

Nuclear shapes, coexistence and collective behaviors studied at ISAC

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ISAC 20 Symposium

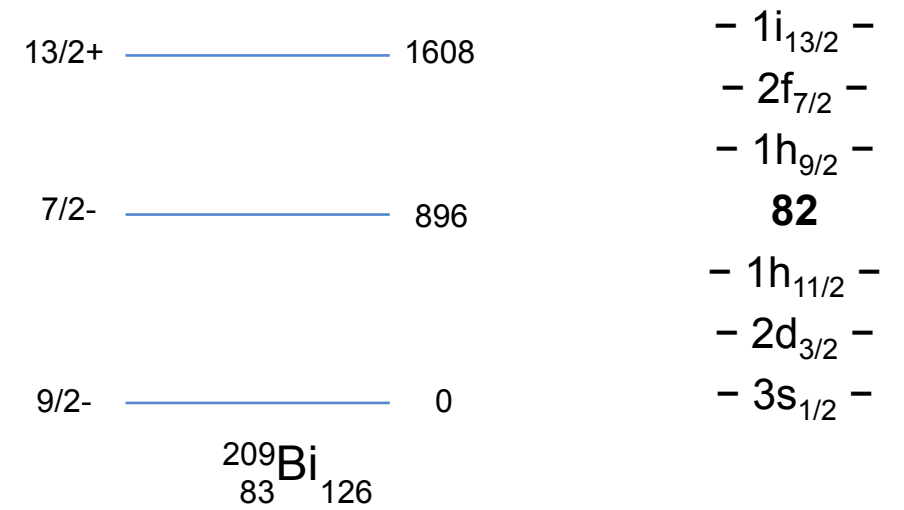
August 21st, 2019; TRIUMF, Vancouver, Canada

Excitations in atomic nuclei

- Microscopic
 - How are the complex and diverse features of nuclear structure constructed from a few elementary building blocks?
 - What is the force that binds nuclei?
- Macroscopic
 - How do complex nuclear systems (~ 200 nucleons) display such simple and regular patterns?
 - What are the simple patterns which nuclei display and what are their origins?

Microscopic

- Single-particle structure or seniority scheme, “Shell model”

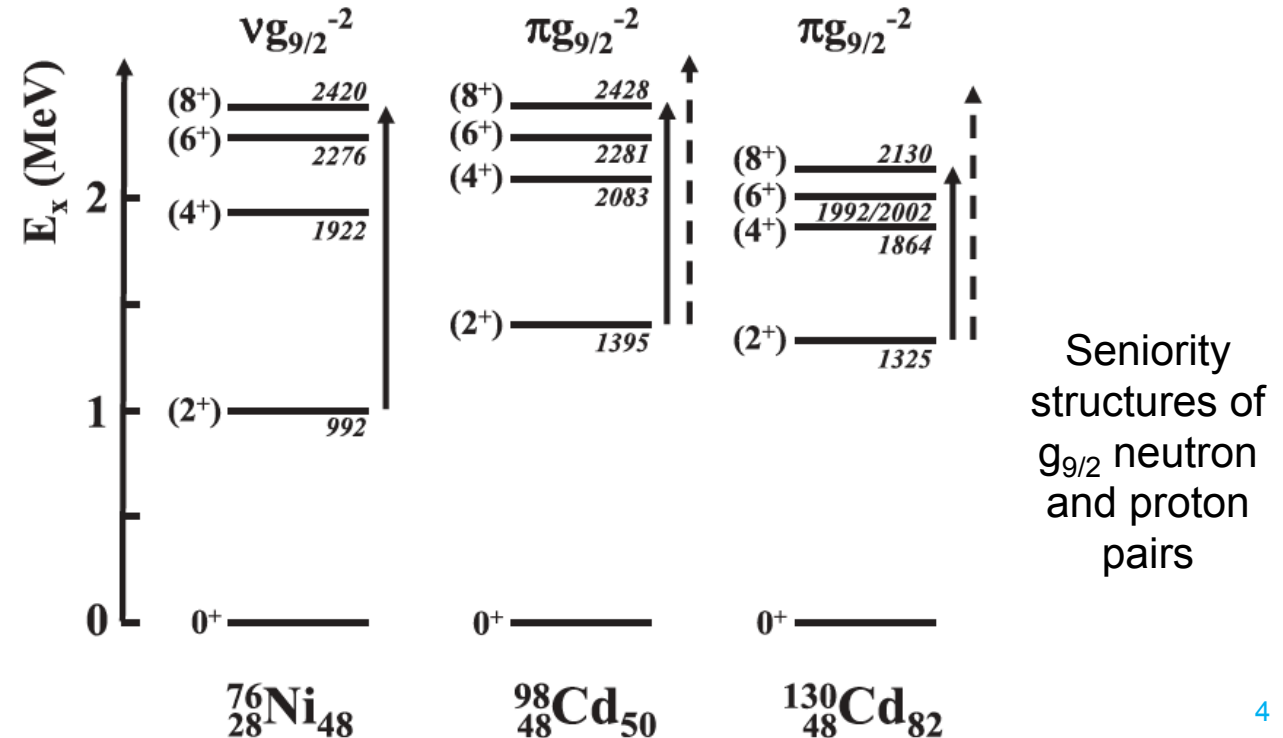
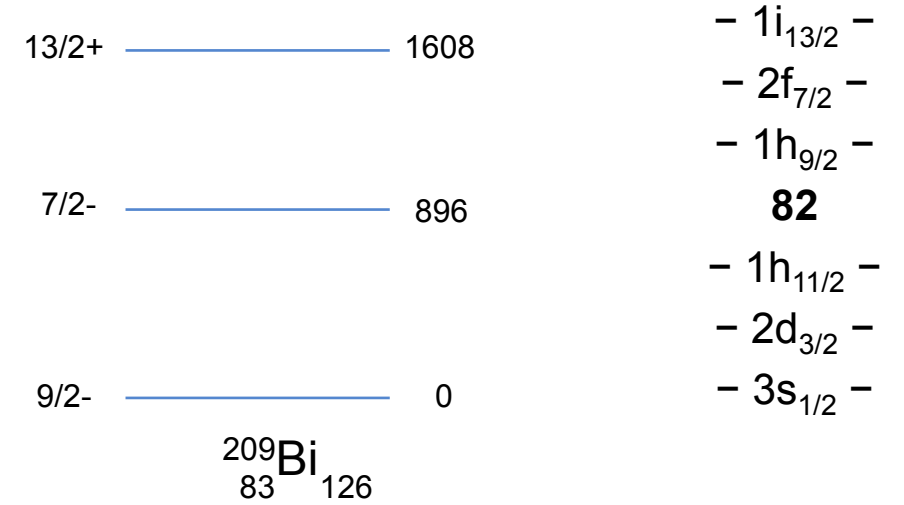


Microscopic

- Single-particle structure or seniority scheme, “Shell model”
- High 2^+ energy, small transition probability
- Angular momentum from alignment of last pair intrinsic spins

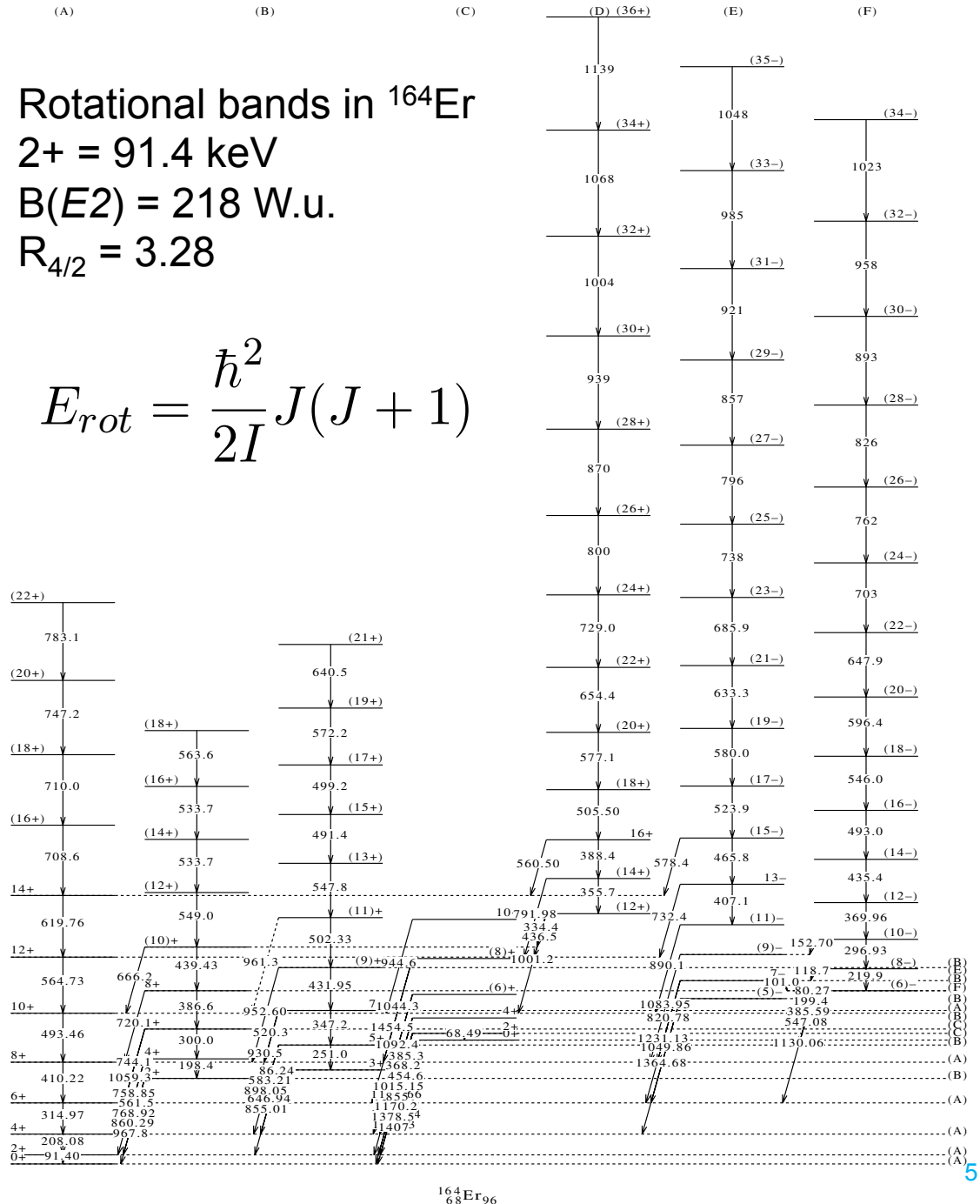
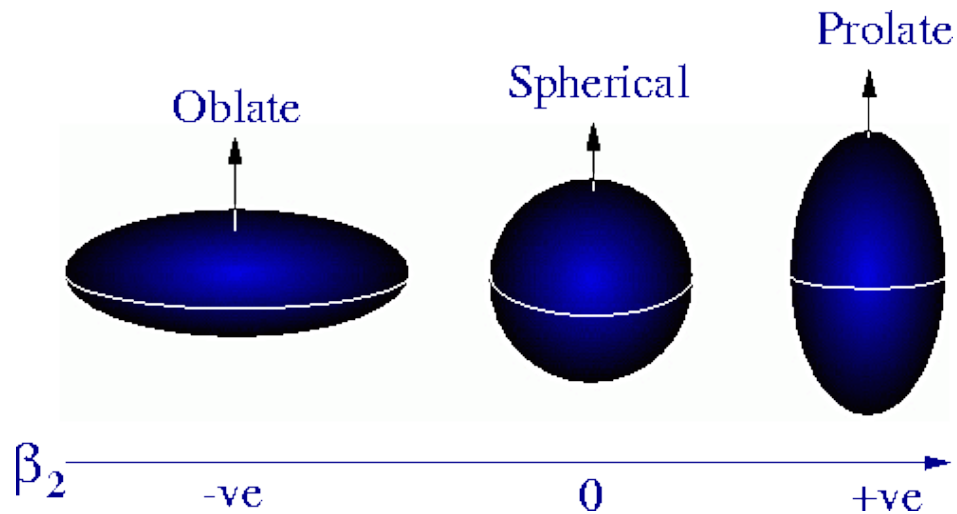
Seniority = number of nucleons not paired to zero angular momentum

Figure from: A. Jungclaus *et al.*, PRL 99, 132501 (2007)

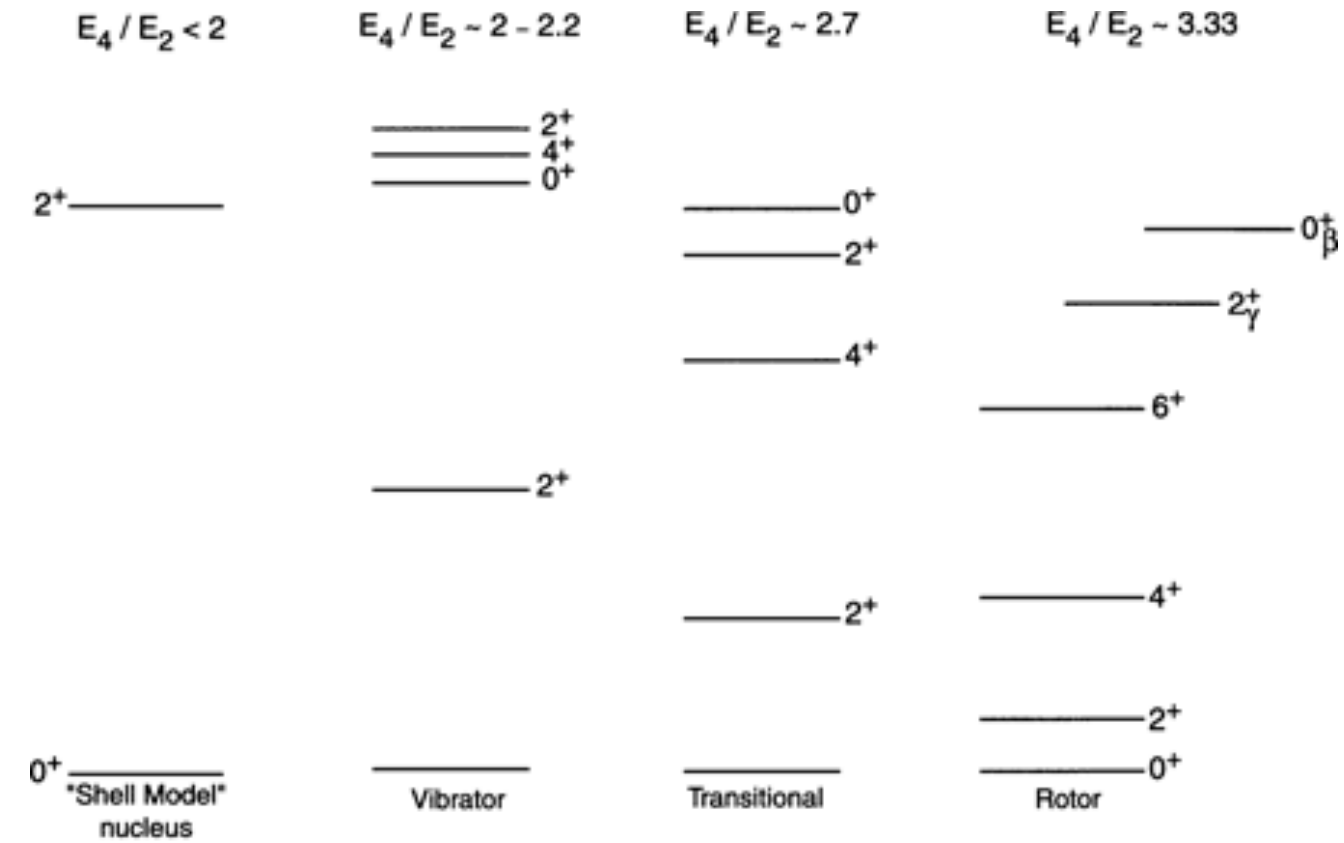


Macroscopic

- Deformed shape, collective motion, rotational bands
- Low 2^+ energy, large transition probability
- Angular momentum from collective motion of entire nucleus



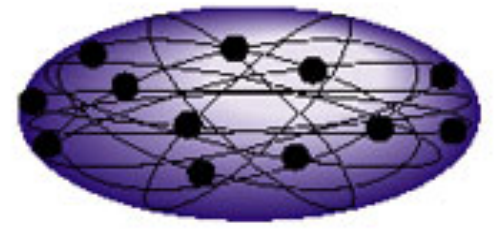
Evolution between Microscopic to Macroscopic



SCHMATIC EVOLUTION OF STRUCTURE
NEAR CLOSED - SHELL → MID SHELL



independent particle motion
(single particle motion)
↓
weak gamma transition
spherical shape



correlated particle motion
(collective rotation, vibration)
↓
strong gamma transition
rugby football or pancake shape

How and why is there a transition from
apparent microscopic to macroscopic
structures?

What is the microscopic origin of the
macroscopic structures?

Figures from:
<http://www.nsl.msui.edu/>, and
R.F. Casten, Nuclear Structure from a simple perspective, 2001

Evolution between Microscopic to Macroscopic

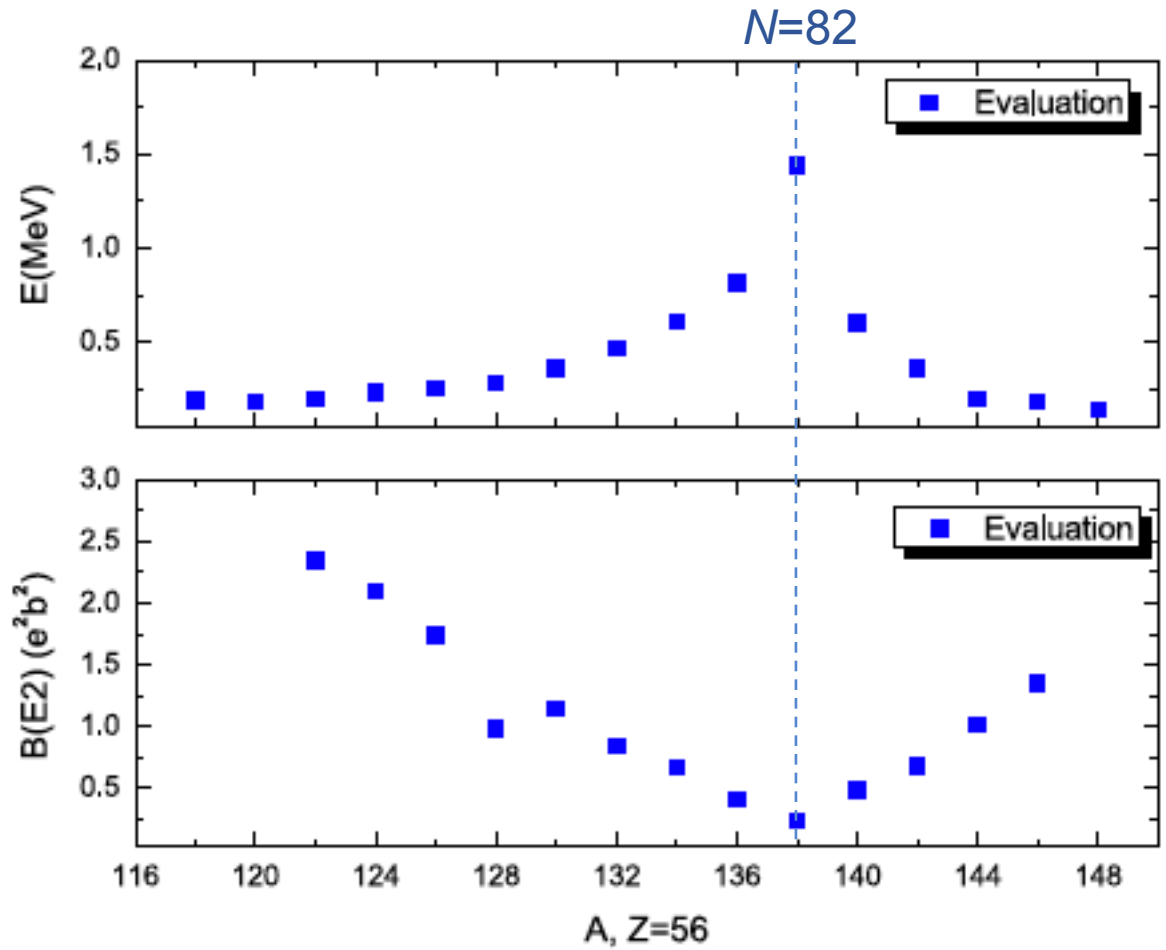
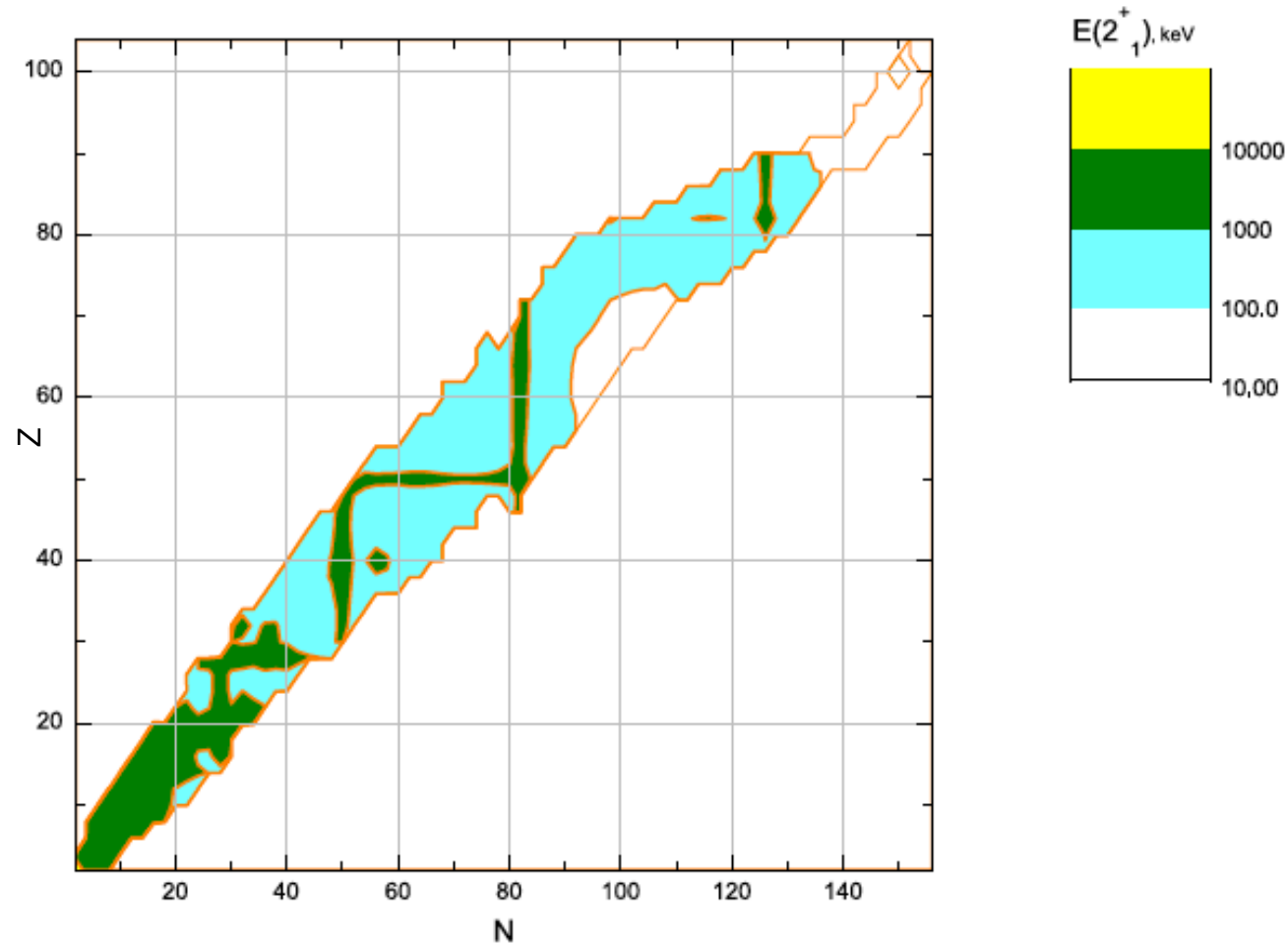


