Indirect experiments for neutron reactions with unstable nuclei

Jeff Blackmon, Louisiana State University

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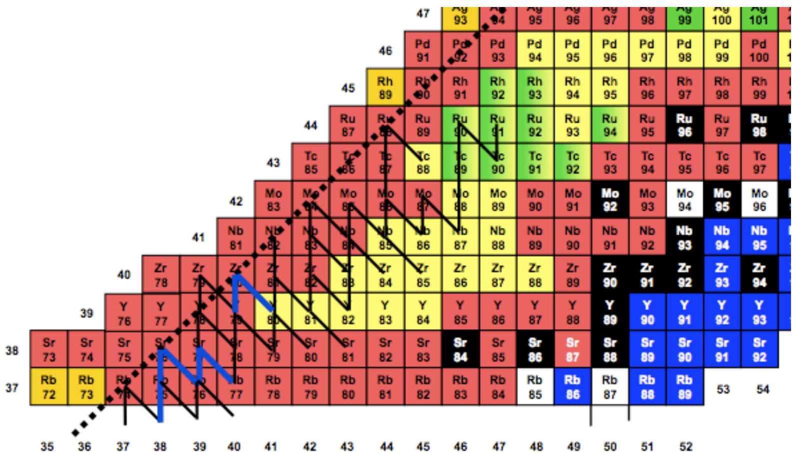
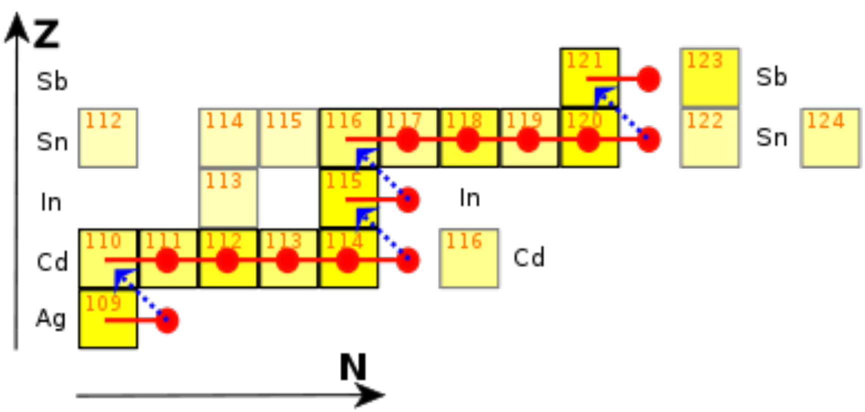
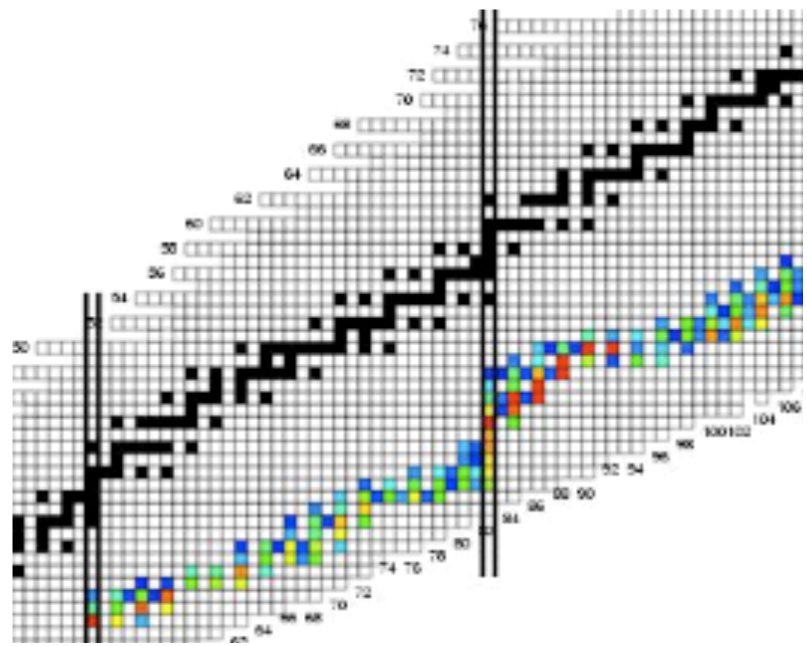


However the heavy elements got made, neutron reactions on unstable nuclei were likely important.





Indirect experiments for neutron reactions with unstable nuclei

Jeff Blackmon, Louisiana State University

We can only directly measure neutron reactions on stable or very long-lived targets!

- Introduction: Neutron reaction rates
- s process
  → Neutron capture rates
  → Surrogate approaches to the exit channel
  → Gd, Zr, Yb
- r process
  → ^{132}Sn & ^{130}Sn
  → (d,pγ)
- νp process
  → Thoughts on (n,p)

Statistical (Hauser-Feschbach)

NON-SMOKER Rauscher & Thielemann, ADNDT **75** (2000)
TALYS Goriely, Hilaire, & Koning, AA **487** (2008)

- Assumptions:
  - → Many levels contribute to MAC/rate
  - → Independent entrance/exit channels¶: $n+A \rightarrow B^* \rightarrow B+\gamma$

$$\sigma_{n\gamma}(E) = \sum_{J\Pi} \sigma_n G_\gamma$$

σ_n (Formation cross section)

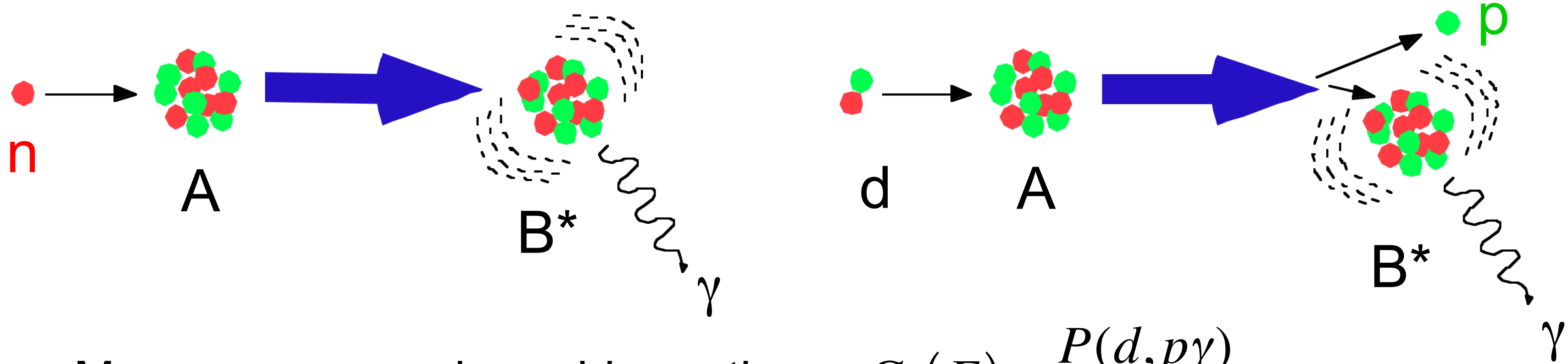
- ***Nuclear level densities***
  - → Constrained by s-wave level spacing (stable nuclei)
  - → Otherwise model (back-shifted Fermi Gas w/ corrections)

G_γ (Gamma branching ratios)

- ***E1 photon strength function***
  - → Near stability: average s-wave radiation width $<\Gamma_\gamma>_0$
  - → ¶Width fluctuation corrections

G_γ by "Surrogate" Approach

What we want | What we can do



- Measure gamma branching ratios $G_\gamma(E) = \frac{P(d,p\gamma)}{P(d,p)}$

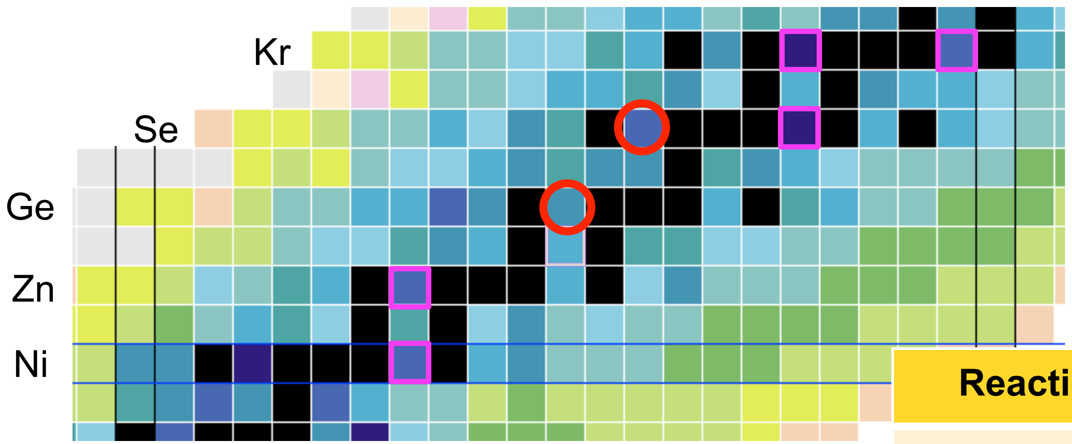
$$\sigma_{n\gamma}(E) = \sum_{J\Pi} \sigma_n G_\gamma$$

BUT Surrogate has different J^π sensitivity than (n,γ)

What to do?

1. Ignore it = Weisskopf-Ewing Approximation
2. Correct using theory
3. Better? = Use (d,pγ) + theory + experimental ratios

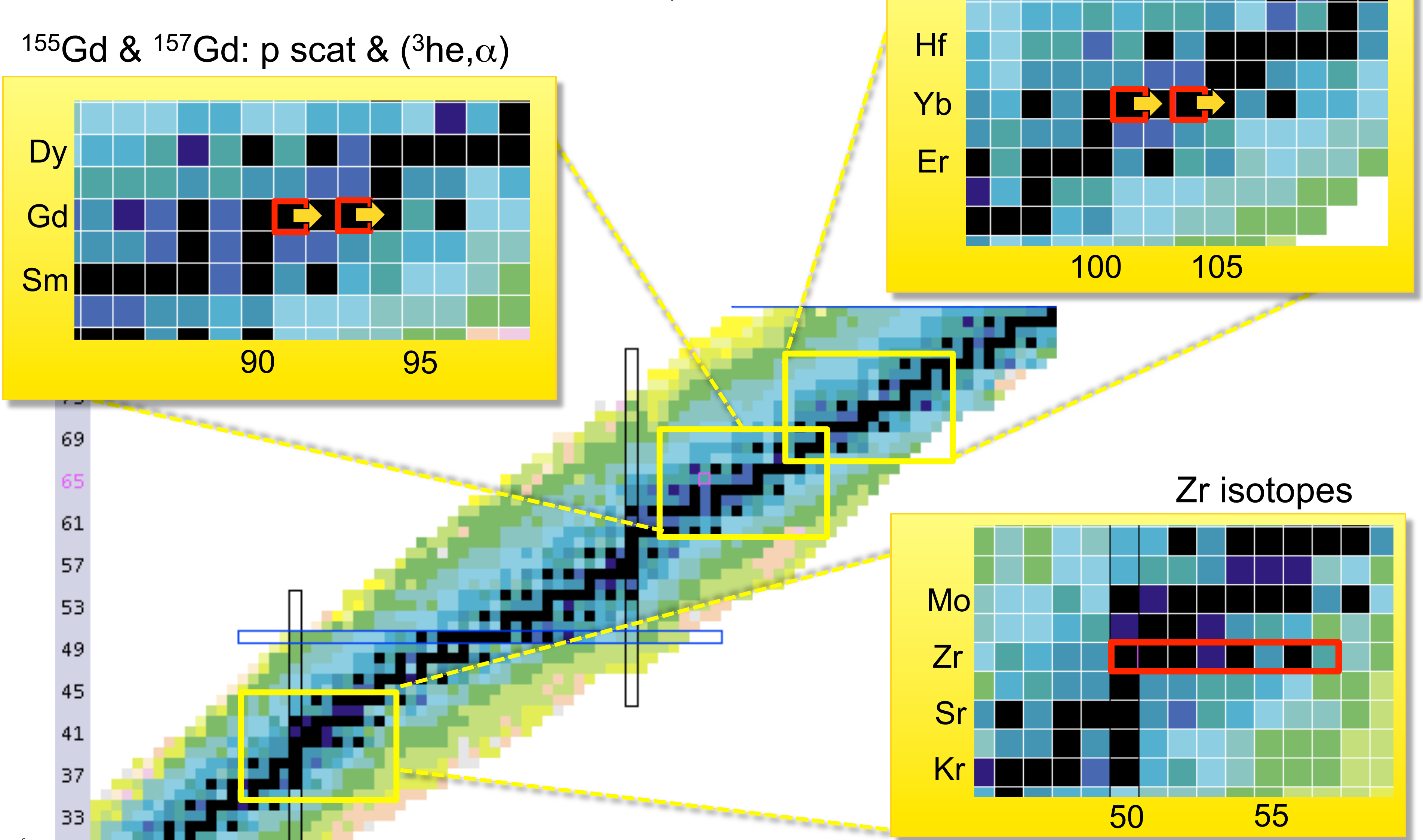
s-process branch points



Reaction	Q-value (MeV)	σ_{30}(mb)
$^{63}Ni(n,\gamma)^{645}Ni$	9.7	31
$^{85}Kr(n,\gamma)^{86}Kr$	8.3	55

