Collective Excitations in Exotic Nuclei

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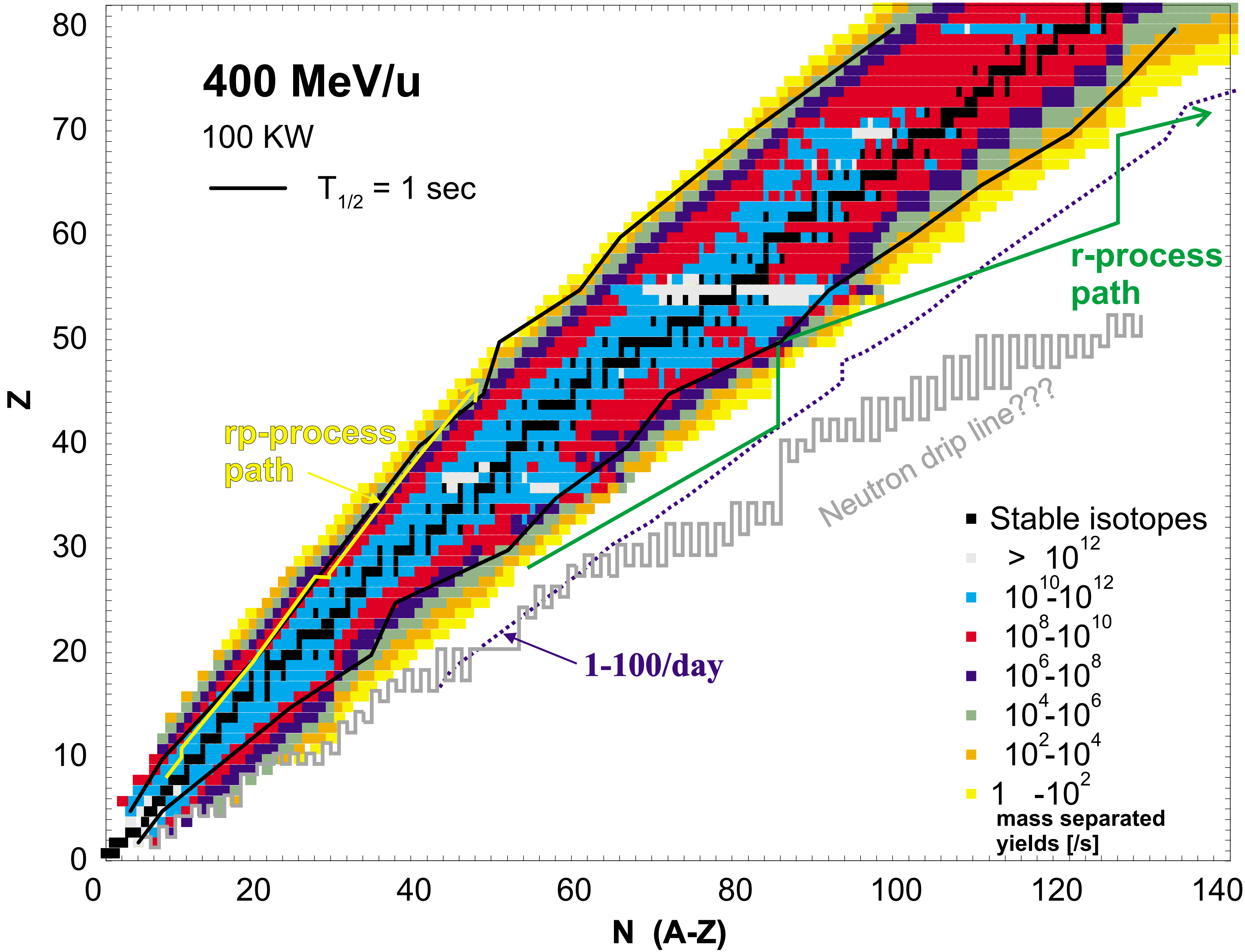
RIA Summer School, August 2002

I Nuclear Excitations: Single particle motion *vs*. Collective motion
Collective Modes: Rotations and Vibrations

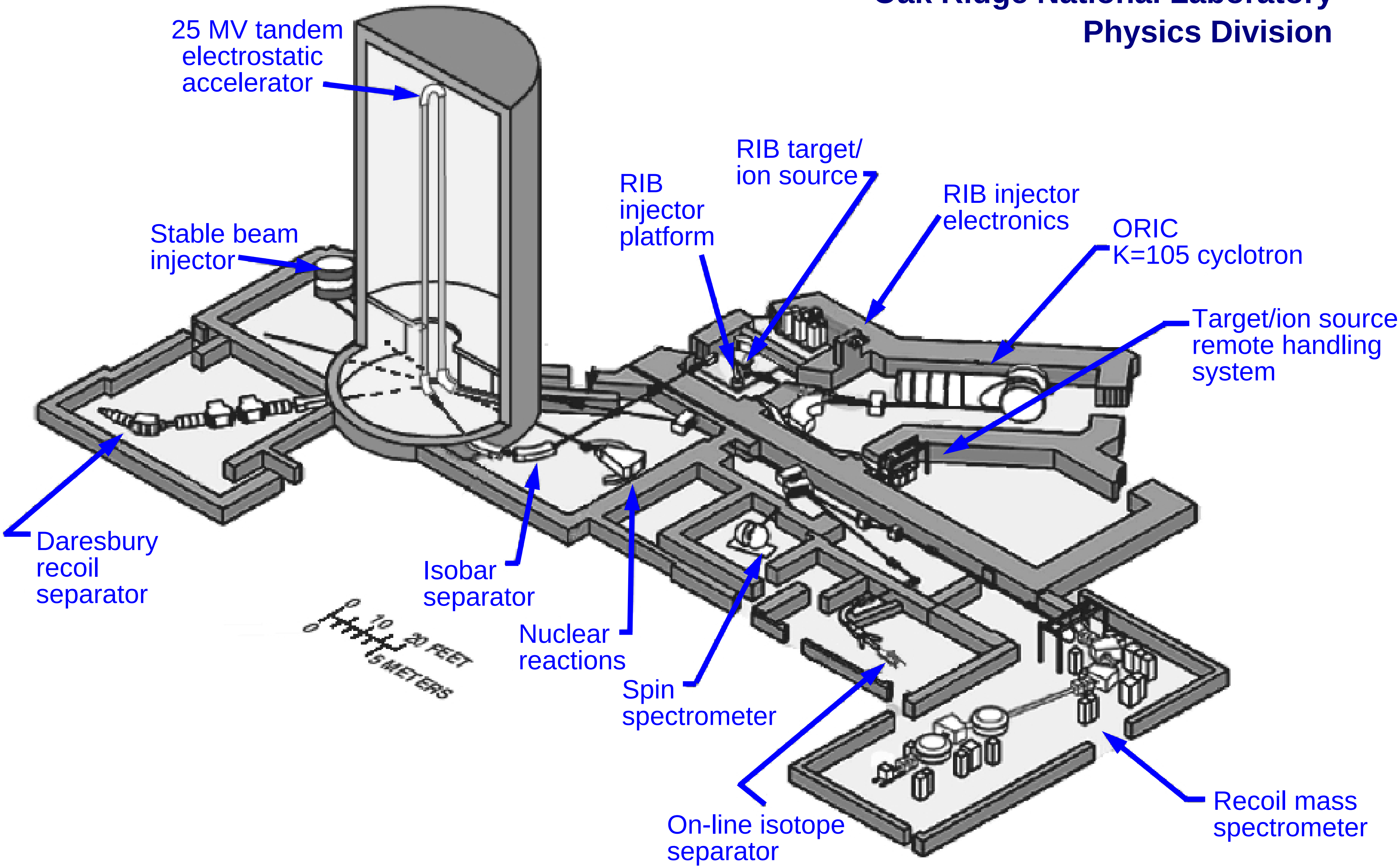
II Experimental Techniques and Examples of Results
- Gamma-Ray Spectroscopy
- Giant Resonances
- Intermediate-Energy Coulomb Excitation

III **Towards RIA**
- Learning to do Nuclear Structure Measurements with Post-accelerated Radioactive Ion Beams
- Experiments with Heavy Neutron-rich Beams at the HRIBF


400 MeV/u
100 KW
$T_{1/2}$ = 1 sec
rp-process path
r-process path
Neutron drip line???
1-100/day
Stable isotopes
> 10^{12}
10^{10}-10^{12}
10^{8}-10^{10}
10^{6}-10^{8}
10^{4}-10^{6}
10^{2}-10^{4}
1 -10^{2}
mass separated yields [/s]
Z
N (A-Z)
0
10
20
30
40
50
60
70
80
0
20
40
60
80
100
120
140

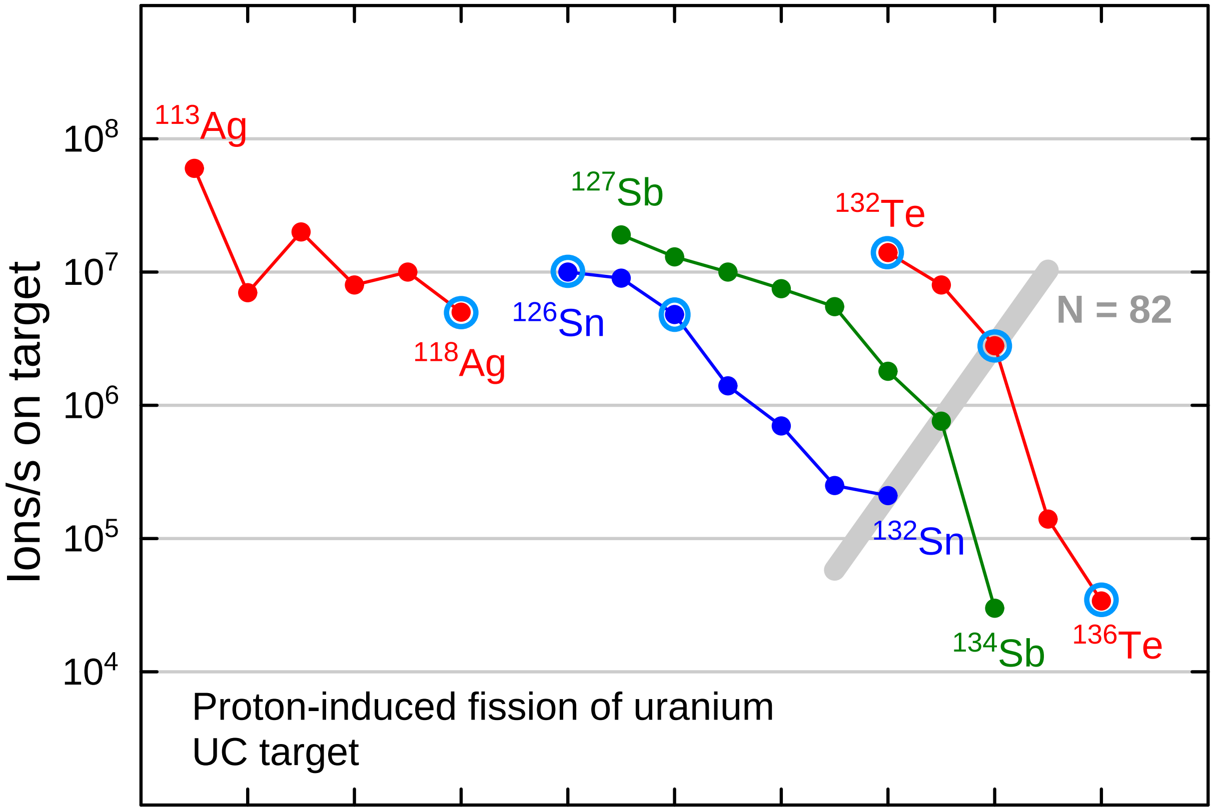
The Holifield Radioactive Ion Beam Facility

Oak Ridge National Laboratory
Physics Division



Some HRIBF beam currents

Singly stripped - suitable for Coulex
For doubly stripped, divide by five



HRIBF will be the only facility that can accelerate these beams above the Coulomb barrier for at least 4 - 5 years.

Total of over 100 beams with at least 10^3 ions/s.

Goal: Physics measurements with neutron-rich RIBS

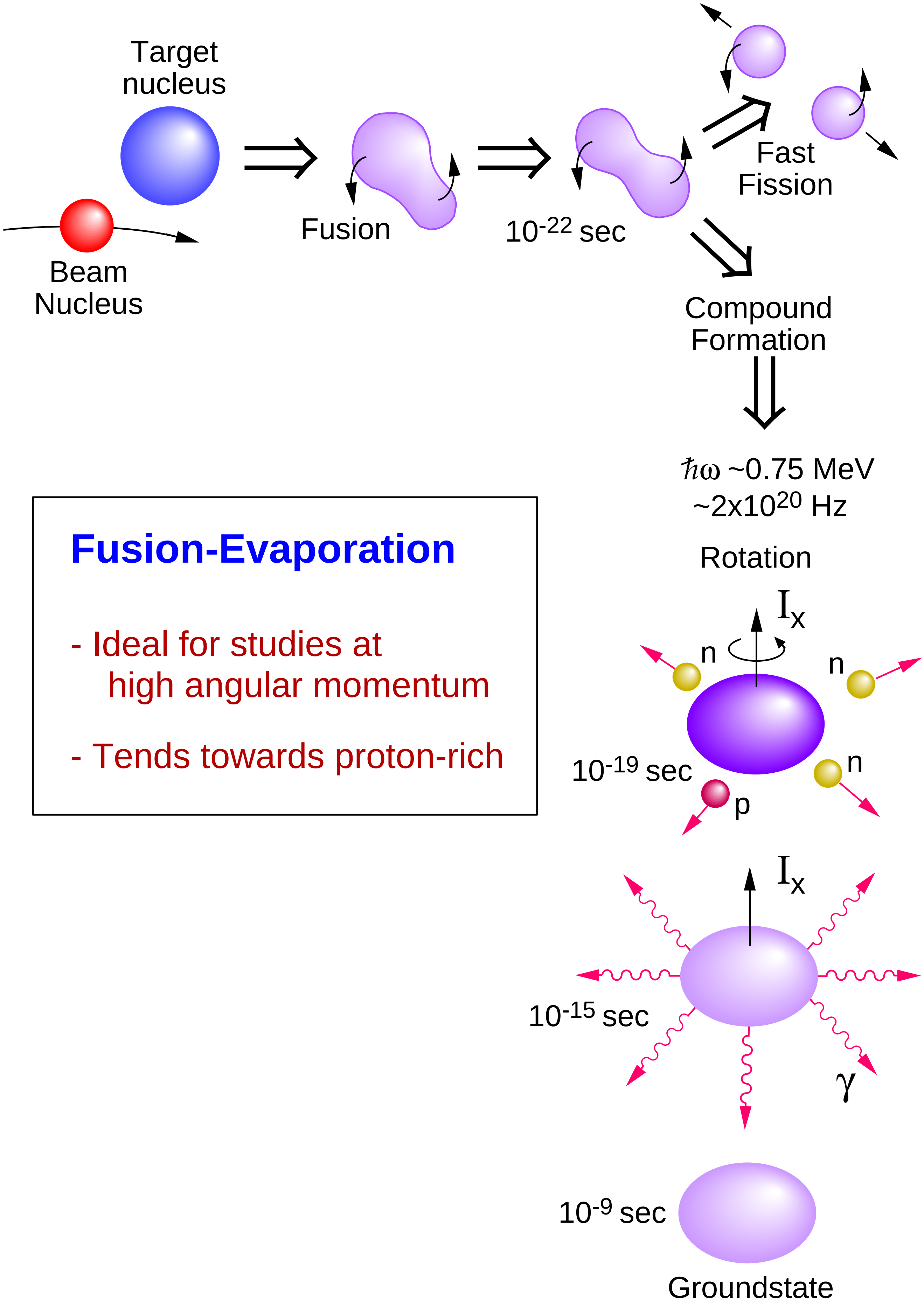
These n-rich RIBs provide a unique opportunity for a whole class of measurements that could never before be applied to nuclei on the n-rich side of stability.