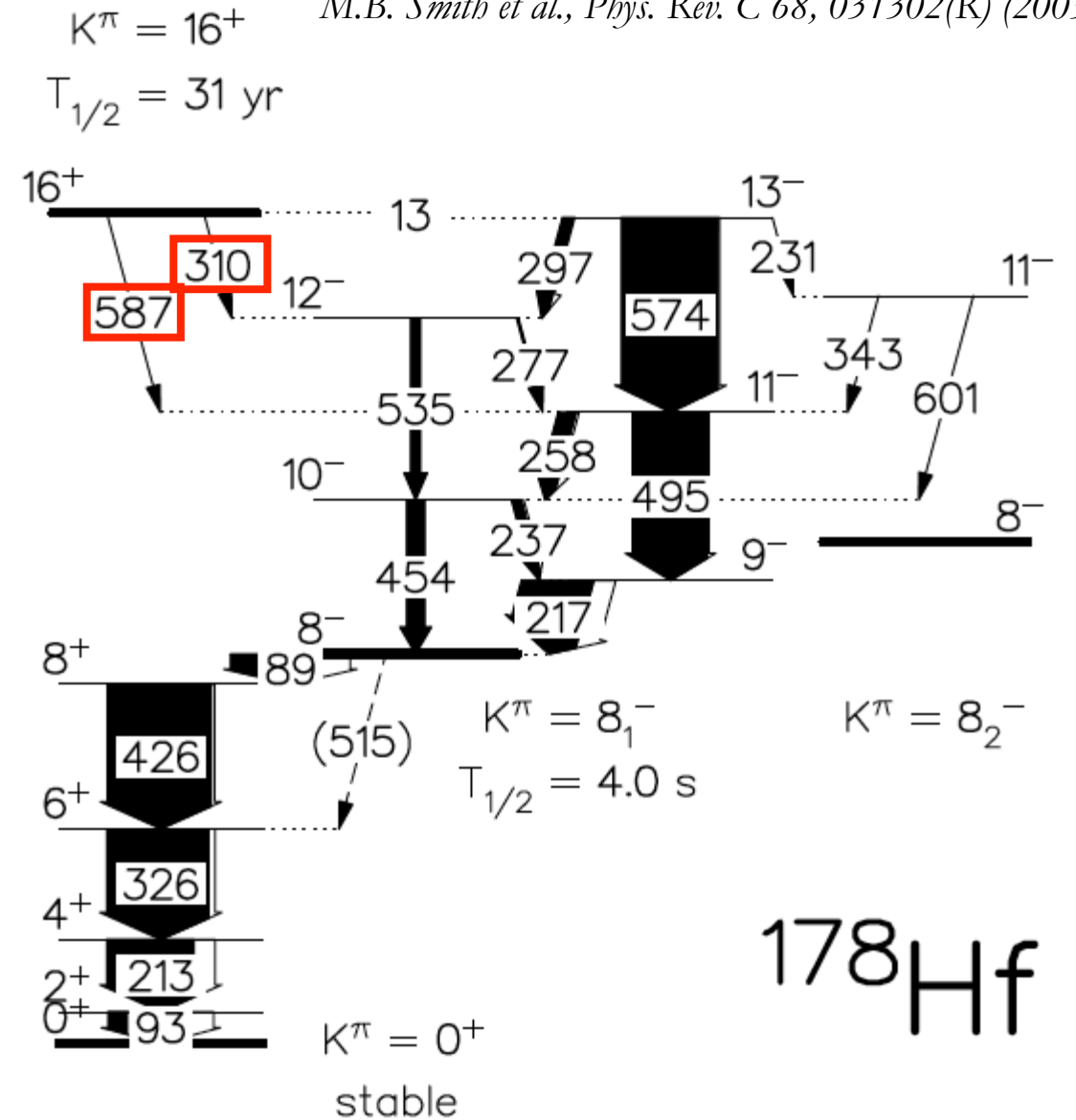
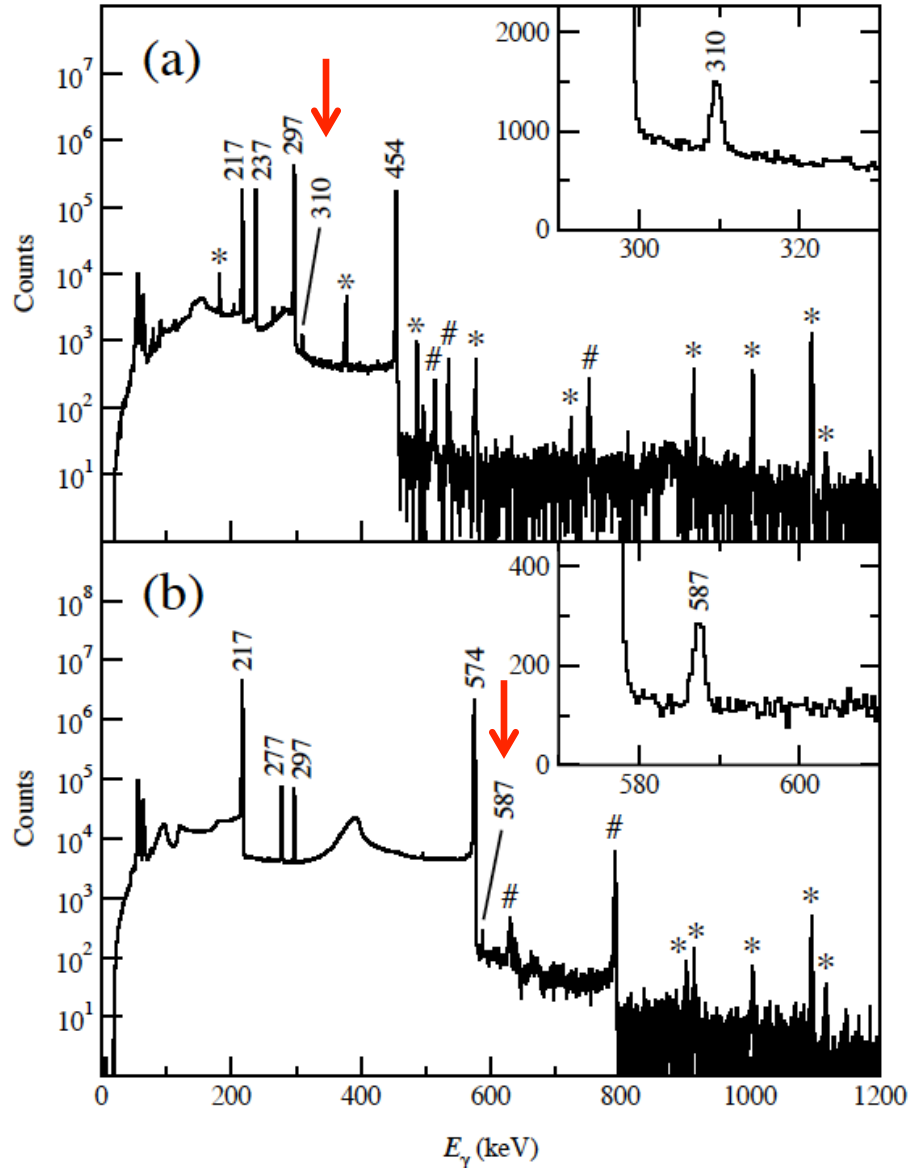
Fig. 3. Energies of 2_1^+ states ($E(2_1^+)$) for even-even $Z = 2-104$ nuclei, in keV.

Graph 28. Evaluated energies, $E(2_1^+)$, and $B(E; 0_1^+ \rightarrow 2_1^+)$ values for Ba nuclei.

8π : Gamma Decay of the 31-year $K^\pi = 16^+$ Isomer in ^{178}Hf

Experiment: December 2002

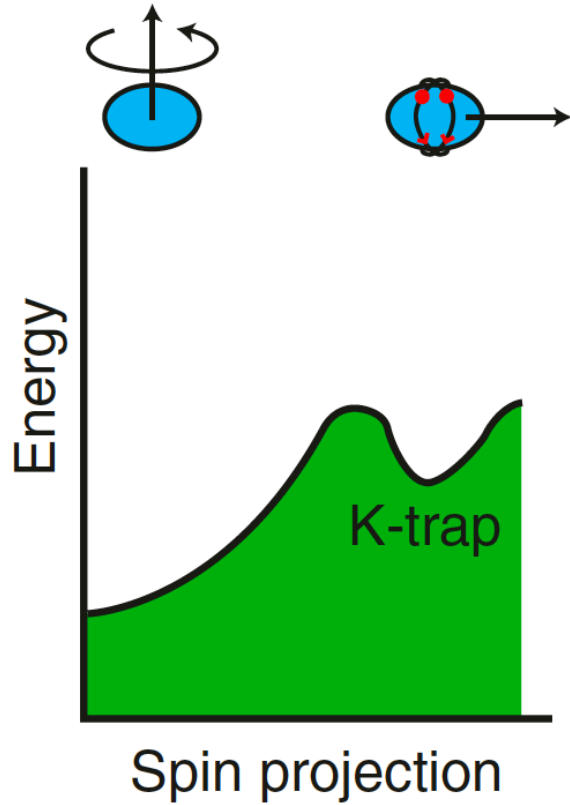
M.B. Smith et al., Phys. Rev. C 68, 031302(R) (2003).



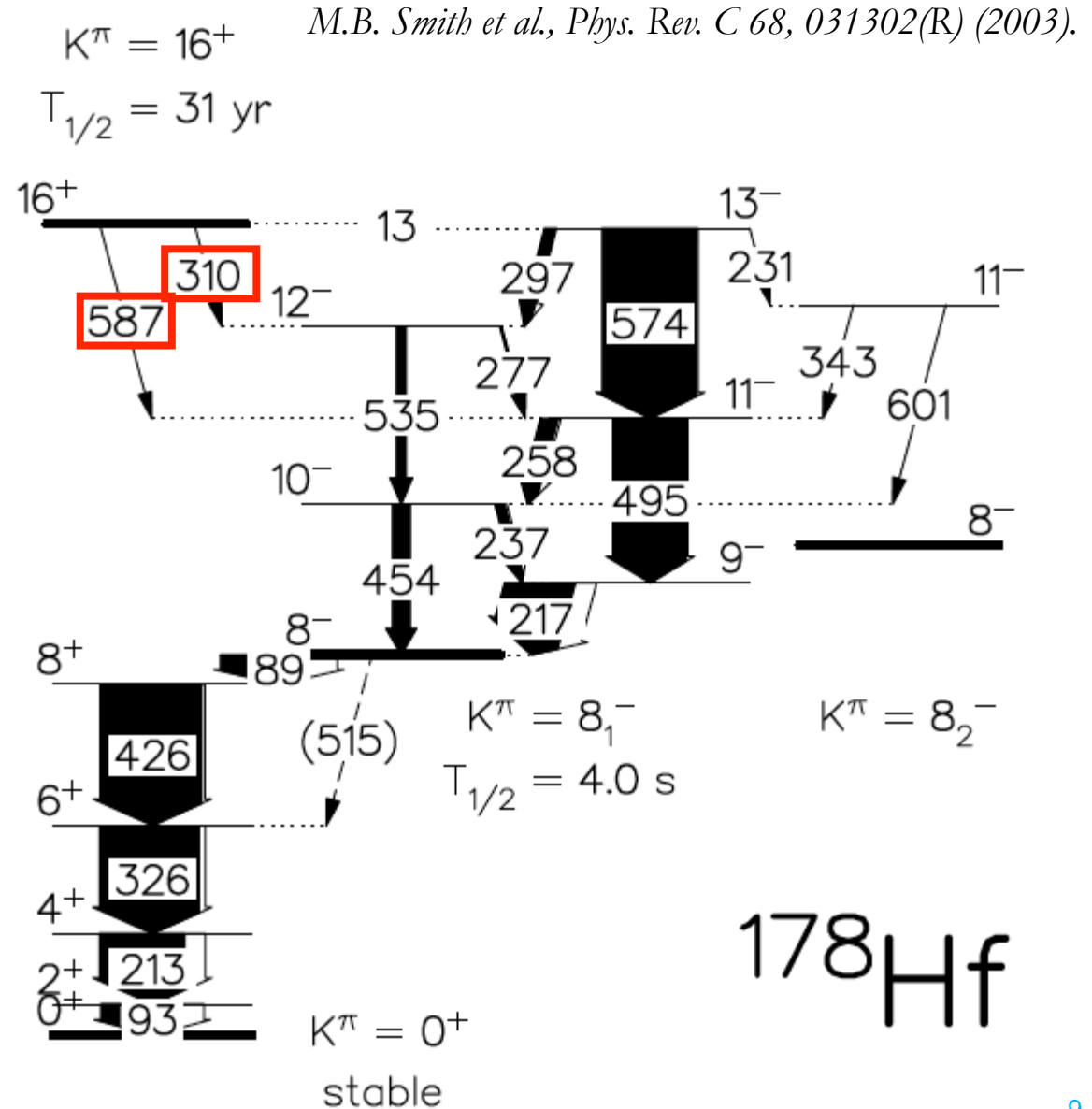
8π: Gamma Decay of the 31-year $K^\pi = 16^+$ Isomer in ^{178}Hf

First observation of M4 and E5 decay of a high-K isomer

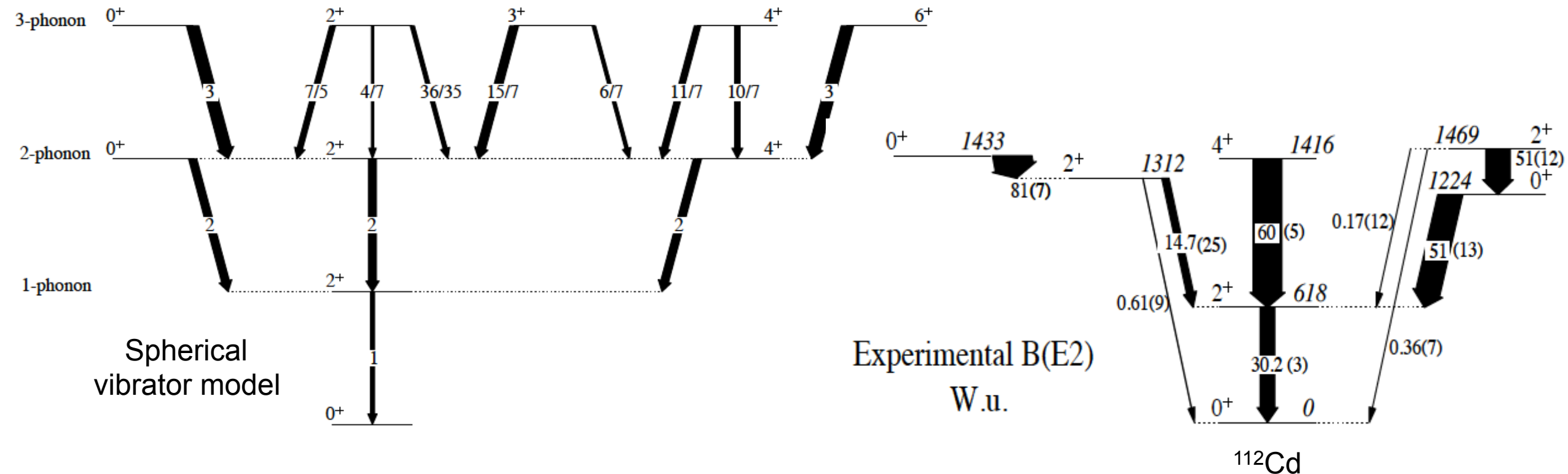
- reduced K hindrances ~ 100



K is total angular momentum projection on symmetry axis



Detailed scrutiny of collective models



Nuclear Structure from High-Statistics Beta-Decay

P.E. Garrett, Univ. of Guelph
C. Andreoiu, SFU

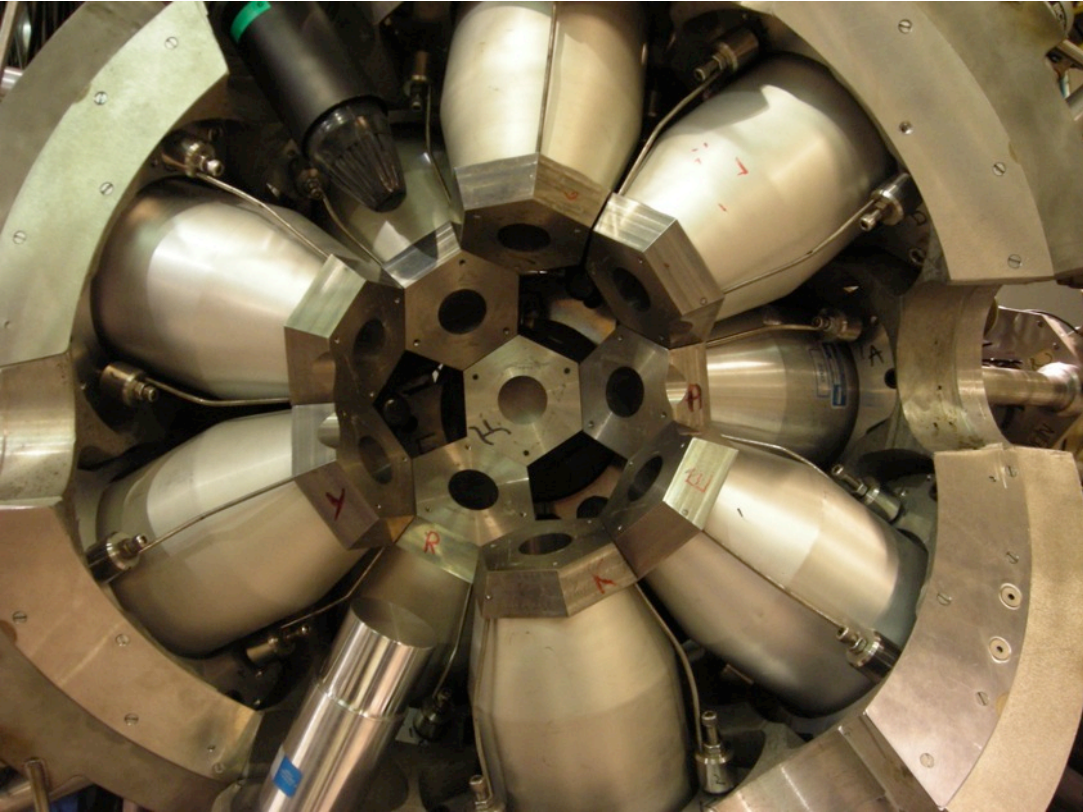
												124	Ba125	Ba126	Ba127	Ba128	Ba129	Ba130
												0 m	3.5 m	100 m	12.7 m	2.43 d	2.23 h	0+
												+	1/2(+)	0+	1/2+	0+	1/2+	0+
												EC	EC	EC	EC	EC	EC	0.106
												123	Cs124	Cs125	Cs126	Cs127	Cs128	Cs129
17 Us	0.57 s	1.4 s	3.84 s	8.4 s	14 s	43.0 s	64 s	155 s	21.0 s	5.94 m	30.8 s	45 m	1.64 m	6.25 h	3.66 m	32.06 h		
	(1+)		>4+	(9/2+)	2	9/2+	2	3/2(+)	1+	1/2+	1+	(1/2+)	1+	1/2+	1+	1/2+		
EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC		
Xe112	Xe113	Xe114	Xe115	Xe116	Xe117	Xe118	Xe119	Xe120	Xe121	Xe122	Xe123	Xe124	Xe125	Xe126				
2.7 s	2.74 s	10.0 s	18 s	59 s	61 s	3.8 m	5.8 m	40 m	40.1 m	20.1 h	2.08 h	1.6E+14 y	16.9 h	0+				
0+		0+	(5/2+)	0+	5/2(+)	0+	(5/2+)	0+	5/2(+)	0+	(1/2)+	0+	(1/2)+	0+				
EC,α	α,EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	ECEC	EC	0.09				
												122	123	124	125			
2.5 s	3.42 s	6.6 s	2.1 s	13 m	2.91 s	2.22 m	13.7 m	19.1 m	81.0 m	2.12 h	3.63 m	13.27 h	4.1760 d	59.408 d				
(5/2+)			1+	(5/2+)	1+	(5/2+)	2-	5/2+	2-	5/2+	1+	5/2+	2-	5/2+				
EC,α	EC,α	α,EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC				
Tell10	Tell11	Tell12	Tell13	Tell14	Tell15	Tell16	Tell17	Tell18	Tell19	Tell20	Tell21	Tell22	Tell23	Tell24				
18.6 s	19.3 s	2.0 m	1.7 m	15.2 m	5.8 m	2.49 h	62 m	6.00 d	16.03 h	0+	16.78 d	0+	1E+13 y	0+				
0+		0+	(7/2+)	0+	7/2+	0+	1/2+	0+	1/2+	0+	1/2+	0+	1/2+	0+				
EC,α	EC	EC	EC	EC	EC	EC	EC	EC	EC	0.096	EC	2.603	0.908	4.816				
Sb109	Sb110	Sb111	Sb112	Sb113	Sb114	Sb115	Sb116	Sb117	Sb118	Sb119	Sb120	Sb121	Sb122	Sb123				
17.0 s	23.0 s	75 s	51.4 s	6.67 m	3.49 m	32.1 m	15.8 m	2.80 h	3.6 m	38.19 h	15.89 m	5/2+	2.7238 d	7/2+				
(5/2+)	3+	(5/2+)	3+	5/2+	3+	5/2+	3+	5/2+	1+	5/2+	1+	5/2+	2-	7/2+				
EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	EC	57.36	EC,β	42.64				
Sn108	Sn109	Sn110	Sn111	Sn112	Sn113	Sn114	Sn115	Sn116	Sn117	Sn118	Sn119	Sn120	Sn121	Sn122				
10.30 m	18.0 m	4.11 h	35.3 m	0+	115.09 d	0+	35.3 m	0+	1/2+	0+	1/2+	0+	27.06 h	0+				
0+	5/2(+)	0+	7/2+	0+	1/2+	0+	1/2+	0+	1/2+	0+	1/2+	0+	3/2+	0+				
EC	EC	EC	EC	0.97	EC	0.65	0.34	14.53	7.68	24.23	8.59	32.59	β	4.63				
In107	In108	In109	In110	In111	In112	In113	In114	In115	In116	In117	In118	In119	In120	In121				
32.4 m	58.0 m	4.2 h	4.9 h	2.8047 d	14.97 m	9/2+	71.9 s	4.41E+14 y	14.10 s	43.2 m	5.0 s	2.4 m	3.08 s	23.1 s				
9/2+	7+	9/2+	7+	9/2+	1+	9/2+	1+	9/2+	1+	9/2+	1+	9/2+	1+	9/2+	1+			
EC	EC	EC	EC	EC	EC,β	4.3	EC,β	98.7	EC,β	β	β	β	β	β	β			
Cd106	Cd107	Cd108	Cd109	Cd110	Cd111	Cd112	Cd113	Cd114	Cd115	Cd116	Cd117	Cd118	Cd119	Cd120	Cd121	Cd122		
0+	6.50 h	0+	462.6 d	0+	1/2+	0+	9.3E+15 y	0+	53.46 h	0+	2.49 h	50.3 m	2.69 m	50.80 s	13.5 s	5.24 s		
0+	5/2+	0+	5/2+	0+	1/2+	0+	1/2+	0+	1/2+	0+	1/2+	0+	3/2+	0+	(3/2+)	0+		
1.25	EC	0.89	EC	12.49	β	24.13	β	28.73	β	7.49	β	β	β	β	β	β		
Ag105	Ag106	Ag107	Ag108	Ag109	Ag110	Ag111	Ag112	Ag113	Ag114	Ag115	Ag116	Ag117	Ag118	Ag119	Ag120	Ag121		
41.29 d	23.96 m	1/2-	237 m	7.35 d	23.6 s	7.35 d	3.130 h	5.37 h	4.6 s	20.0 m	2.68 m	72.8 s	3.76 s	2.1 s	1.23 s	0.78 s		
1/2-	1+	1/2-	1+	1/2-	1+	1/2-	2(-)	1/2-	1+	1/2-	(2-)	(1/2-)	(1-)	(7/2+)	(3+)	(7/2+)		
EC	EC,β	51.839	EC,β	48.161	EC,β	β	β	β	β	β	β	β	β	β	β	β-n		

High-statistics studies of Cd, Sn, Xe with 8pi:

D.C. Cross *et al.* Eur. Phys. J. A 53, 216 (2017).
 J.L. Pore *et al.*, Eur. Phys. J. A 53, 27 (2017).
 B. Jigmeddorj *et al.*, Eur. Phys. J. A, 52, 36 (2016).
 A.J. Radich *et al.*, Phys. Rev. C 91, 044320 (2015).
 P.E. Garrett *et al.*, PRC 86, 044304 (2012).
 P.E. Garrett *et al.*, Acta Phys.Pol. B42, 799 (2011).
 P.E. Garrett *et al.*, AIP Conf.Proc. 1377, 211 (2011).
 K.L. Green *et al.*, PRC 80, 032502 (2009).

Combined with results from (n,n'), (n,γ), Coulex, transfer reactions...

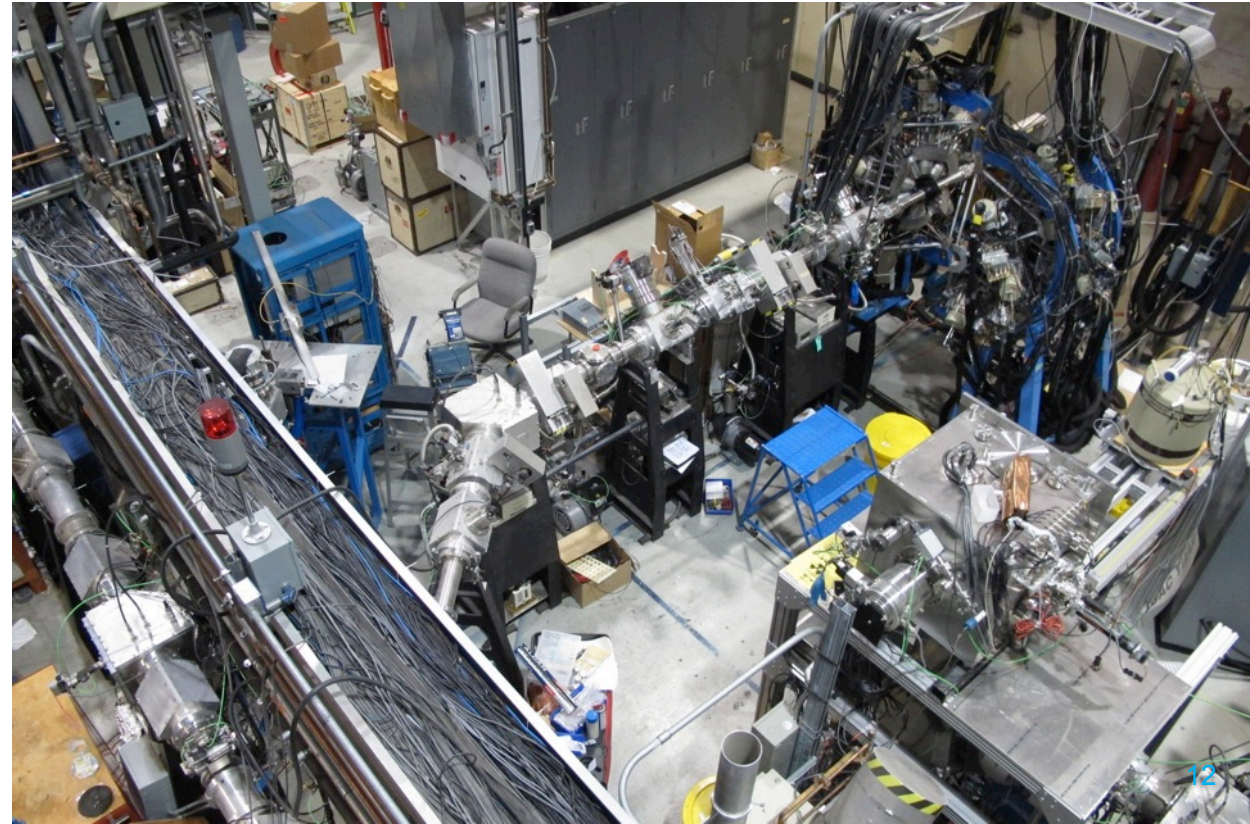
The 8π Spectrometer at TRIUMF-ISAC



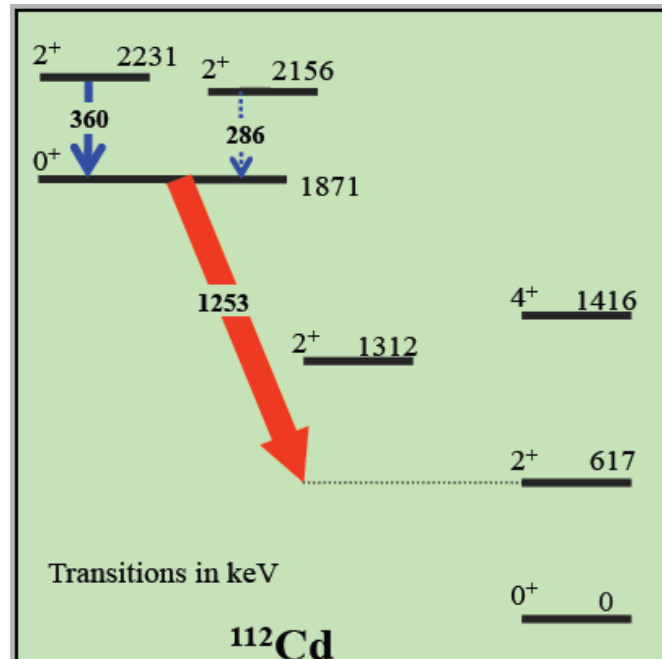
Performed decay spectroscopy at TRIUMF-ISAC-I from Feb 2002 to Dec 2013

Researchers from 24 institutions from 8 countries.