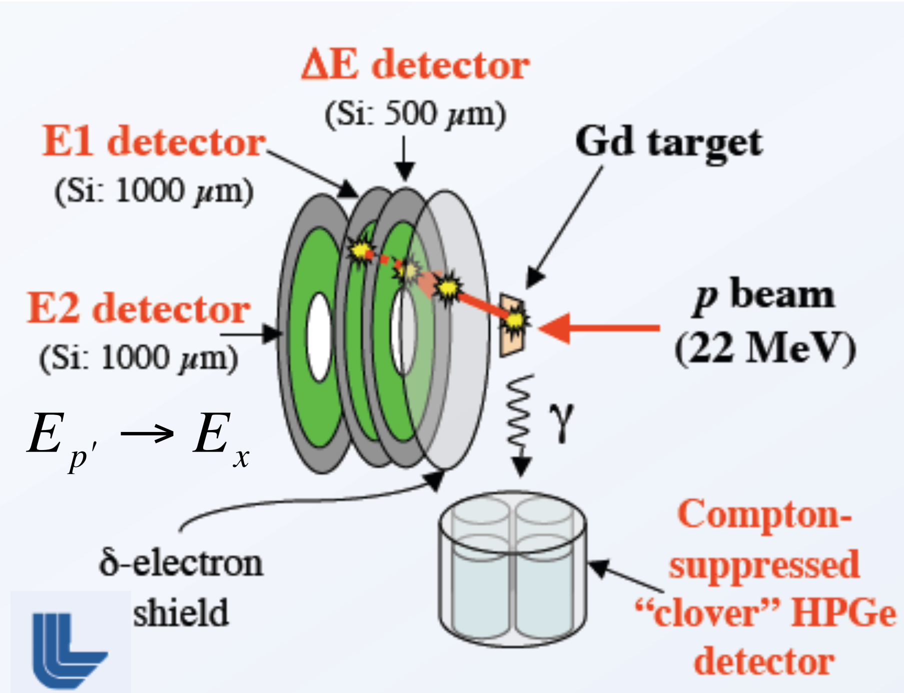
- ***Near stability***
  - → Some can/will be measured directly (nToF & DANCE)
  - → High Q-value and high level density → *HF* Good
    - ○ Level density is well known from regional systematics
    - ○ But would like a very accurate cross section
    - ○ Largest uncertainty is gamma-branching ratios *(G_γ)*
- ***Importance of other branch points for LEPP?***
  - → *^{71}Ge (11 d), ^{75}Se (120 d), . . .*

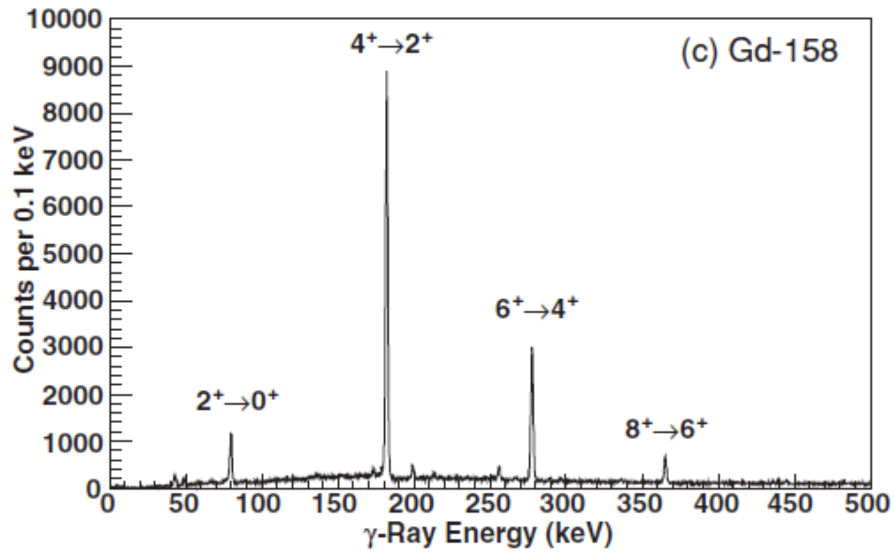
Surrogate G_γ Tests



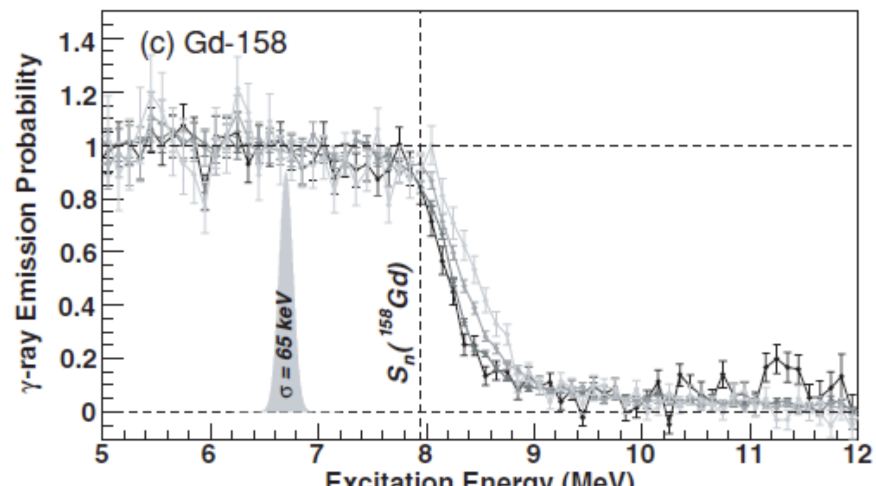
Gd isotopes

Experiments: Scielzo PRC **81** (2010)
Theory: Escher & Dietrich PRC **81** (2010)





$$G_\gamma(E) = \frac{P(p,p'\gamma)}{P(p,p')}$$

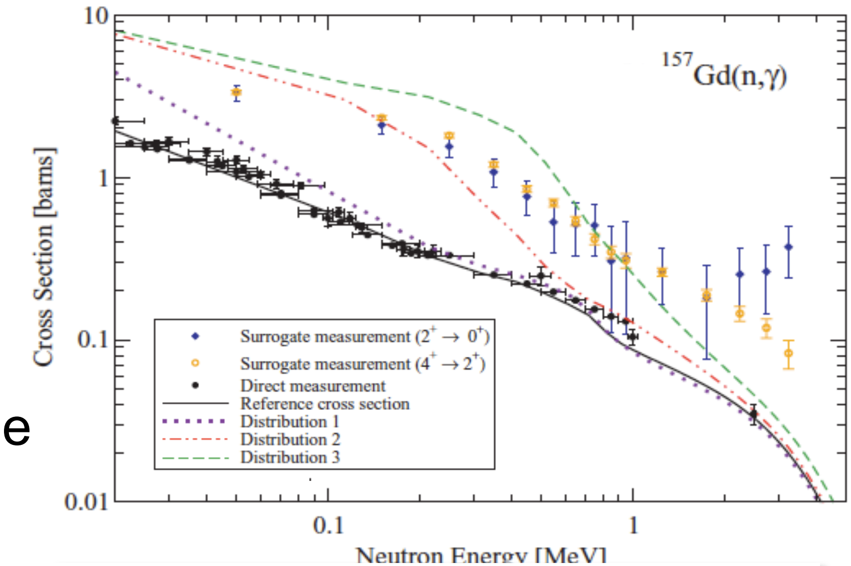


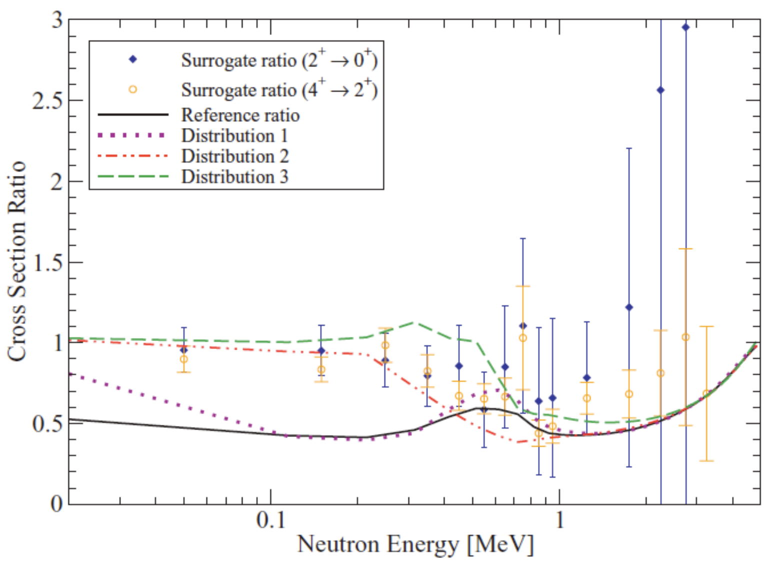
- Experimental issues
  - →p energy resolution
  - →Conversion and ε_γ

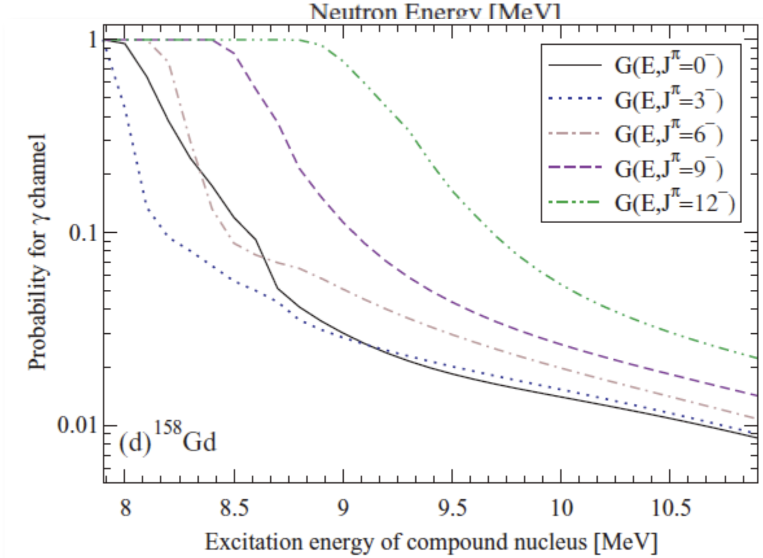
Gd isotopes

Experiments: Scielzo PRC **81** (2010)
Theory: Escher & Dietrich PRC **81** (2010)