To do these studies, we want to learn how to do the following types of measurements with RIBs:

- **Coulomb excitation**
  - B(E2) values → transition matrix elements
  - Static quadrupole moments by reorientation → nuclear shape
- **Fusion-evaporation; $\gamma\gamma$ spectroscopy**

  → band structure, *etc.*
- **Transfer reactions**
  - *e.g.* (d,p) (^{3}He,d) Spectroscopic factors

    → shell-model wavefunctions

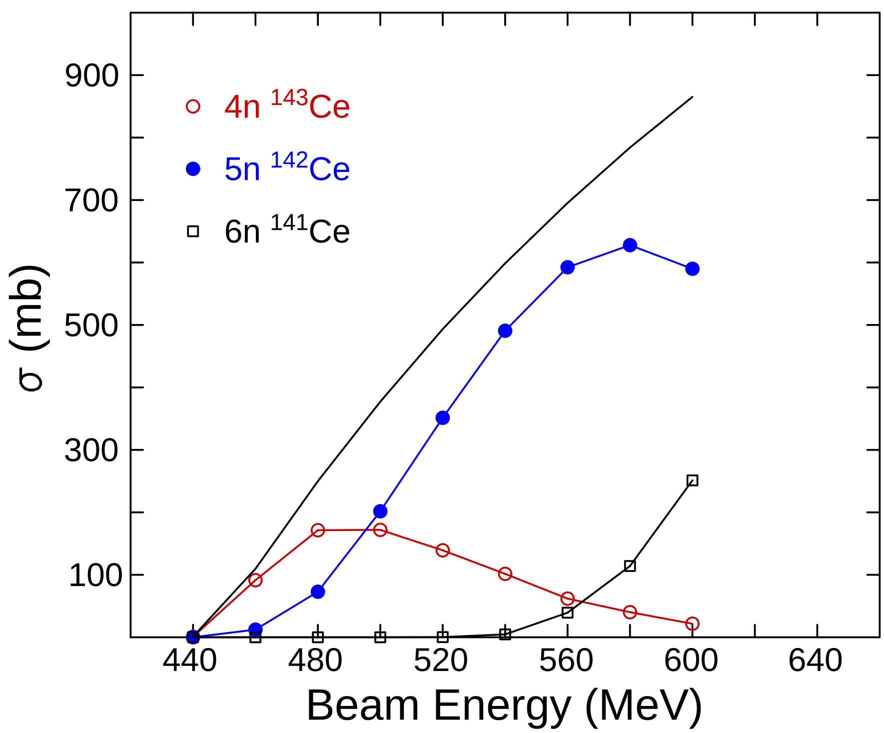


Fusion-Evaporation

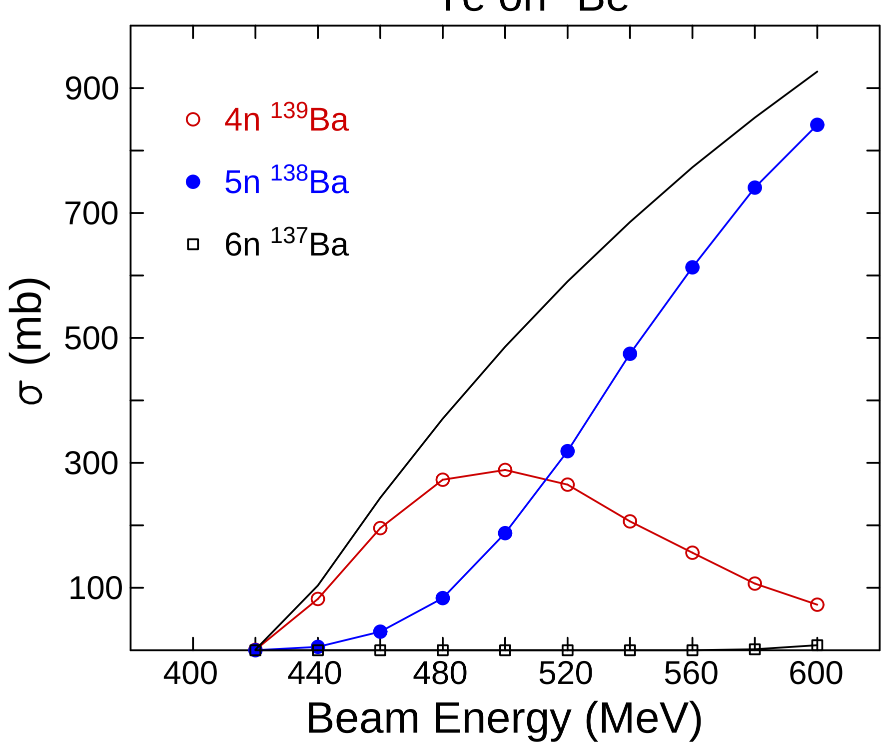
- Ideal for studies at high angular momentum
- Tends towards proton-rich

