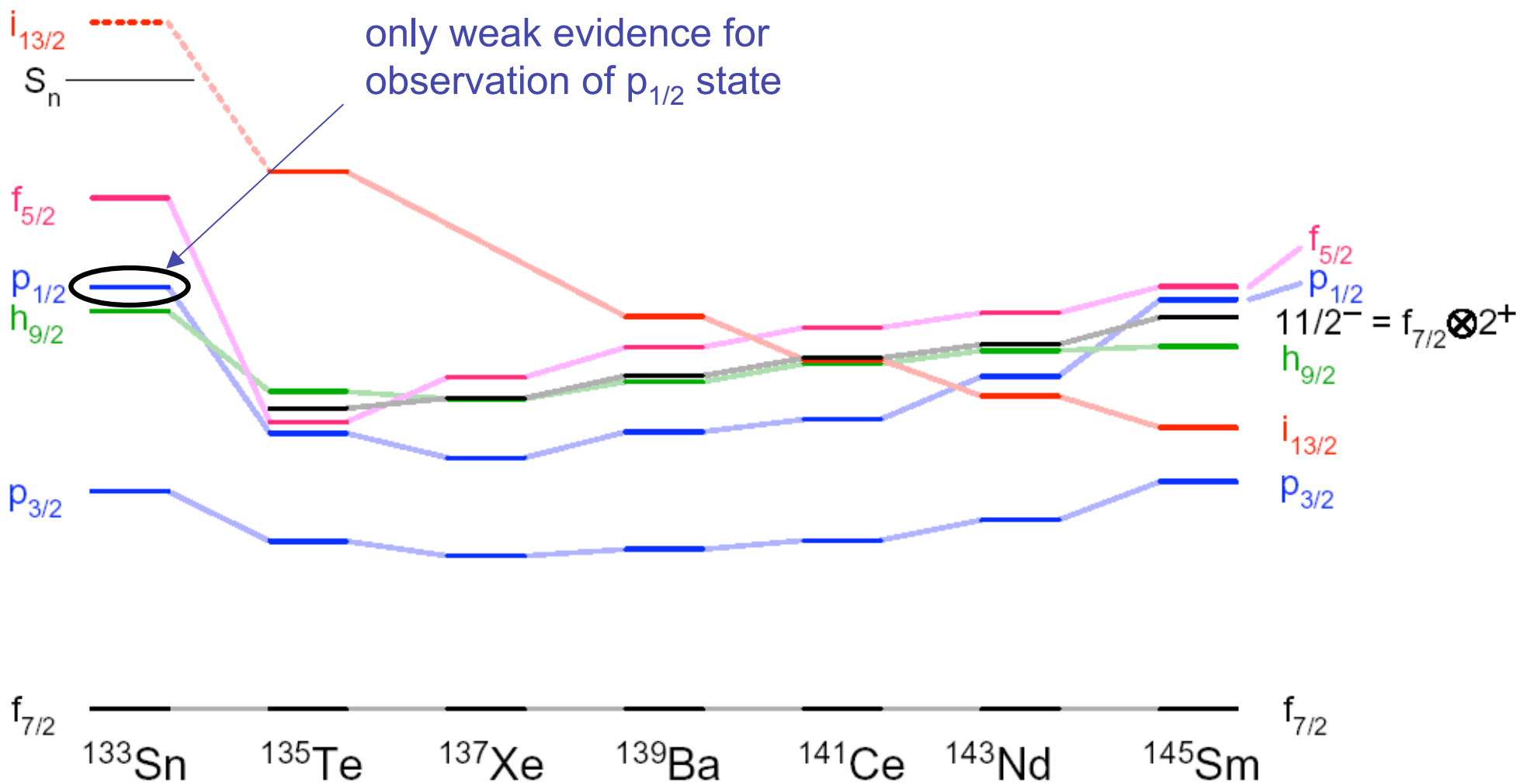
Transfer Measurements Around ^{132}Sn



Double shell closure Z=50, N=82

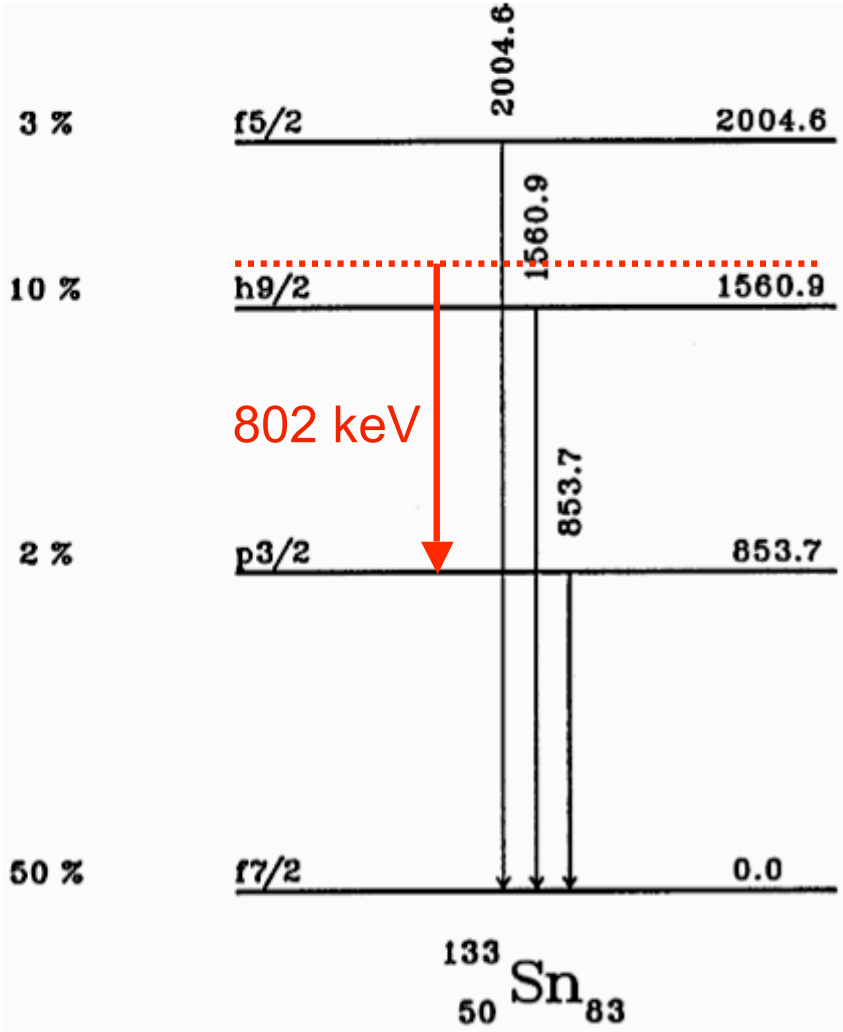
^{132}Sn(d,p), ^{130}Sn(d,p) and ^{134}Te(d,p) completed

N=83 Systematics



Location of p1/2 state

- Tentatively observed via β-delayed neutron decay P.Hoff et al PRL 77, 1020 (1996).
- Not observed in γ-rays following prompt fission of ^{248}Ca W.Urban et al Eur. Phys. J. A. **5** 239

