

$K = 4^+$ Band-heads in ^{160}Gd

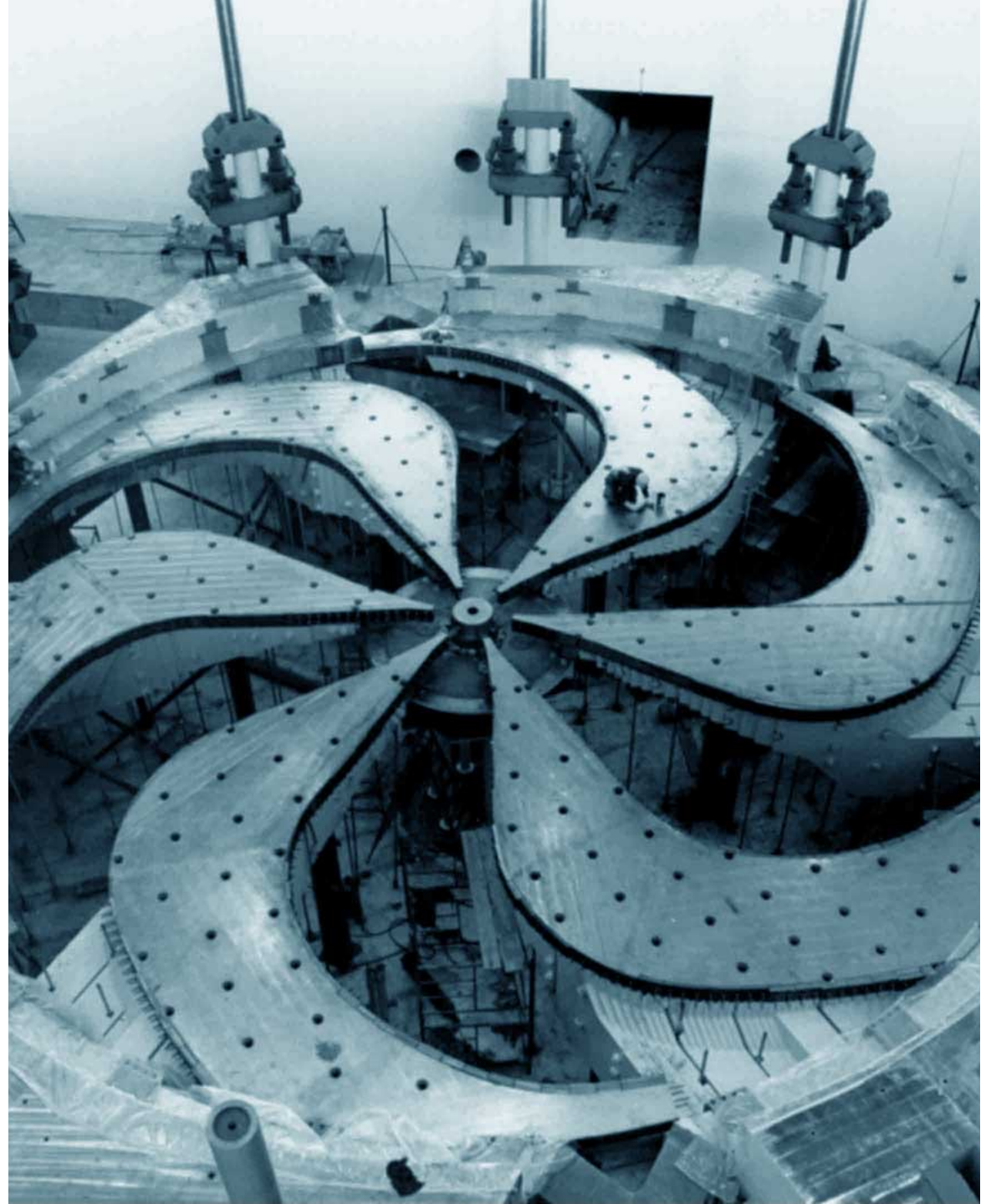
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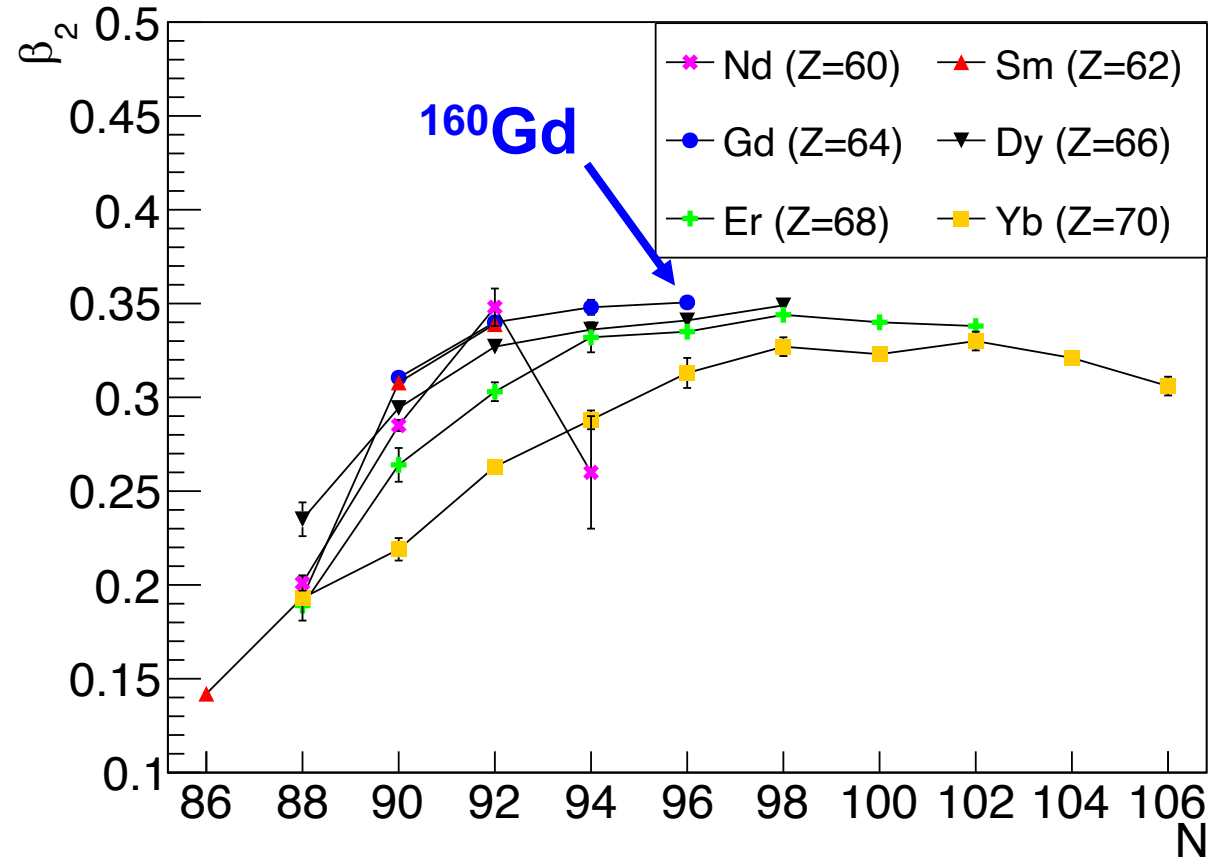
Nuclear Structure 2022