EvapOR cross section calculations
Neutron-rich RIBs, light targets

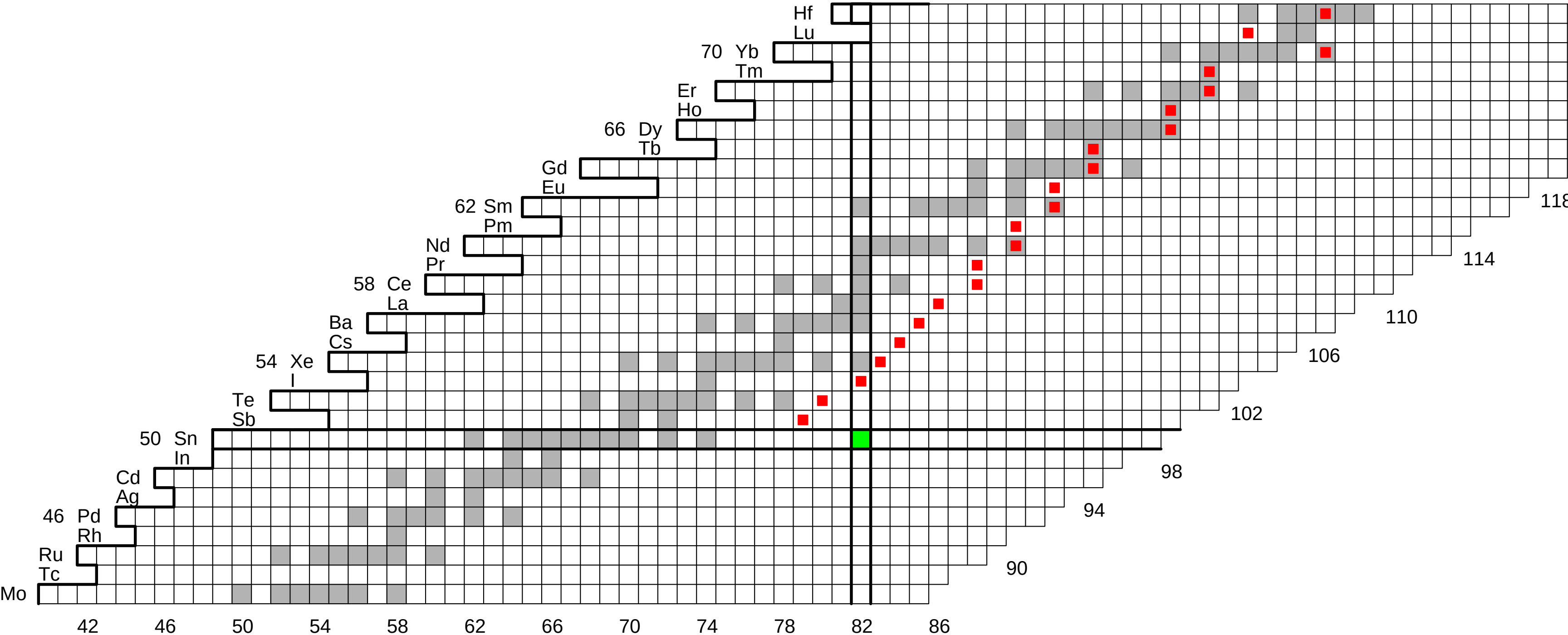
^{134}Te on ^{13}C



^{134}Te on ^{9}Be



4n-evaporation products from ^{132}Sn on most n-rich stable targets

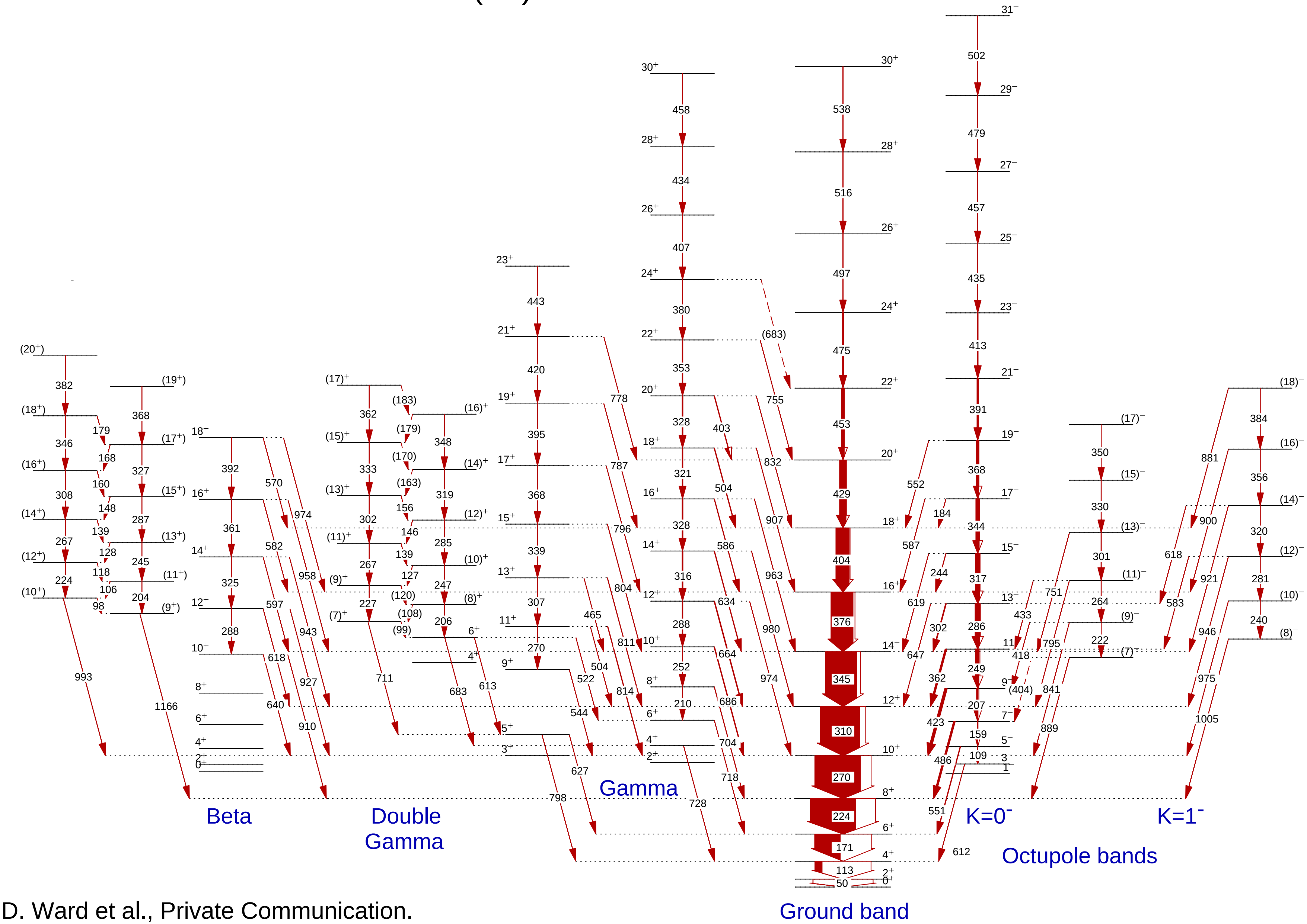


^{232}Th

Coulomb Excited by ^{209}Bi at E = 6 MeV/u

"Unsafe Coulex" - some contribution from nuclear interactions

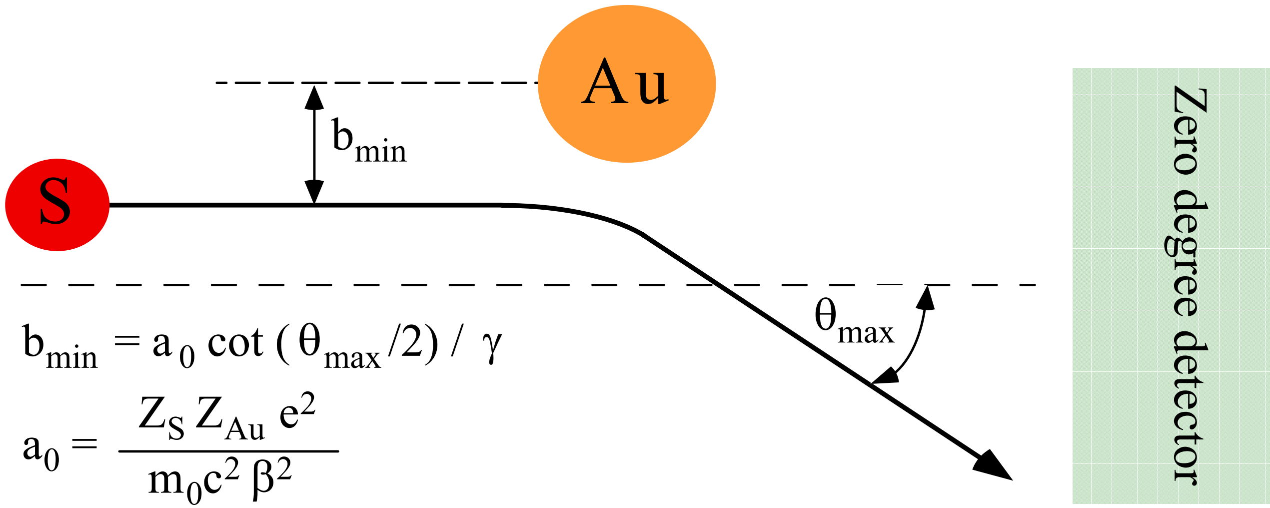
No absolute B(E2)'s extracted



D. Ward et al., Private Communication.

Intermediate energy Coulomb excitation

- Ideally suited for beam-fragmentation products



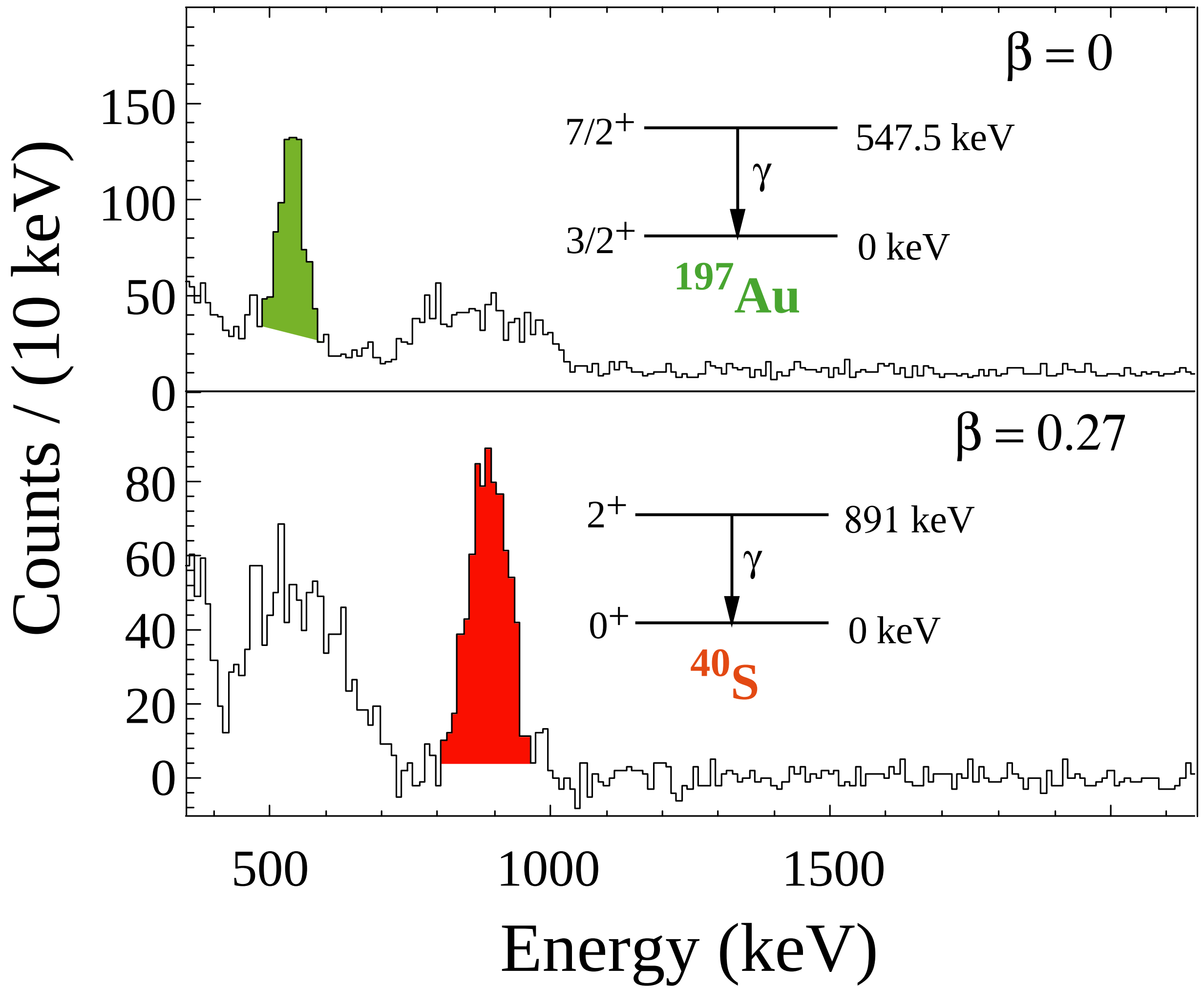
$$b_{min} = a_0 \cot(\theta_{max}/2) / \gamma$$

$$a_0 = \frac{Z_S Z_{Au} e^2}{m_0 c^2 \beta^2}$$

- $E_{beam} \approx 40$ MeV/nucl.
- $\beta \approx 0.3,\ \gamma \approx 1.05$
- $b_{min} \approx 20$ fm
- "touching spheres" $1.2(A_S^{1/3}+A_{Au}^{1/3}) = 11$ fm
- $\sigma \sim 100$ mb
- target ~ 100 mg/cm^2

- K. Alder *et al.*, Rev. Mod. Phys. **28**, 432 (1956).
- A. Winther and K. Alder, Nucl. Phys. **A 319**, 518 (1979).
- C.A. Bertulani and G. Baur, Phys. Rep. **163**, 300 (1988).
- T. Glasmacher, Ann. Rev. Nucl. Part. Sci. **48** (1998), 1.

Energy spectra in target and projectile frames for $^{40}S+^{197}Au$



H. Scheit *et al*. Phys. Rev. Lett. **77** (1996) 3967

Reaction Rates

$$\frac{N_{Reactions}}{N_{Beam\ Particles}} = \frac{6 \times 10^{-7}}{A} \sigma t$$

σ = cross section, mb
t = target thickness, mg/cm^2
A = mass of target, a.m.u.

Derive:
$N_A = 6 \times 10^{23}$ atoms/mole
1 barn = 100 fm^2

Beam Requirements

- Two days to do experiment ~1.7×10^5 s
- At least 100 counts detected

A) Intermediate Energy Coulex; sd-shell nuclei

$\sigma \sim 100$ mb t ~ 100 mg/cm^2 A = 197

$\rightarrow N_R/N_B \sim 3 \times 10^{-5}$

$\varepsilon_\gamma = 0.2 \rightarrow N_\gamma/N_B \sim 6 \times 10^{-6}$
$N_\gamma = 100 \rightarrow N_B \sim 1.7 \times 10^7$
$\rightarrow$ **100 s^{-1} Beam**

A) Low Energy Coulex; ^{132}Sn Region

$\sigma \sim 10$ mb t ~ 1 mg/cm^2 A = 12

$\rightarrow N_R/N_B \sim 5 \times 10^{-7}$

$\varepsilon_\gamma = 0.02 \rightarrow N_\gamma/N_B \sim 10^{-8}$
$N_\gamma = 100 \rightarrow N_B \sim 10^{10}$
$\rightarrow$ **6×10^4 s^{-1} Beam**

Experimental Challenges

- **Beams are radioactive**
  - Stopped/scattered beam can give huge background

  - Good tandem beam quality, careful tuning

- **Beams are weak**
  - γ, $\gamma\gamma$ rates comparable to room background

  - Require clean trigger (usually HyBall)

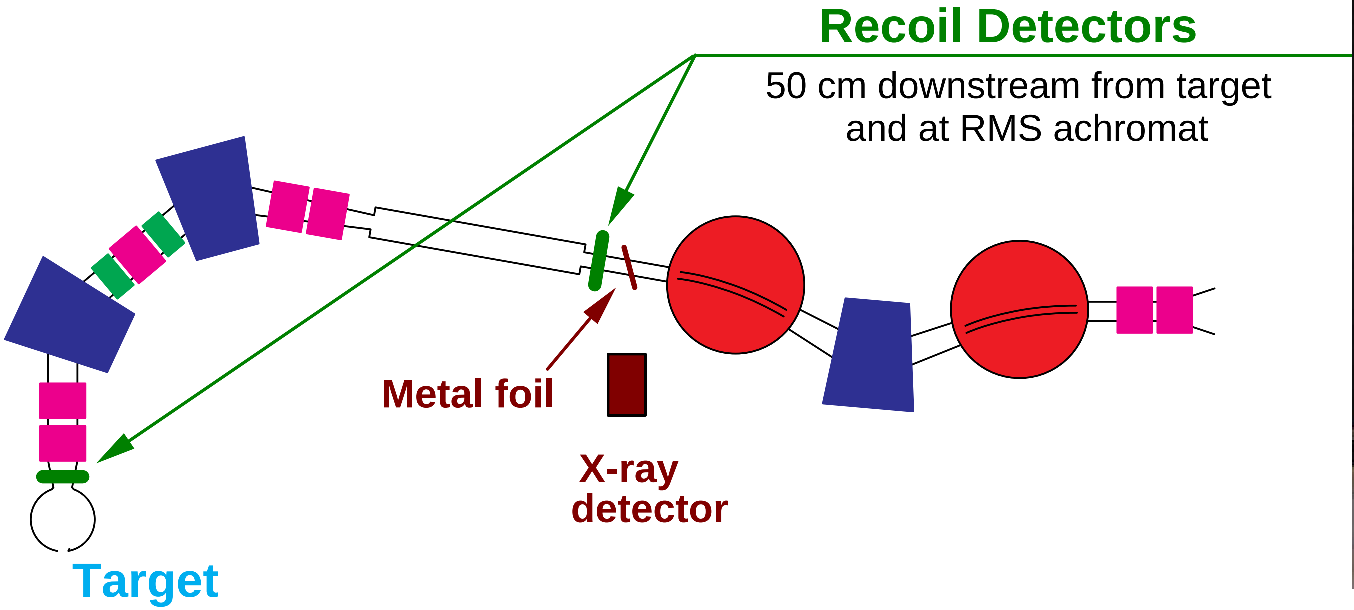
- **Beams are isobar cocktails, *i.e.* contaminated**

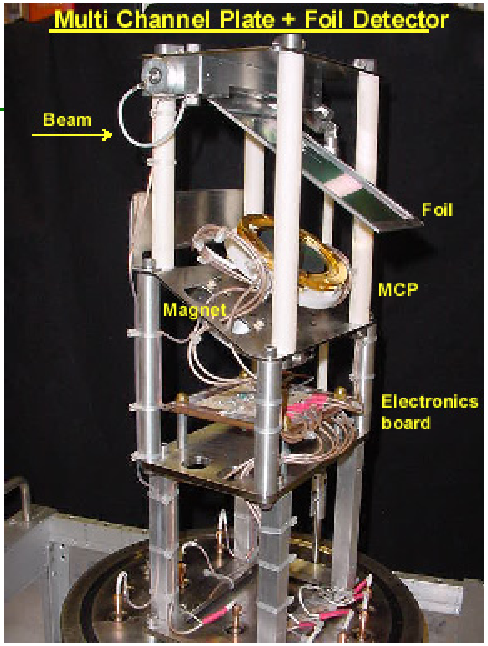
  - Can be helped by high-resolution γ-ray detection

- **Require light targets, inverse kinematics**
  - Large recoil velocity, Doppler broadening