>25 post-docs,
8PhD, 13MSc, 1MPhys
>43 peer-reviewed publications

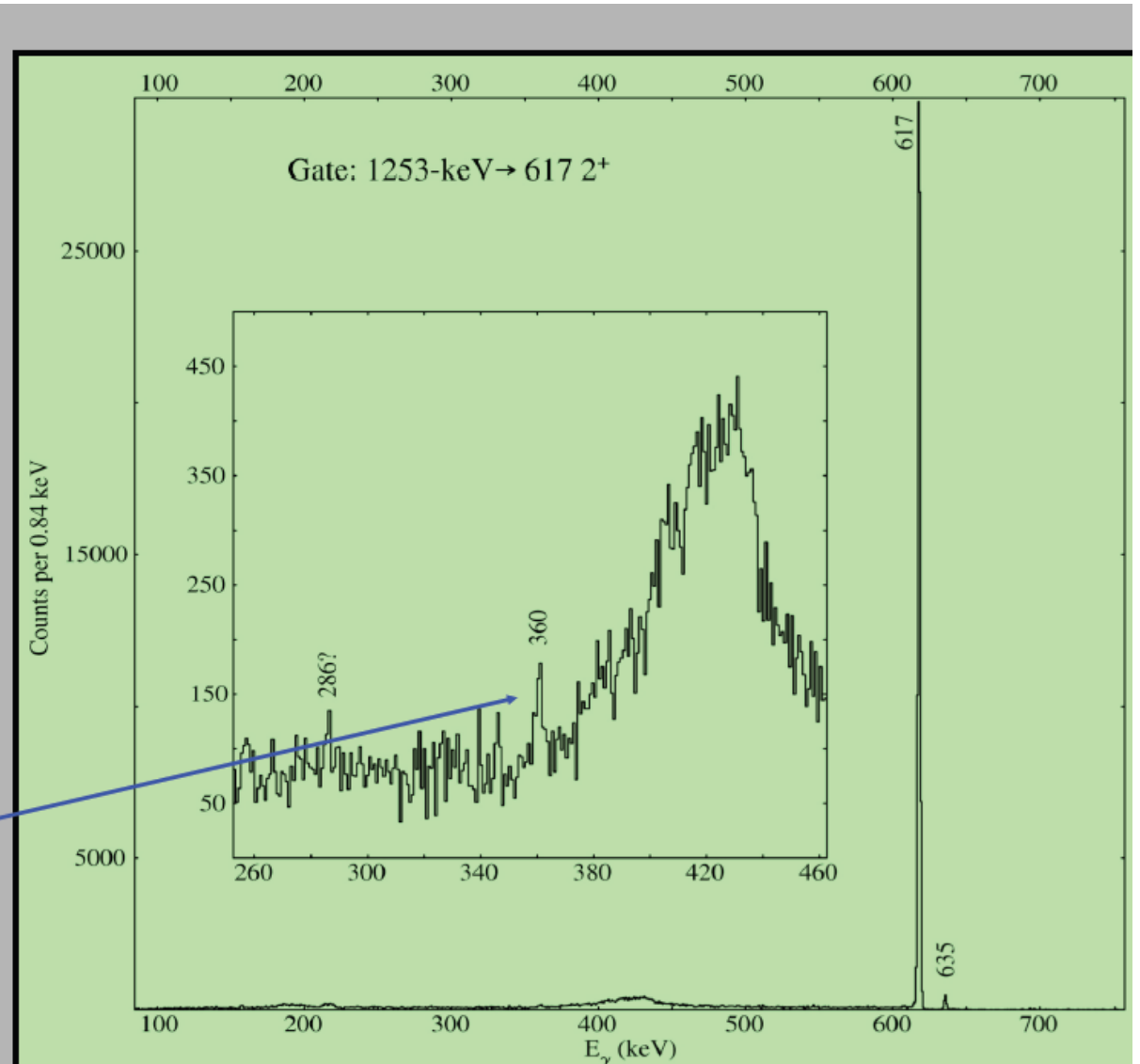


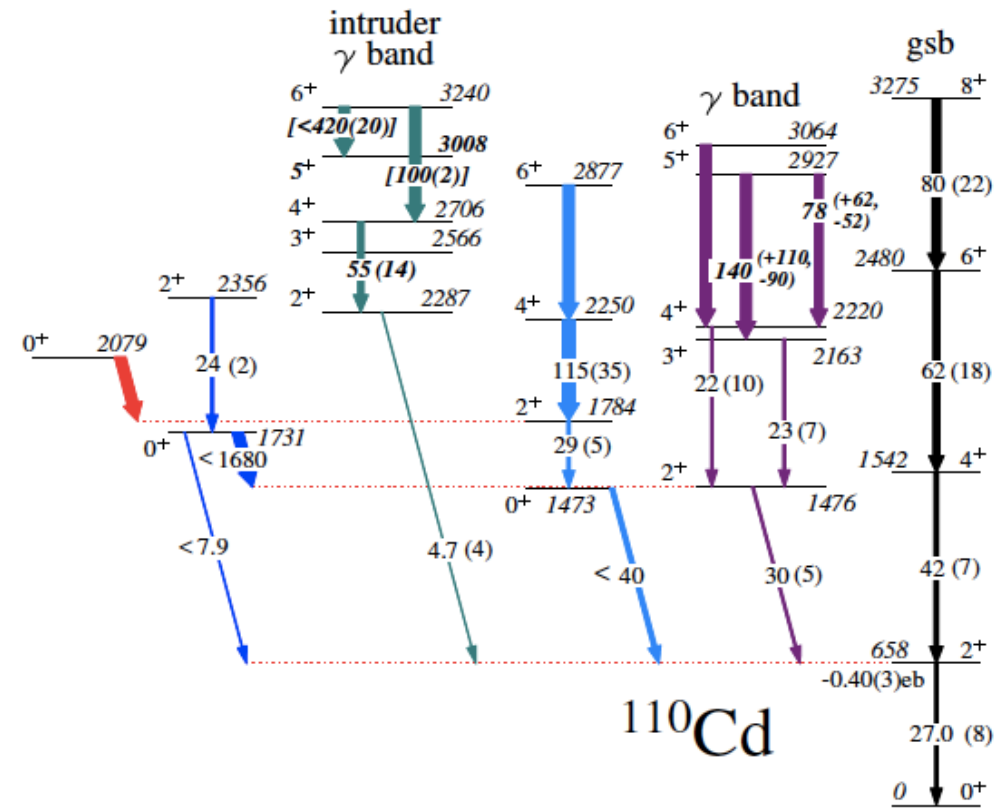
Nuclear Structure from High-Statistics Beta-Decay

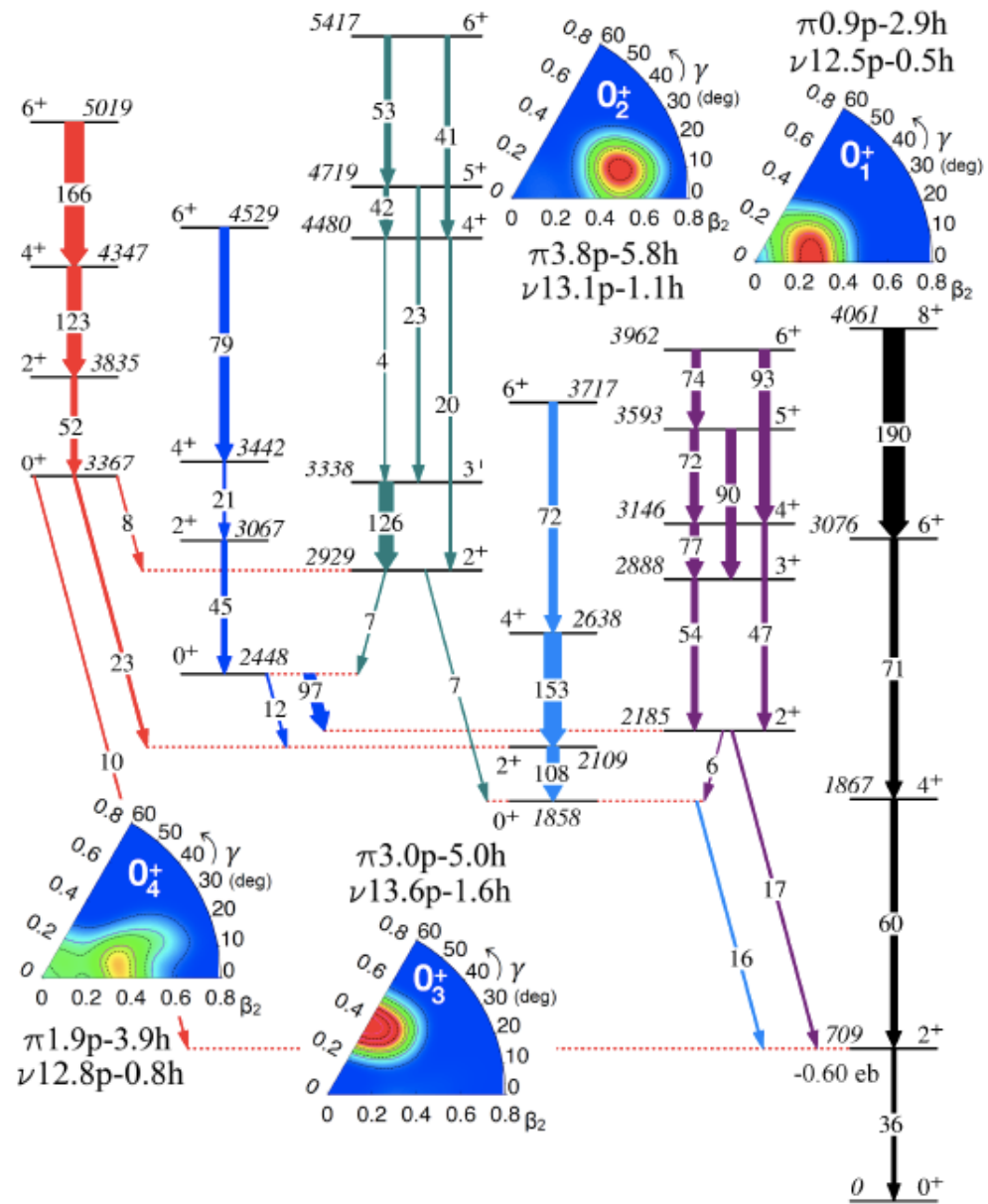


5×10^{-4} γ branch from
2231-keV level

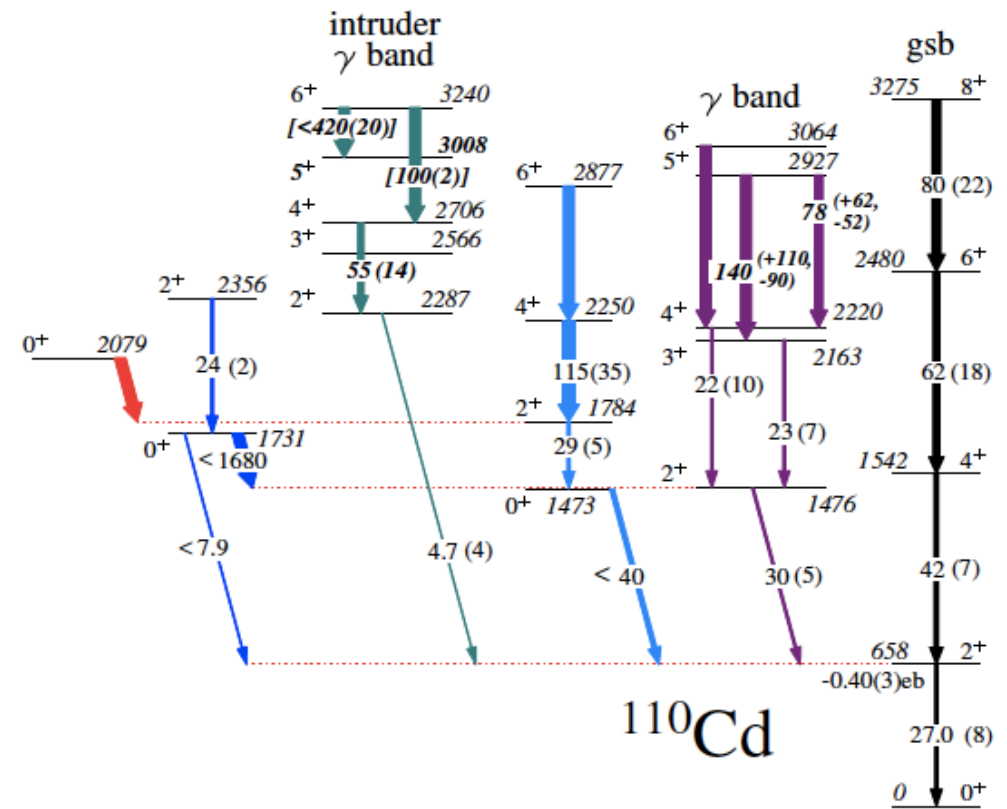
$I_\gamma(360) \approx 10^{-6}$ of
 $I_\gamma(617\text{-keV}, 2^+ \rightarrow 0^+)$





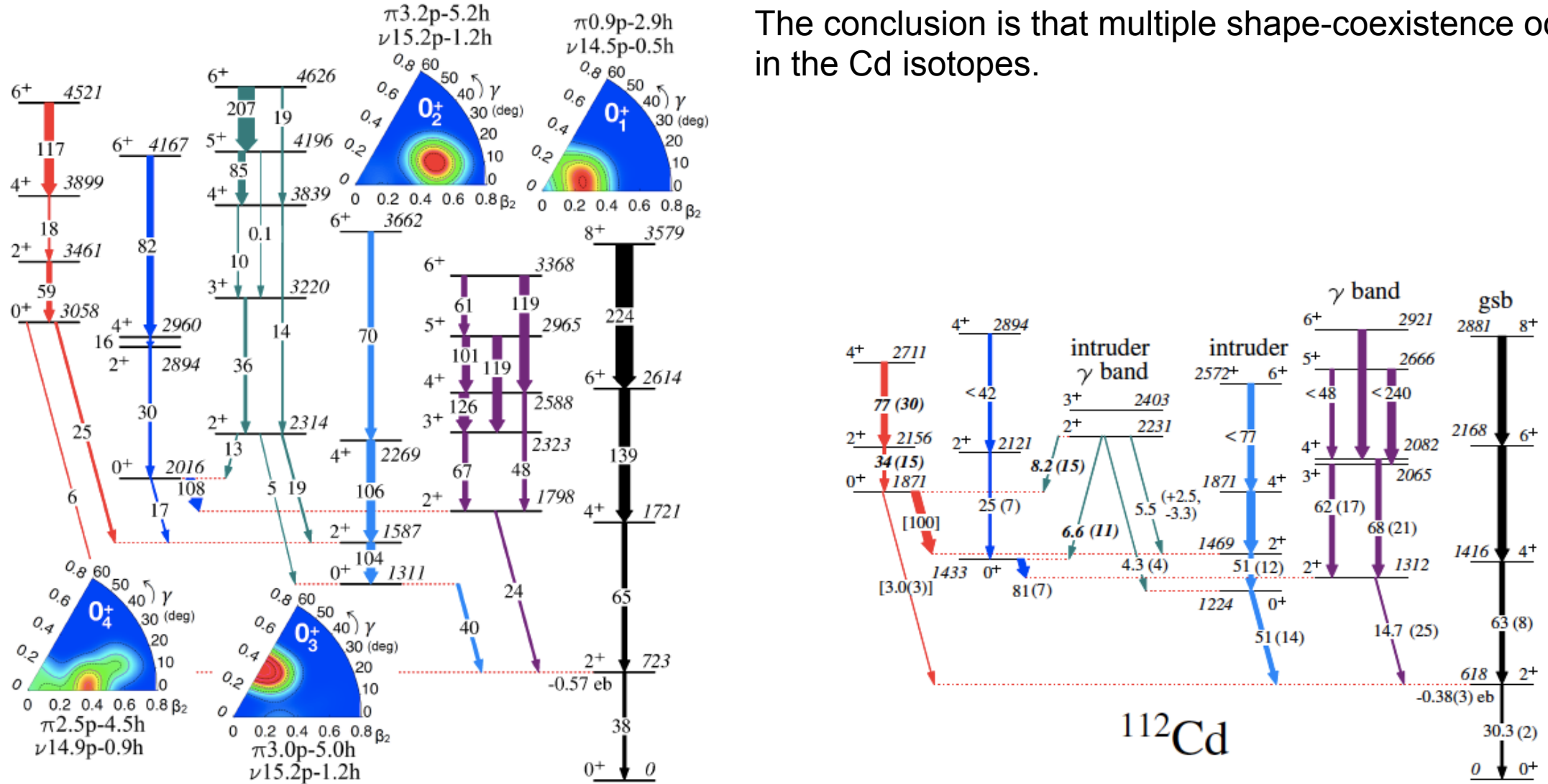


Beyond-mean-field calculations employing the symmetry conserving configuration method with the Gogny D1S energy density functional. The agreement with the data for ^{110}Cd is remarkable.



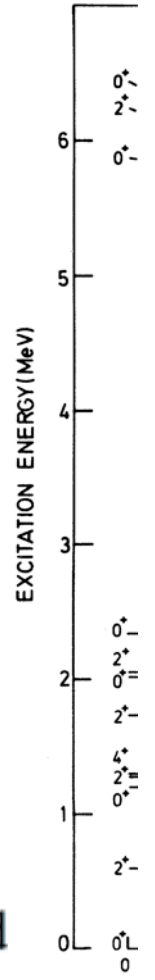
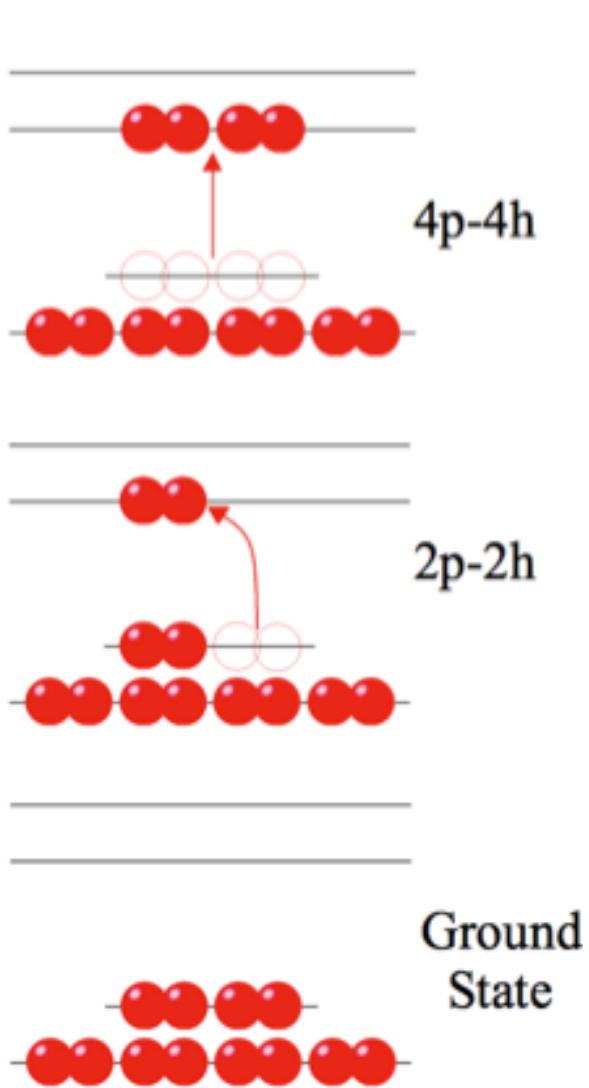
...and also for ^{112}Cd .

The conclusion is that multiple shape-coexistence occurs in the Cd isotopes.



Shape coexistence from Particle-Hole Excitations or “Intruder” states

Heyde & Wood, Rev. Mod. Phys. 83, 1467 (2011).

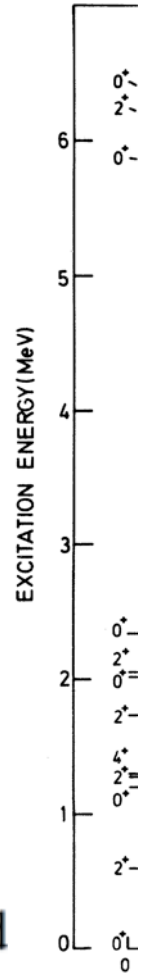
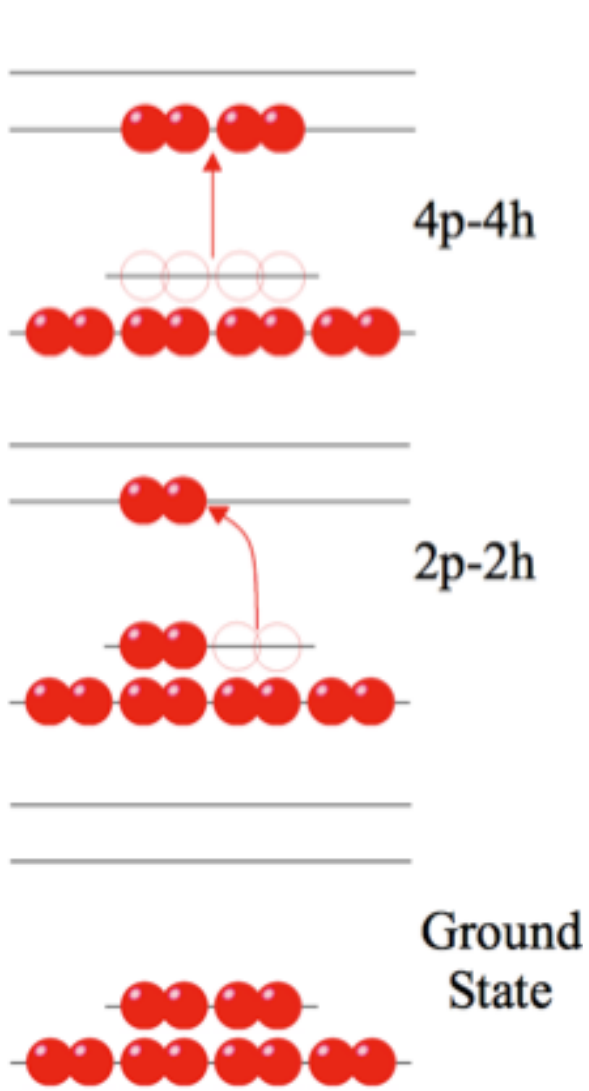


Shell-gap Energy $\sim +4-8\text{MeV}$

$$E_{\text{intr}}(0^+) = 2(\epsilon_{j_\pi} - \epsilon_{j'_\pi})$$

Shape coexistence from Particle-Hole Excitations or “Intruder” states

Heyde & Wood, Rev. Mod. Phys. 83, 1467 (2011).



