TRIUMF

Nuclear shapes, coexistence and collective behaviors studied at ISAC

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Senior Scientist, TRIUMF

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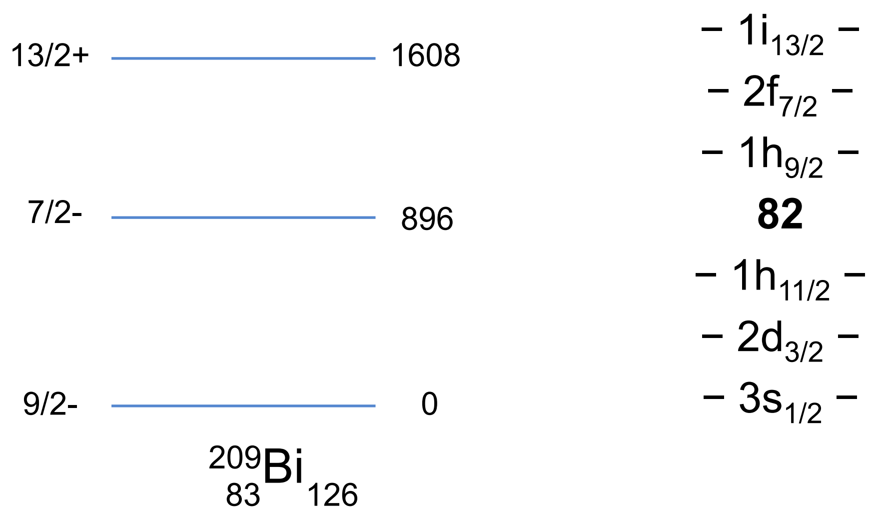
Excitations in atomic nuclei

- 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?

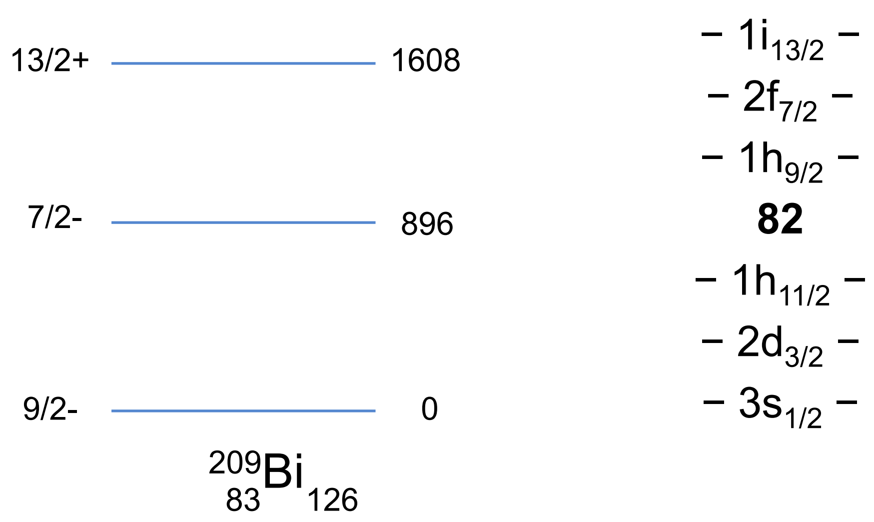
Microscopic

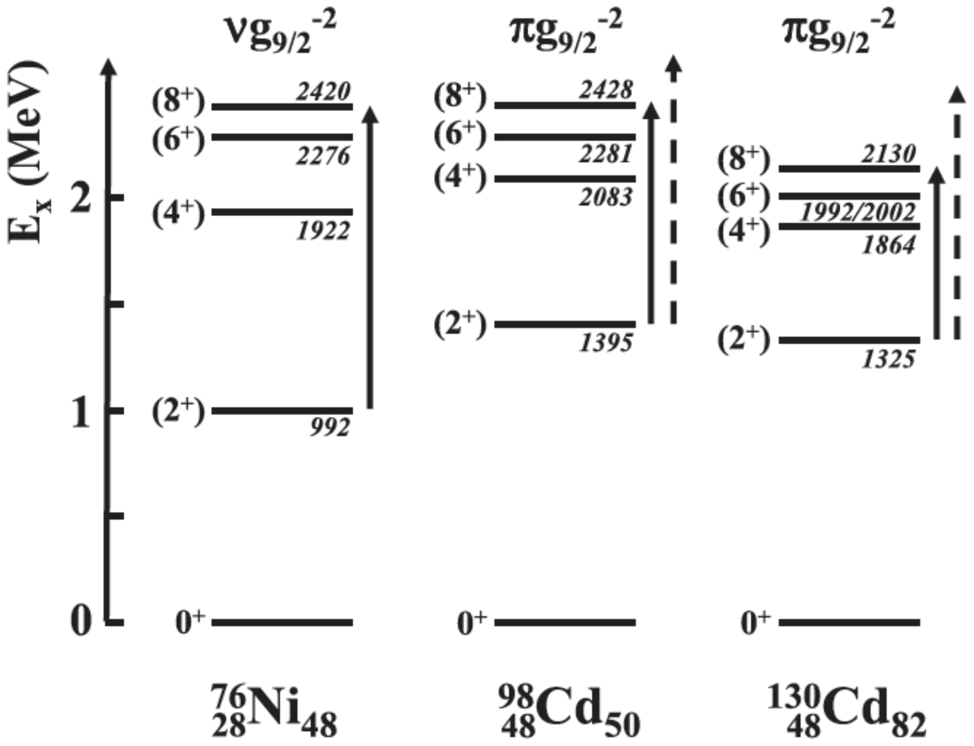
- Single-particle structure or seniority scheme, “Shell model”



Microscopic

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





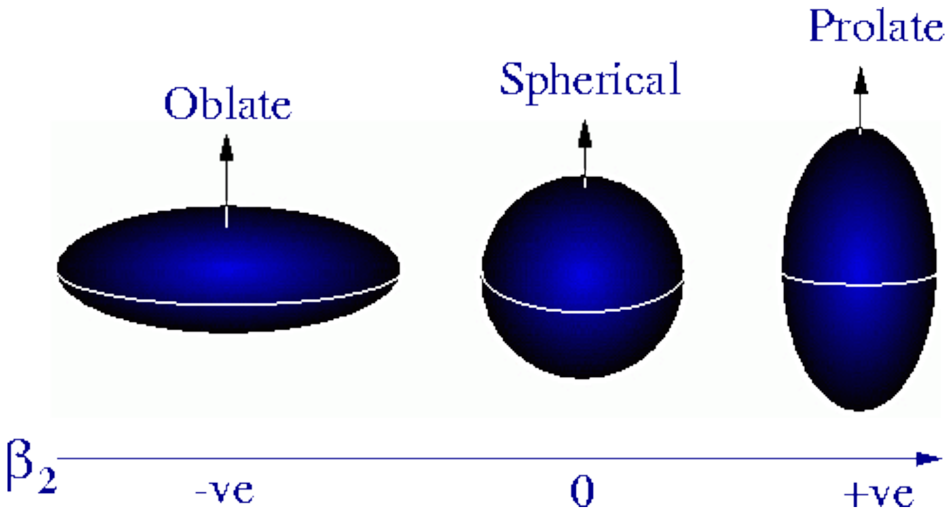
Seniority structures of $g_{9/2}$ neutron and proton pairs

Seniority = number of nucleons not paired to zero angular momentum

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

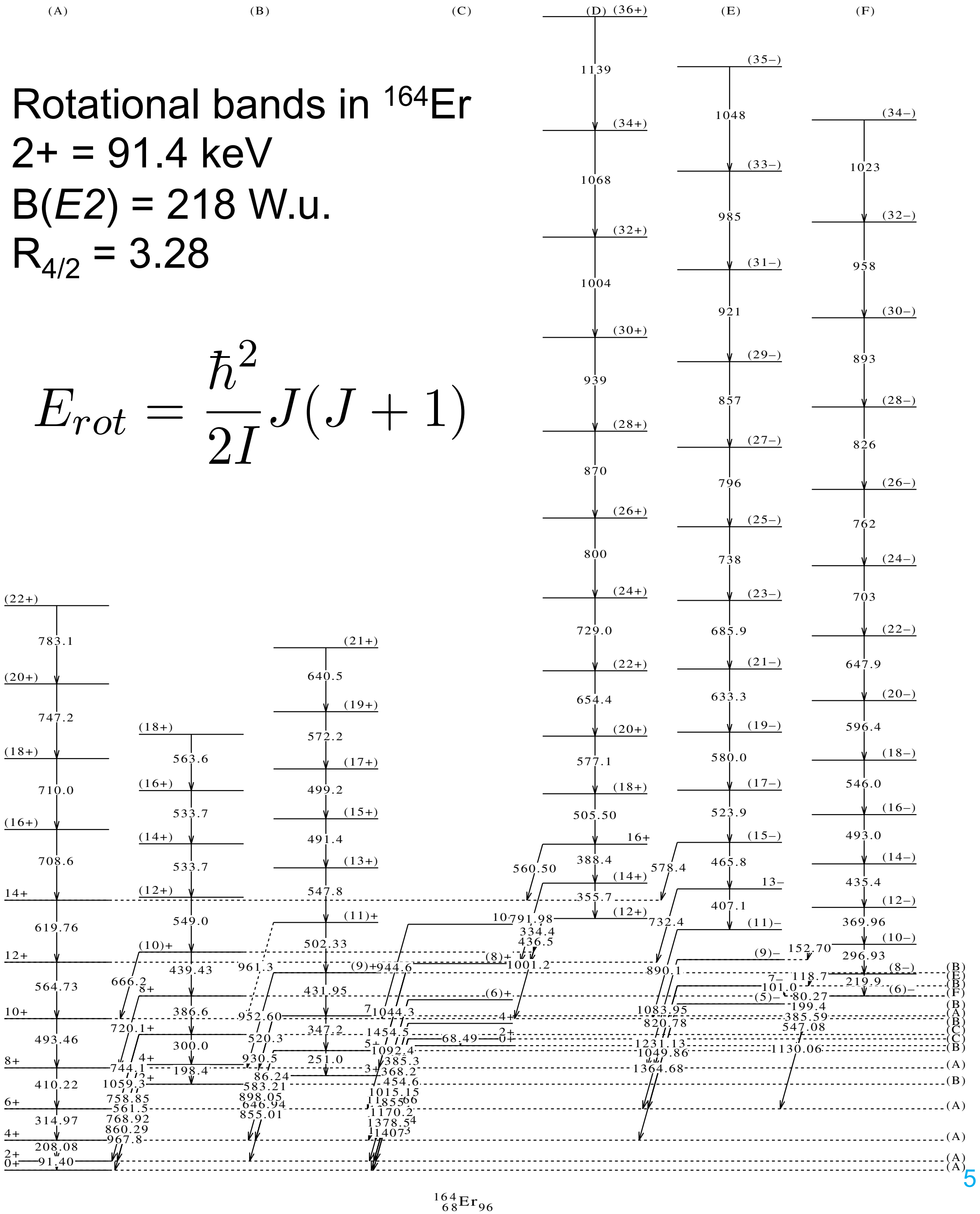
Macroscopic

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

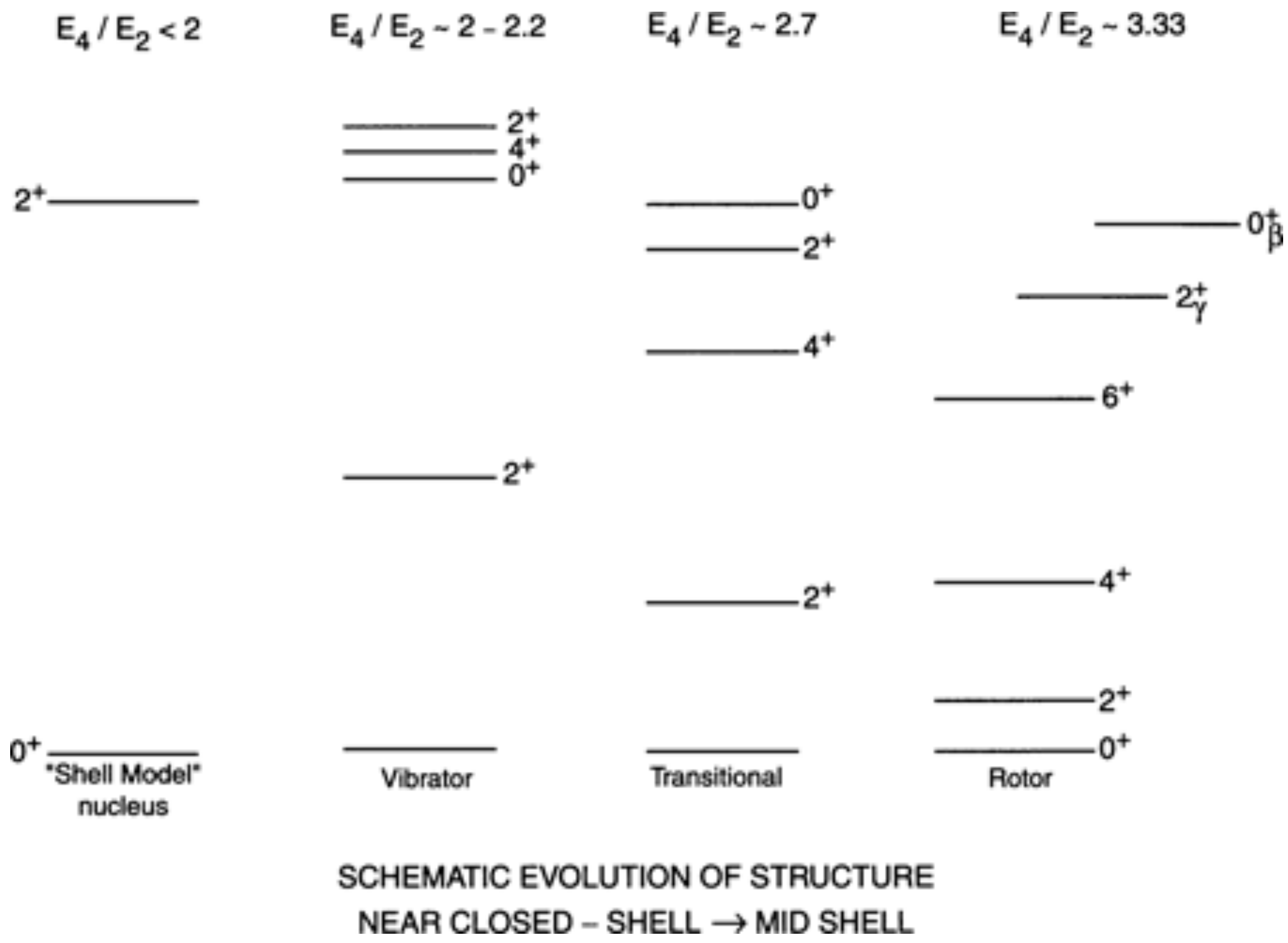


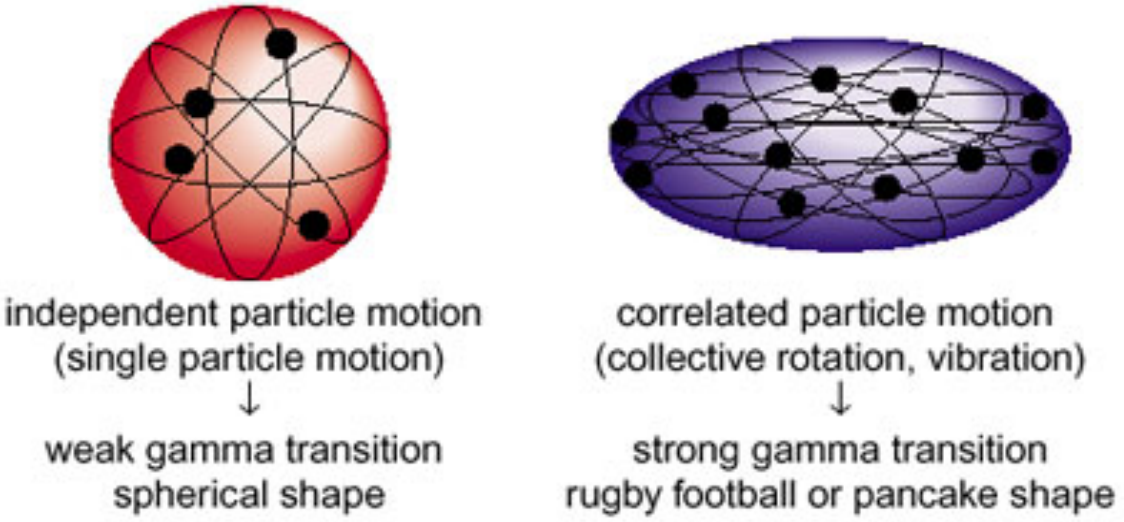
Rotational bands in ^{164}Er
2+ = 91.4 keV
$B(E2)$ = 218 W.u.
$R_{4/2}$ = 3.28

$$E_{rot} = \frac{\hbar^2}{2I} J(J+1)$$



Evolution between Microscopic to Macroscopic





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.nscl.msu.edu/, and
R.F. Casten, Nuclear Structure from a simple perspective, 2001

Evolution between Microscopic to Macroscopic

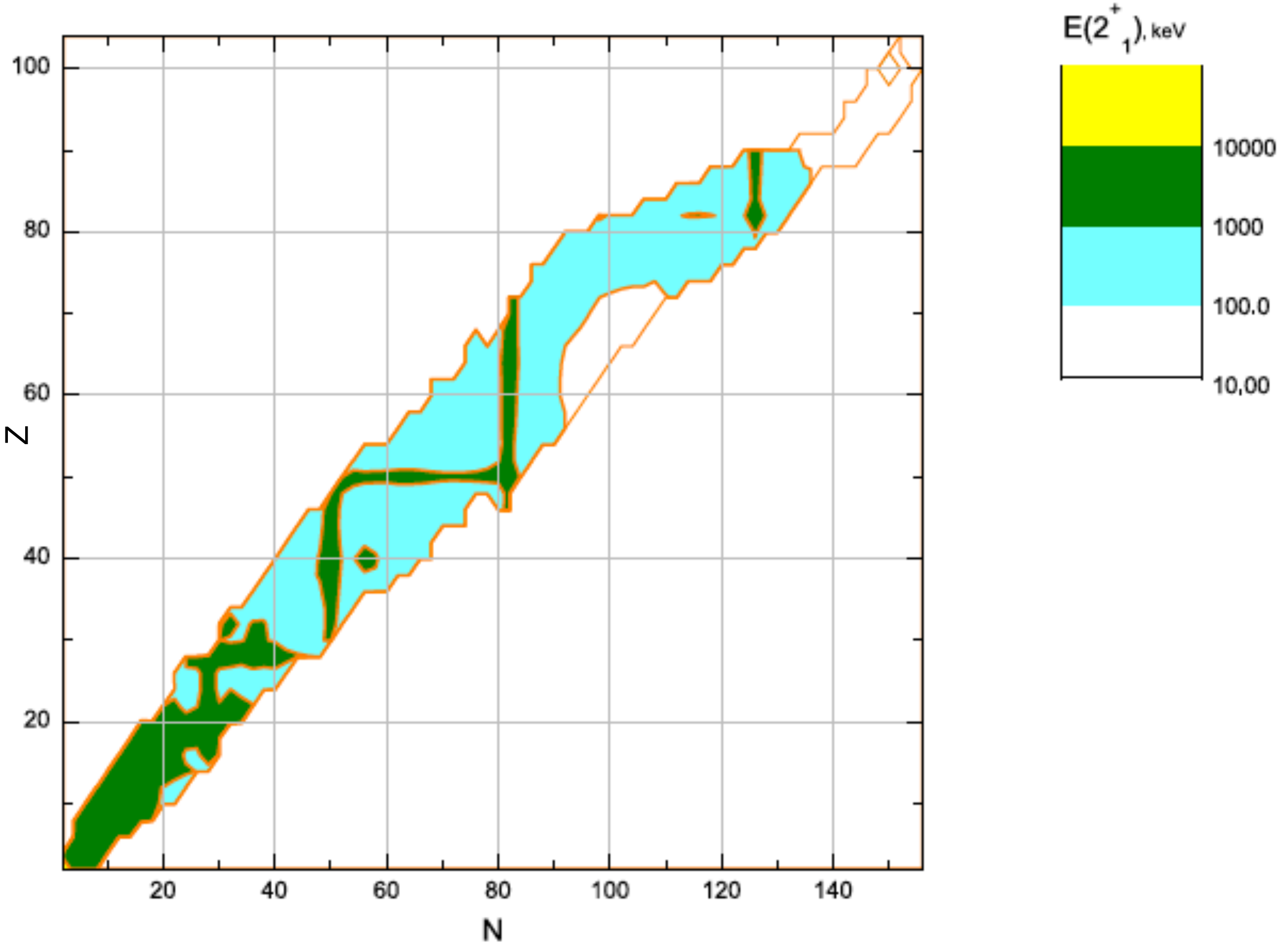
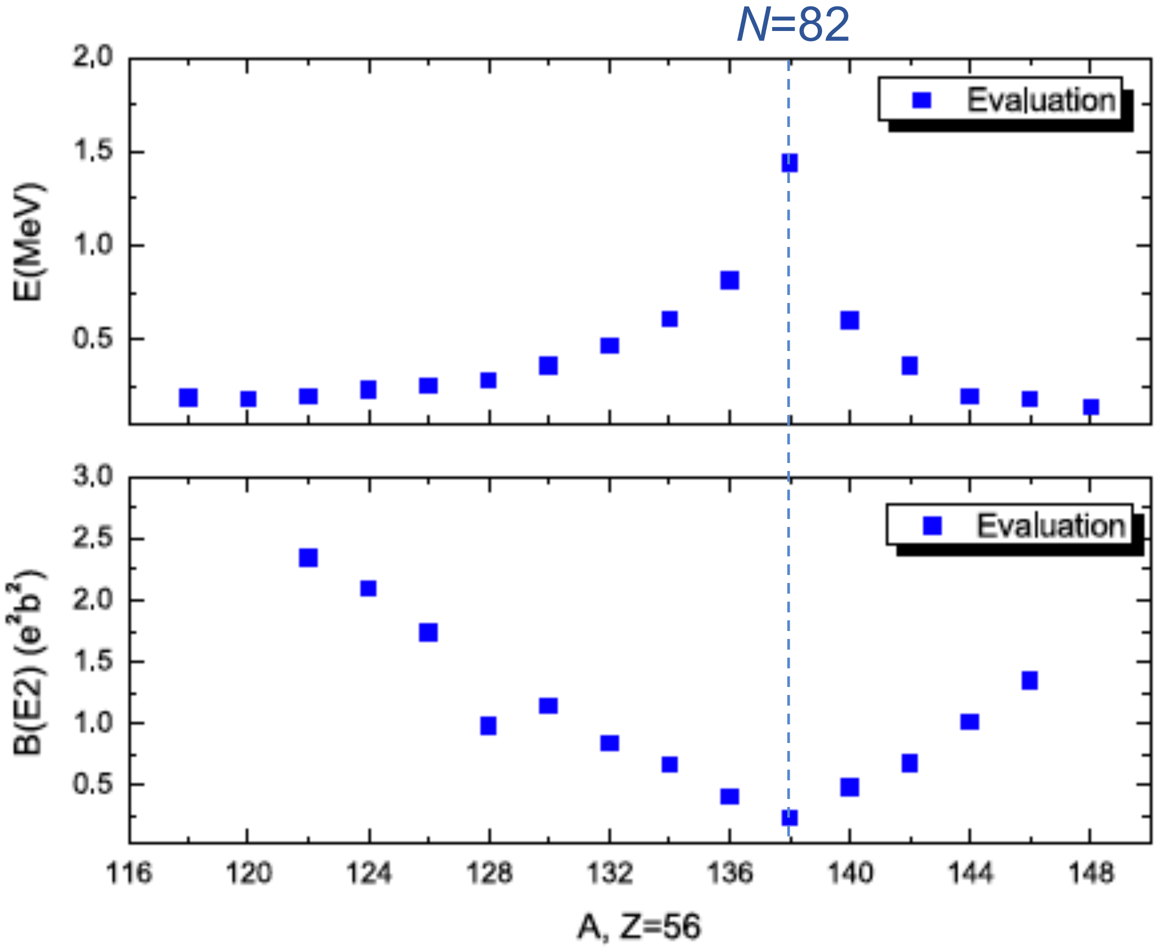


Fig. 3. Energies of 2^+_1 states ($E(2^+_1)$) for even–even $Z = 2$–104 nuclei, in keV.