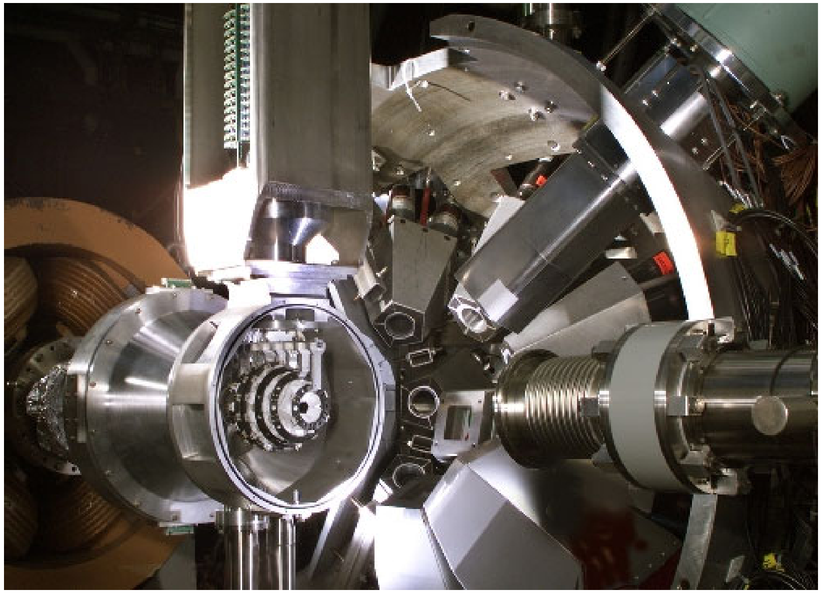
  - Segmented clover array CLARION

Setup for experiments with neutron-rich RIBS





Foil plus multichannel plate



CLARION

11 segmented clover Ge detectors

10 smaller Ge detectors

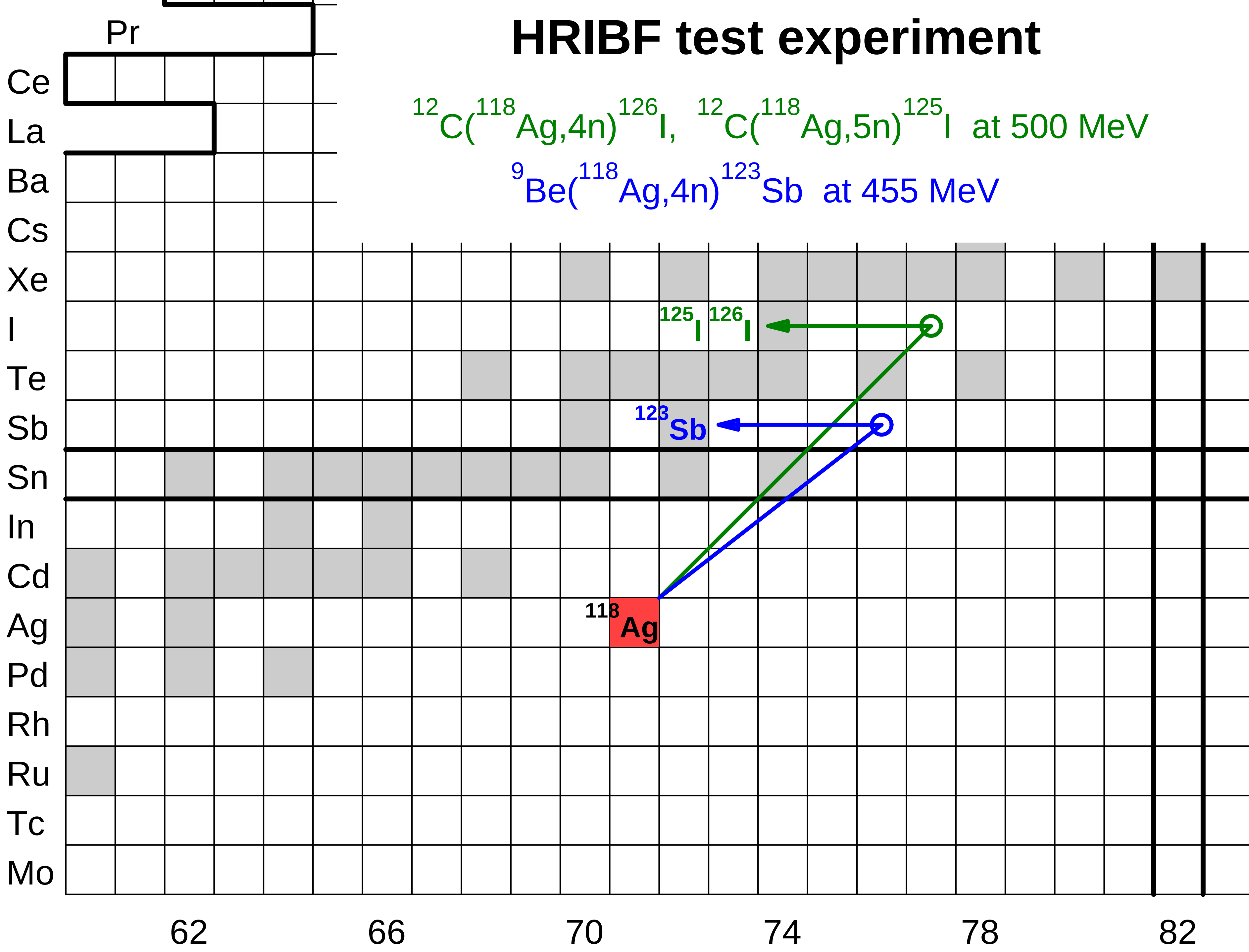
HyBall

95 CsI detectors with photodiodes

HRIBF test experiment

$^{12}C(^{118}Ag,4n)^{126}I$, $^{12}C(^{118}Ag,5n)^{125}I$ at 500 MeV

$^{9}Be(^{118}Ag,4n)^{123}Sb$ at 455 MeV

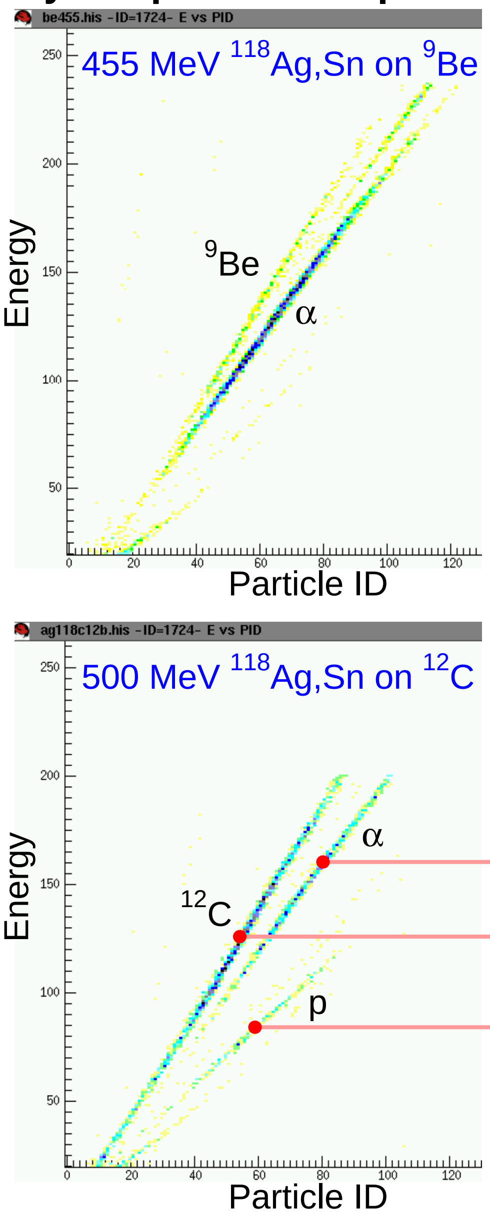


^{118}Ag Test Experiment: Particle-Gamma Coincidences

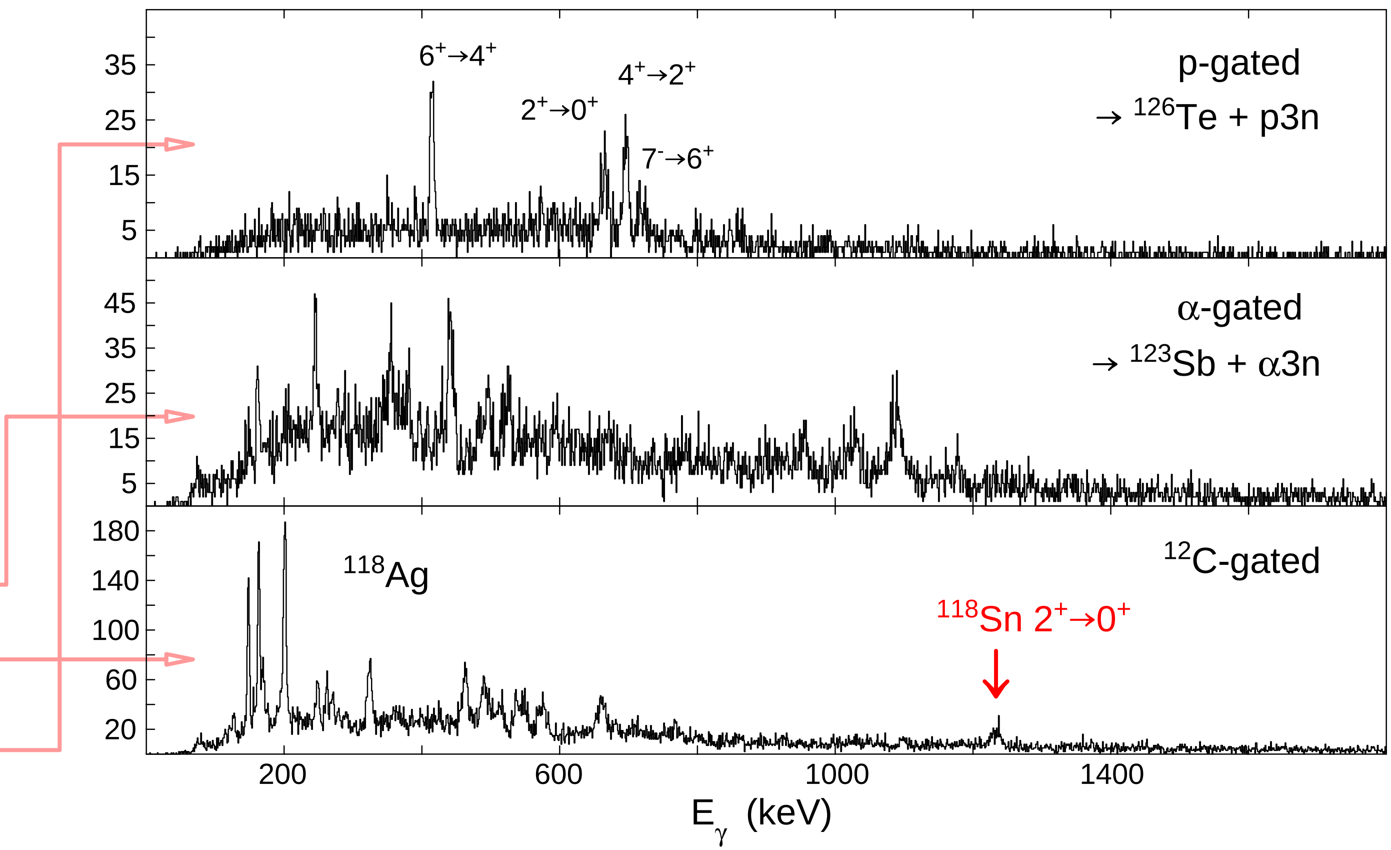
HyBall particle ID spectra:

^{118}Ag on Be and C targets

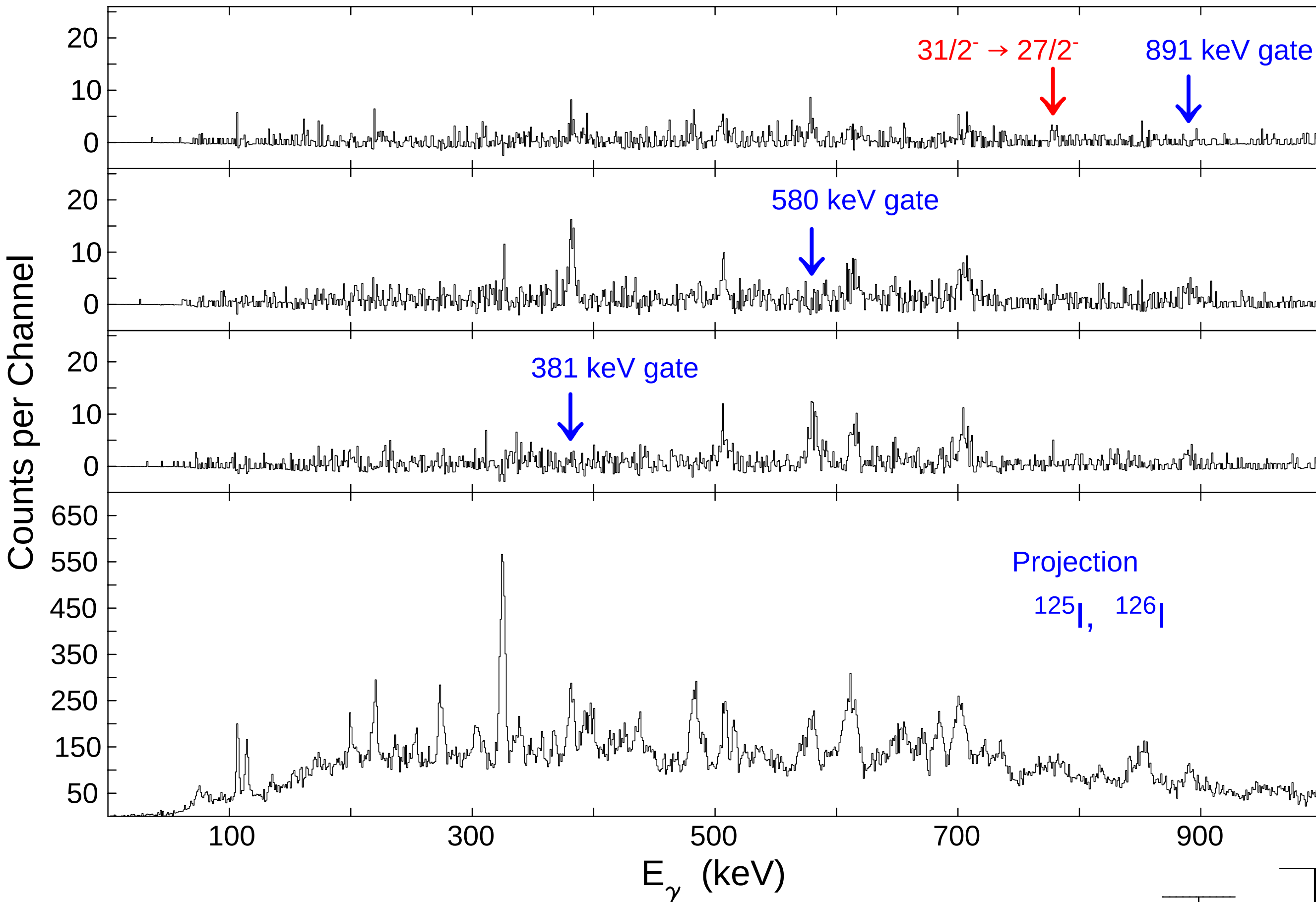
Small ^{118}Sn component of beam (~10%)