2022-06-16

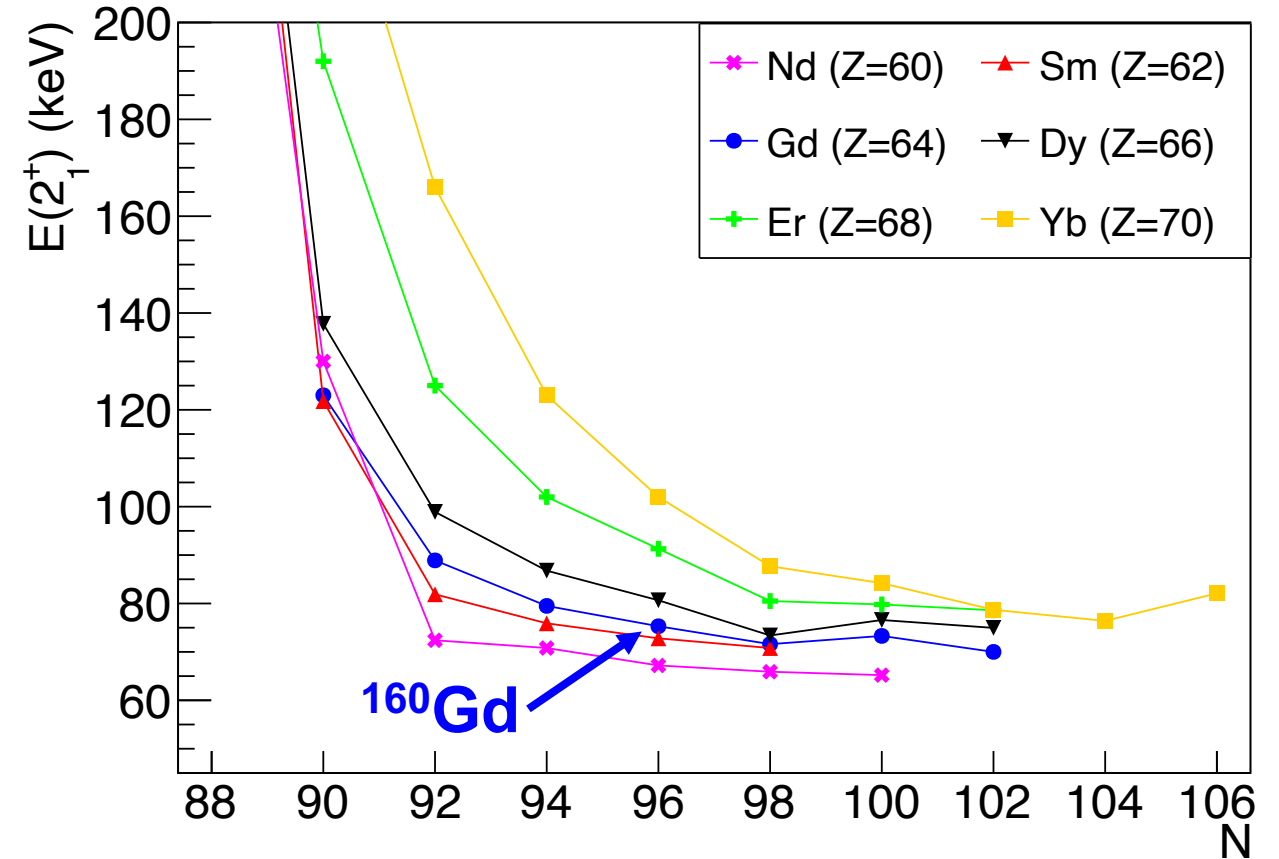


Onset of Deformation in Rare-Earth Isotopes

Ground-state Quadrupole Deformations

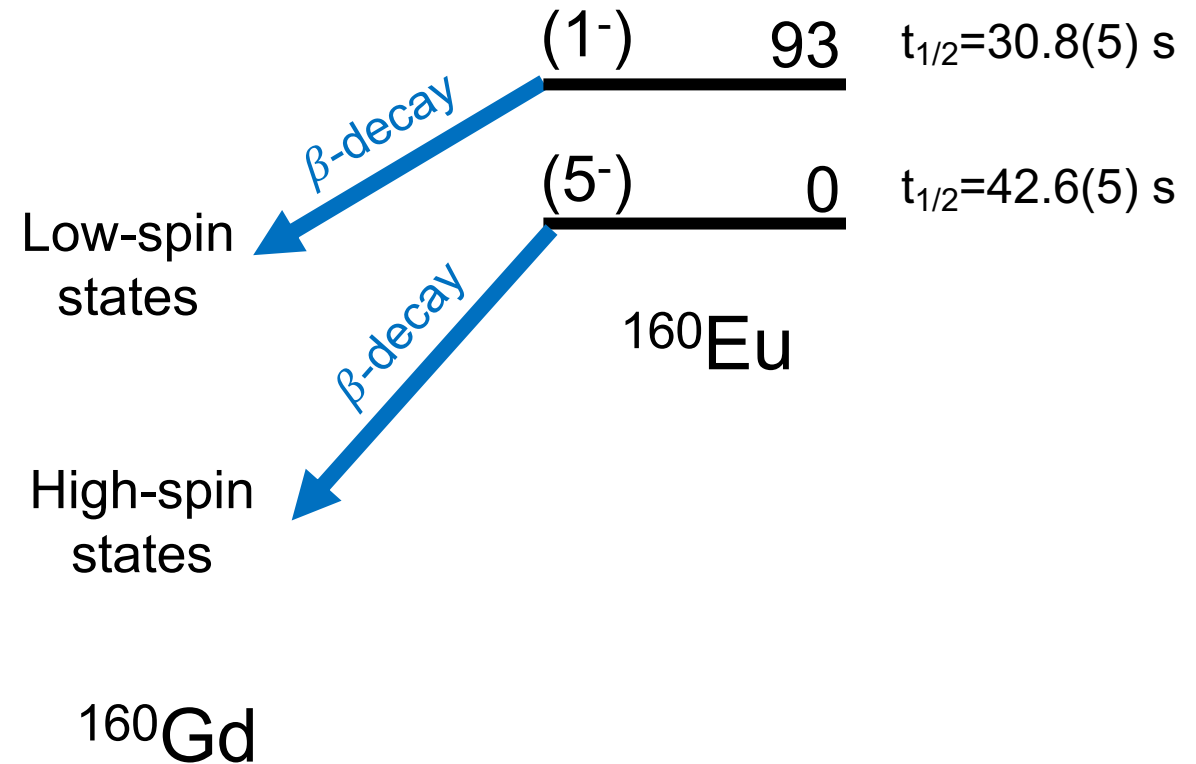


First Excited State Energy



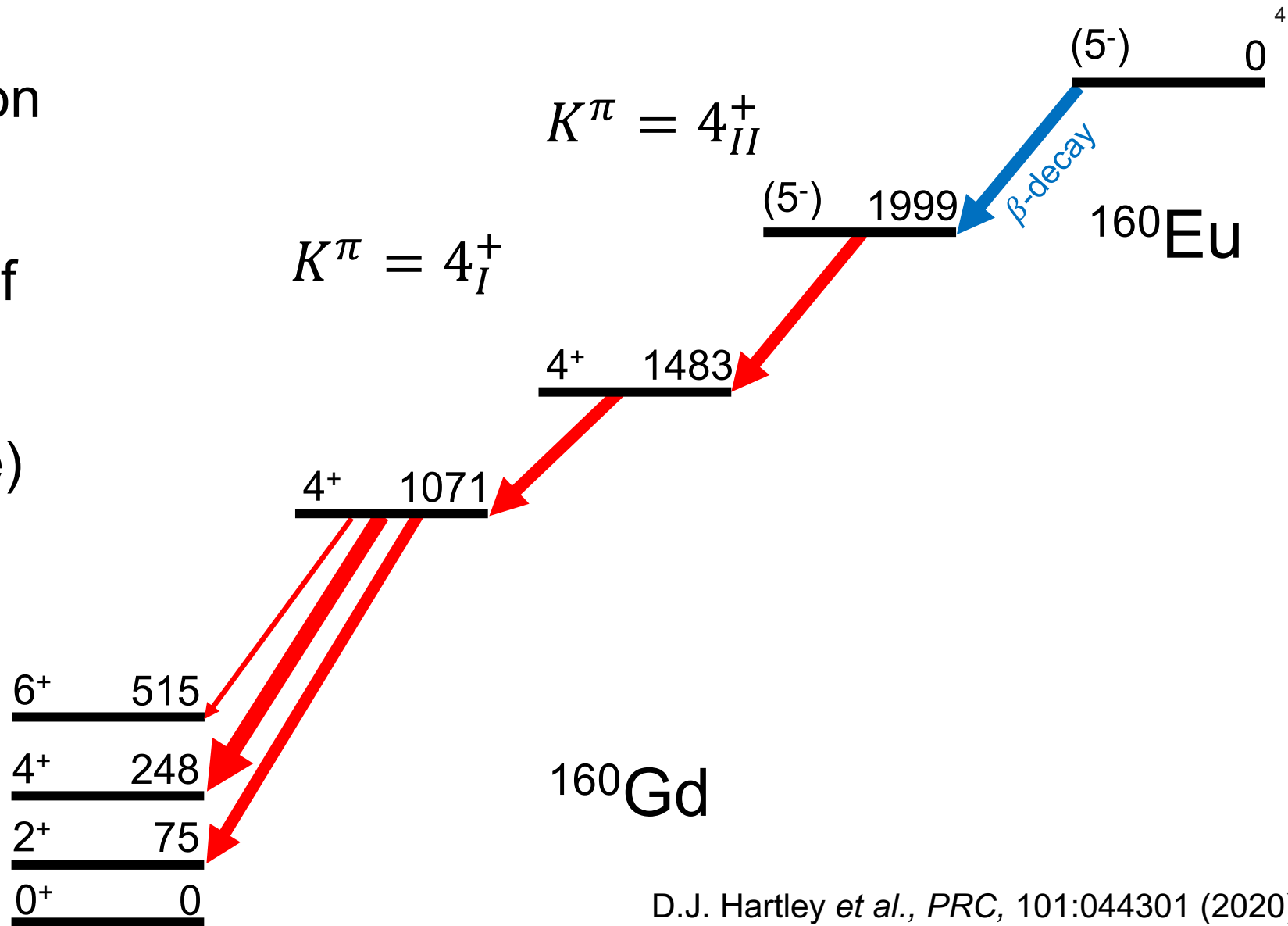
Possible Structure in ^{160}Eu

- β -decay at ATLAS facility at ANL
- Hartley *et al.* first identified β -decaying isomer and ground-state



$K^\pi = 4^+$ Bands in ^{160}Gd

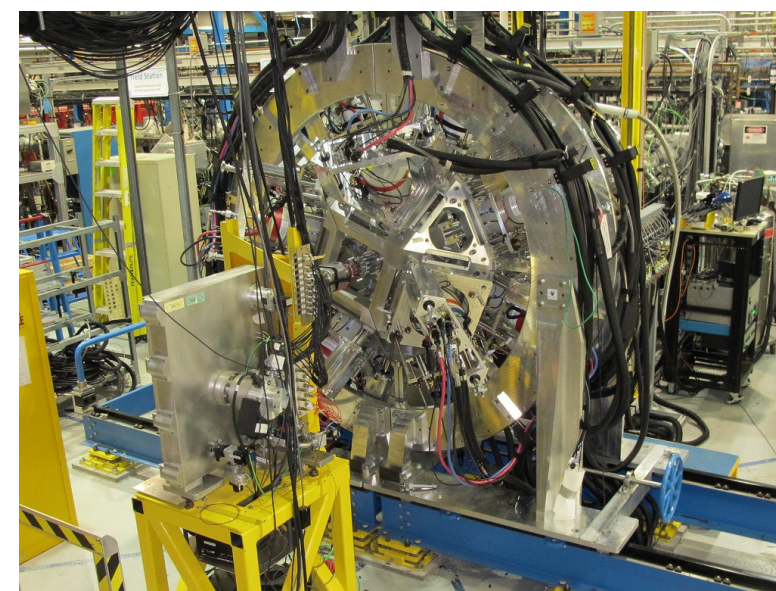
- Predominant de-excitation through $K^\pi = 4^+$ band-heads
- Multiple interpretations of $K^\pi = 4^+$ bands
 - Double- γ (Börner)
 - Hexadecapole (Burke)
 - Quasiparticle excitations (Hartley)



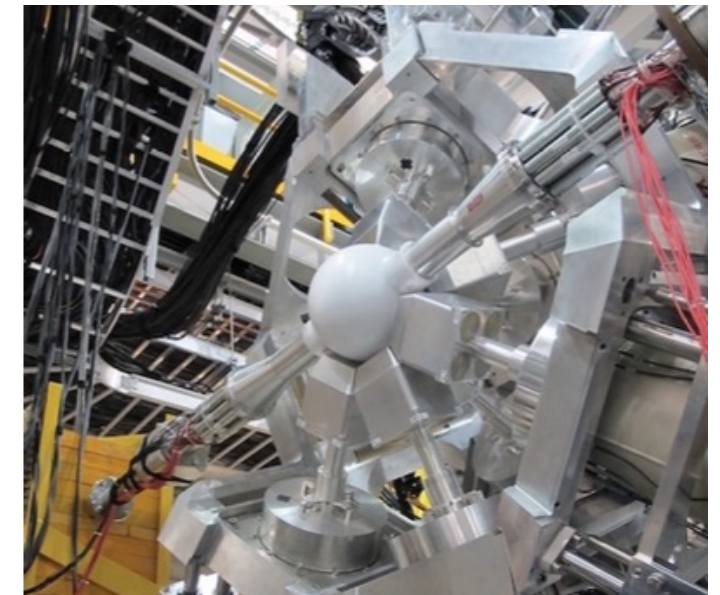
β -decay of ^{160}Eu at TRIUMF-ISAC

- TRIUMF-ISAC radioactive beam facility
- Beam of $^{160}\text{Eu}^{\text{g,m}}$ at ~ 3000 pps for 4 hours

