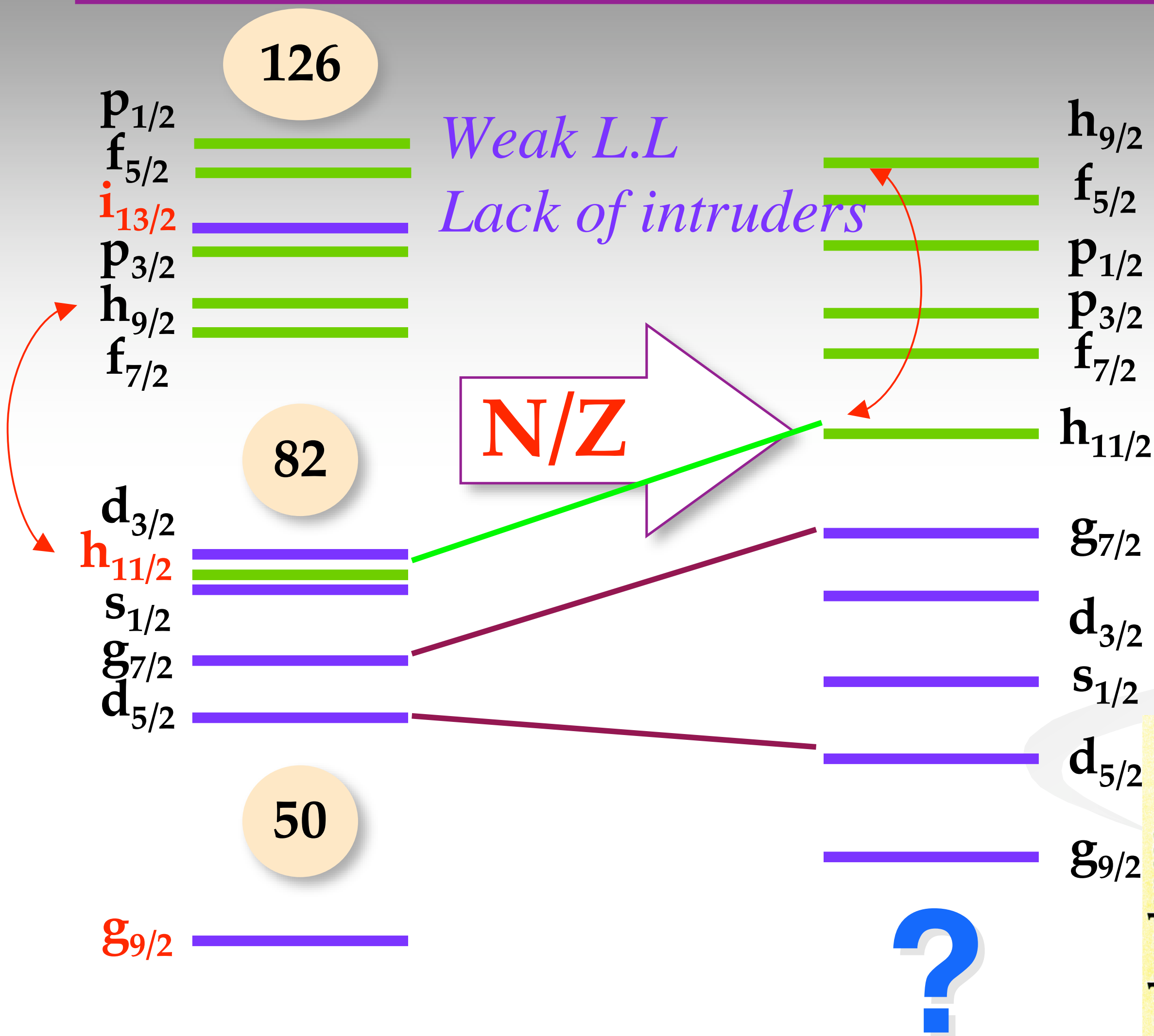
(Selected) Nuclear Structure Studies with Radioactive Ion Beam at HRIBF

Cyrus Baktash
Oak Ridge National Laboratory

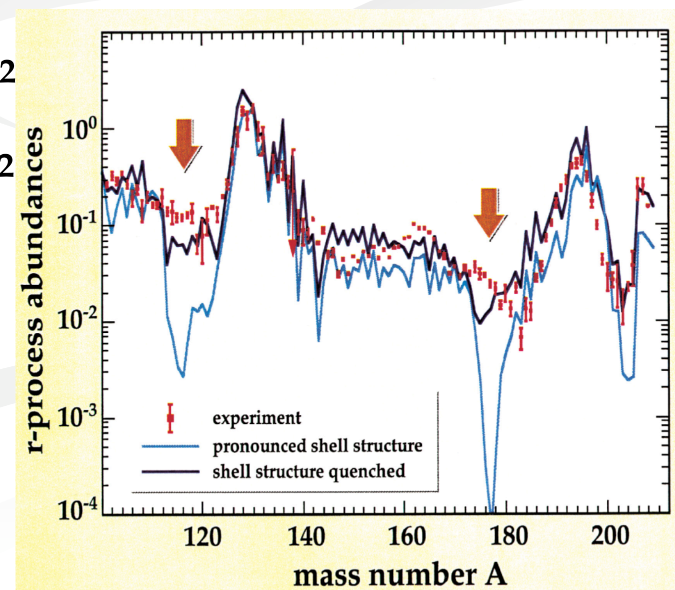
USNDP Meeting, BNL, November 2006

Modification of shell structure near neutron drip line



Questions:

- **What is the shell structure near neutron drip line?**
- **How to experimentally determine quenching of the old or emergence of the new magic numbers?**



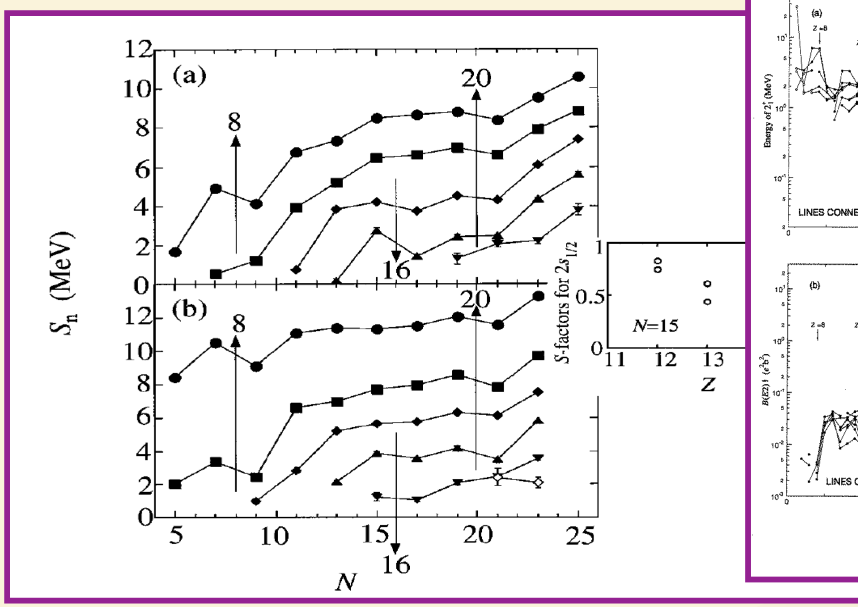
Around the valley of nuclear stability
N/Z ≈ 1 - 1.6

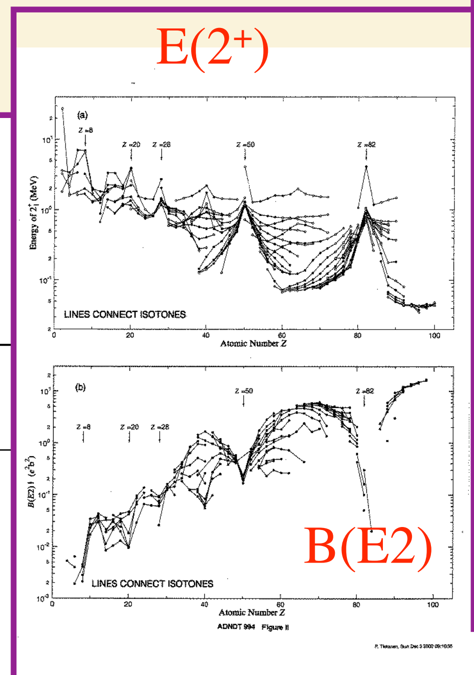
Neutron-rich nuclei
N/Z ≈ 3

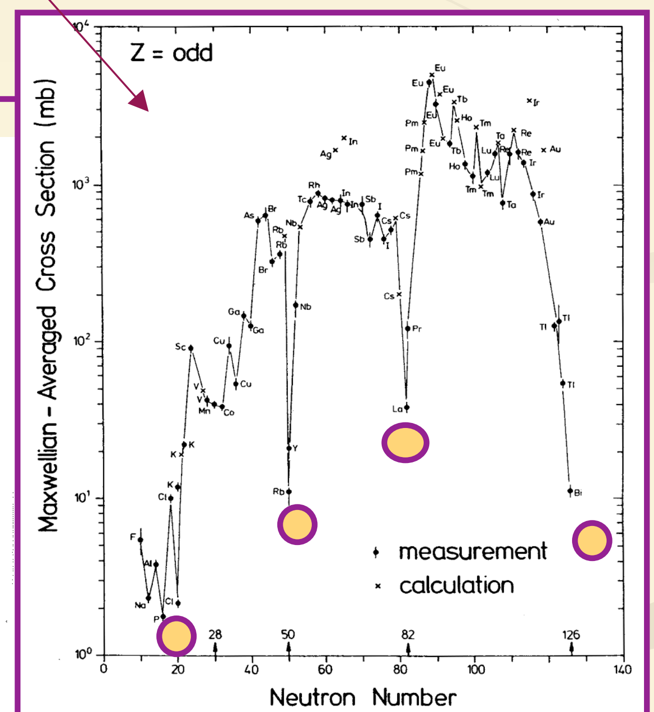
Signatures of large shell gaps & magic numbers

***Combinations of*:**

- **Kinks in *1n* and *2n* separation energies**
- **Large E(2$^+$) and small B(E2) -- signature of rigid spheres**
- **Small σ(n,γ) (peaks in element abundances)**
- **Kinks in single-particle energies**
- **Kinks in radii**







Ozawa *et al.*, Phys. Rev. Lett. 84 (2000) 5493

Measurements to probe shell structure far from stability

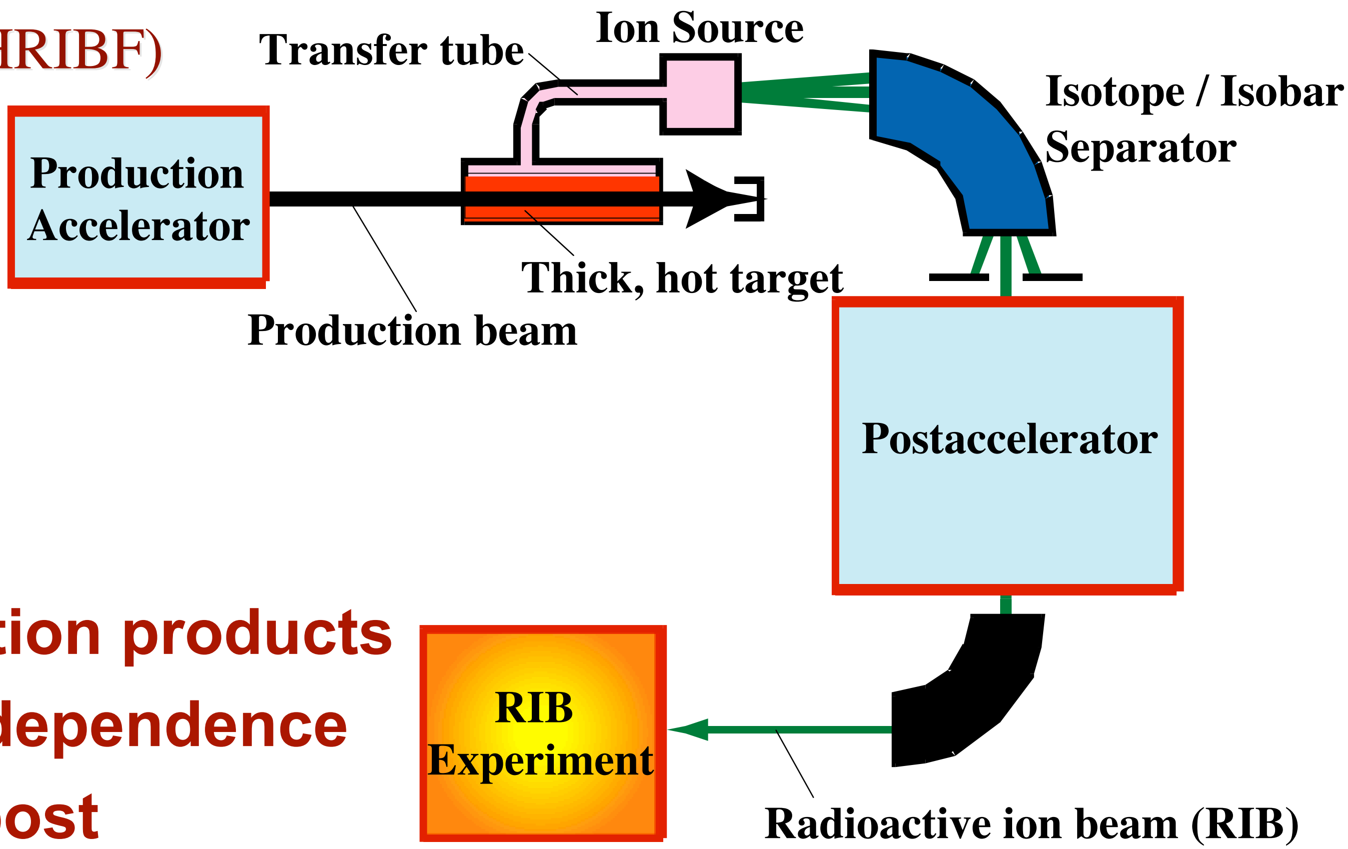
- **Gross properties:**
  - **Masses (binding energies)**
  - **Half lives**
  - **Radii**
  - **Level densities**
  - **$\sigma(n,\gamma)$ -- related to r-process abundances, [use (*d,p*)]**
- **Single-particle properties:**
  - **Energy, spin, parity, spectroscopic factors, g-factors**
  - **Parallel momenta in knock out reactions (fast beams)**
- **Collective properties:**
  - **Low-lying energy spectra (*e.g.,* 2^+ states, 4^+)**
  - **B(E2) & electromagnetic moments**
  - **Higher spin states (band structures)**

To measure & interpret these observables we need 3 pillars:

- **Radioactive ion beams (intense; pure; up to ~7 MeV/u)**
- **Powerful detectors, new experimental techniques, novel targets**
- **Theory to interpret the data and to guide future measurement**

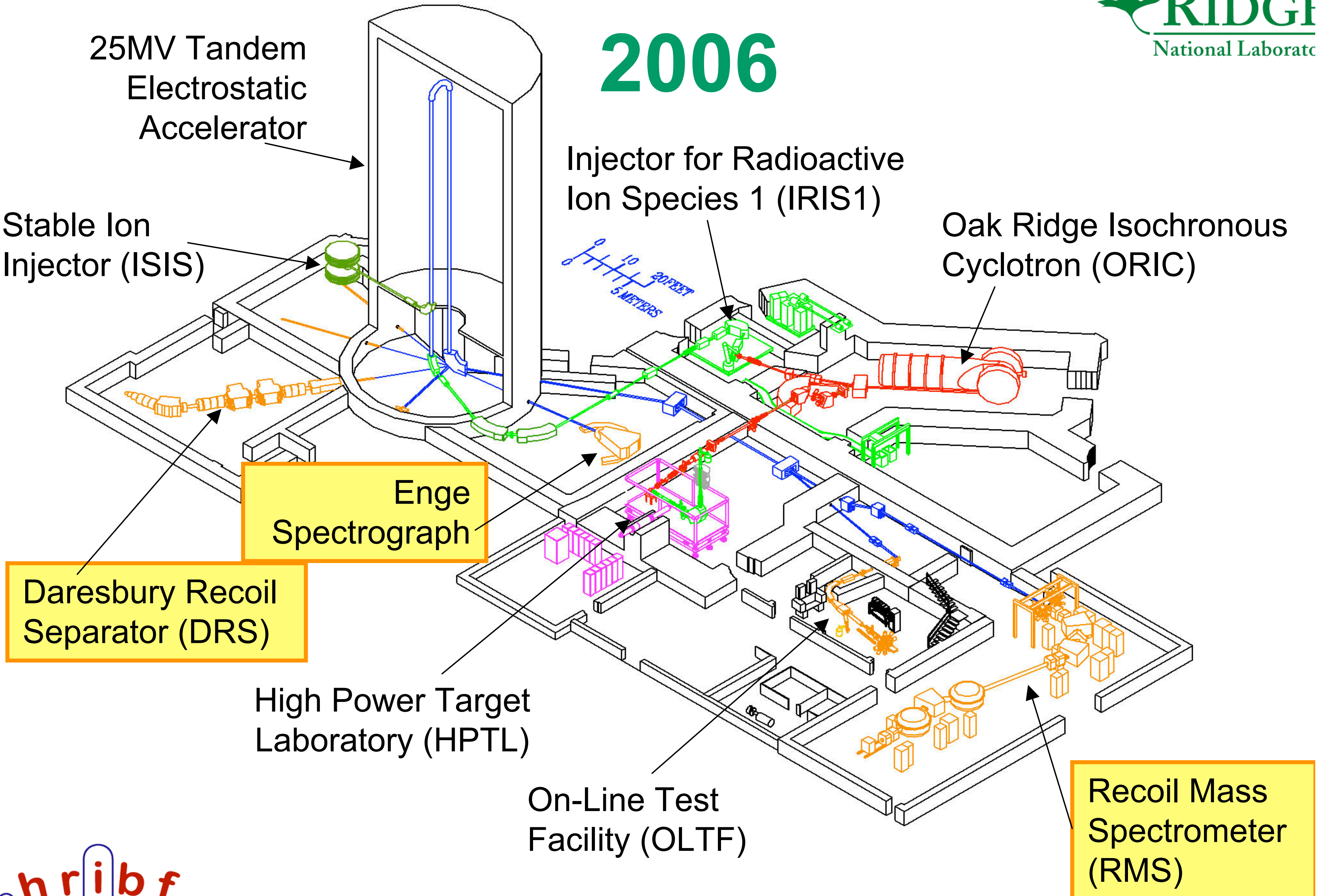
The Ion Source On Line Method

Light ions (ISOLDE, HRIBF)
Heavy ions (SPIRAL)
Electrons (ORSAY)