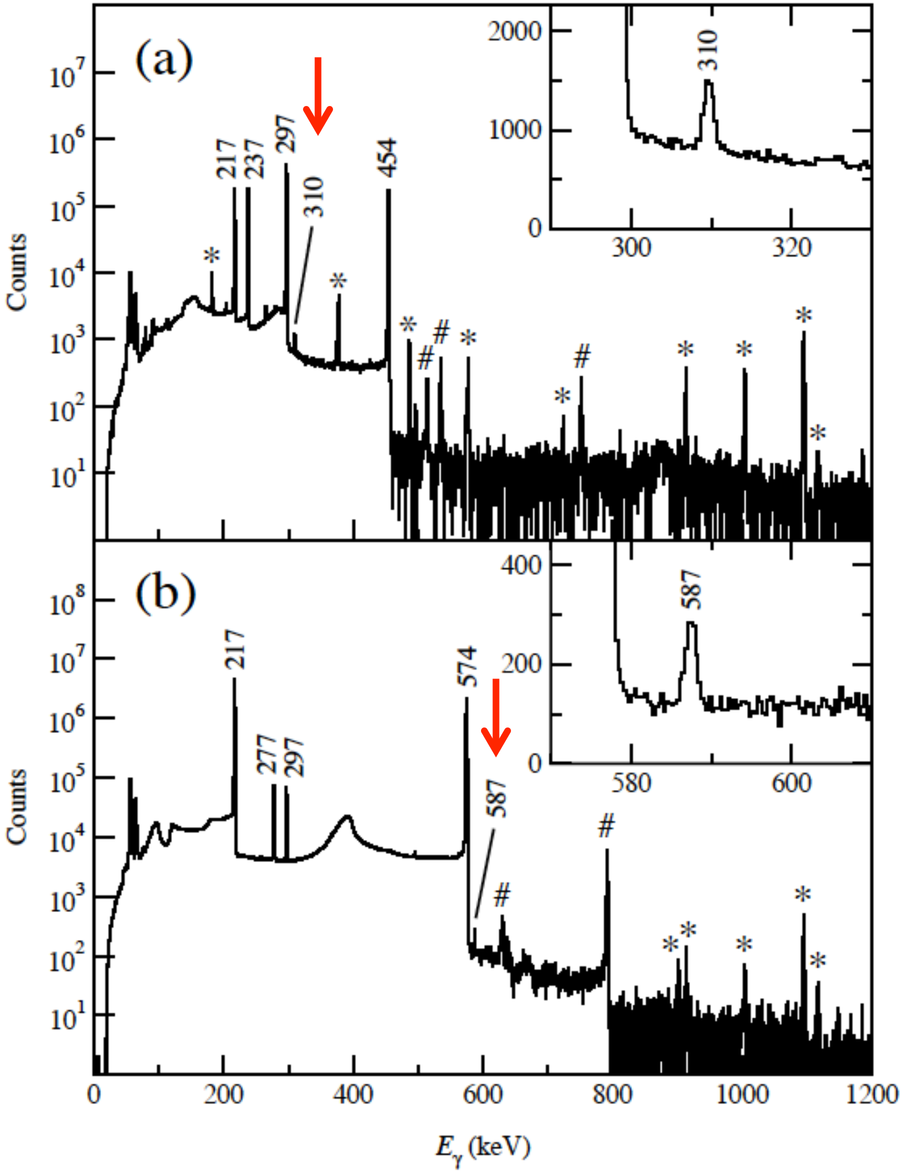
Graph 28. Evaluated energies, $E(2^+_1)$, and $B(E; 0^+_1 \to 2^+_1)$ values for Ba nuclei.

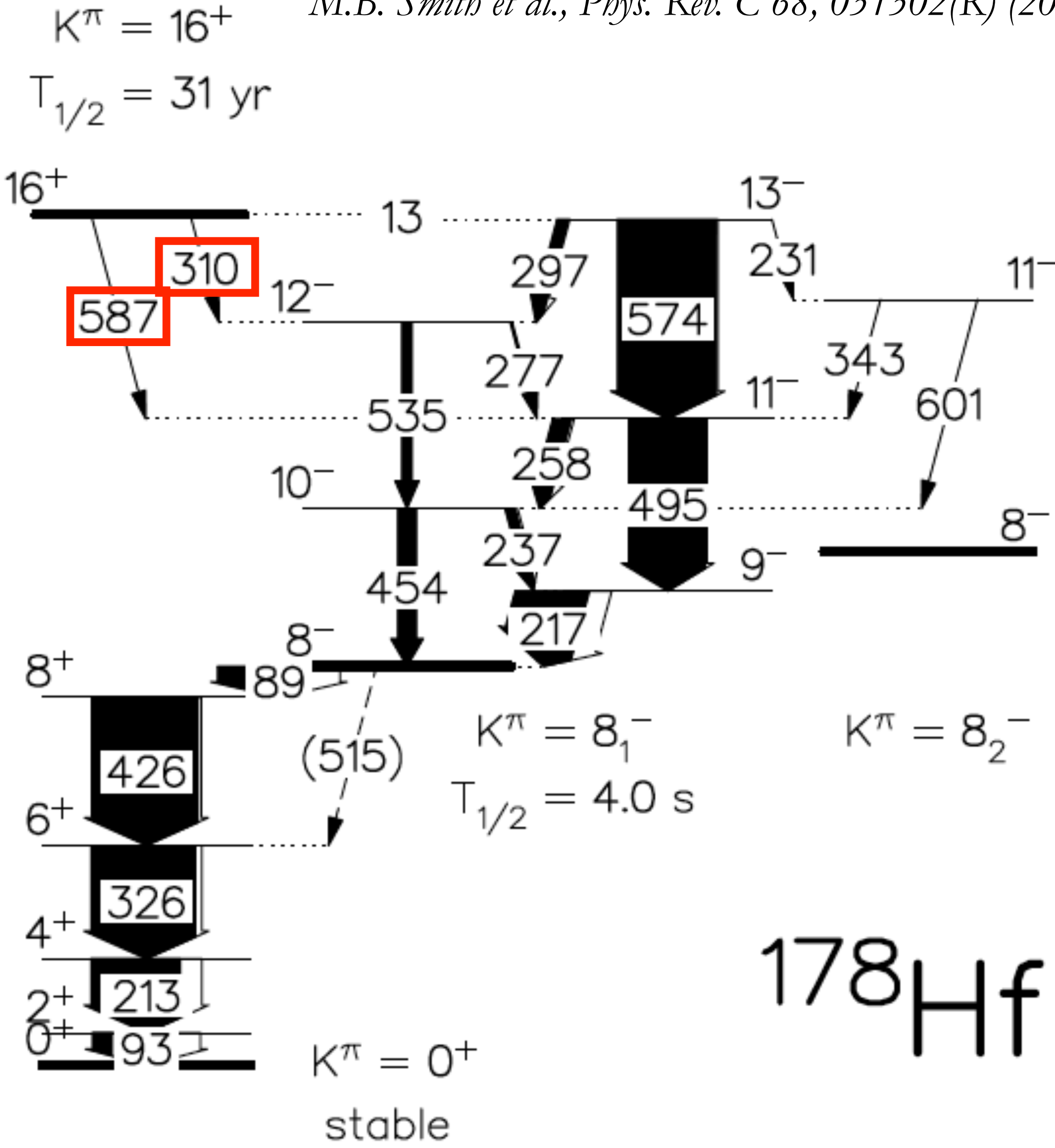
Pritychenko *et al.*, Atomic Data & Nucl. Data Tables, 107 (2016)

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).



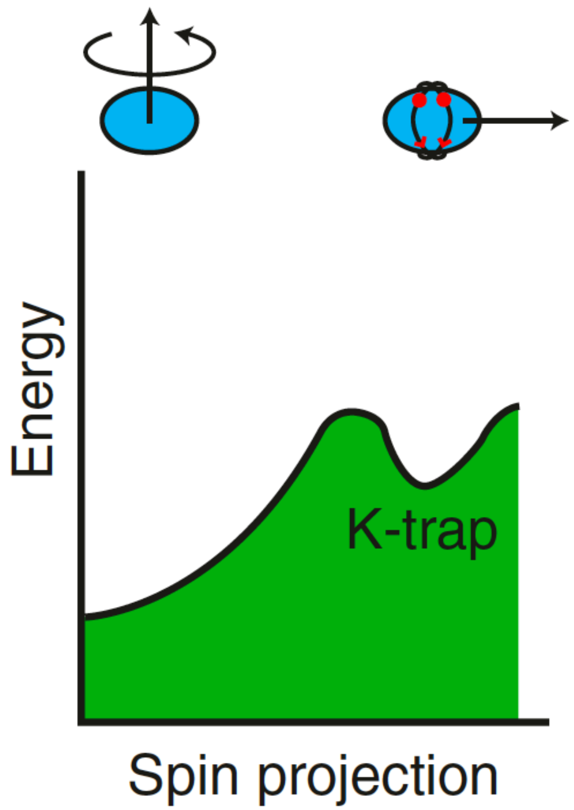


8π: Gamma Decay of the 31-year $K^{\pi} = 16^{+}$ Isomer in ^{178}Hf

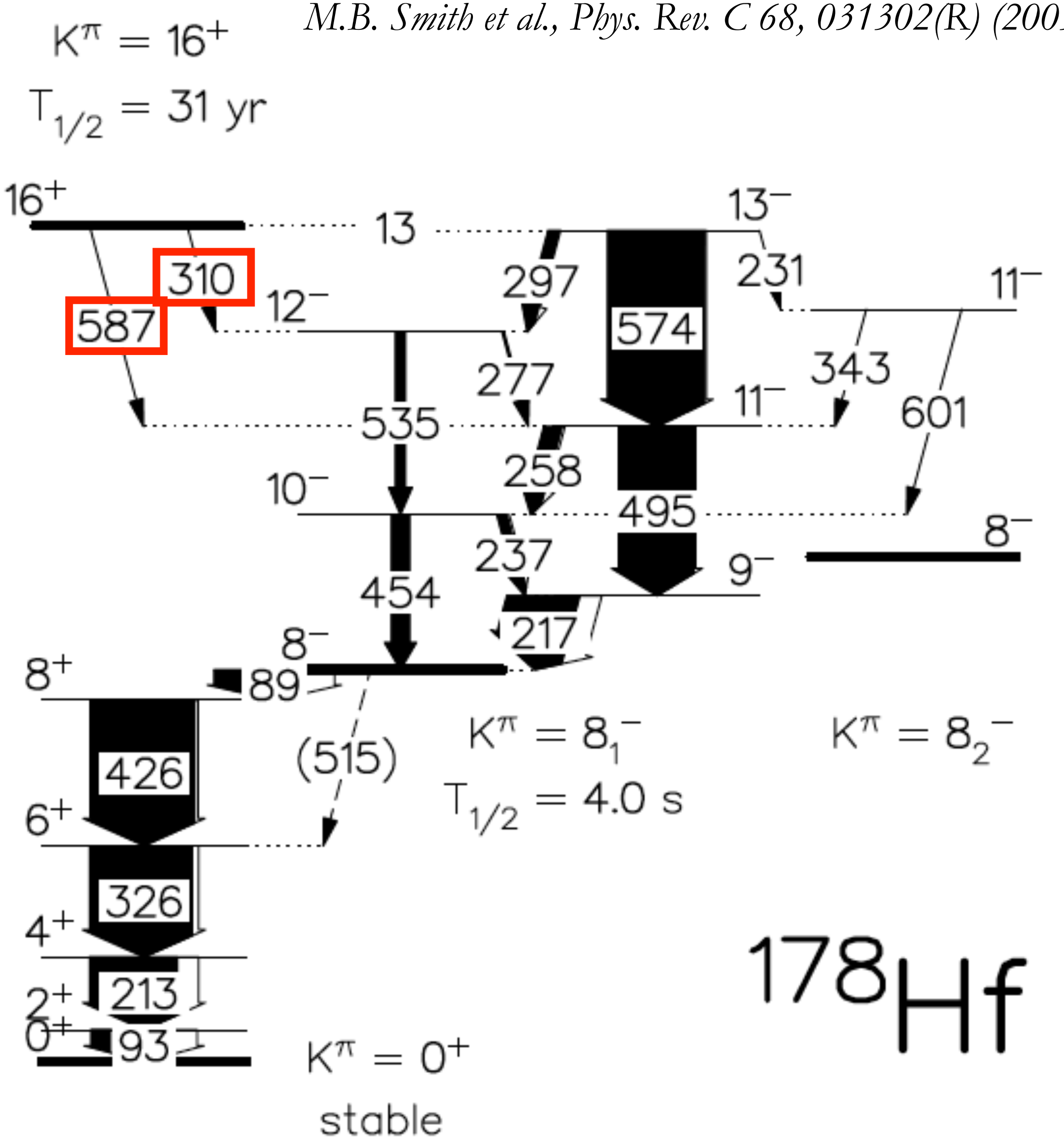
M.B. Smith et al., Phys. Rev. C 68, 031302(R) (2003).

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

- reduced K hindrances ~ 100

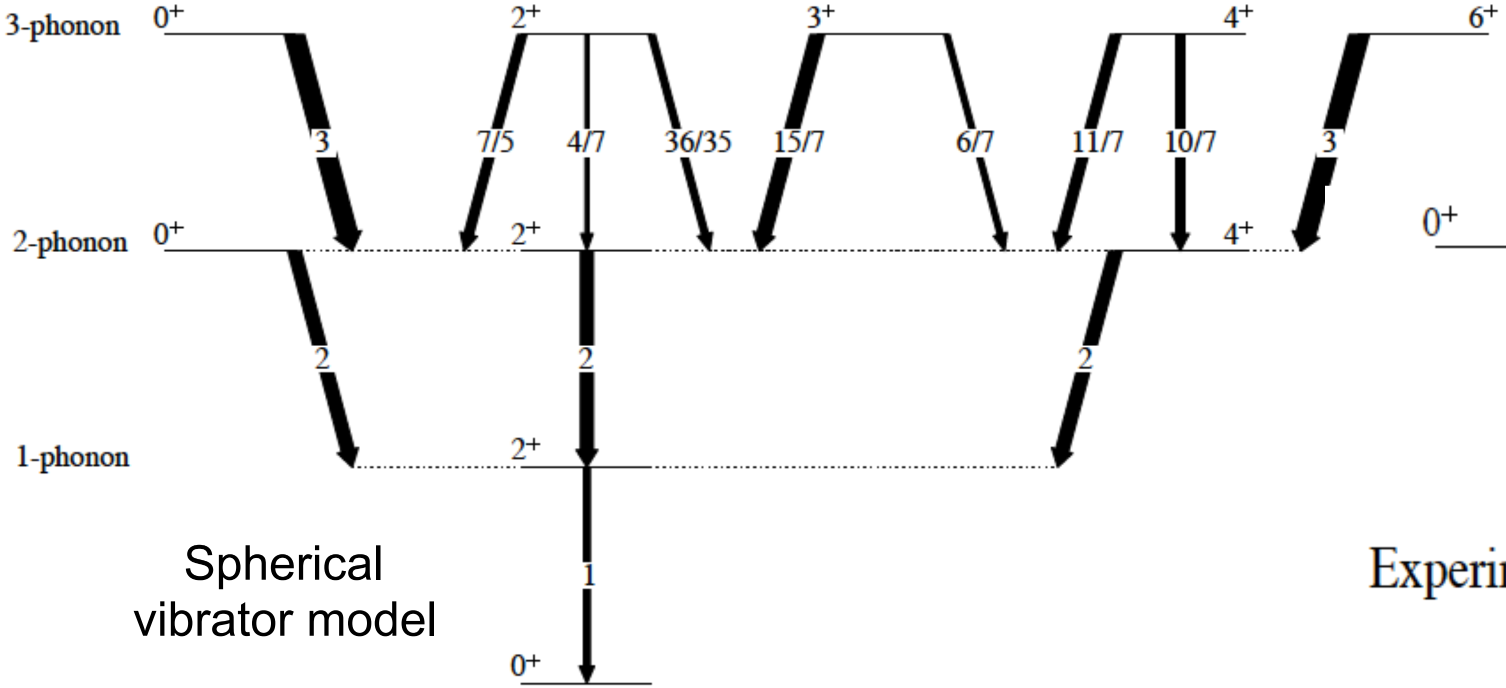


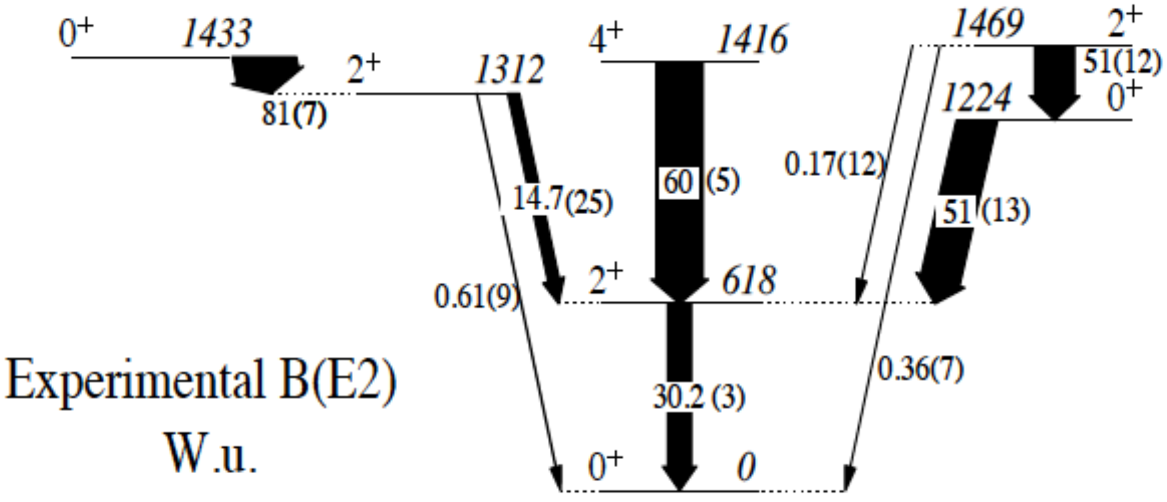
K is total angular momentum projection on symmetry axis



P.M. Walker and G. Dracoulis , Nature 399, 35 (1999).

Detailed scrutiny of collective models



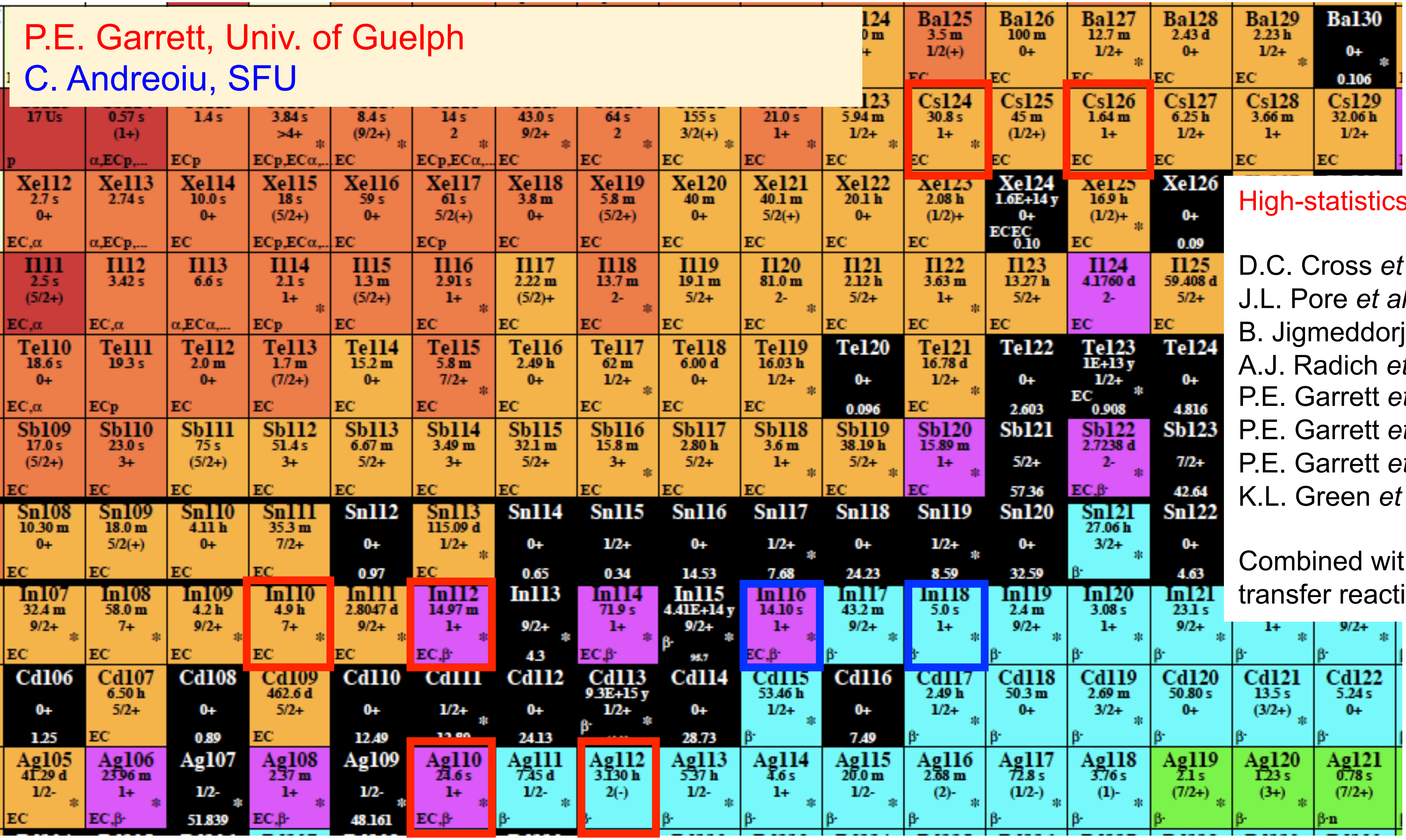


^{112}Cd

Figures from K.L.Green, MSc thesis, Univ. of Guelph (2009)

Nuclear Structure from High-Statistics Beta-Decay

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

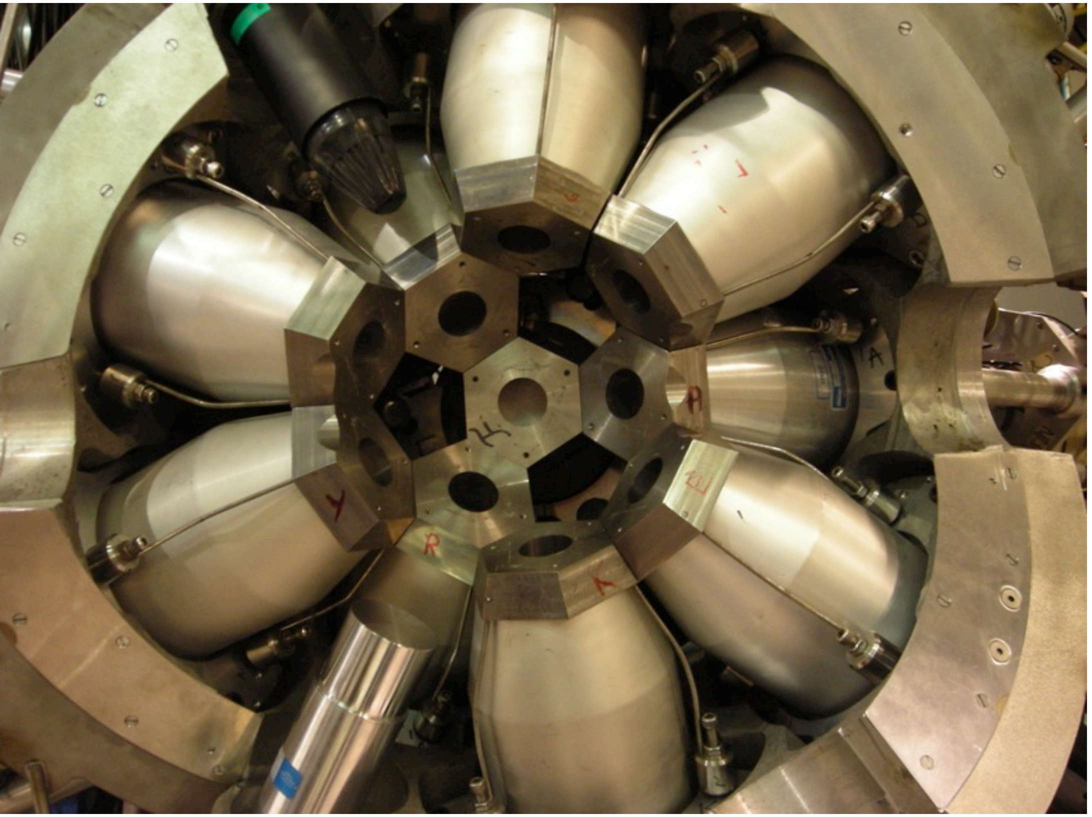


High-statistics studies of Cd, Sn, Xe with 8pi:

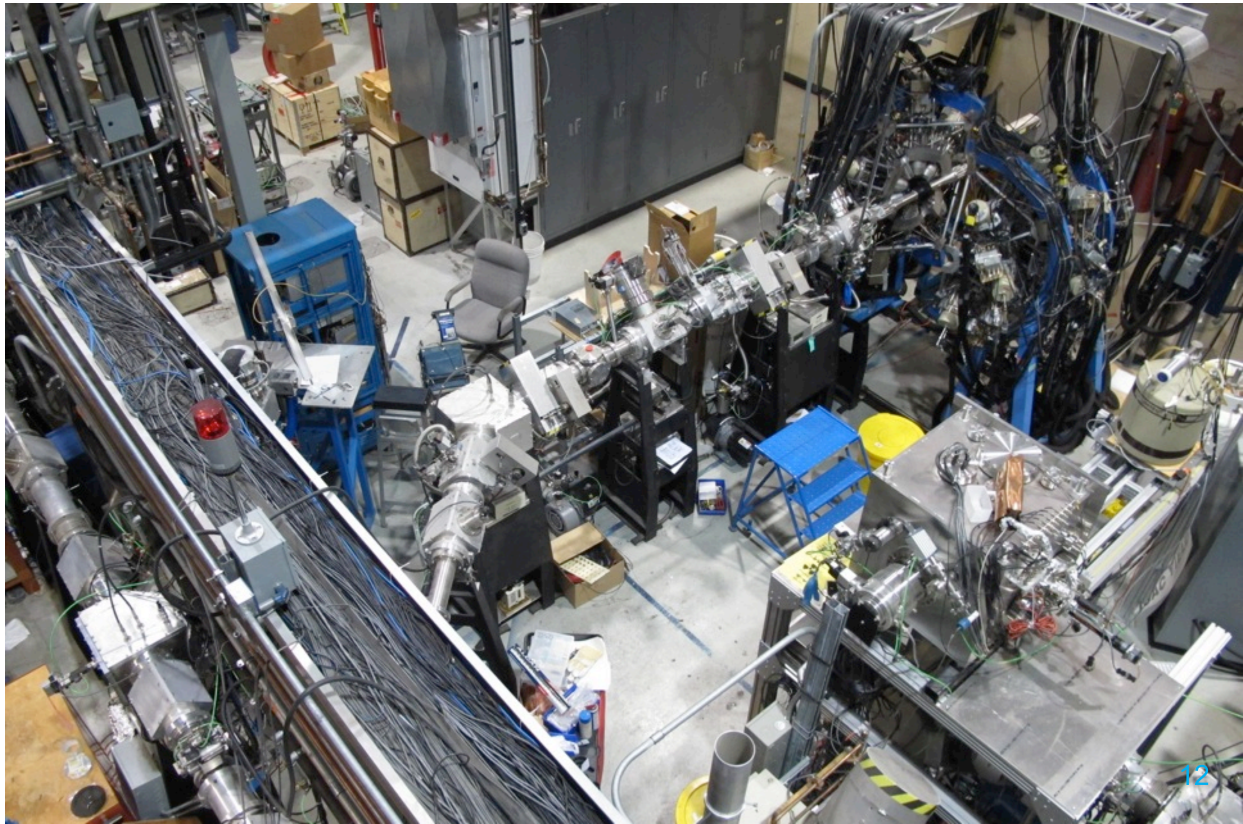
- D.C. Cross *et al*. Eur. Phys. J. A 53, 216 (2017).
- J.L. Pore *et al*., Eur. Phys. J. A 53, 27 (2017).
- B. Jigmeddorj *et al*., Eur. Phys. J. A, 52, 36 (2016).
- A.J. Radich *et al*., Phys. Rev. C 91, 044320 (2015).
- P.E. Garrett *et al*., PRC 86, 044304 (2012).
- P.E. Garrett *et al*., Acta Phys.Pol. 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



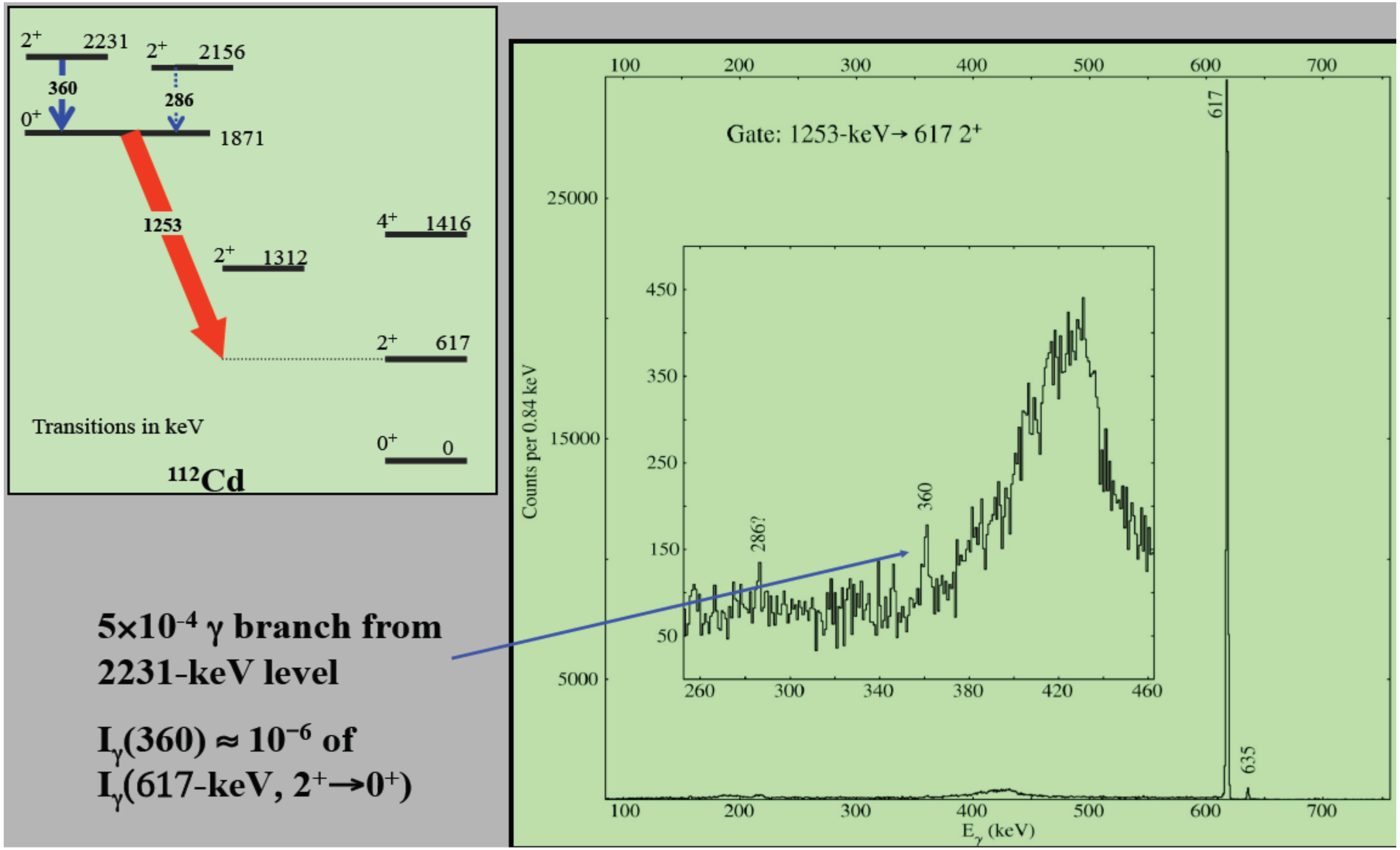
Performed decay spectroscopy at TRIUMF-ISAC-I from Feb 2002 to Dec 2013



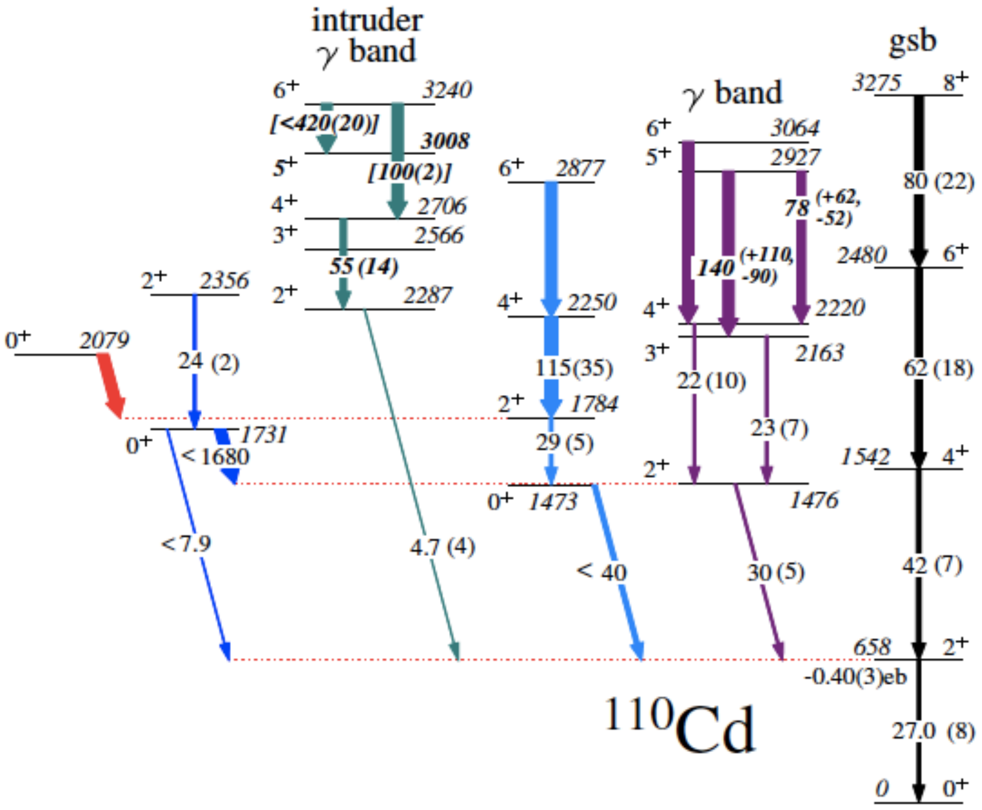
Researchers from 24 institutions from 8 countries.

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

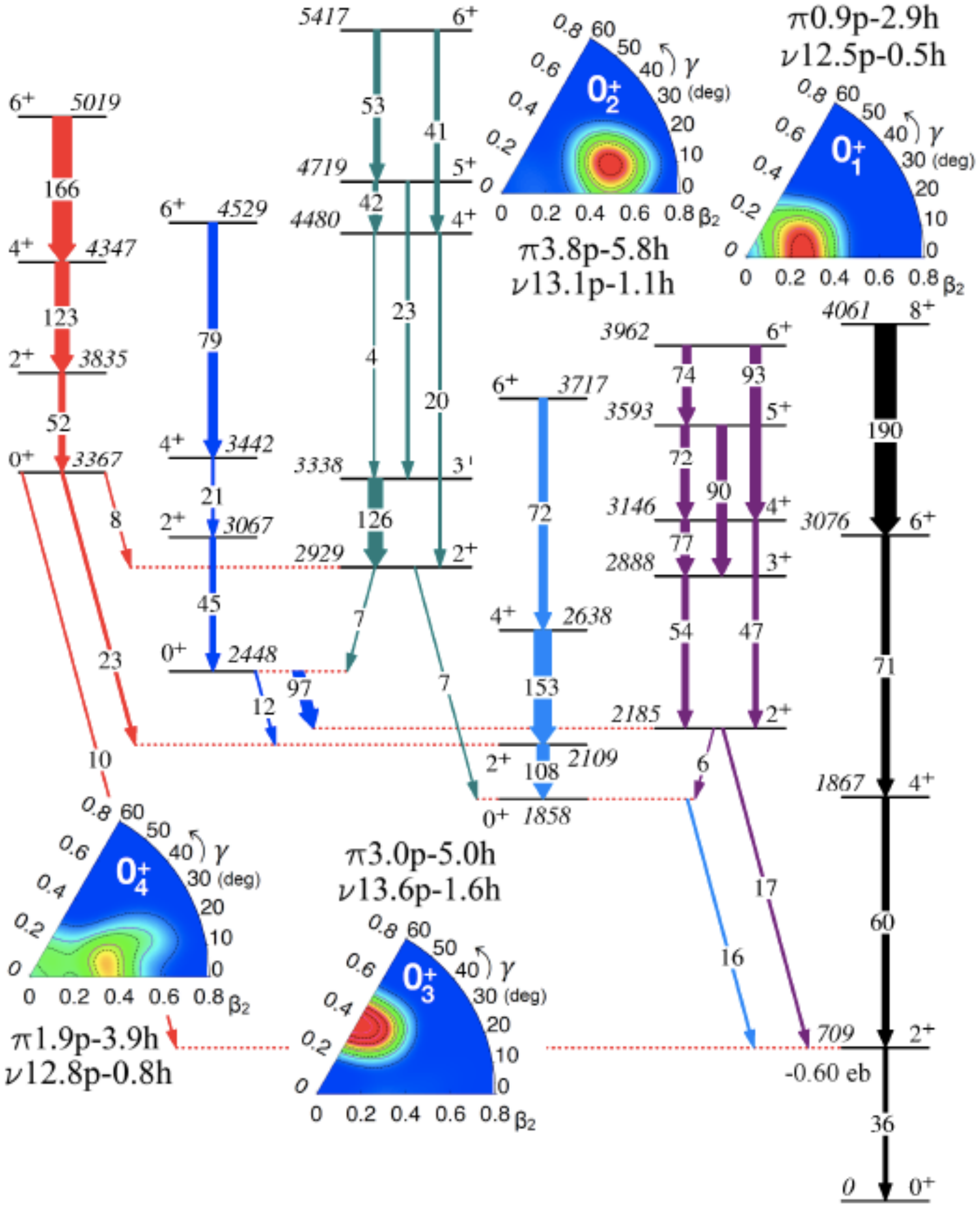
Nuclear Structure from High-Statistics Beta-Decay



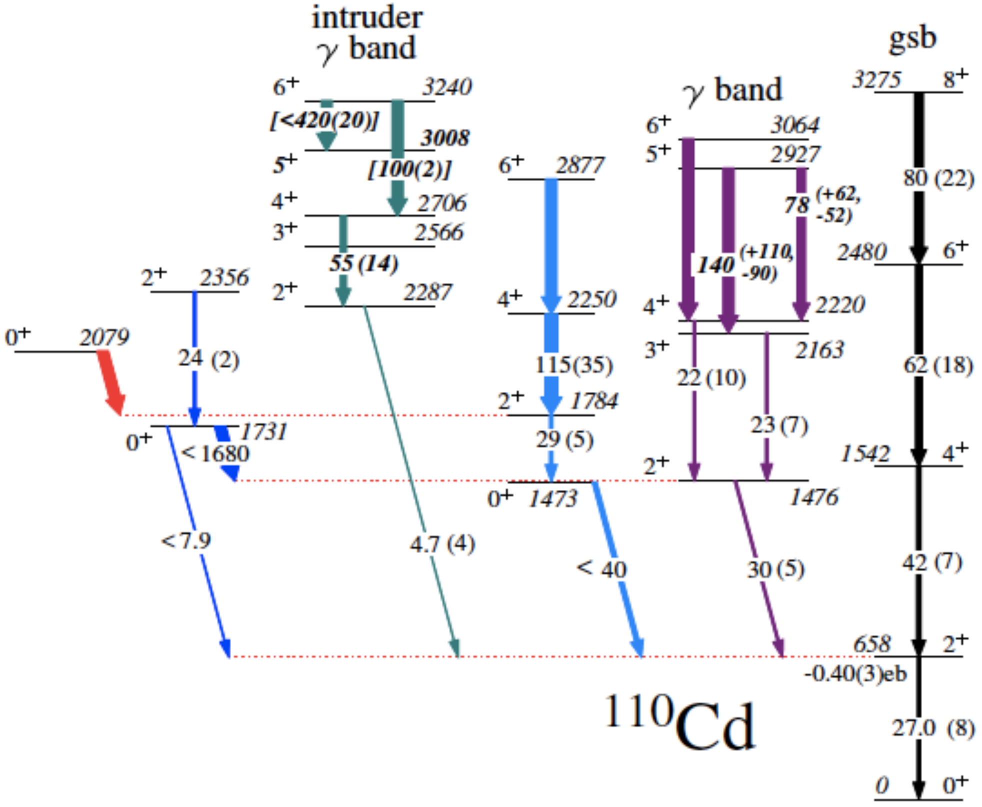
P.E. Garrett et al., Phys.Rev. C 86, 044304 (2012)



P.E. Garrett, T.R. Rodríguez et al., Submitted to PRL (2019).



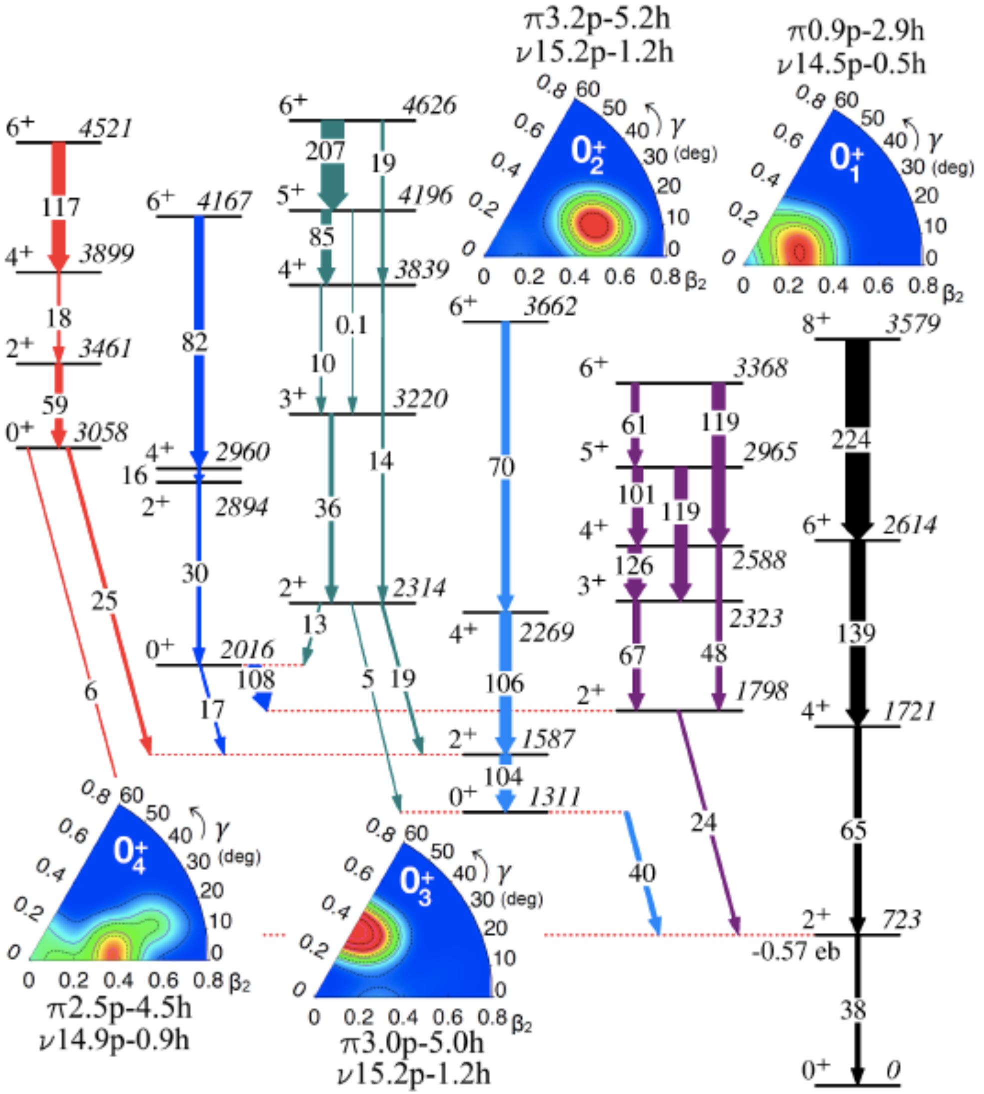
Beyond-mean-field calculations employing the symmetry conserving configuration method with the Gogny D1S energy density functional.
The agreement with the data for ^{110}Cd is remarkable.

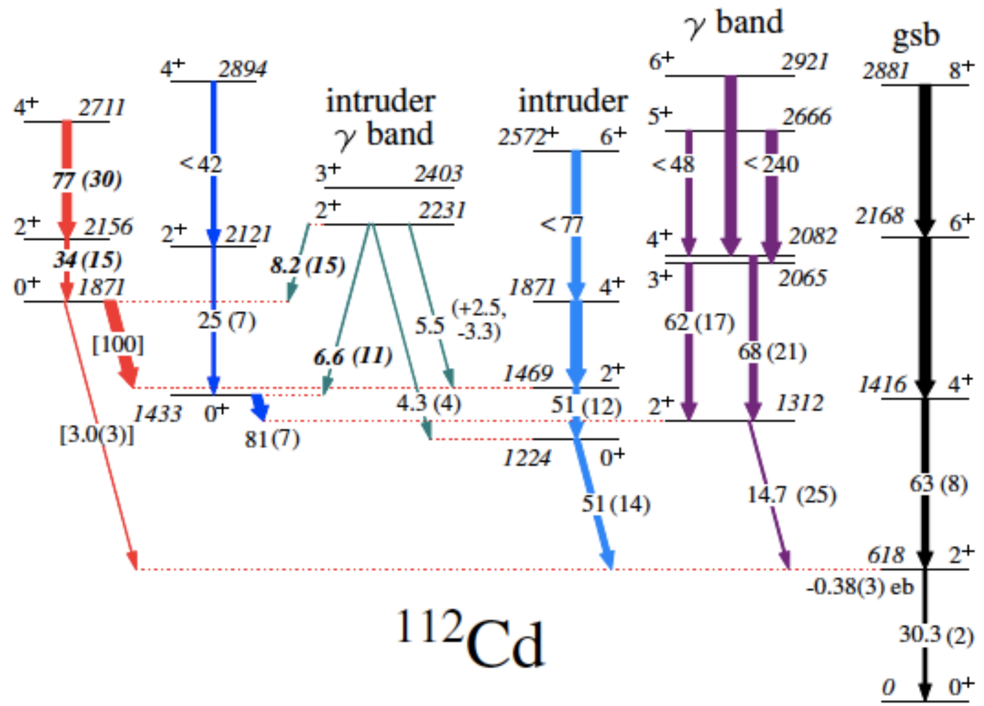


P.E. Garrett, T.R. Rodríguez et al., Submitted to PRL (2019).

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

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

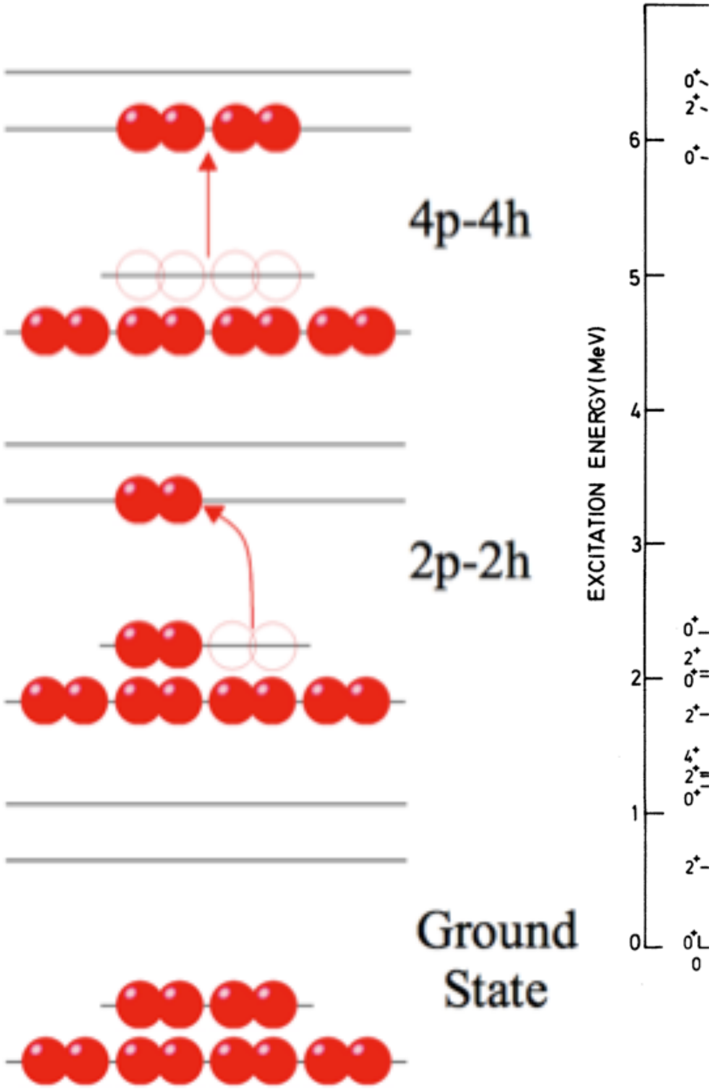




P.E. Garrett, T.R. Rodríguez et al., Submitted to PRL (2019).