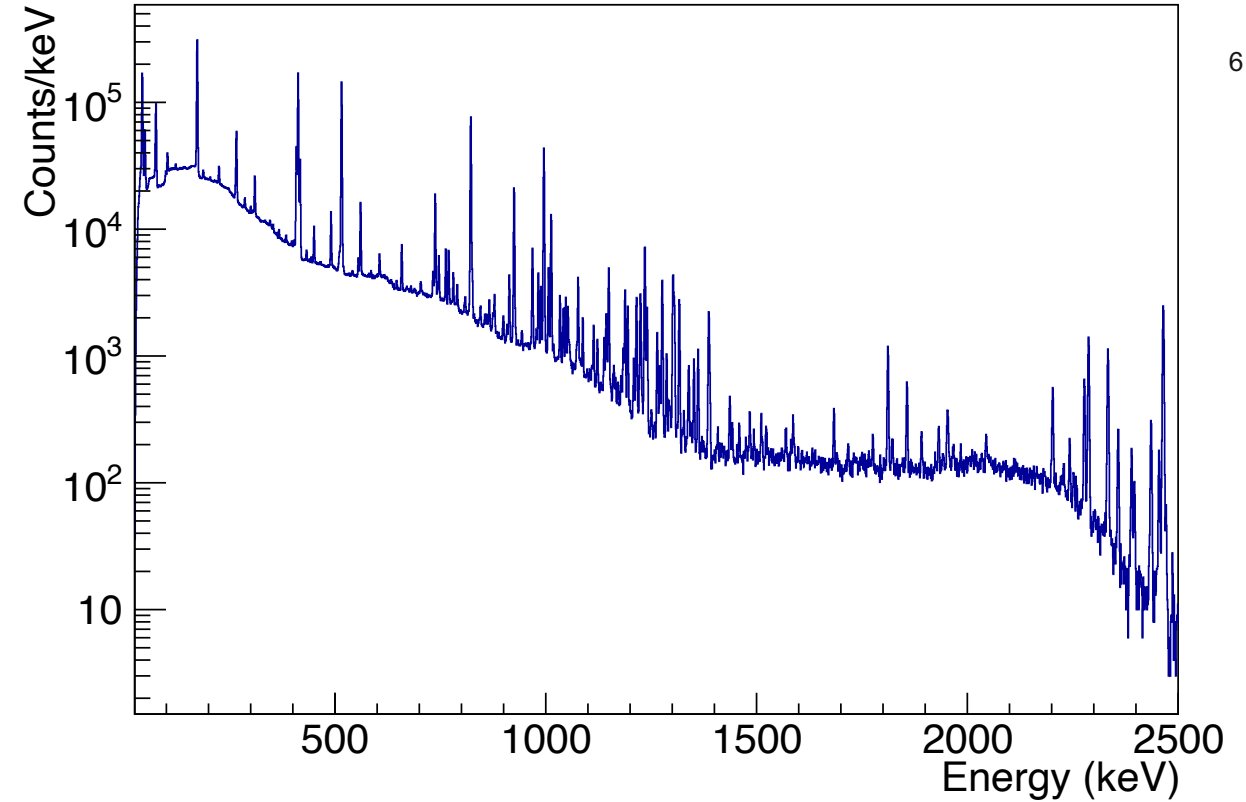
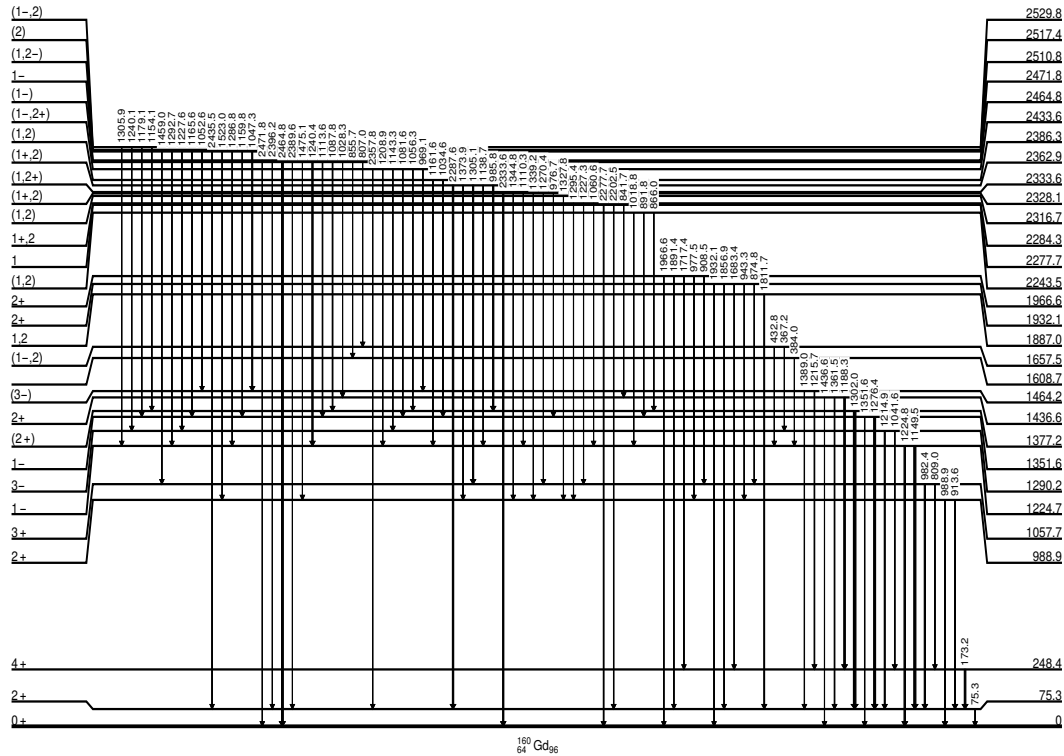
- GRIFFIN facility for β - and γ -decay spectroscopy
 - 15 High-purity Ge detectors
 - $\text{LaBr}_3(\text{Ce})$ fast-timing array
 - Conversion electron spectrometer



GRIFFIN: Gamma-Ray Infrastructure for Fundamental Investigations of Nuclei



Summary of Low-spin β -decay



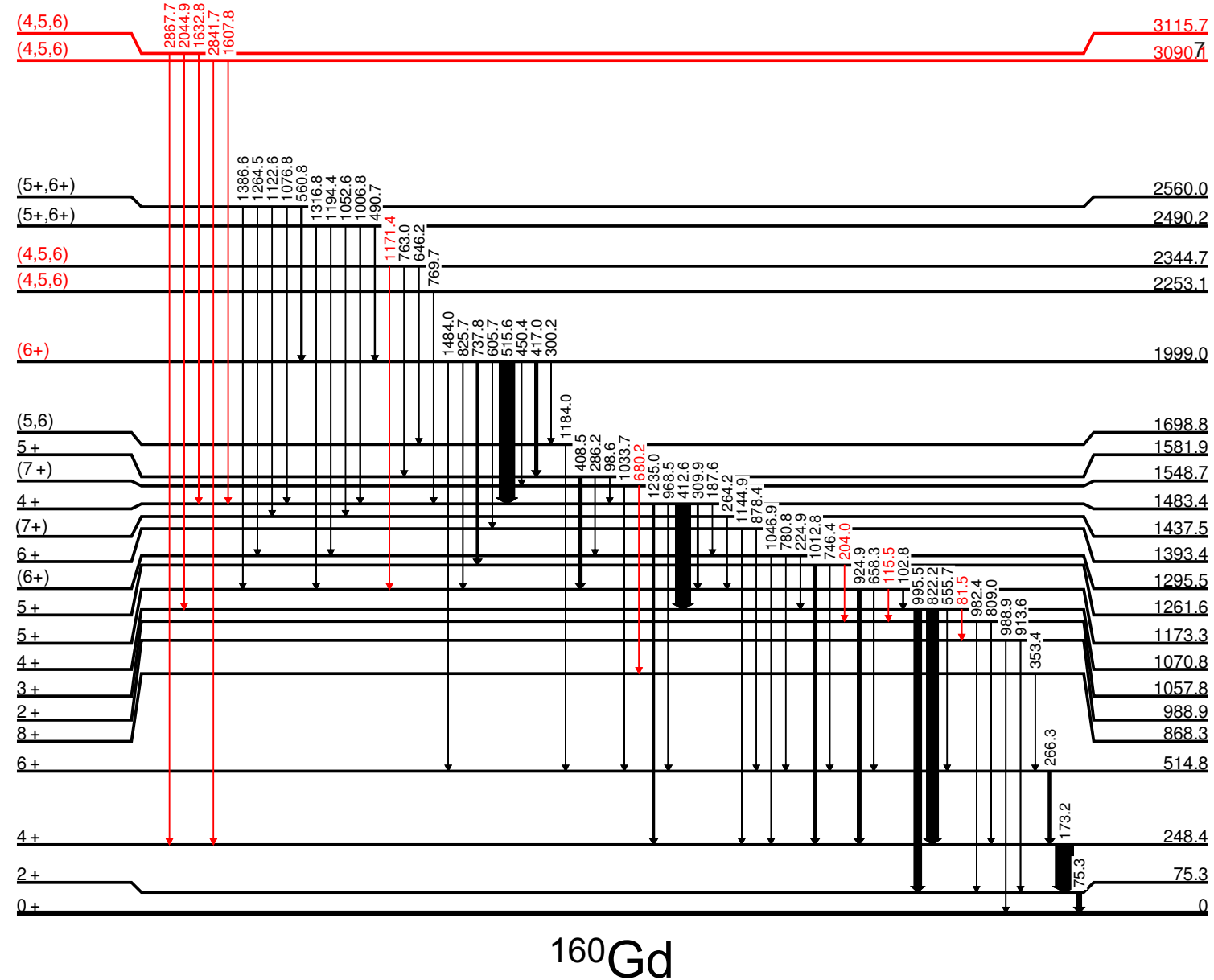
- All levels confirmed
- 86/94 transitions confirmed
- Different half-life of low-spin β -decay
 - $t_{1/2} = 26.0(8) \text{ s}$
 - $t_{1/2,\text{lit}} = 30.8(9) \text{ s}$

$\sim 8 \times 10^6$ total β -decays
(low and high spin)

Data compared to:
D.J. Hartley *et al.*, *PRL*, 120:182502 (2018).
D.J. Hartley *et al.*, *PRC*, 101:044301 (2020).

Summary of High-spin β -decay

- All levels, most transitions confirmed
- **2 new levels**
- **10 new transitions**
- Confirmed half-life of high-spin β -decay
 - $t_{1/2} = 42.5(7) \text{ s}$
 - $t_{1/2, \text{lit}} = 42.6(5) \text{ s}$
- 3 new mixing ratios
- 4 new lifetimes