0^+_{-}
 2^+_{-}
 0^+_{-}
 $0^+_{=}$
 2^+_{-}
 $4^+_{=}$
 $2^+_{=}$
 0^+_{-}
 2^+_{-}
 0^+_{L}
 0

Shell-gap Energy $\sim +4-8\text{MeV}$

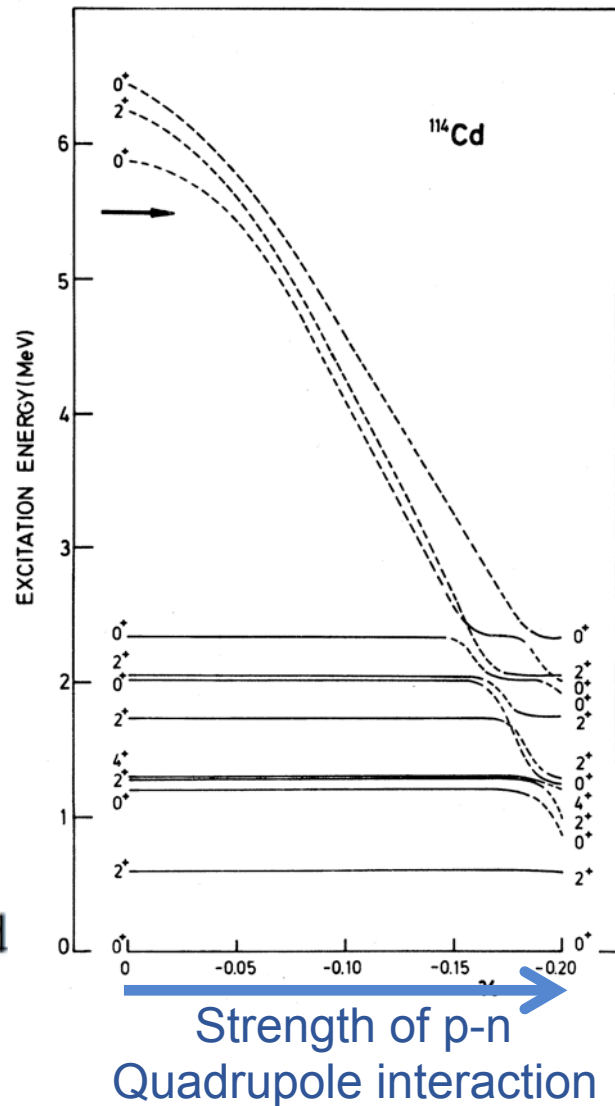
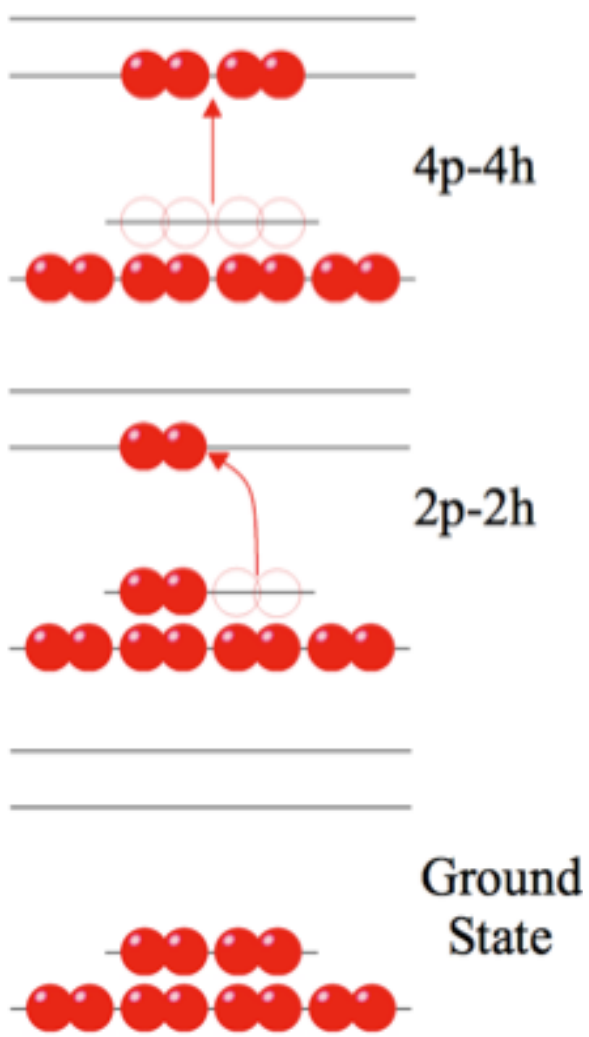
Monopole shift $\sim \pm 0-1\text{MeV}$

Pairing $\sim -2.5\text{MeV}$

$$E_{\text{intr}}(0^+) = 2(\varepsilon_{j_{\pi}} - \varepsilon_{j'_{\pi}}) - \Delta E_{\text{pair}} + \Delta E_M$$

Shape coexistence from Particle-Hole Excitations or "Intruder" states

Heyde & Wood, Rev. Mod. Phys. 83, 1467 (2011).

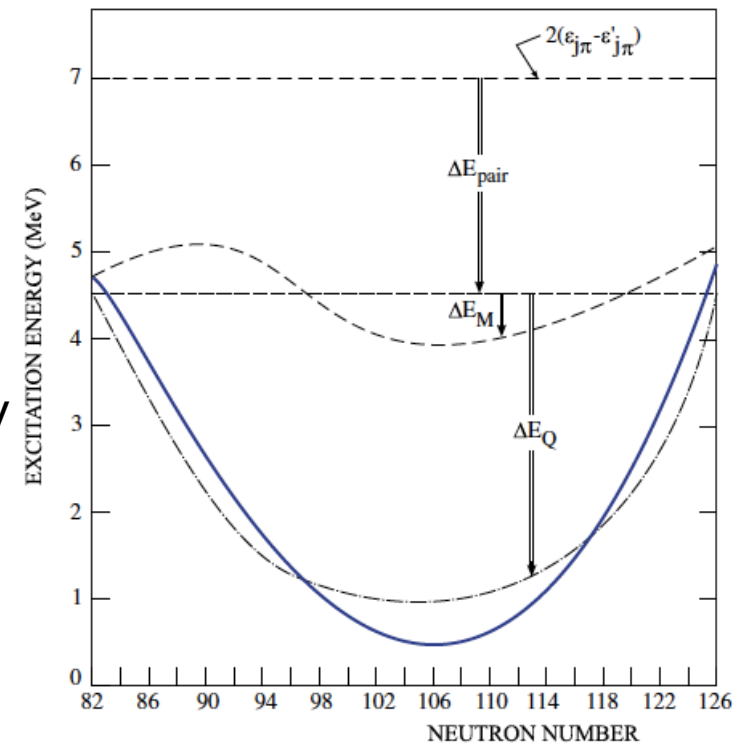


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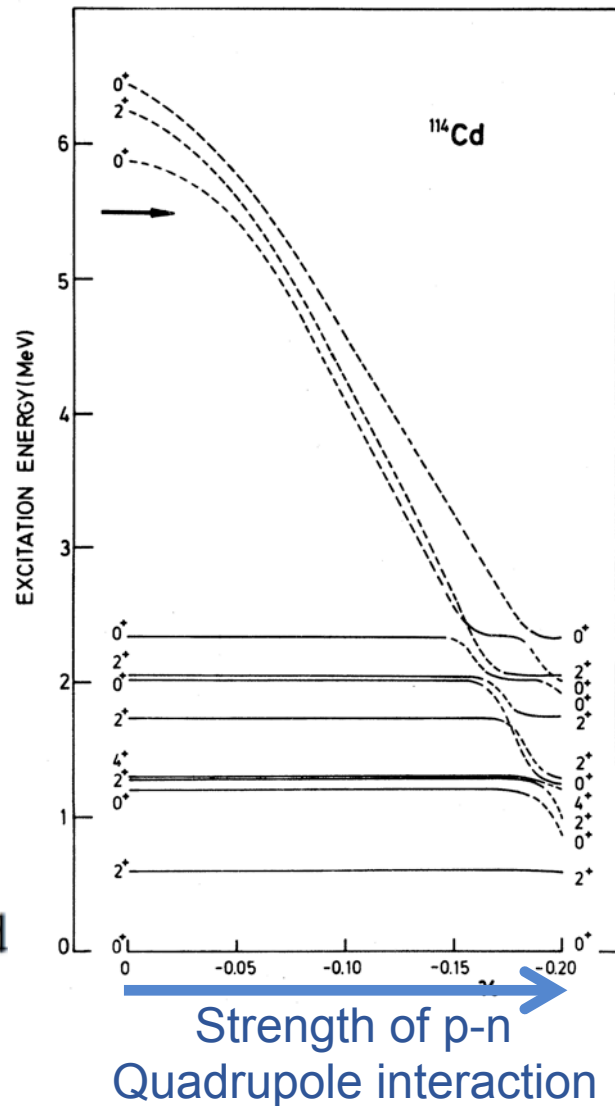
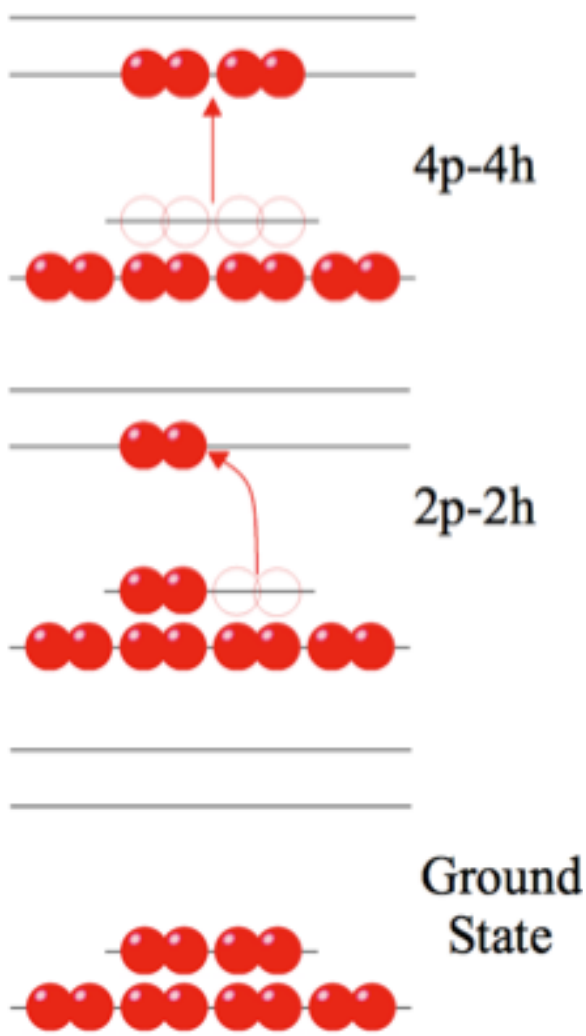
p-n quadrupole $\sim -0-3\text{MeV}$



$$E_{\text{intr}}(0^+) = 2(\varepsilon_{j_\pi} - \varepsilon_{j'_\pi}) - \Delta E_{\text{pair}} + \Delta E_M + \Delta E_Q$$

Shape coexistence from Particle-Hole Excitations or "Intruder" states

Heyde & Wood, Rev. Mod. Phys. 83, 1467 (2011).

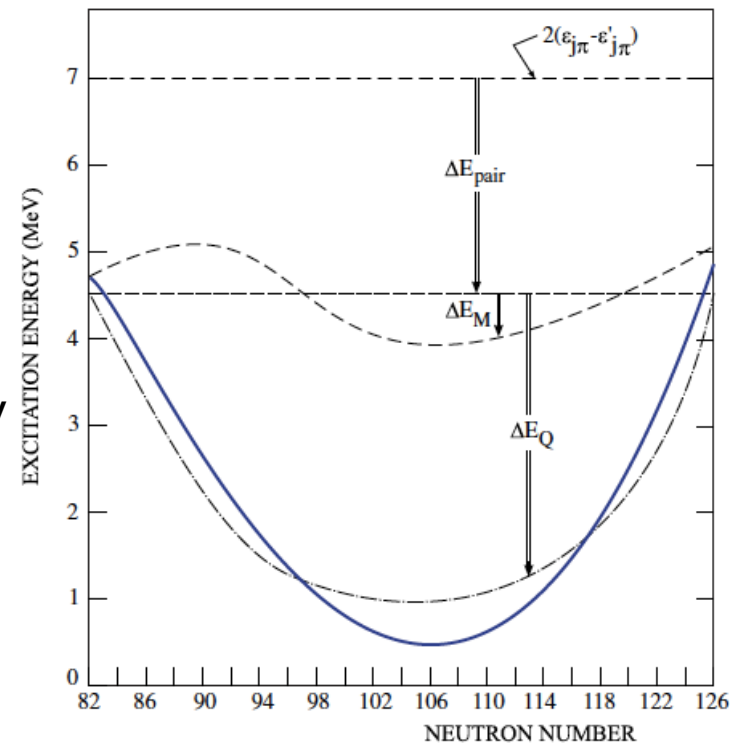


Shell-gap Energy $\sim +4-8\text{MeV}$

Monopole shift $\sim \pm 0-1\text{MeV}$

Pairing $\sim -2.5\text{MeV}$

p-n quadrupole $\sim -0-3\text{MeV}$



$$E_{\text{intr}}(0^+) = 2(\varepsilon_{j_\pi} - \varepsilon_{j'_\pi}) - \Delta E_{\text{pair}} + \Delta E_M + \Delta E_Q$$

Unperturbed Wavefunctions \rightarrow Mixing \rightarrow Mixed Wavefunctions

E_1, Ψ_1
 E_2, Ψ_2

E_1, Φ_1

$$\Phi_1 = \alpha\Psi_1 + \beta\Psi_2$$

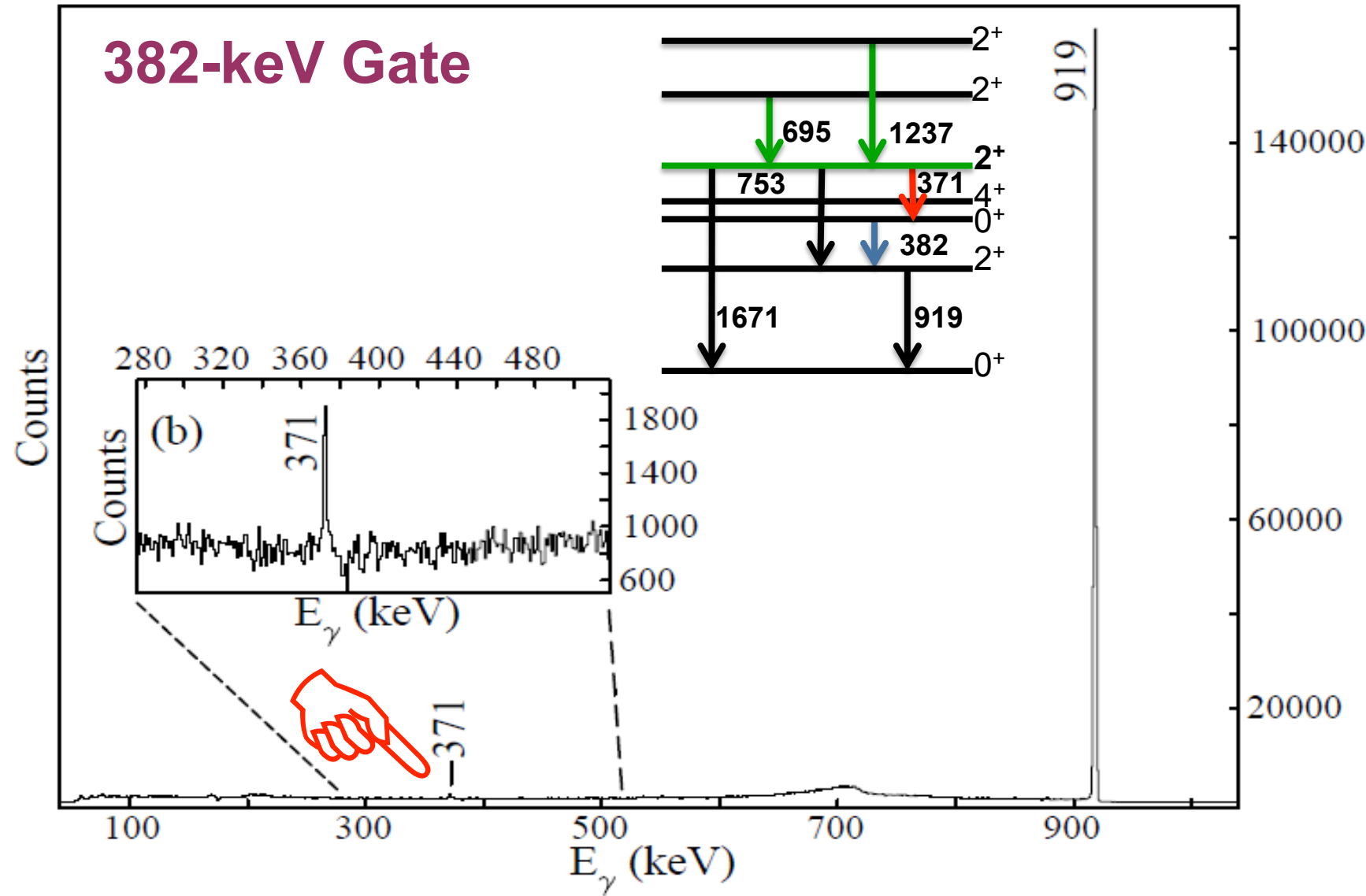
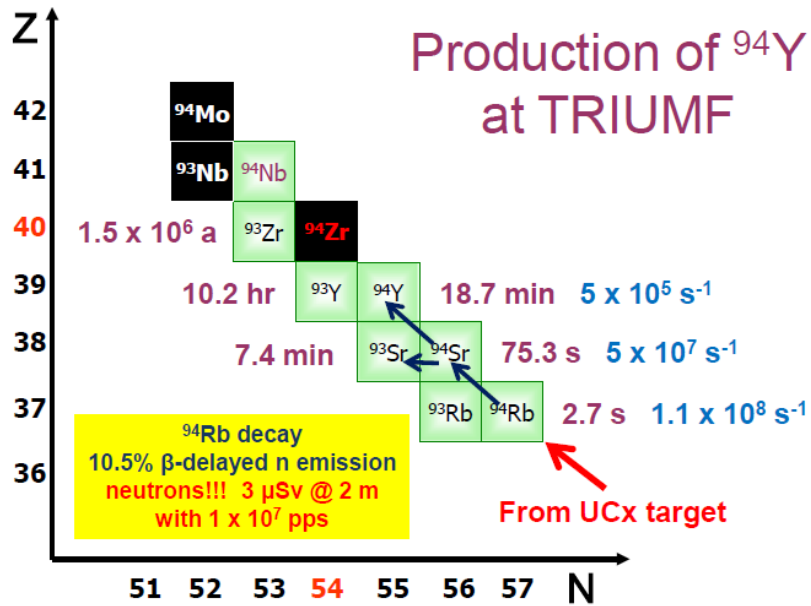
$$\Phi_2 = -\beta\Psi_1 + \alpha\Psi_2$$

E_2, Φ_2

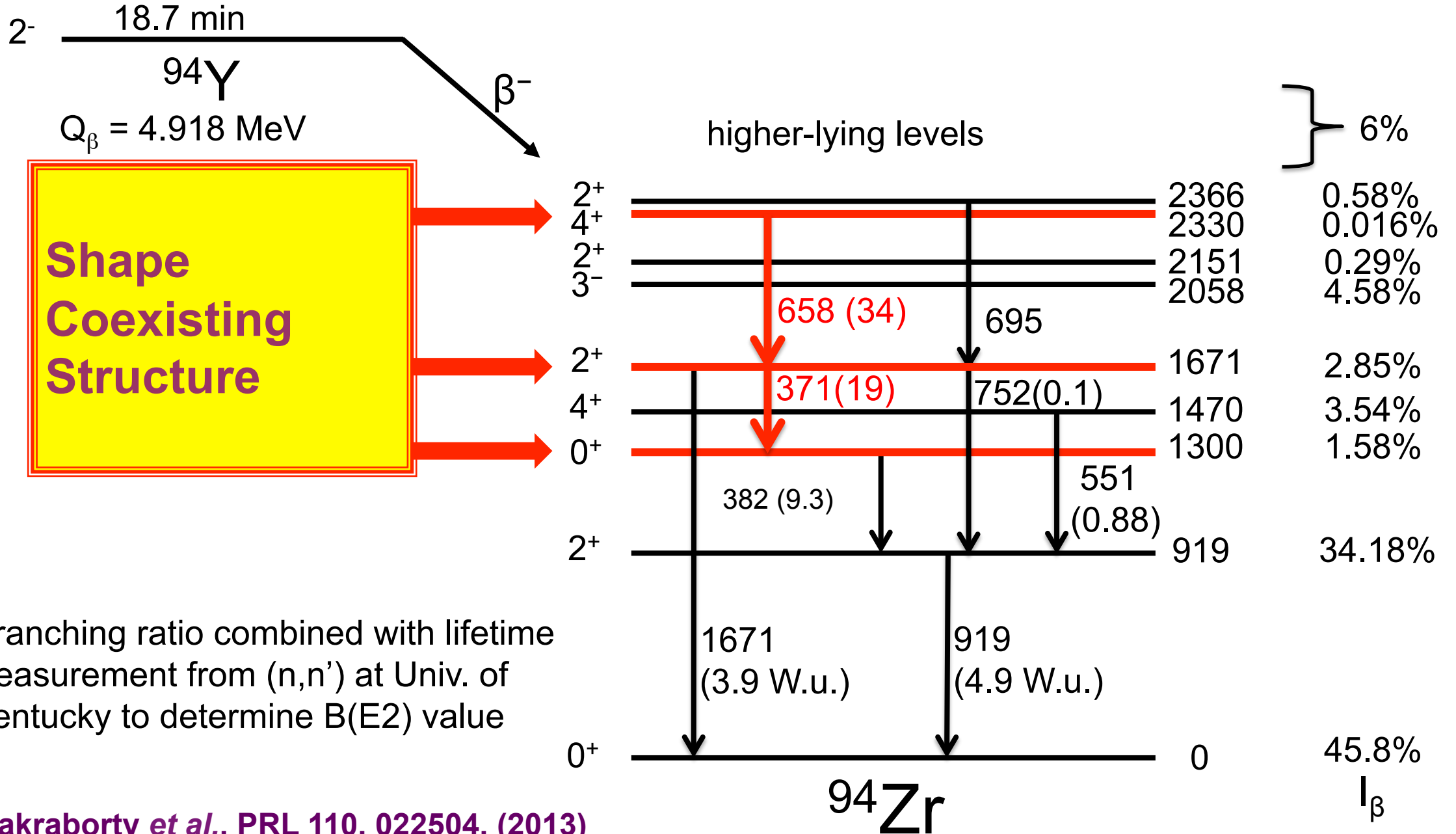
Where: $\alpha^2 + \beta^2 = 1$

The amount of mixing depends on the mixing amplitude and the initial separation energy of the states (ΔE)

High-Statistics Beta-Decay of ^{94}Y to ^{94}Zr



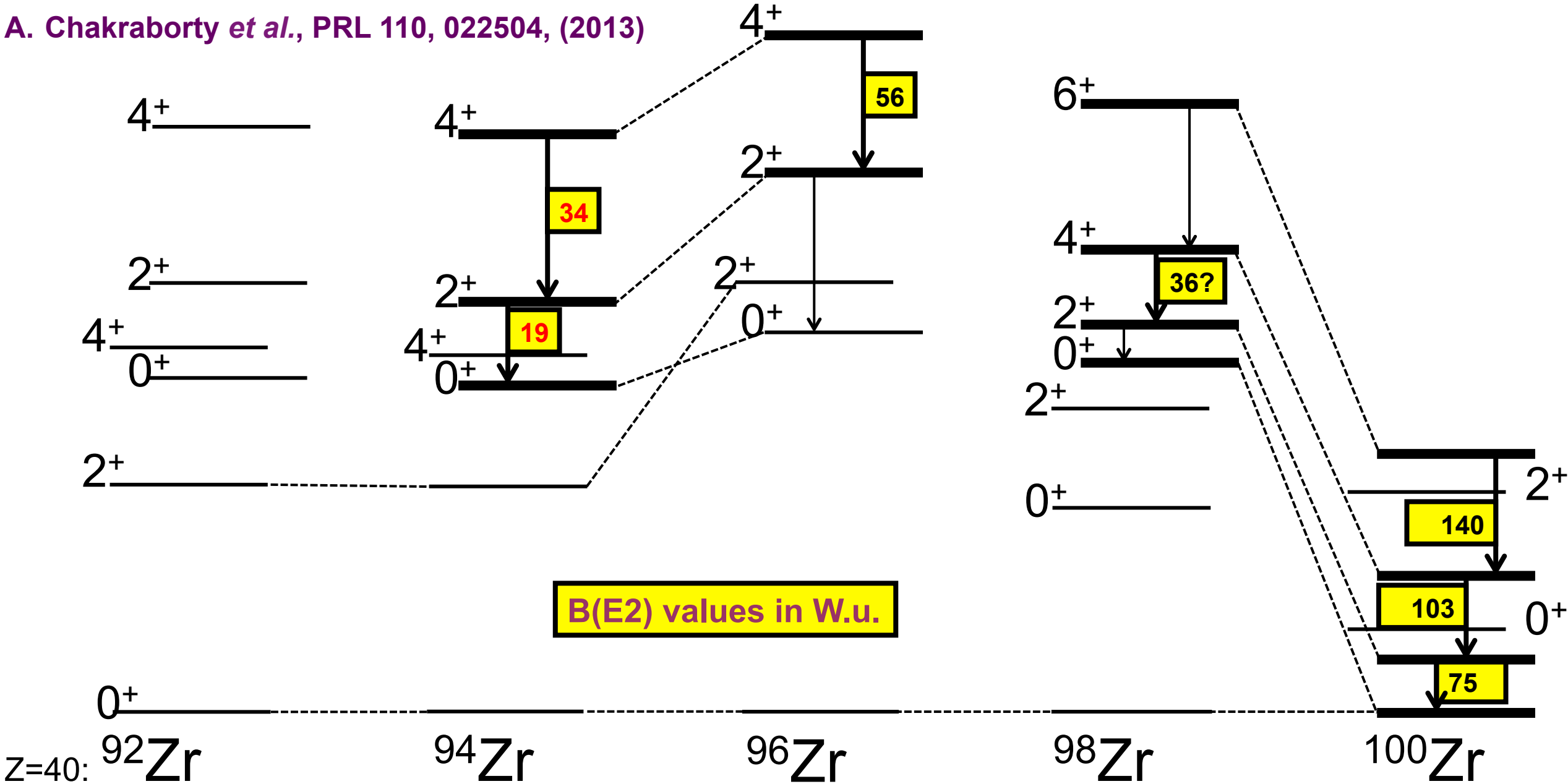
Identification of Coexisting structures in ^{94}Zr



8pi branching ratio combined with lifetime measurement from (n,n') at Univ. of Kentucky to determine B(E2) value

Coexisting Structures in ^{94}Zr : *First evidence of particle-hole excitation across a sub-shell gap*