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

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



Shell-gap Energy ~+4-8MeV

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

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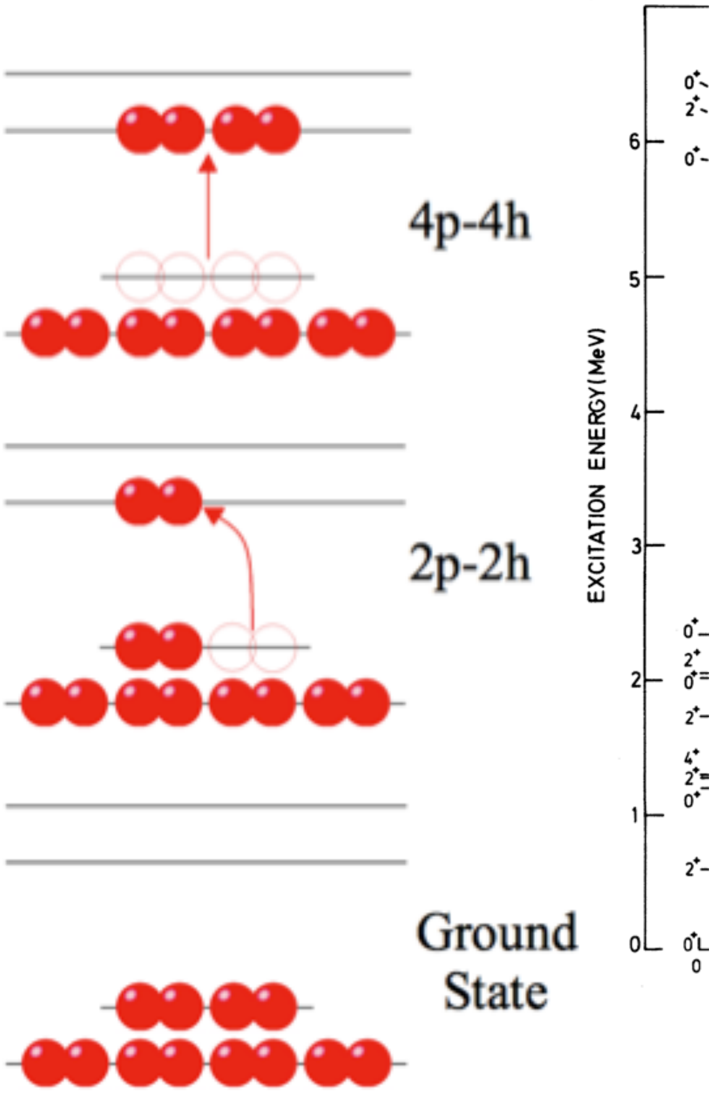

Shell-gap Energy ~+4-8MeV

Monople shift ~ ±0-1MeV

Pairing ~-2.5MeV

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

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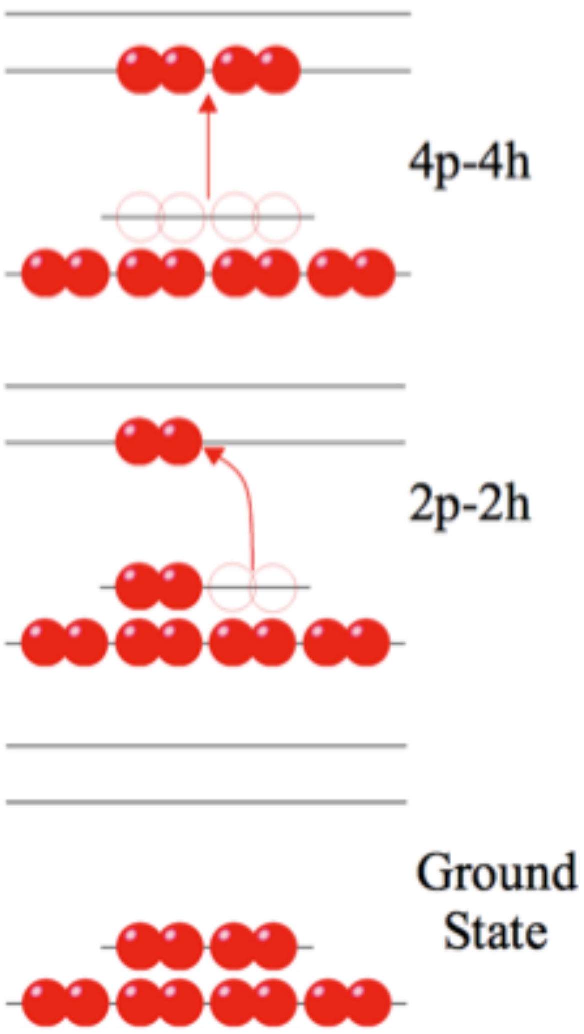
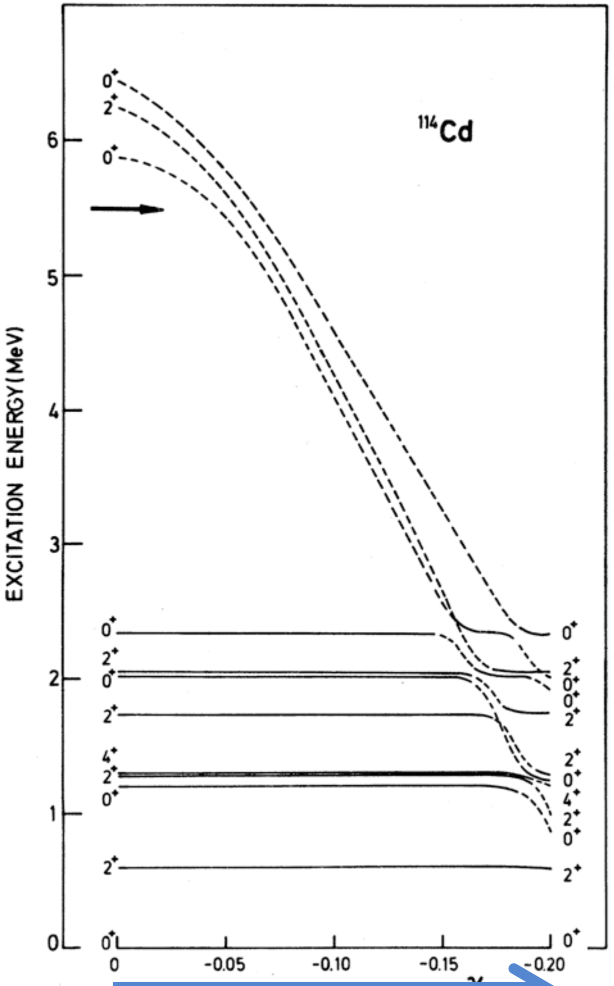
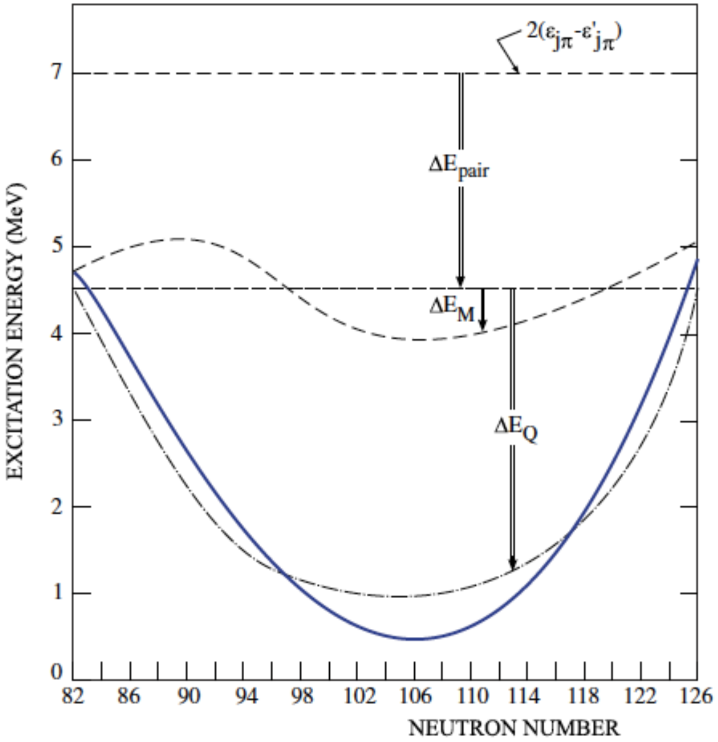
Heyde & Wood, Rev. Mod. Phys. 83, 1467 (2011).





Strength of p-n Quadrupole interaction

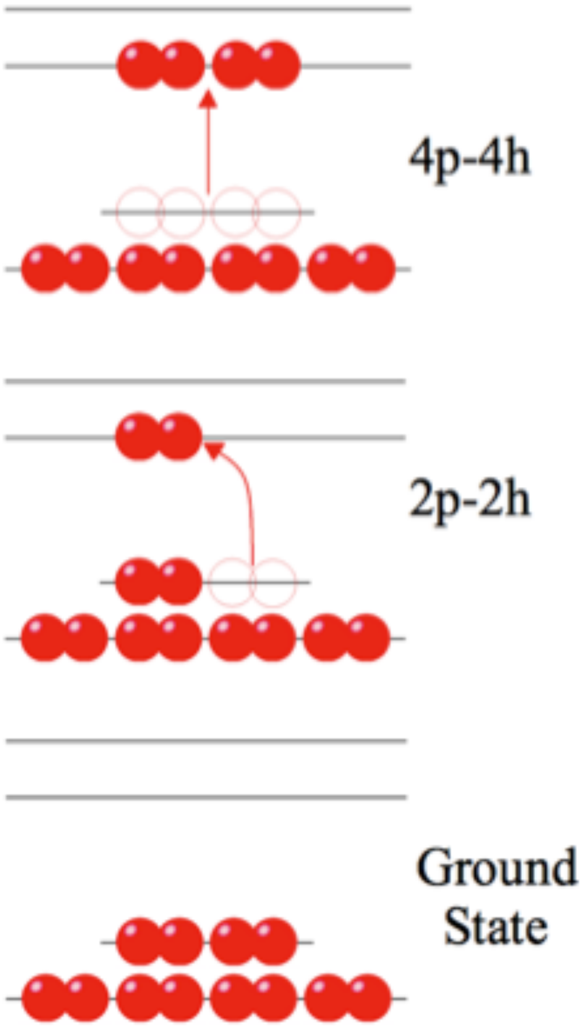
Shell-gap Energy	~+4-8MeV
Monople shift	~ ±0-1MeV
Pairing	~-2.5MeV
p-n quadrupole	~-0-3MeV

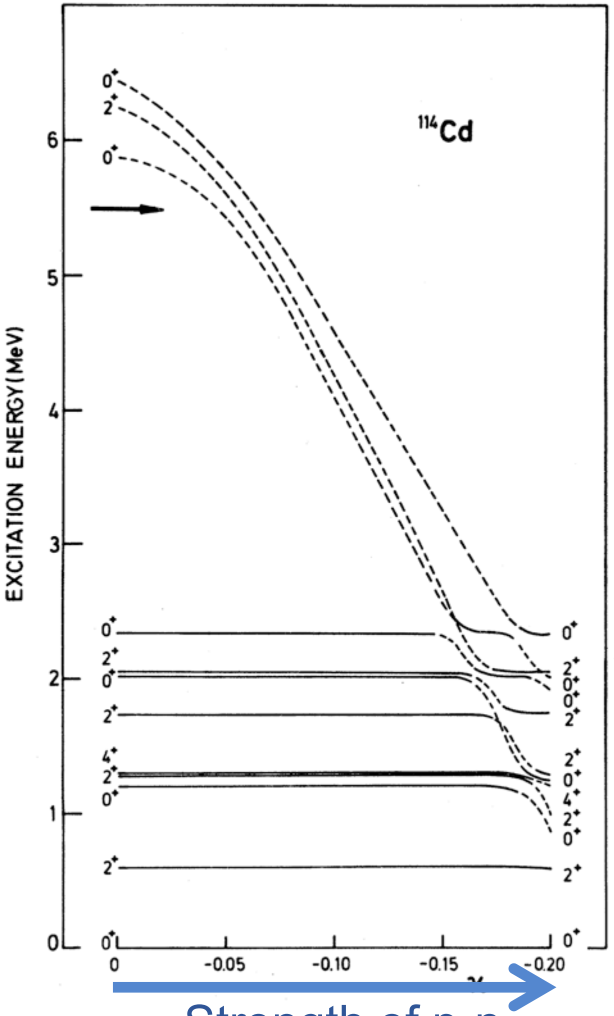


$$E_{\rm intr}(0^+) = 2(\varepsilon_{j_\pi} - \varepsilon_{j'_\pi}) - \Delta E_{\rm pair} + \Delta E_M + \Delta E_Q$$

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

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





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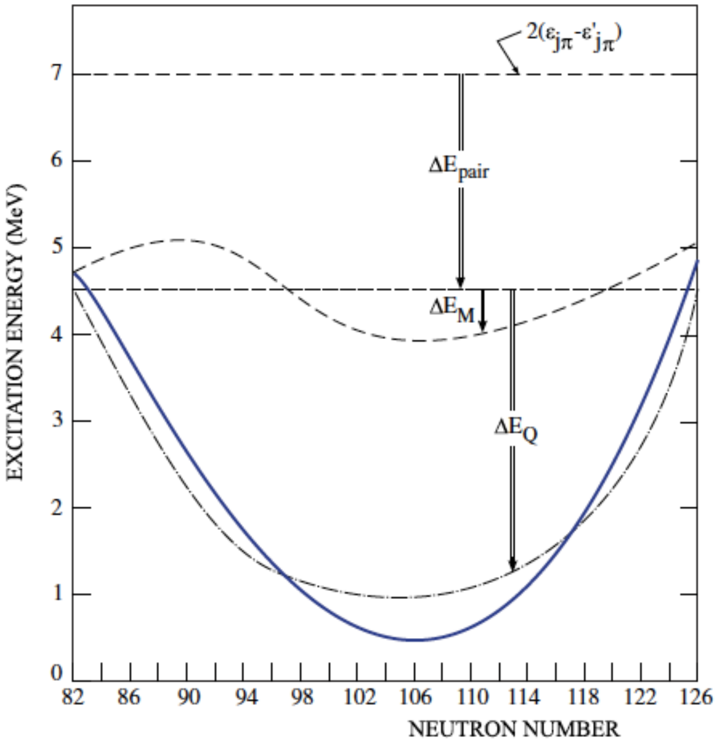
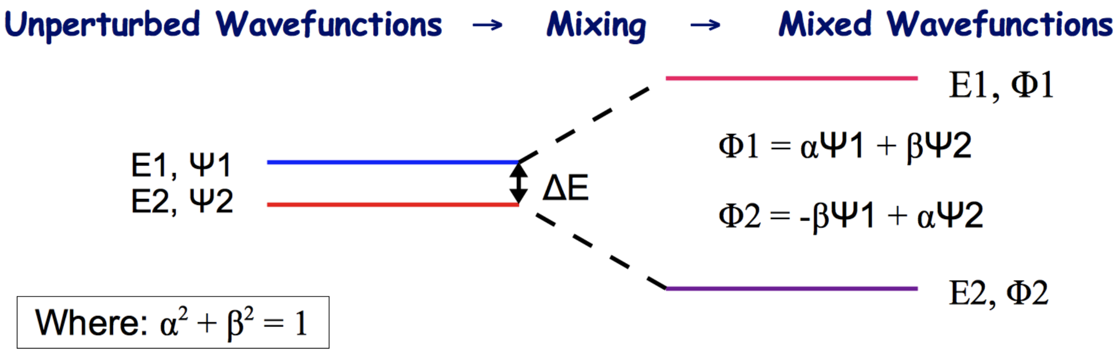
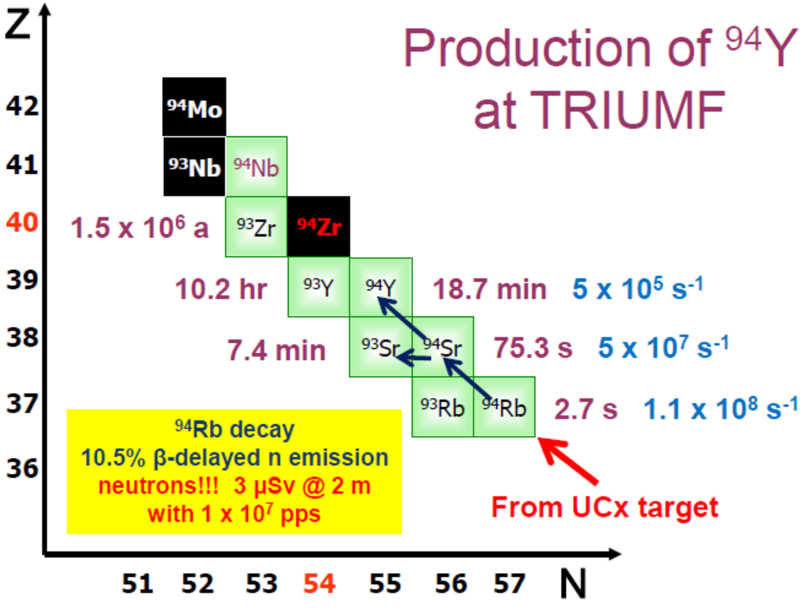


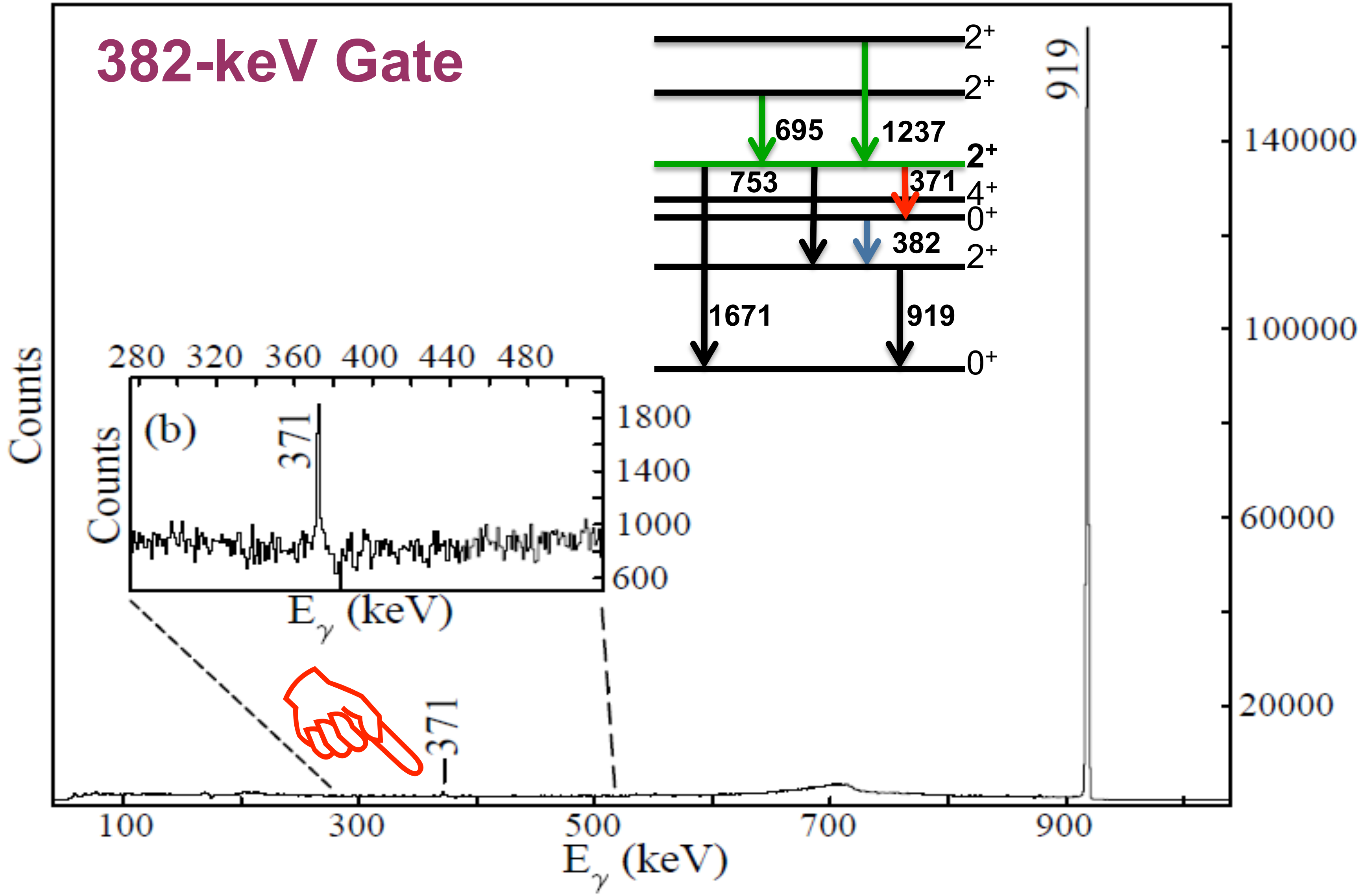
$$E_{\text{intr}}(0^+) = 2(\varepsilon_{j_\pi} - \varepsilon_{j'_\pi}) - \Delta E_{\text{pair}} + \Delta E_M + \Delta E_Q$$



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

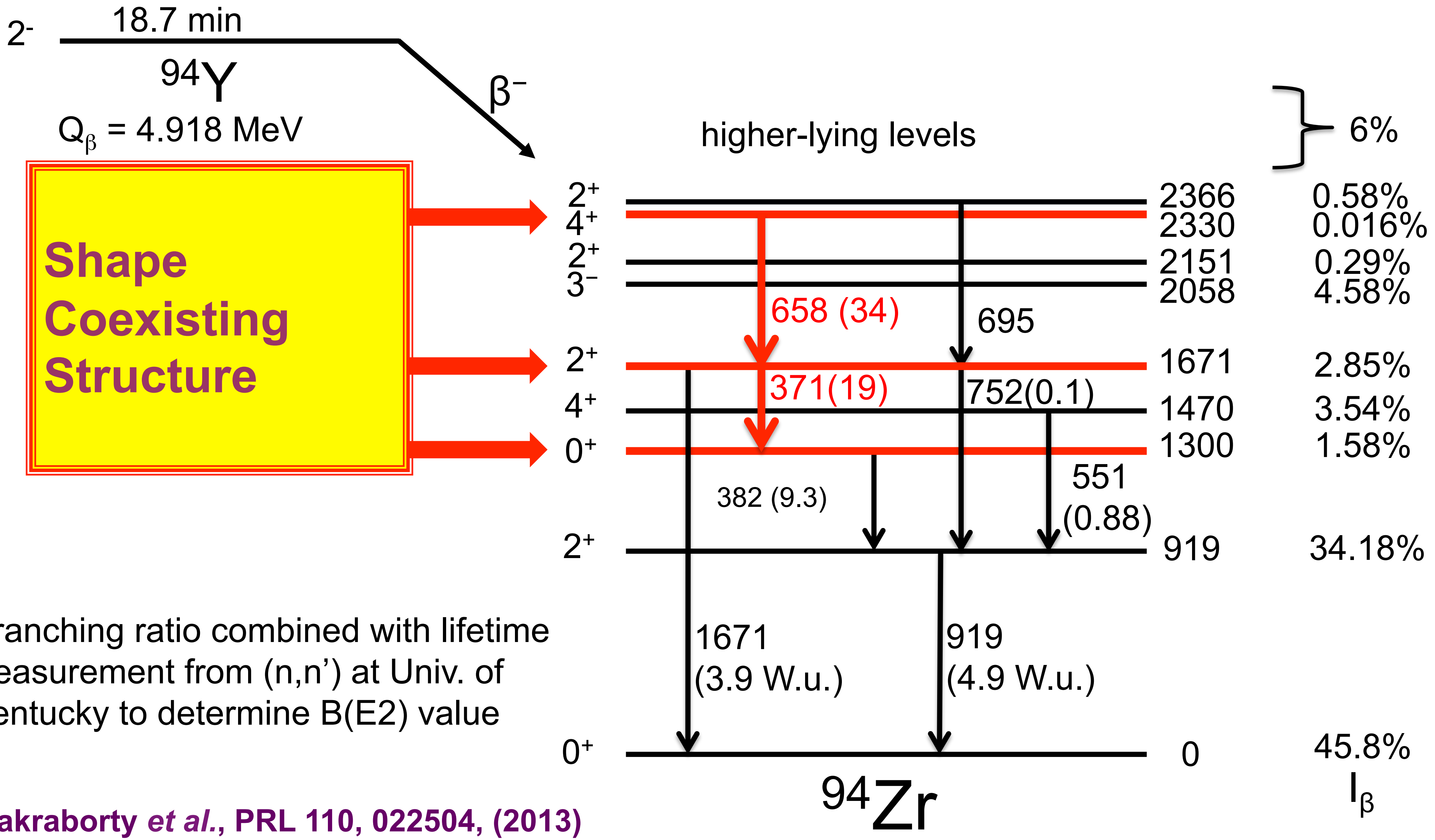
High-Statistics Beta-Decay of ^{94}Y to ^{94}Zr





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

Identification of Coexisting structures in ^{94}Zr

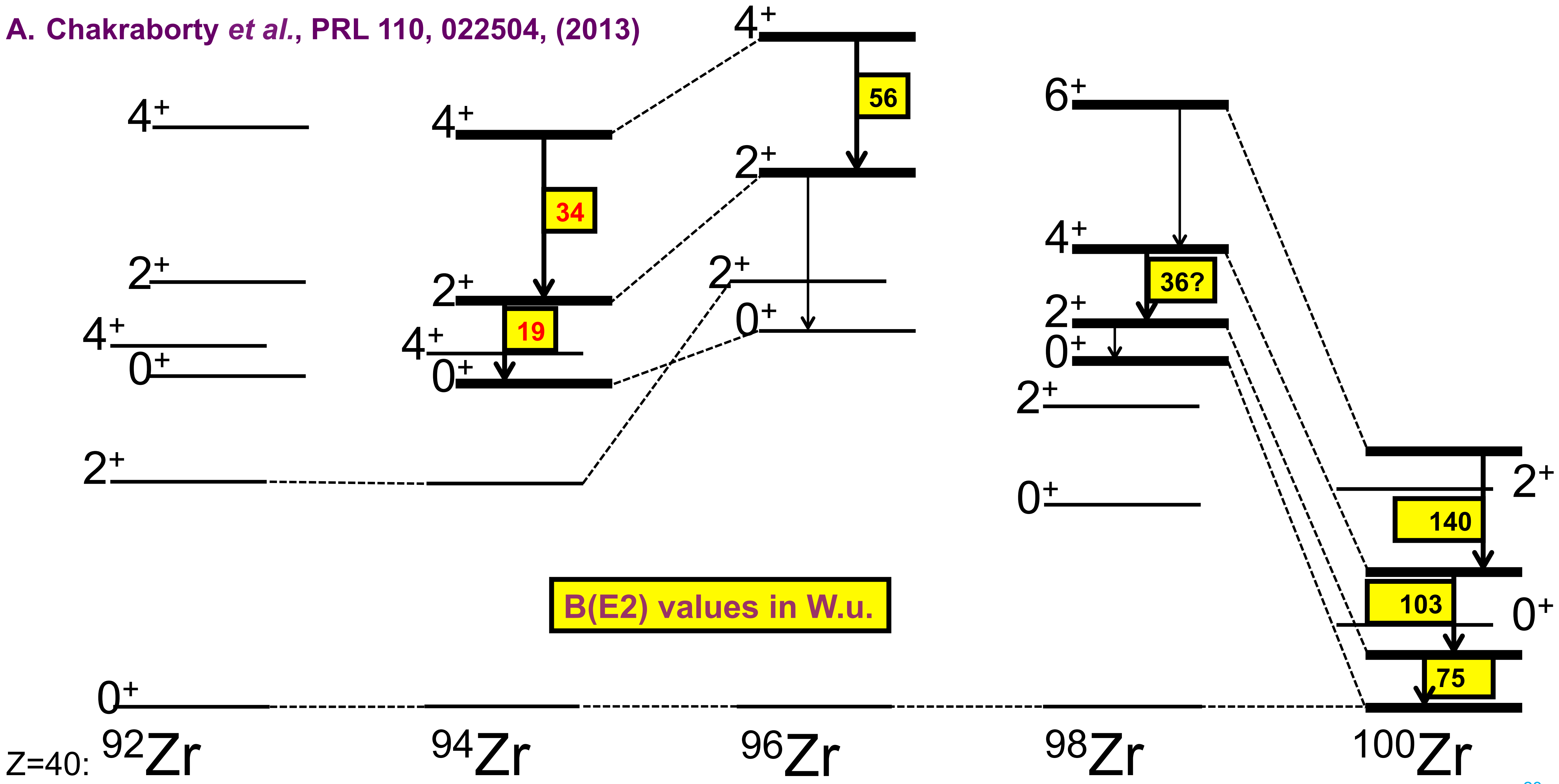


8pi branching ratio combined with lifetime measurement from (n,n') at Univ. of Kentucky to determine B(E2) value