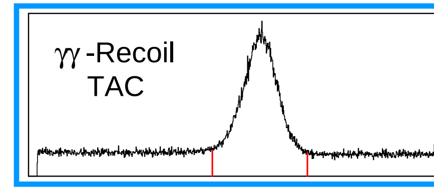


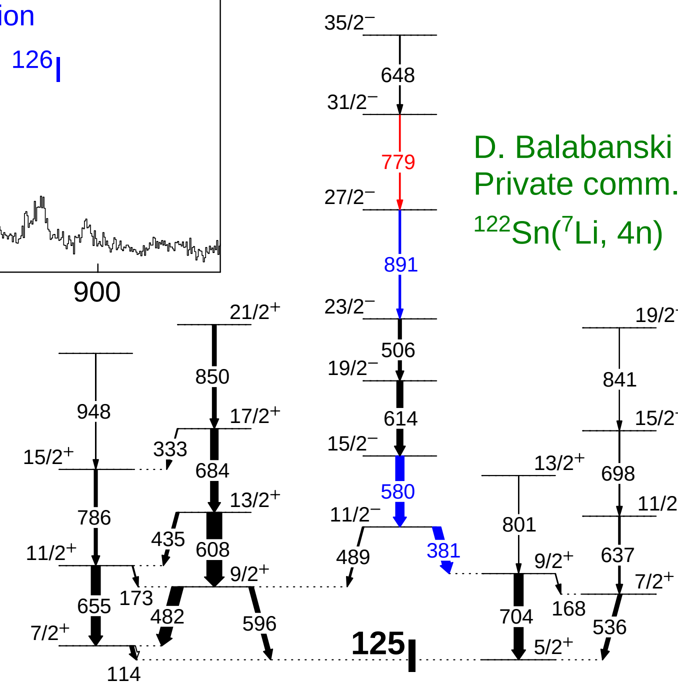
Gammas gated by charged particles:



Fusion-Evaporation Reactions







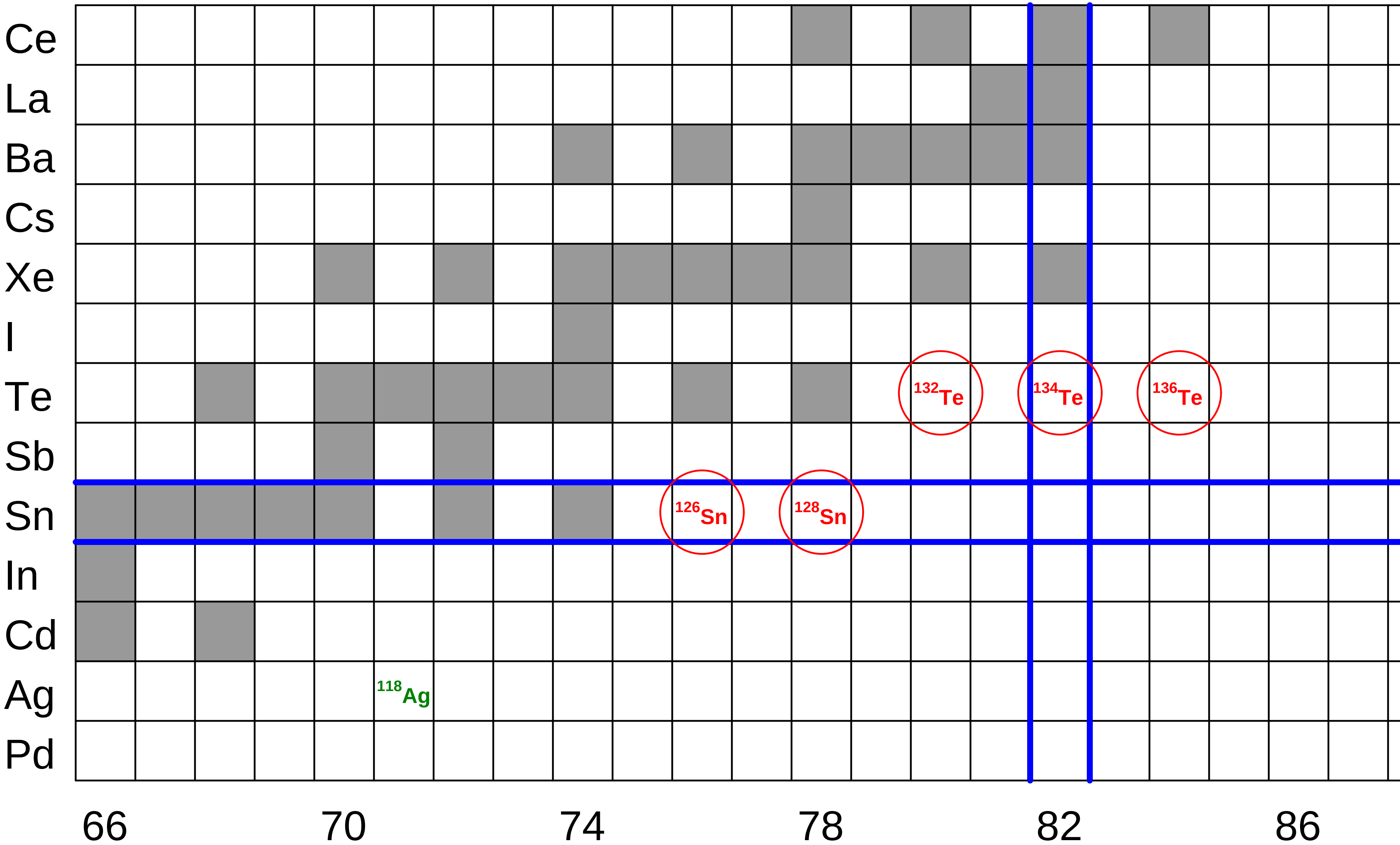
D. Balabanski *et al.* Private comm.

$^{122}Sn(^{7}Li, 4n)$

$^{12}C(^{118}Ag,5n)^{125}I$ at 500 MeV **γγ gates**

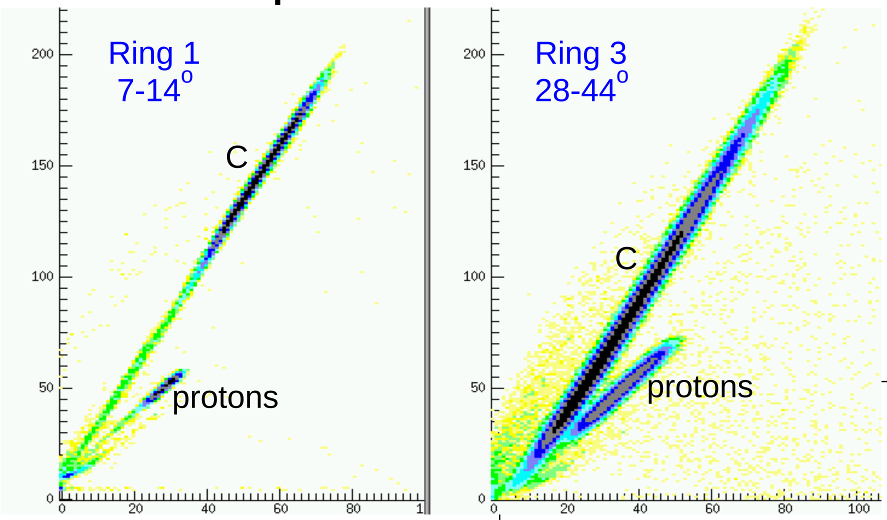
~10^6 ^{118}Ag /s for 33 hours

Coulomb Excitation Measurements Near ^{132}Sn



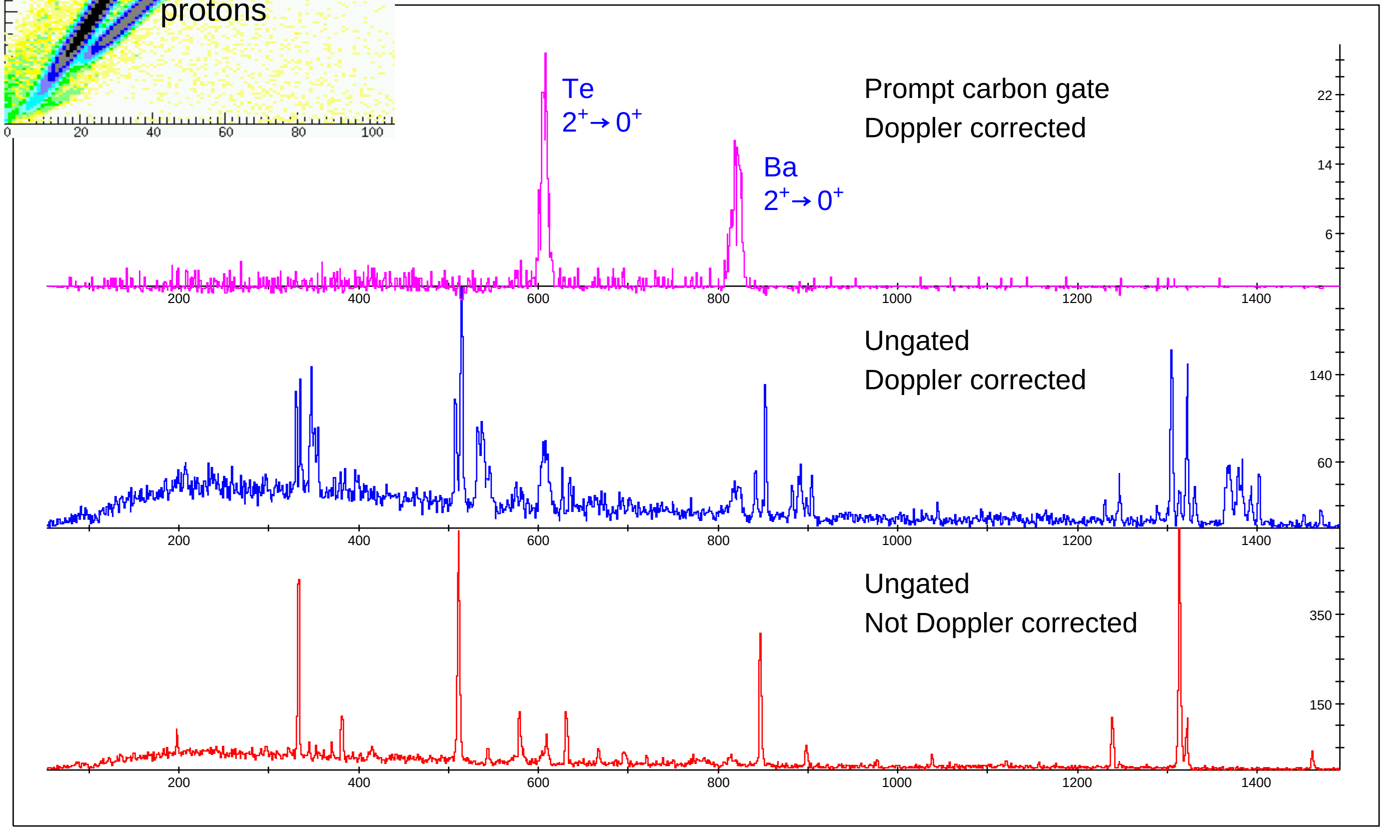
Example: A = 136 Coulex

Particle ID Spectra:

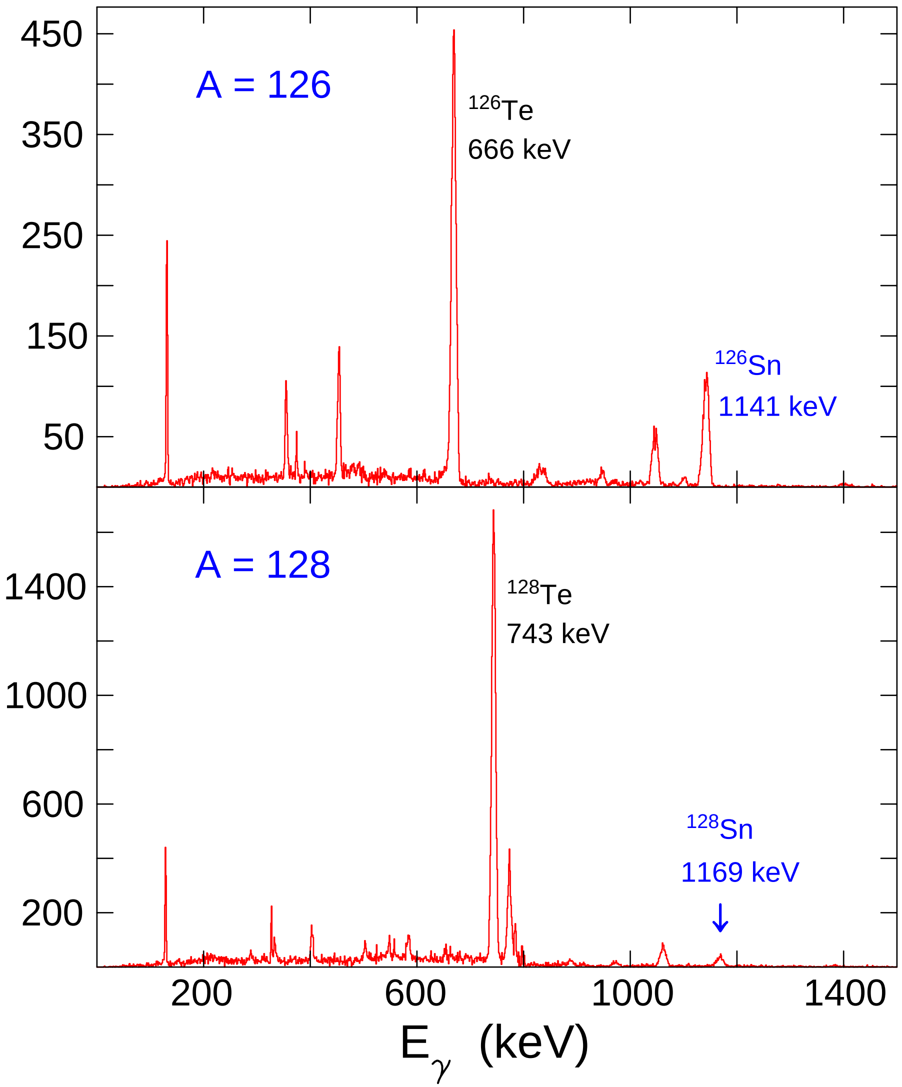


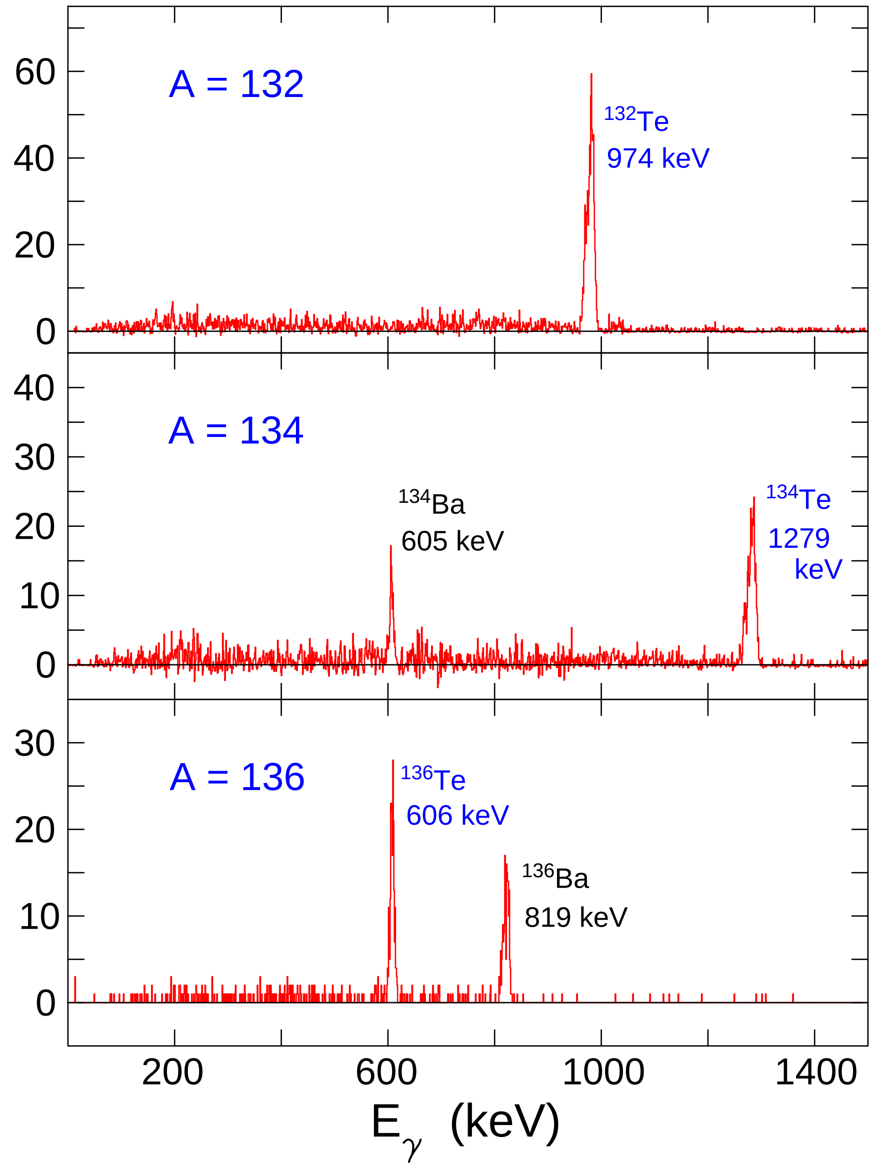
396 MeV ^{136}Te + ^{136}Ba

on 0.83 mg/cm^2 C target



Coulex Results: Sn & Te Spectra





Note multiple beam components

RIB Coulex Analysis

- **Measure** $$\frac{\gamma\text{-HyBall coincidences}}{\text{HyBall singles}} = \frac{\sigma_C}{\sigma_R}\,\varepsilon_\gamma$$

- **Calculate** $\frac{d\sigma}{d\Omega}$ **for Coulex and Rutherford as a function of B(E2)**

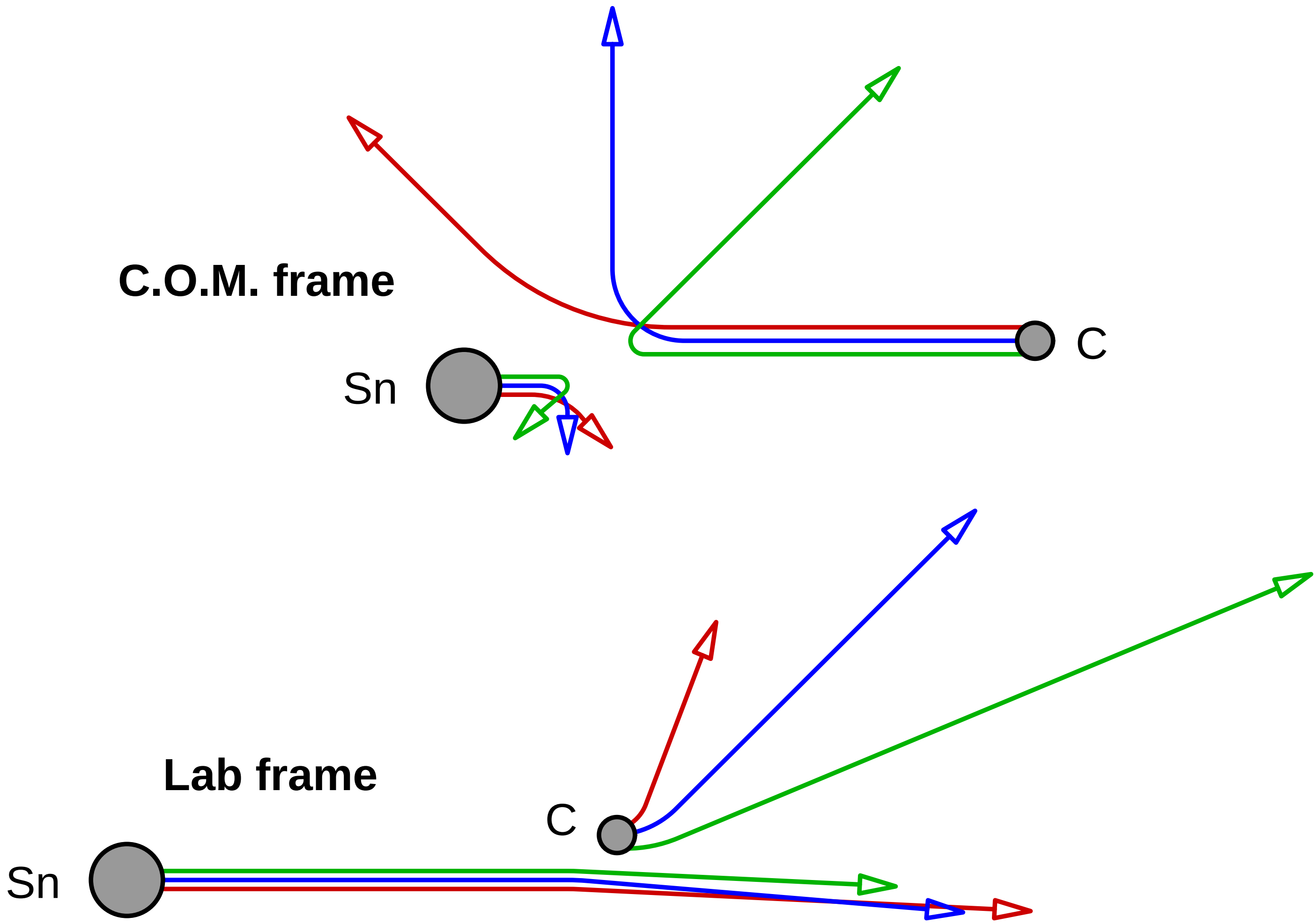
- **Integrate** σ **over the first three rings of HyBall**

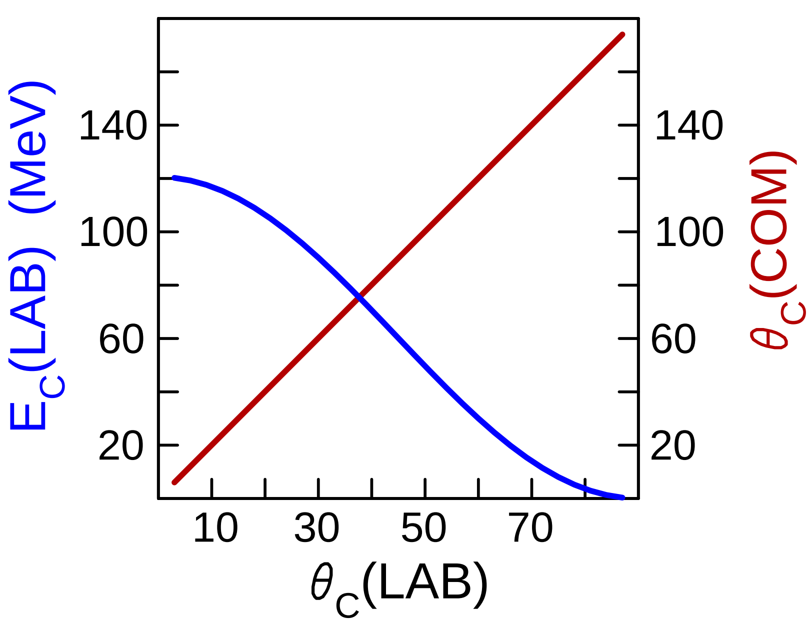
- **Compare calculated** $\frac{\sigma_C}{\sigma_R}\,\varepsilon_\gamma$ **with observed** $\frac{\gamma H}{H}$ **to get B(E2)**

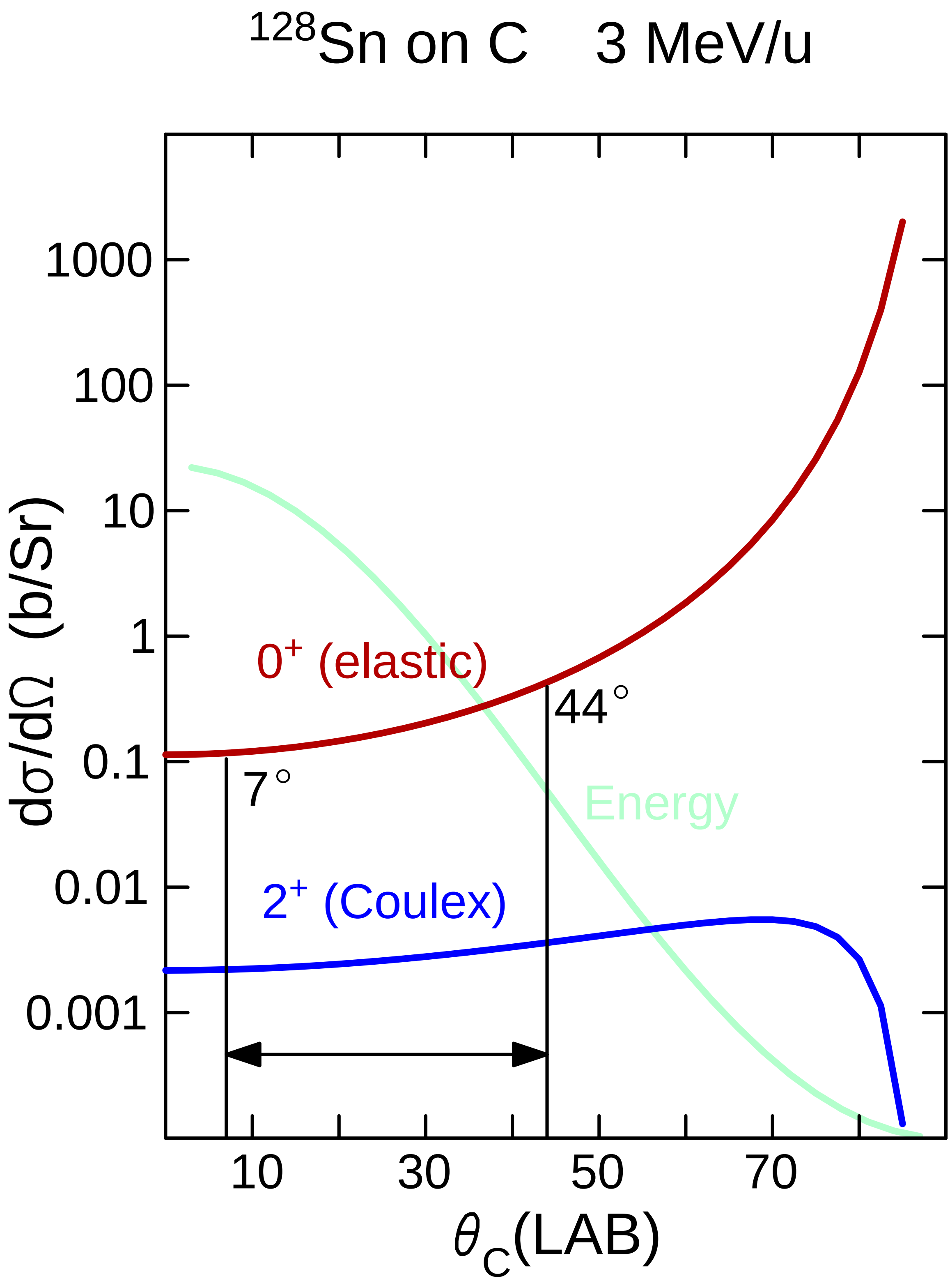
- **Correct for isobaric content of the beam**

  - determined from Coulex of stable contaminants,
    decay counting and X-ray spectra