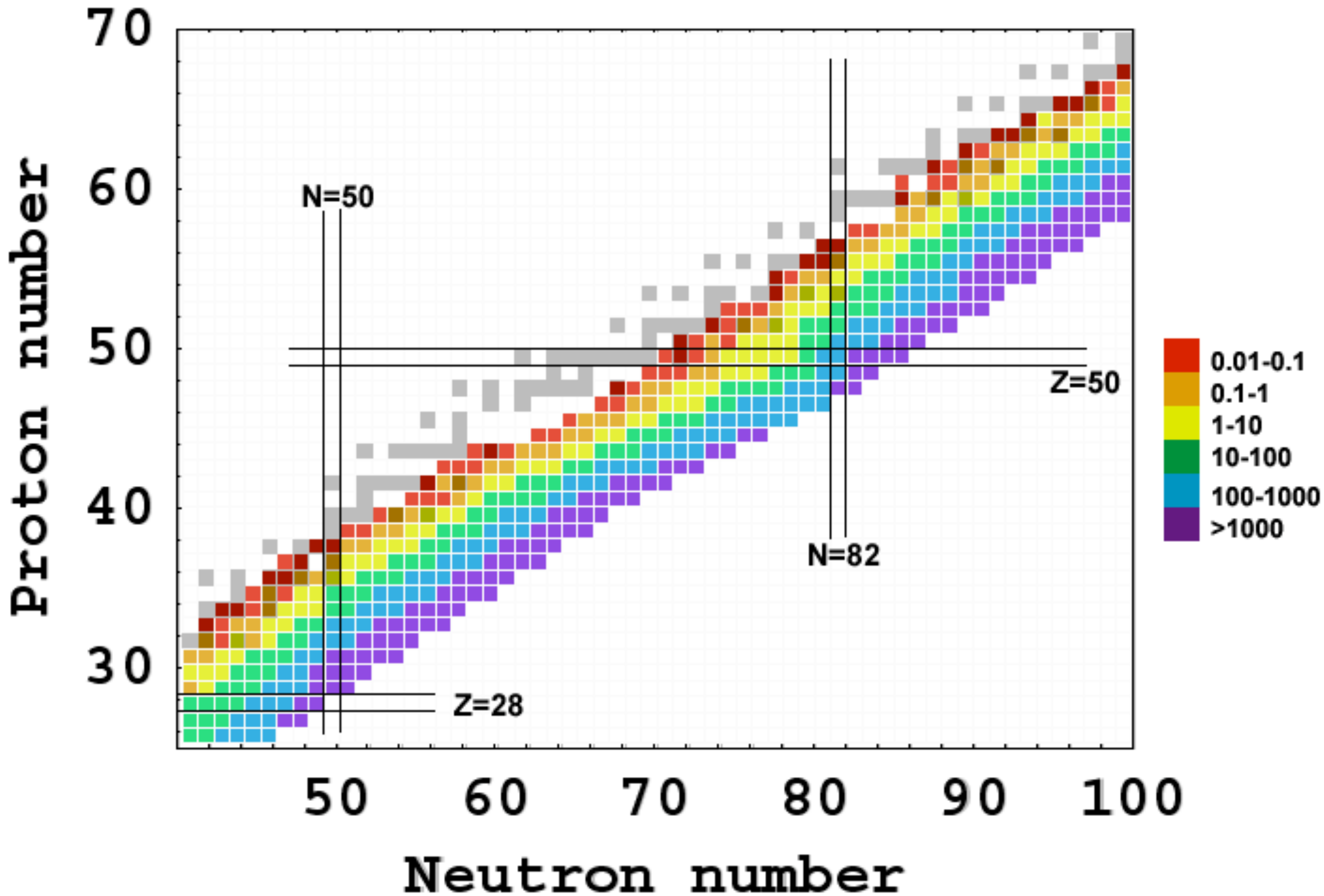
- Thick targets
- Stopped reaction products
- “Chemistry” dependence
- High quality post accelerated RIB beam

HRIBF 2006



25MV Tandem Electrostatic Accelerator
Stable Ion Injector (ISIS)
Injector for Radioactive Ion Species 1 (IRIS1)
Oak Ridge Isochronous Cyclotron (ORIC)
20 FEET
5 METERS
Enge Spectrograph
Daresbury Recoil Separator (DRS)
High Power Target Laboratory (HPTL)
On-Line Test Facility (OLTF)
Recoil Mass Spectrometer (RMS)

Photofission at HRIBF



$$\frac{10^{13}\ \text{ph-f/s}}{10\ \mu\text{A}\ 40\ \text{MeV p}}$$

Broad Outline of Research Programs

- ***Nuclear Structure (Coulex, transfer reactions, incomplete fusion, g-factors, decay studies)***

- ***Reaction Dynamics (sub-barrier fusion, break up, inverse fission)***

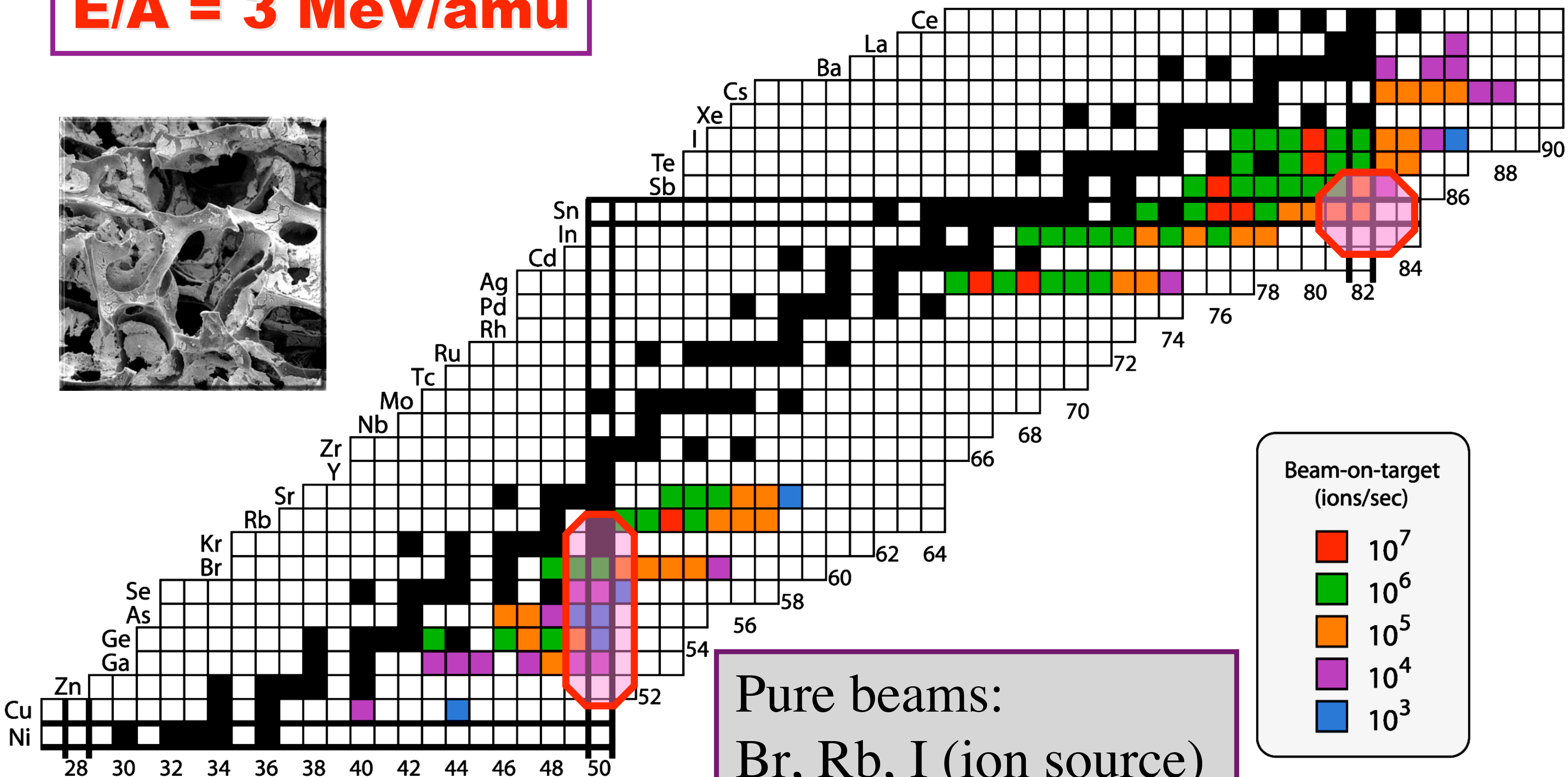
- ***Nuclear Astrophysics (rp-process using p-rich RIBs -- capture, resonance)***

HRIBF annually provides nearly 1500 hr RIBs and 2500 hr stable beams to users from the US and abroad

Accelerated Neutron-rich Radioactive Ion Beams

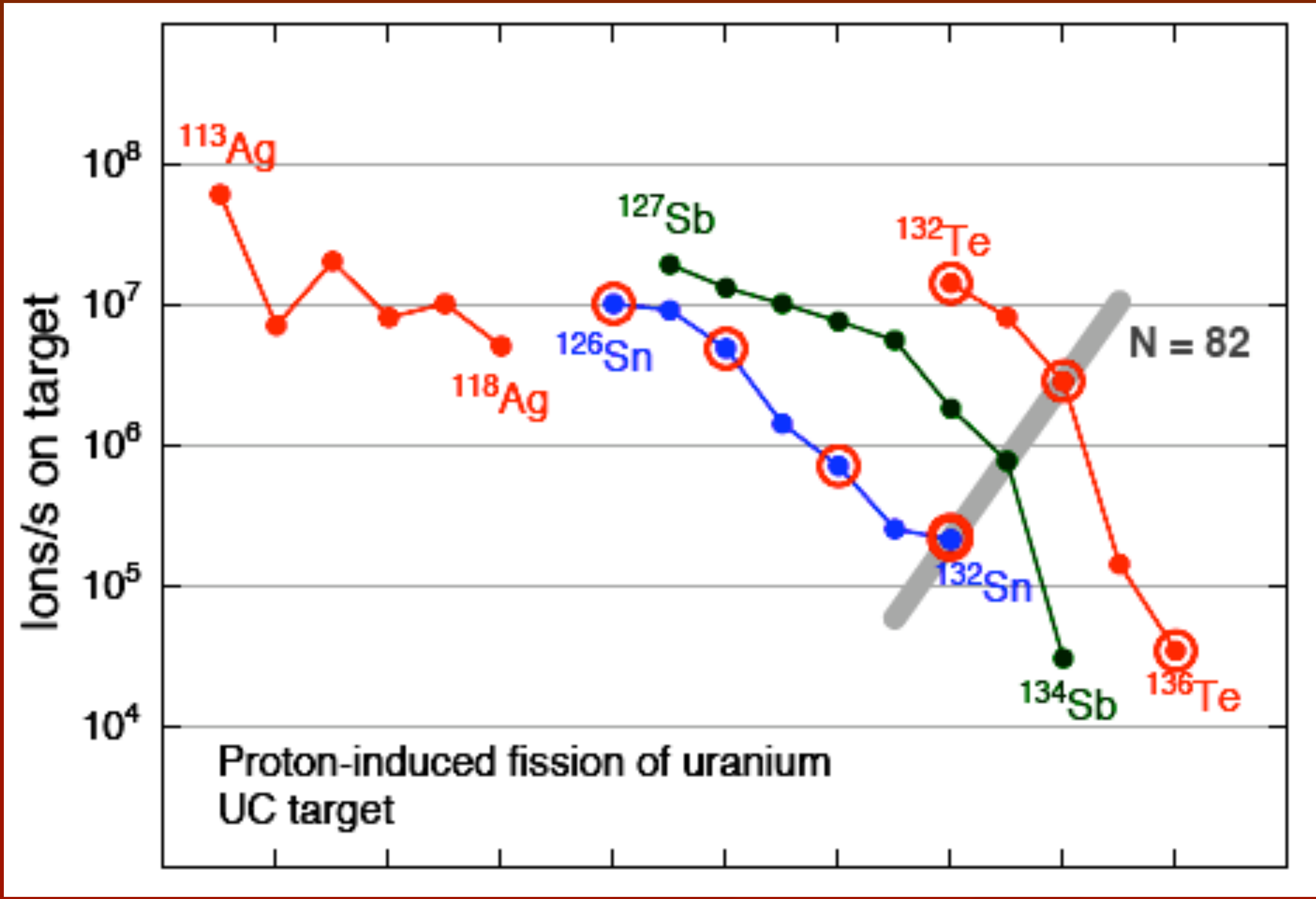
(over 100 beams with intensities ≥10^3 ions/sec)

E/A = 3 MeV/amu



Pure beams:
Br, Rb, I (ion source)
Ge, Sn (molecules)

Intensities of Accelerated Beams in Sn Region



Experimental Challenges With RIBs

- **Experiments with radioactive ion beams are very challenging**
  - » **RIBs have low intensities**
    (typically 4 to 7 orders of magnitude less than SIBs)
  - » **High β & γ background due to the decay of RIBs**
  - » **Isobaric beam contamination**

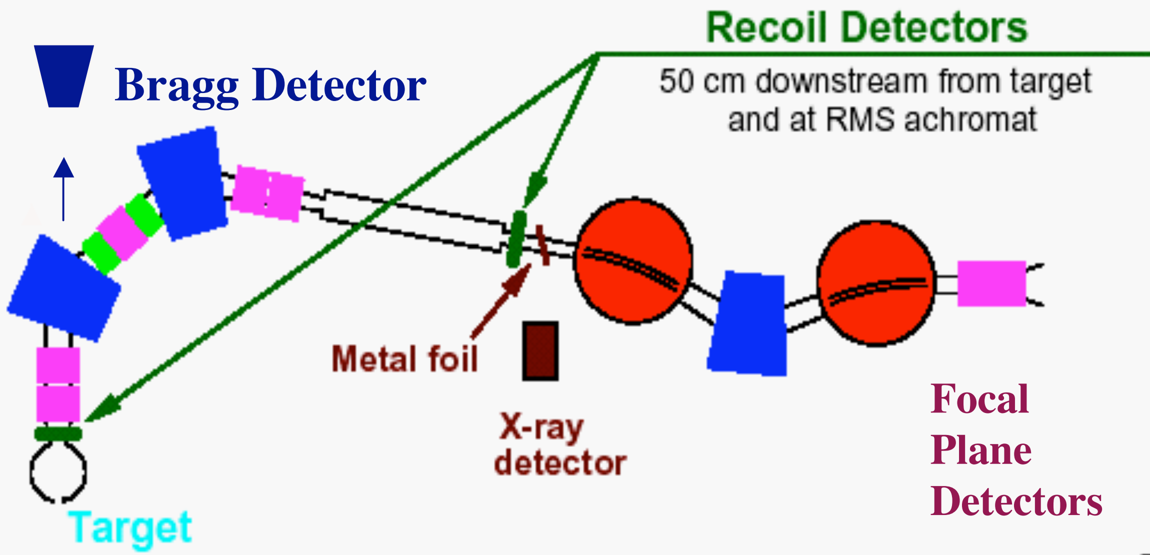
- **How to cope with these problems?**
  - » **Low intensity: Maximize detection efficiencies of all subsystems**
  - » **High background: Require coincidences between two or more detectors**
    - γ rays, charged particles, beam particles, recoils, recoil decays
  - » **Isobaric contamination: Identify Z**
    - Charged particles, x-ray, Bragg detector, ionization chamber, ΔE-E