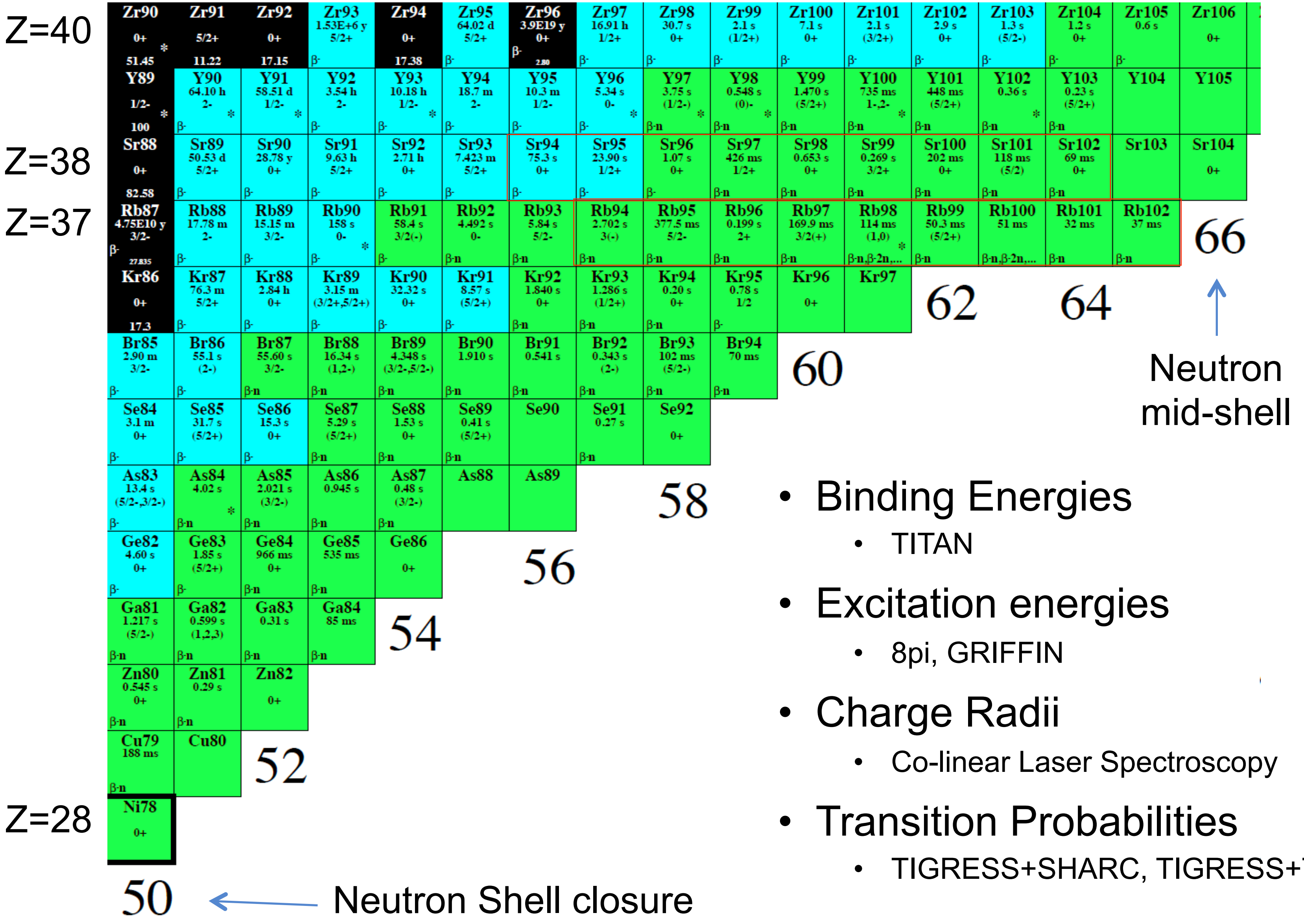
A. Chakraborty *et al.*, PRL 110, 022504, (2013)

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

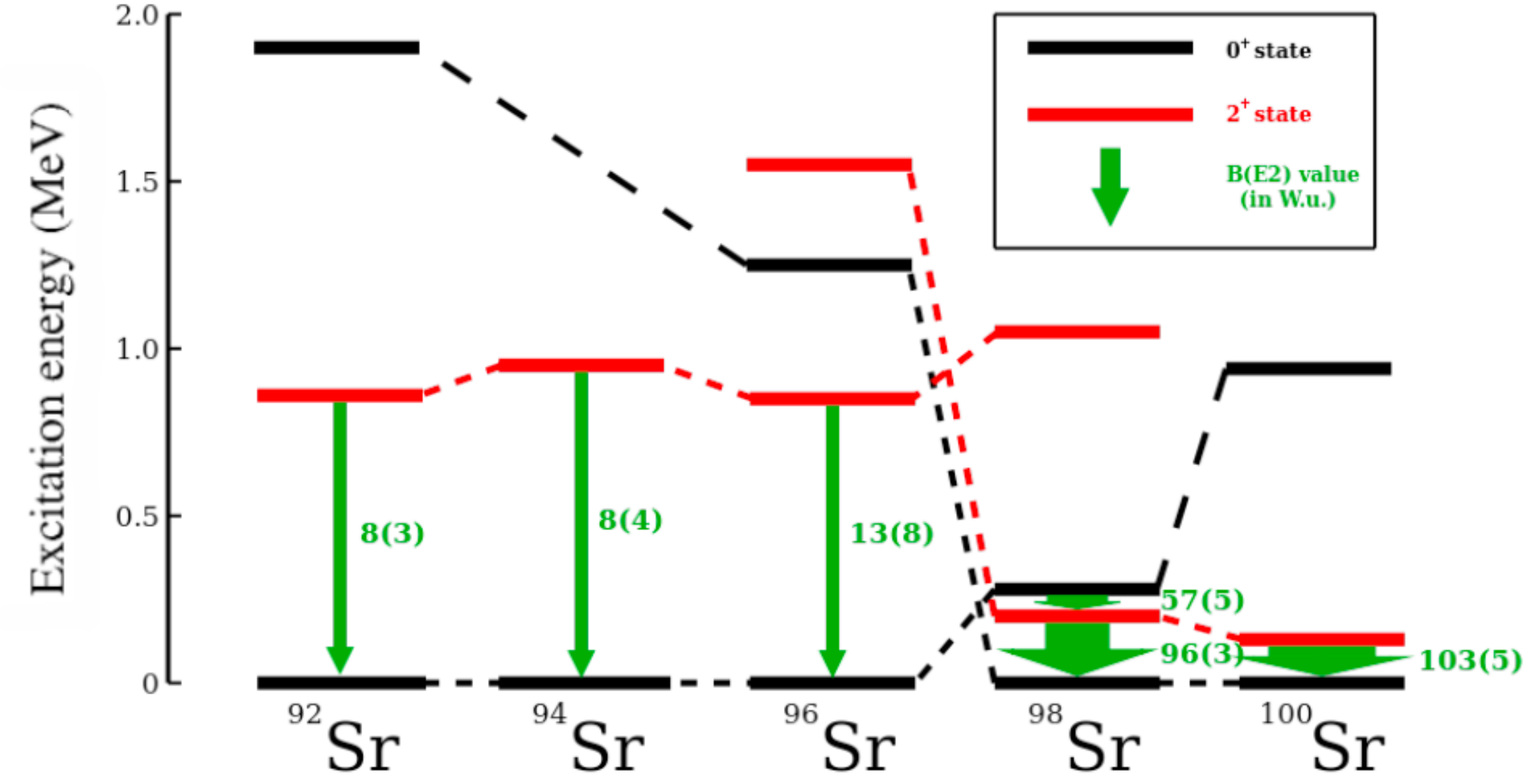


ISAC studies around *N*=60:

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
- Charge Radii
  - Co-linear Laser Spectroscopy
- Transition Probabilities
  - TIGRESS+SHARC, TIGRESS+TIP, GRIFFIN+PACES+$LaBr_3$

Dramatic Change in Ground-State Structure

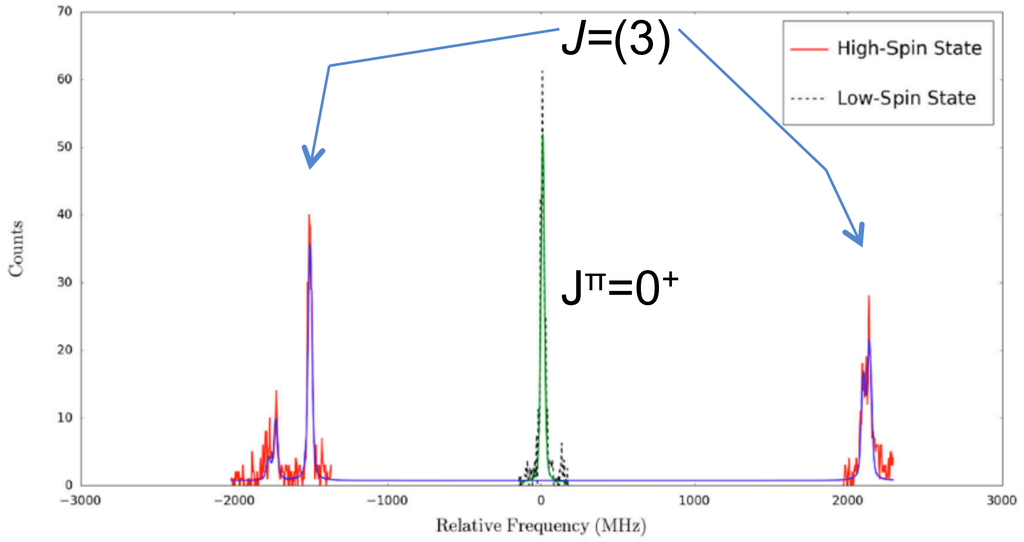


N = 54 56 58 60 62

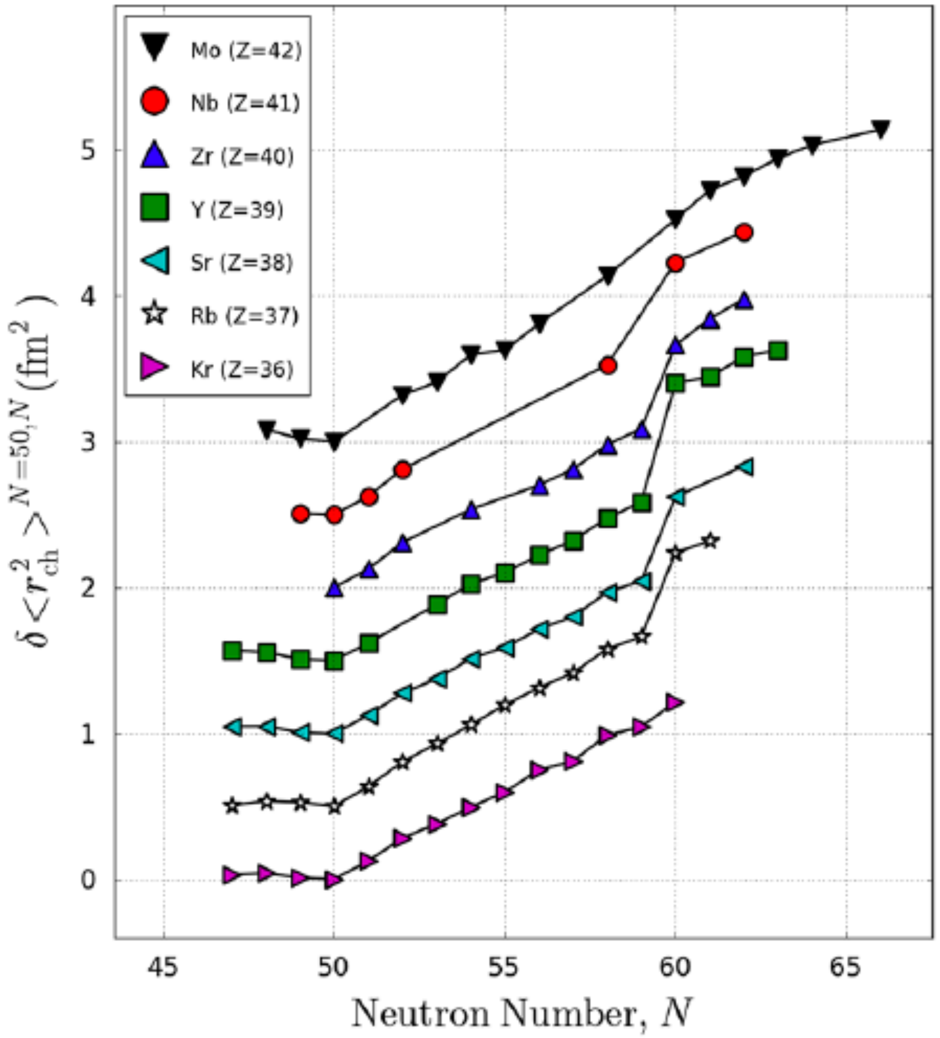
Spin assignments and charge radii from colinear Laser Spectroscopy

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

First direct observation of isomer in ^{98}Rb

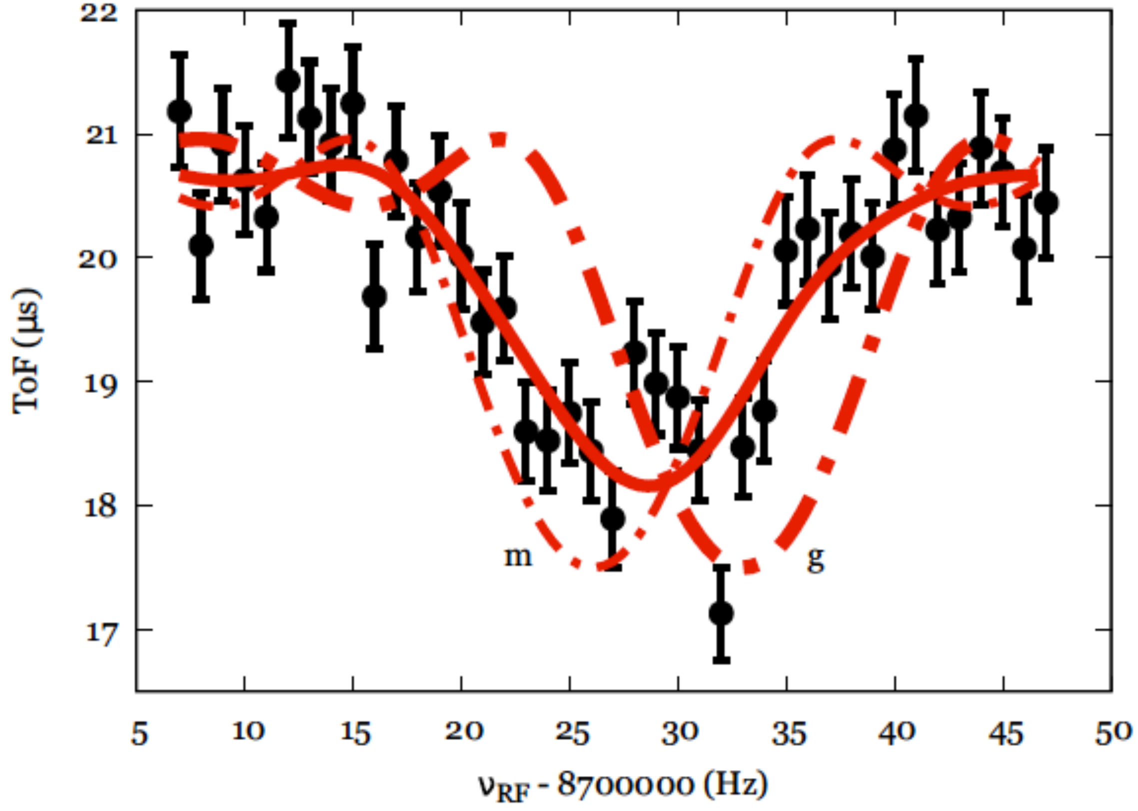


The groundstate and isomer in ^{98}Rb have very similar charge radii.

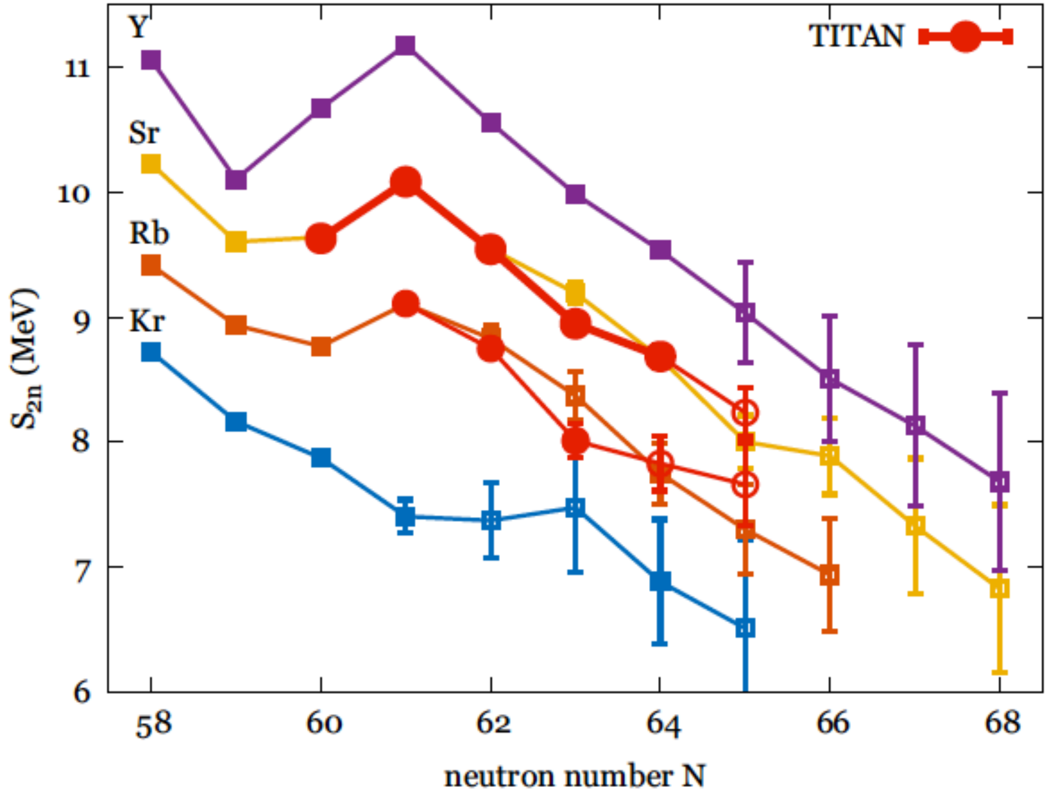


Precision mass measurements from TITAN

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



$^{98}Rb^{m;q=15+}$ and $^{98}Rb^{g;q=15+}$ 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, $\rho_{if} = \frac{\langle\Phi_1|\mathrm{m}(E0)|\Phi_2\rangle}{eR^2}$

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

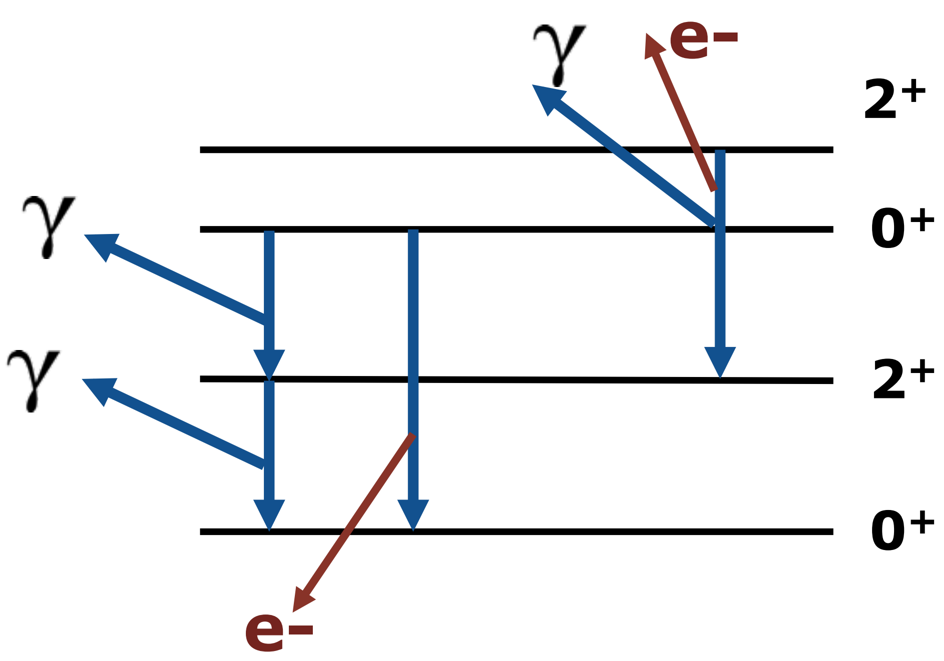
$\langle\Phi_1|\mathrm{m}(E0)|\Phi_2\rangle \simeq \alpha\beta\Delta\langle r^2\rangle$

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

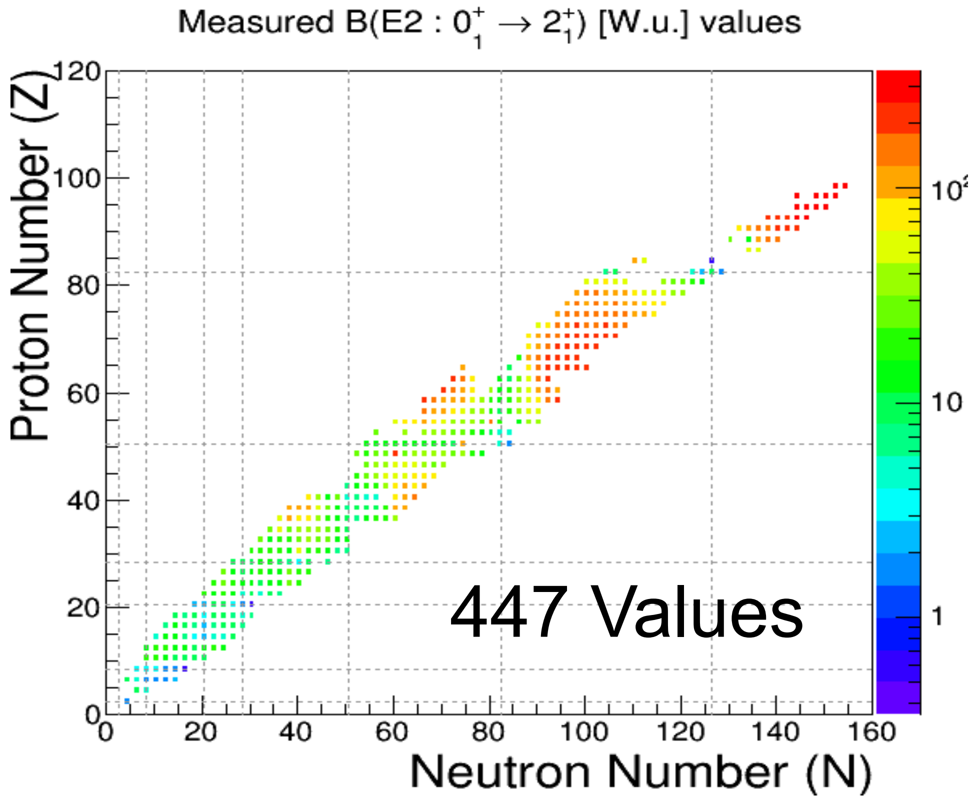
$$M(E0) = \sum_k e_k r_k^2$$

e_k = effective charge
r_k = radius of *k*th nucleon

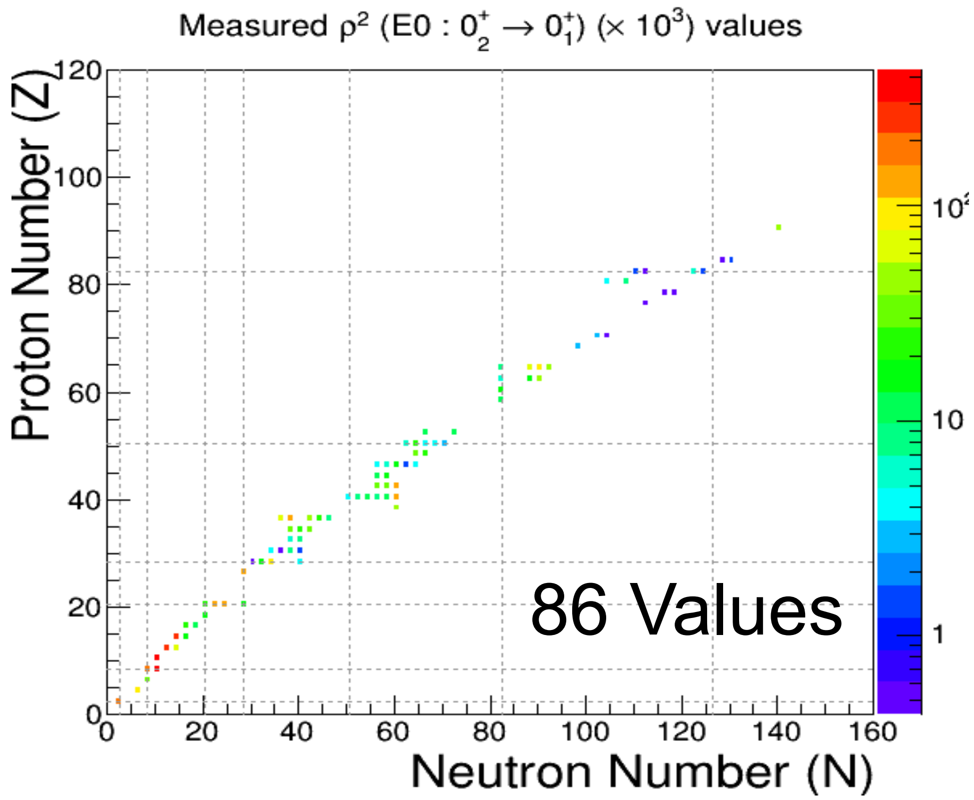
PACES Si(Li)