Inverse Kinematics for Coulomb excitation





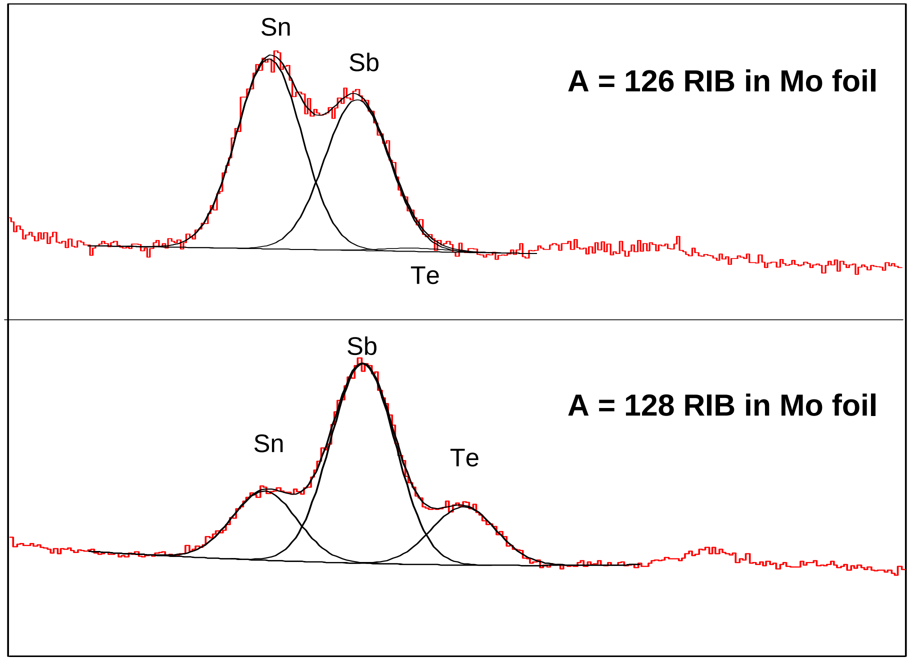


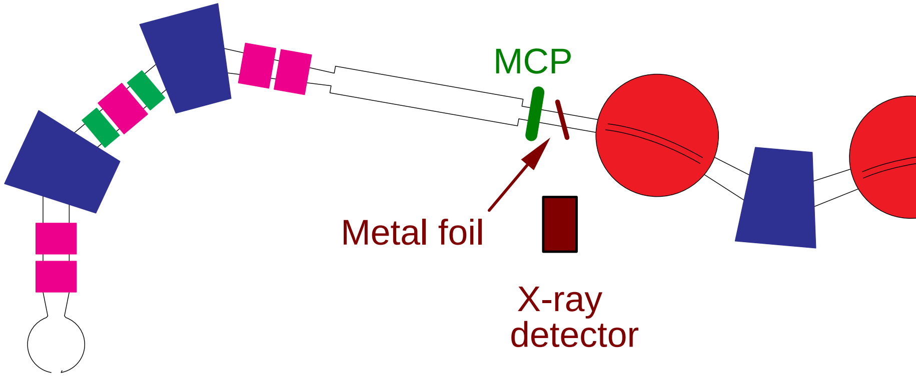
Angle-integrated:

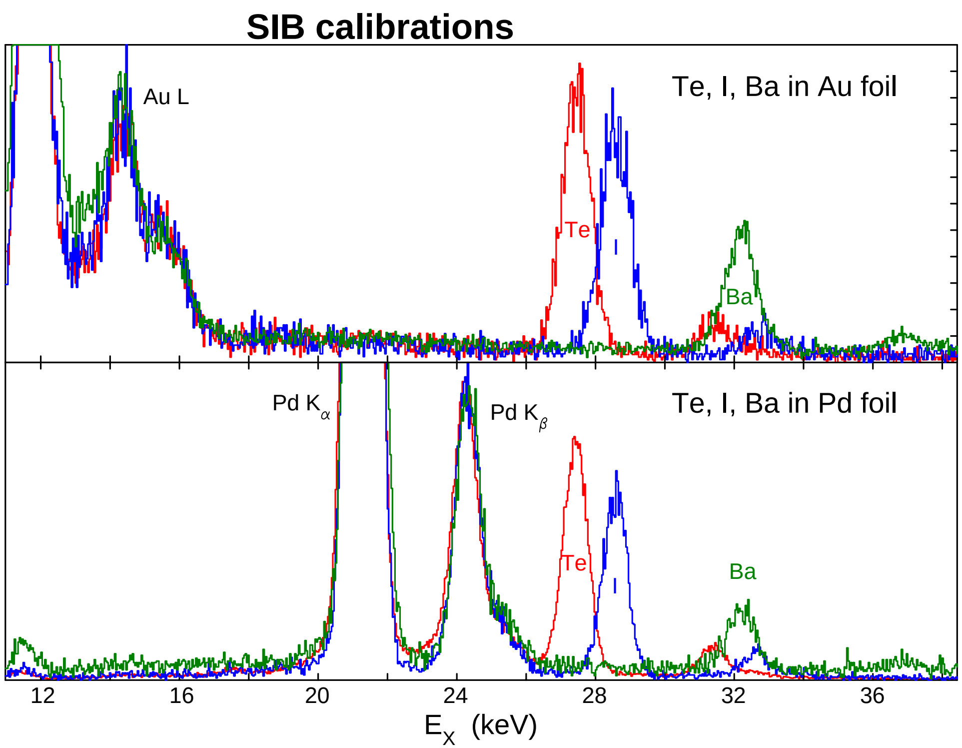
σ_{0^+} = 1460 mb

σ_{2^+} = 5 mb [for B(E2) = 0.1e^2b^2]

Beam Composition from X-rays







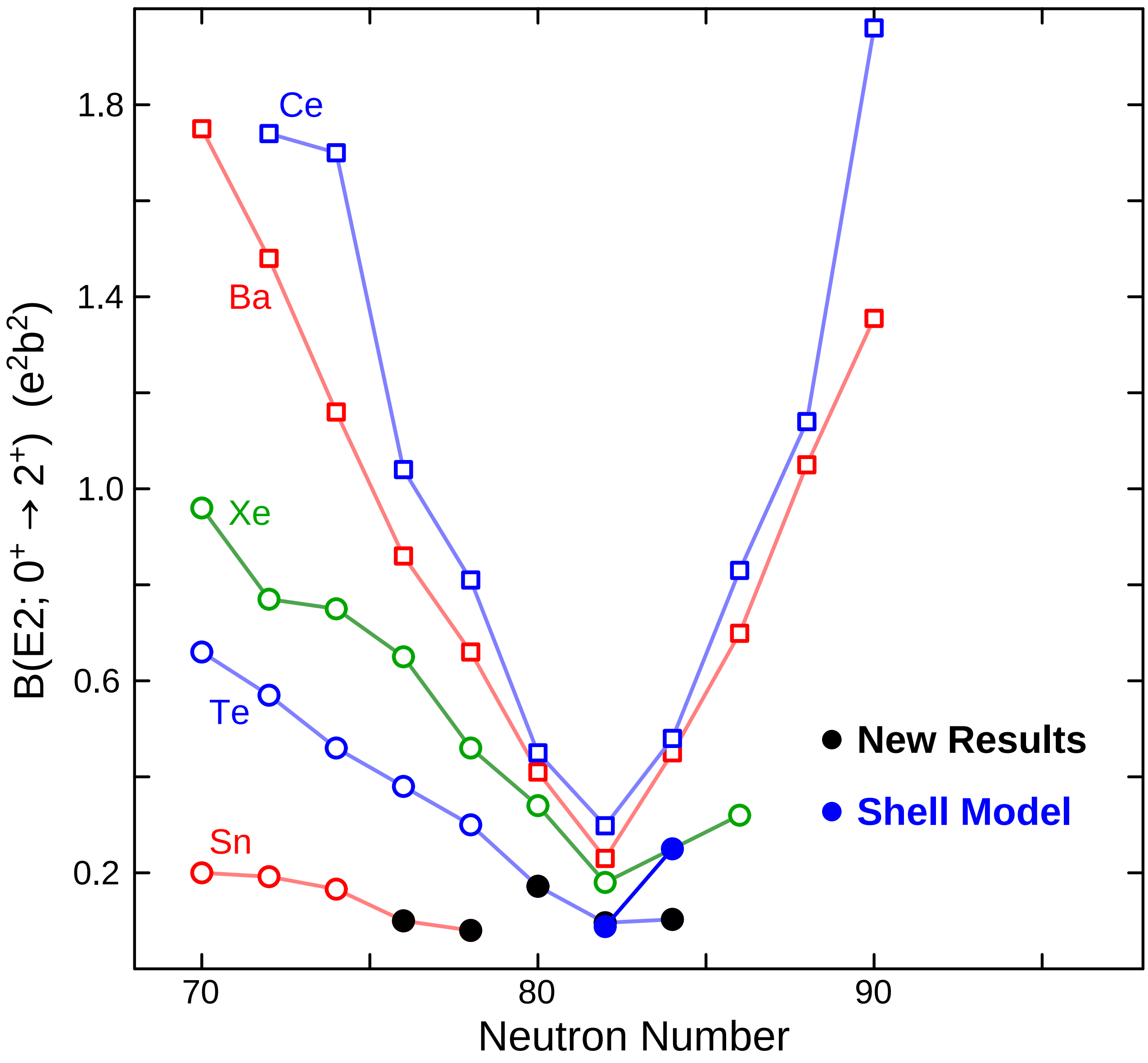
Tellurium Results

Beam	Nuclide	**fraction** (%)	γ-C	C	**B(E2; $0^+ \rightarrow 2^+$)** (e^2b^2)	
A=132 RIB	^{132}Te	86(4)	790(10)	1.7×10^7	0.172(17)	
	^{132}Sb	11(3)				
	^{132}Sn	1.3(3)				
	^{132}I	1.3(6)				
A=134 RIB	^{134}Te	87(4)	377(22)	1.6×10^7	0.096(12)	
	^{134}I	11(3)				
	^{134}Ba	1.0(2)[a]	119(15)			
	^{134}Sb	0.9(3)				
A=136 RIB	^{136}Te	59(5)	224(15)	3×10^6	0.103(15)	
	^{136}Ba	29(3)[a]				
	^{136}I	12(3)				
^{128}Te SIB	^{128}Te	100	1790(44)	5.5×10^6	0.346(26)	[0.383(6)]
^{136}Ba SIB	^{136}Ba	100	280(17)	1.4×10^6	0.46(4)	[0.410(8)]

[a]Calculated from observed excitation, using adopted values for the B(E2; $0^+ \rightarrow 2^+$) (0.66 e^2b^2 for ^{134}Ba, 0.41 e^2b^2 for ^{136}Ba)

[Adopted values]