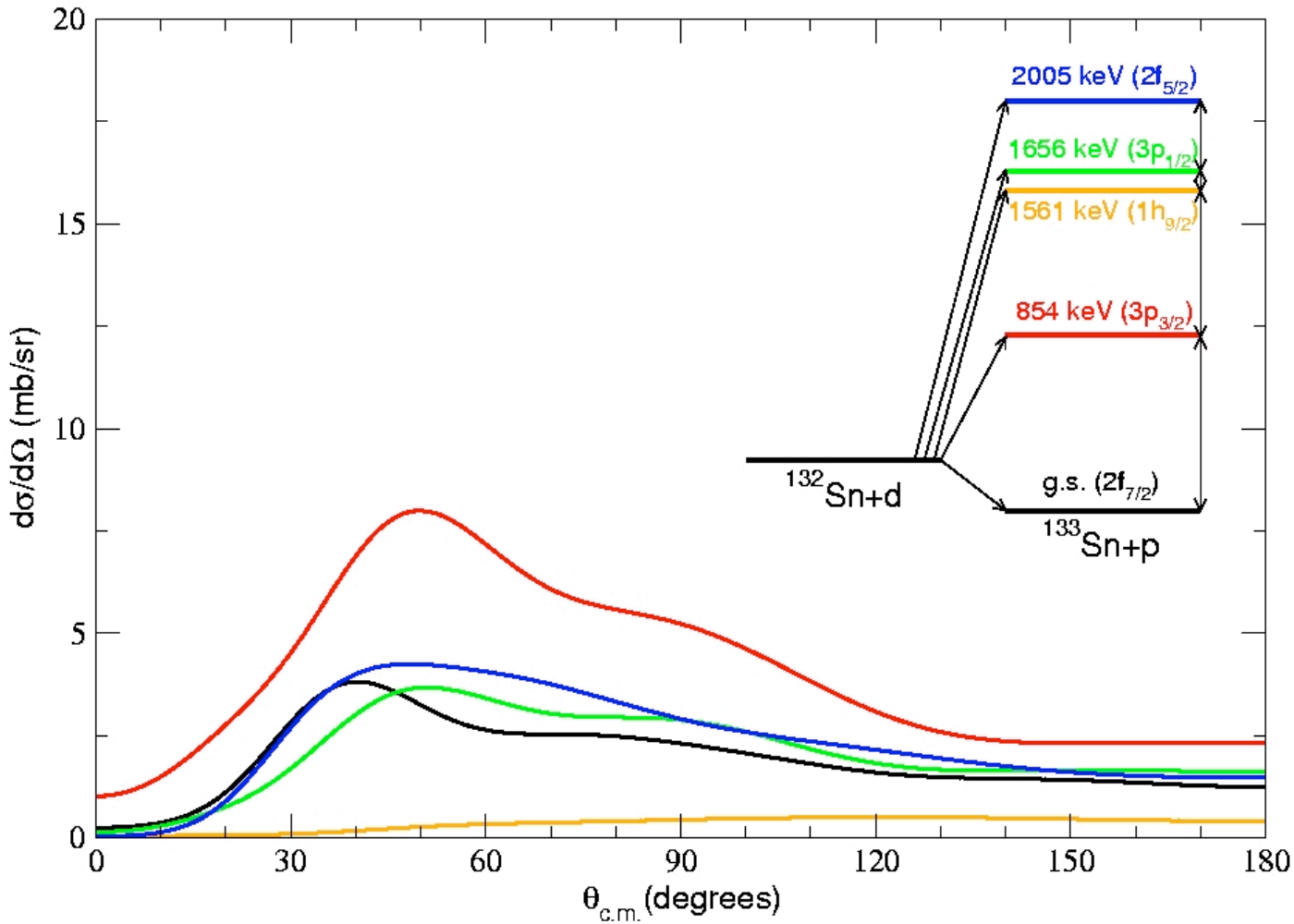


Location of p1/2 state

- β-decay dominated by $g_{9/2}$ proton $\rightarrow$ $7/2^+$, $9/2^+$, $11/2^+$ neutron
- $p_{1/2}$ state not easily populated following β-decay
- fission tends to populate higher spin states
- (d,p) preferentially populates low spin states, ideal method to observe and measure state
- This is in addition to checking ℓ-values of other states, and measure spectroscopic factors

Reaction Calculations

CCBA ^{132}Sn(d,p) @ 630MeV



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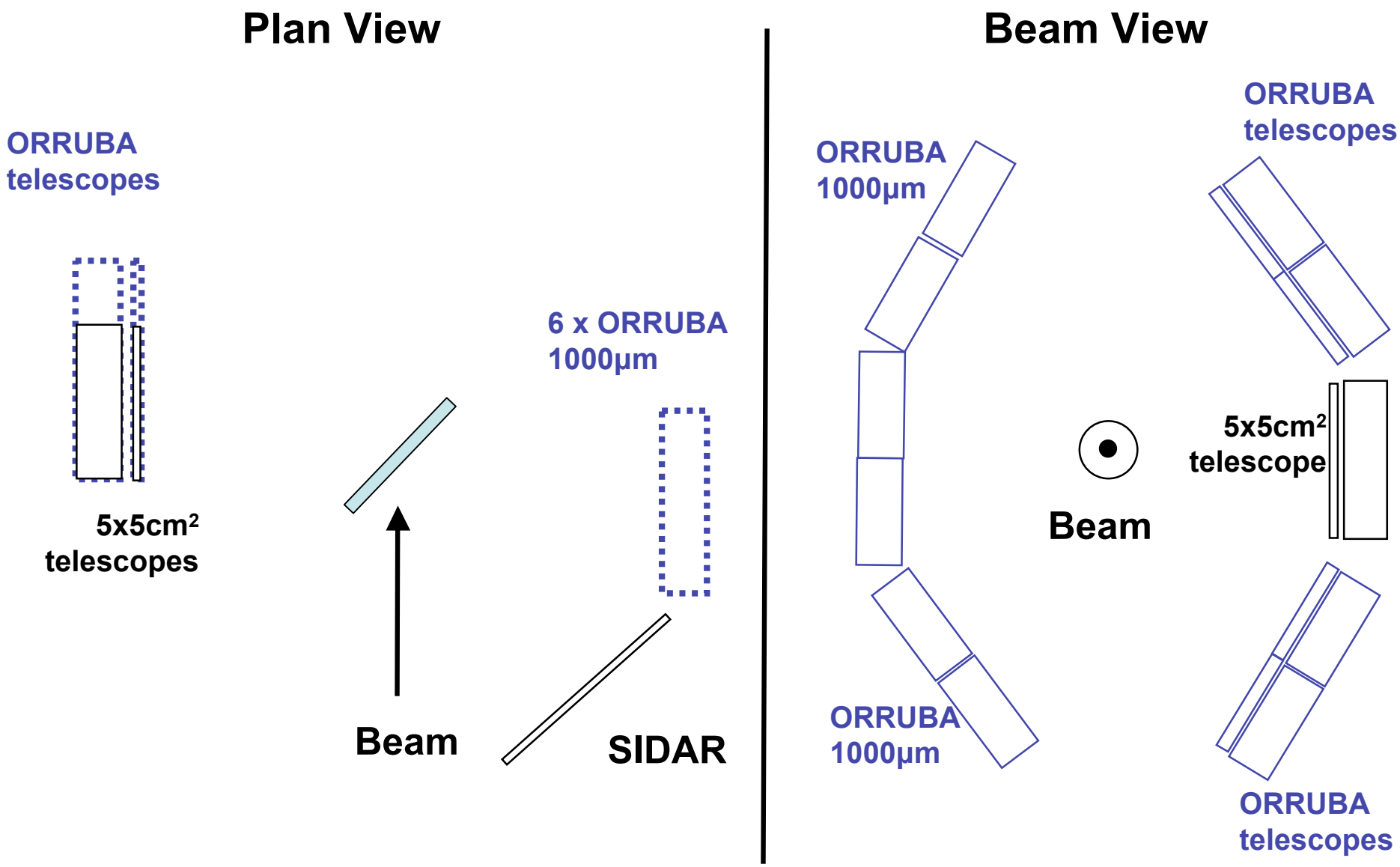
^{132}Sn(d,p) detectors