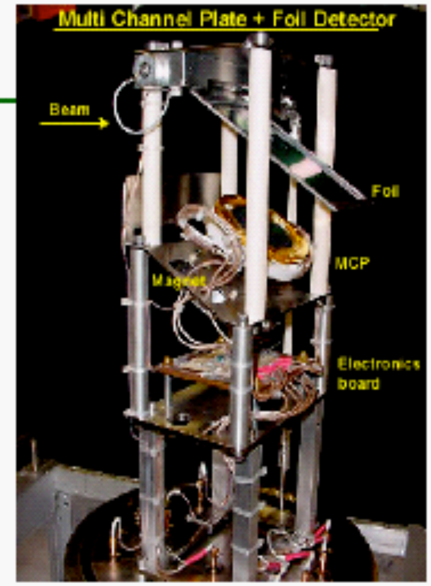
- ***Nearly all RIB reactions are done in inverse kinematics***
  - **Kinematic focusing - reaction products are forward peaked**
  - **Large Doppler shifts**
  - **Need highly segmented detectors (for both γ & charged particles)**

Experiments are very challenging & require new tools & techniques

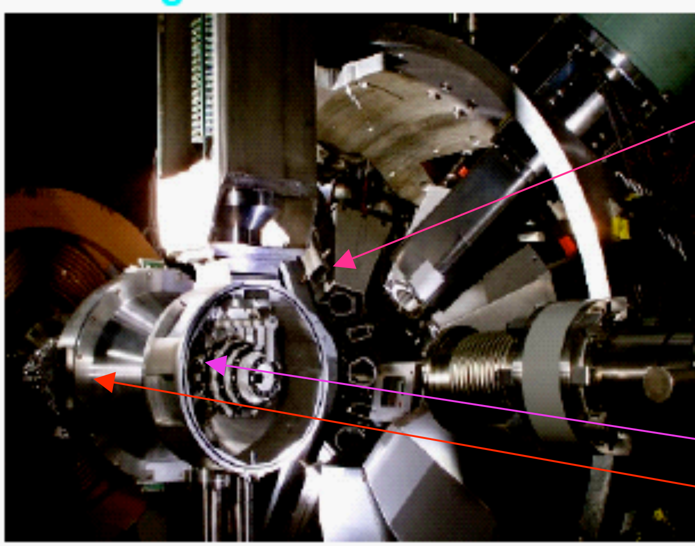
CHARMS (Clarion-HyBall Array, and RMS)

Specifically designed for γ spectroscopy with RIBs





Foil plus multichannel plate



Neutron detectors

CLARION

11 segmented clover Ge detectors

10 smaller Ge detectors

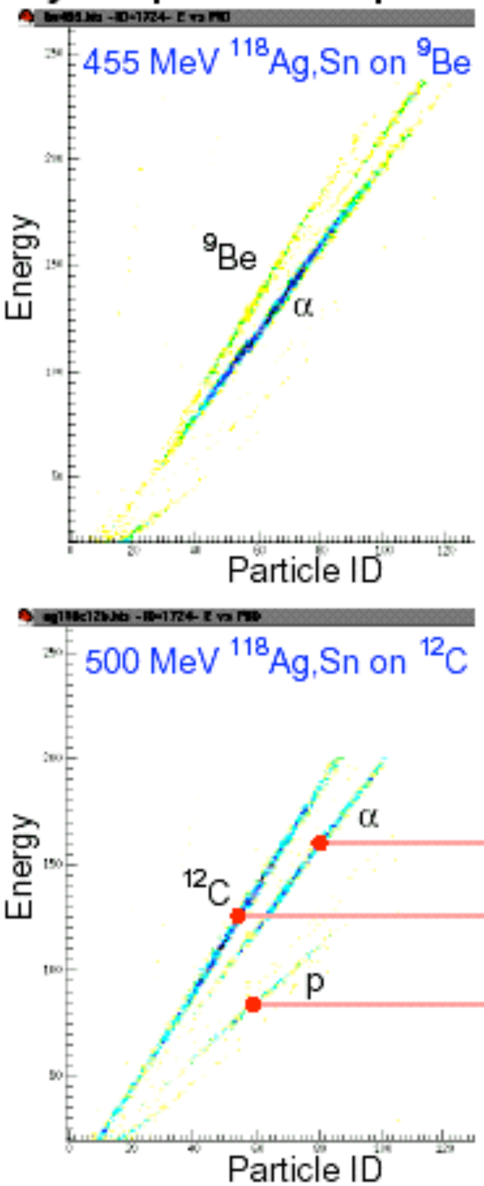
HyBall

95 CsI detectors with photodiodes

Forward array of DSSD, ΔE-E & "fan tail"

Reaction tagging by charged particles

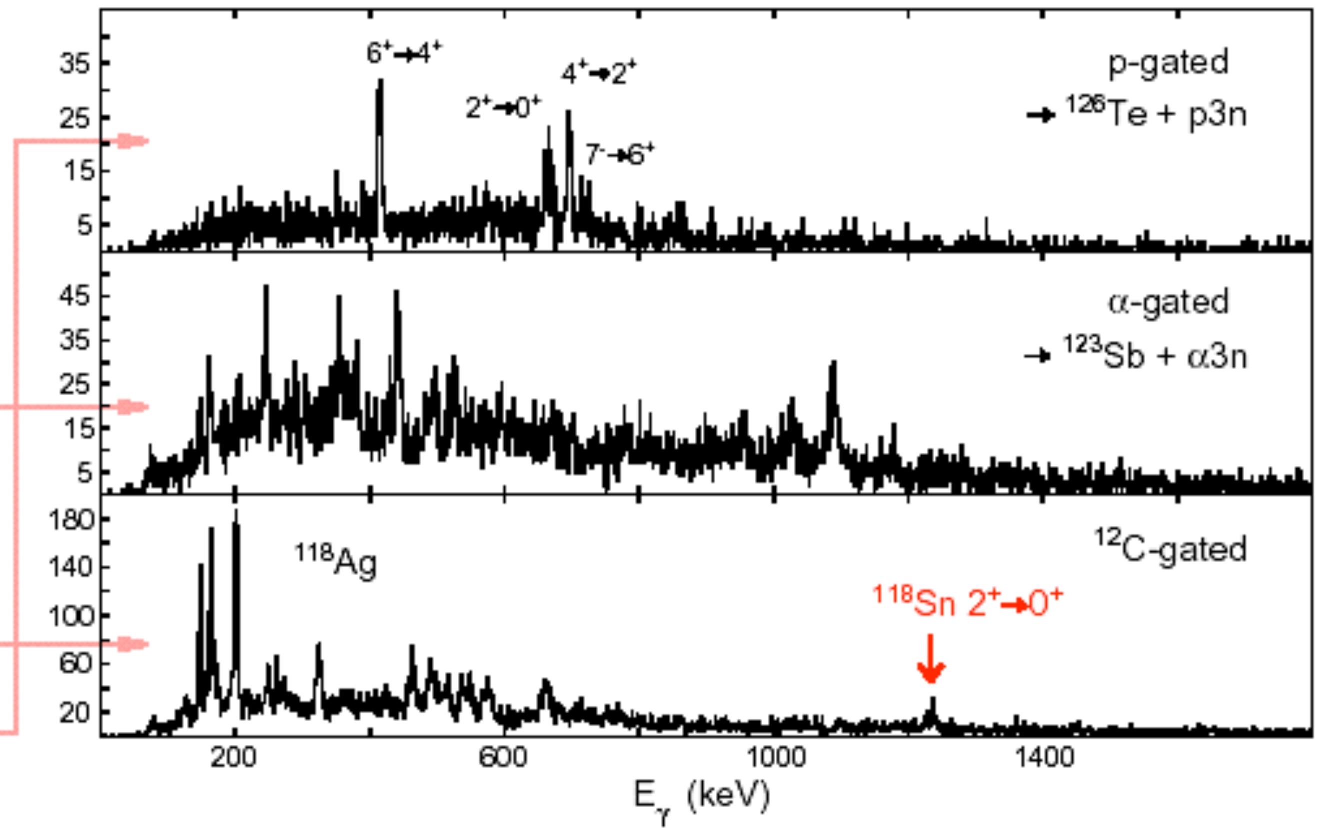
HyBall particle ID spectra:



^{118}Ag on Be and C targets

Small ^{118}Sn component of beam (~10%)

Gammas gated by charged particles:

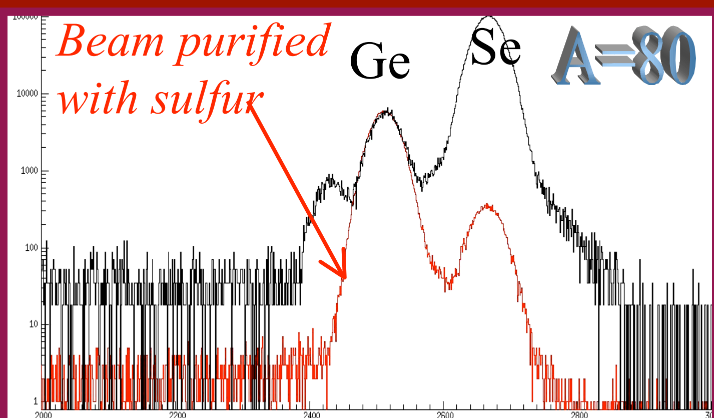


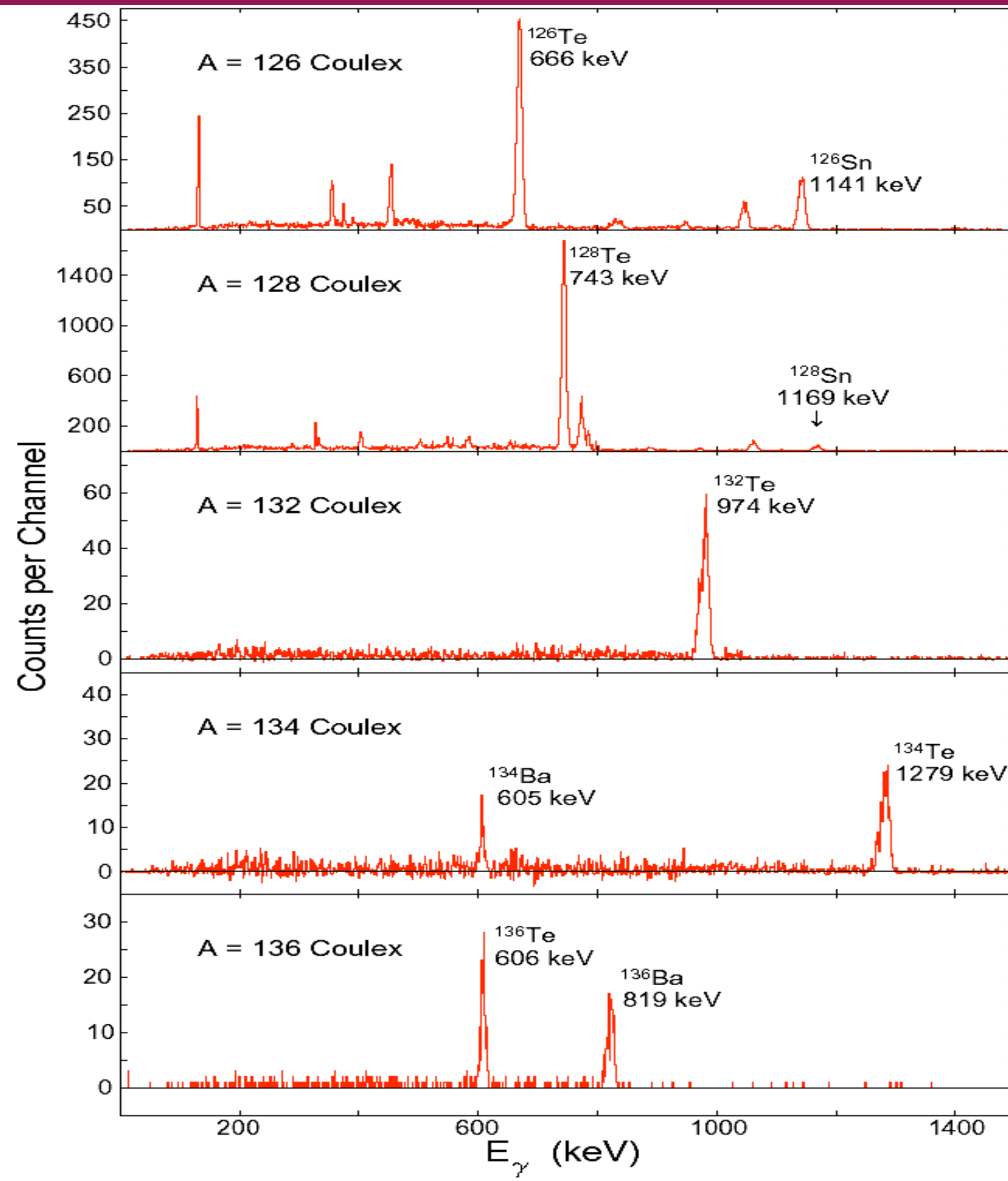
Coulex Studies in the ^{132}Sn Region (with HyBall & CLARION)

Isobaric impurity assessment is very important.

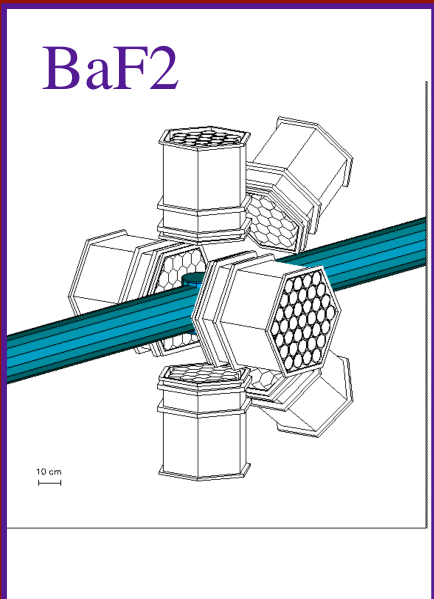
We now use a Bragg curve detector to continuously monitor the beam composition