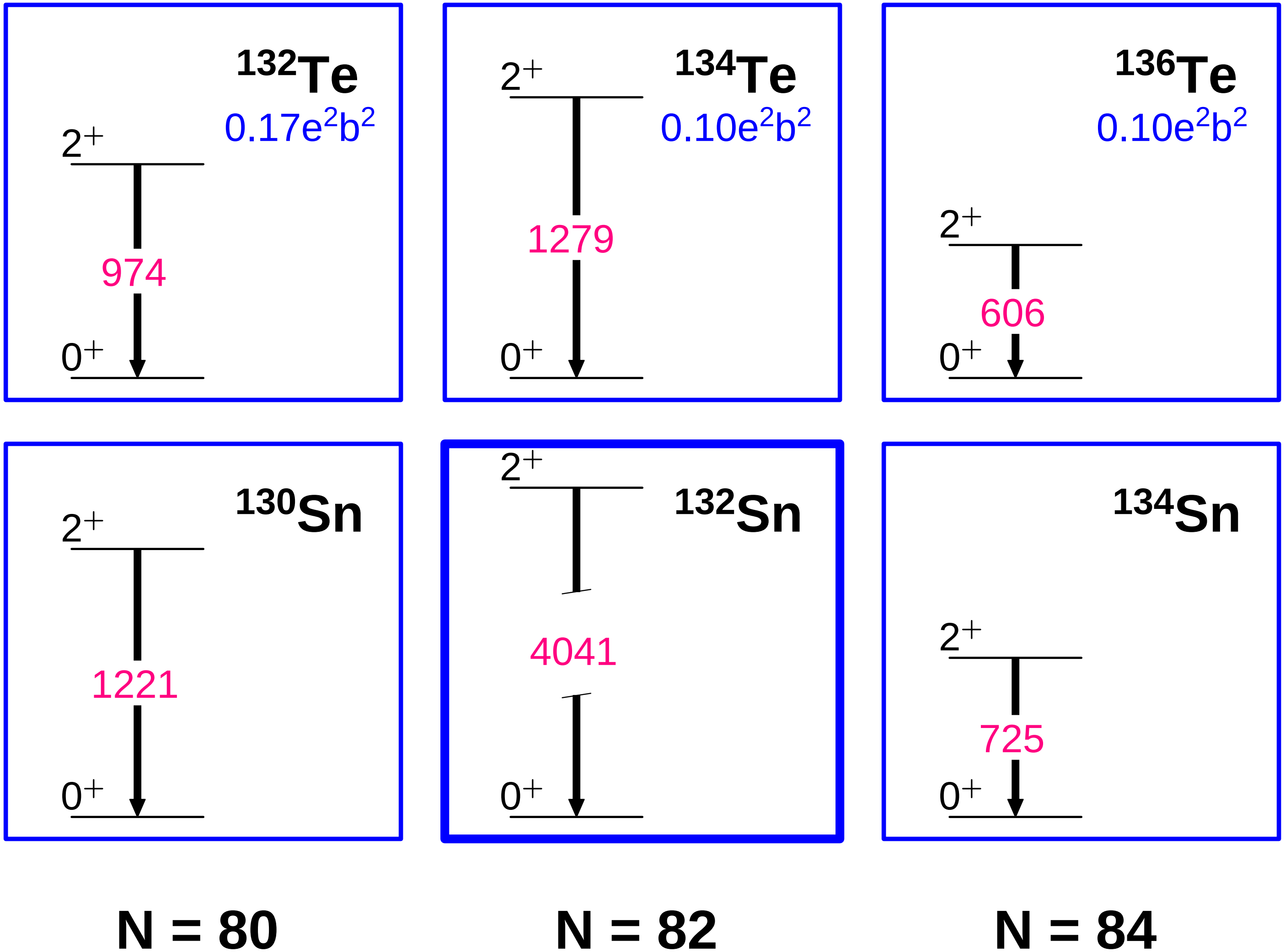
B(E2) Results and Systematics



^{136}Te: Low B(E2) Value

The low value for the B(E2) in ^{136}Te is very surprising

- Energy of 2^+ levels is also low



Quasiparticle RPA Calculations - J. Terasaki *et al.*

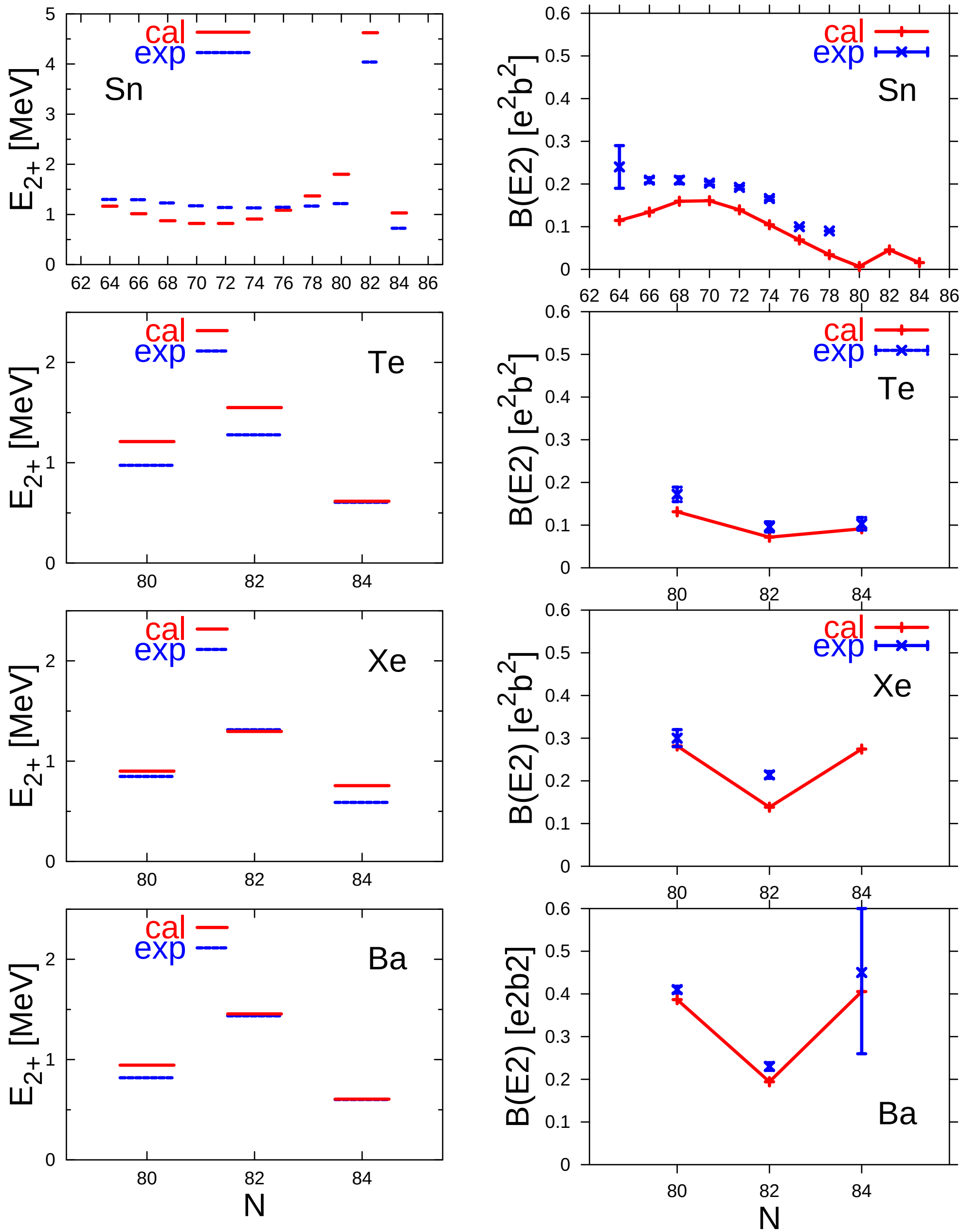
- Used separable quadrupole-plus-pairing Hamiltonian

- Single-particle energies taken from experiment whenever possible

- Two-body interaction: isQQ + ivQQ + Q-pairing forces

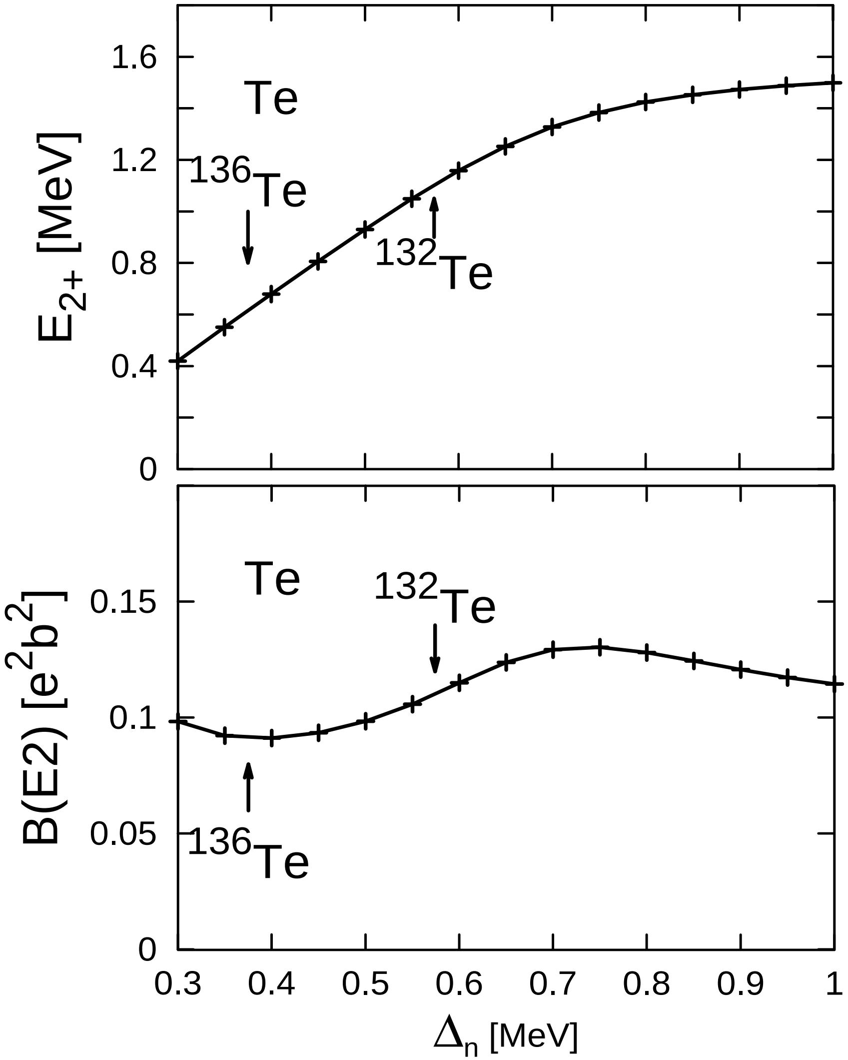
- Monopole pairing gaps taken from renormalized experimental odd-even mass differences where possible

- Large configuration space; B(E2)s calculated with bare charges



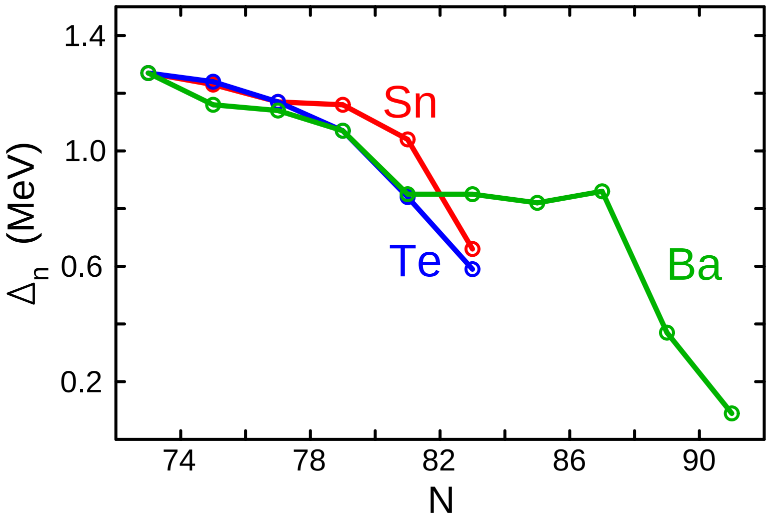
Submitted to Phys. Rev. C, 0208042

Quasiparticle RPA Calculations - J. Terasaki *et al.*



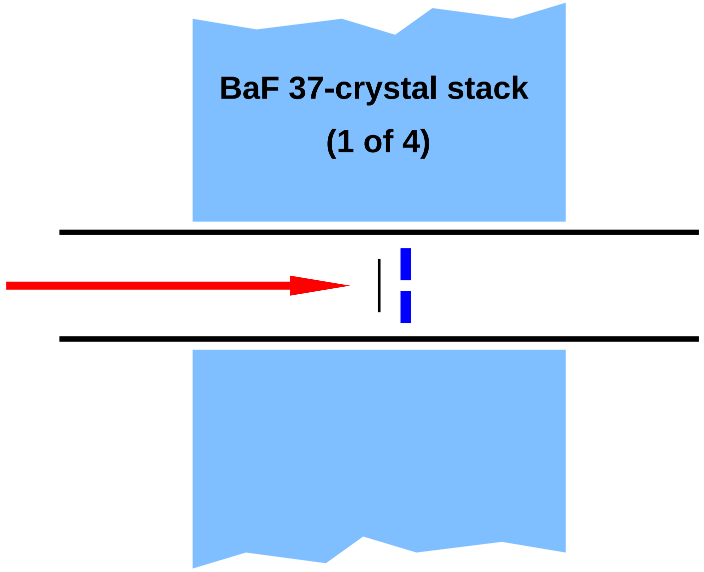
Energy and B(E2) both **decrease** for small values of neutron pairing gap

Neutron pairing strength from odd-even mass differences:



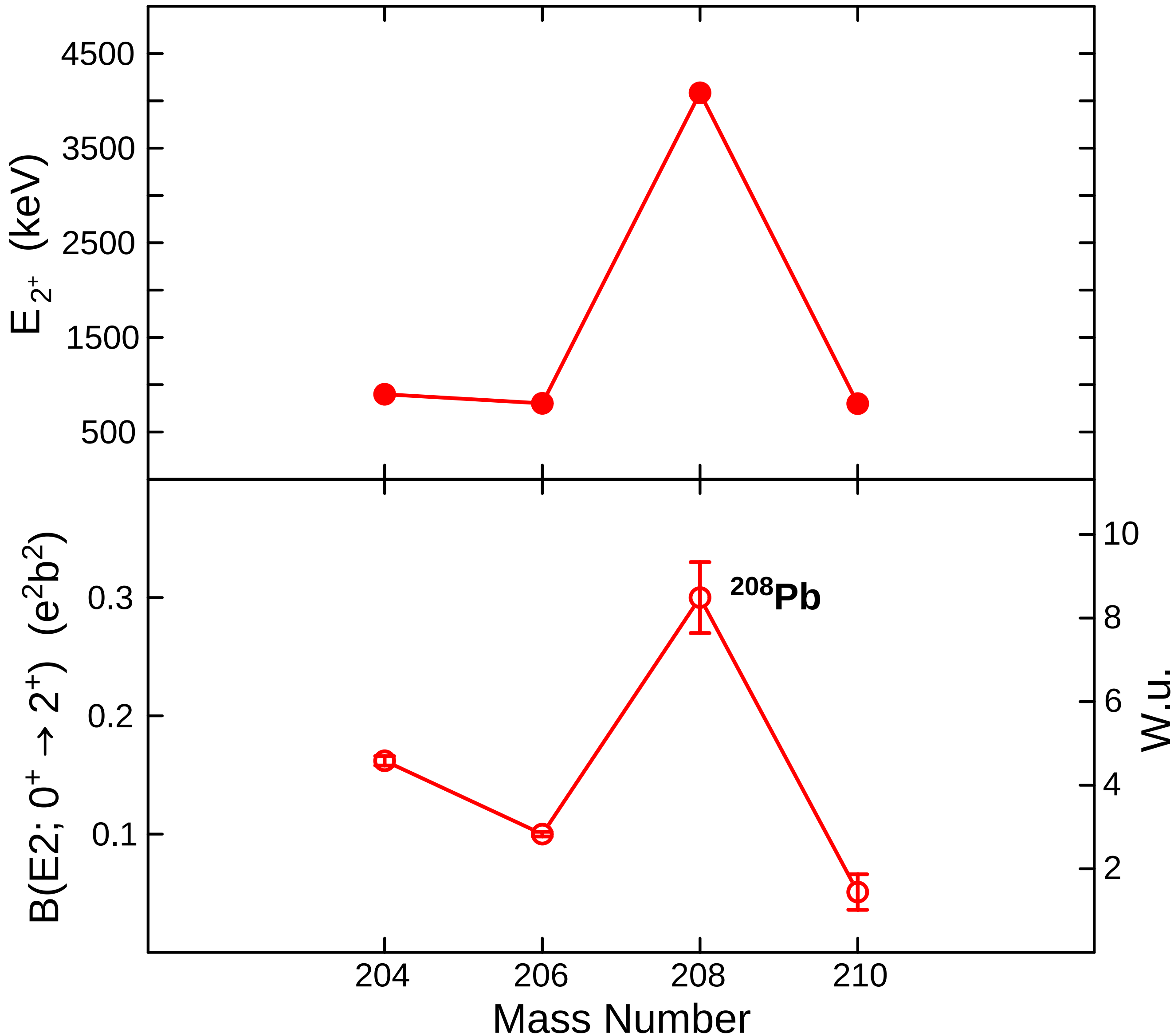
Future Plans: Coulex

- **B(E2) in ^{130}Sn** using pure Sn beam
- **Q_{2+} in ^{126}Sn by reorientation**
- **Odd-even and odd-odd nuclei**
  - Could populate many levels not observed in beta decay
- **B(E2) of 2^+ in ^{132}Sn** using pure Sn beam
  - E_x > 4 MeV
  - Analog to ^{208}Pb?
  - Use BaF array for high γ efficiency (~60%)
  - Use ^{48}Ti target and "slightly unsafe" energy



Lead B(E2) Systematics

^{208}Pb   B(E2) = 8.5 W.u.;   19% of Isoscalar E2 EWSR



Conclusions

- **Nuclear structure experiments with heavy post-accelerated RIBs are:**
  - → **Exciting**
  - → **Challenging**
  - → **Feasible!**

  Need a good clean trigger
  - combine detection of γ, light-ion, recoil, etc.

- **Have already shown that we can do fusion-evaporation and Coulex**

- **Transfer reactions are harder**
  - → Will need high-efficiency γ-detection to select populated levels

→ Waiting for RIA with much anticipation!