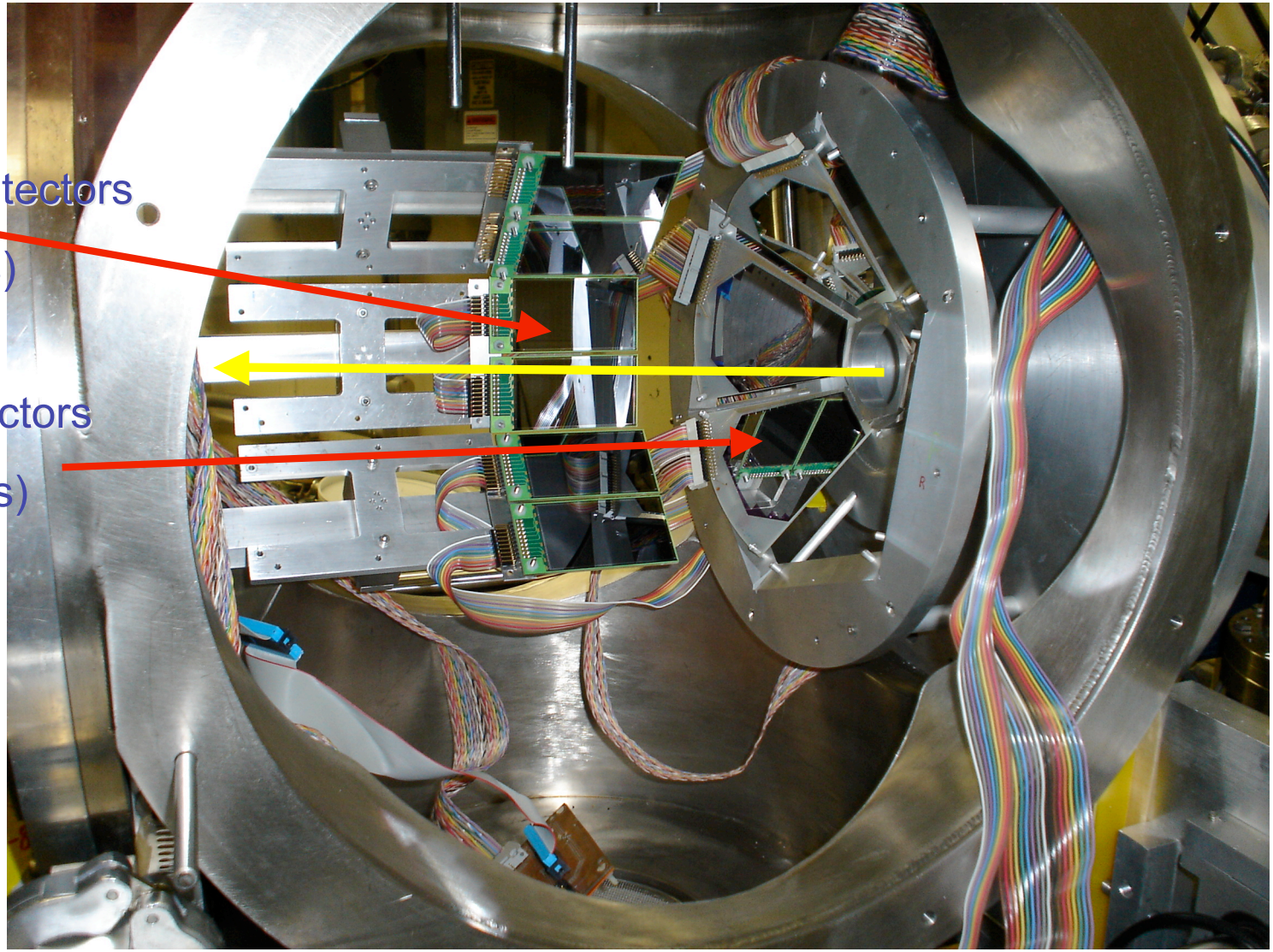
^{132}Sn(d,p) photo

ORRUBA detectors

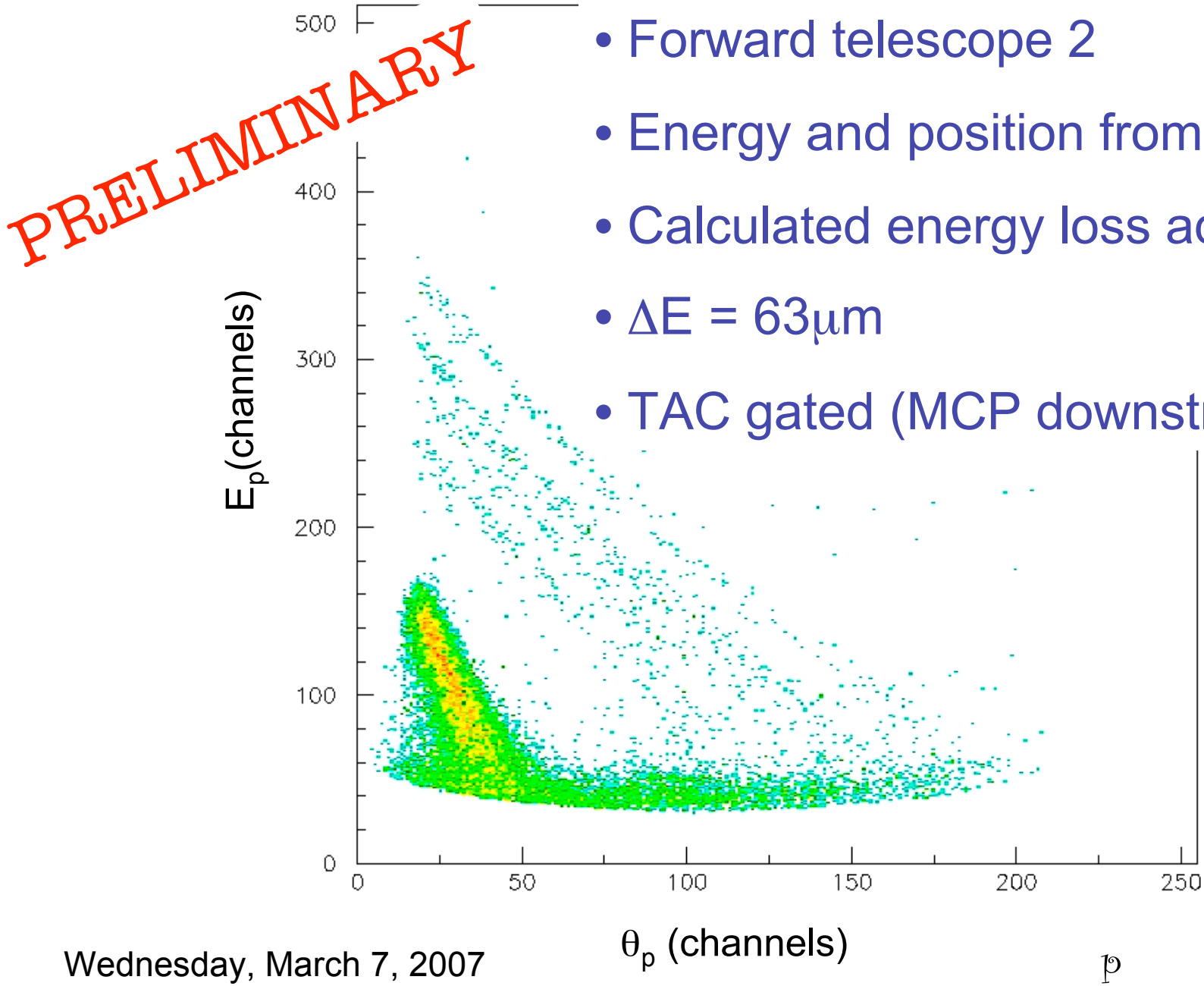
(back angles)

SIDAR detectors

(back angles)