Knowledge of ρ^2 (*E0*) values



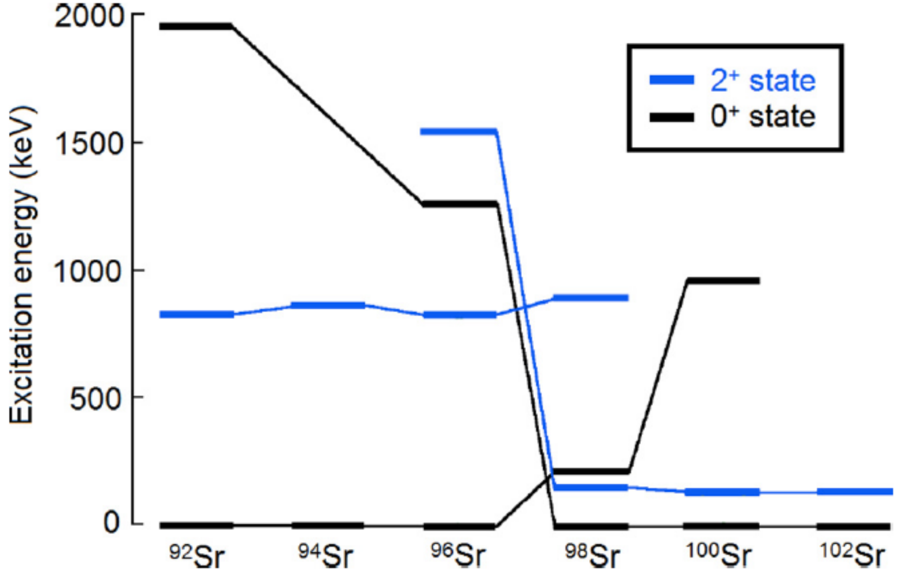
Pritychenko *et al.*, Atomic Data & Nucl. Data Tables, 107 (2016)

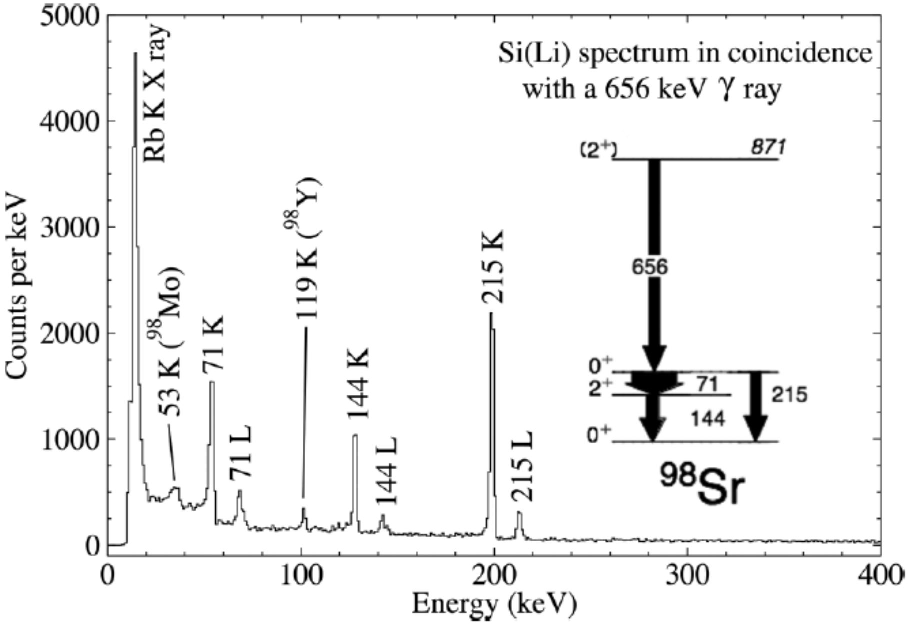


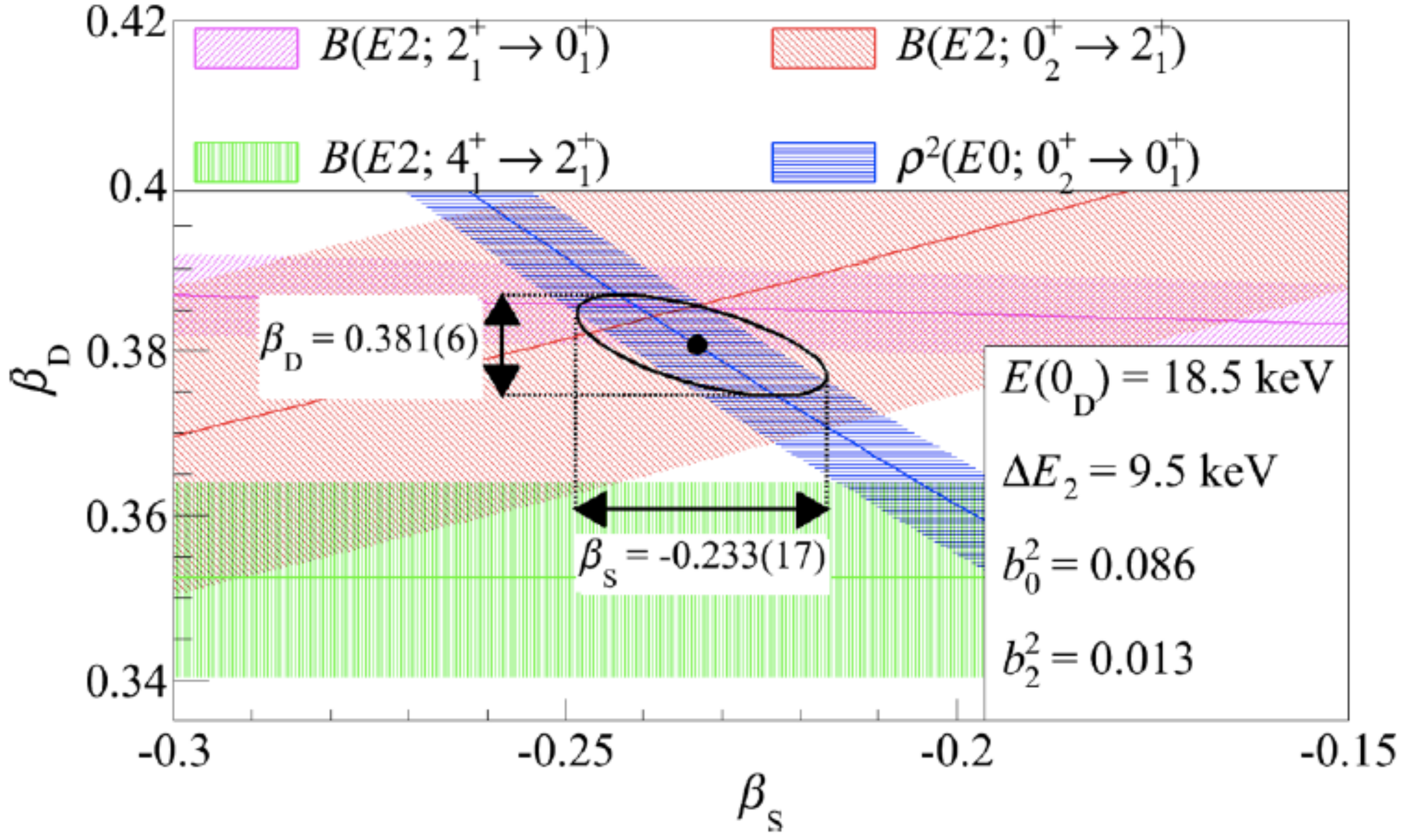
Kibédi & Spear, Data Nucl. Data Tables, 89 (2005)

~120 new values in 15 years

Shape coexistence in ^{98}Sr







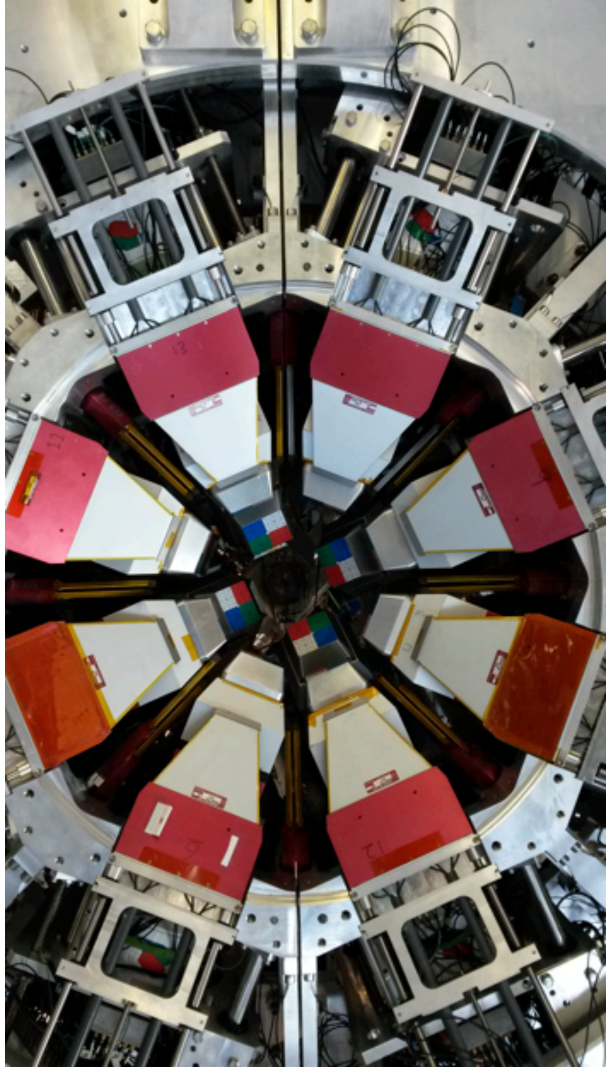
Minimization in two-state mixing using all available experimental data indicates:

9% mixing of 0^+ state, 1.3% in 2^+ states.

Deformation difference in β of 0.38.

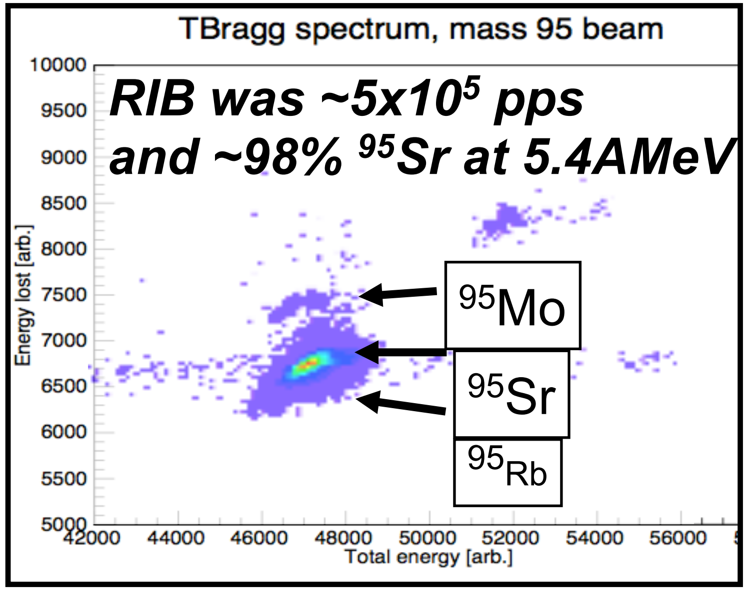
J. Park *et al.*, PRC 96, 014315 (2016).

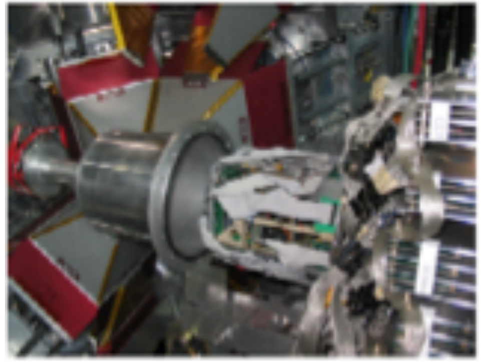
Shape Coexistence at Z~40 N~60

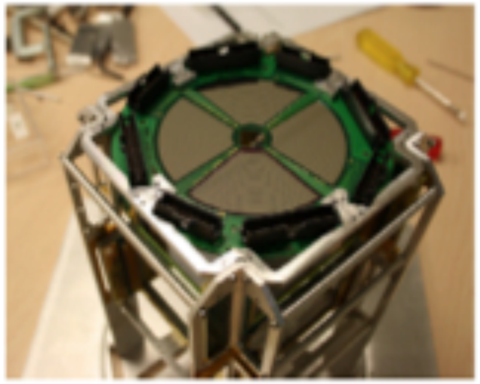


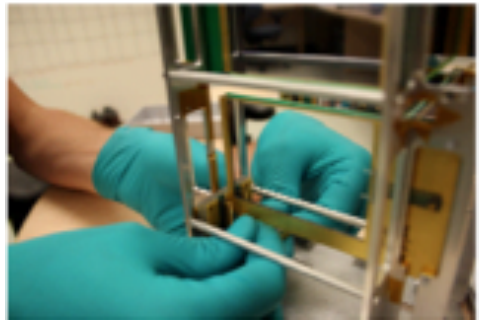
Measurements of single particle levels in ^{95,96,97}Sr essential for a detailed description of this transitional region.

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



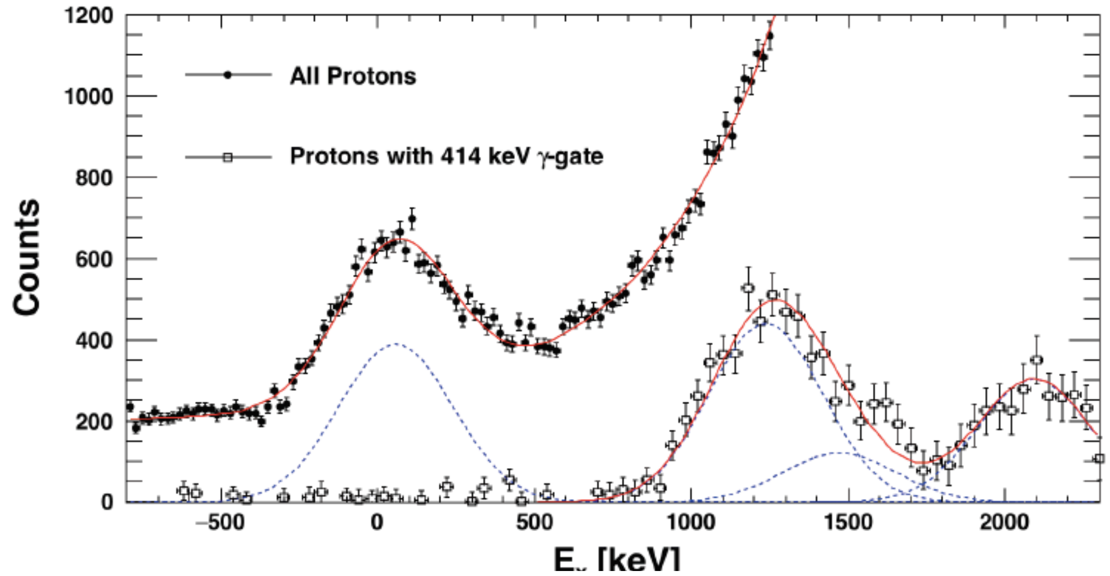


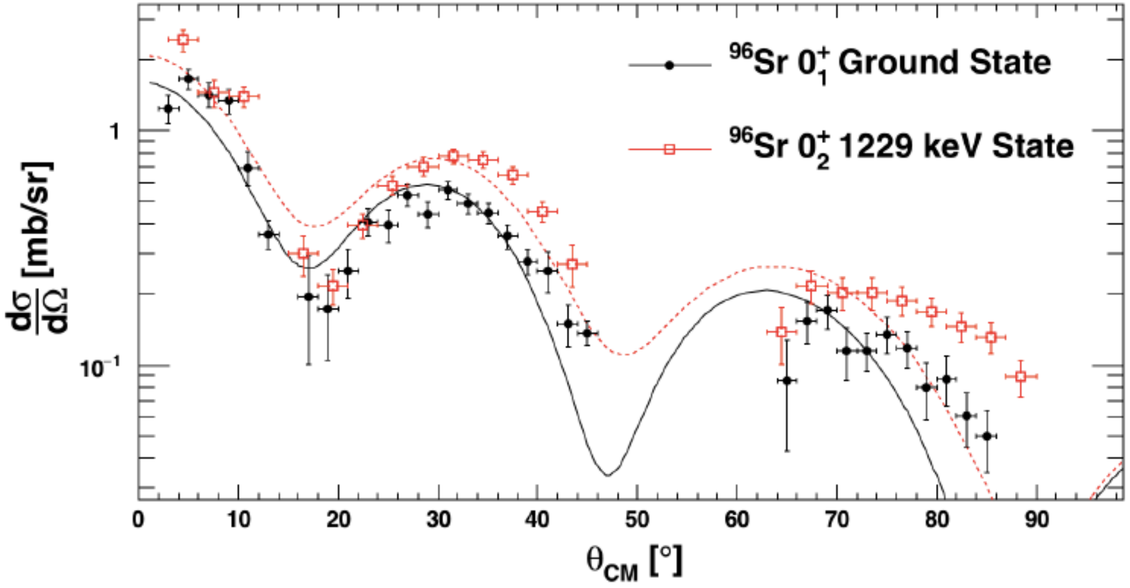




Shape coexistence around N=60

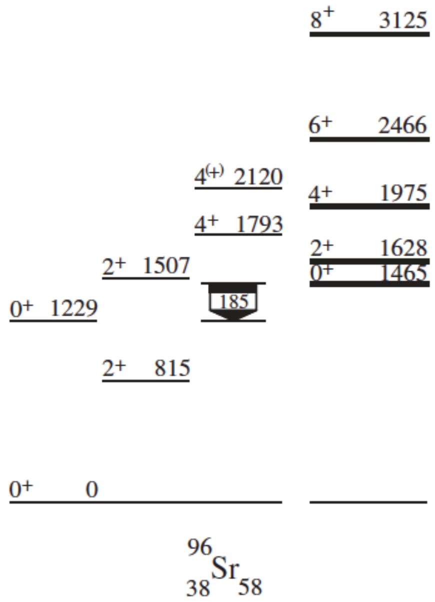
S. Cruz *et al.* Phys. Letts. B 786, 94 (2018).

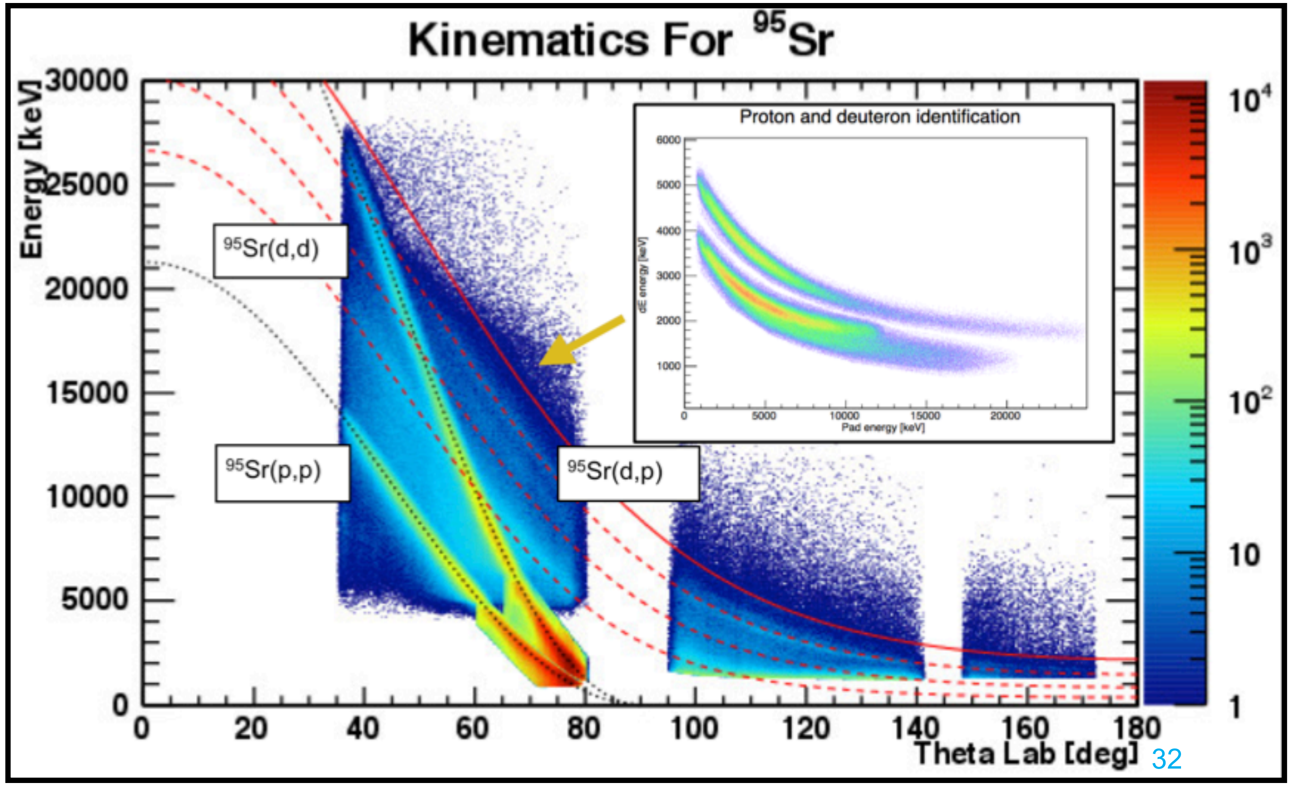




d(^{95}Sr,p)^{96}Sr, 5.4 MeV/u, ~5.10^{5}pps
TIGRESS+SHARC

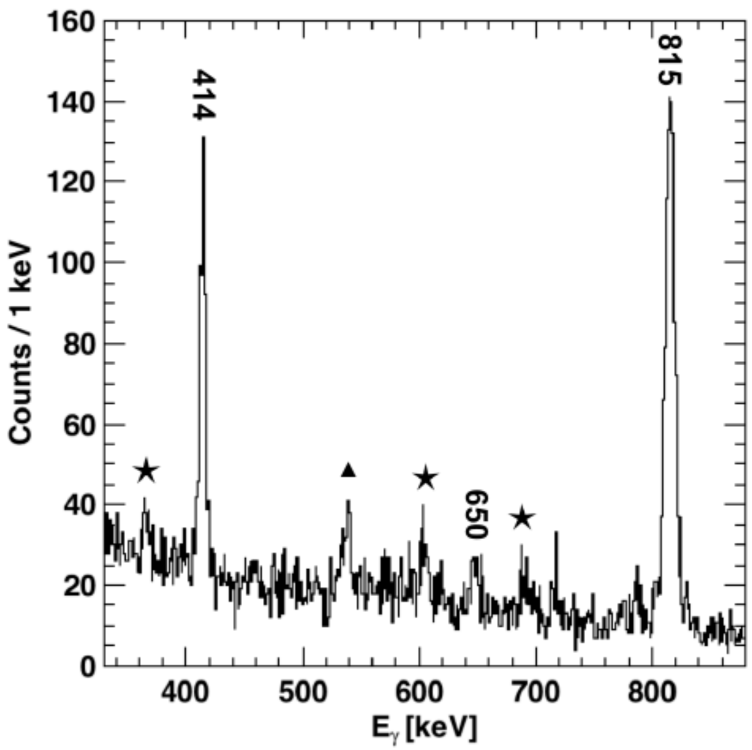
ΔE-E Si telescopes for particle ID.
HPGe for gamma-ray detection.