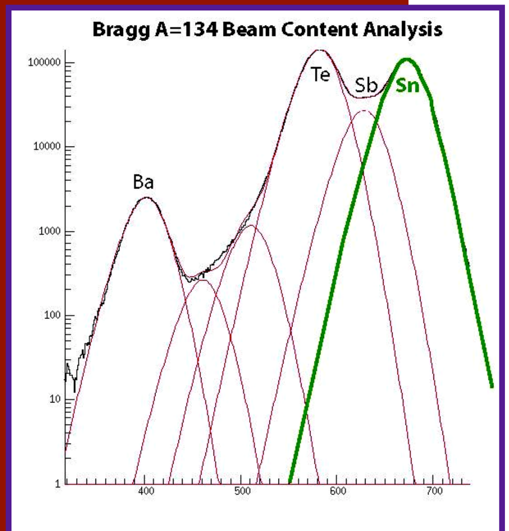
Bragg spectrum purified Ge

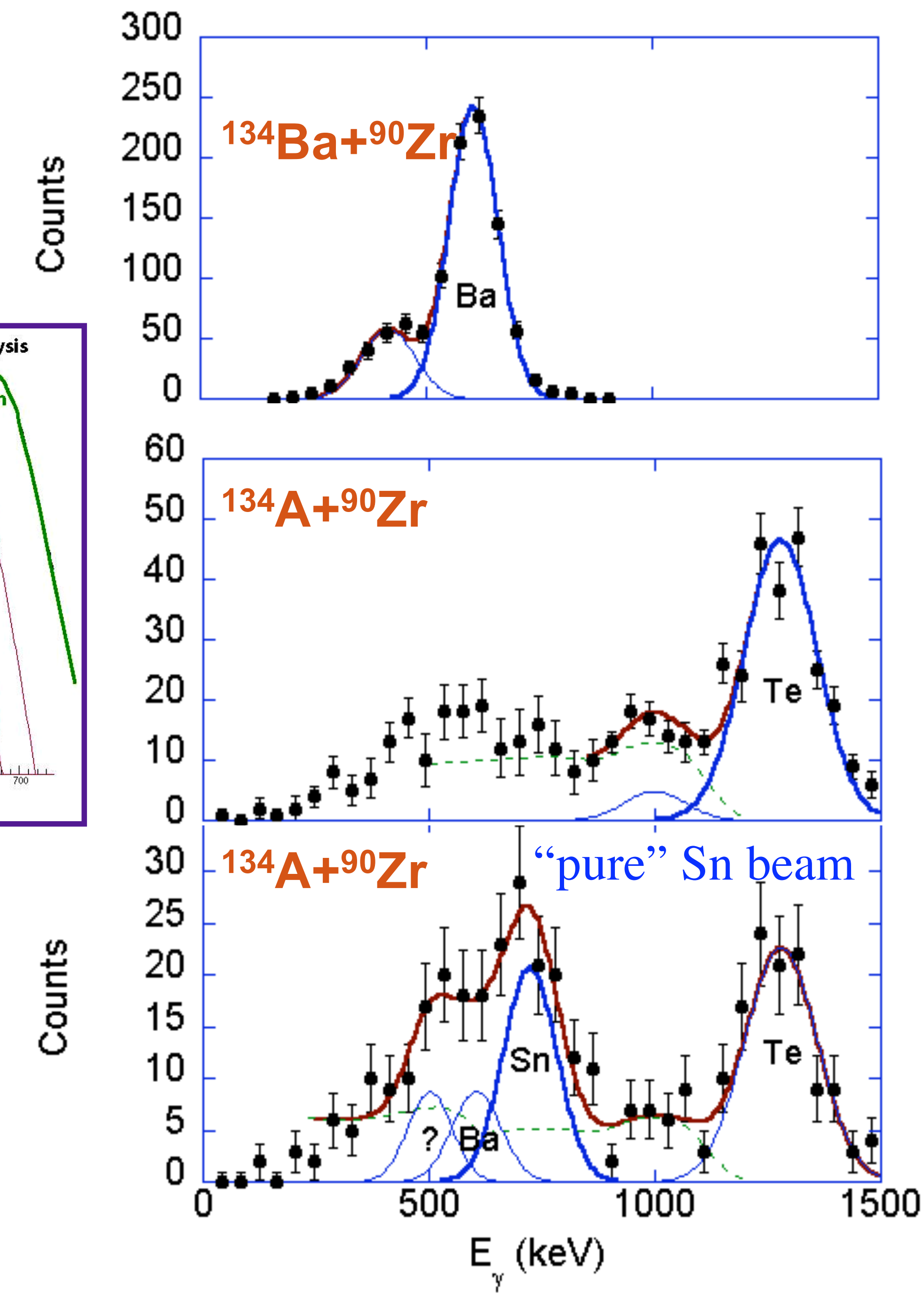




^{134}Sn Coulex





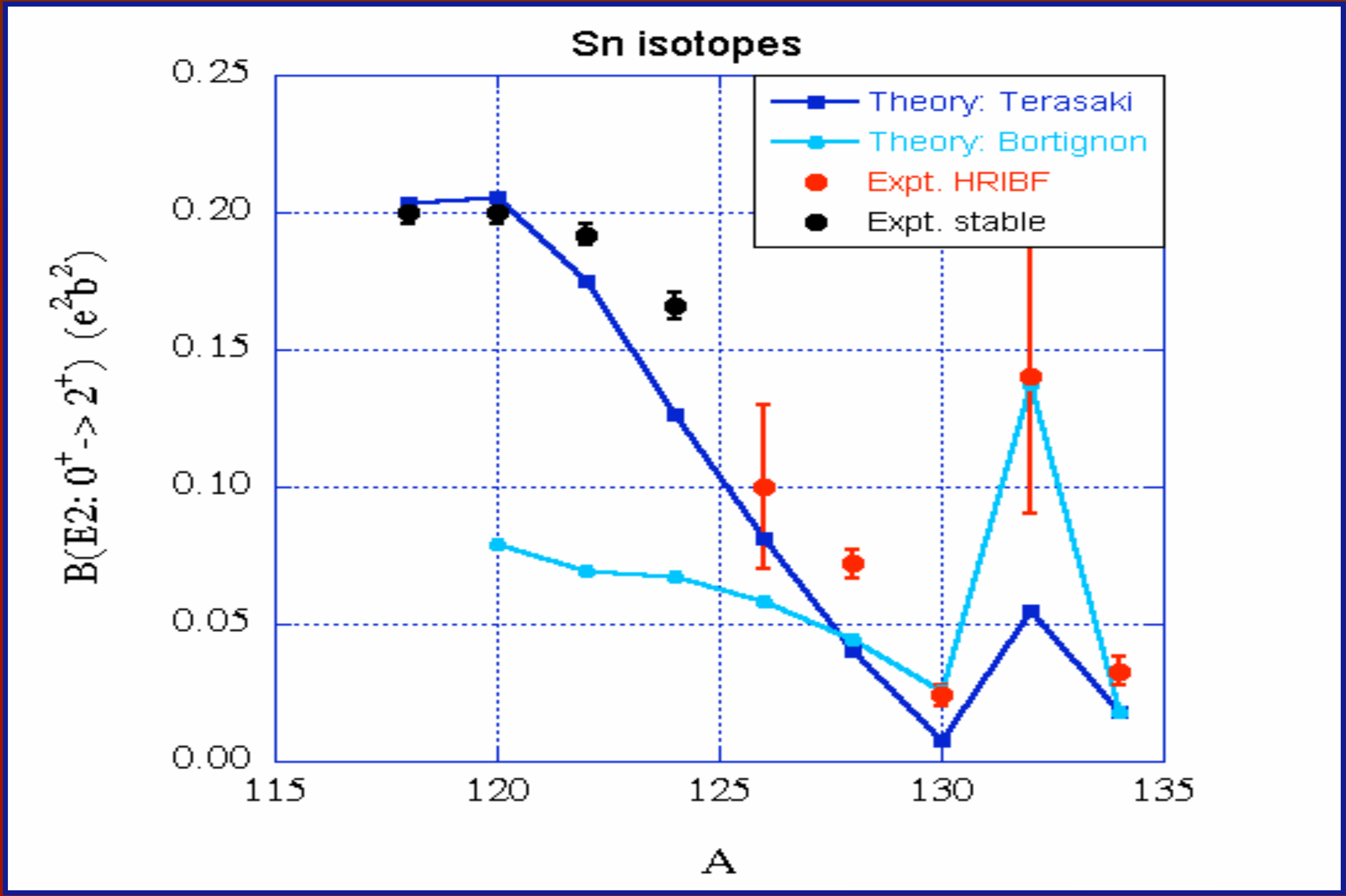


- ^{132}Sn: B(E2)= 0.14(6) e^2b^2
  –15% L=2, T=0 EWSR
- ^{134}Sn: B(E2)=0.029(5) e^2b^2
- ^{134}Te: B(E2)=0.106(10) e^2b^2

Effective π & ν charges!

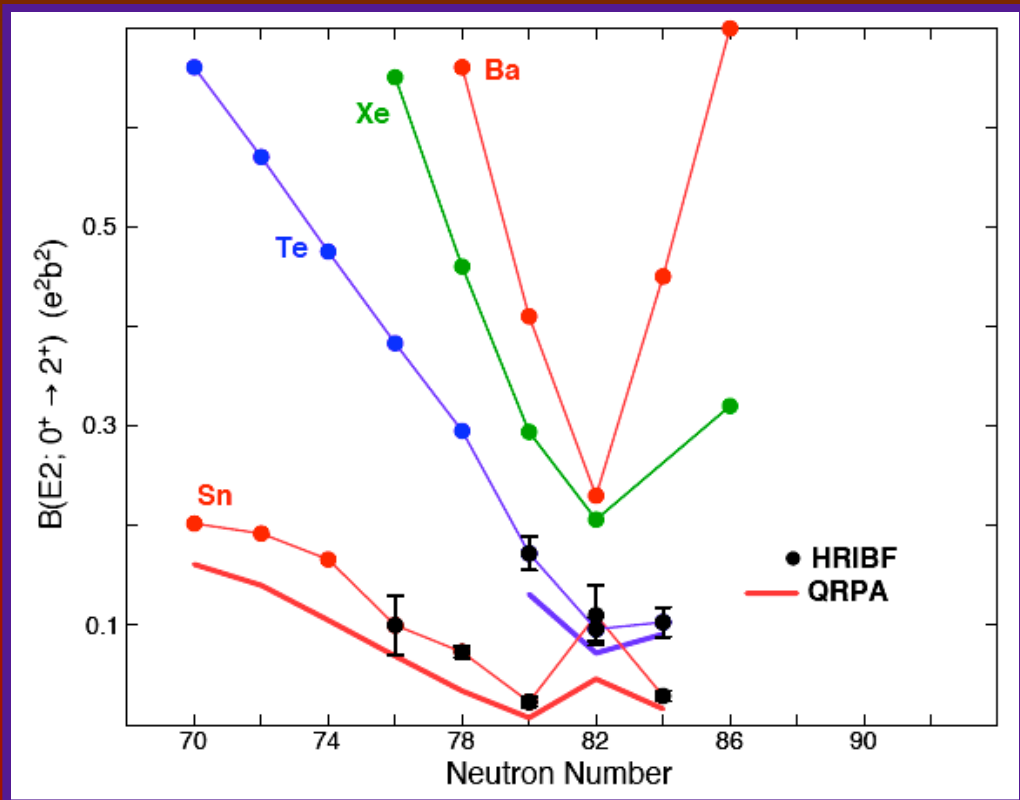
Varner, Beene, et al.

Coulex of ^{132,134}Sn using BaF Array

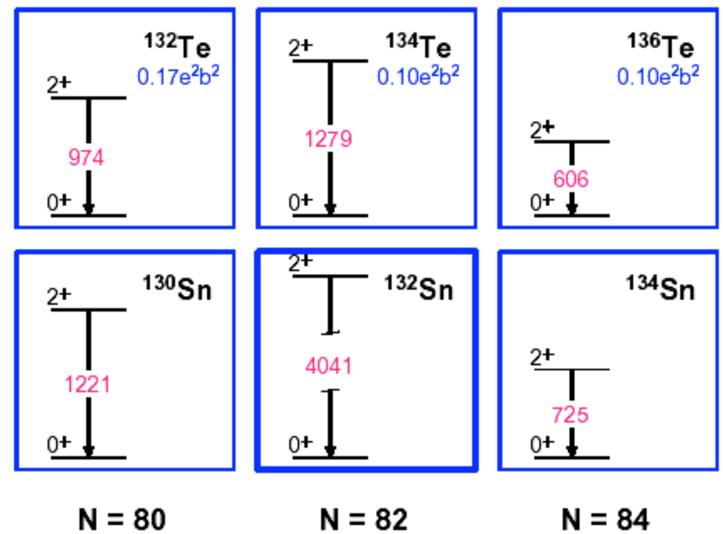


Beene, Varner, *et al.*

Trends of B(E2) for Sn & Te isotopes



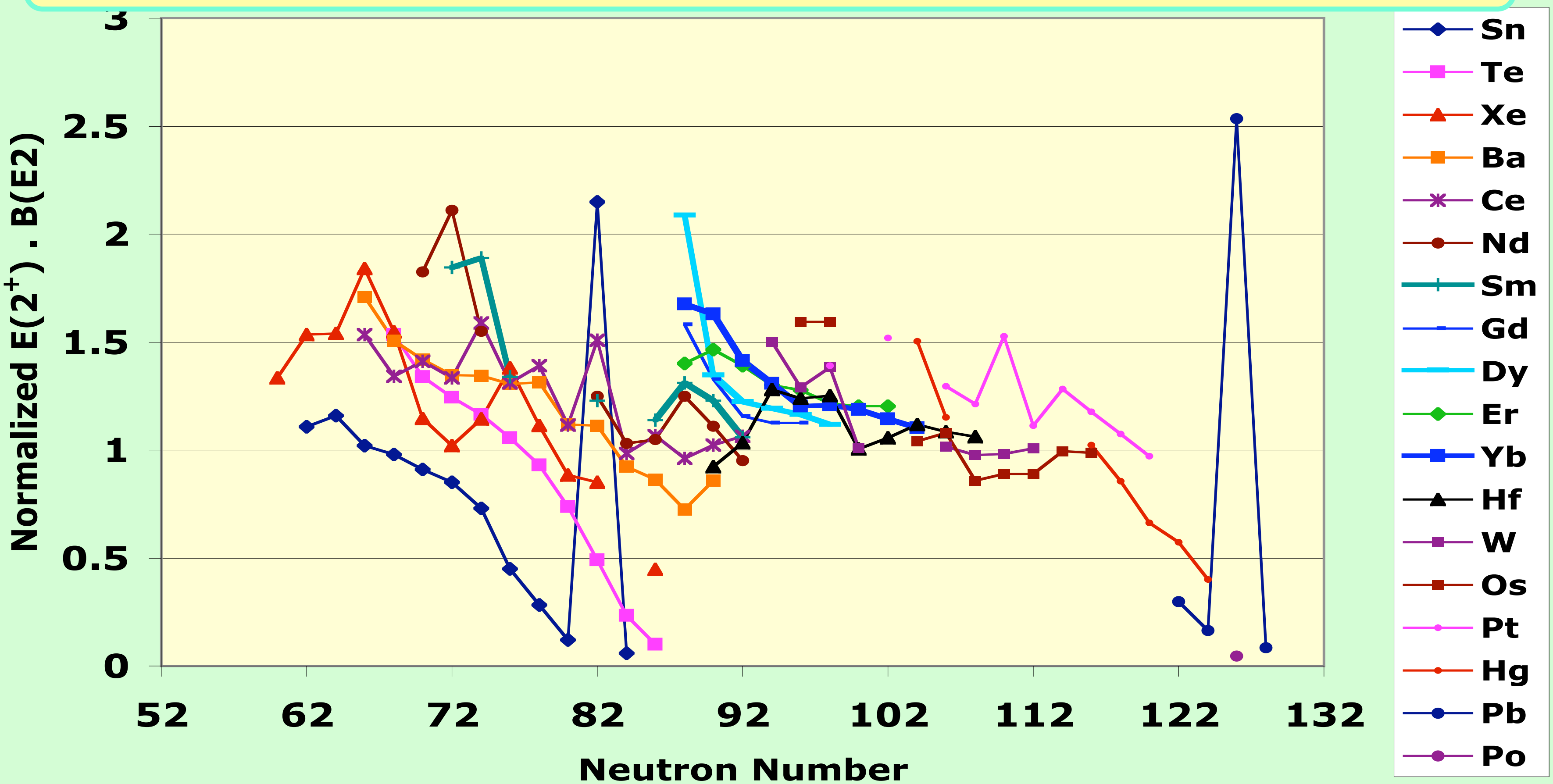
Grodzins-Raman Scaling:
Product of B(E2; 0 -> 2) . E(2$^+$)
~ [2.6 * Z^2/ A$^{2/3}$]



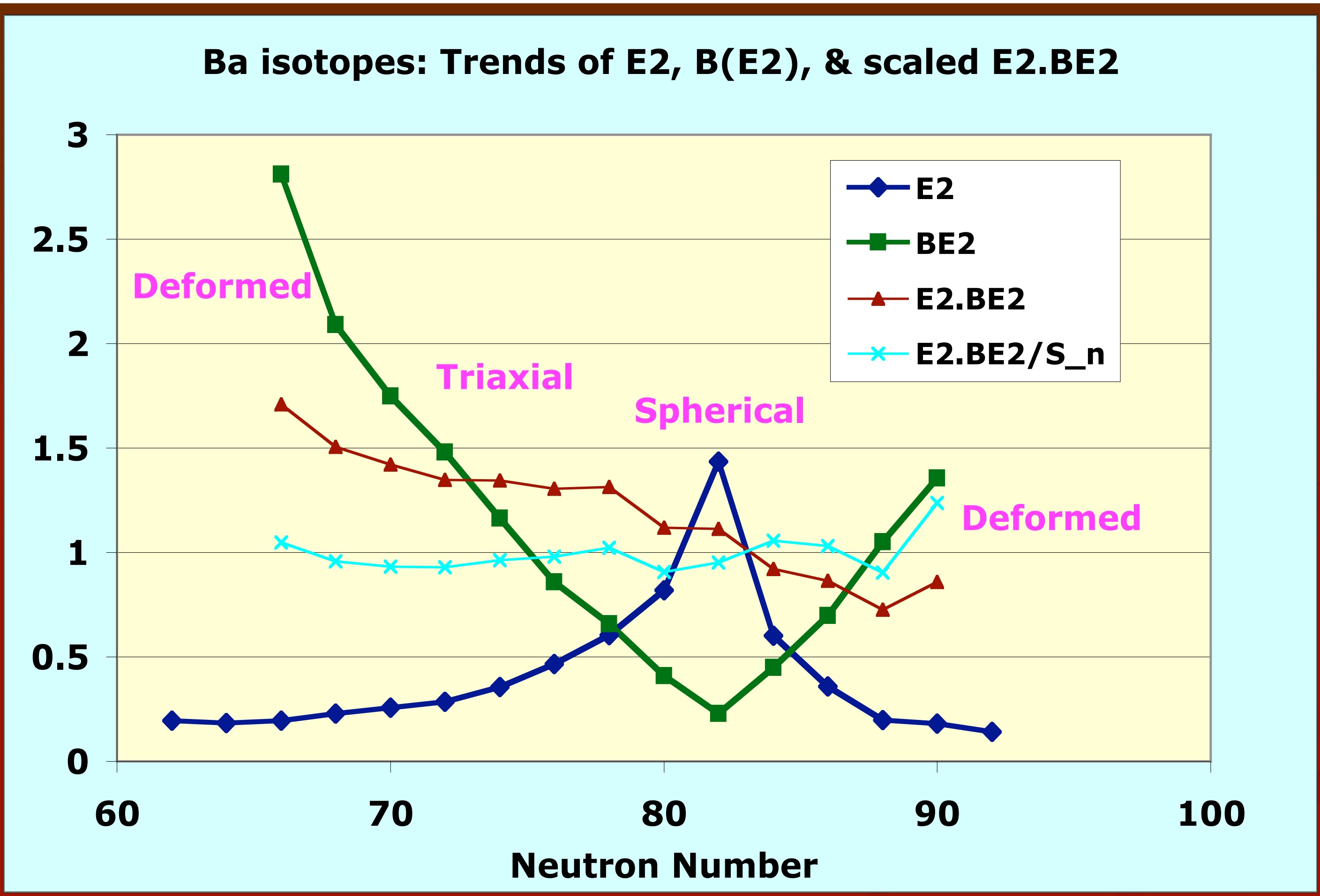
Radford et al., PRL 88, 222501 (2002)

- Surprising low B(E2) for ^{136}Te in the first exp't. This is contrary to Grodzins scaling
- A new measurement indicates 50% higher B(E2), in excellent agreement with Shell Model calculations (Naples & Tokyo)
- Small B(E2) in ^{136}Te attributed to dominance of neutron in the w.f.