A. Chakraborty *et al.*, PRL 110, 022504, (2013)



Shape coexistence at $N=60$: Zr, Y, Sr, Rb Isotopes

Z=40	Zr90 0+ 51.45 s β	Zr91 5/2+ 11.22 s β	Zr92 0+ 17.15 s β	Zr93 1.53E+6 y 5/2+ β	Zr94 0+ 17.38 s β	Zr95 64.02 d 5/2+ β	Zr96 3.9E19 y 0+ β	Zr97 16.91 h 1/2+ β	Zr98 30.7 s 0+ β	Zr99 2.1 s (1/2+) β	Zr100 7.1 s 0+ β	Zr101 2.1 s (3/2+) β	Zr102 2.9 s 0+ β	Zr103 1.3 s (5/2-) β	Zr104 1.2 s 0+ β	Zr105 0.6 s β	Zr106 0+ β	
Z=38	Y89 1/2- 100 s β	Y90 64.10 h 2- β	Y91 58.51 d 1/2- β	Y92 3.54 h 2- β	Y93 10.18 h 1/2- β	Y94 18.7 m 2- β	Y95 10.3 m 1/2- β	Y96 5.34 s 0- β	Y97 3.75 s (0)- β-n	Y98 0.548 s (1/2-) β-n	Y99 1.470 s (5/2+) β-n	Y100 735 ms 1-2- β-n	Y101 448 ms (5/2+) β-n	Y102 0.36 s (5/2+) β-n	Y103 0.23 s (5/2+) β-n	Y104 β-n	Y105 β-n	
Z=37	Sr88 0+ 82.58 s β	Sr89 50.53 d 5/2+ β	Sr90 28.78 y 0+ β	Sr91 9.63 h 5/2+ β	Sr92 2.71 h 0+ β	Sr93 7.423 m 5/2+ β	Sr94 75.3 s 0+ β	Sr95 23.90 s 1/2+ β	Sr96 1.07 s 0+ β	Sr97 426 ms 1/2+ β	Sr98 0.653 s 0+ β	Sr99 0.269 s 3/2+ β	Sr100 202 ms 0+ β	Sr101 118 ms (5/2) β	Sr102 69 ms 0+ β	Sr103 1/2+ β	Sr104 0+ β	
	Rb87 4.75E10 y 3/2- β	Rb88 17.78 m 2- β	Rb89 15.15 m 3/2- β	Rb90 158 s 0- β	Rb91 58.4 s 3/2- β	Rb92 4.492 s 0- β	Rb93 5.84 s 5/2- β	Rb94 2.702 s 3- β	Rb95 377.5 ms 5/2- β	Rb96 0.199 s 2+ β	Rb97 169.9 ms 3/2(+) β	Rb98 114 ms (1,0) β-n,β-2n...	Rb99 50.3 ms (5/2+) β	Rb100 51 ms β-n,β-2n...	Rb101 32 ms β-n	Rb102 37 ms β-n		
	Kr86 0+ 17.3 s β	Kr87 76.3 m 5/2+ β	Kr88 2.84 h 0+ β	Kr89 3.15 m (3/2+,5/2+) β	Kr90 32.32 s 0+ β	Kr91 8.57 s (5/2+) β	Kr92 1.840 s 0+ β	Kr93 1.286 s (1/2+) β	Kr94 0.20 s 0+ β	Kr95 0.78 s 1/2 β	Kr96 0+ β	Kr97 β						
	Br85 2.90 m 3/2- β	Br86 55.60 s (2-) β	Br87 16.34 s 3/2- β	Br88 4.348 s (1,2-) β	Br89 4.348 s (3/2-,5/2-) β	Br90 1.910 s β	Br91 0.541 s β	Br92 0.343 s (2-) β	Br93 102 ms (5/2-) β	Br94 70 ms β								
	Se84 3.1 m 0+ β	Se85 31.7 s (5/2+) β	Se86 15.3 s 0+ β	Se87 5.29 s (5/2+) β	Se88 1.53 s 0+ β	Se89 0.41 s (5/2+) β	Se90 β	Se91 0.27 s β	Se92 0+ β									
	As83 13.4 s (5/2-,3/2-) β	As84 4.02 s β	As85 2.021 s (3/2-) β	As86 0.945 s β	As87 2.021 s (3,2-) β	As88 β	As89 β											
	Ge82 4.60 s 0+ β	Ge83 1.85 s (5/2+) β	Ge84 966 ms 0+ β	Ge85 535 ms β	Ge86 0+ β													
	Ga81 1.217 s (5/2-) β-n	Ga82 0.599 s (1,2,3) β-n	Ga83 0.31 s β-n	Ga84 85 ms β-n														
	Zn80 0.545 s 0+ β-n	Zn81 0.29 s β-n	Zn82 0+ β-n															
	Cu79 188 ms β-n	Cu80 β-n																
Z=28	Ni78 0+ β-n																	

ISAC studies around $N=60$:

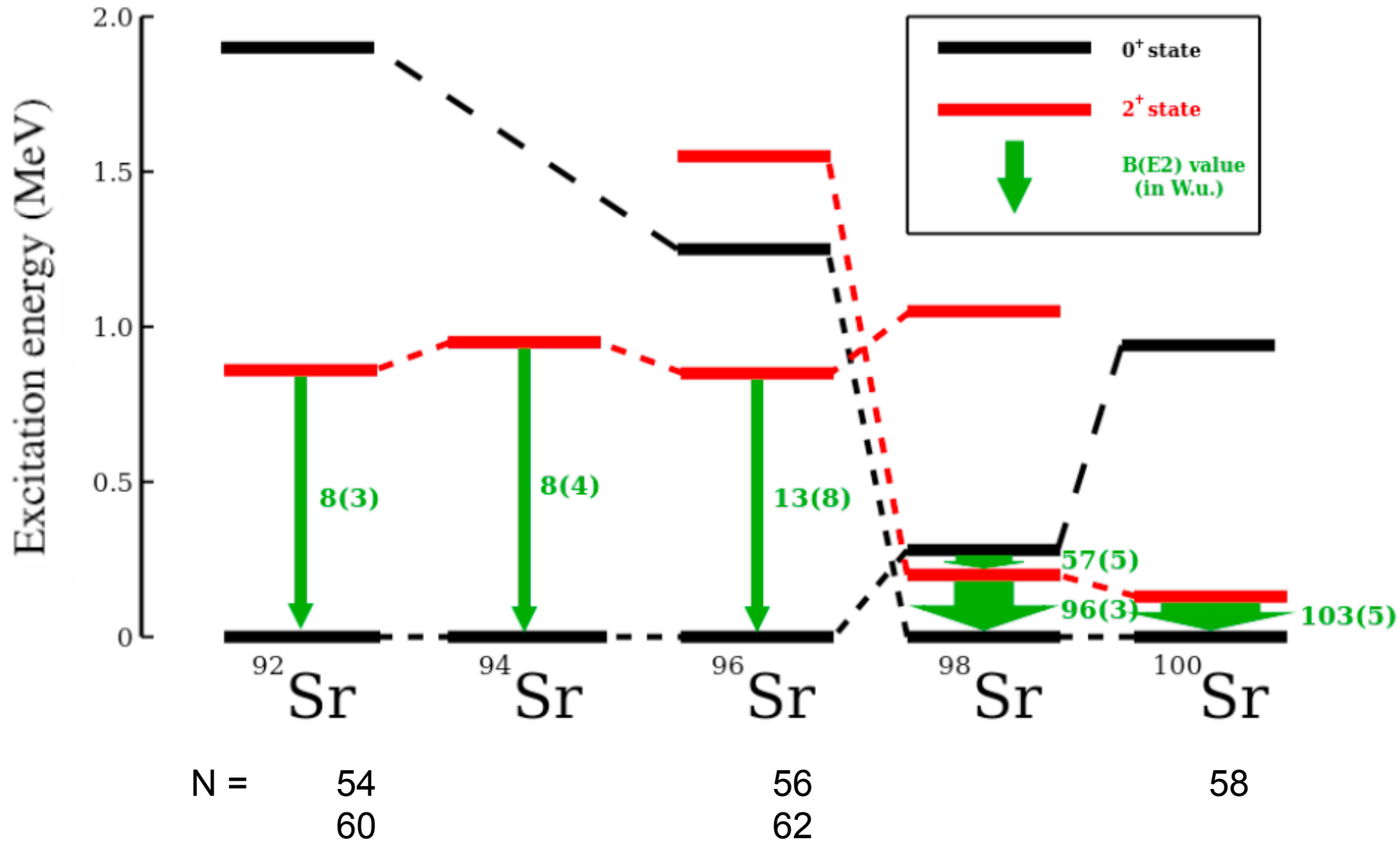
S. Cruz *et al.*, Phys. Letts. B 786, 94 (2018).
 A. Chester *et al.*, PRC 96, 011302(R) (2017).
 Z.M. Wang, *et al.*, PRC 93, 054301 (2016).
 R. Klawitter *et al.*, PRC 93, 045807 (2016).
 J. Park *et al.*, PRC 96, 014315 (2016).
 T.J. Procter *et al.*, Eur. Phys. J. A 51, 23 (2015).
 A. Chakraborty *et al.*, PRL 110, 022504 (2013).
 V.V. Simon *et al.*, PRC 85, 064308 (2012).

66
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 Neutron mid-shell

- Binding Energies
 - TITAN
- Excitation energies
 - 8pi, GRIFFIN
- Charge Radii
 - Co-linear Laser Spectroscopy
- Transition Probabilities
 - TIGRESS+SHARC, TIGRESS+TIP, GRIFFIN+PACES+LaBr₃

50 ← Neutron Shell closure

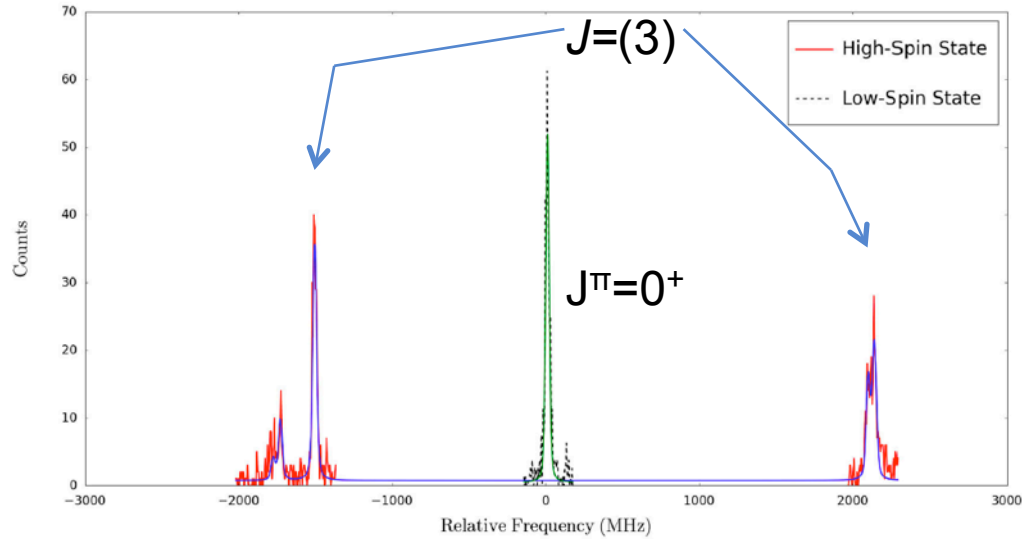
Dramatic Change in Ground-State Structure



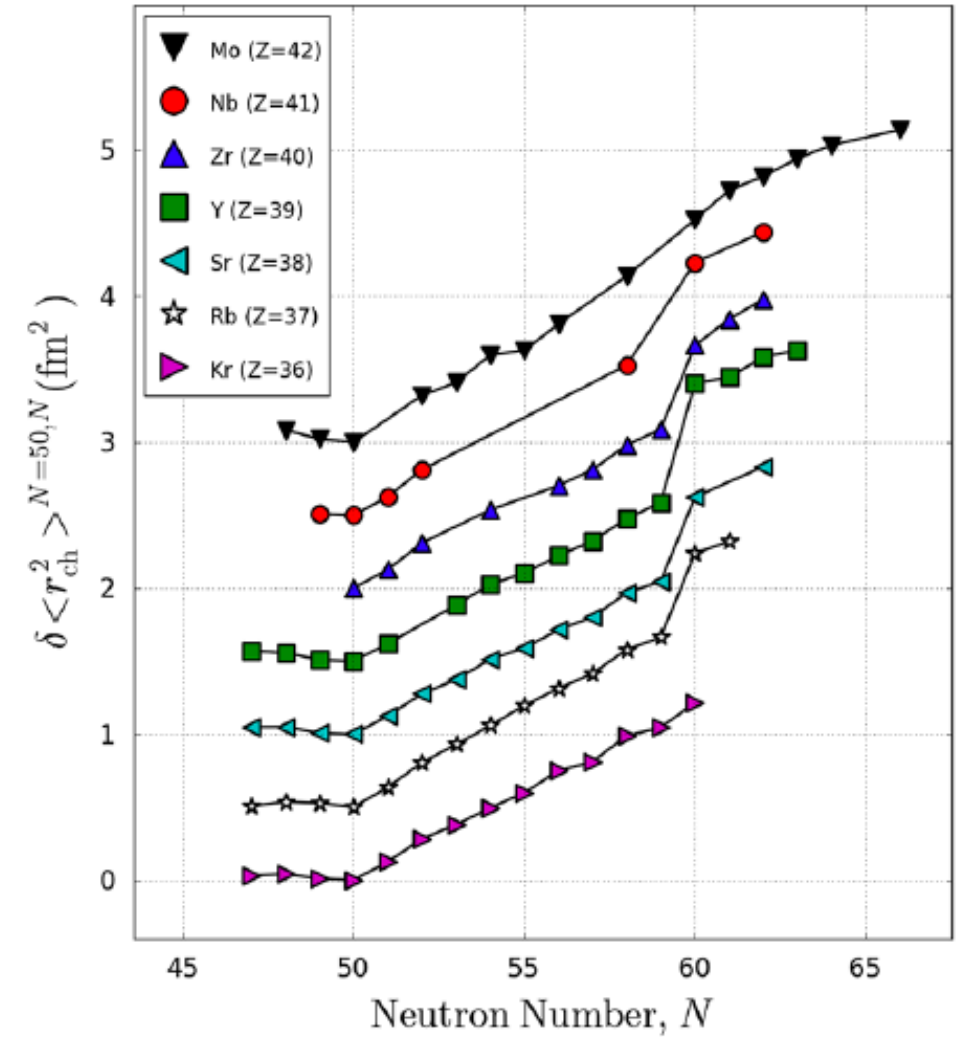
Spin assignments and charge radii from colinear Laser Spectroscopy

T.J. Procter *et al.*, Eur. Phys. J. A 51, 23 (2015).

First direct observation of isomer in ^{98}Rb

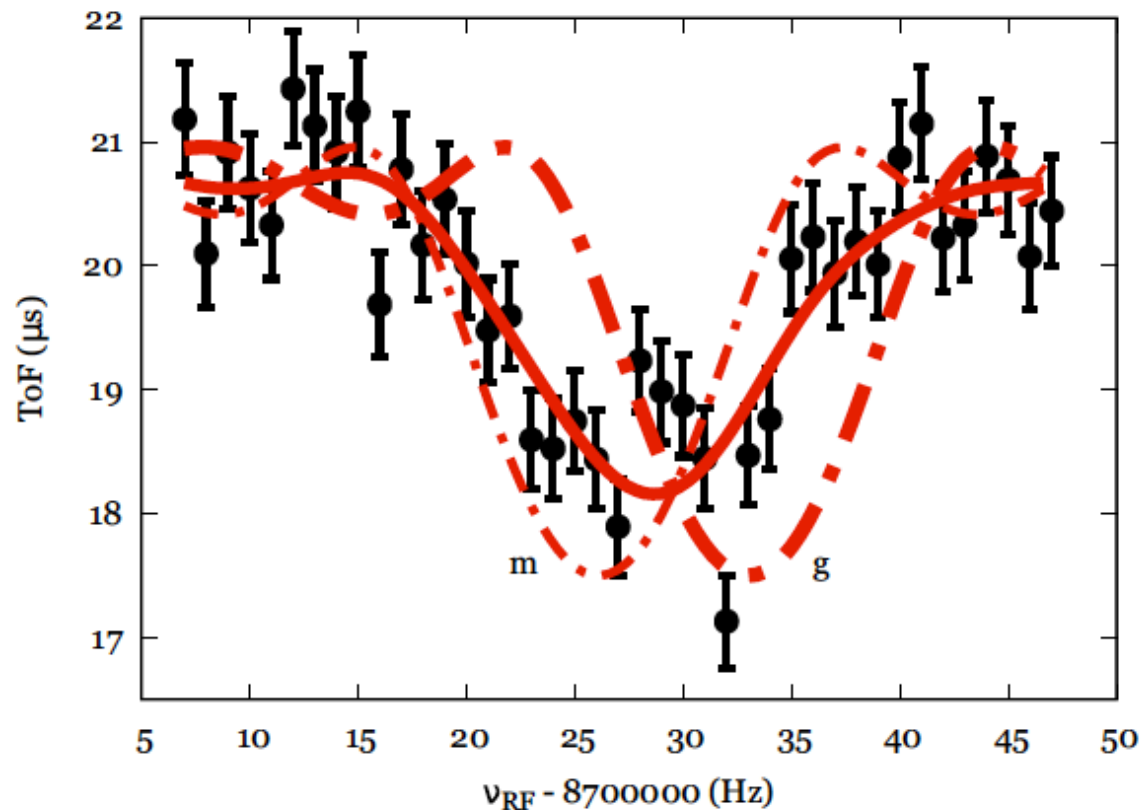


The groundstate and isomer in ^{98}Rb have very similar charge radii.

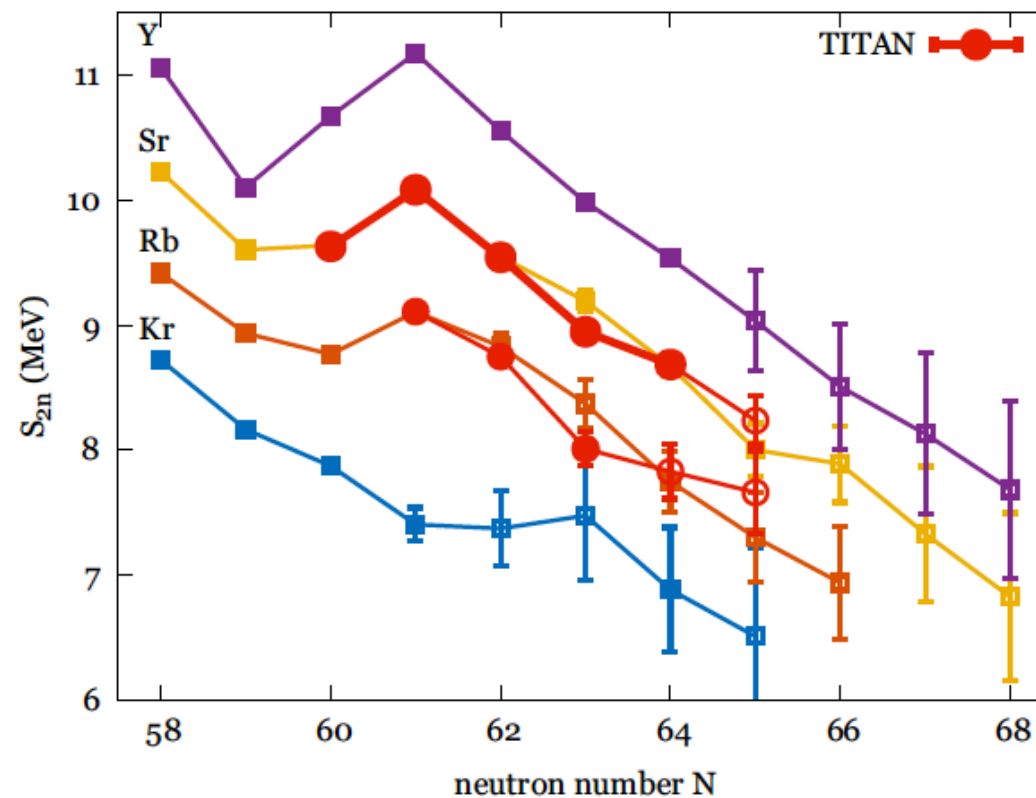


Precision mass measurements from TITAN

R. Klawitter *et al.*, PRC 93, 045807 (2016).



$^{98}\text{Rb}^{m; q=15+}$ and $^{98}\text{Rb}^{g; q=15+}$ individually (dashed lines)
and fit to both states together (solid line).
Energy of excited state is 80(36) keV.



Two-neutron separation energies of
neutron-rich Y, Sr, Rb and Kr isotopes.

$E0$ Transition Strengths

Recall that:

$$\Phi_1 = \alpha\Psi_1 + \beta\Psi_2$$

$$\Phi_2 = -\beta\Psi_1 + \alpha\Psi_2$$

where: $\alpha^2 + \beta^2 = 1$

For a transition between these states the $E0$ strength, $\rho_{if} = \frac{\langle \Phi_1 | m(E0) | \Phi_2 \rangle}{eR^2}$

where e = electric charge
and $R = 1.2A^{\frac{1}{3}} fm$ and

$$\langle \Phi_1 | m(E0) | \Phi_2 \rangle \simeq \alpha\beta\Delta\langle r^2 \rangle$$

Therefore the $E0$ strength is directly proportional to the **difference in deformation** and the **amount of mixing**

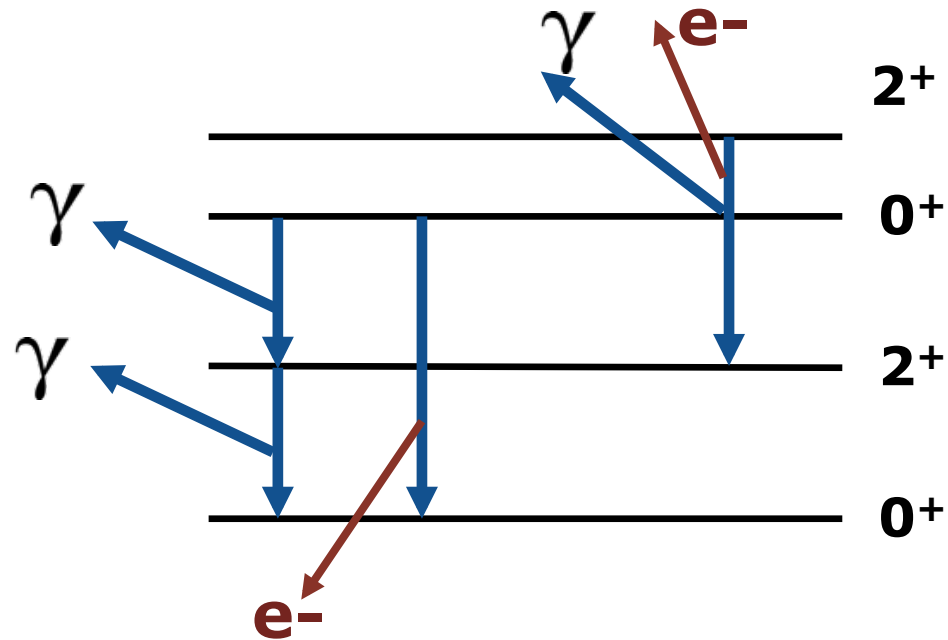
$$M(E0) = \sum_k e_k r_k^2$$

e_k = effective charge

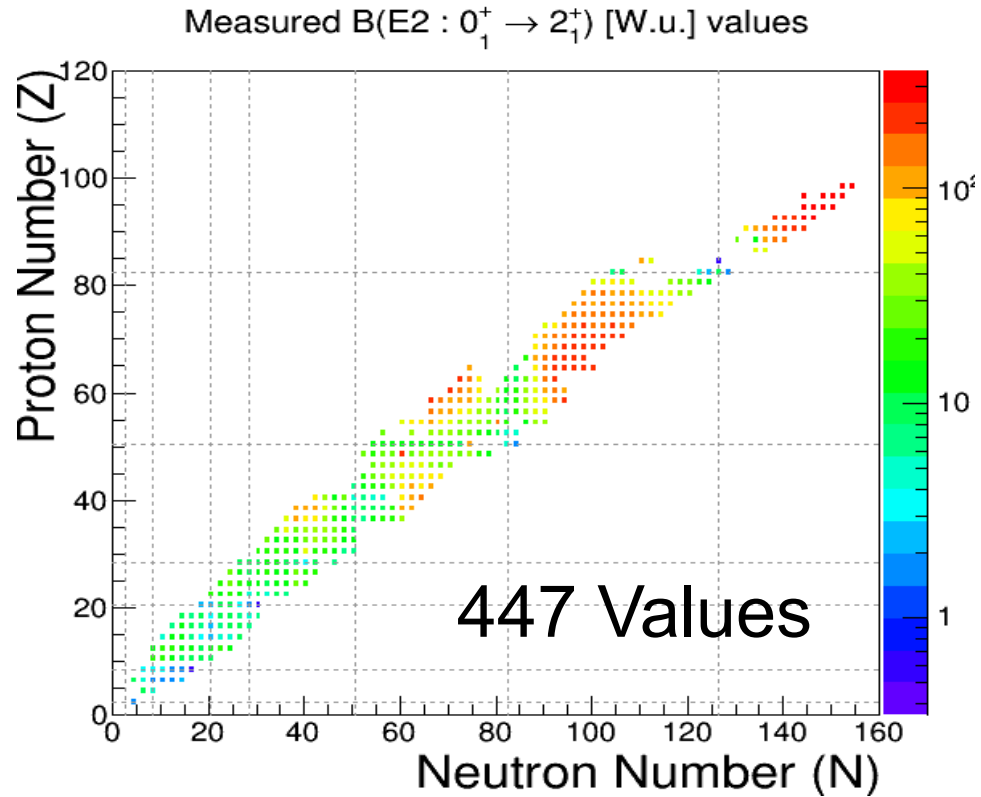
r_k = radius of k th nucleon



PACES Si(Li)