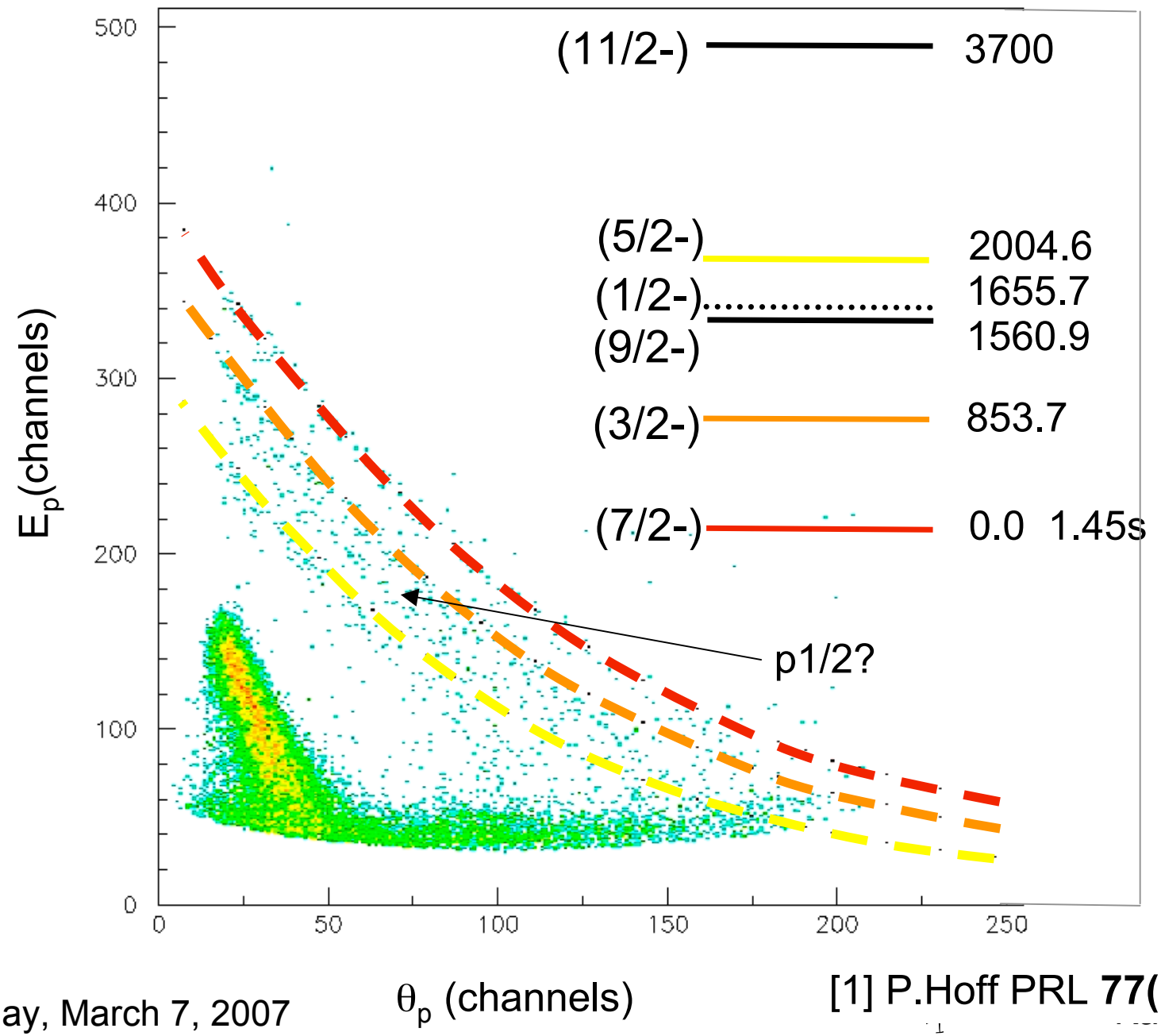


^{132}Sn(d,p) data



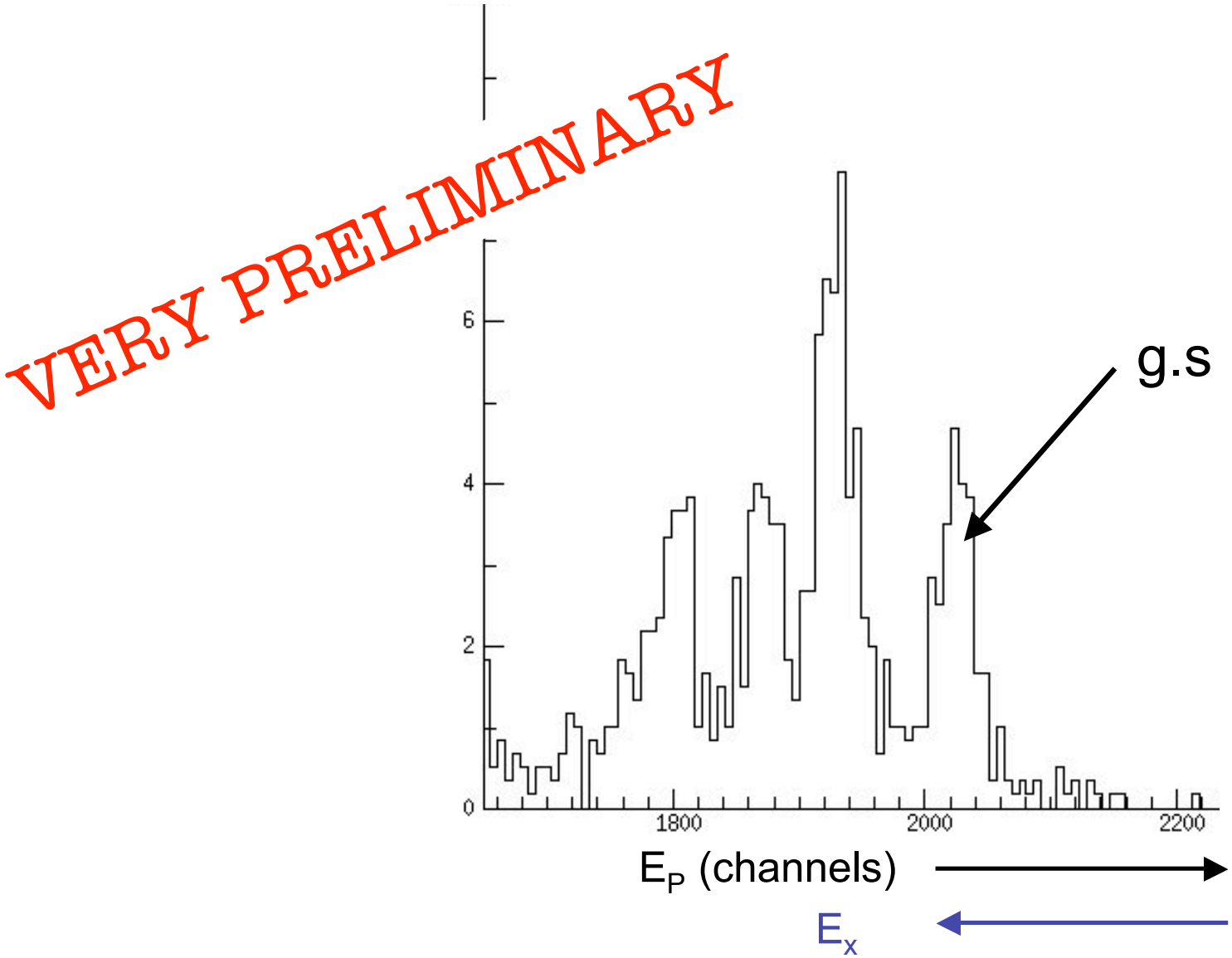
- Forward telescope 2
- Energy and position from E detector
- Calculated energy loss added
- $\Delta E = 63\mu m$
- TAC gated (MCP downstream)