Quenching of Quadrupole Strength of 2+ with Increasing *N*



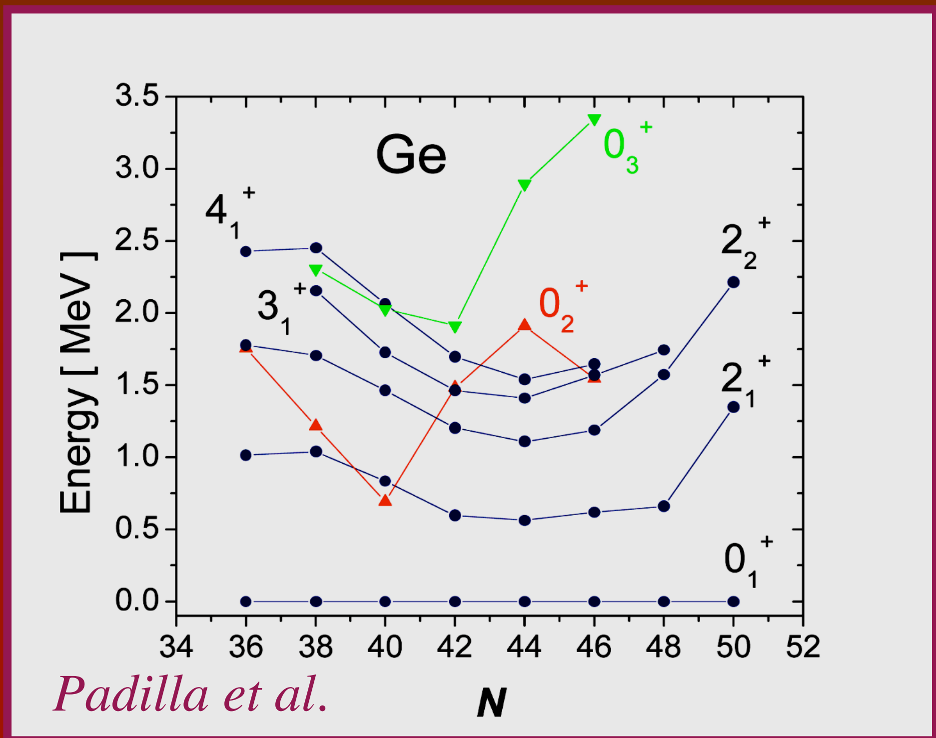
- Grodzins' scaled $E(2^+)$. B(E2) products for isotopic chains are not constant, but steadily decrease with increasing *N*
- Decrease in $E(2^+)$. B(E2) becomes steeper as we approach magic numbers
- The trend persists even across magic numbers & is not correlated with shapes (see Ba isotopes).

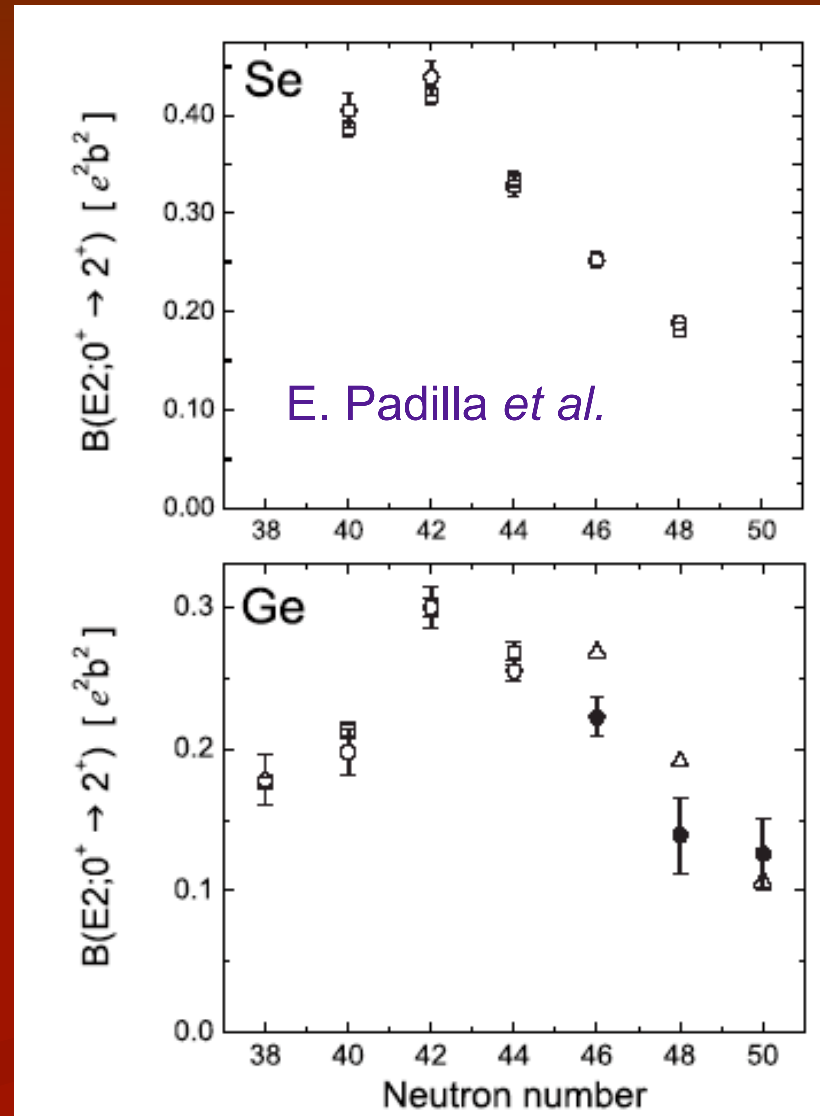


- Decrease in $E(2^+)$ x B(E2) is not usually correlated with shapes
- This indicates that first 2^+ exhausts a smaller fraction of En. Wt. Sum Rule in n-rich nuclei -- Weaker n-pairing increases n-contribution to the w.f. of 2^+
- Proton-dominated states lie at higher energy, contributing more to EWSR
- Division by S_n seems to compensates for this, thus providing a better tool to predict B(E2) from known $E(2^+)$ values

Shapes & Collectivity:

Sensitive tests of models in transitional nuclei



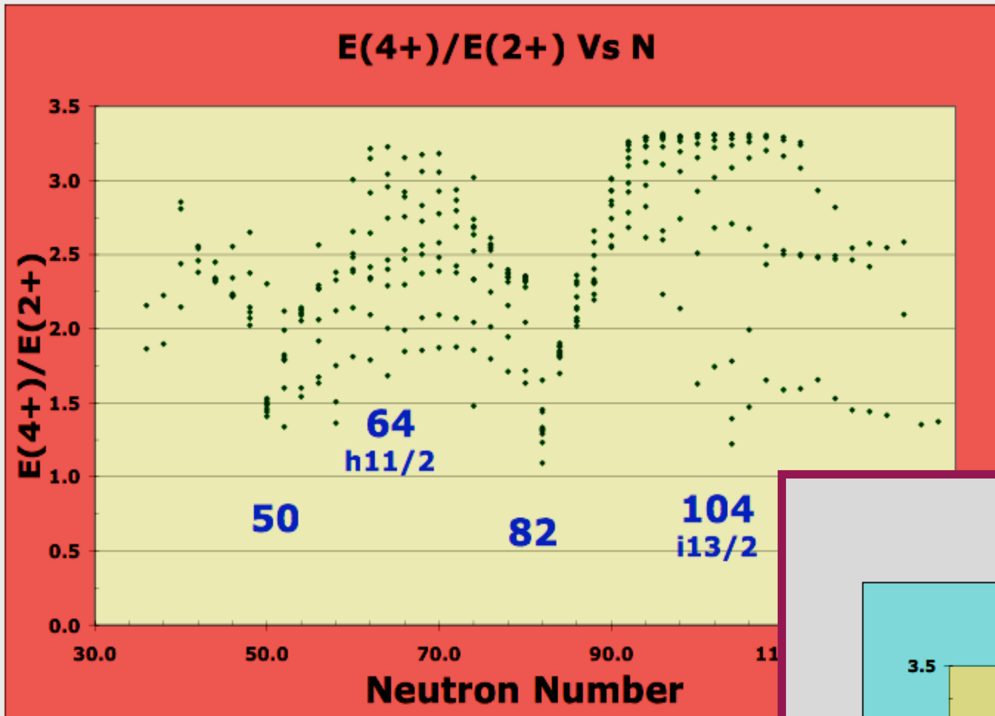


Triaxiality is reflected in simple quantities:

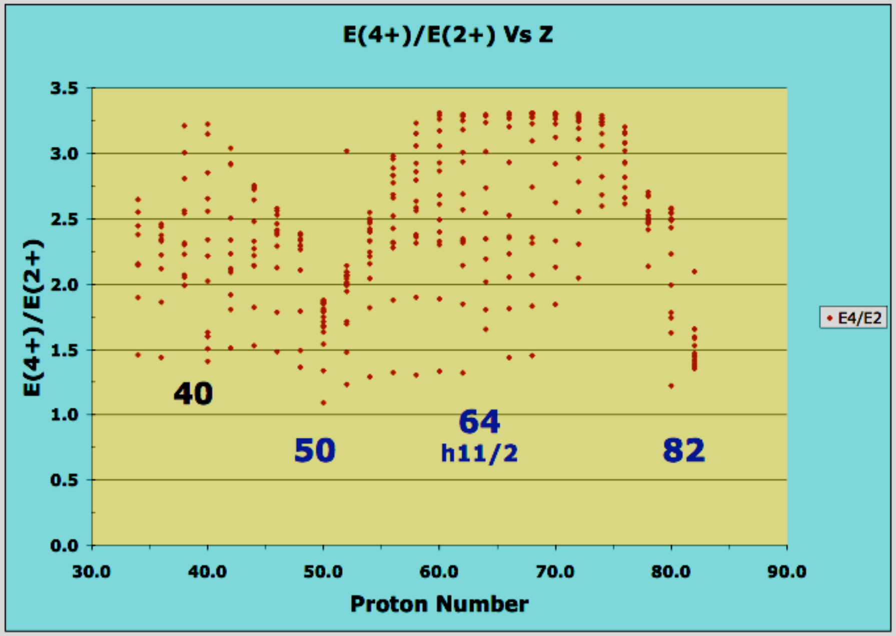
- Relative positions of 4_1 and 2_2
- Branching ratios of $(2_2 \rightarrow 2_1)/(2_2 \rightarrow 0)$
- Quadrupole moments

We have studied B(E2) of first 2^+ in N~50 isotopes of Ge & Se

$E(4_1)/E(2_1)$: Indicator of Shells & Subshells



N= 64, 104 subshells, but no N=40



Z=40, 64 subshells

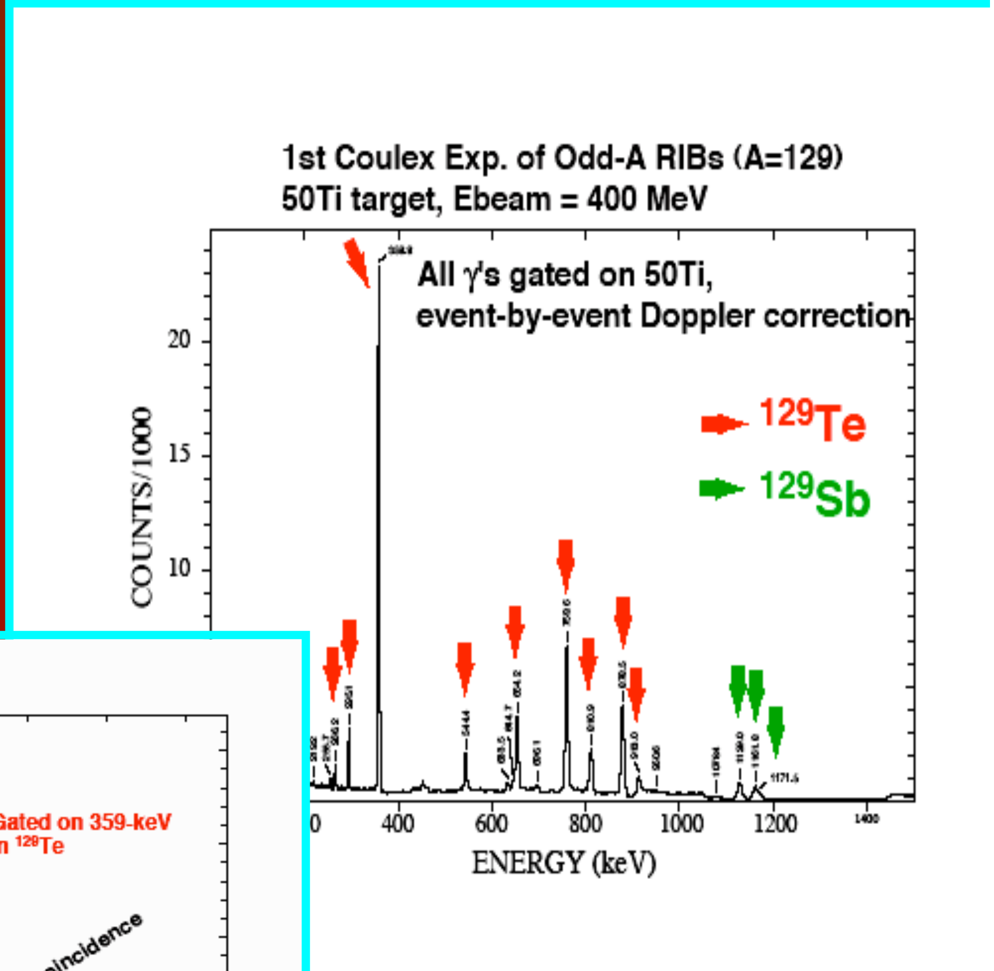
Challenges in Coulex of odd- and odd-odd nuclei

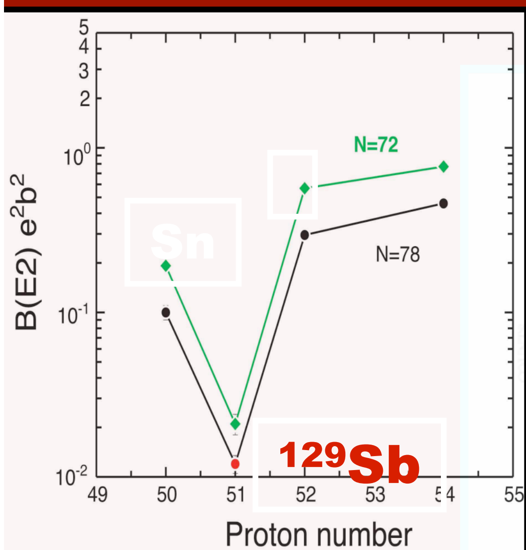
Need good γ energy resolution: large number of γ rays in the beam & its isobars

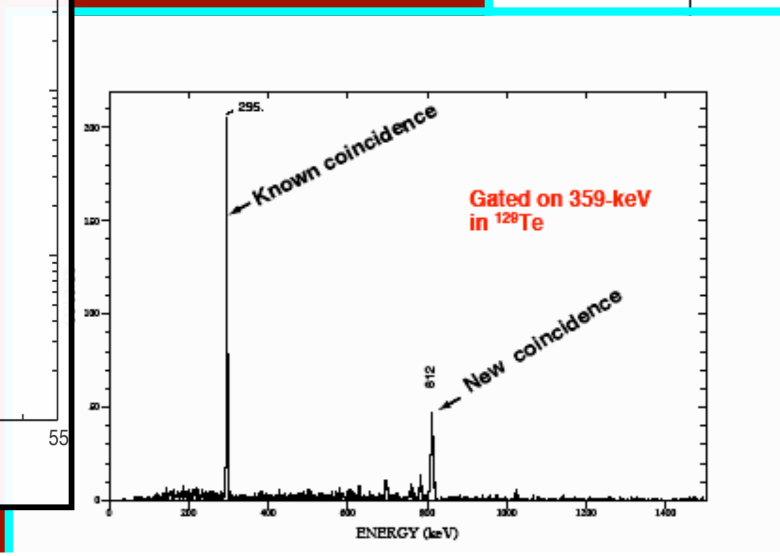
Need good γ efficiency:

> fragmentation of B(E2) strength
> intensity fragmentation due to branching
> need for γ–γ coincidence data to establish reliable level schemes

Need high beam intensity







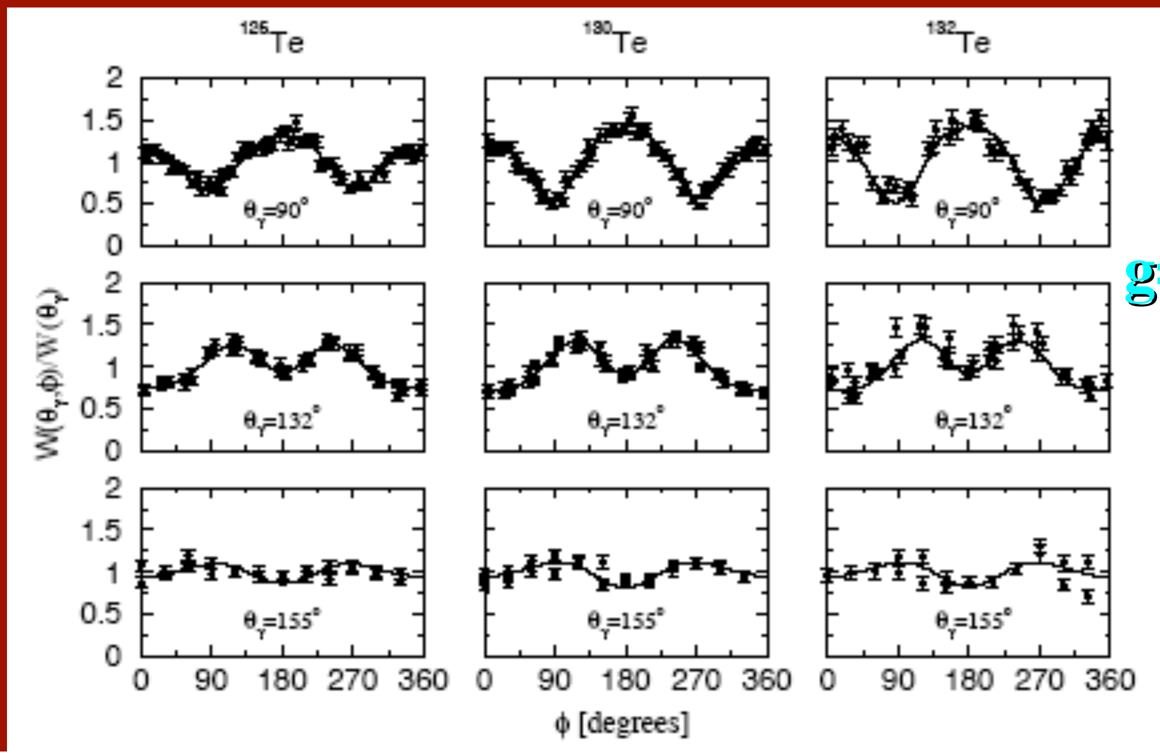
C.-H. Yu et al

g-factor measurements: Excellent probe of s.p. states

- Transient field technique -- Challenging: Large background due to thick target. Will be tested for ^{132}Te (Rutgers Group)
- Recoil into Vacuum Technique (magnitude only):

- Measure part-γ angular correlation for stopped and moving recoils to determine attenuation of angular distribution coeff's
- Method was applied to ^{132}Te, will be applied to ^{134}Te (& ^{136}Te)

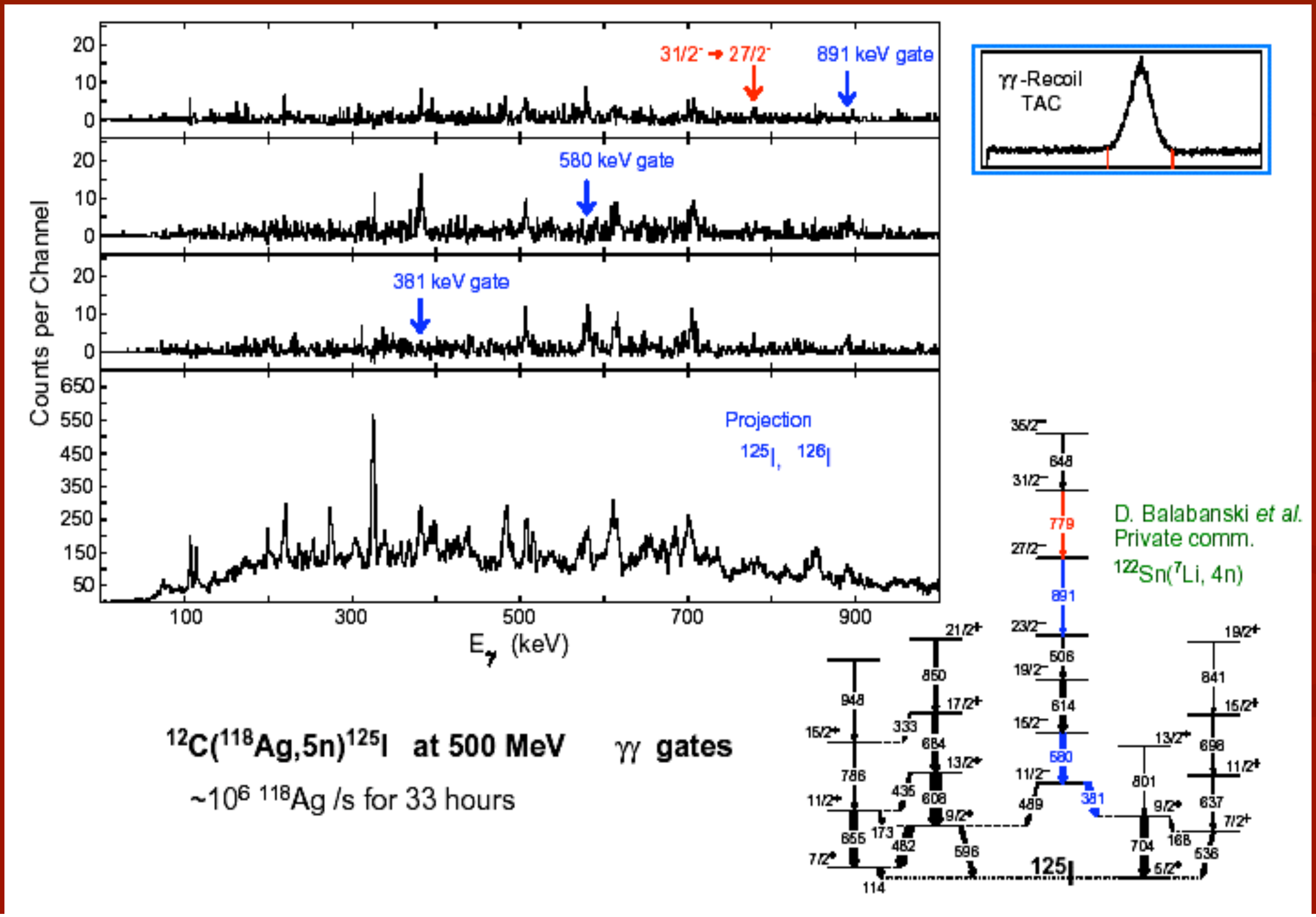
N. Stone,
A. Stuchbery et al.



g=0.35(5)

Fusion-evaporation reactions with RIBs:

- Not a profitable reaction to make very neutron-rich nuclei (large X section, but evaporate 3 or more neutrons for ~ C targets; too hot!)
- However, it is an essential tool for production of p-rich nuclei; very useful for ^{56}Ni beam to reach ^{100}Sn region

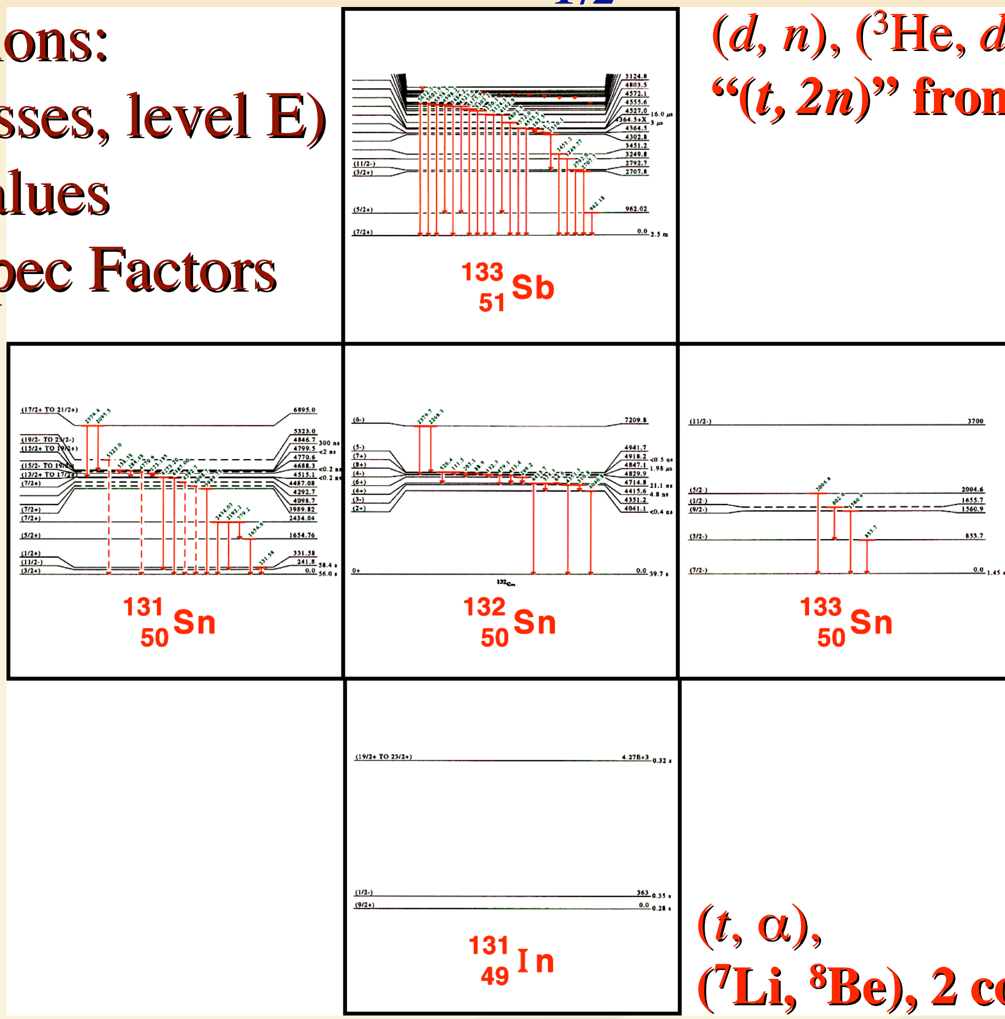


Missing single-particle levels around ^{132}Sn

π: $s_{1/2}$

Transfer Reactions:
- Q-values (masses, level E)
- Ang Dist: *l* values
- Cross Sec.: Spec Factors

(*d*, *n*), (^{3}He, *d*): difficult targets
"(*t*, 2*n*)" from ^{7}Li break up



ν: $i_{13/2}$
unbound

(*d*, *p*)
(^{9}Be, ^{8}Be)
(^{13}C, ^{12}C)

(*t*, α),
(^{7}Li, ^{8}Be), 2 correlated α,
and 2 uncorrelated α from
^{7}Li break up

π^{-1}: $p_{3/2}$, $f_{5/2}$

Selective Neutron Transfer with "Heavy" Targets

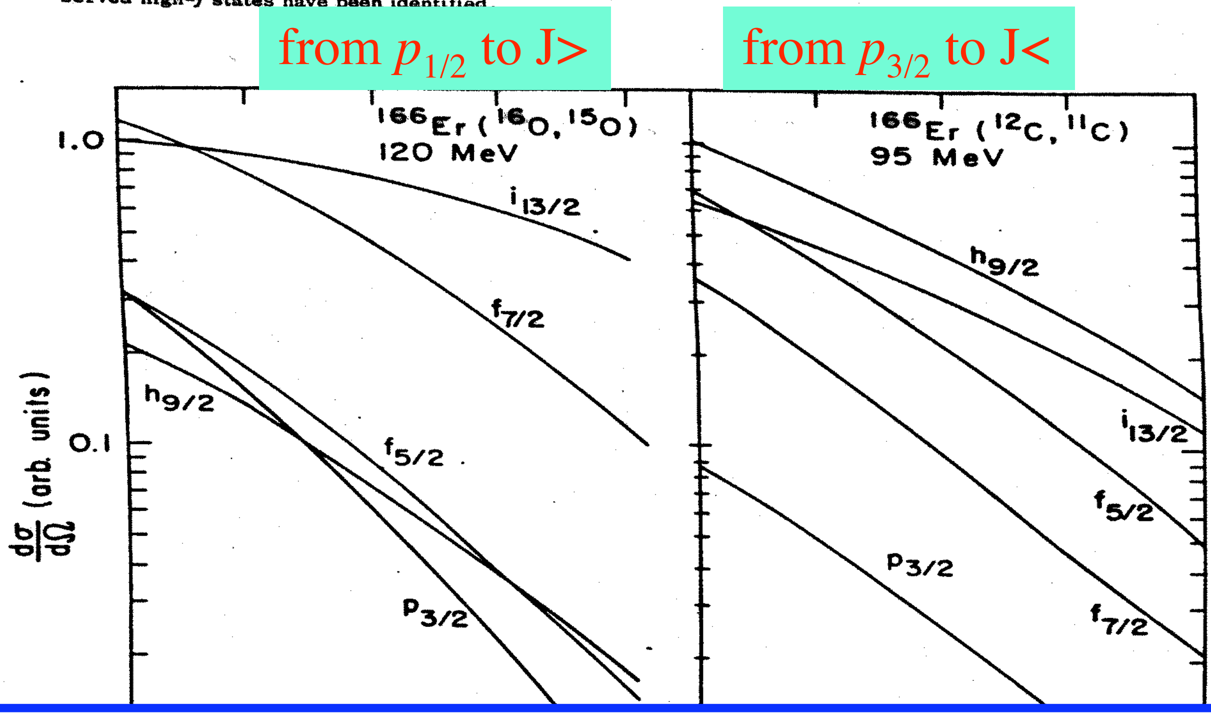
Transfer of a $J_>$ particle selectively populates $J_<$ and vice versa

VOLUME 46, NUMBER 24 PHYSICAL REVIEW LETTERS 15 JUNE 1981

Selective Population of High-*j* Orbitals in Er Nuclei by Heavy-Ion–Induced Transfer

P. D. Bond, J. Barrette, C. Baktash, C. E. Thorn, and A. J. Kreiner
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 February 1981)

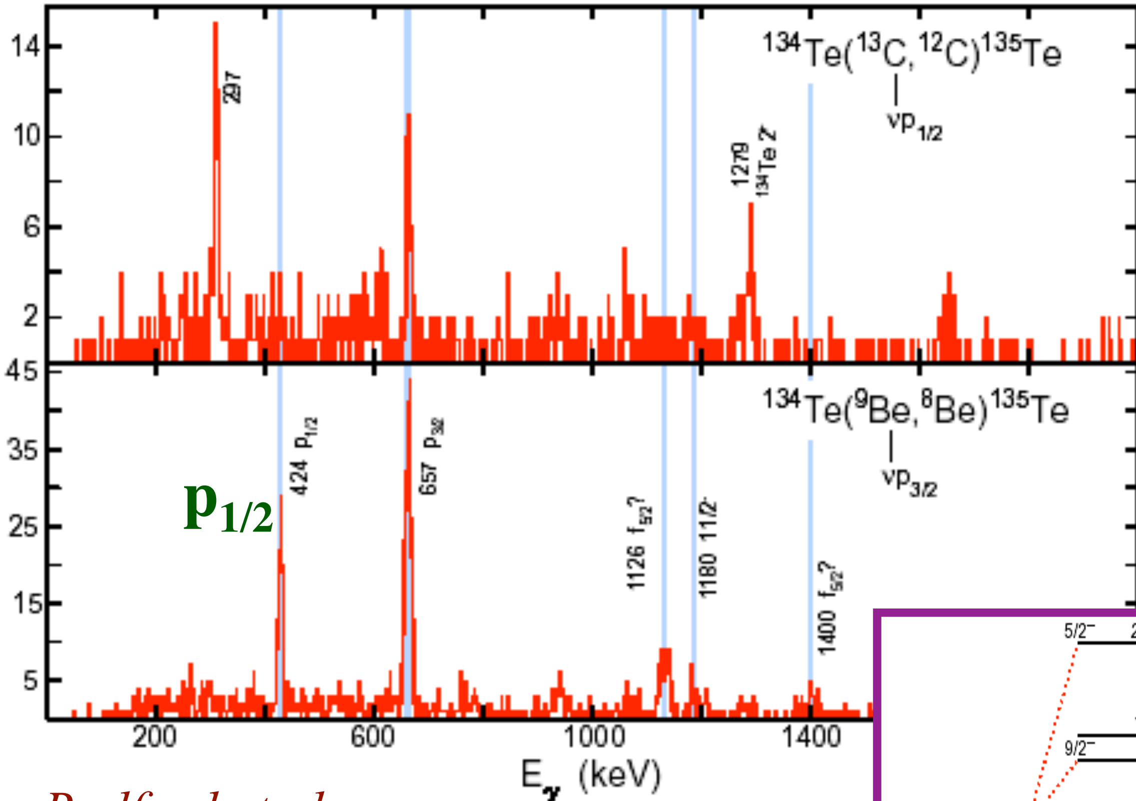
Selective population of high-*j* and high-*K* states in $^{167,169,171}Er$ nuclei has been observed in heavy-ion–induced single-neutron–transfer reactions. γ rays in coincidence with outgoing particles have been used to aid in level assignments and several previously unobserved high-*j* states have been identified.