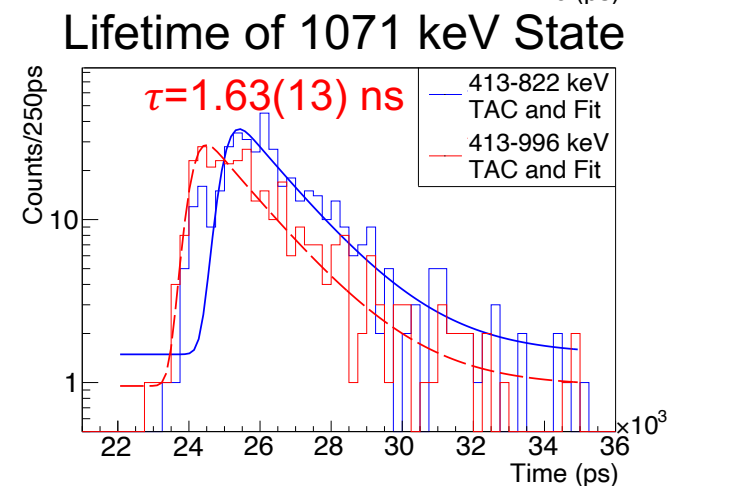
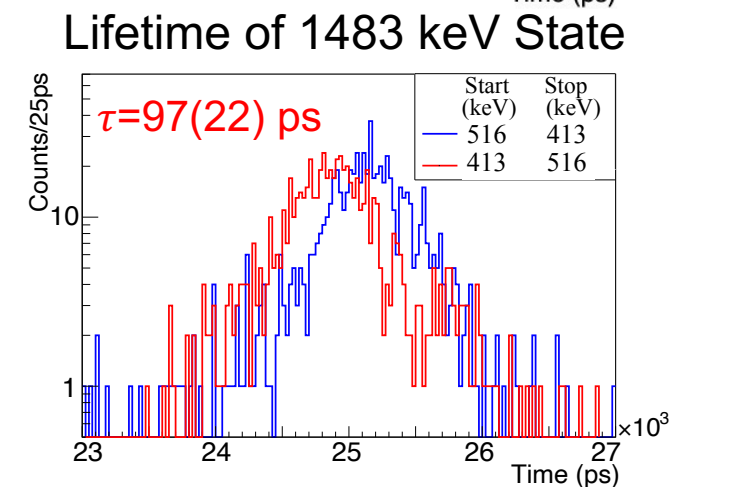
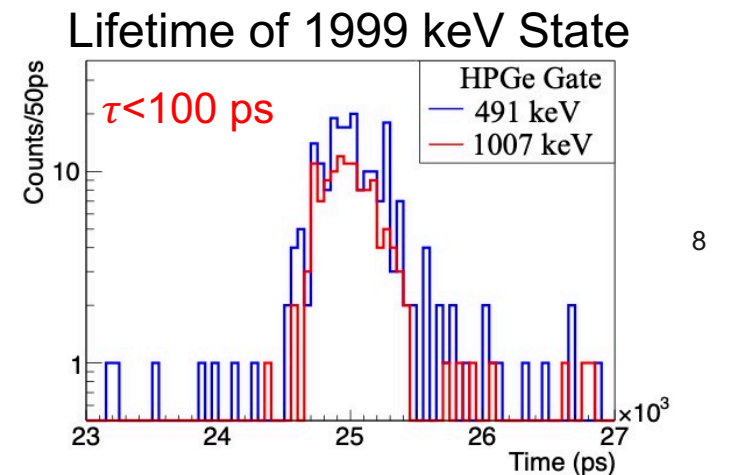
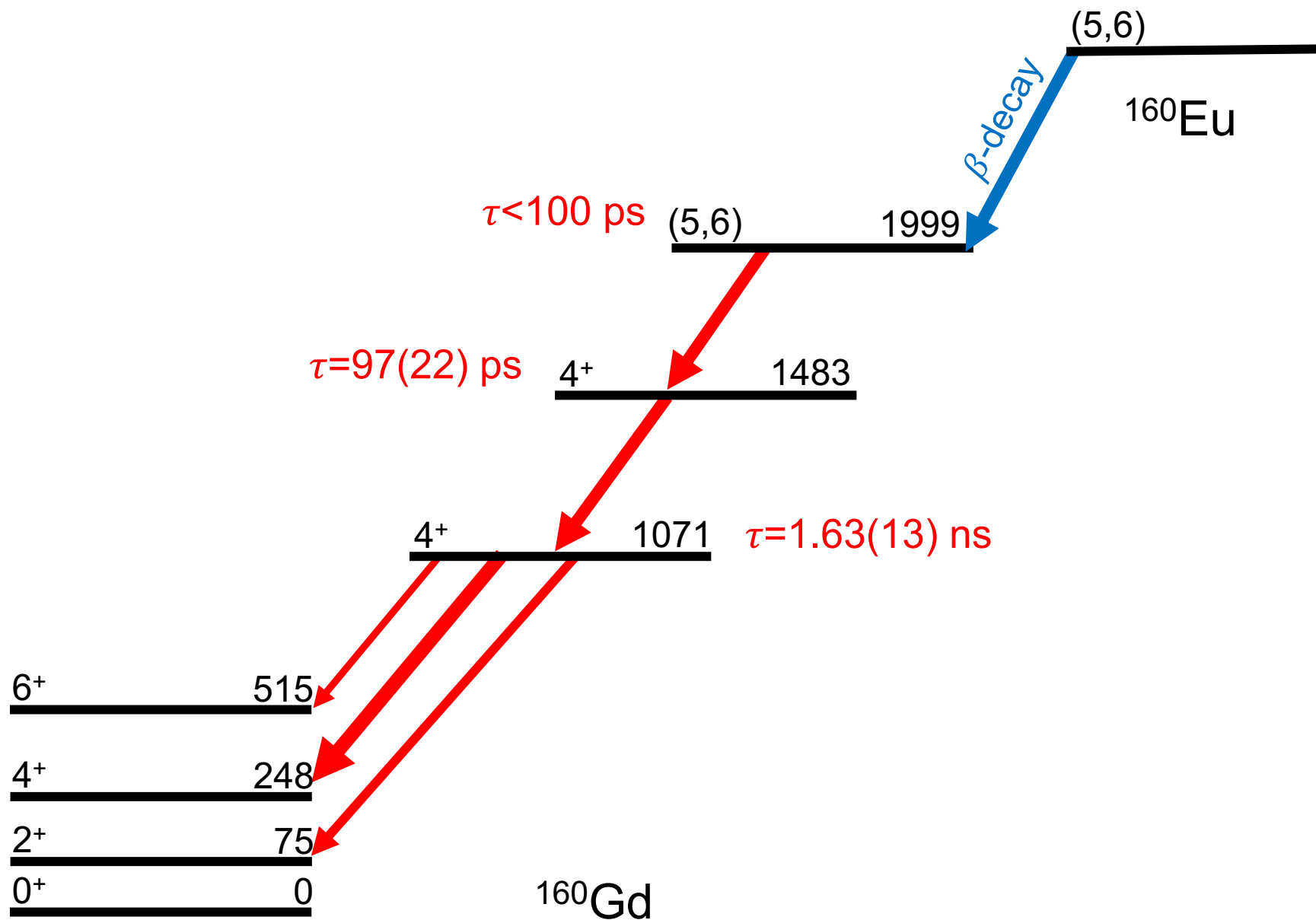


Data compared to:

D.J. Hartley *et al.*, *PRL*, 120:182502 (2018).

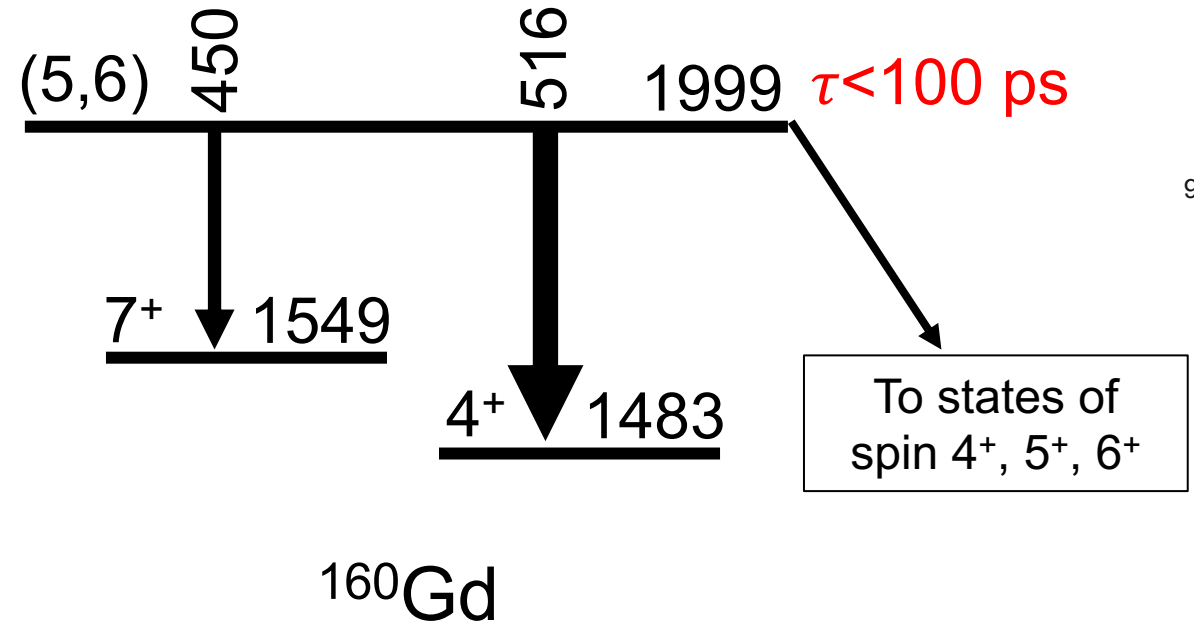
D.J. Hartley *et al.*, *PRC*, 101:044301 (2020).