- Weisskopf-Ewing: factor 2-10 off
- Compare ratio of reactions?
  - → ^{155,157}Gd similar deformations
  - → Ground state $J^{\pi} = 3/2^{+}$
  - → Off by factor ~2x
- Model relative J^{π} dependence
  - → Good description possible if done correctly



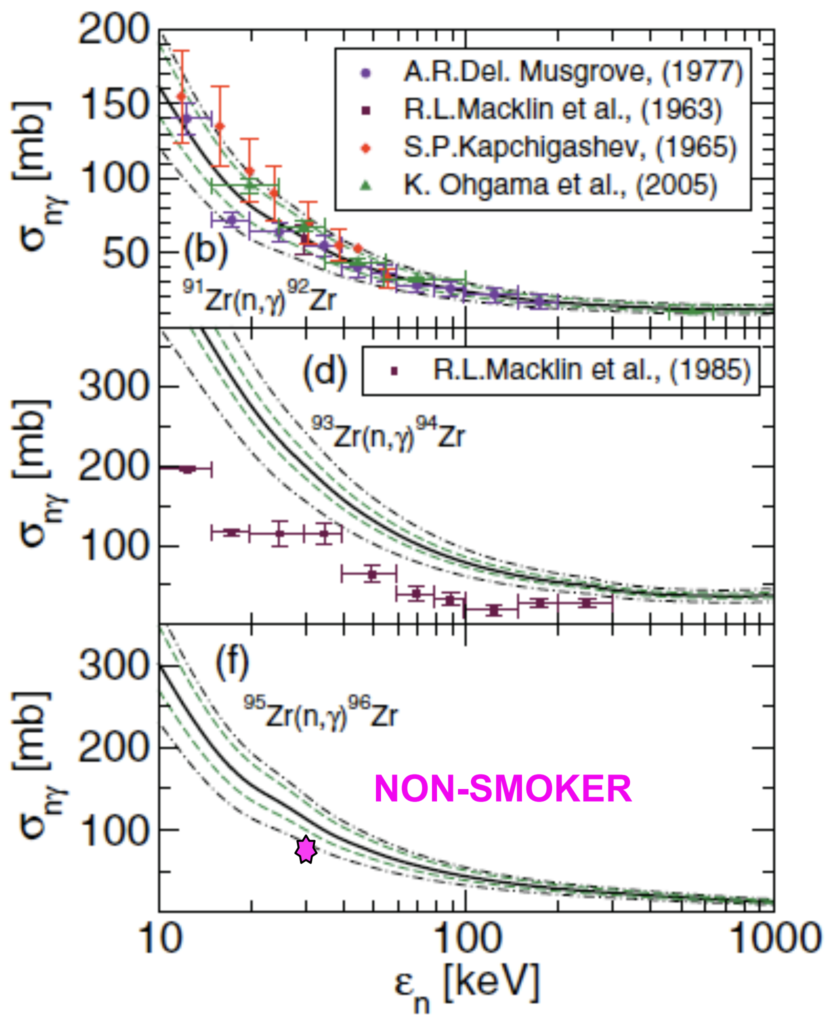


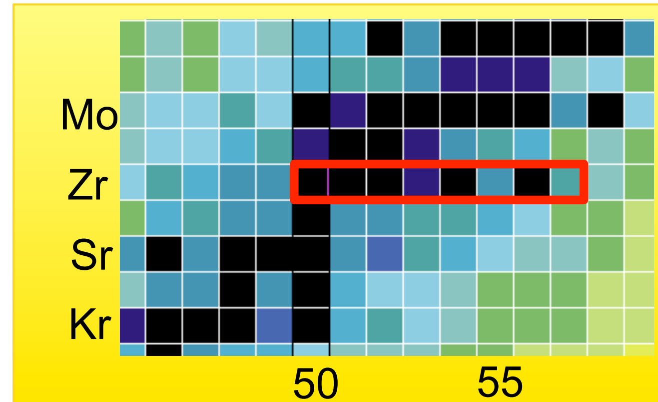


Zr Isotopes

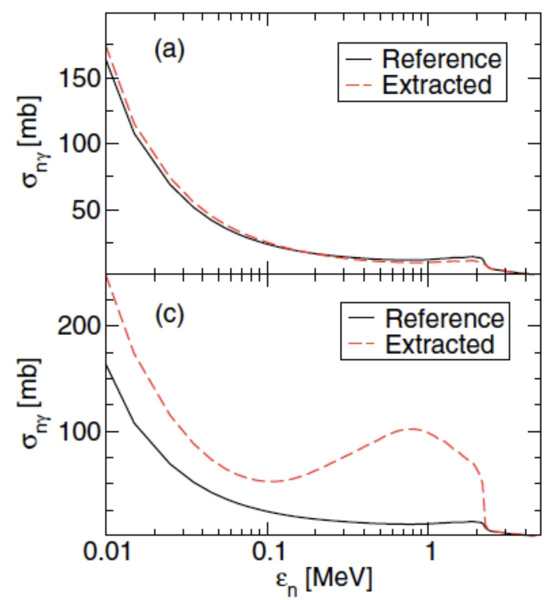
Forssén *et al.*, *PRC* **75** (2007).

- Careful analysis of theoretical cross section based on regional systematics





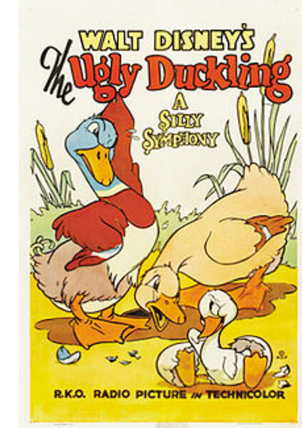
- Good results if J^{π} population matches



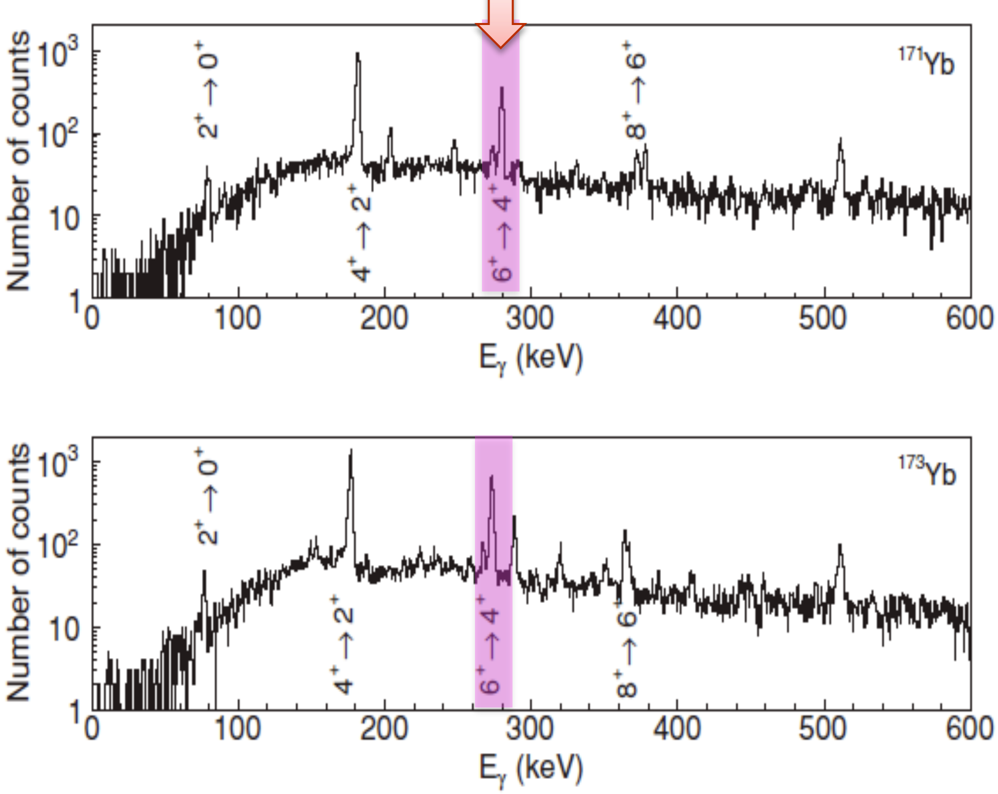
^{171,173}Yb(d,pγ)

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

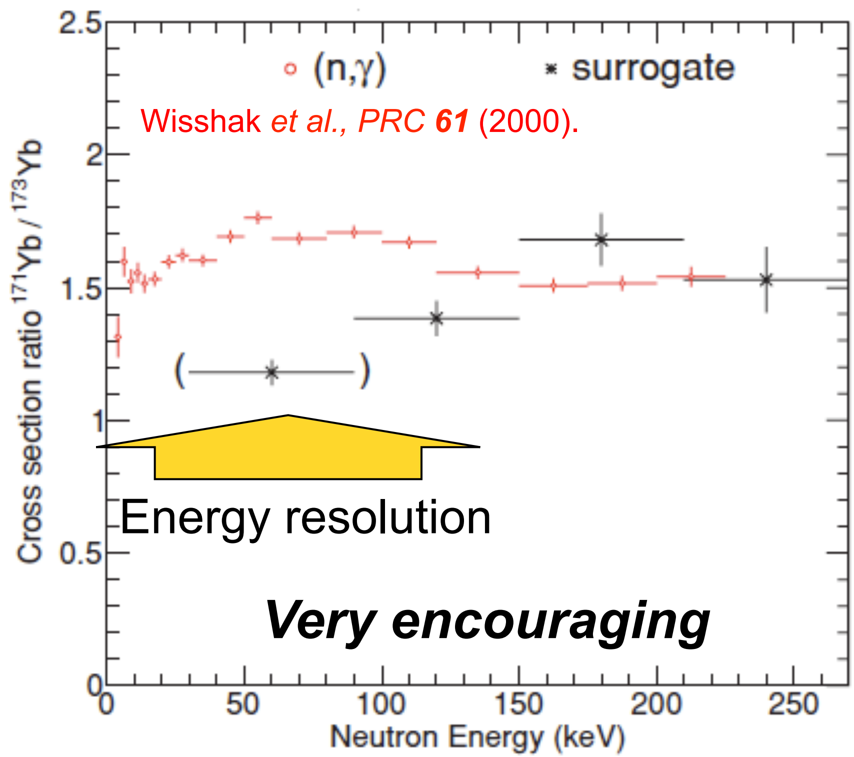
- Similar experimental approach as Gd measurements
  → (d,p) populates low angular momentum states



But not perfect match



Restrict to direct feeing of 4^+

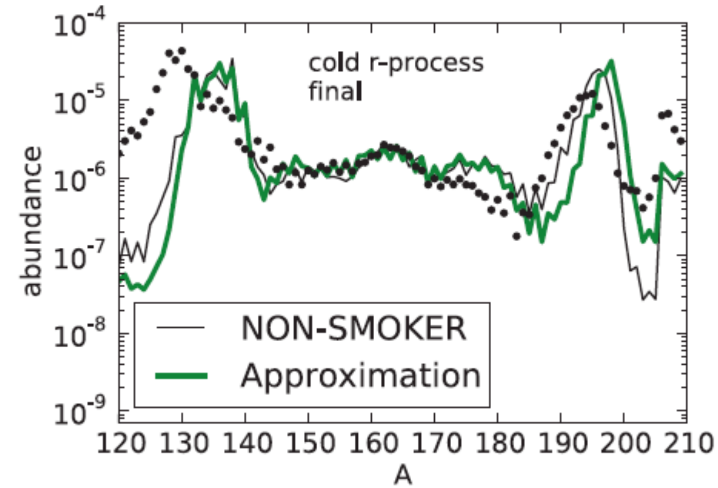


Neutron capture and r process

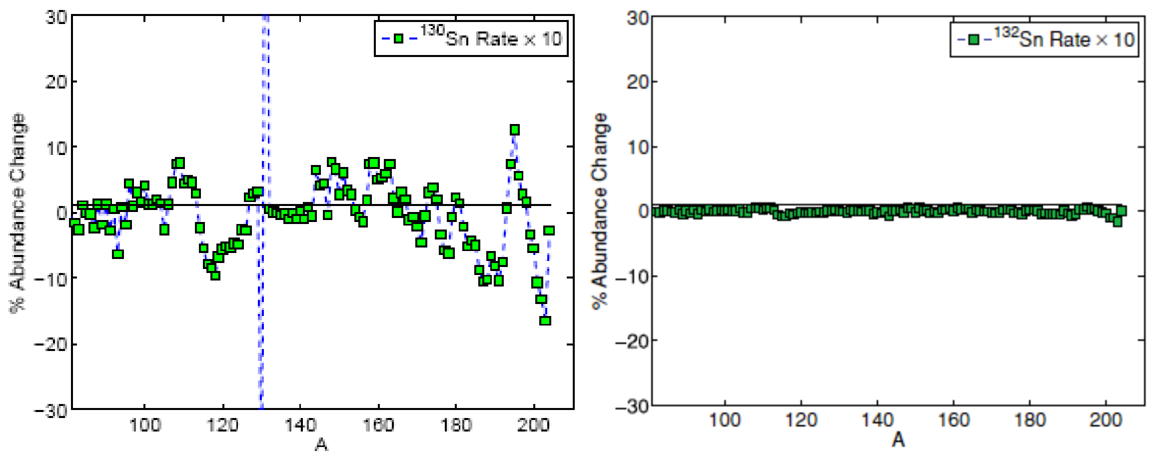
- ***Some*** n-capture rates affect abundances