^{132}Sn (d,p) data + kinematics calculations



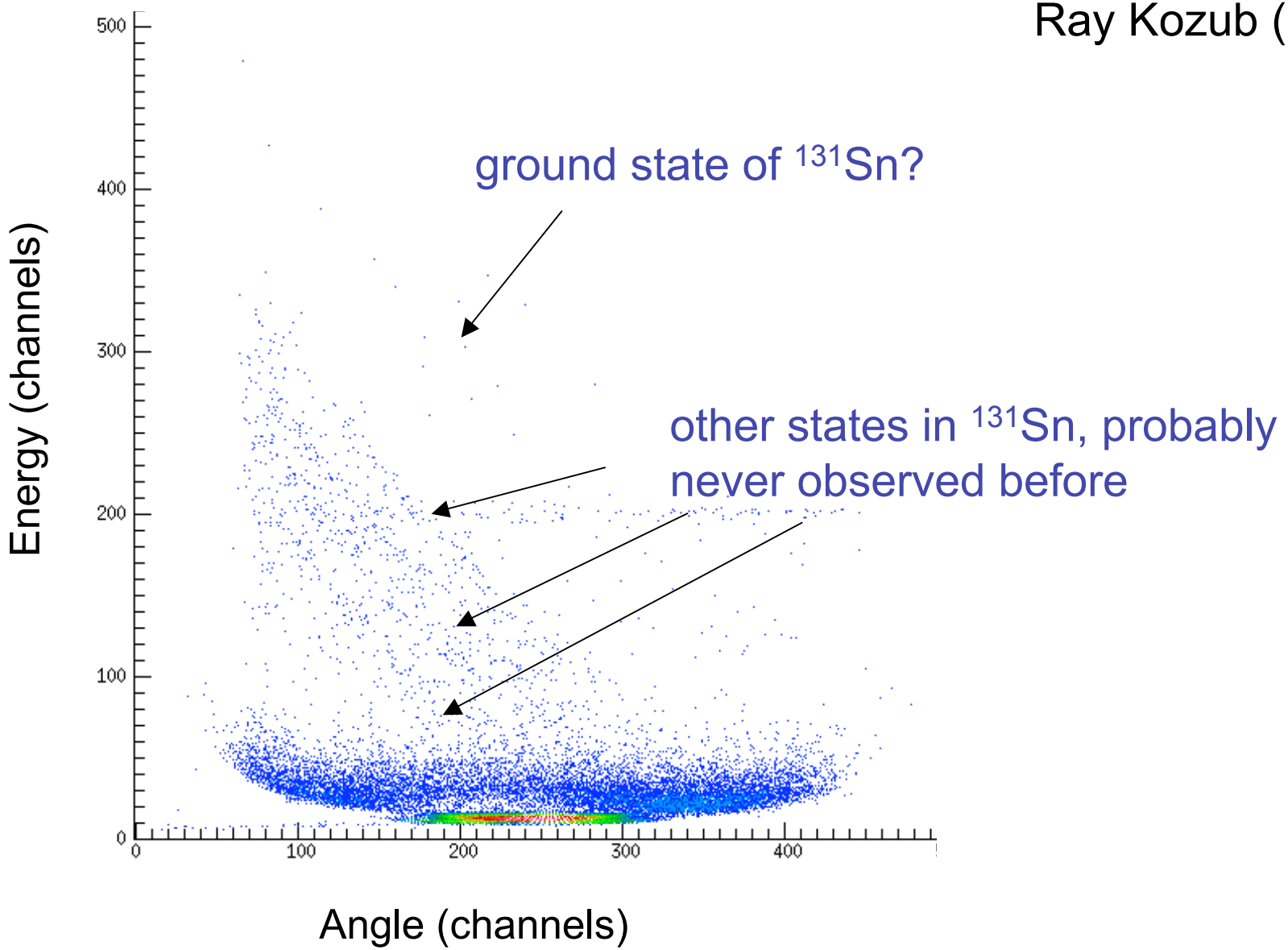
[1] P.Hoff PRL **77(1996)**1020

Q-value plot



^{130}Sn(d,p) Data

Ray Kozub (TTU)

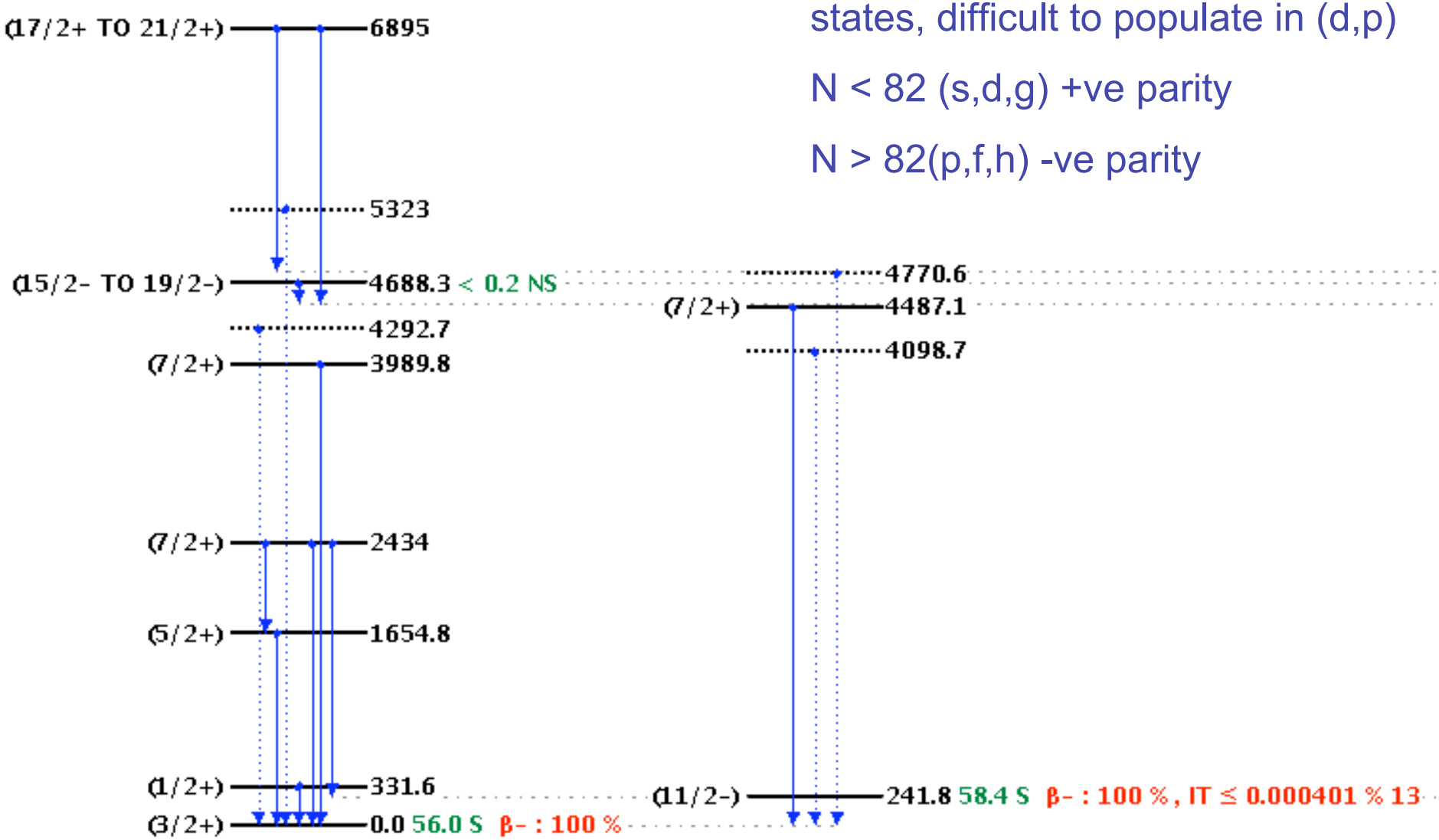


Known States in ^{131}Sn

Positive parity states are hole states, difficult to populate in (d,p)