Lifetimes in ^{160}Gd



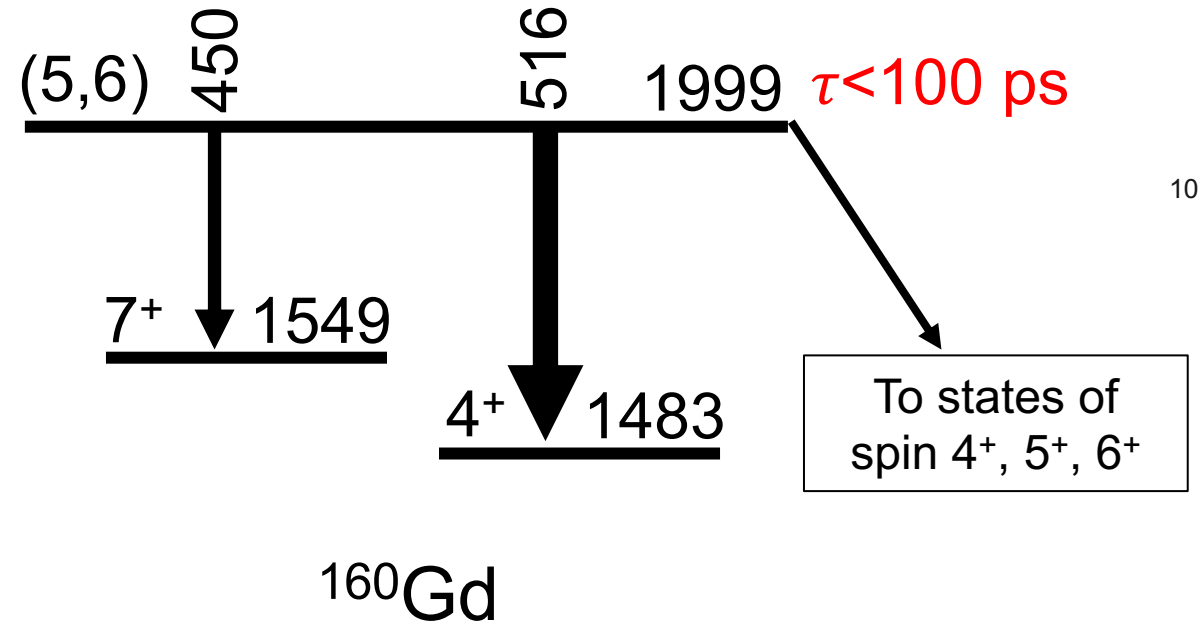
Spin of 1999 keV State in ^{160}Gd

- Constrain spin based on lifetime $\tau < 100$ ps



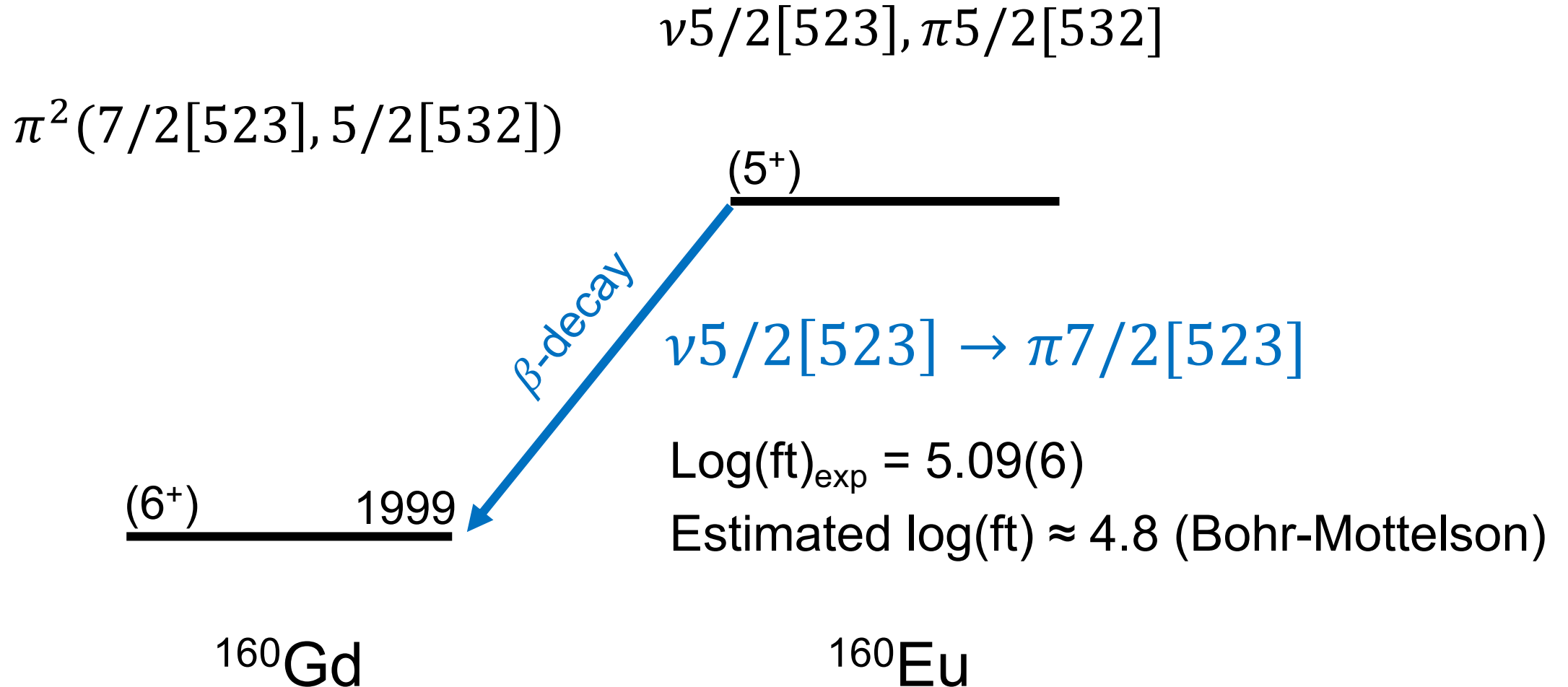
Spin of 1999 keV State in ^{160}Gd

- Constrain spin based on lifetime $\tau < 100$ ps



J^{π}_{1999}	Possible?	Reason
5^-	No	$B(M2; 450 \text{ keV}) > 17 \text{ W.u.}$
6^-	No	$B(M2; 516 \text{ keV})$ and $B(E3; 516 \text{ keV})$ are unreasonably large
5^+	No	$B(M1)$ and $B(E2)$ ok No orbitals available to couple to 5^+ configuration
6^+	Yes	$B(\sigma L)$ ok Available Nilsson configuration

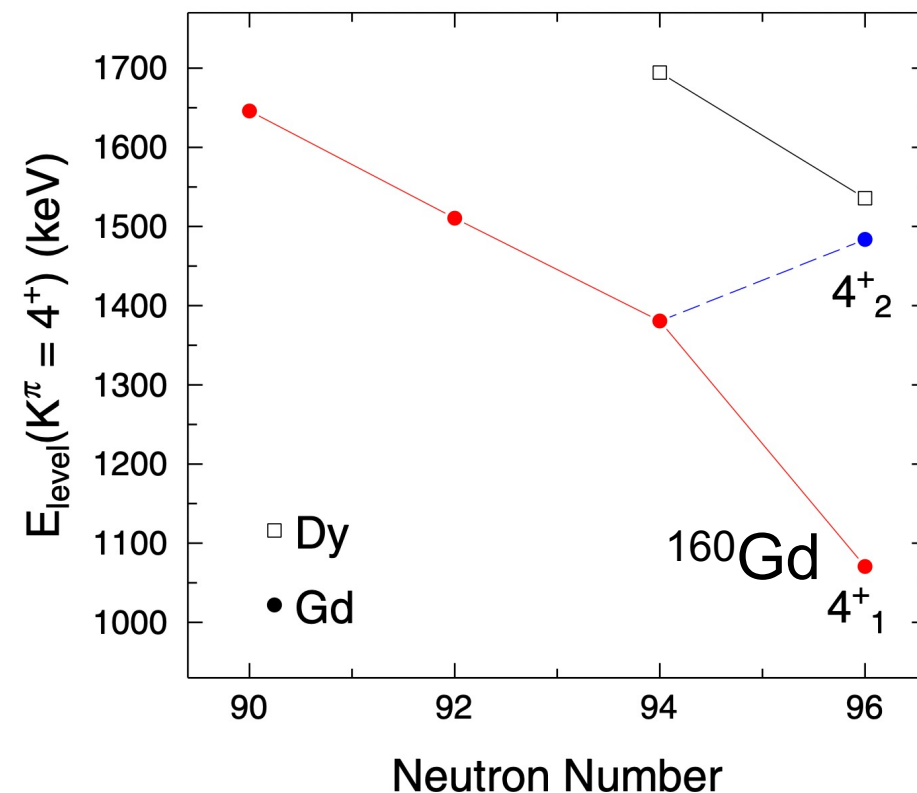
New Proposed Configuration of ^{160}Eu β -decay



Previously Proposed Structure of $K^\pi = 4^+$ Bands

- Hartley *et al.* proposed
 - Band-heads result from $\sim 50/50$ mixing of nearly degenerate quasiparticle
 - $\nu^2(5/2[523], 3/2[521])$
 - $\pi^2(5/2[413], 3/2[411])$
 - 4^+_I band quickly evolves to pure 2ν quasiparticle band based on $B(M1)/B(E2)$ ratios from Coulex

$$\begin{array}{ccc} & & \underline{4^+} \quad 1483 \\ & & \\ \underline{4^+} \quad 1071 & & K^\pi = 4^+_{II} \\ & & \\ & & K^\pi = 4^+_I \end{array}$$



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Simple Quantum Rotor for 4_1^+ Band

- Simple rotor reproduces $K^\pi = 4_1^+$ band quite well
- Consistent with entire band mixed or none of band mixed

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

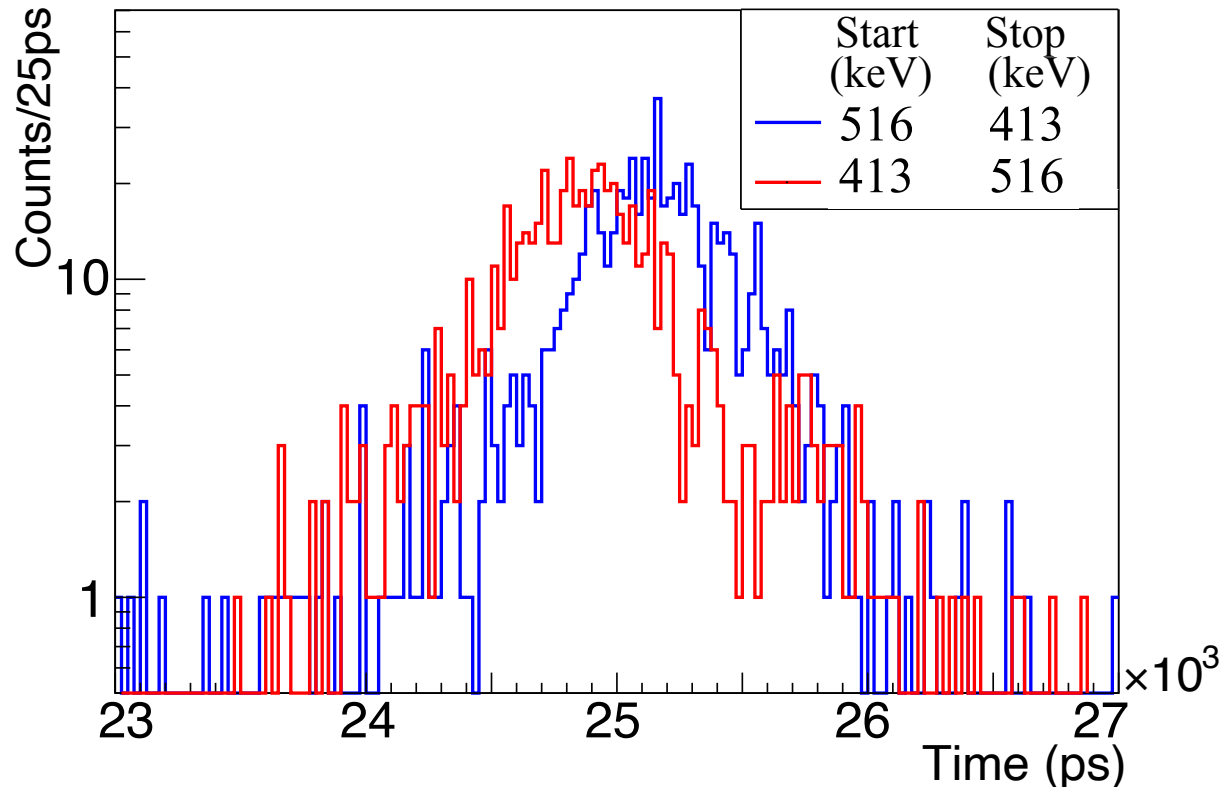
Calculated from 5^+ and 4^+ levels

Experiment		Simple Rotor	
<u>10⁺</u>	<u>1978</u>	<u>10⁺</u>	<u>1998</u>
<u>9⁺</u>	<u>1780</u>	<u>9⁺</u>	<u>1792</u>
<u>8⁺</u>	<u>1600</u>	<u>8⁺</u>	<u>1607</u>
<u>7⁺</u>	<u>1438</u>	<u>7⁺</u>	<u>1442</u>
<u>6⁺</u>	<u>1296</u>	<u>6⁺</u>	<u>1298</u>
<u>5⁺</u>	<u>1173</u>	<u>5⁺</u>	<u>1173</u>
<u>4⁺</u>	<u>1071</u>	<u>4⁺</u>	<u>1071</u>

New Lifetime Gives More Information on Bands

New lifetime of 4_{II}^+ state:

$\tau = 97(22) \text{ ps}$



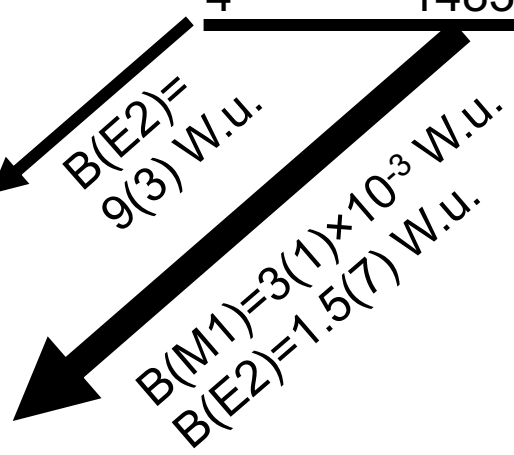
$K^\pi = 4_I^+$

<u>9⁺</u>	<u>1780</u>
8 ⁺	1600
7 ⁺	1438
<u>6⁺</u>	<u>1296</u>
5 ⁺	1173
<u>4⁺</u>	<u>1071</u>