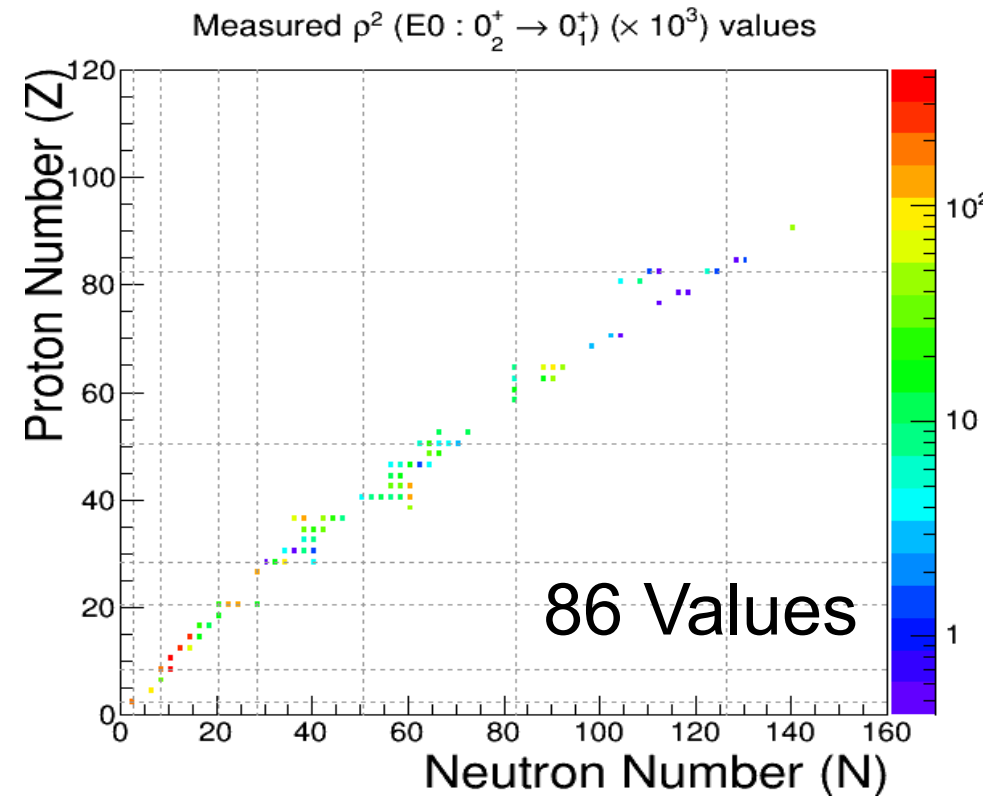


Knowledge of ρ^2 ($E0$) values



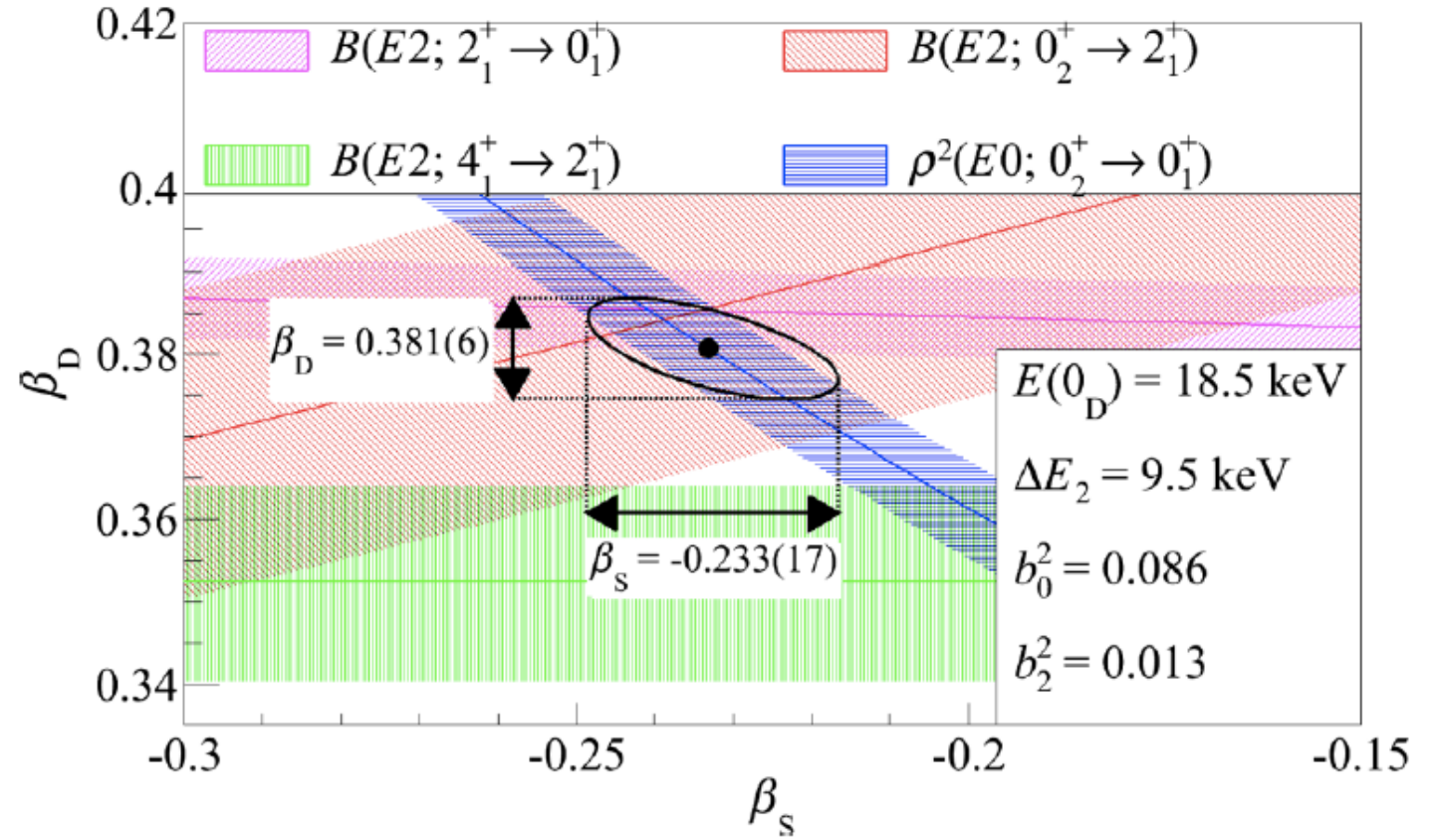
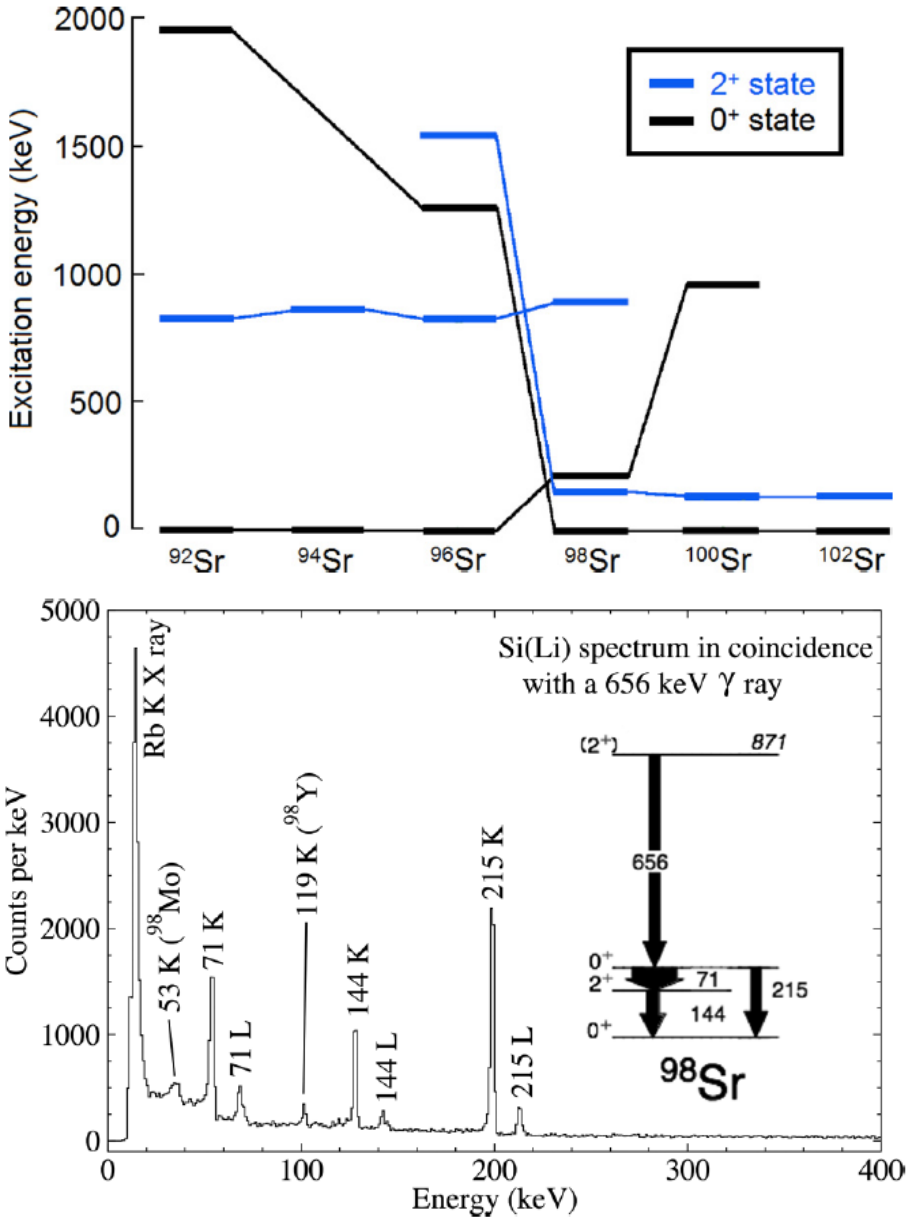
Pritychenko *et al.*, Atomic Data & Nucl. Data Tables, 107 (2016)

~120 new values in 15 years



Kibédi & Spear, Data Nucl. Data Tables, 89 (2005)

Shape coexistence in ^{98}Sr

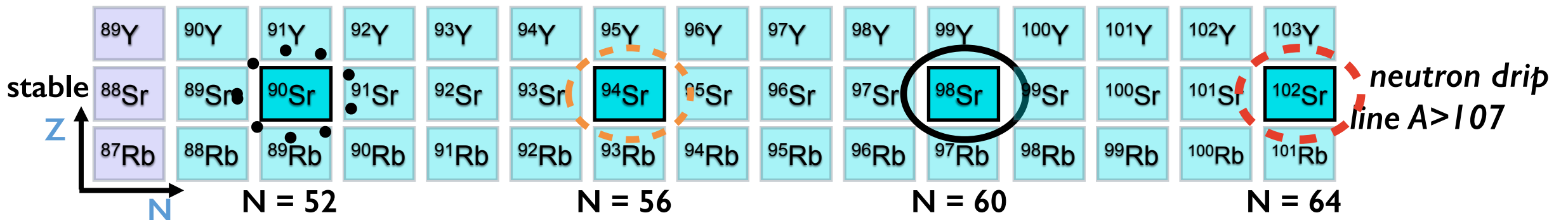
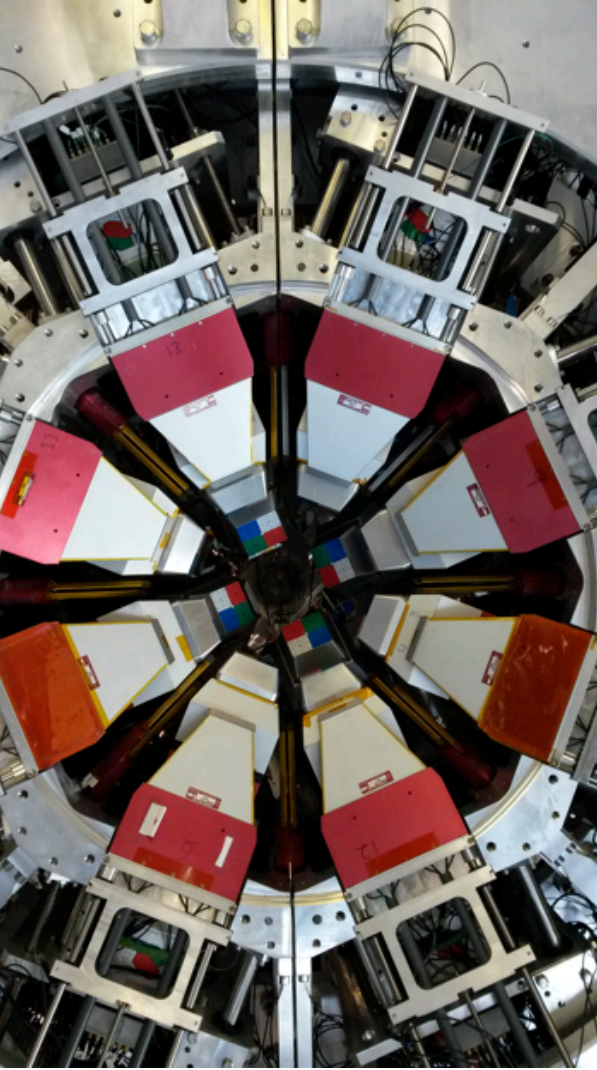
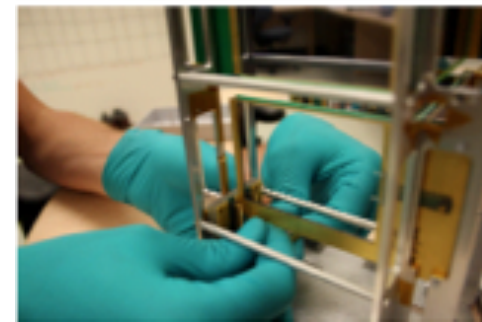
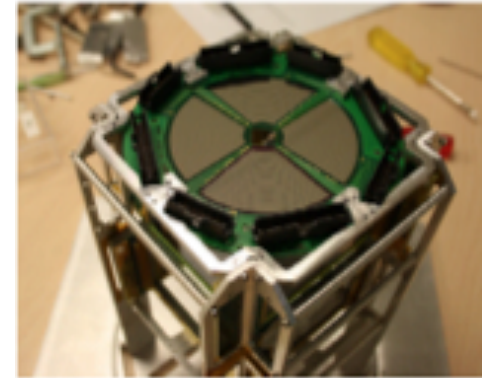
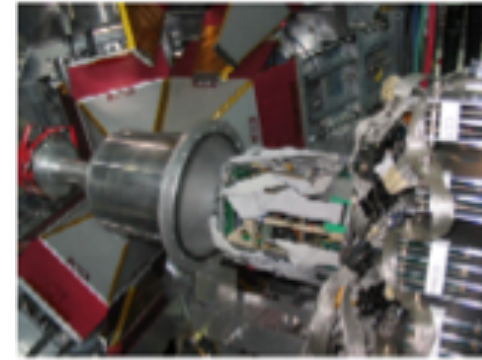
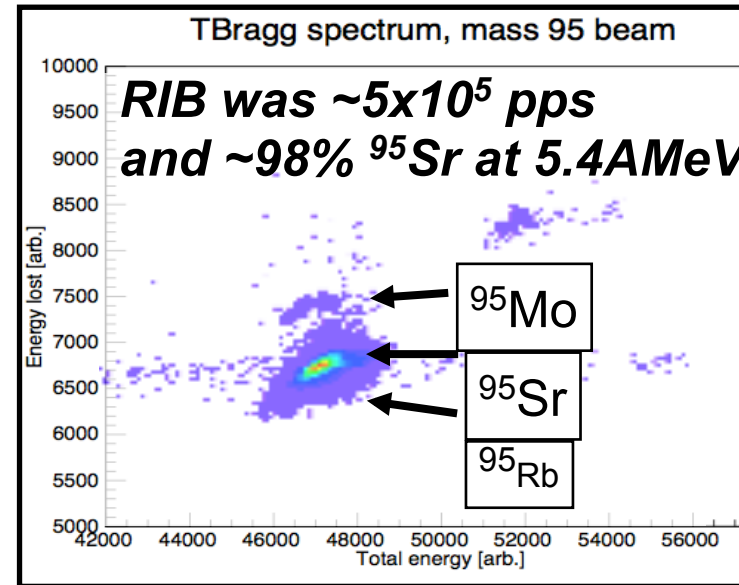


Minimization in two-state mixing using all available experimental data indicates:
 9% mixing of 0^+ state, 1.3% in 2^+ states.
 Deformation difference in β of 0.38.

Shape Coexistence at $Z \sim 40$ $N \sim 60$

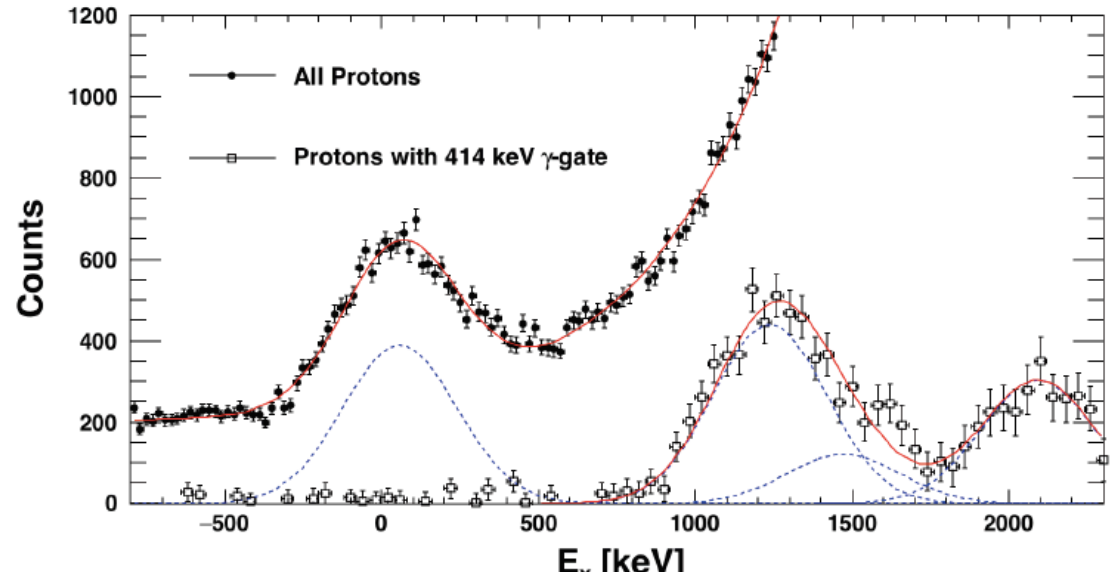
Measurements of single particle levels in $^{95,96,97}\text{Sr}$ essential for a detailed description of this transitional region.

First series of experiments with CSB charge-bred beams at ISAC



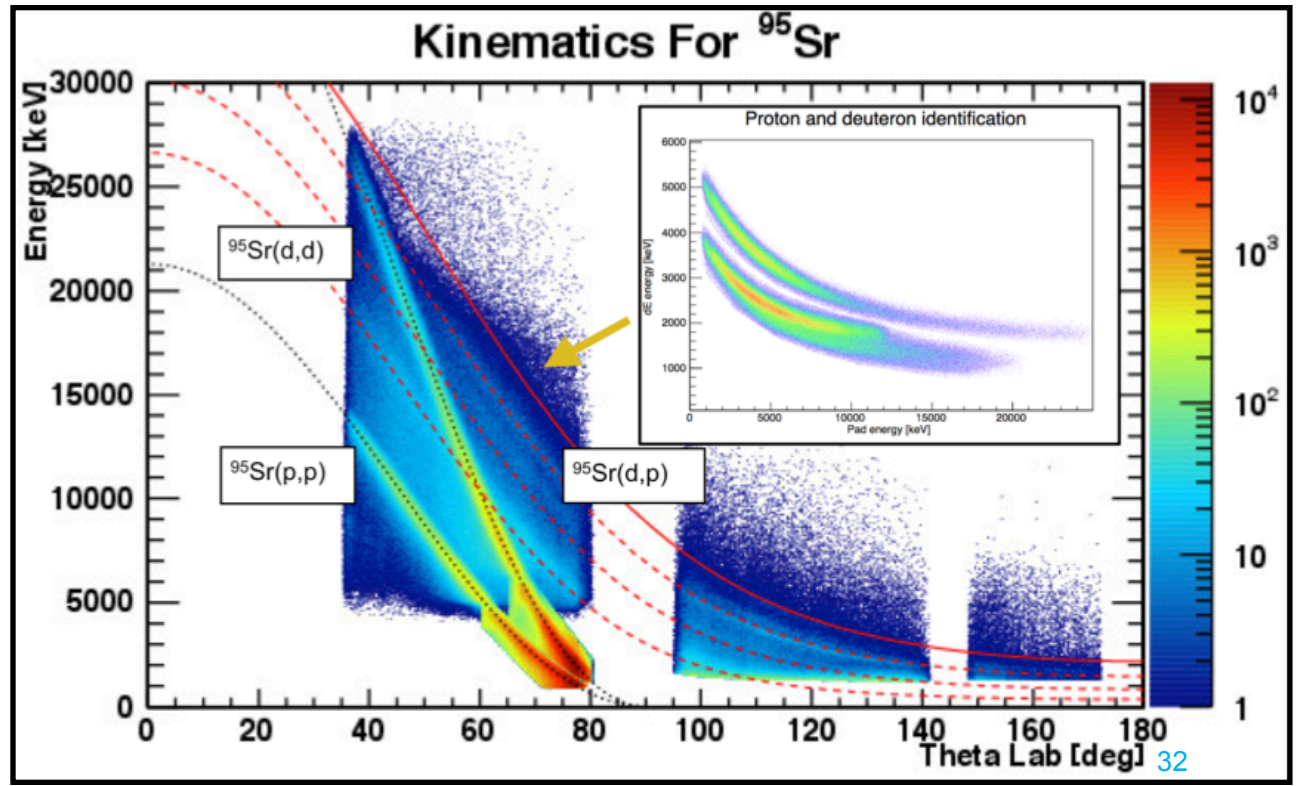
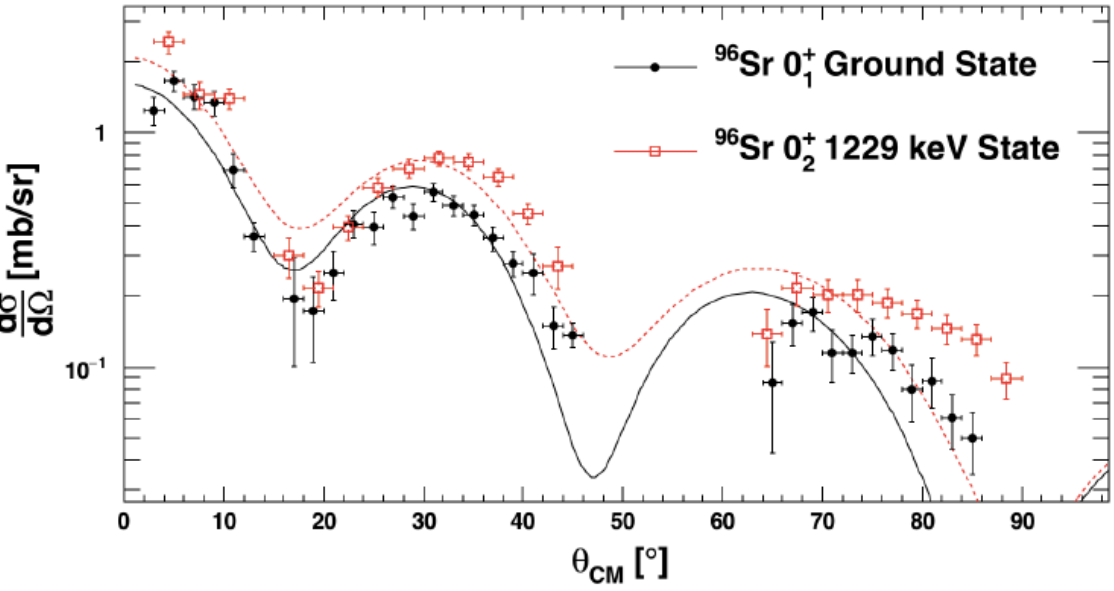
Shape coexistence around $N=60$

S. Cruz *et al.* Phys. Letts. B 786, 94 (2018).



$d(^{95}\text{Sr},p)^{96}\text{Sr}$, 5.4 MeV/u, $\sim 5 \cdot 10^5$ pps
TIGRESS+SHARC

ΔE -E Si telescopes for particle ID.
HPGe for gamma-ray detection.



Shape coexistence around $N=60$

S. Cruz *et al.* Phys. Letts. B 786, 94 (2018).

$$\rho^2(E0) = \left(\frac{3}{4\pi}\right)^2 Z^2 a^2 (1 - a^2) [\Delta(\beta^2)]^2$$

$$a^2=0.40(14) \text{ and } \beta_{\text{def}}=0.31(3), V_{\text{mix}} = 113\text{keV}$$

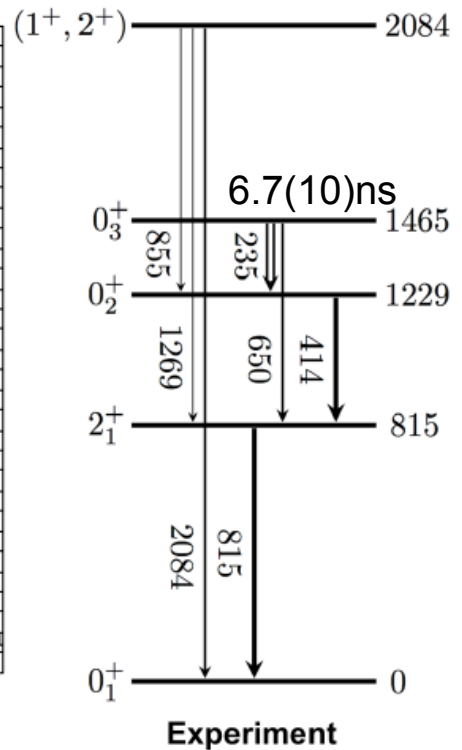
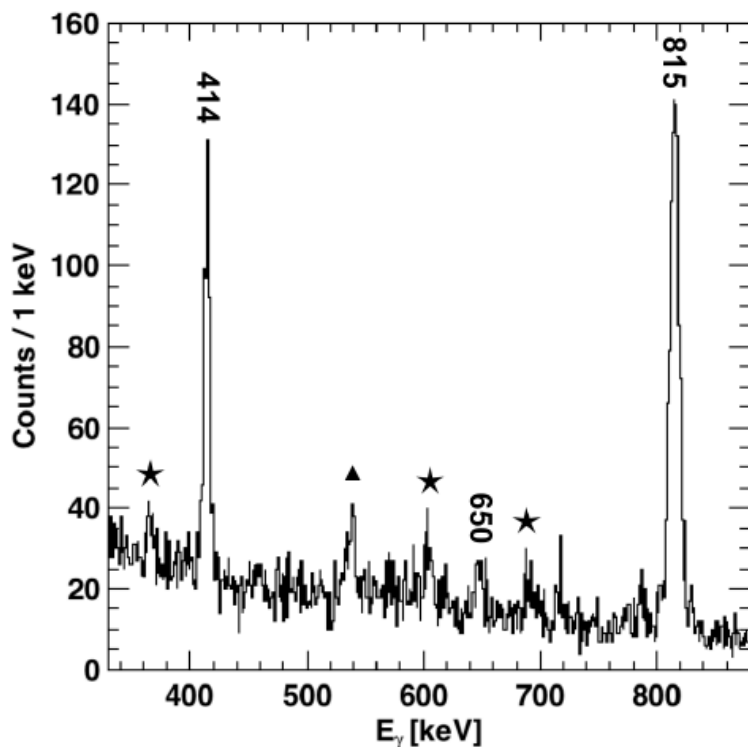
Shell model, proton valence space:

glek a: protons inert in $[1p_{3/2}]^4$

glek b: excitations allowed to $[1p_{3/2}]^2[1p_{1/2}]^2$

glek c: $0g_{9/2}$ allowed (max 2)

Calculations work well for C^2S in $d(^{94}\text{Sr},p)$.