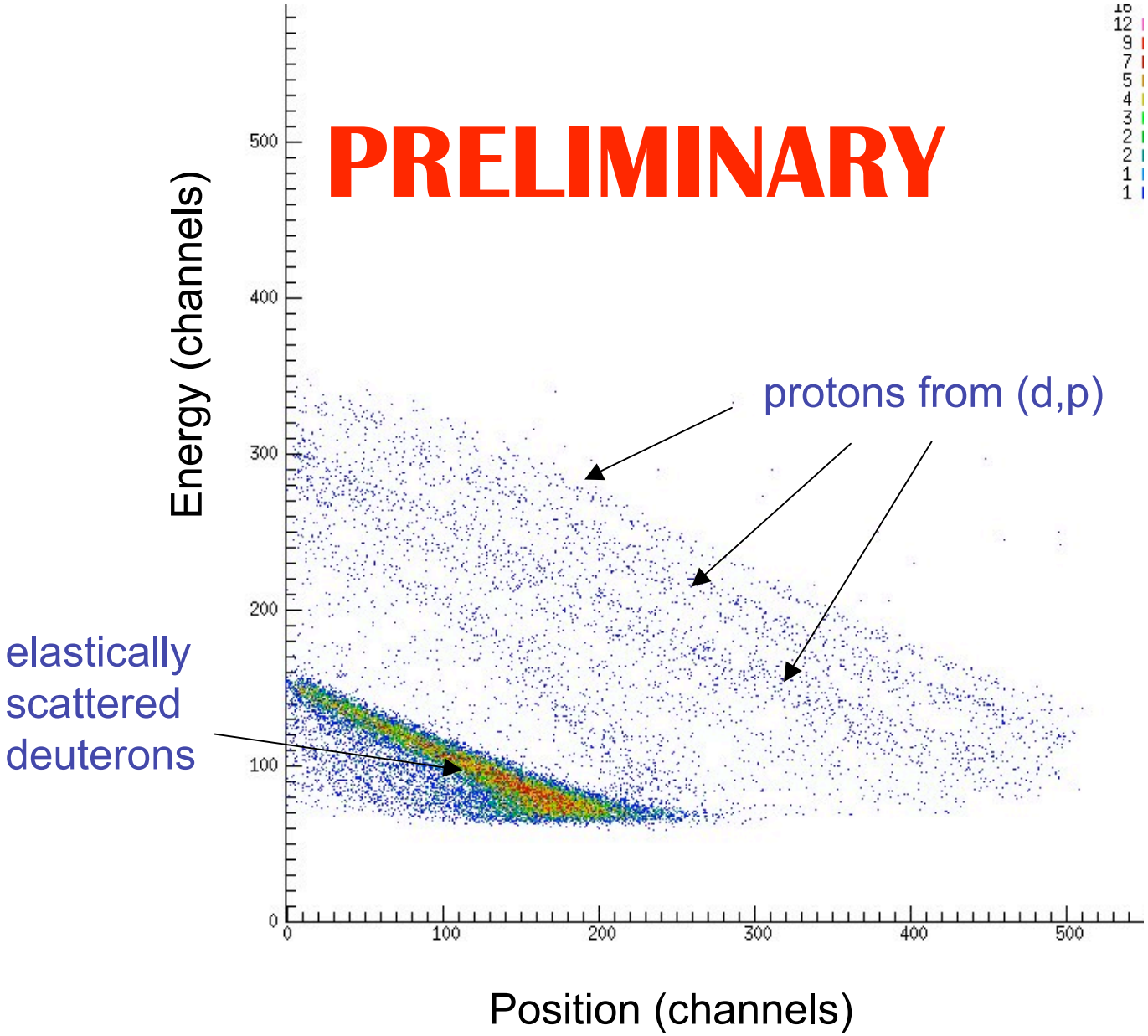
N < 82 (s,d,g) +ve parity

N > 82(p,f,h) -ve parity



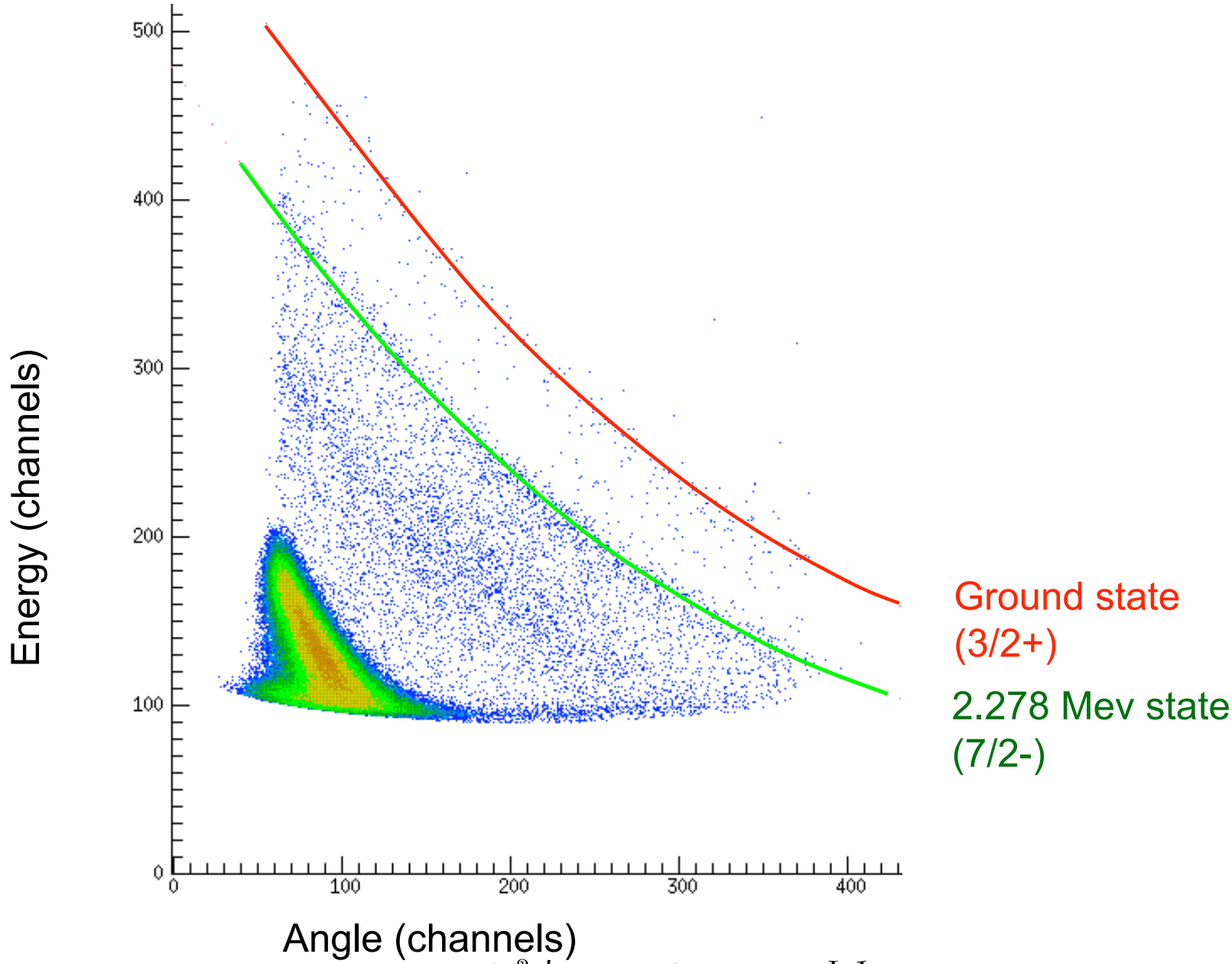
^{134}Te(d,p) Data

Steve Pain (Rutgers)



Online spectrum, energy versus position (not angle), many corrections to be included

Calibration Data ^{130}Te(d,p)