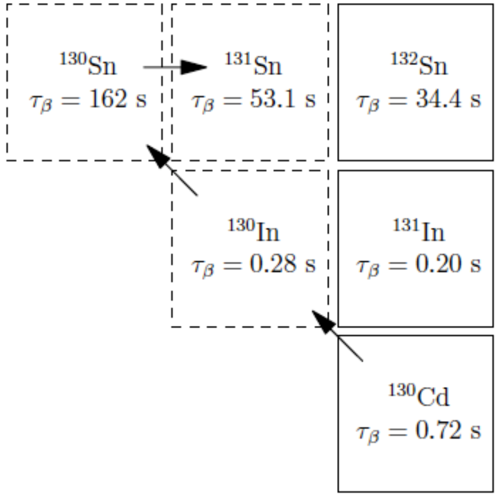
- What rates seem most important?
  - → Closer to stability (freeze-out)
  - → Abundant nuclei
  - → Even-even "before" close neutron shells

Arcones & Martinez-Pinedo., *PRC* **83** (2011).



J. Beun *et al., JPG* **36** (2009).





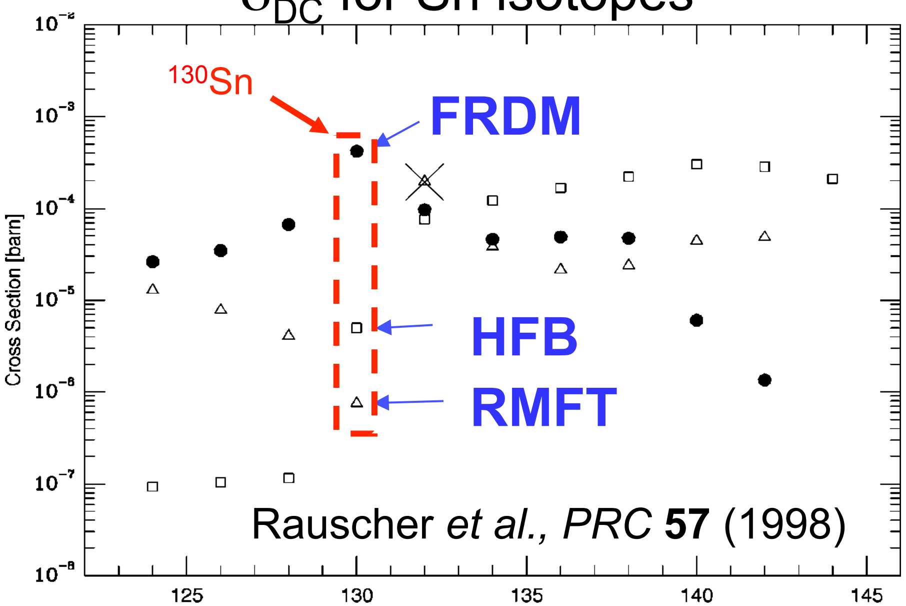
Rate calculations

- Most important rates are very difficult to estimate
  - → Level density low and cross sections are low
  - → Statistical models not robust
  - → Contribution of direct-capture is uncertain

Reaction	Q-value (MeV)	σ_{30}(mb)
^{84}Kr(n,γ)^{85}Kr	7.12	18
^{80}Ge(n,γ)^{81}Ge	4.86	3
^{130}Sn(n,γ)^{131}Sn	5.25	4

- ^{130}Sn(n,γ)^{131}Sn
  - →Very sensitive to energy of 3p neutron orbitals
  - →s-wave (E1) n capture

σ_{DC} for Sn isotopes

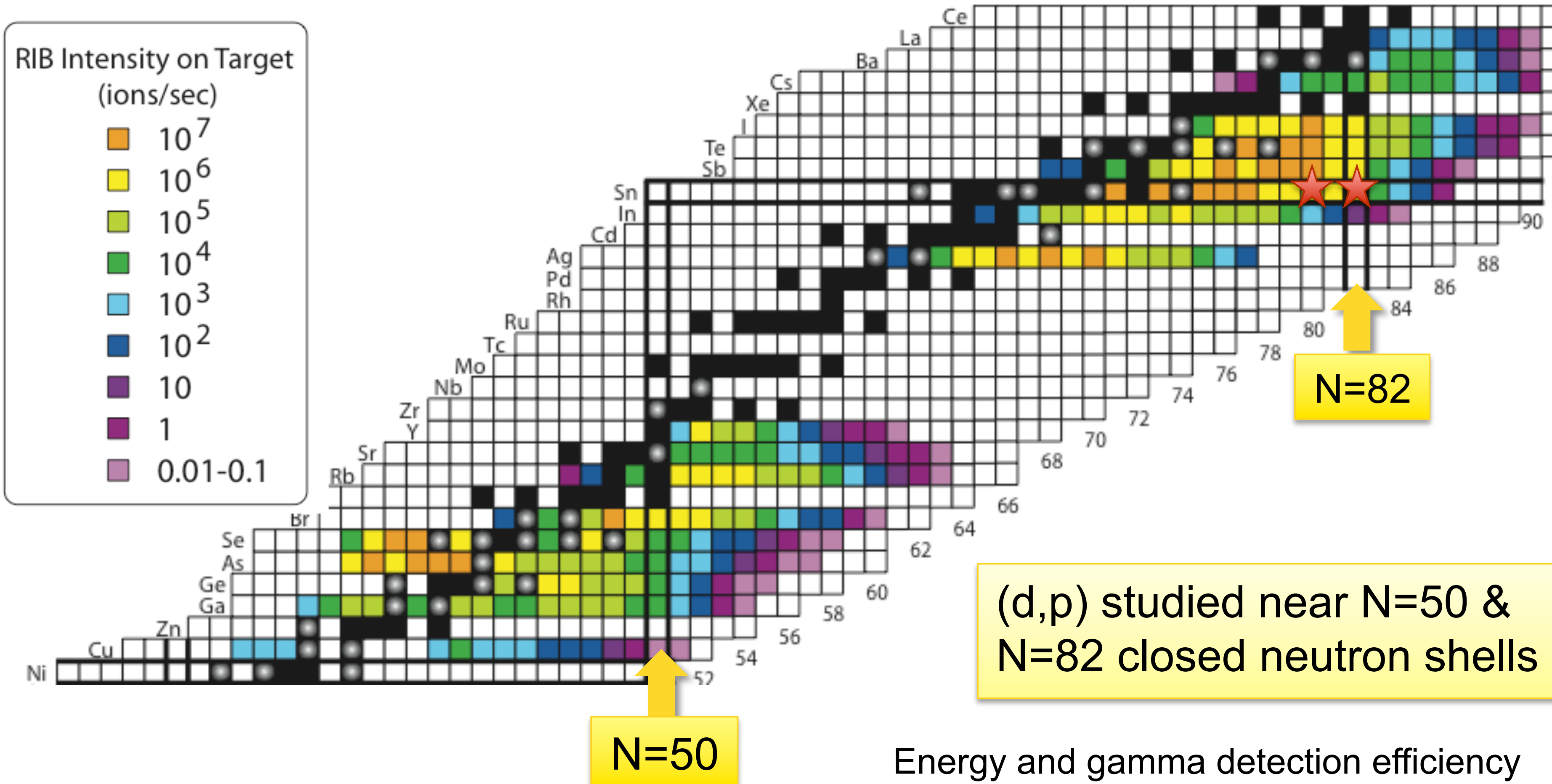


No experimental information on neutron single-particle strength in ^{131}Sn.

The entrance channel is also important!

(d,p) at HRIBF

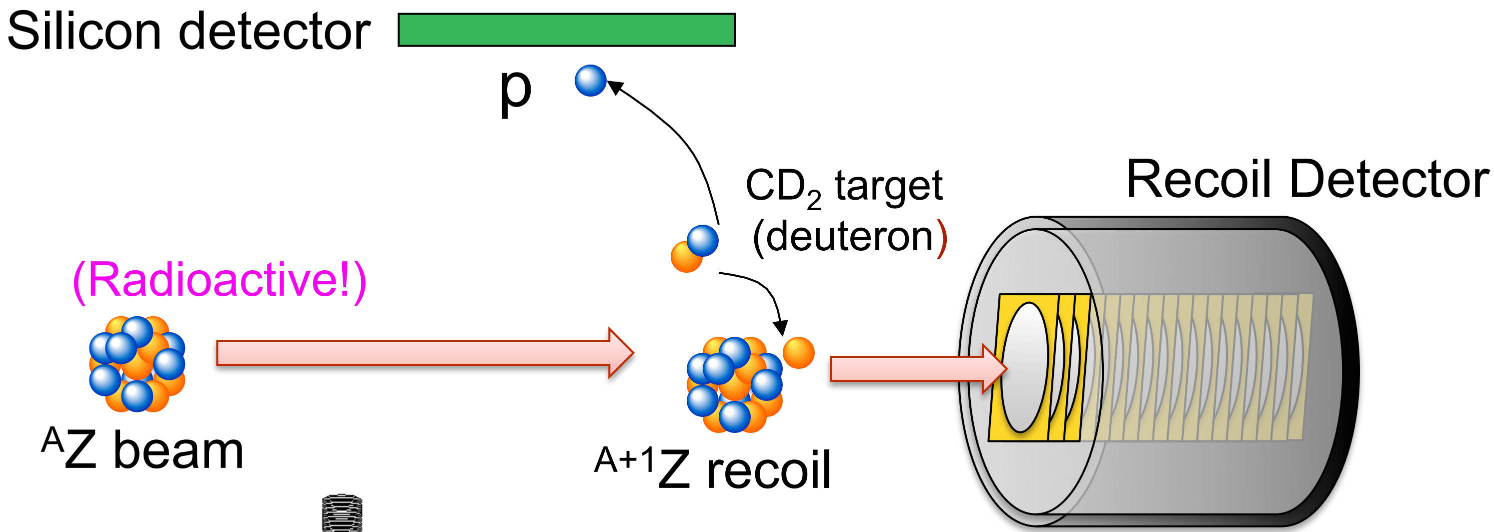
- Over 100 isotopes of n-rich nuclei from uranium fission accelerated