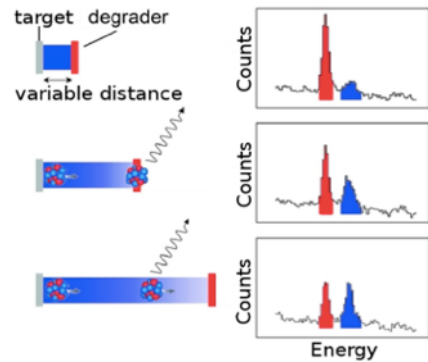
Exp.		Unmixed		glek Ⓐ		glek Ⓑ		glek Ⓒ	
E_x (keV)	C^2S	E_x (keV)	C^2S	E_x (keV)	C^2S	E_x (keV)	C^2S	E_x (keV)	C^2S
0	0.19(3)	0	0.19(3)	0	1.742	0	1.575	0	1.455
1229	0.22(3)	1314	0	-	-	-	-	-	-
1465	0.33(13)	1380	0.55(13)	2271	0.056	1691	0.098	444	0.105

$T_{1/2}$ from H. Mach *et al.*, PRC 41, 226 (1990).

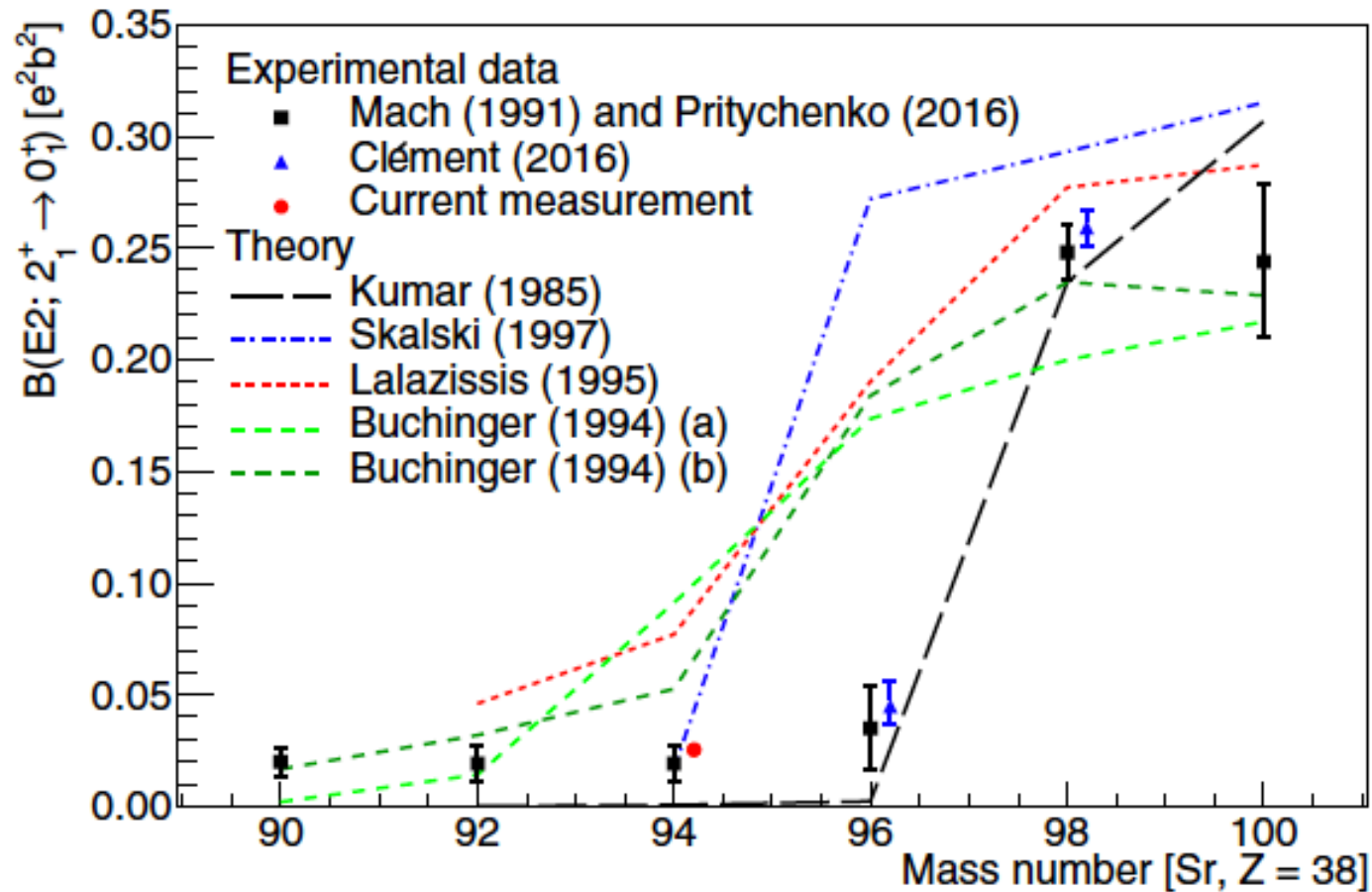
Precision lifetime measurement in ^{94}Sr

A. Chester *et al.*, PRC 96, 011302(R) (2017).

Reference	Technique	Lifetime τ (ps)	$B(E2; 2_1^+ \rightarrow 0_1^+) (e^2b^2)$
Current work	Coulex-RDM	$7.80^{+0.50}_{-0.40}(\text{stat.}) \pm 0.07(\text{sys.})$	$0.0253^{+0.0014}_{-0.0015}(\text{stat.}) \pm 0.0002(\text{sys.})$
Mach <i>et al.</i>	Fast timing	10 ± 4	0.020 ± 0.008



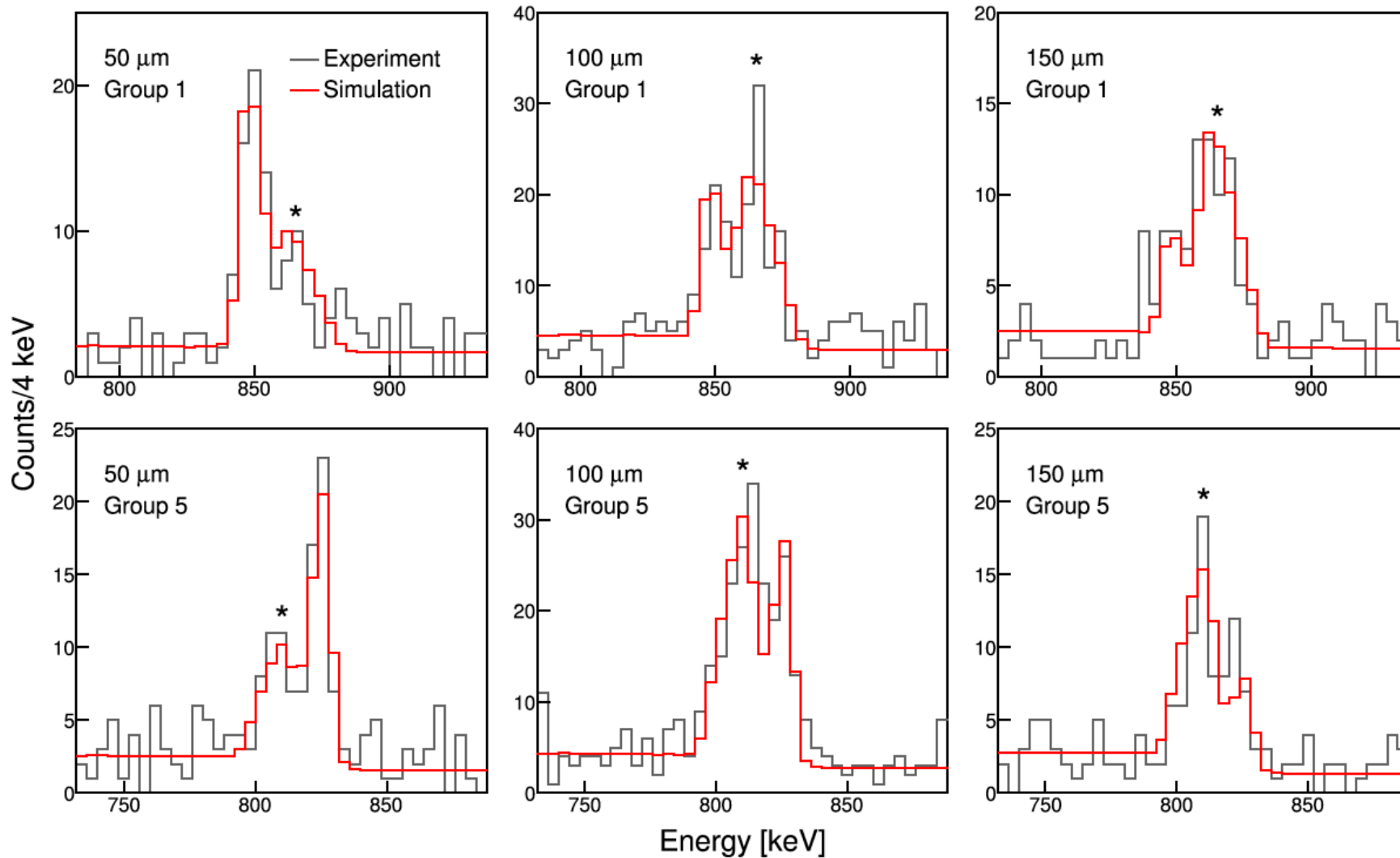
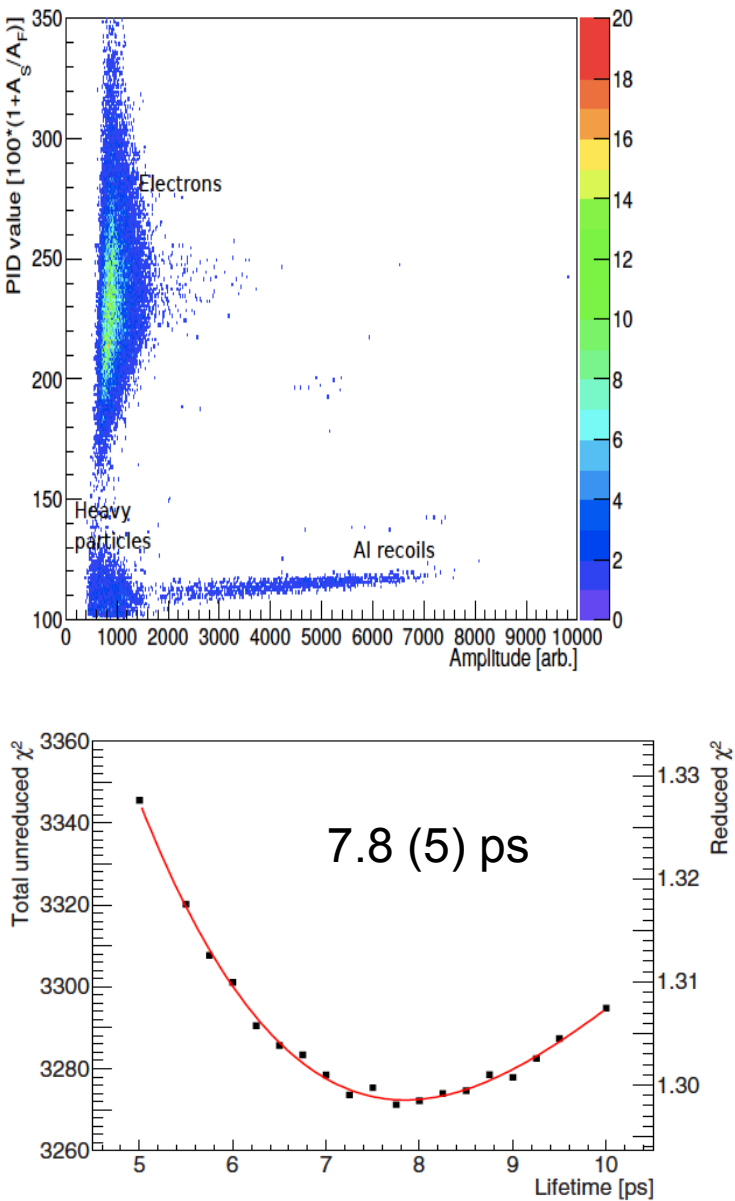
- TIGRESS Integrated Plunger
- Improves uncertainty in the $B(E2)$ value from 40% to <6%.
- Confirms sudden onset of deformation in ground-state structure.



H. Mach *et al.*, NPA 523, 197 (1991).

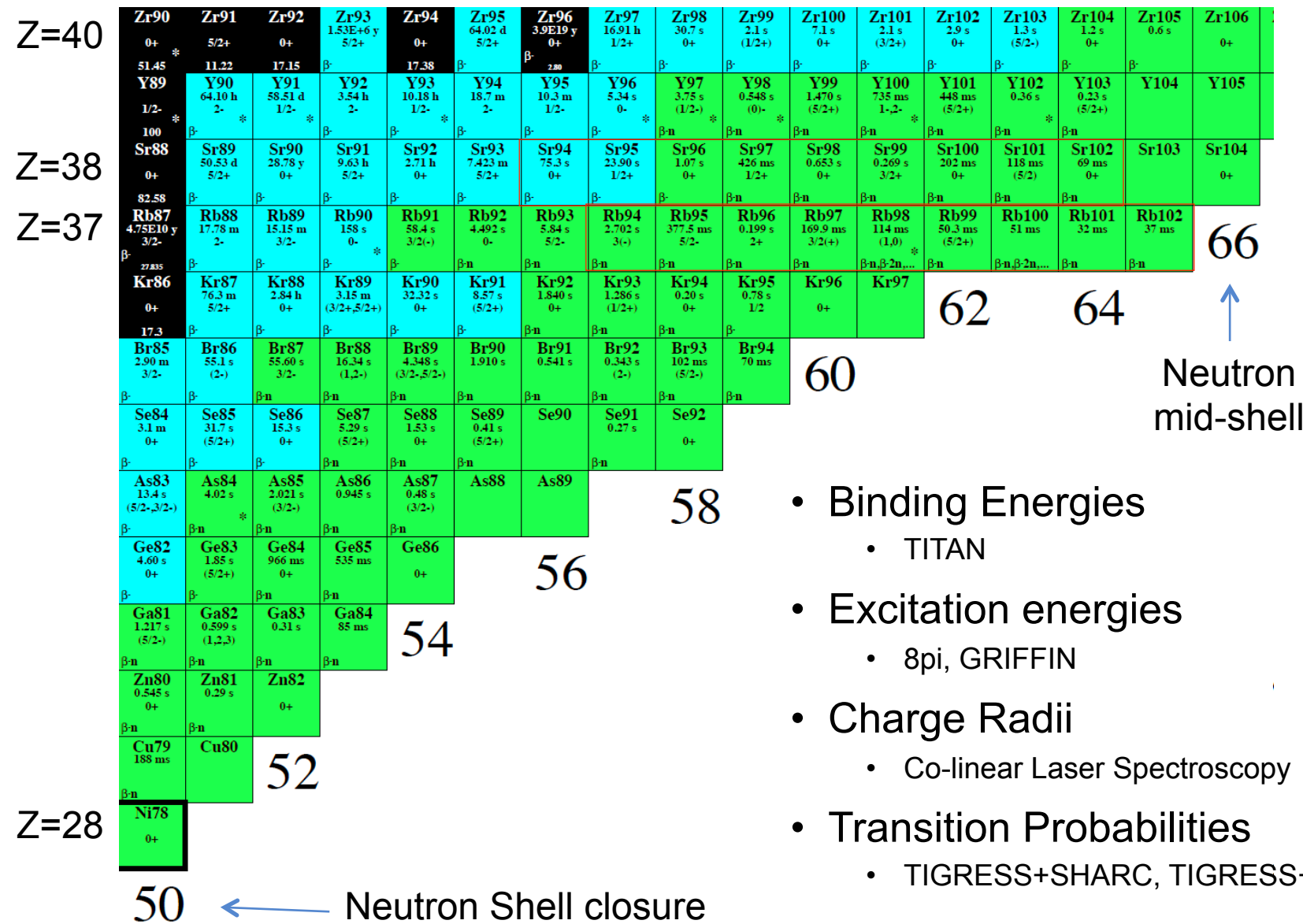
Precision lifetime measurement in ^{94}Sr

First 2^+ state populated in unsafe Coulex of ^{94}Sr beam



A. Chester *et al.*, PRC 96, 011302(R) (2017).

Shape coexistence at $N=60$: Zr, Y, Sr, Rb Isotopes



ISAC studies around $N=60$:

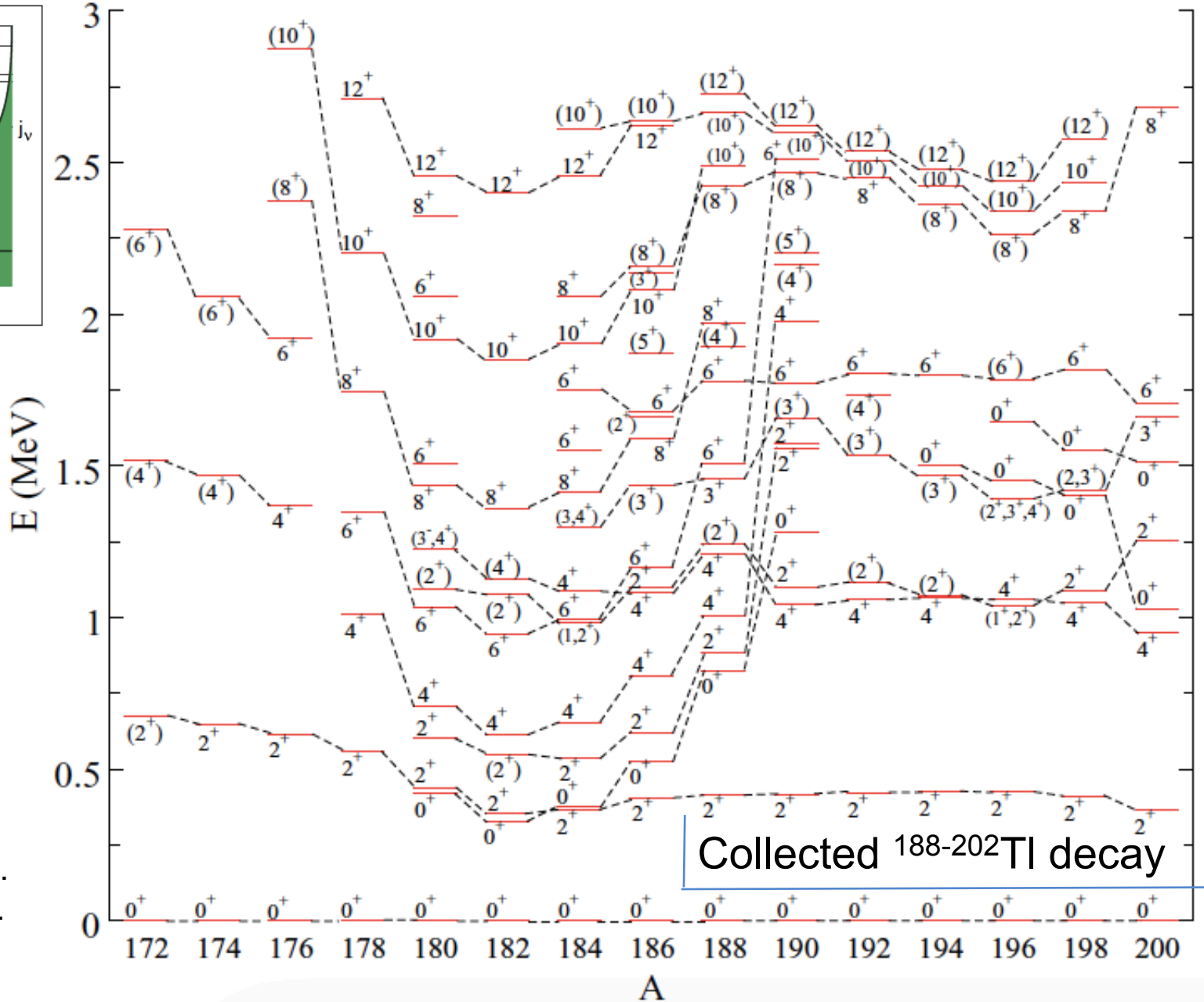
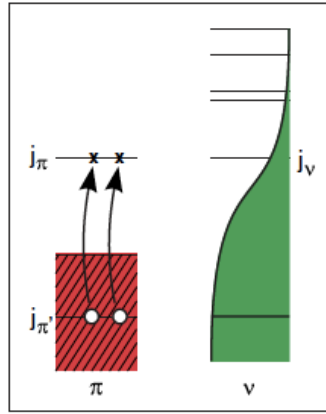
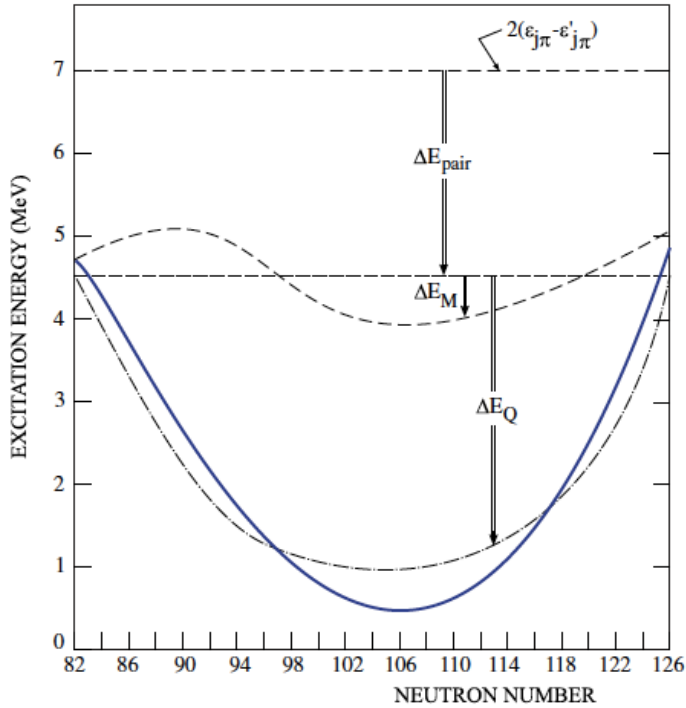
S. Cruz *et al.*, Phys. Letts. B 786, 94 (2018).
 A. Chester *et al.*, PRC 96, 011302(R) (2017).
 Z.M. Wang, *et al.*, PRC 93, 054301 (2016).
 R. Klawitter *et al.*, PRC 93, 045807 (2016).
 J. Park *et al.*, PRC 96, 014315 (2016).
 T.J. Procter *et al.*, Eur. Phys. J. A 51, 23 (2015).
 A. Chakraborty *et al.*, PRL 110, 022504 (2013).
 V.V. Simon *et al.*, PRC 85, 064308 (2012).

- Binding Energies
 - TITAN
- Excitation energies
 - 8pi, GRIFFIN
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- Transition Probabilities
 - TIGRESS+SHARC, TIGRESS+TIP, GRIFFIN+PACES+LaBr₃

What's next for ISAC?