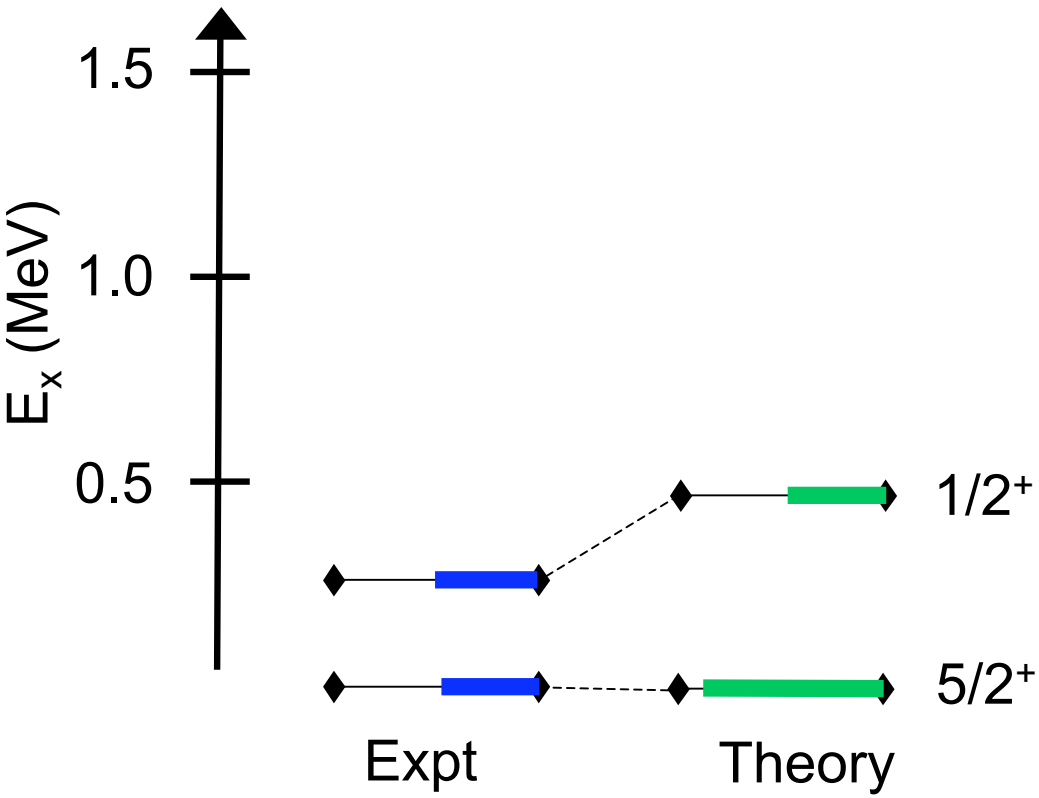
Summary and Comments

- N=51
  - Completed ^{82}Ge(d,p) and ^{84}Se(d,p)
  - Measured S_n (mass) for ^{83}Ge, and E_x for 1st excited state
  - Measured angular distributions, confirmed $5/2^+$ gs, $1/2^+$ 1st ex state
  - Extracted spectroscopic factors
  - Shell model calculations for n-rich even-Z N=51 isotones
- ^{132}Sn(d,p)
  - Can see at 3 previously measured states
  - See $p_{1/2}$ state (for first time), energy soon
  - Calibrations using ^{130}Te data completed, analysis in progress
- ^{130}Sn(d,p), ^{134}Te(d,p)
  - (previously unmeasured?) states seen in ^{131}Sn,
  - Same calibrations as above for ^{130}Sn, energies coming soon

Collaboration

- RIBENS / Center of Excellence collaboration
  - ORNL D. Bardayan, J. Blackmon, M. Smith, C.Nesaraja, D. Shapira, F. Liang
  - ORAU M. Johnson
  - UT KLJ, K. Chae, Z. Ma, B. Moazen
  - Rutgers University J. Cizewski, S. Pain, R. Hatarik, P.O'Malley
  - Tennessee Tech Ray Kozub, J.Shriner, S.Paulauskas, J.Howard, D.Sissom
  - University of Surrey J. Thomas, C.Harlin, N. Patterson
  - Colorado School of Mines U.Greife, R. Livesay, L.Erikson
  - Ohio University A. Adekola
  - Furman A.Gaddis

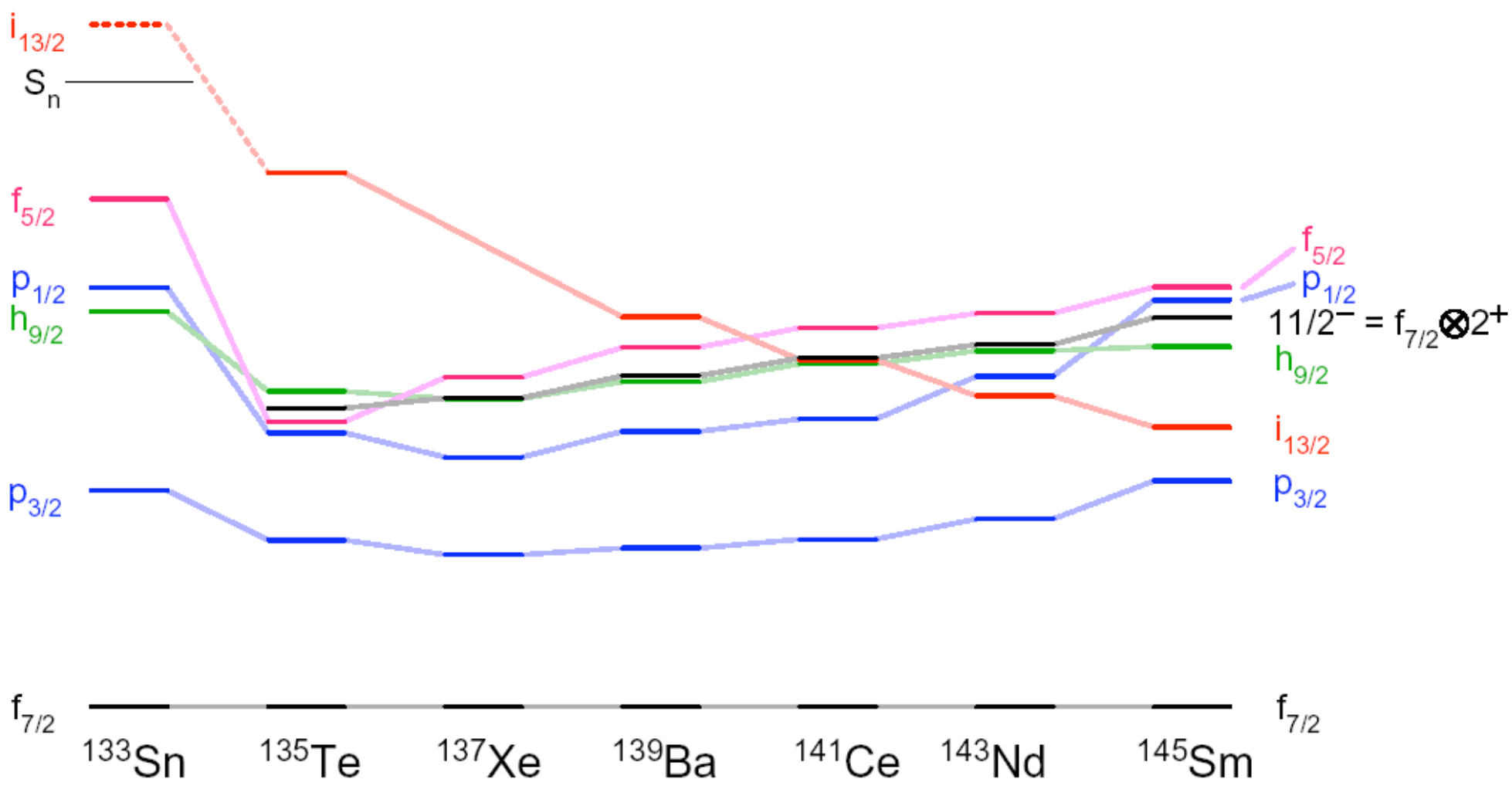
Shell model calculations: ^{83}Ge



Calculations from Alex Brown (private communication). Skyrme mean field, adjusted to reproduce the global single particle energies

Calculation of ^{83}Ge [A. Brown, MSU] predicts **stronger shell closure** than seen in HRIBF ^{82}Ge(d,p)^{83}Ge experiment