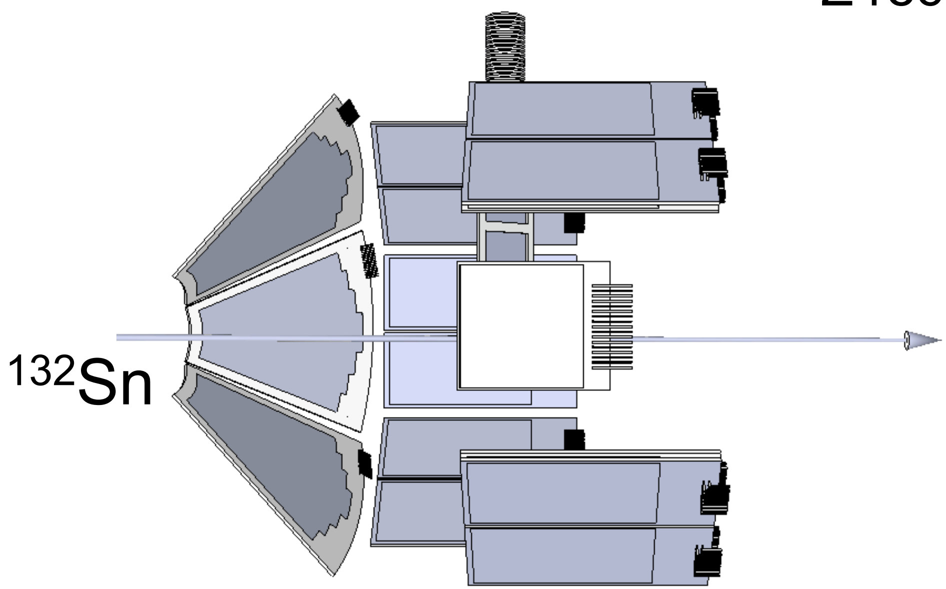


(d,p) studied near N=50 & N=82 closed neutron shells

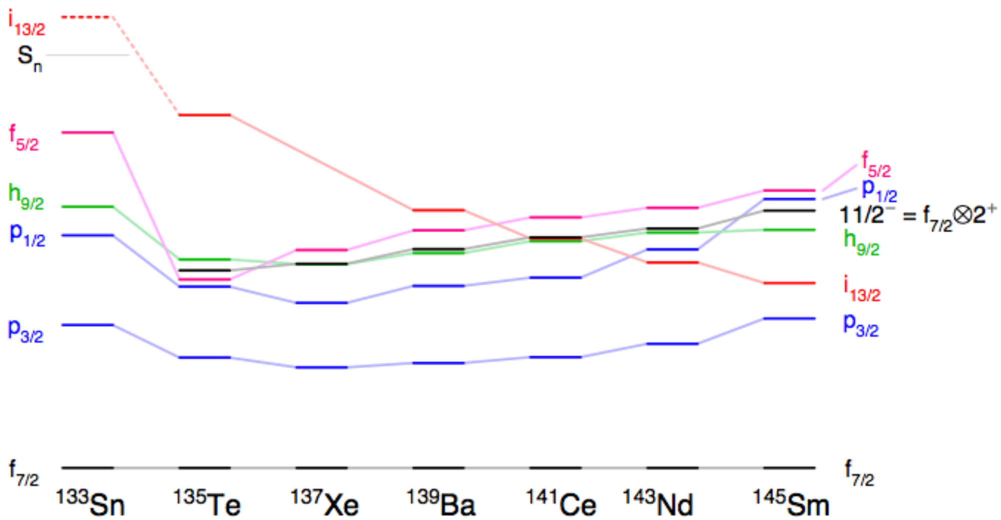
Energy and gamma detection efficiency make (d,pγ) difficult

(d,p) in "Inverse Kinematics"

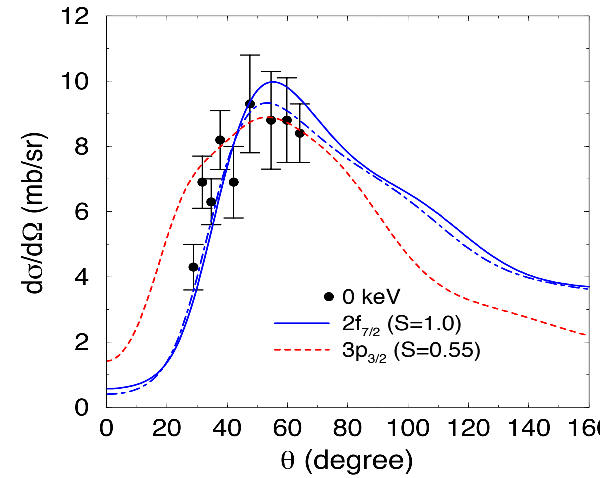


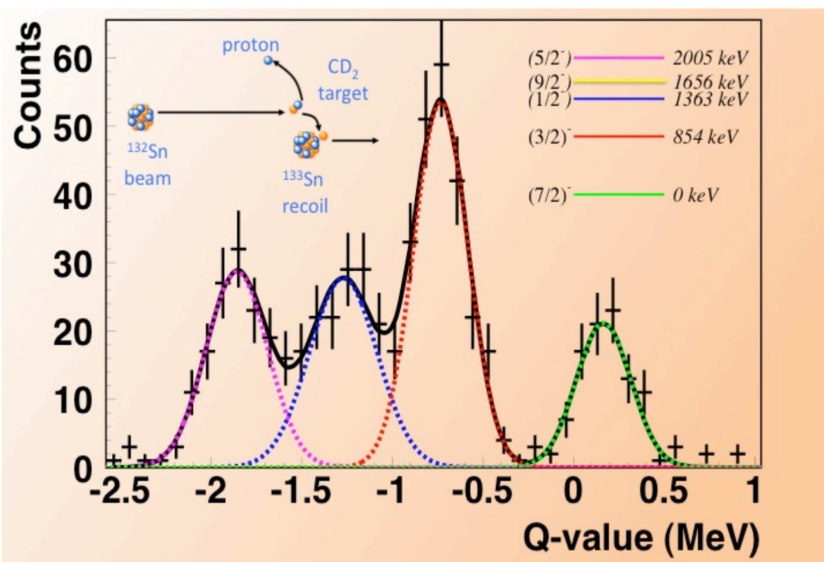


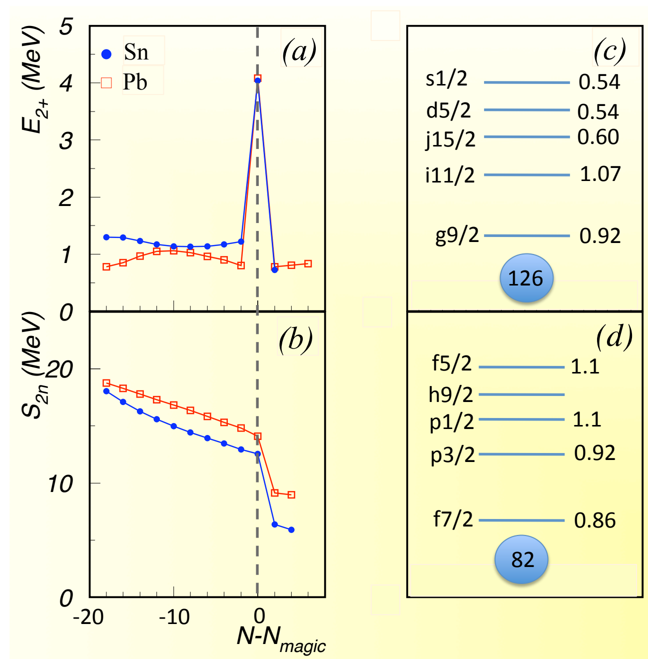
$^{132}Sn(d,p)^{133}Sn$



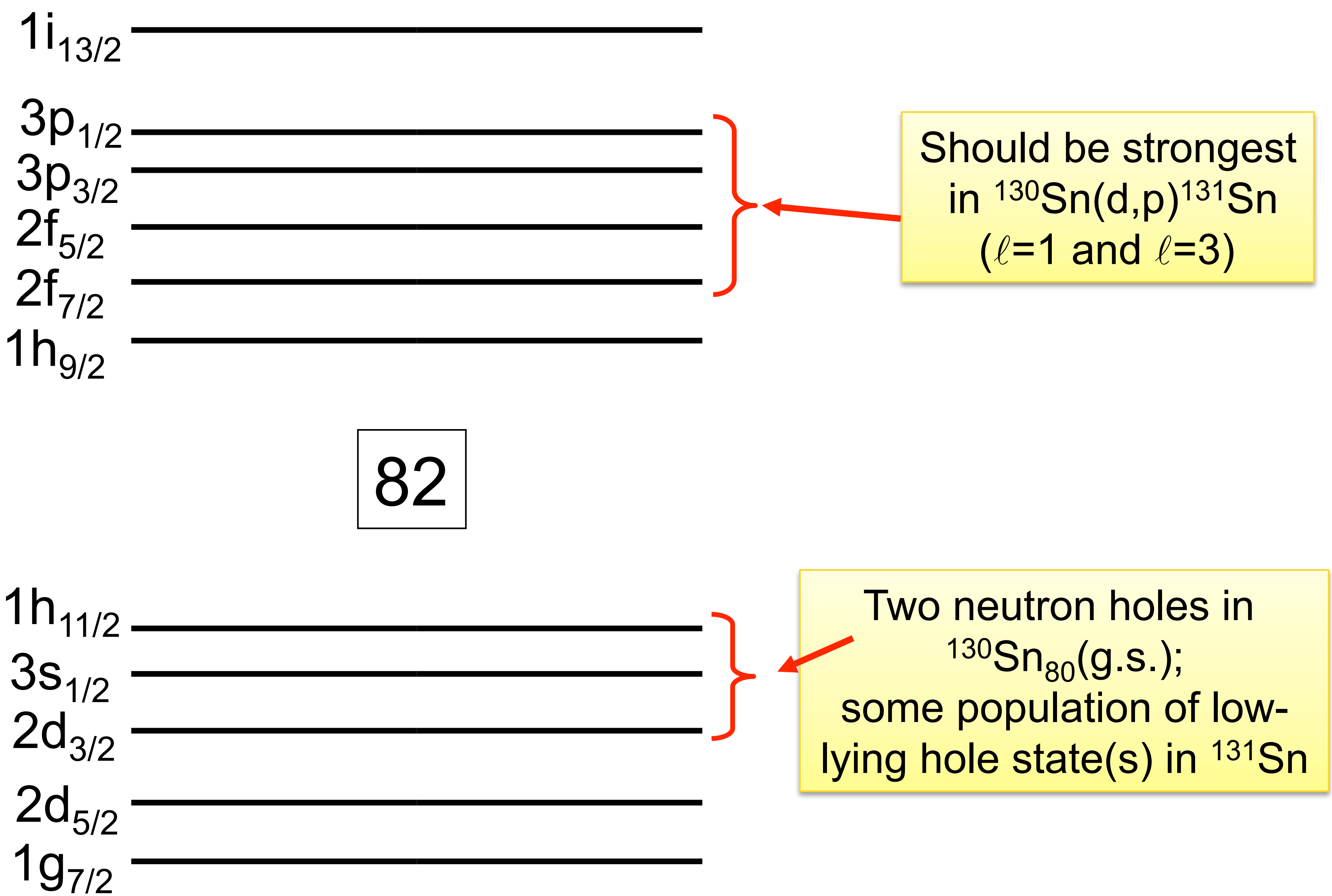
K.L. Jones et al., Nature (2010)