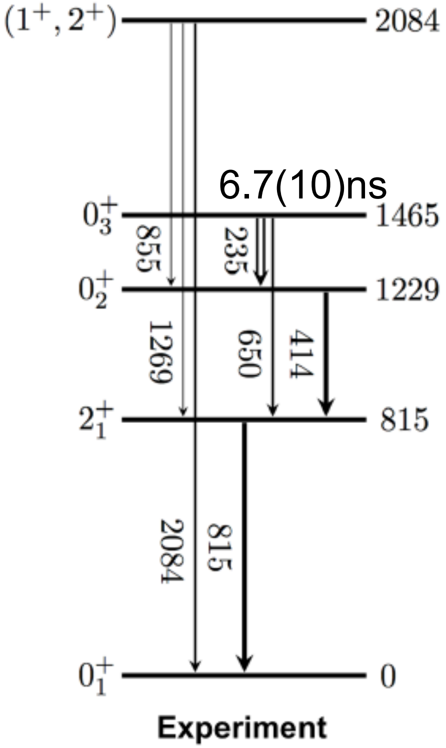




Shape coexistence around N=60

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





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

a^2=0.40(14) and β_{def}=0.31(3), V_{mix} = 113keV

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}Sr,p).

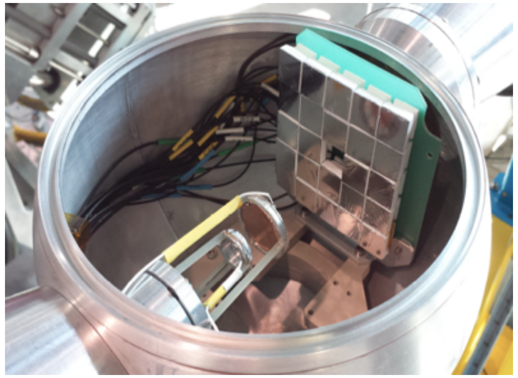
Exp.		Unmixed		*glek* ⓐ		*glek* ⓑ		*glek* ⓒ	
E_x (keV)	C^2S	E_x (keV)	C^2S	E_x (keV)	C^2S	E_x (keV)	C^2S	E_x (keV)	C^2S
0	0.19(3)	0	0.19(3)	0	1.742	0	1.575	0	1.455
1229	0.22(3)	1314	0	–	–	–	–	–	–
1465	0.33(13)	1380	0.55(13)	2271	0.056	1691	0.098	444	0.105

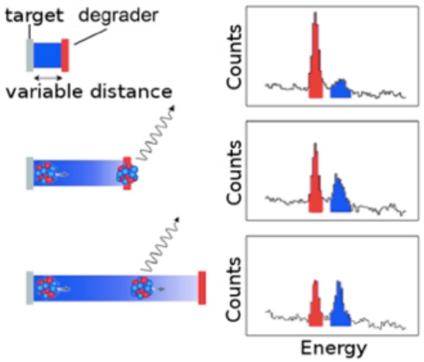
$T_{1/2}$ from H. Mach *et al.*, PRC 41, 226 (1990).

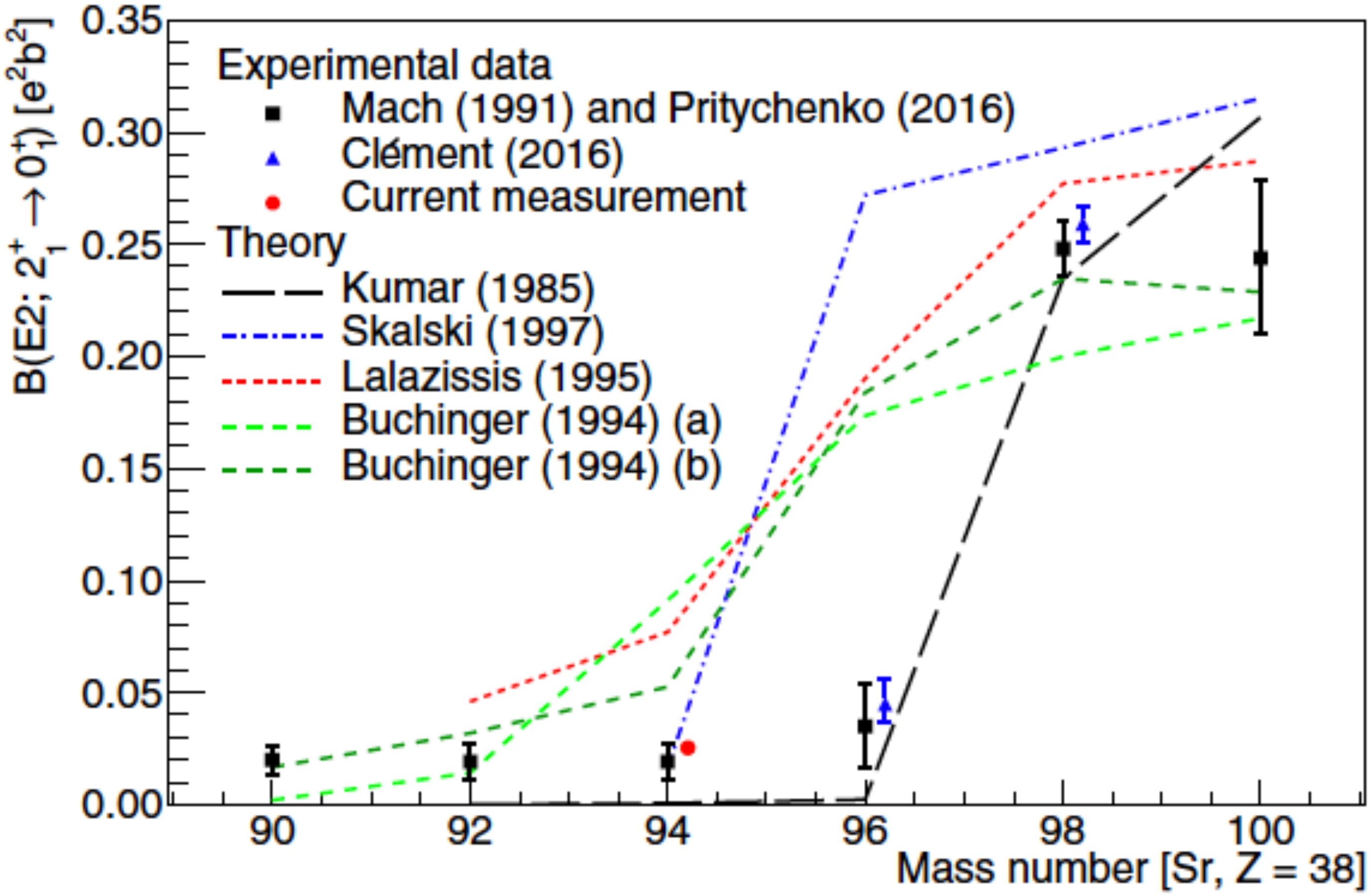
Precision lifetime measurement in ^{94}Sr

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	$7.80^{+0.50}_{-0.40}$(stat.) $\pm$ 0.07(sys.)	$0.0253^{+0.0014}_{-0.0015}$(stat.) $\pm$ 0.0002(sys.)
Mach *et al.*	Fast timing	10 ± 4	0.020 ± 0.008



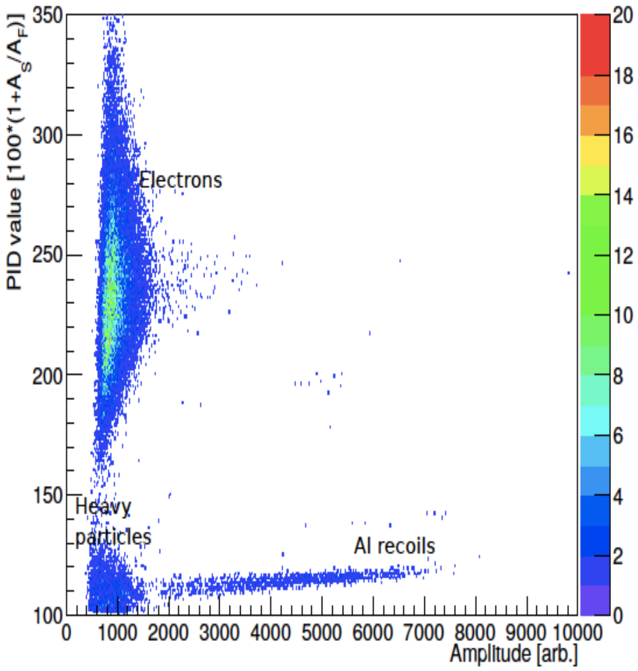




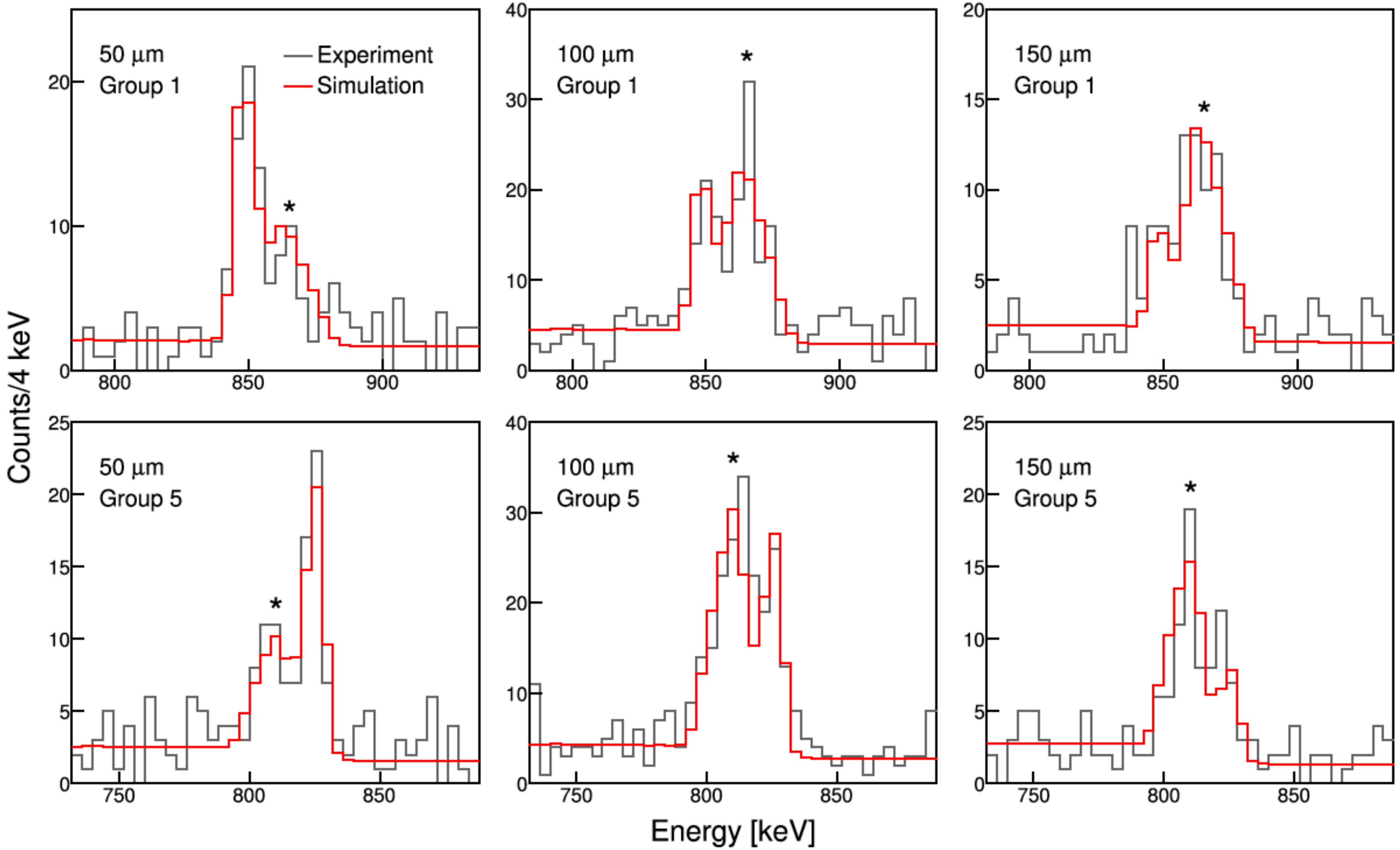
- TIGRESS Integrated Plunger
- Improves uncertainty in the *B(E2)* value from 40% to <6%.
- Confirms sudden onset of deformation in ground-state structure.

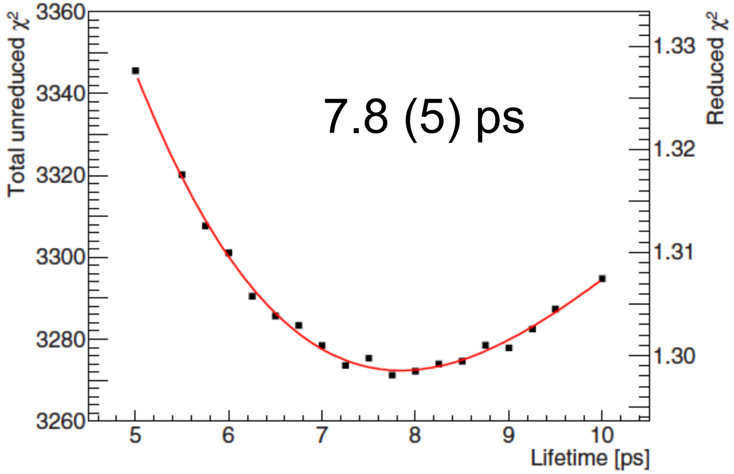
H. Mach et al., NPA 523, 197 (1991).

Precision lifetime measurement in ^{94}Sr



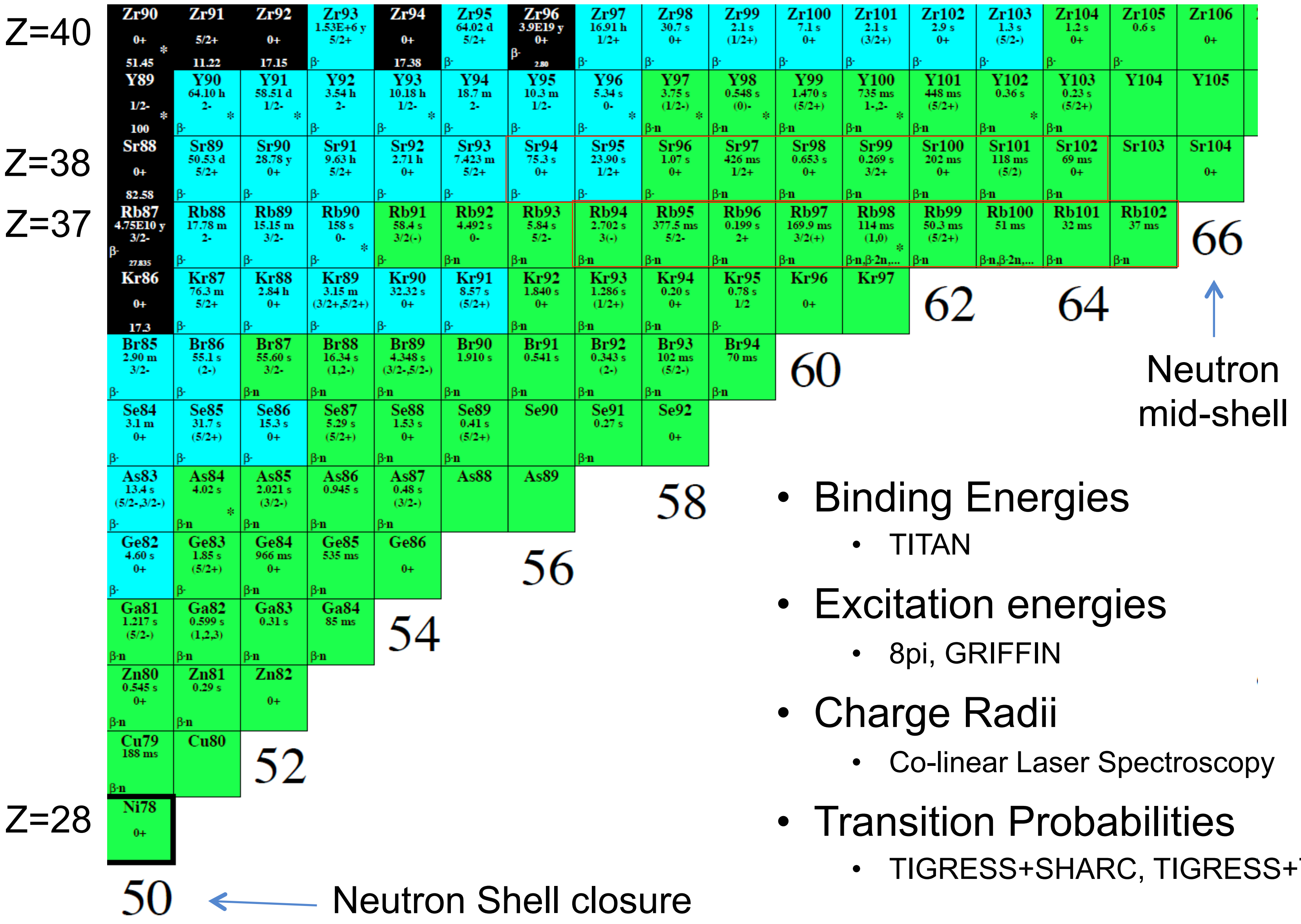
First 2^+ state populated in unsafe Coulex of ^{94}Sr beam





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

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



ISAC studies around *N*=60:

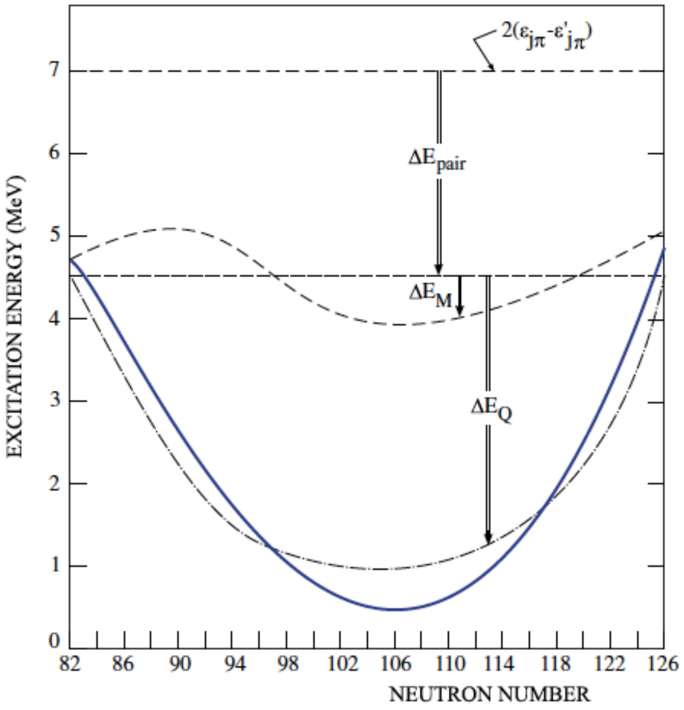
S. Cruz *et al*., Phys. Letts. B 786, 94 (2018).
A. Chester *et al*., PRC 96, 011302(R) (2017).
Z.M. Wang, *et al.*, PRC 93, 054301 (2016).
R. Klawitter *et al*., PRC 93, 045807 (2016).
J. Park *et al*., PRC 96, 014315 (2016).
T.J. Procter *et al*., Eur. Phys. J. A 51, 23 (2015).
A. Chakraborty *et al*.,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

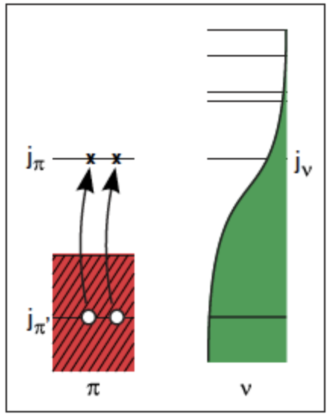
- Binding Energies
  - TITAN
- Excitation energies
  - 8pi, GRIFFIN
- Charge Radii
  - Co-linear Laser Spectroscopy
- Transition Probabilities
  - TIGRESS+SHARC, TIGRESS+TIP, GRIFFIN+PACES+$LaBr_3$

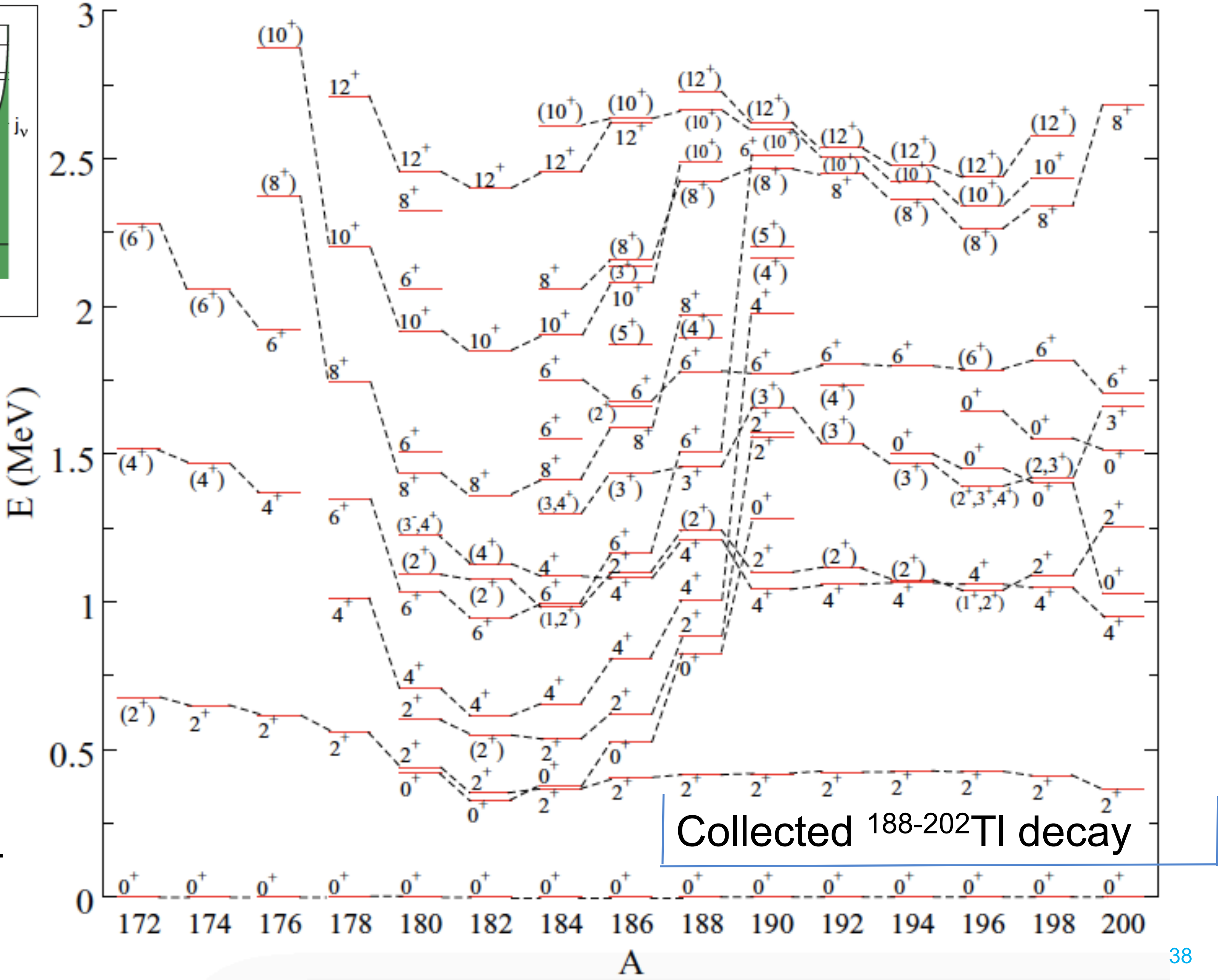
What's next for ISAC?