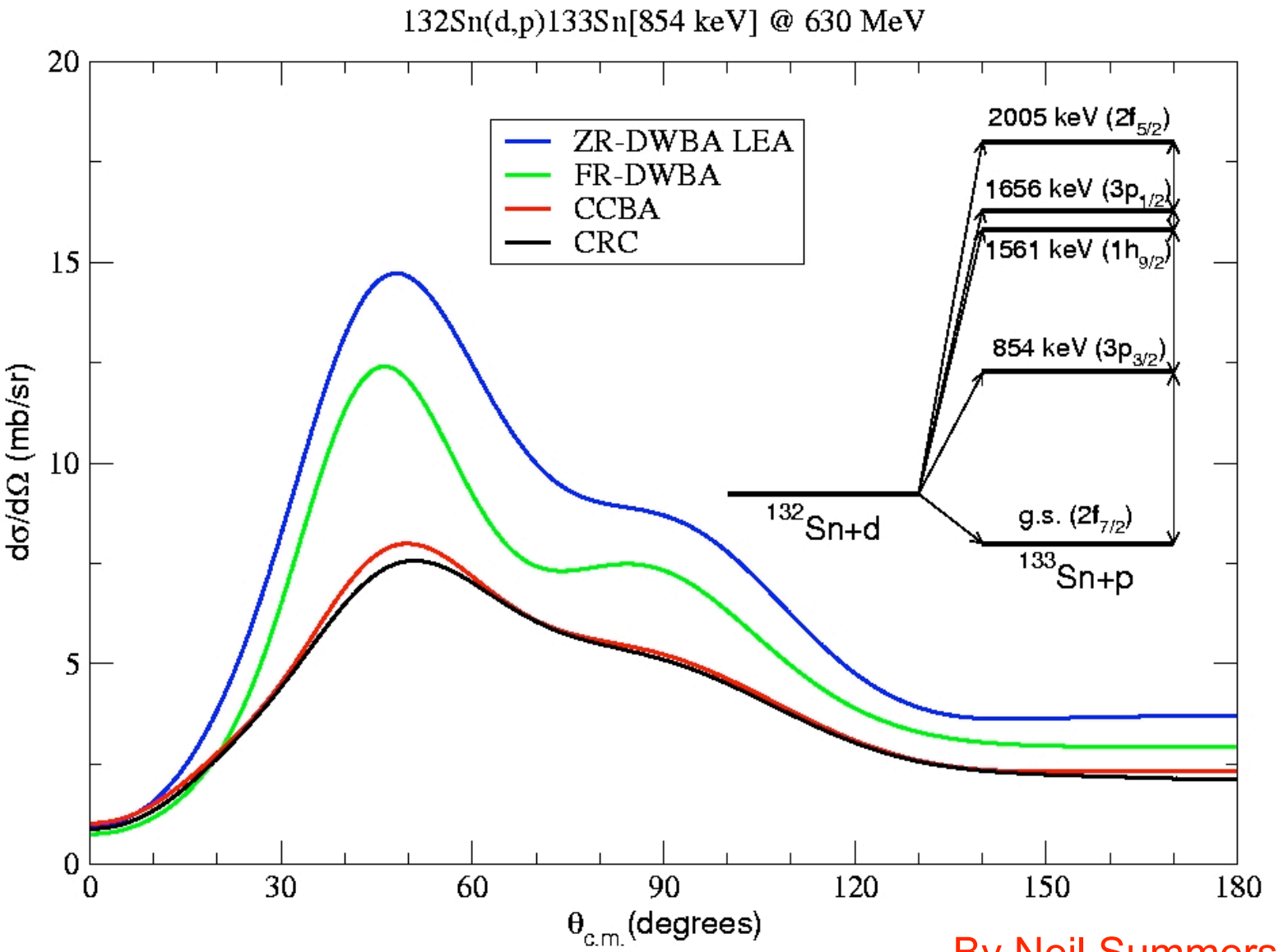
N=83 Systematics



(n,γ) direct capture calculations

- G. Arbanas [ORNL] using the code Cupido (F.Dietrich) to calculate direct capture for ^{88}Sr, ^{84}Se and ^{82}Ge
  - Cupido (F.Dietrich) compared with TEDCA calculations from T. Rausher
  - Used SF from HRIBF measurements
  - Koning-Delaroche global optical potential
- E1 capture of p-wave neutrons dominates capture cross section into both ^{83}Ge and ^{85}Se.
- Semidirect capture through the GDR reduces cross section by ~10%
- Results show capture cross sections that are a factor of 10 down from that into ^{89}Sr (stable case)

Reaction Calculations $^{132}Sn(d,p)^{133}Sn[854]$



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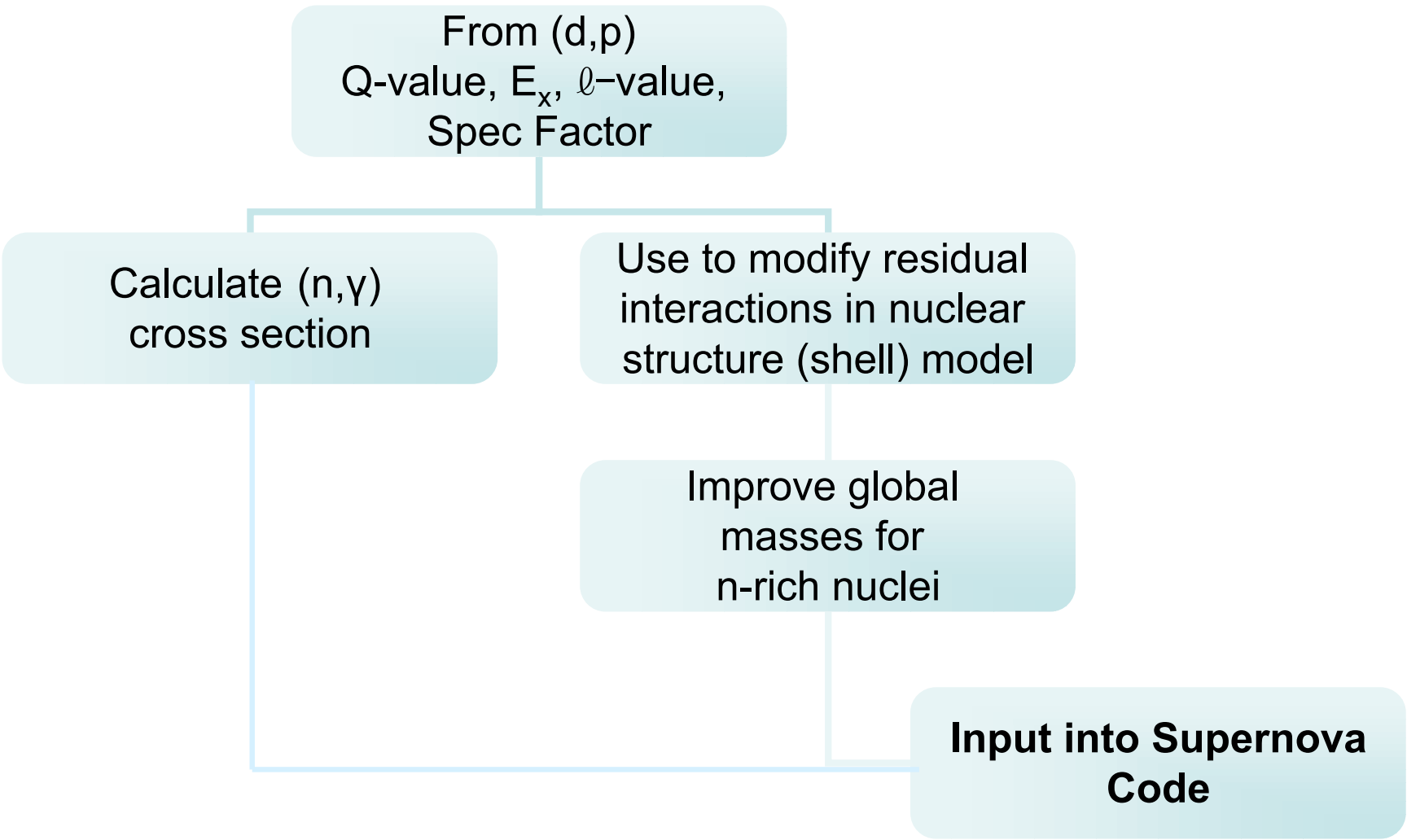
Nuclear data input into r-process calculations



Other utility of (d,p) reactions - masses

r-process waiting point approximation

$$\frac{Y(Z,A+1)}{Y(Z,A)} = \frac{n_n \langle v\sigma_{n,\gamma}(Z,A)\rangle}{\lambda_{\gamma,n}(Z,A+1)}$$

$$= n_n \left(\frac{2\pi\hbar^2}{m_u kT}\right)^{3/2} \left(\frac{A+1}{A}\right)^{3/2} \frac{G(Z,A+1)}{2G(Z,A)} \exp\left[\frac{S_n(Z,A+1)}{kT}\right]$$

- r-process involves thousands of (n,γ) reactions
- Nuclear masses are needed
  - to calculate energy released in the r-process
  - to calculate capture cross sections with a Statistical model
  - for the "waiting point approximation" used in many r-process calculations
- (d,p) reactions can measure masses
  - Precision adequate for r-process studies
  - Requires reacceleration

New shell model calculations

- New effort by David Dean & M. Hjorth-Jensen to calculate all neutron-rich N=51 nuclei simultaneously
- Working with excitations built on a ^{78}Ni core
- Cannot currently reproduce measured spacing of 1st excited state energies for n-rich N=51 nuclei
- Appears necessary to activate g9/2 protons - which will significantly enlarge model space
- Very preliminary results - work in progress