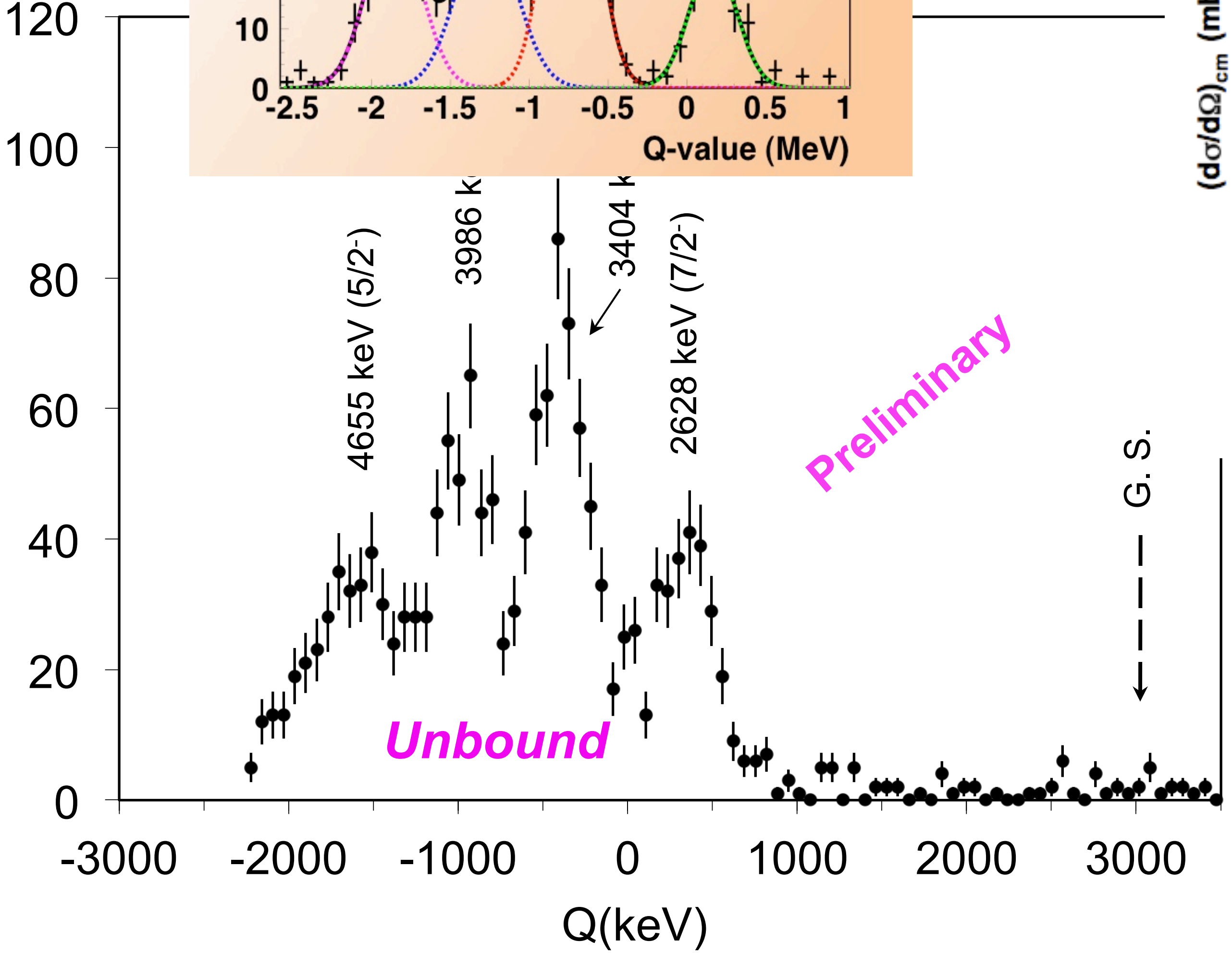


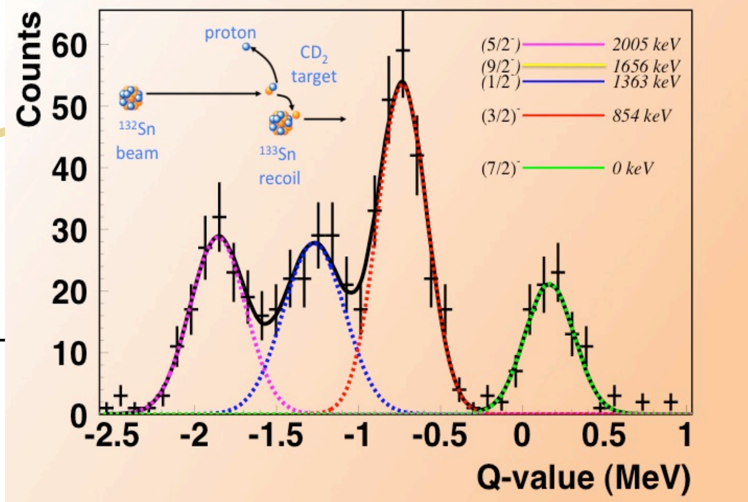
^{131}Sn – “Before closed shell”

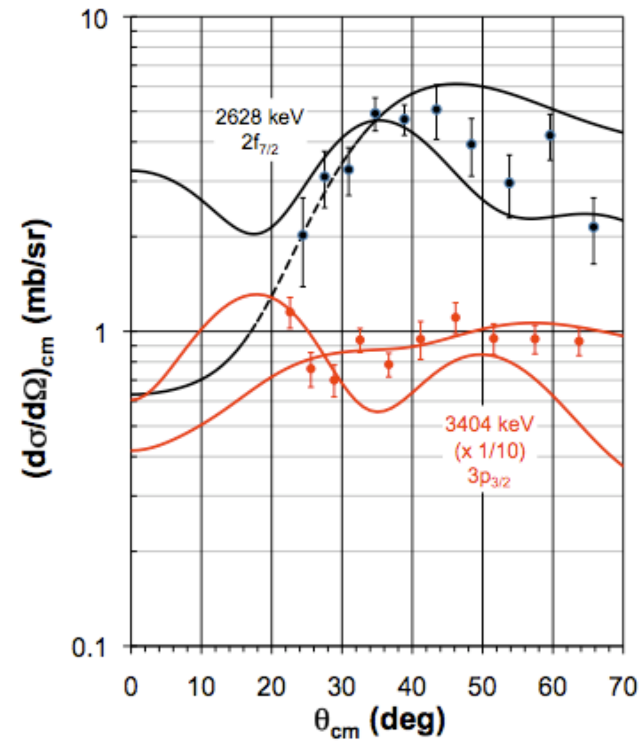


p)^{131}Sn

t al., in prep.





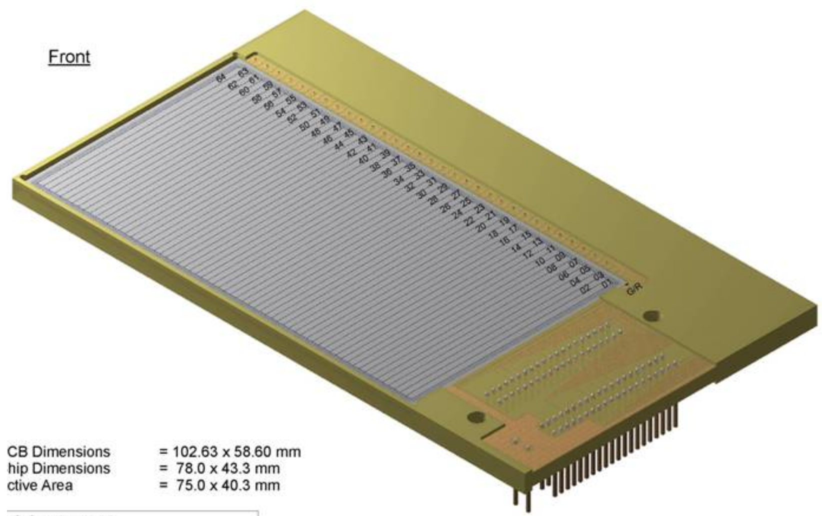


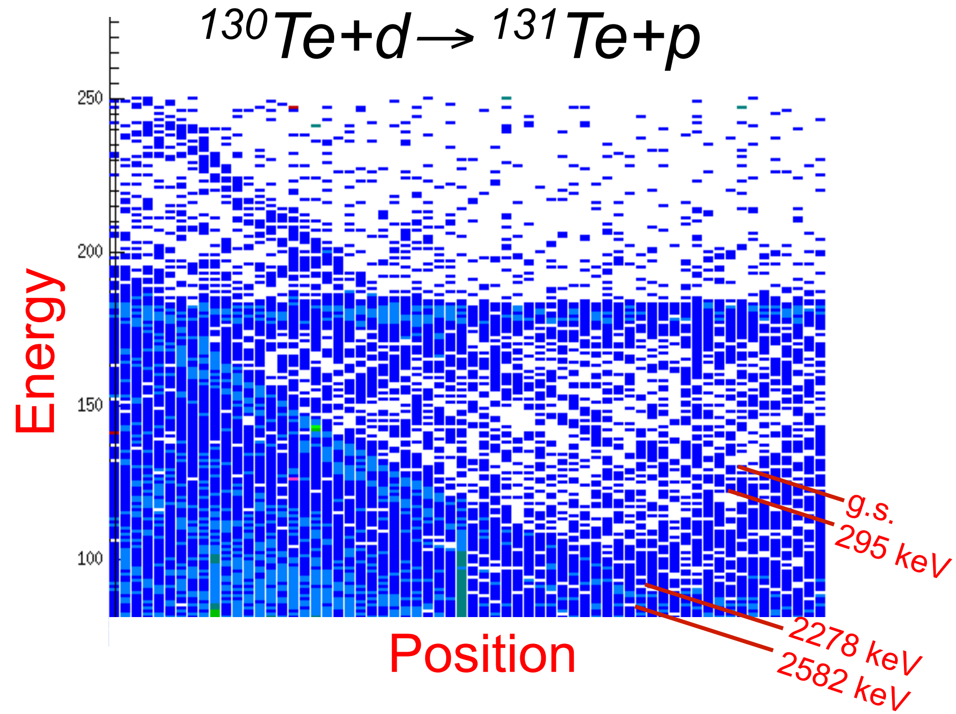
- Hint:
  - → Low DC
  - → High HF Rate

(d,pγ) in inverse kinematics

- 3 challenges:
  1. Energy resolution (protons)
  2. Background
  3. Yield (Beam + γ efficiency)

1. Better p detection = SuperORRUBA
   → 24 Highly-segmented detectors
   → 1700 Individual channels





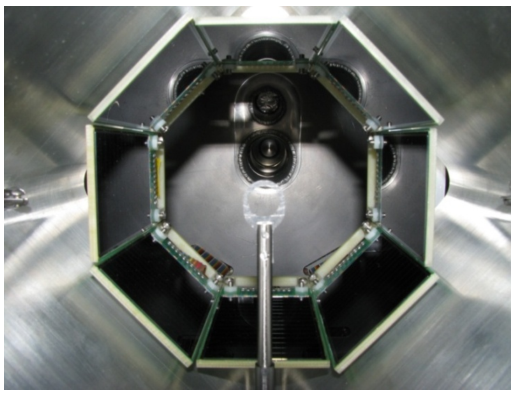
Energy resolution limited only by target thickness

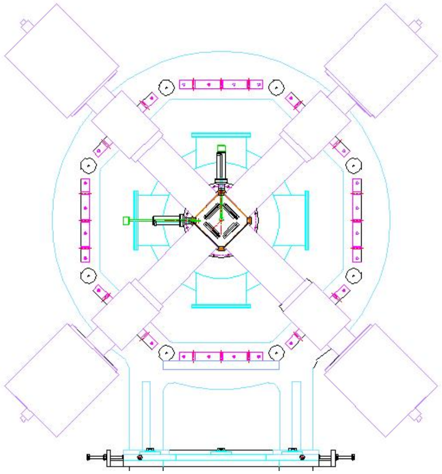
2. Background: ^{75}As(d,pγ)^{76}As Test

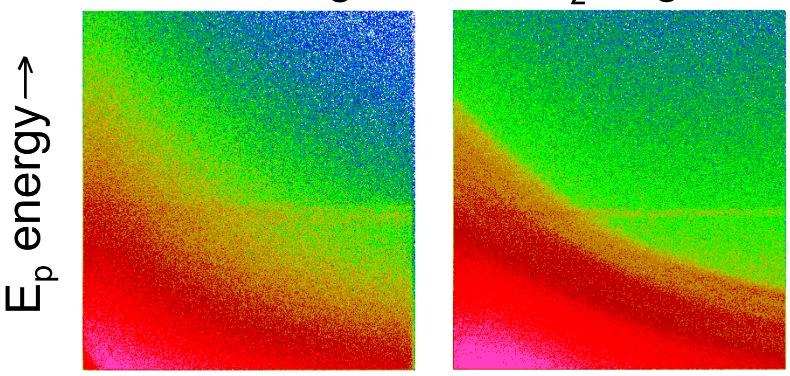
W.A. Peters *et al., In prep.*

- Protons must be clearly defined (without gamma rays) to measure relative gamma branching ratios
  - →Problem is background from carbon (using CH_2 targets)