$K^\pi = 4_{II}^+$

8 ⁺	1600
<u>5⁺</u>	<u>1582</u>
<u>4⁺</u>	<u>1483</u>

$\tau = 97(22) \text{ ps}$



New Lifetime Gives More Information on Bands

- Strong mixing would suggest significant difference in band-head deformations

$$K^\pi = 4_I^+$$

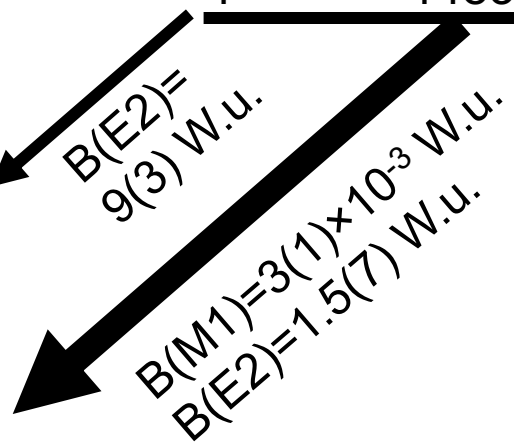
9 ⁺	1780
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8 ⁺	1600
7 ⁺	1438
6 ⁺	1296
5 ⁺	1173
4 ⁺	1071

$$K^\pi = 4_{II}^+$$

5 ⁺	1582
4 ⁺	1483

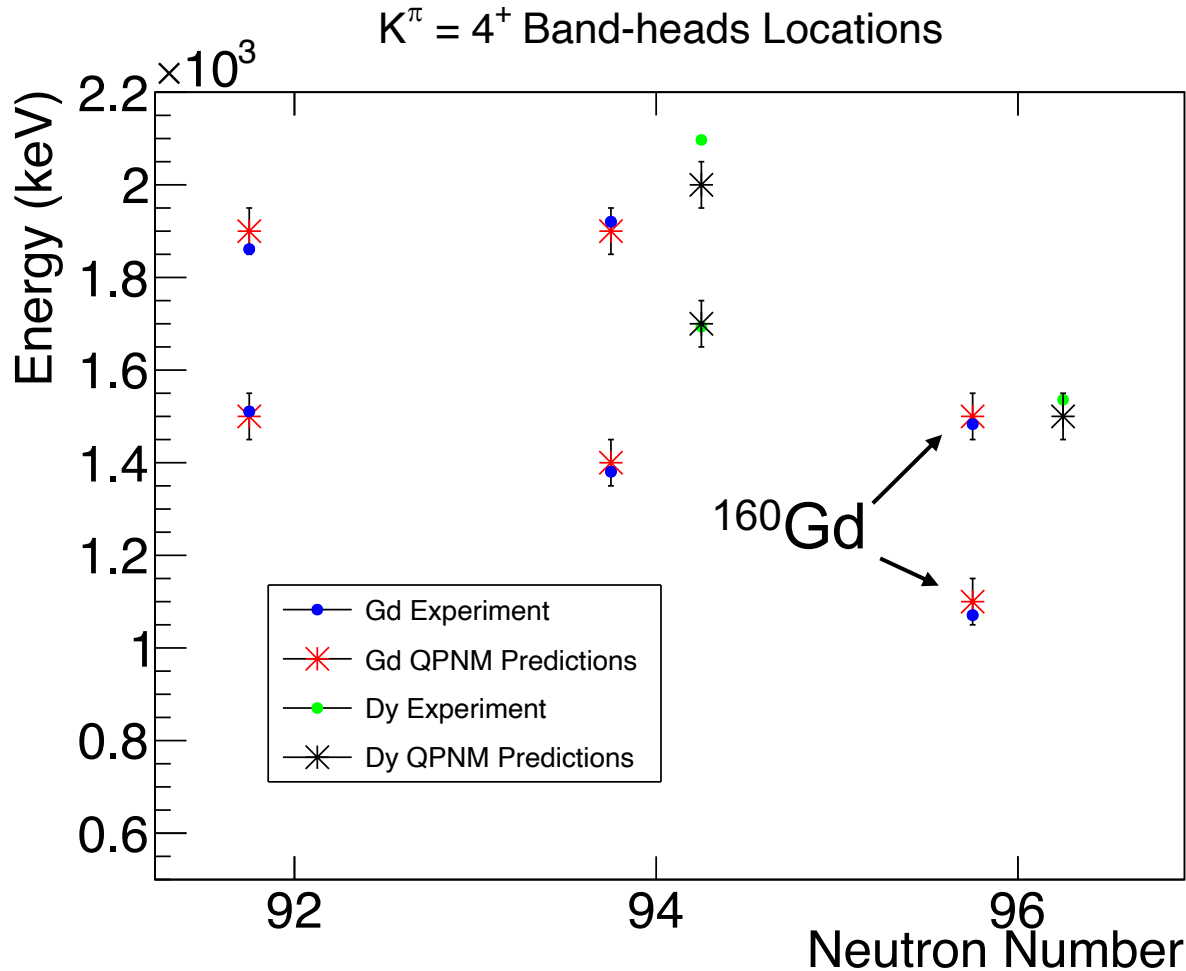
$\tau = 97(22)$ ps



$$\underbrace{|\langle 4_1^+ | E2 | 4_1^+ \rangle - \langle 4_2^+ | E2 | 4_2^+ \rangle|}_{\text{Unmixed quadrupole moments}} = 2 \cdot \underbrace{[(2 \cdot J_i + 1) \cdot B(E2; 4_{II}^+ \rightarrow 4_I^+)]^{\frac{1}{2}}}_{\text{Mixed transition rate}} = 53(12) \text{ efm}^2$$

$\rightarrow \Delta\beta = 25(6)\%$

Alternate Interpretations: Hexadecapole Phonons



- Quasiparticle phonon nuclear model (QPNM) calculations reproduce $K^\pi = 4^+$ band-head energies
- Dominant hexadecapole component creating admixture:
 - $\nu^2(5/2[523], 3/2[521])$
 - $\pi^2(5/2[413], 3/2[411])$

Experimental data from ENSDF.
 QPNM data from Soloviev *et al.*, *Int. Journal Mod. Physics E*, 06(03):437 (1997).

*Error bars on QPNM predictions are half of last digit given for energy levels (± 50 keV).

Conclusions

- Structure of ^{160}Gd measured via β -decay of $^{160}\text{Eu}^{\text{g,m}}$ at TRIUMF-ISAC using GRIFFIN
- Confirmed most levels and transitions
- New:
 - Excited states
 - Transitions
 - Lifetimes
 - Mixing ratios
- Proposed new configuration for ^{160}Eu and 1999 keV state in ^{160}Gd
- Data consistent with $K^\pi = 4^+$ band-heads as hexadecapole phonons

Thank you Merci

D. Yates^{1,2}, R. Krücken^{1,2}, I. Dillmann^{1,3},

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1 TRIUMF

2 UBC

3 UVic

4 Guelph

5 SFU

6 Reed College

7 Tennessee Tech

8 Surrey

9 Colorado Mines

10 Waterloo

11 Orsay

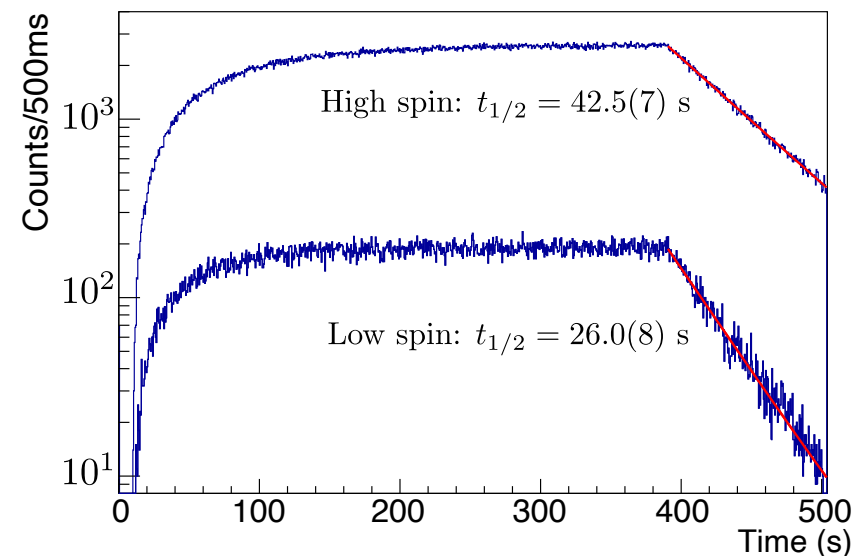
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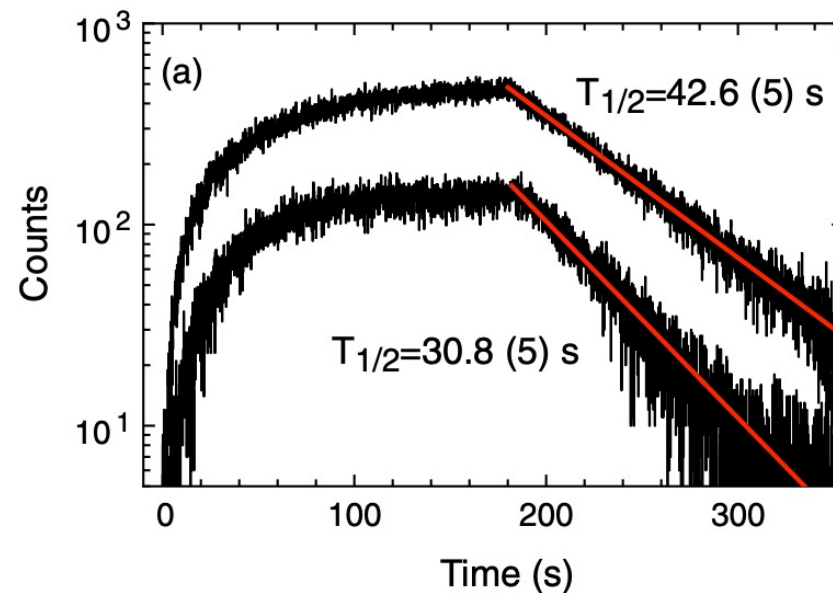
Backup Slides

β -decaying half-lives

- Confirmed half-life of high-spin β -decay
 - $t_{1/2} = 42.5(7)$ s
 - $t_{1/2,\text{lit}} = 42.6(5)$ s
- Different half-life of low-spin β -decay
 - $t_{1/2} = 26.0(8)$ s
 - $t_{1/2,\text{lit}} = 30.8(9)$ s



This work



D.J. Hartley *et al.*, *PRL*, 120:182502 (2018).