Evidence for Recoil Effects in Heavy-Ion Transfer Reactions*

D. G. Kovar, B. G. Harvey, F. D. Becchetti, J. Mahoney, D. L. Hendrie, H. Homeyer,†
W. von Oertzen,‡ and M. A. Nagarajan
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 5 March 1973)

Selective neutron transfer: Comparison of ^{13}C & ^{9}Be targets

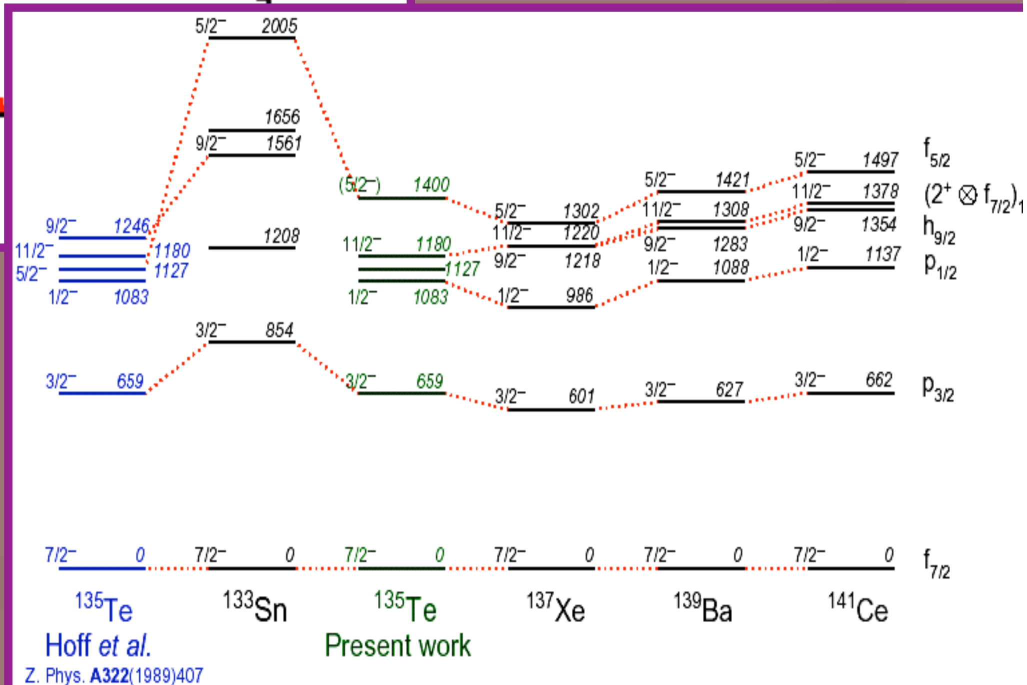


Radford et al.

Selectively populates J>; *e.g.*, $p_{3/2}$ & $i_{13/2}$

Selectively populates J<; *e.g.*, $p_{1/2}$ & $f_{5/2}$

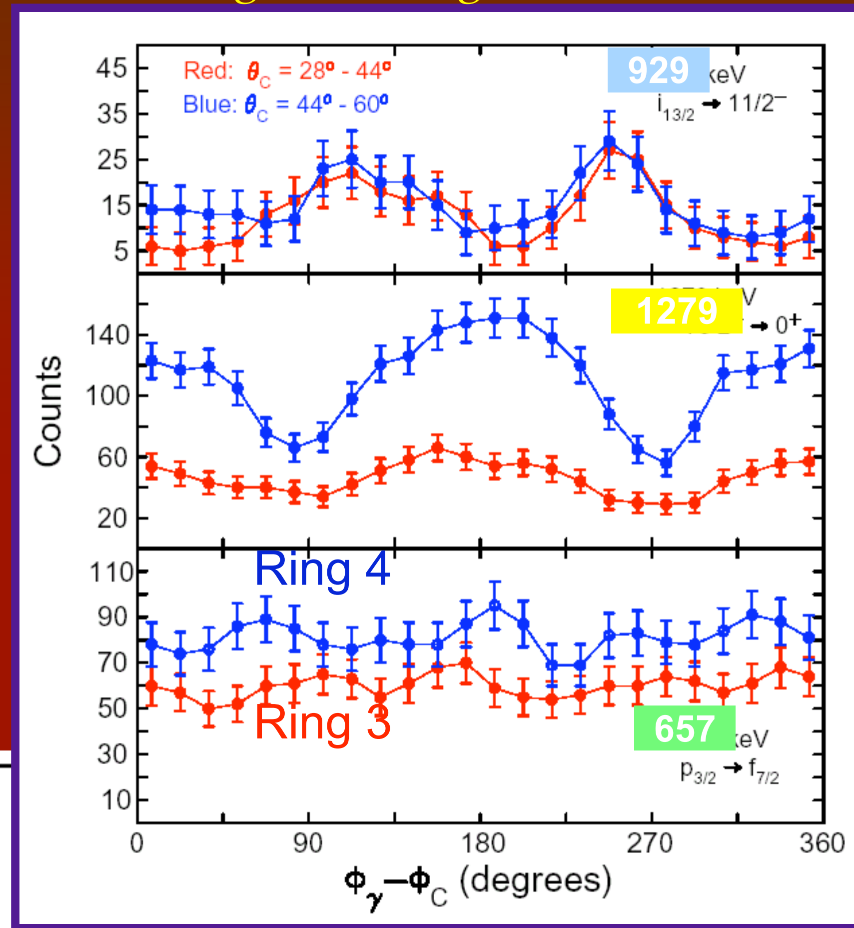
We recently identified $i_{13/2}$ in ^{135}Te, which is the first bound N= 83 $i_{13/2}$

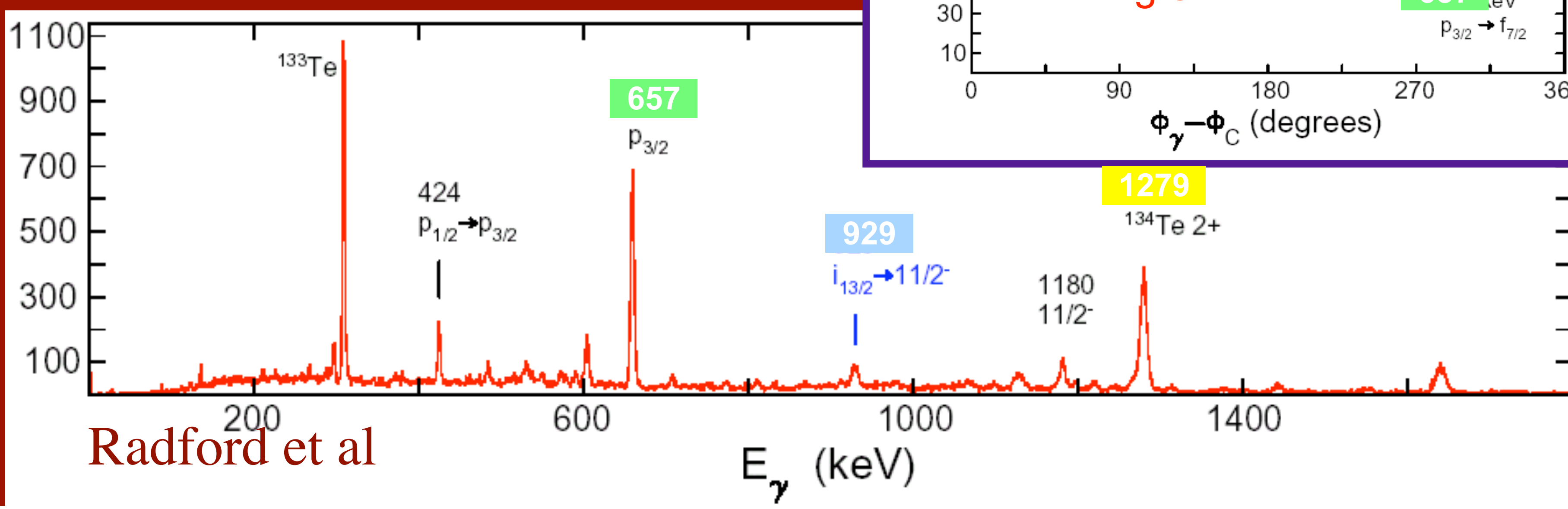


Revisit $^{13}C(^{134}Te,^{12}C)^{135}Te$

- Established coincidence between a new γ (929 keV) and the previously known 1180; decay of 11/2 $^{-}$ to the 7/2^{-} ground state
- Used particle-gamma correlation data to established the multipolarity of 929 to be stretched dipole
- The energy of the new $i_{13/2}$ fits nicely into the systematics of N=82 isotones
- Plan to use same reaction with ^{132}Sn

Particle-gamma angular correlations





Radford et al

Proton "transfer": Incomplete Fusion with a ^{7}Li target
Breakup of ^{7}Li to (t+α) produces t- and α- like targets

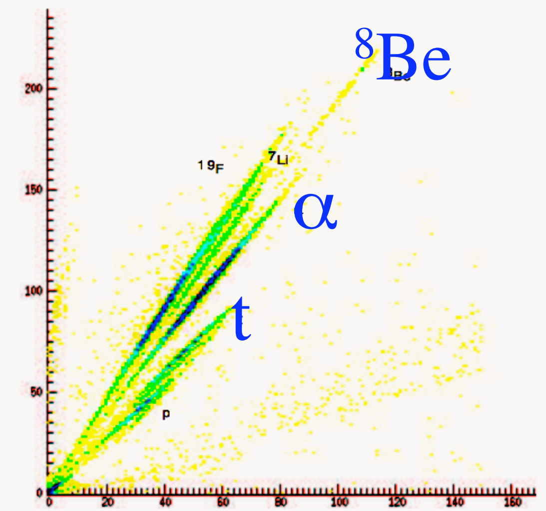
"*1p*-pickup" channel: Gate on alpha to select *(t, 2n)*
"*2p & 2pn* pickup" channel: Gate on *t* to select *(α, 2n)*, *(α, n)*

- Large cross section ~100 mb
- Can use thick targets;
  γ- γ coincidence becomes possible
- Populates all spin states;
- Promising for the π $s_{1/2}$ state in ^{131,133}Sb

Similar selectivity is expected for ^{6}Li

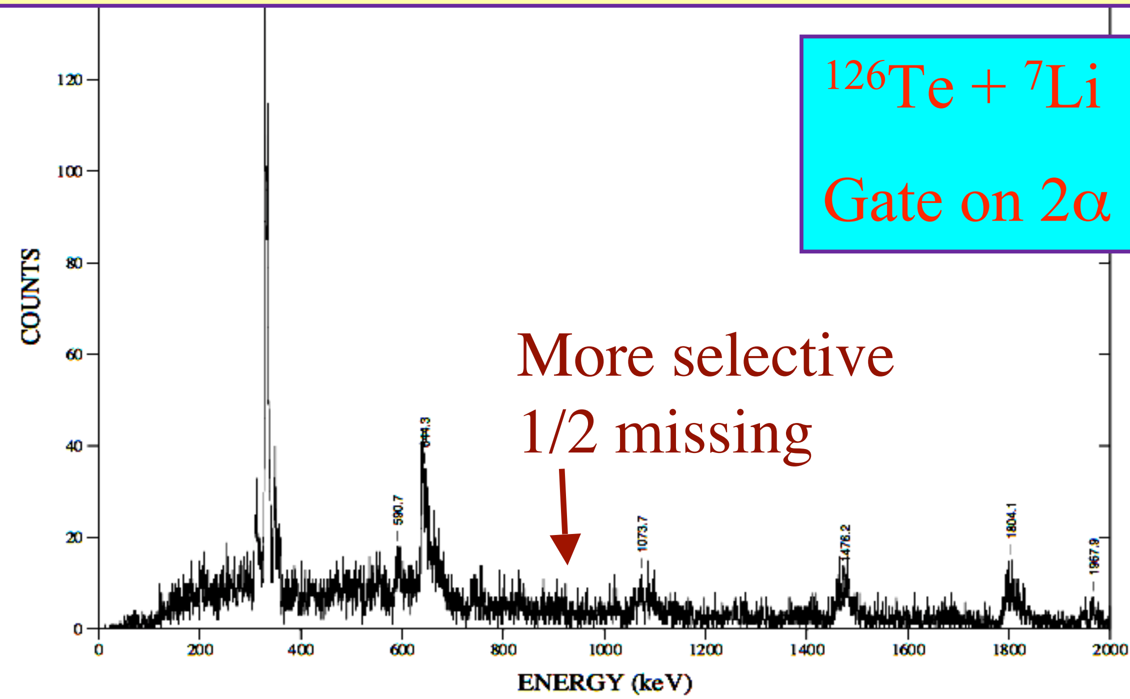
"*1p*-stripping" channel: Gate on two-α to select *(t, α)* or (^{7}Li, ^{8}Be)

- Very small cross section
- Selective population



Particle ID with HyBall

Reaching ^{125}Sb by selective “p-transfer”



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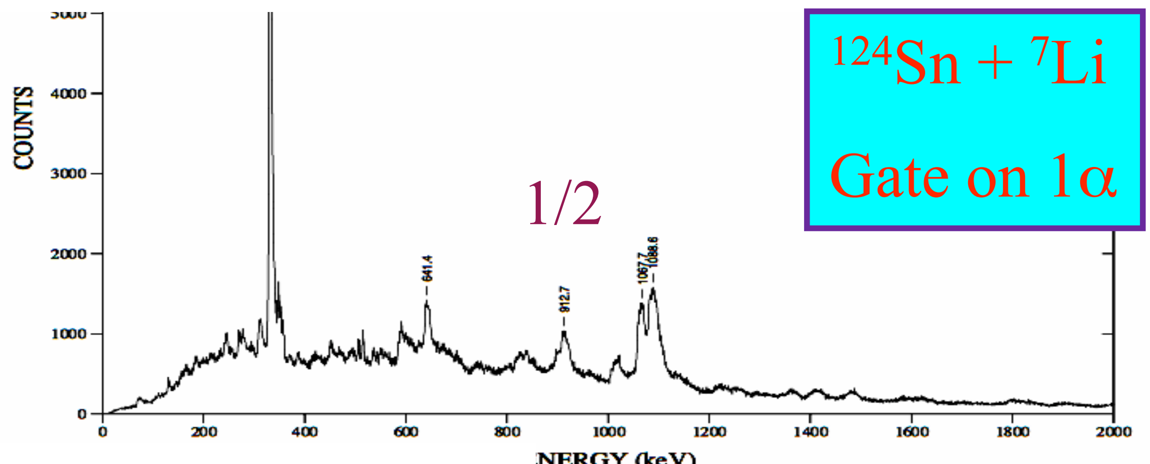
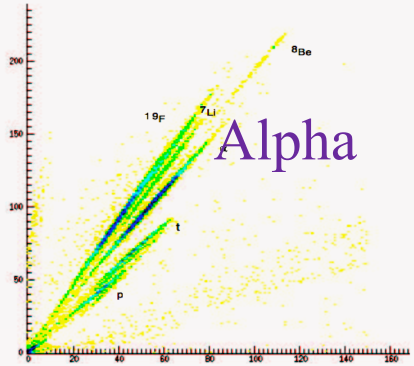
20-Nov-02 12:19:37 Nuclear Structure Group, ORNL <chy>



Gomez del Campo et al.