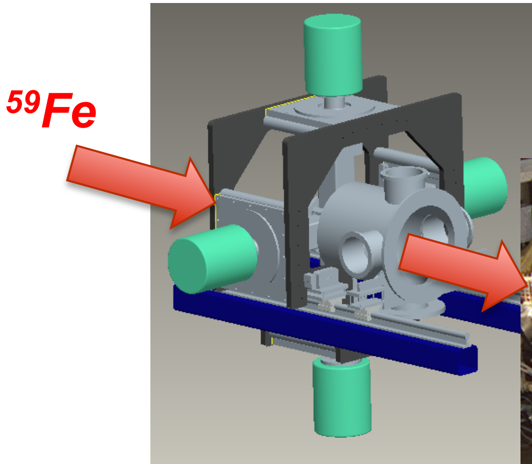
Beam's view



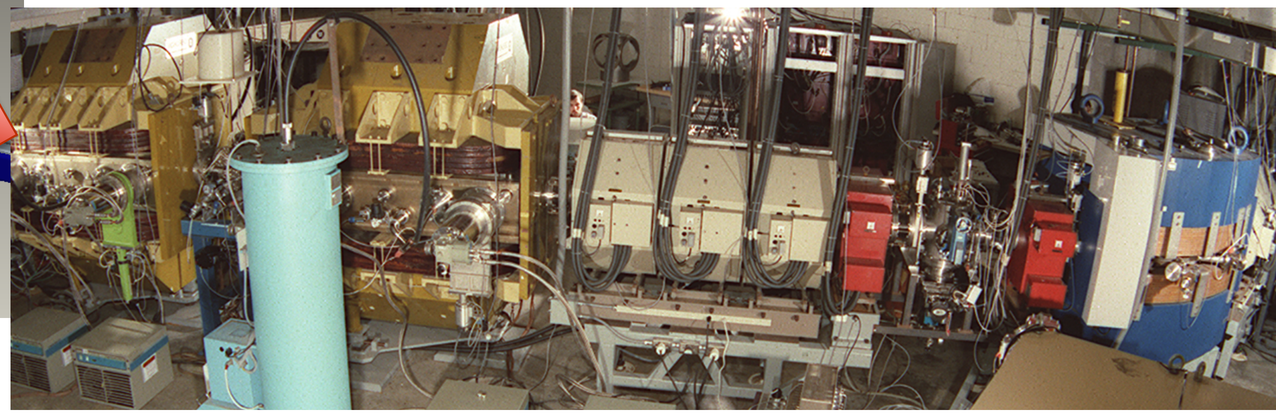




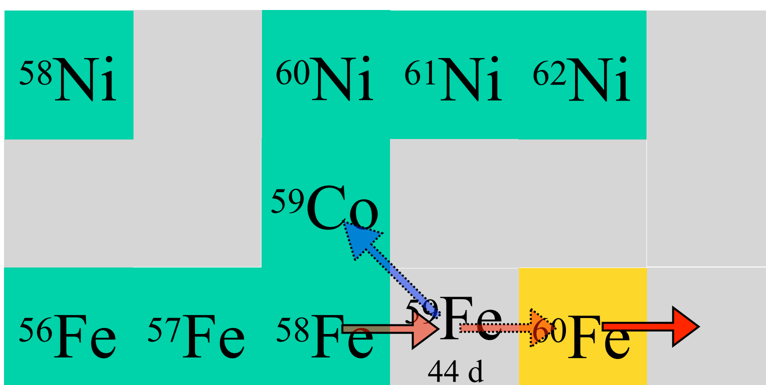
Recoil Selection



- Electromagnetically separate $^{59}Fe/^{60}Fe$
  →*Daresbury Recoil Separator*

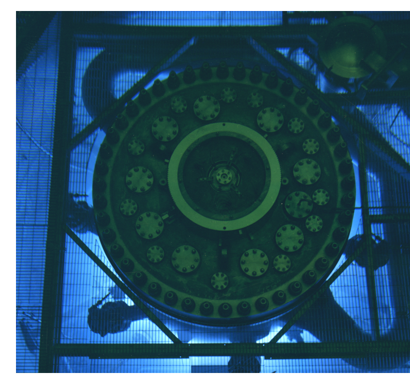


1st Science Case: $^{59}Fe(d,p\gamma)$ [Matos et al.]



^{59}Fe produced at HFIR

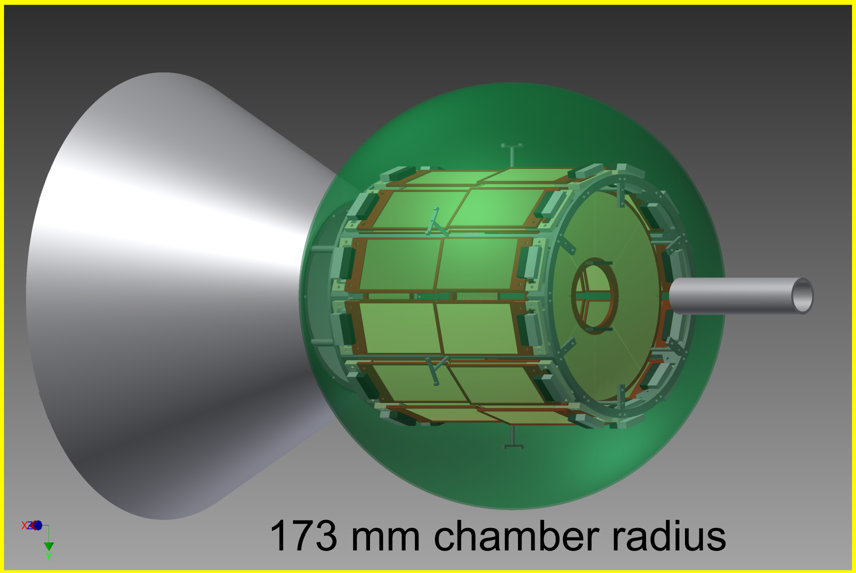
1982 HEAO-3
1994 SMM
1997 CGRO
1998 GRIS
2004 RHESSI
2004 Deep sea sediments
2004 Meteorites
2005 INTEGRAL
2009 Lunar samples (Cook)