γ - γ Angular Correlations

- AC performed for two intense cascades

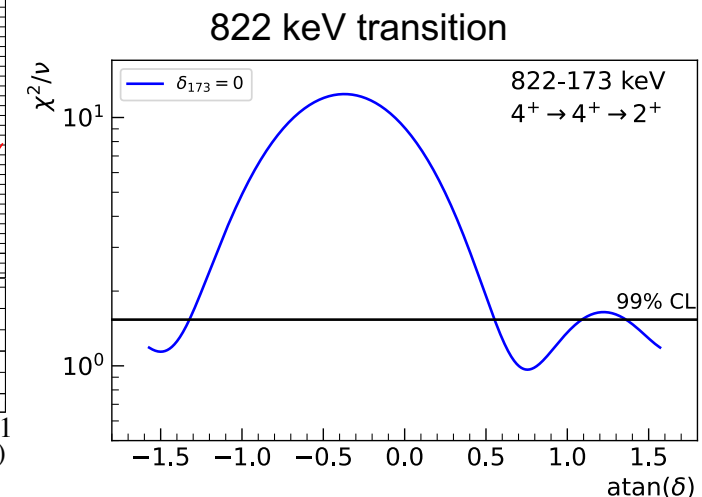
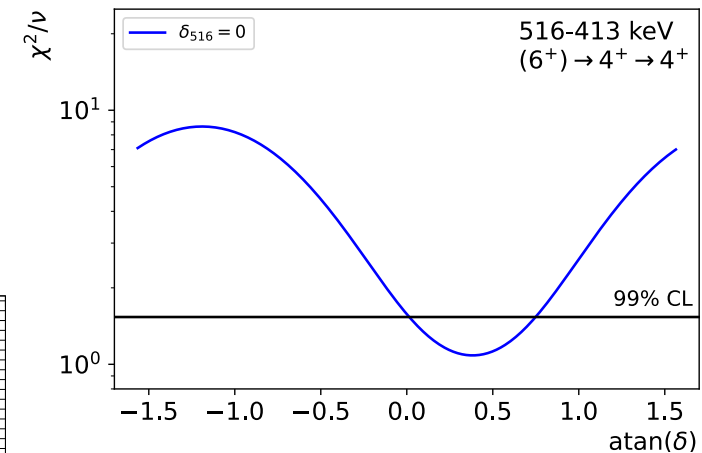
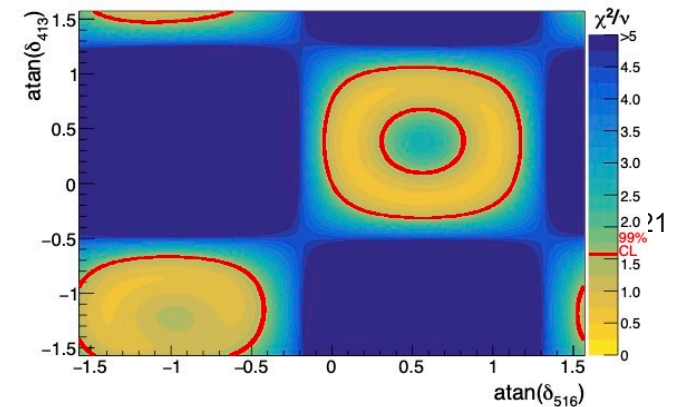
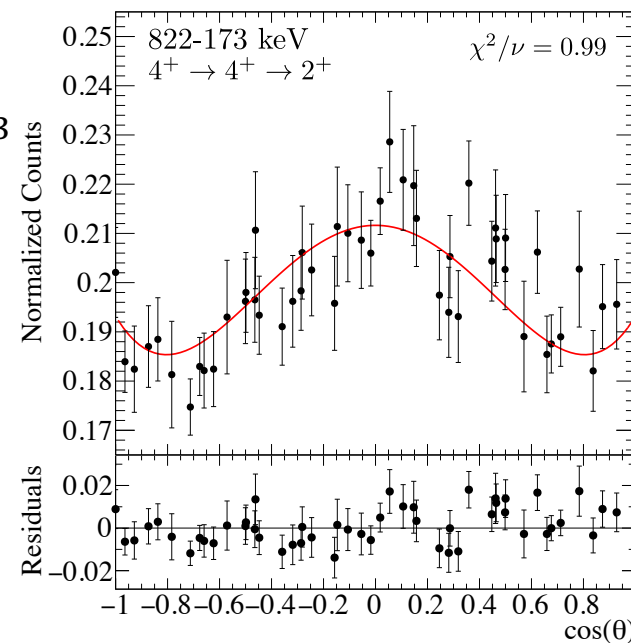
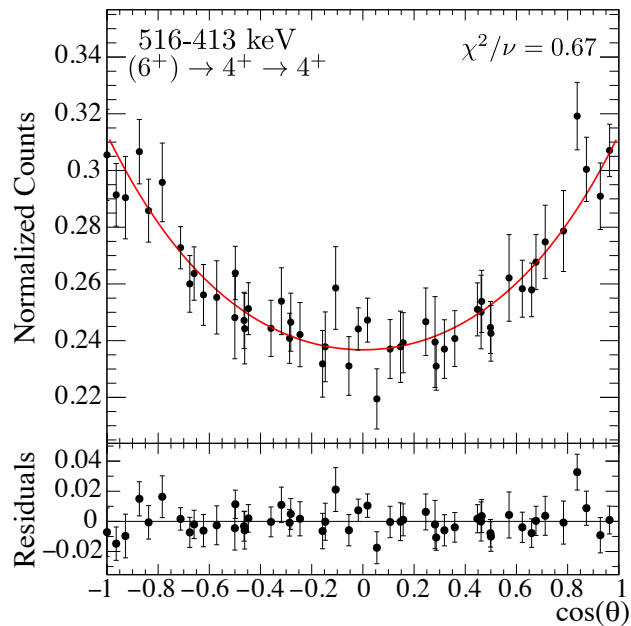
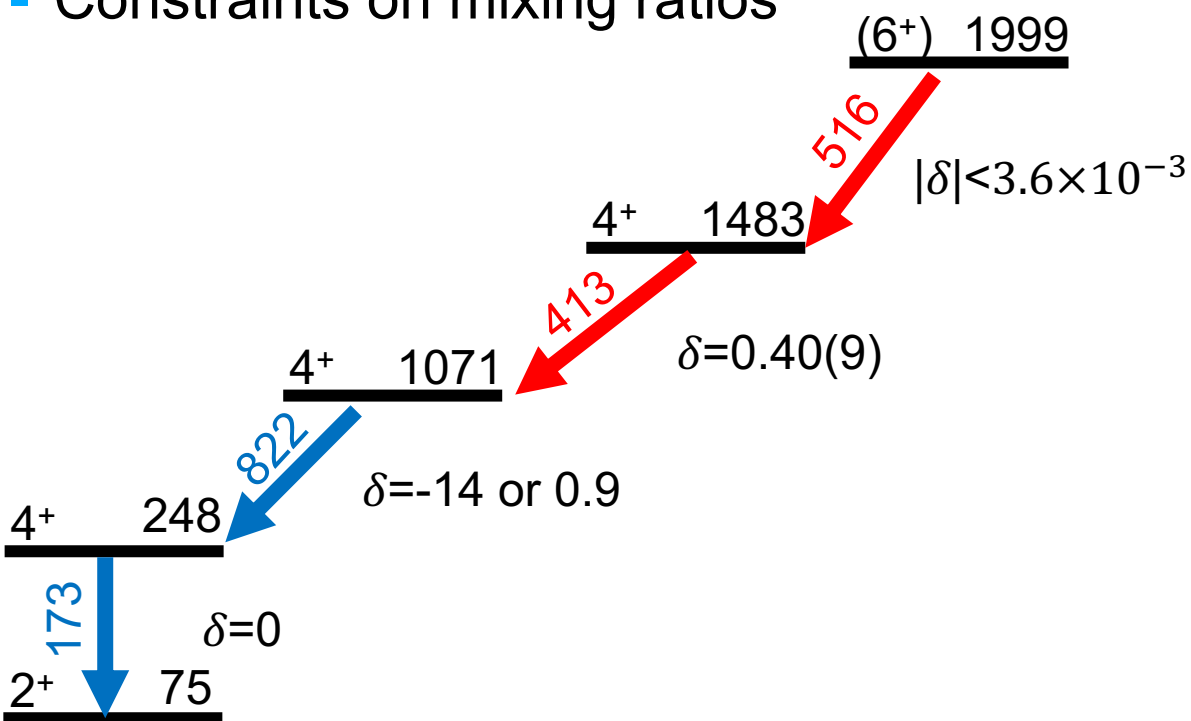
- 516-413 keV

- $(6^+) \rightarrow 4^+ \rightarrow 4^+$

- 822-173 keV

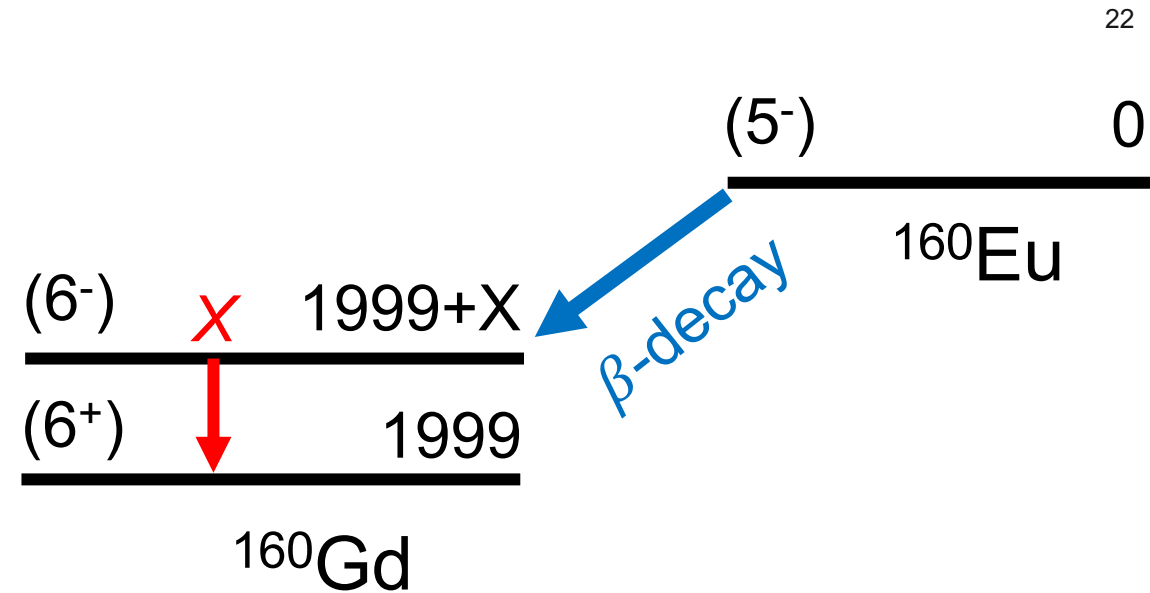
- $4^+ \rightarrow 4^+ \rightarrow 2^+$

- Constraints on mixing ratios



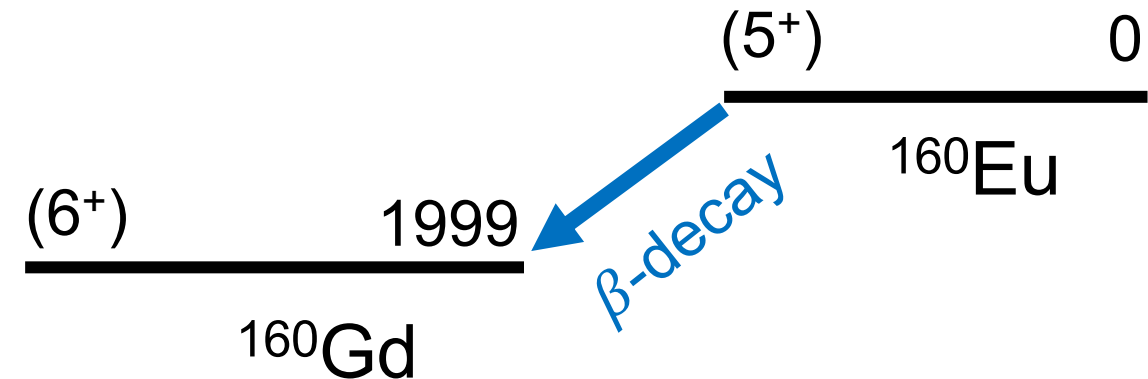
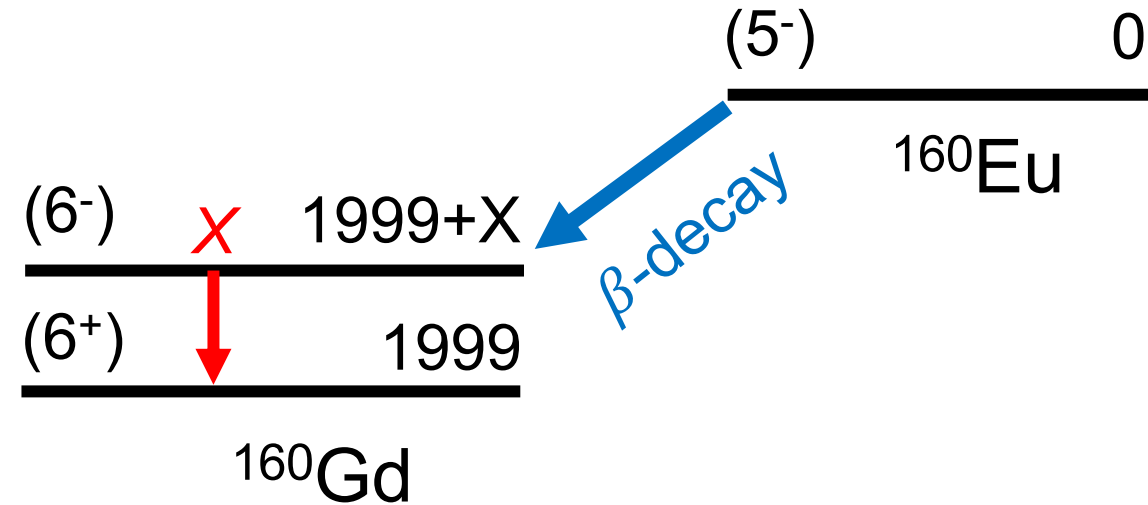
Spin of Parent ^{160}Eu Ground State?