HyBall Spectrum

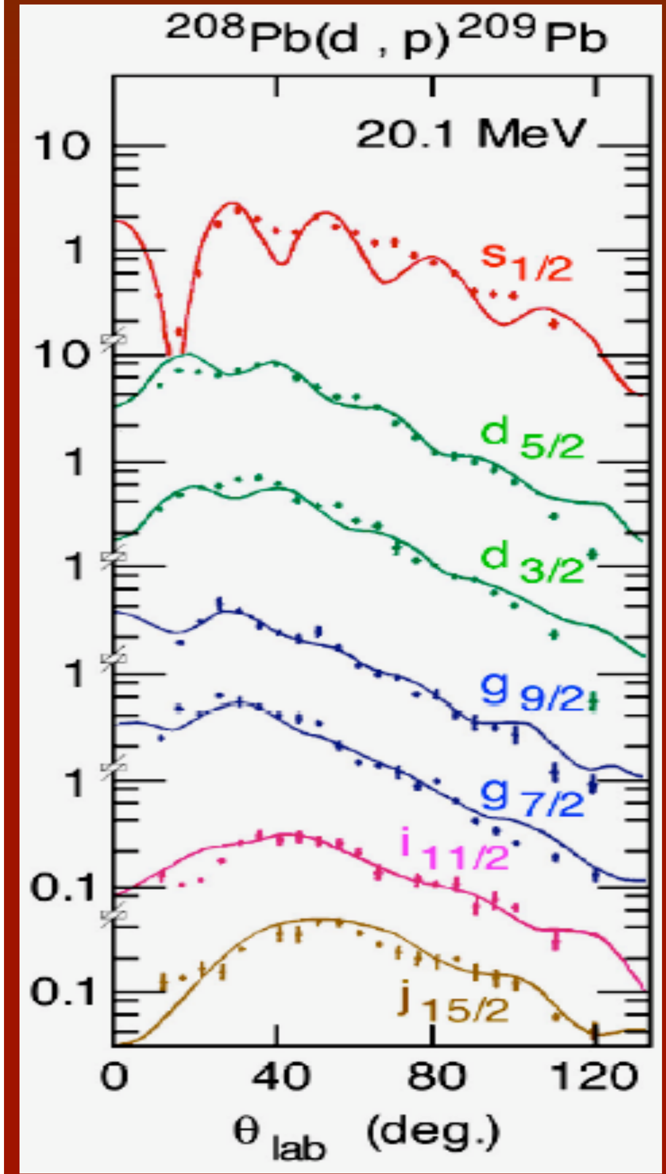
From above:
(^{7}Li, ^{8}Be)
“(t,α)”

“(t,2n)”
From below

Preliminary data on ^{131}Sb

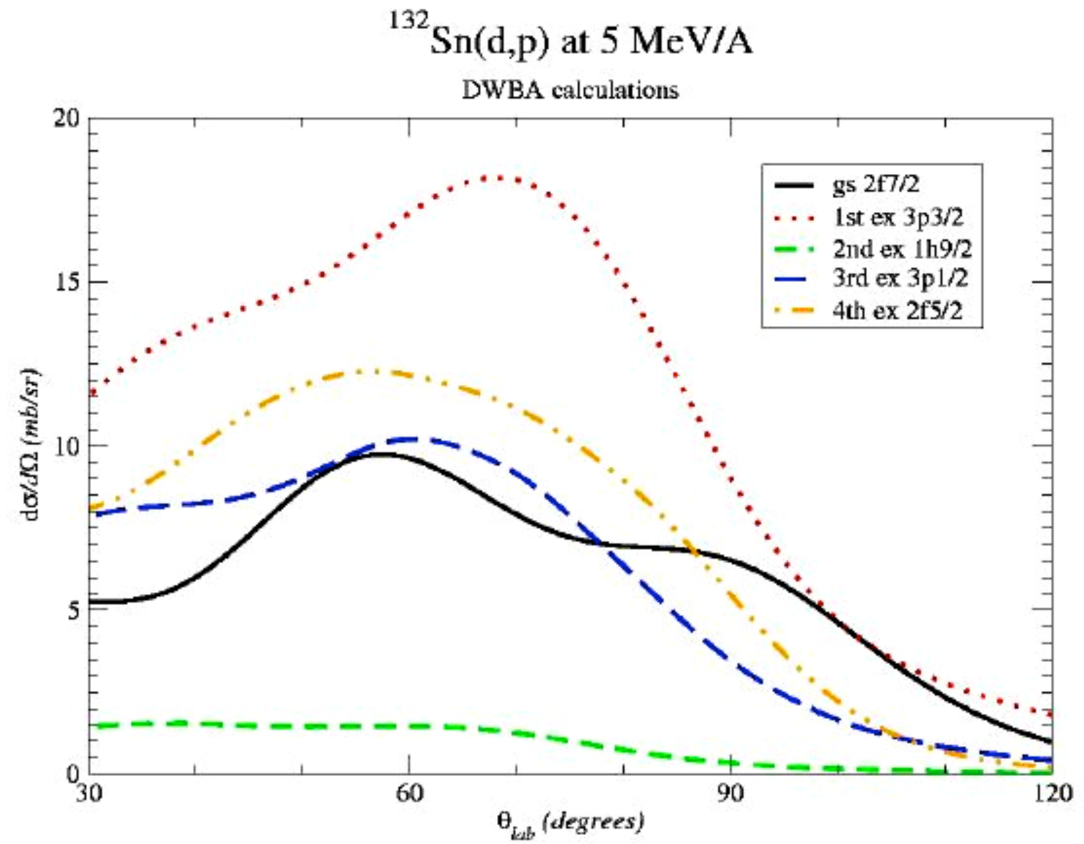
Angular distributions for transfer reactions in:

Normal Kinematics

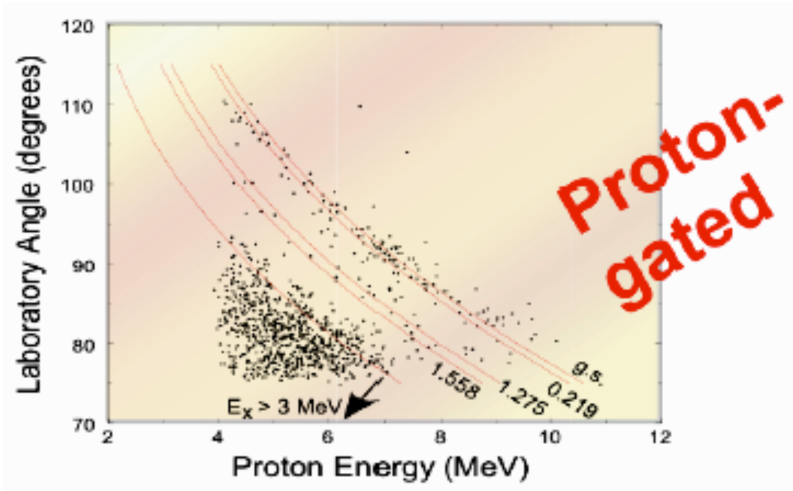


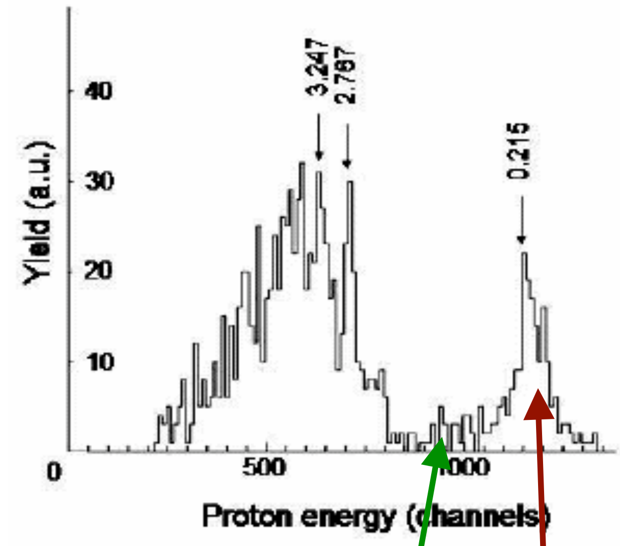
Inverse Kinematics: Challenging

- Ang. Dist. not v. distinct (note linear scale)
- Poor energy resolution



(d, p) Transfer reactions in inverse kinematics: A test case with ^{124}Sn
Planned experiments with ^{130,132}Sn





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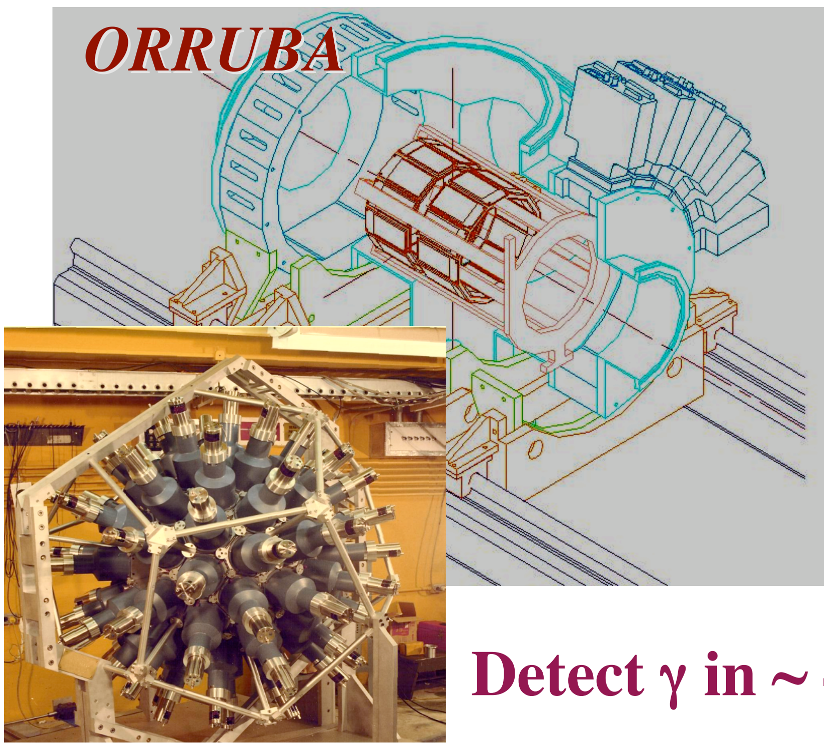
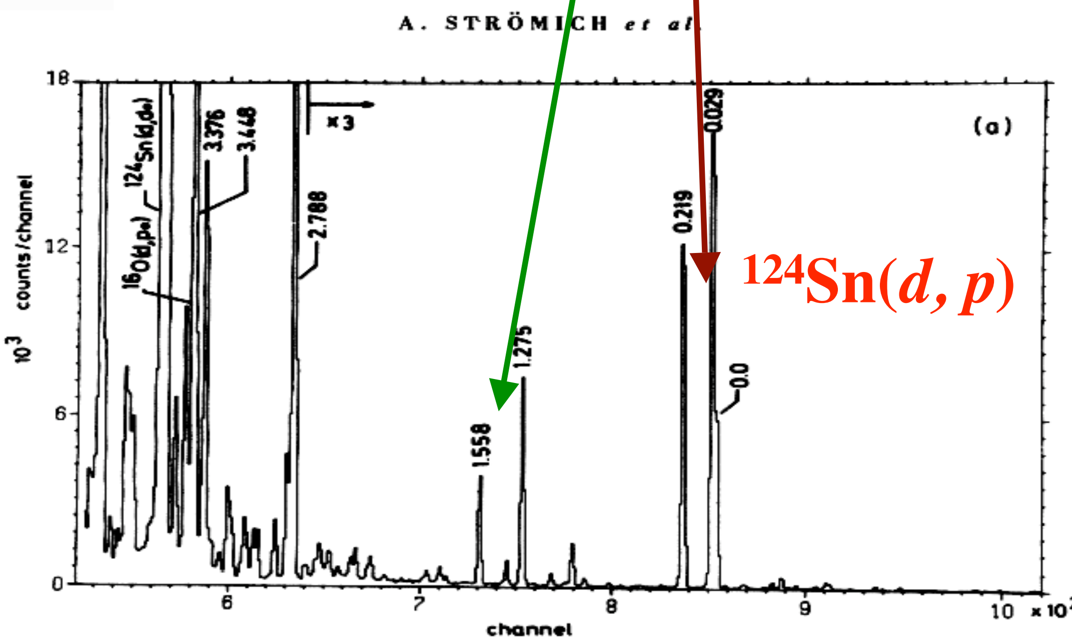
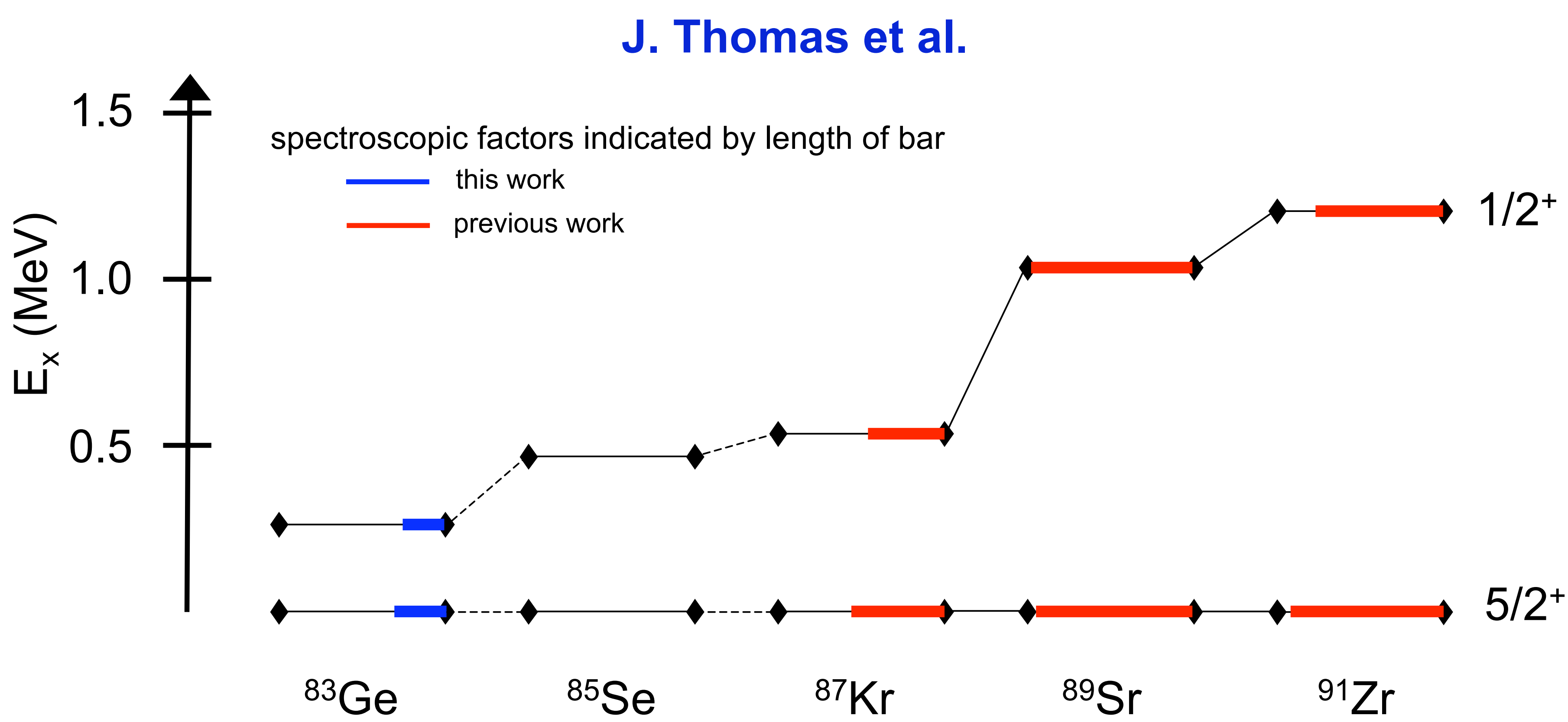




Detect γ in ~ 4π to resolve overlapping peaks

Spectroscopic Factors for ^{83}Ge & other N=51



- Surprisingly low-lying "1/2+ state," assigned based on *l* =0
- $s_{1/2}$ should lie much higher; phonon contribution?
- Need γ decay information (multipolarity & transition strength)

Summary

- We have begun a systematic study of s.p. & collective properties of nuclei near ^{132}Sn using accelerated radioactive ion beams:
  - *Coulex: B(E2) for $^{126\text{-}134}$Sn, ^{129}Sb, and $^{130\text{-}136}$Te:*
    - *Effective charges in ^{134}Sn & ^{134}Te*
    - *Systematic trends for B(E2) in n-rich Sn & Te*
    - *Coulex of odd-A to better understand s.p. structures*
  - *Moments: g-factor for ^{132}Te & planned Q measurements*
  - *Transfer: Planned studies of ^{131,133}Sn by (d, p) & (^{9}Be,^{8}Be)*
  - *Incomplete fusion: "1-p" transfer to reach ^{131}Sb*
- No evidence for "unexpected" changes in shell structure near ^{132}Sn, which is not very far from stability.
- But we have succeeded in developing the necessary tools and techniques that could be applied to study drip line nuclei with more interesting ISOL beams at future facilities.