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

Hg isotopes from Tl decay





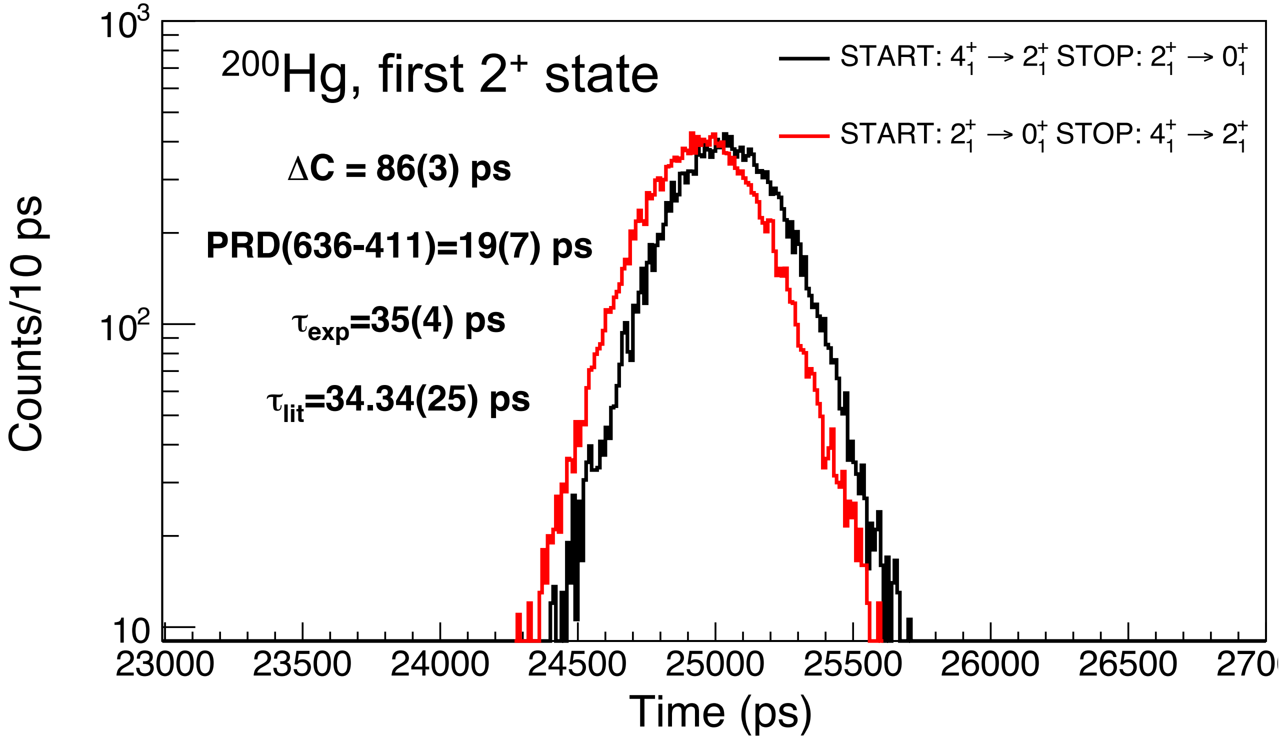


Hg isotopes display characteristic parabolic systematic of GS coexistence with a deformed intruder configuration

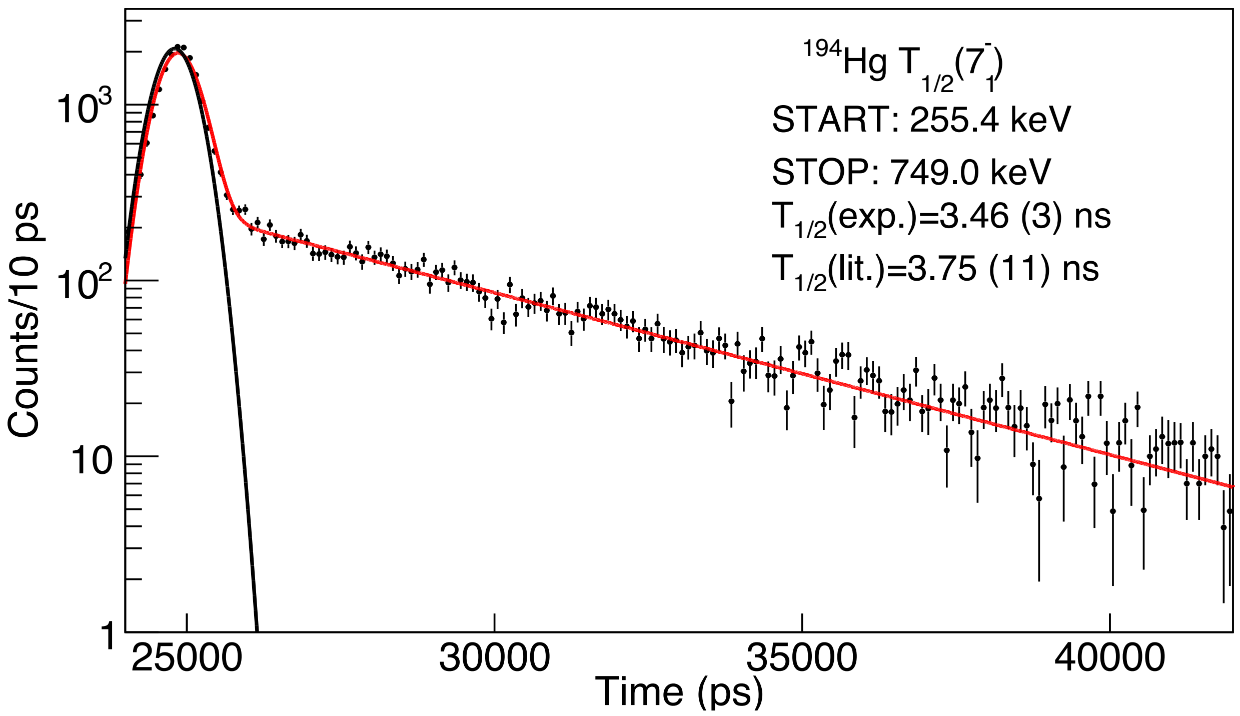
Heyde & Wood, Rev. Mod. Phys. 83, 1467 (2011).
Garcia-Ramos & Heyde, PRC 89, 014306 (2014).

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 $LaBr_3(Ce)$ crystals



Centroid shift method



Slope fitting method

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

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

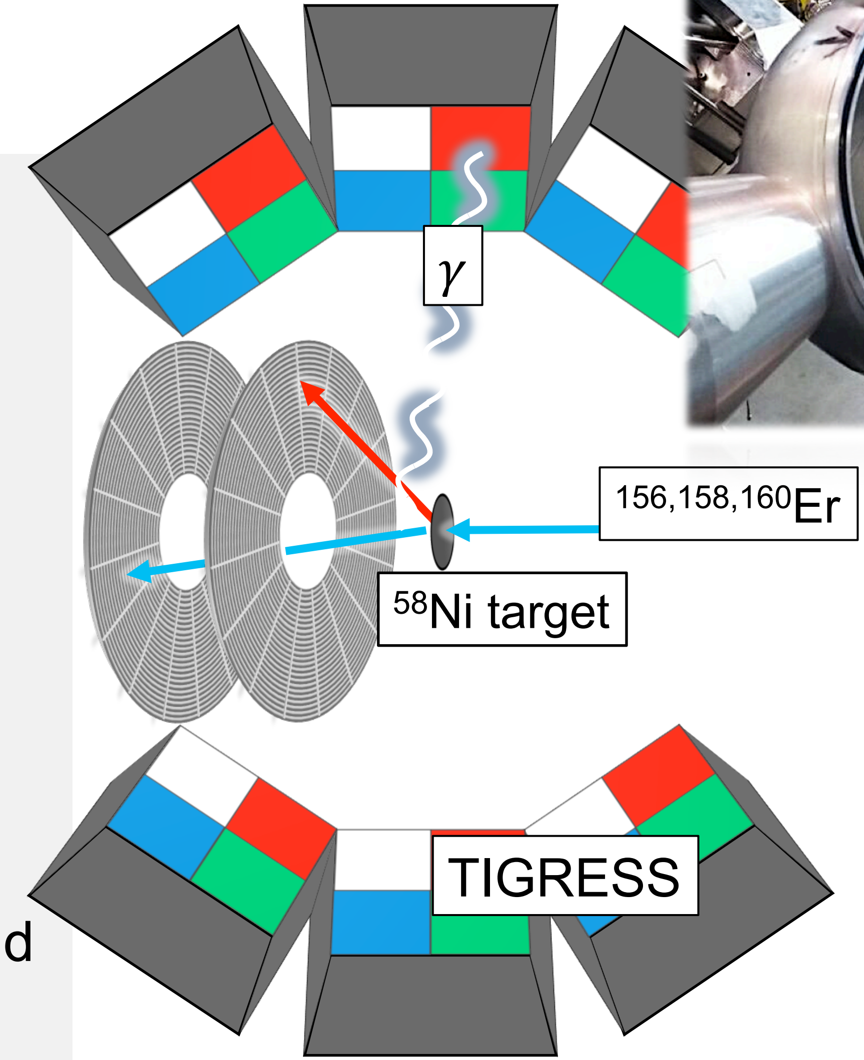
A>29 beams require charge-breeding.
- Currently use ISAC CSB
- CANREB EBIS from 2019

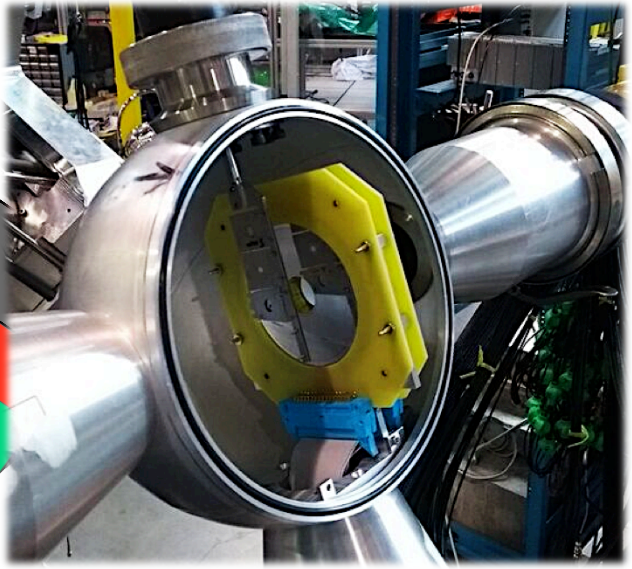
S1750, J. Smallcombe & A.B. Garnsworthy
HPTa target with TRILIS and CSB.
Beams delivered to TIGRESS, Oct 2017:

$^{156}Er^{23+}$: 1x10^8 total pps, 25% ^{156}Er, ~14hrs
$^{158}Er^{23+}$: 1x10^8 total pps, 50% ^{158}Er, ~14hrs
$^{160}Er^{23+}$: 1x10^8 total pps, 50% ^{160}Er, ~14hrs

3.9 AMeV Coulex on ^{58}Ni target

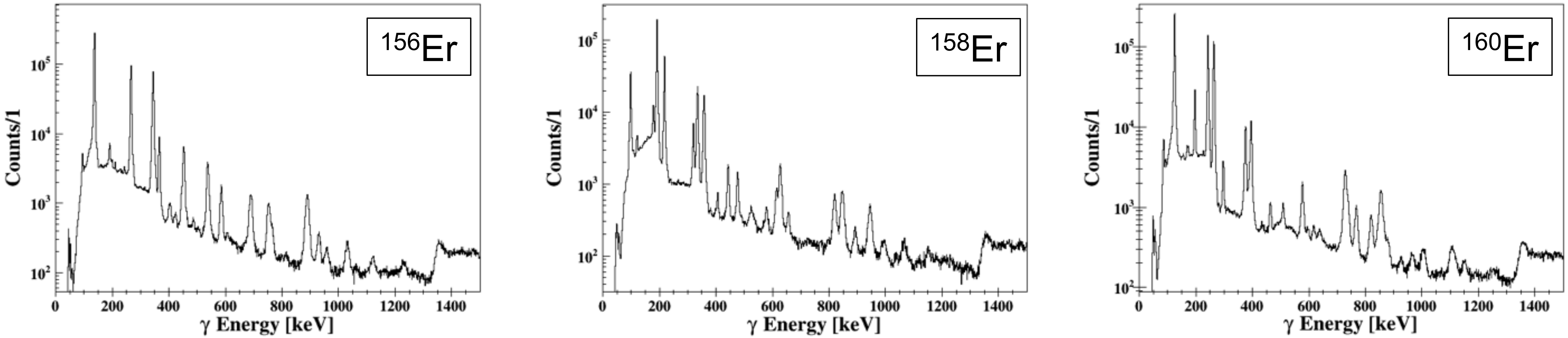
Will measure quadrupole moments of low-lying states to determine the shape of these nuclei, and investigate coexistence at N=88,90.

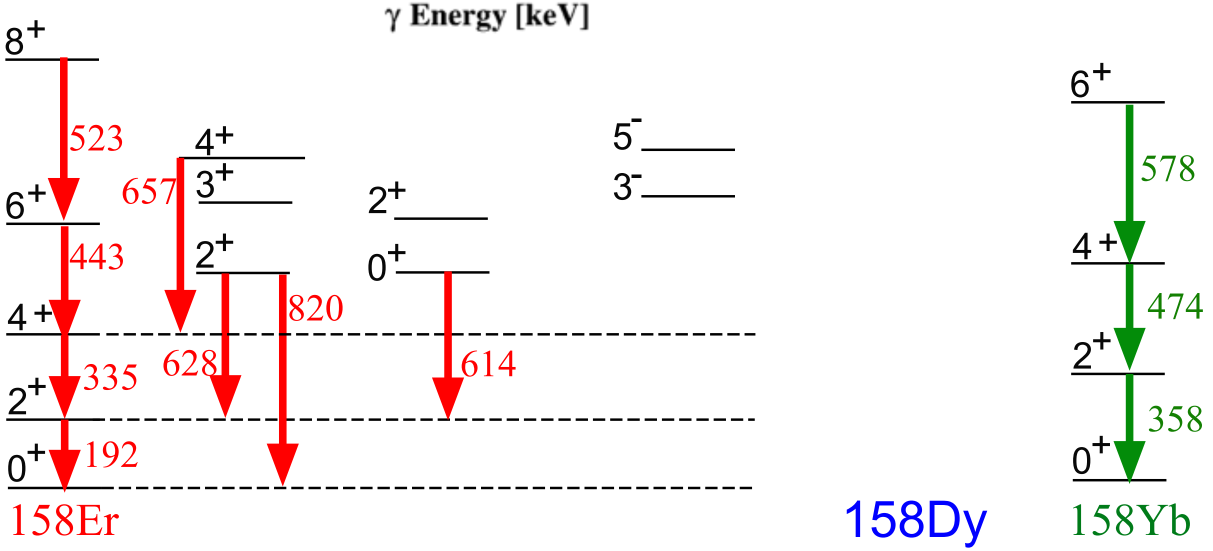




Two downstream S3 detectors to increase angular coverage

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





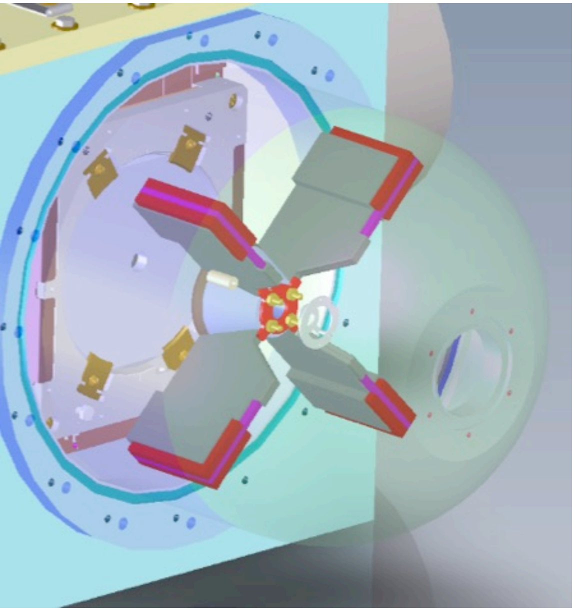
- Excellent Coulex dataset
- Excitation up to fourth 2^+ state seen (good for invariant analysis)
- GOSIA analysis ongoing – Dy and Yb contaminants will also be analysed

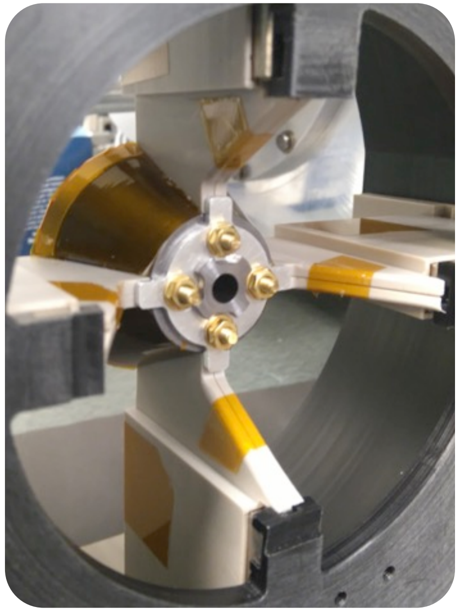
Analysis by Paulina Siuryte (MPhys) and James Smallcombe

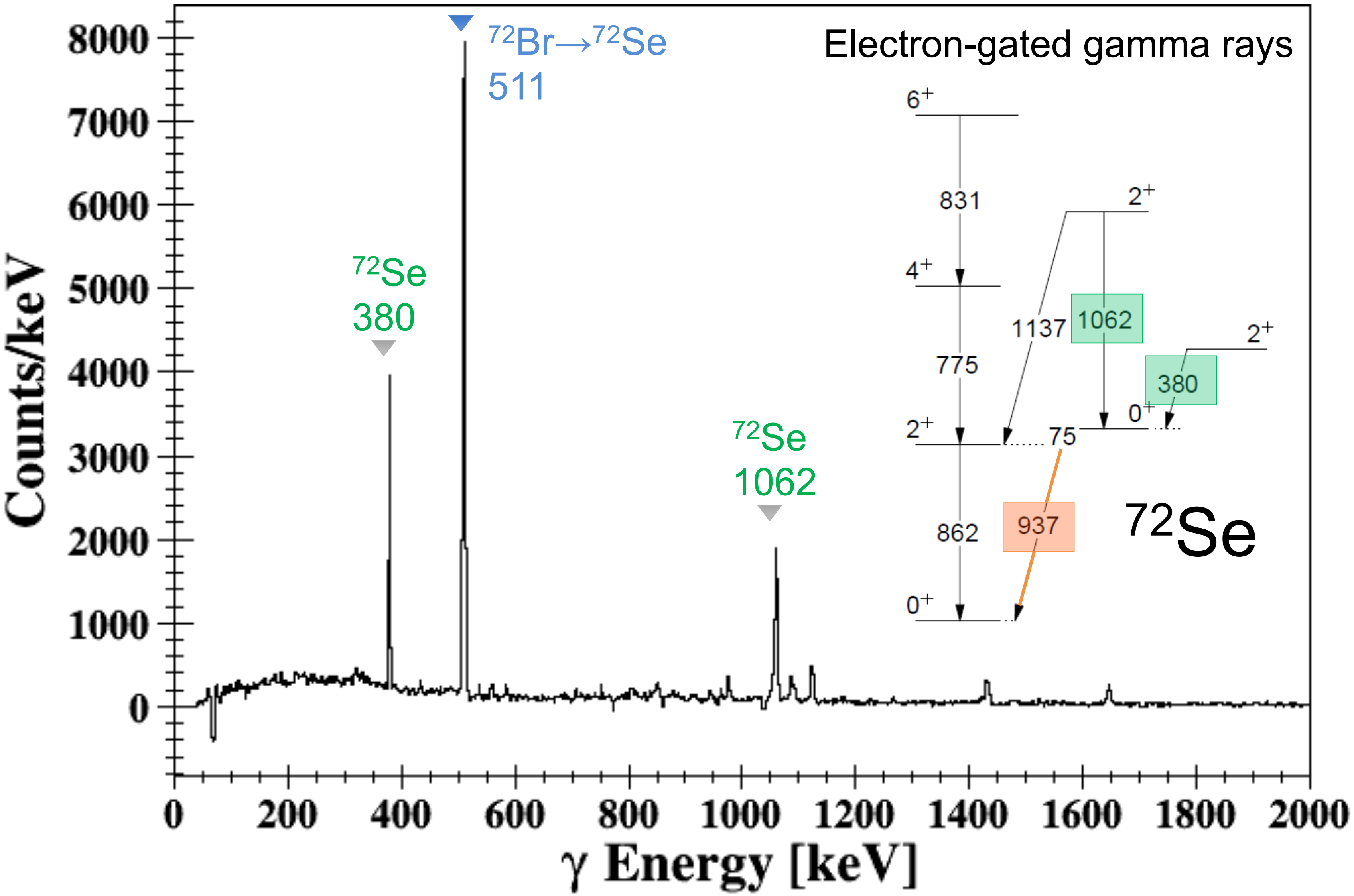
SPICE in-beam electron spectrometer

Shape coexistence in ^{72}Se

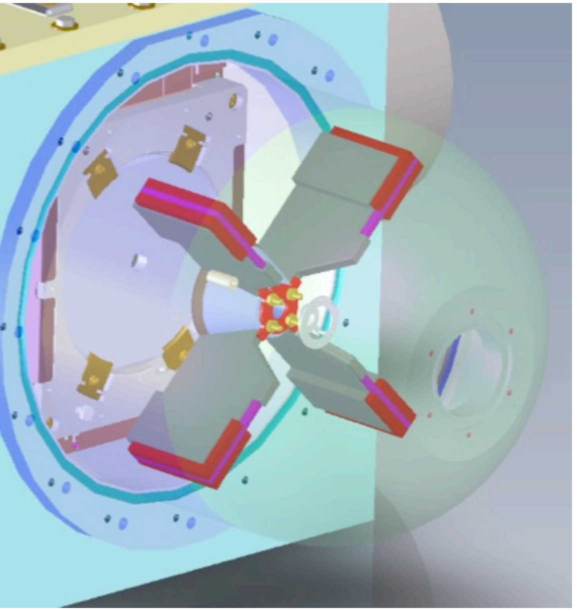
J. Smallcombe, W. Korten *et al.*

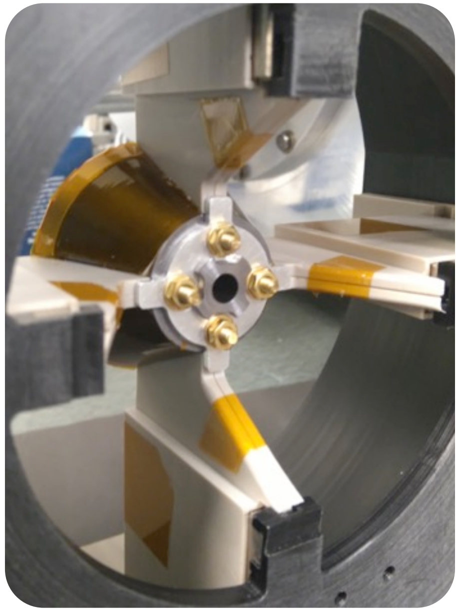






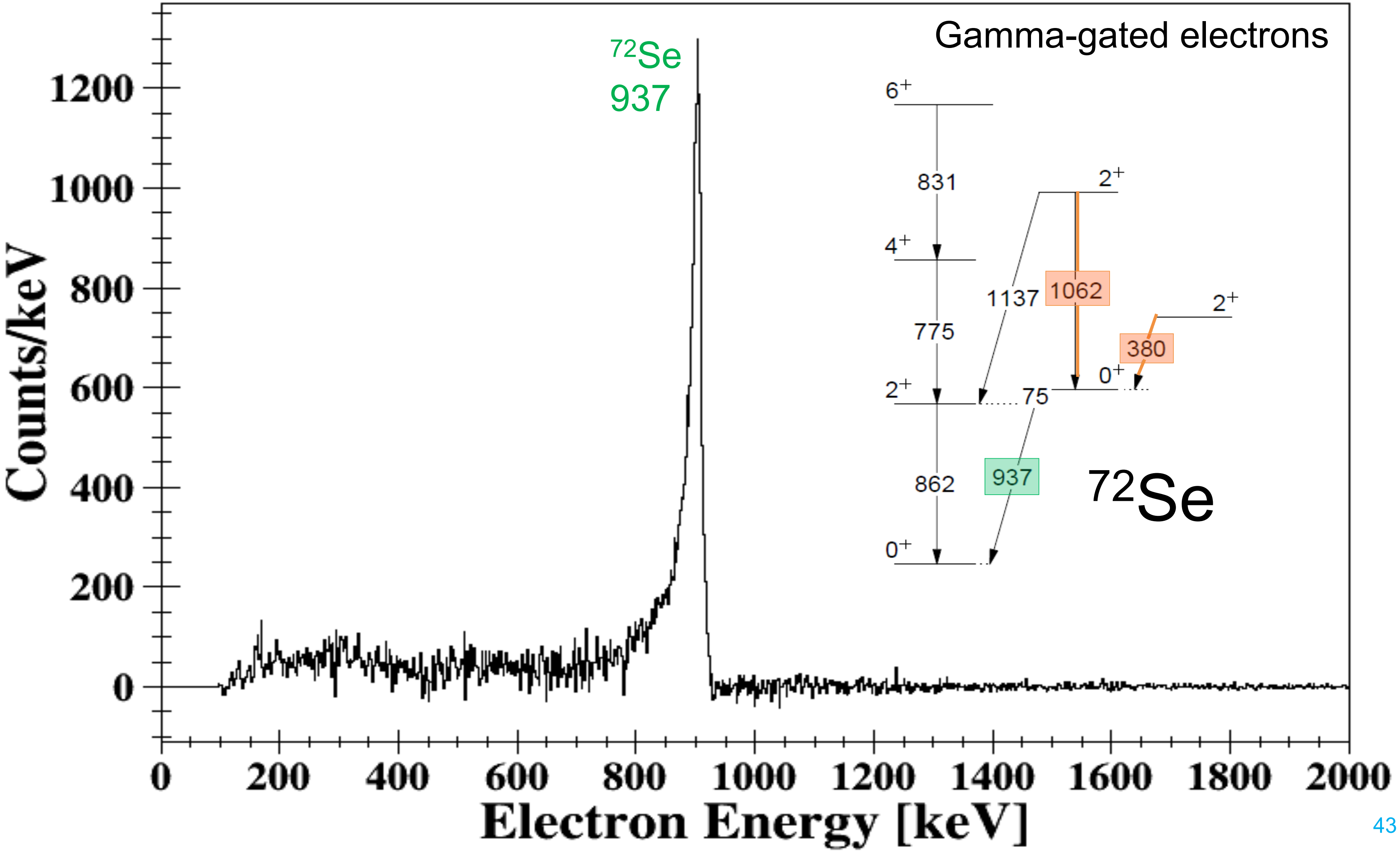
SPICE in-beam electron spectrometer





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!