- Many experiments already performed and under analysis in:
 - Structure of deformed nuclei
 - Shape coexistence
 - Octupole correlations and deformation

Hg isotopes from Tl decay

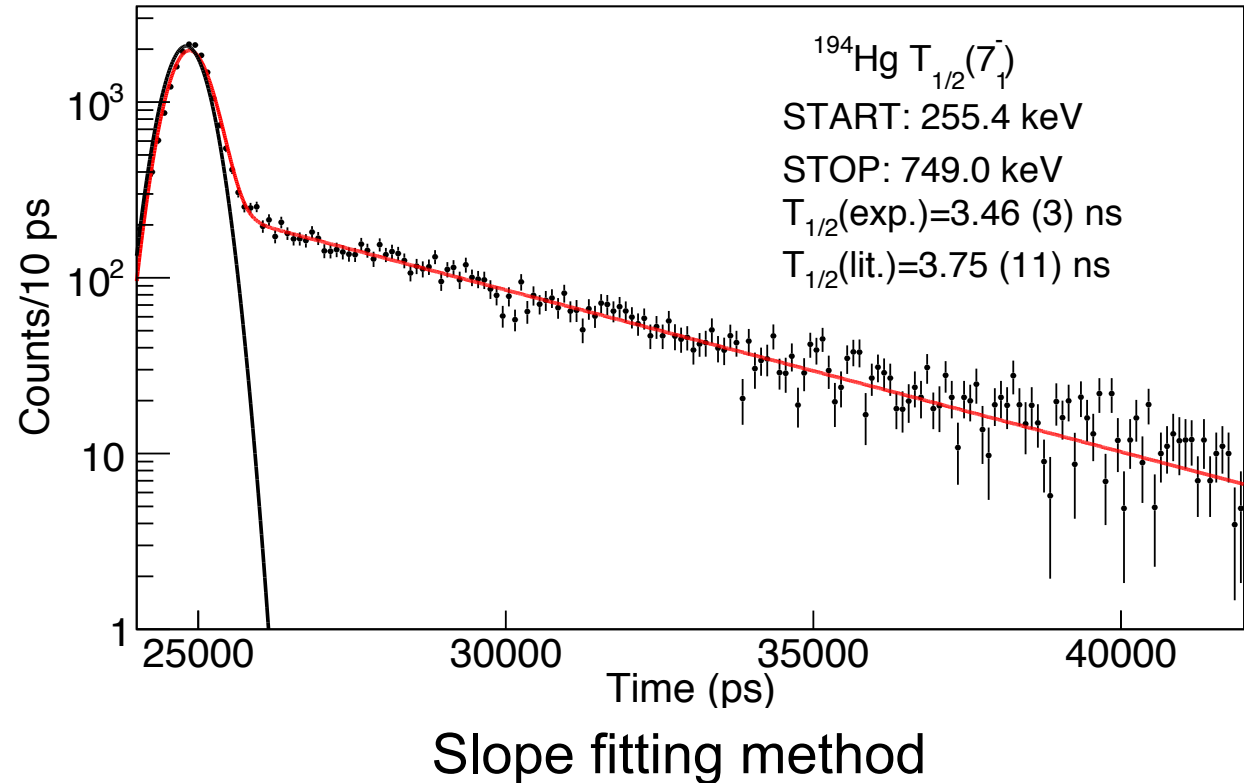
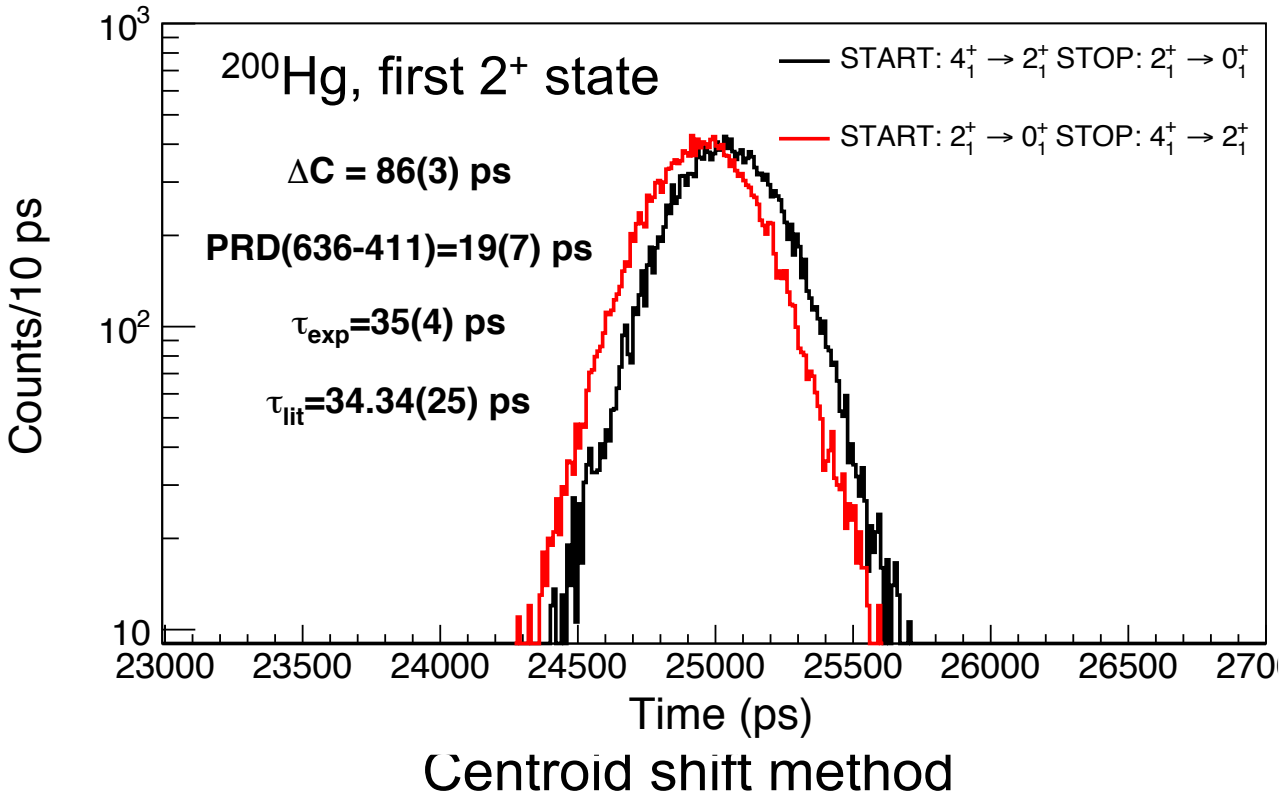


Hg isotopes display characteristic parabolic systematic of GS coexistence with a deformed intruder configuration

Heyde & Wood, Rev. Mod. Phys. 83, 1467 (2011).
Garcia-Ramos & Heyde, PRC 89, 014306 (2014).

Shape coexistence in the neutron-deficient lead region: Lifetimes in the even-even 188-200Hg with GRIFFIN

- Lifetimes extracted in LaBr-LaBr-TAC-HPGe coincidences
- Employed the Generalized Centroid Shift method with 7 LaBr₃(Ce) crystals



B. Olaizola *et al.*, PRC 100, 024301 (2019).

ISAC-II High Mass: $^{156,158,160}\text{Er}$ Coulomb Excitation with TIGRESS

$A > 29$ beams require charge-breeding.

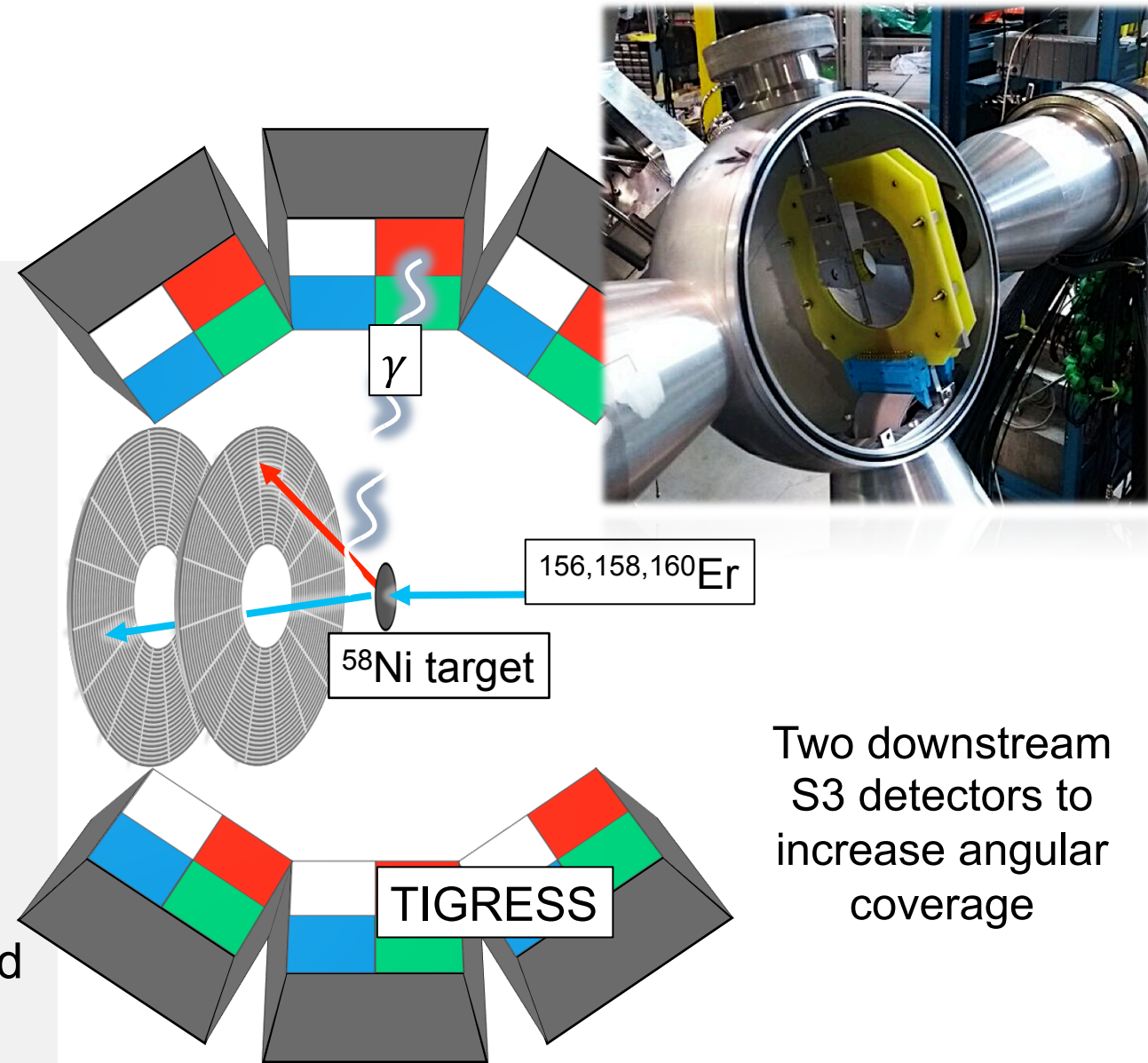
- Currently use ISAC CSB
- CANREB EBIS from 2019

S1750, J. Smallcombe & A.B. Garnsworthy
HPTa target with TRILIS and CSB.
Beams delivered to TIGRESS, Oct 2017:

$^{156}\text{Er}^{23+}$: 1×10^8 total pps, 25% ^{156}Er , ~14hrs
 $^{158}\text{Er}^{23+}$: 1×10^8 total pps, 50% ^{158}Er , ~14hrs
 $^{160}\text{Er}^{23+}$: 1×10^8 total pps, 50% ^{160}Er , ~14hrs

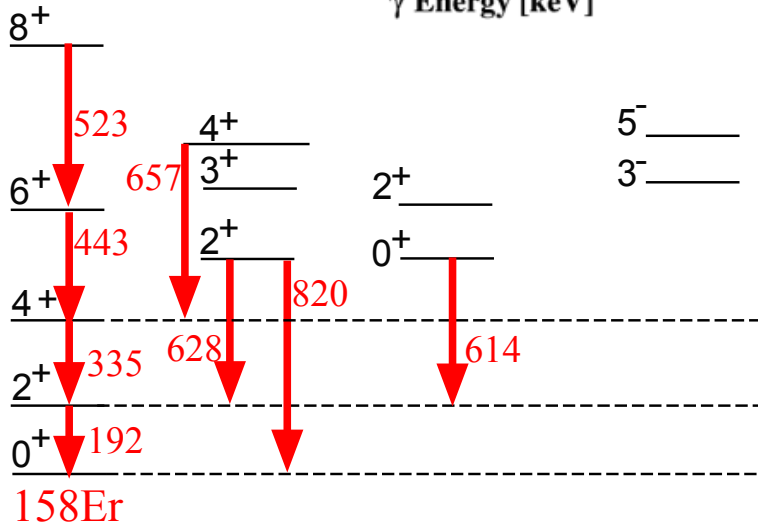
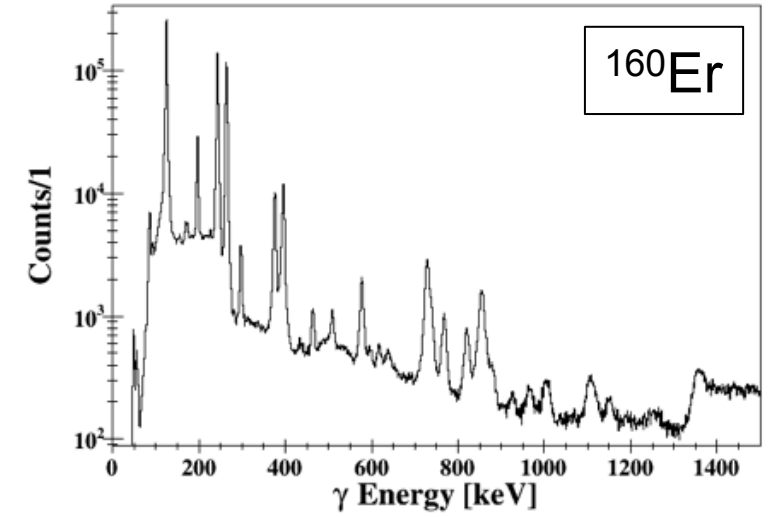
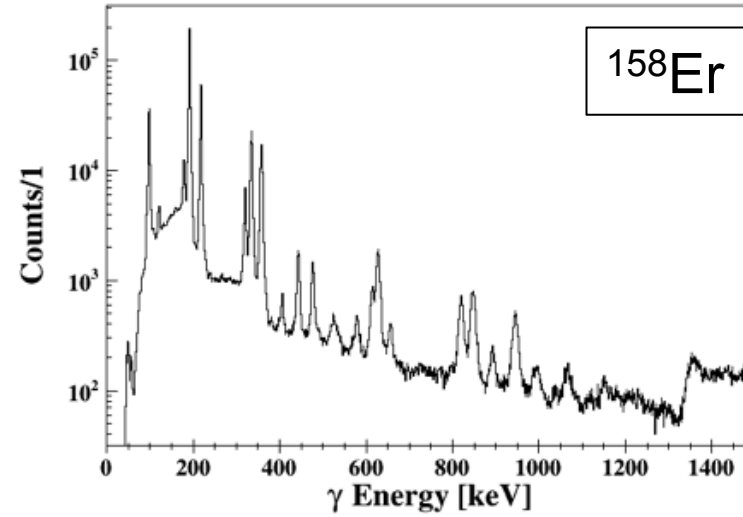
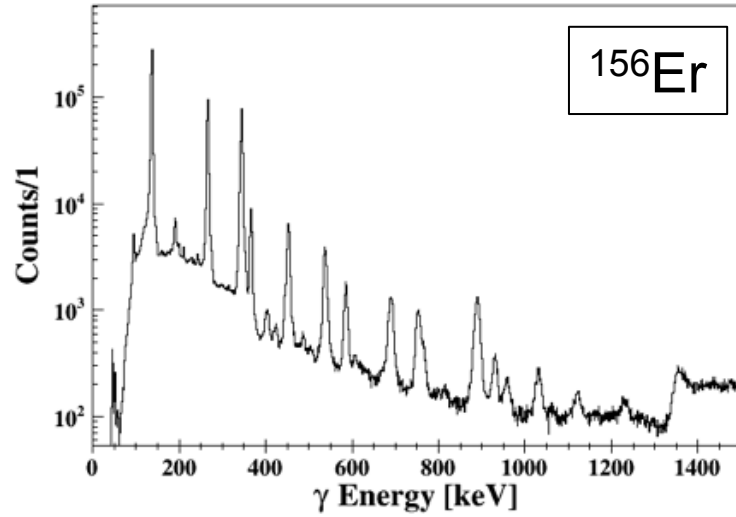
3.9 AMeV Coulex on ^{58}Ni target

Will measure quadrupole moments of low-lying states to determine the shape of these nuclei, and investigate coexistence at $N=88,90$.

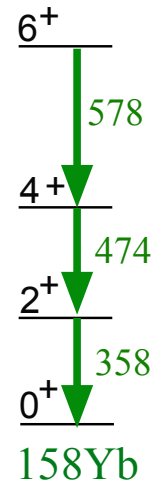


Two downstream
S3 detectors to
increase angular
coverage

ISAC-II High Mass: $^{156,158,160}\text{Er}$ Coulomb Excitation with TIGRESS



^{158}Dy



^{158}Yb

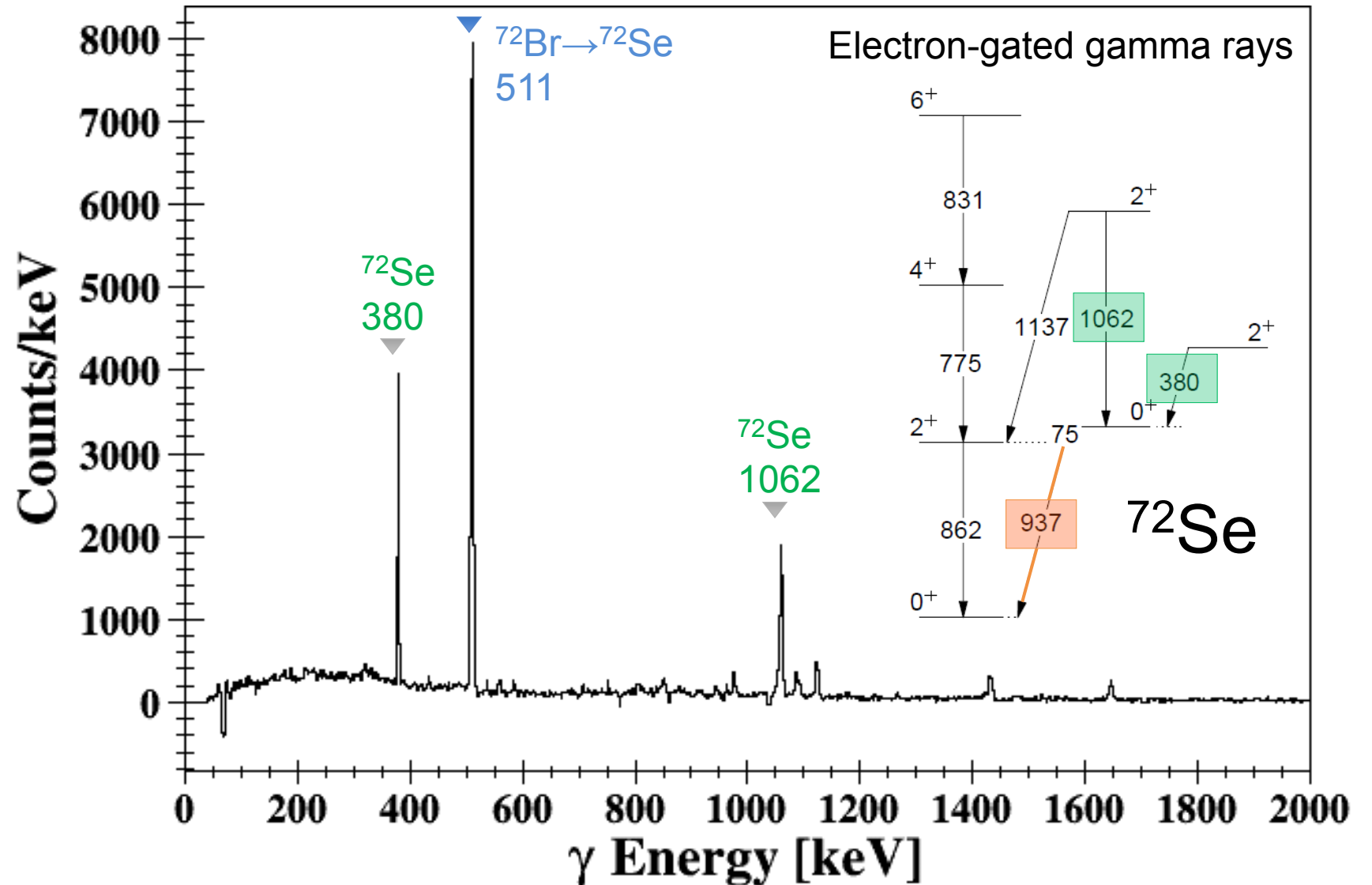
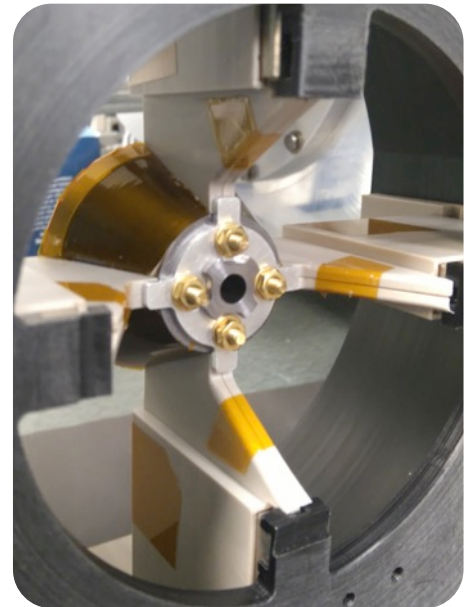
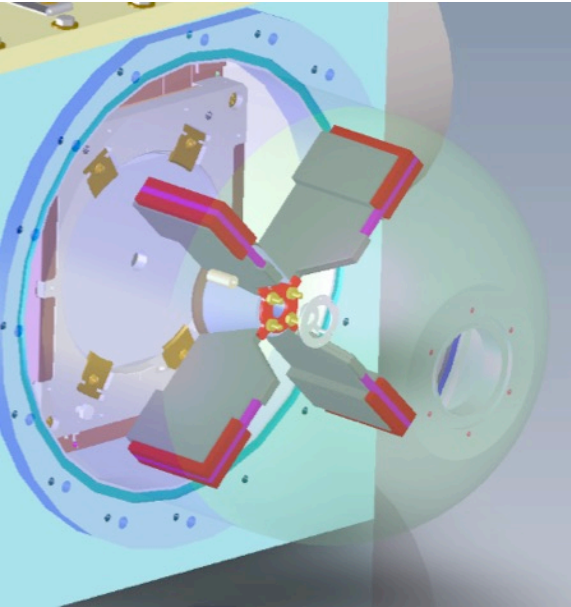
- Excellent Coulex dataset
- Excitation up to fourth 2^+ state seen (good for invariant analysis)
- GOSIA analysis ongoing – Dy and Yb contaminants will also be analysed

Analysis by Paulina Siuryte (MPhys) and James Smallcombe

SPICE in-beam electron spectrometer

Shape coexistence in ^{72}Se

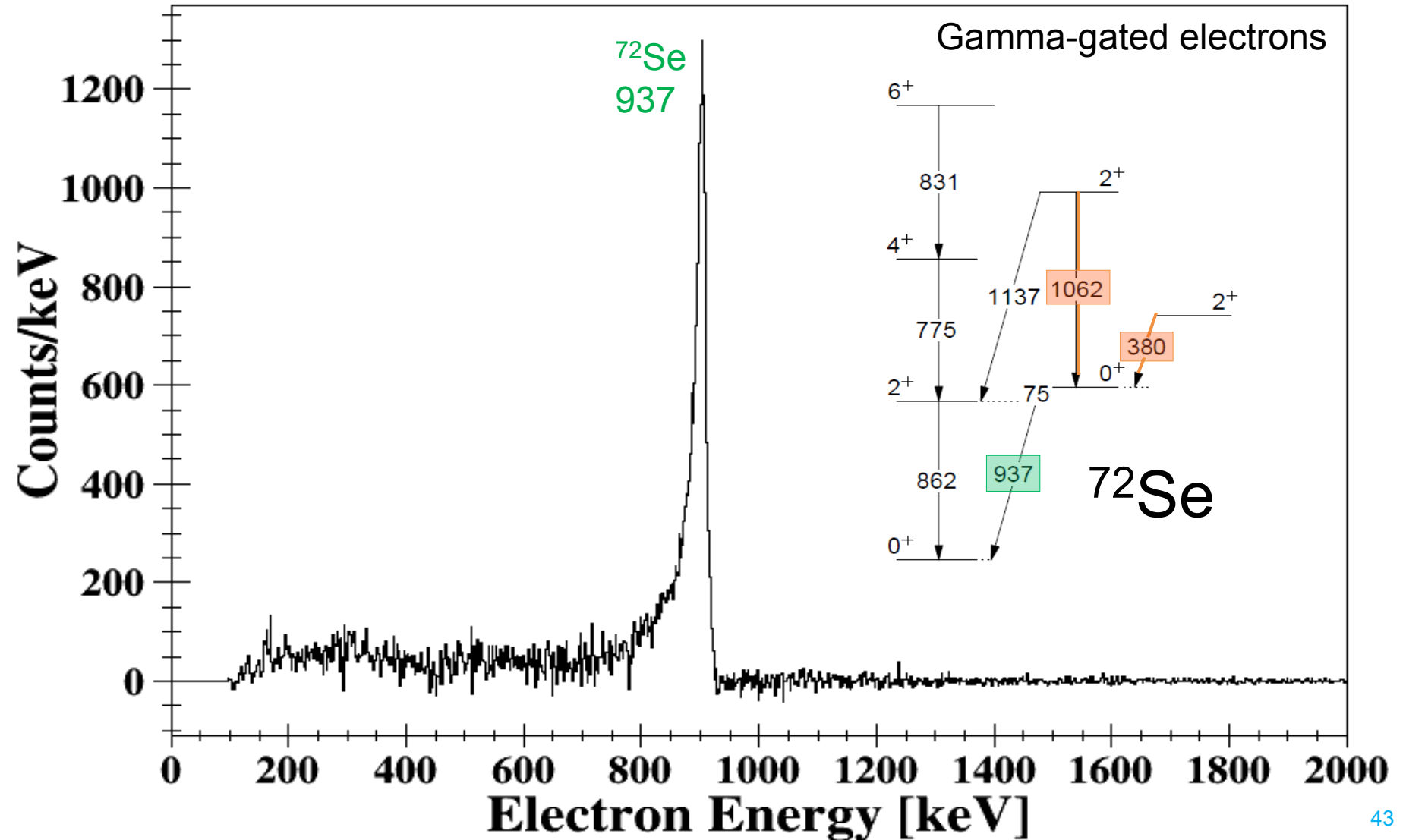
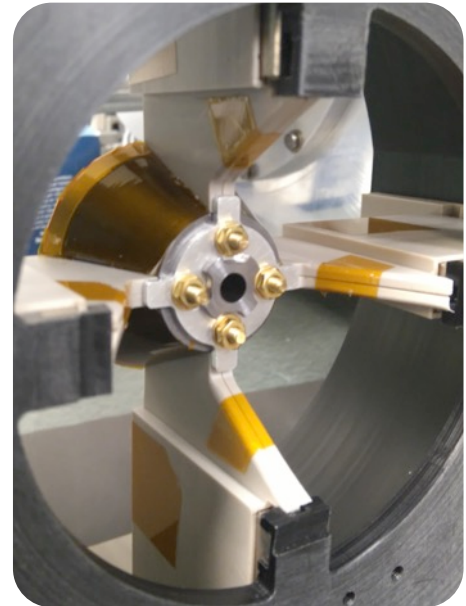
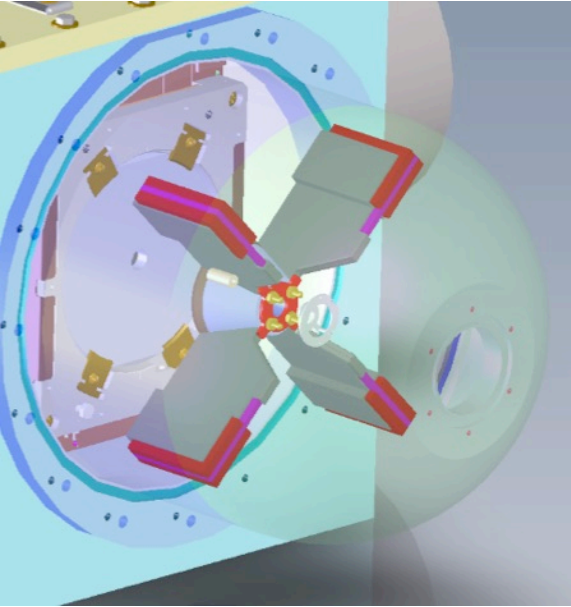
J. Smallcombe, W. Korten *et al.*



SPICE in-beam electron spectrometer

Shape coexistence in ^{72}Se

J. Smallcombe, W. Korten *et al.*



TRIUMF-ISAC is a beautiful place to do physics

Excellent instrumentation to explore nuclear shapes, coexistence and collective behaviors:

- GRIFFIN
- TITAN
- Colinear laser spec.
- TIGRESS
- TIP
- SPICE
- plus others...

There are some great results which are influencing present research directions.

Many exciting new results to come in the future!