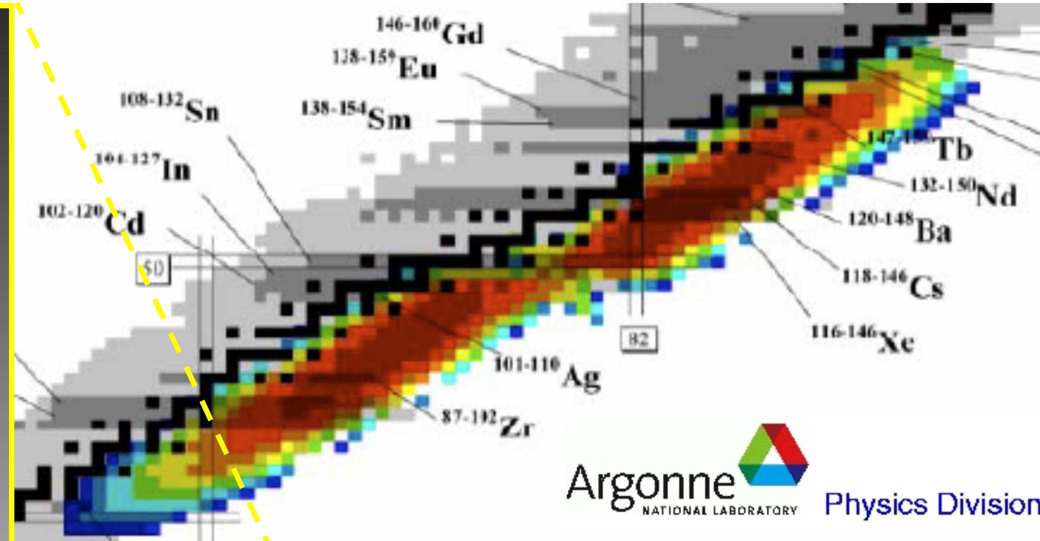


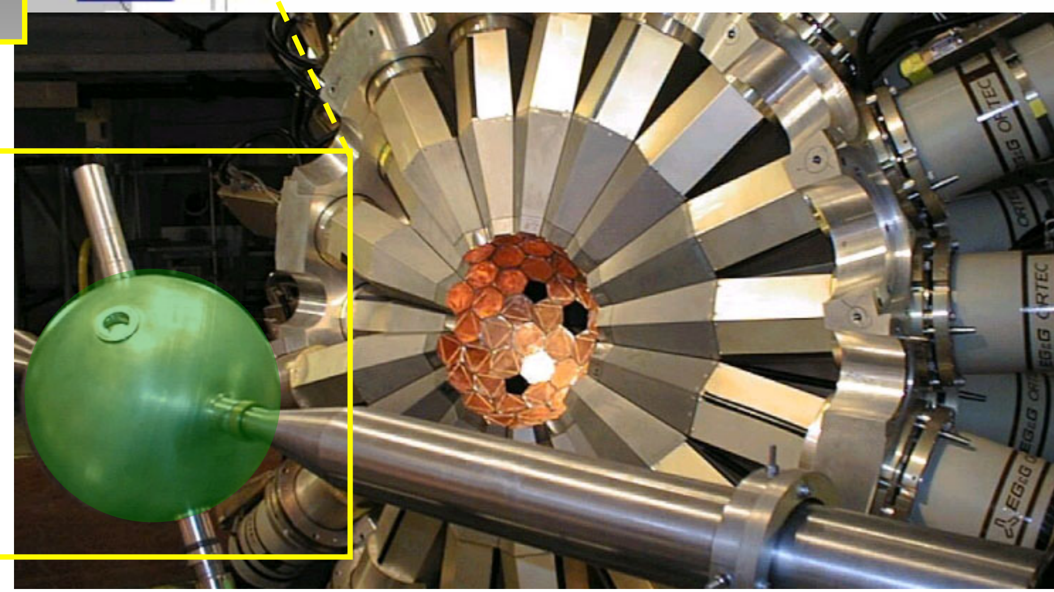
Apr 2012

S. D. Pain *et al.*

3. CARIBU+Gammasphere





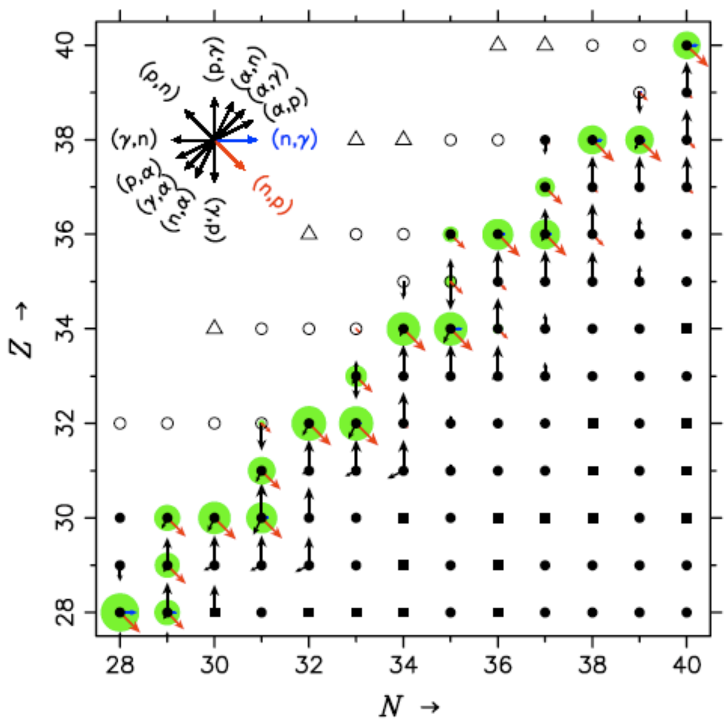


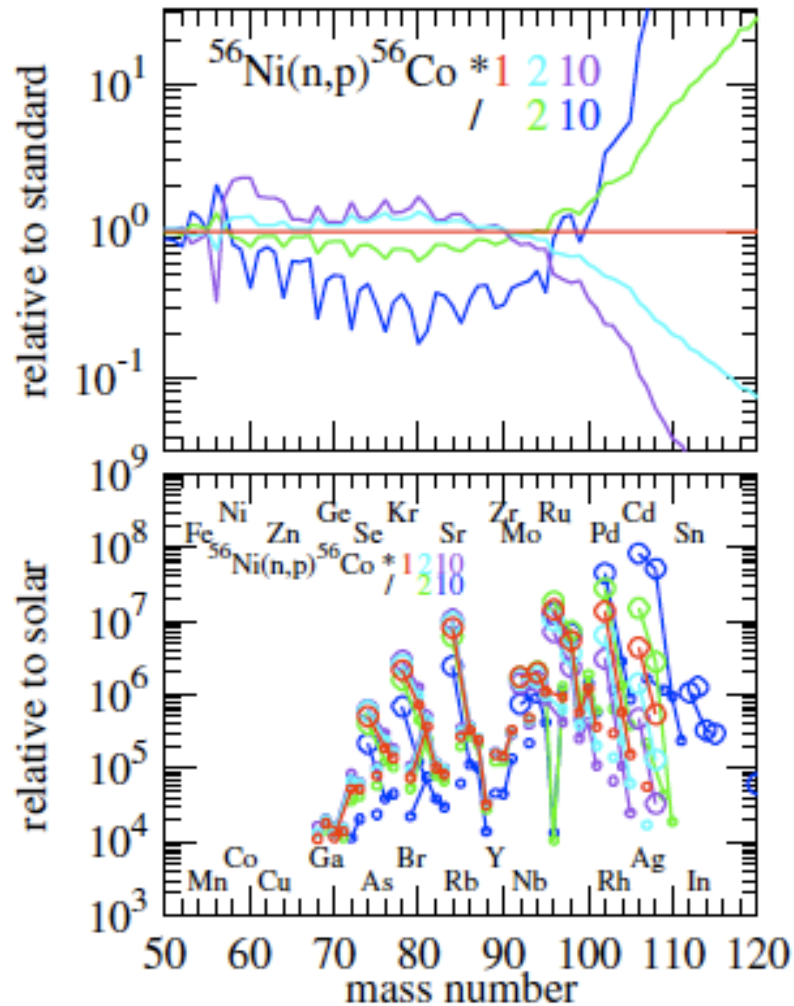
- ^{252}Cf fission fragments
- 10 MeV/u beam energy
- 108 Germanium detectors
- Recoil selection by FMA

(n,p) reactions & νp process

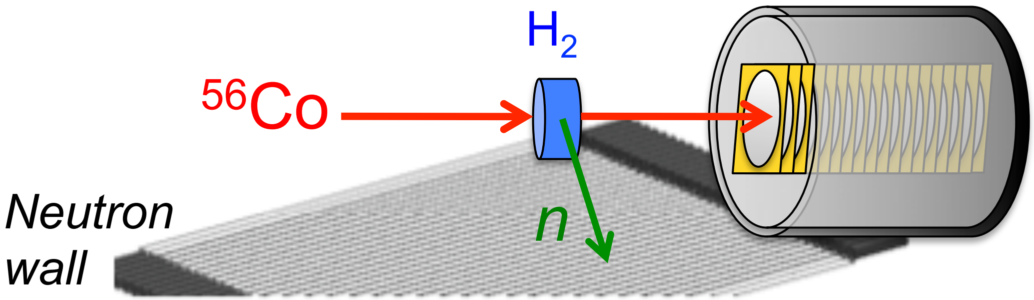
Wanajo, Janka, Kubono, APJ **729** (2011)

- But maybe LEPP is proton-rich!
  - →νp process [Fröhlich *et al*., PRC **96** (2006)]
- (n,p) rates are very important
  - → ^{56}Ni, ^{64}Ge, ^{86}Se, . . .

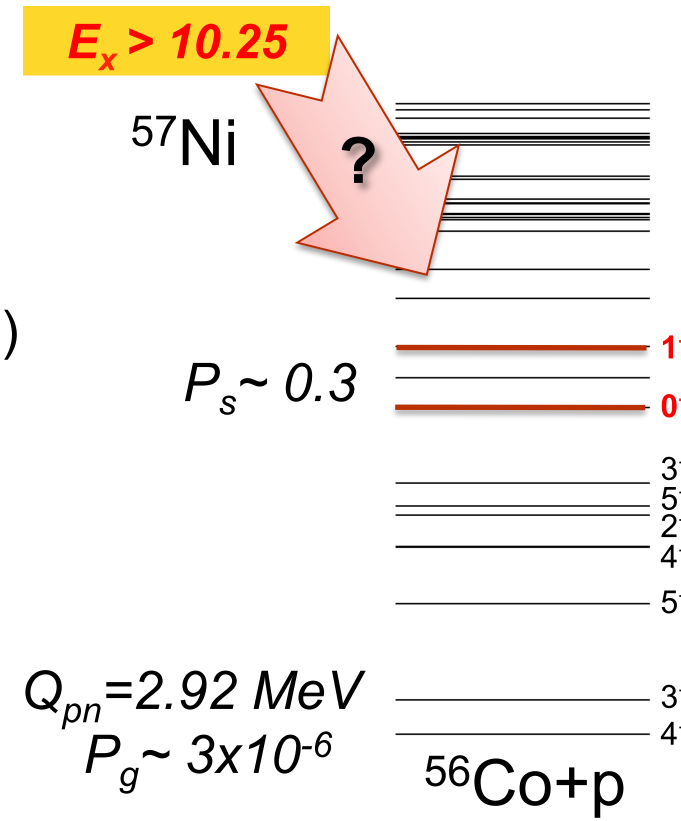




Measure (p,n) as inverse to (n,p)?



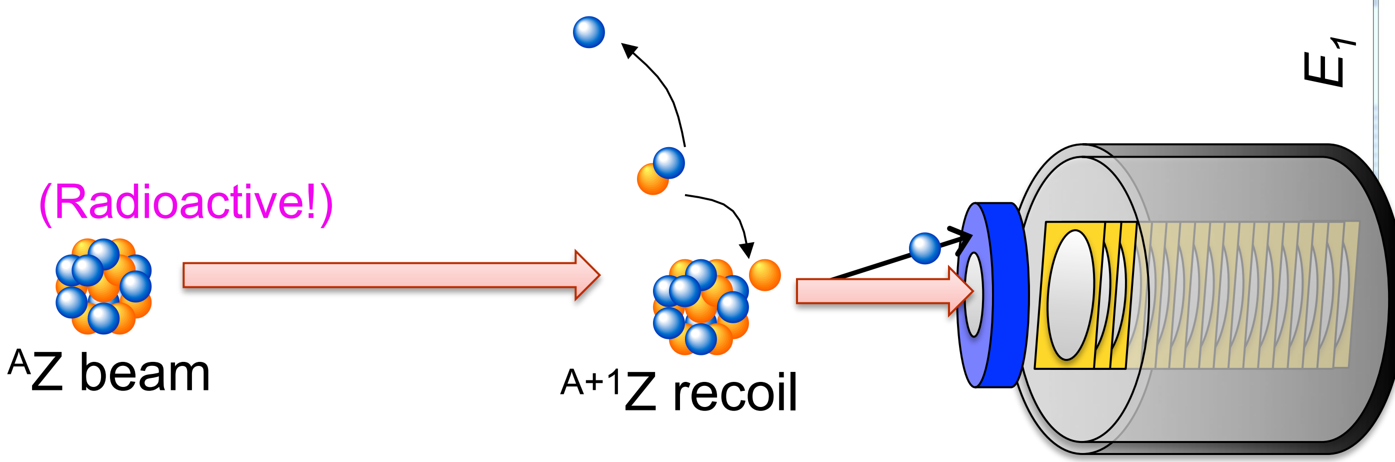
BUT

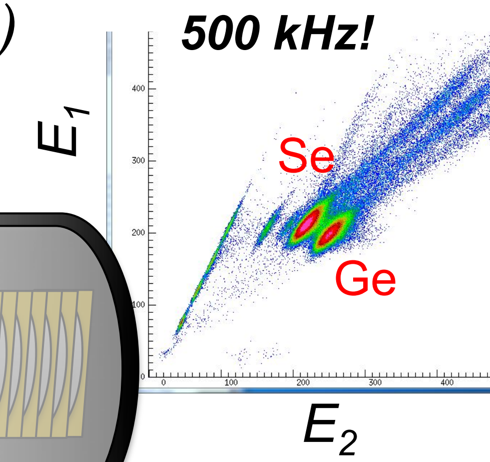


- Advantages:
  - → Higher beam intensities (~5x at ReA3)
  - → Higher beam energies
  - → Proton targets are easy
- Disadvantage
  - → Low energy neutron detection
- Similar situation with ^{68}Se . . .
  - → Might work for ^{64}Ge ?

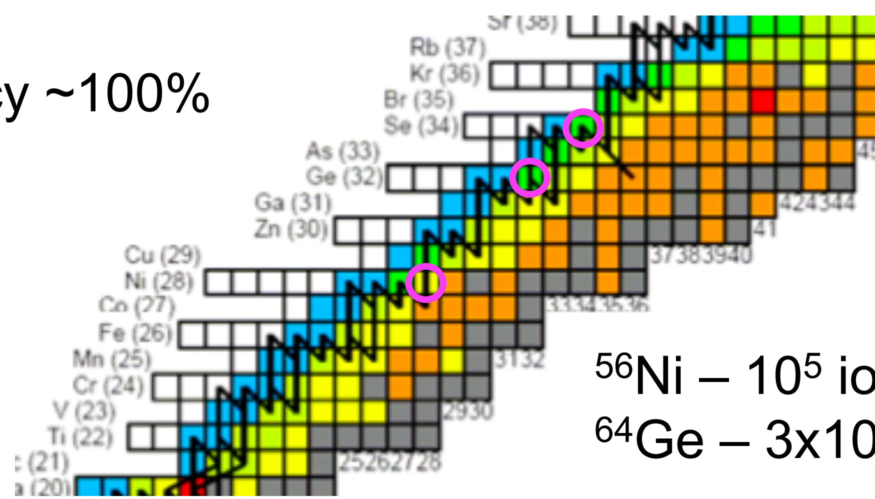
More general approach: (d,2p)

$^{56}\text{Ni} + d \rightarrow \mathbf{p} + {}^{57}Ni^{*} \rightarrow \mathbf{p} + {}^{56}Co\ (+\gamma)$





- Possible at ReA3 at NSCL?
  - → Proton detection efficiency ~100%
  - → First beams in 2012
- Issues?
  - → $\theta_{lab}(^{56}Co+p) < 27^{\circ}\ (0^{+})$
  - → High E_x will be challenging



^{56}Ni – 10^5 ions/s

^{64}Ge – $3\text{x}10^4$ ions/s

Summary

- Neutron reactions on unstable nuclei are likely important for the synthesis of heavy nuclei
  - →Can not be directly measured except for long-lived cases
- Hauser-Feshbach reaction rates are not always highly reliable
- Indirect approaches can improve the reliability of neutron rates

  Need:
  - →Improved radioactive beams
  - →Efficient gamma detection
  - →Theoretical support

- Many thanks to U.S. DOE, the Livermore group and my collaborators, especially: G. Arbanas, J.A. Cizewski, K.L. Jones, R.L. Kozub, M. Matoš, and S.D. Pain

- Congratulations to John Cowan
  - →Thanks for so many inspiring contributions to the field