- $\log(ft) \approx 5.0$ indicates allowed transition
- Option 1: Parent is 5^- , populates a 6^- state just above the 1999 keV state
 - Highly-converted $E1$ transition to 1999 keV state



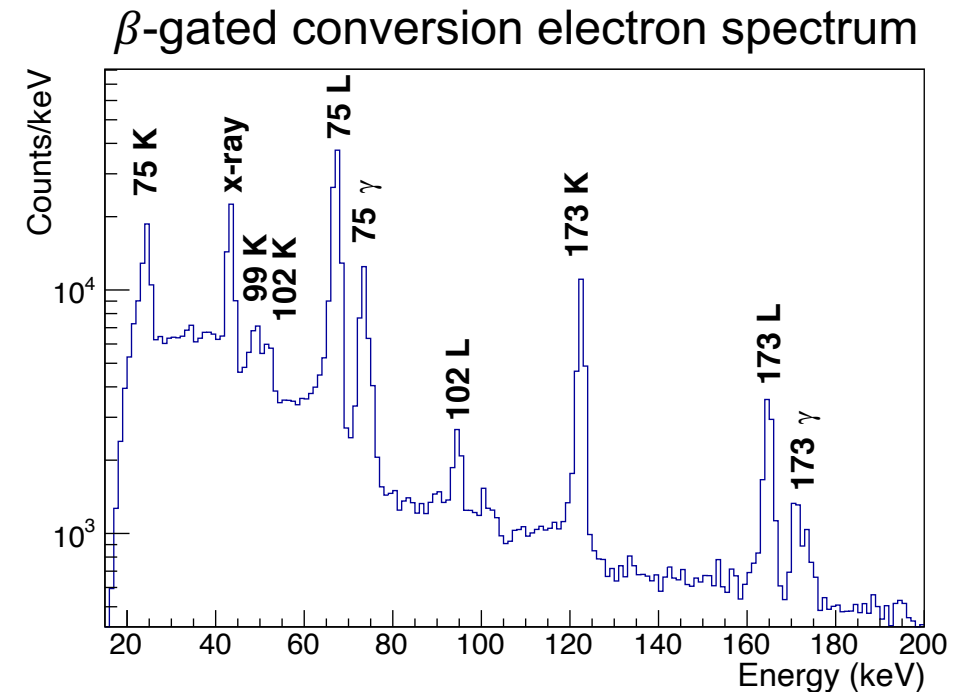
Spin of Parent ^{160}Eu Ground State?

- $\log(ft) \approx 5.0$ indicates allowed transition
- Option 1: Parent is 5^- , populates a 6^- state just above the 1999 keV state
 - Highly-converted $E1$ transition to 1999 keV state
 - **No evidence of this**
- Option 2: Parent is positive parity (likely 5^+) and decays directly to 1999 keV 5^+ state



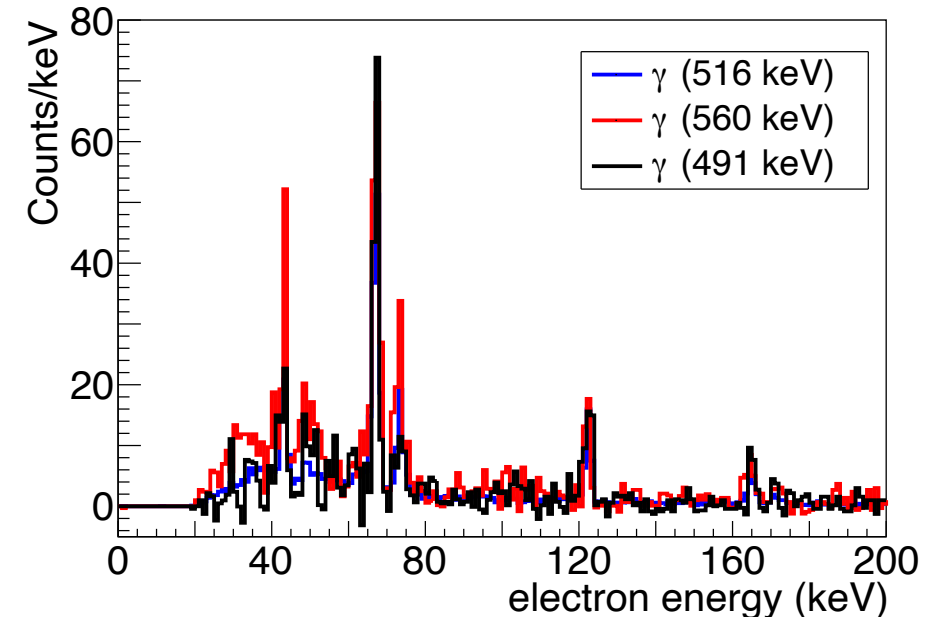
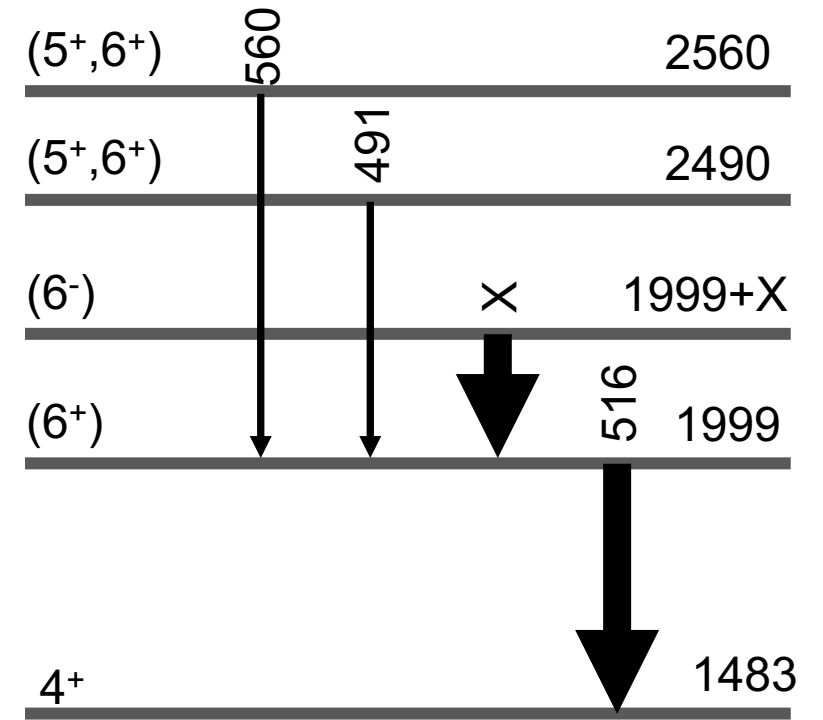
No Evidence for 6⁻ State

- $B(E1) \lesssim 10^{-2}$ W.u. requires $E_\gamma > 50$ keV
- No viable conversion electron observed
- No associated γ -ray
- Hidden under the 75 keV $2^+ \rightarrow 0_{gs}^+$ transition?
 - No excess intensity in 75 keV γ -ray

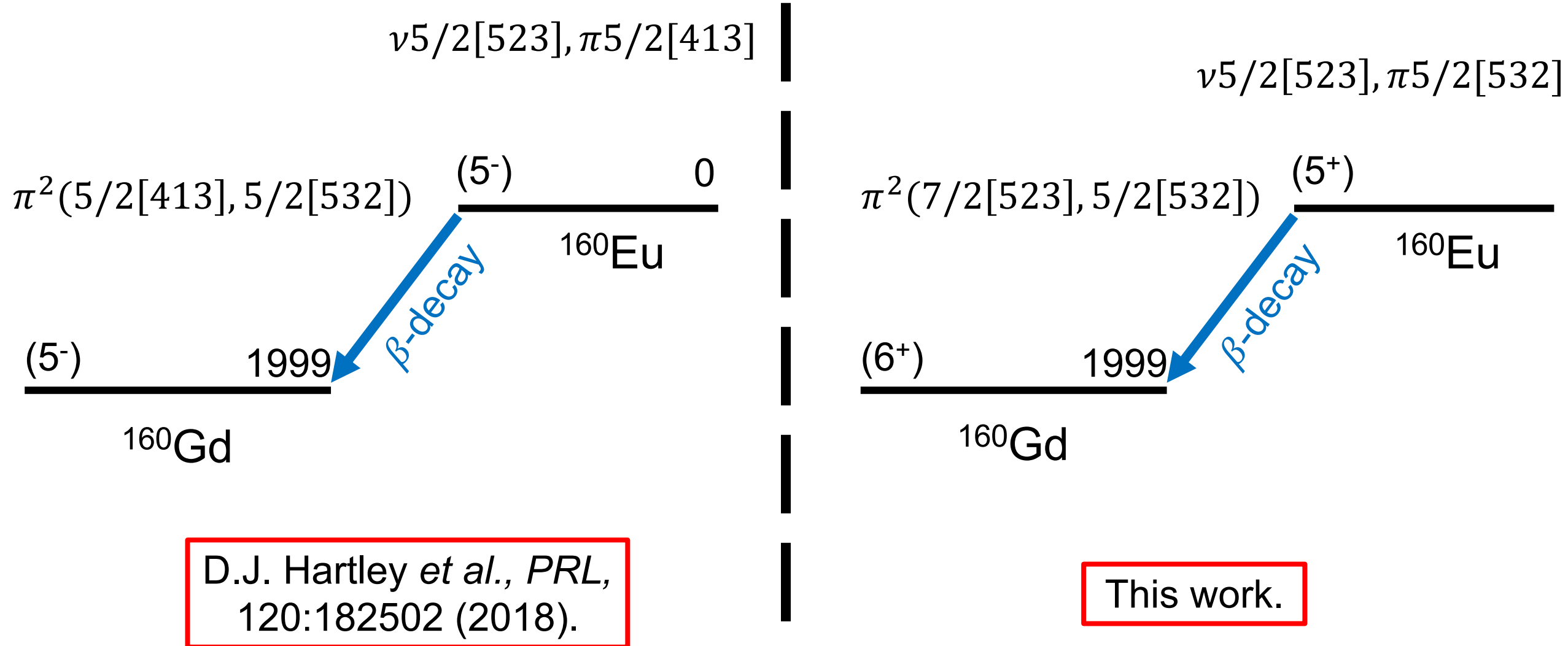


No Evidence for 6⁻ State

- Conversion electron peak from this hypothetical transition would appear in the 516 keV γ -ray gate and wouldn't in the 491 and 560 keV γ -ray gates
- No obvious peak

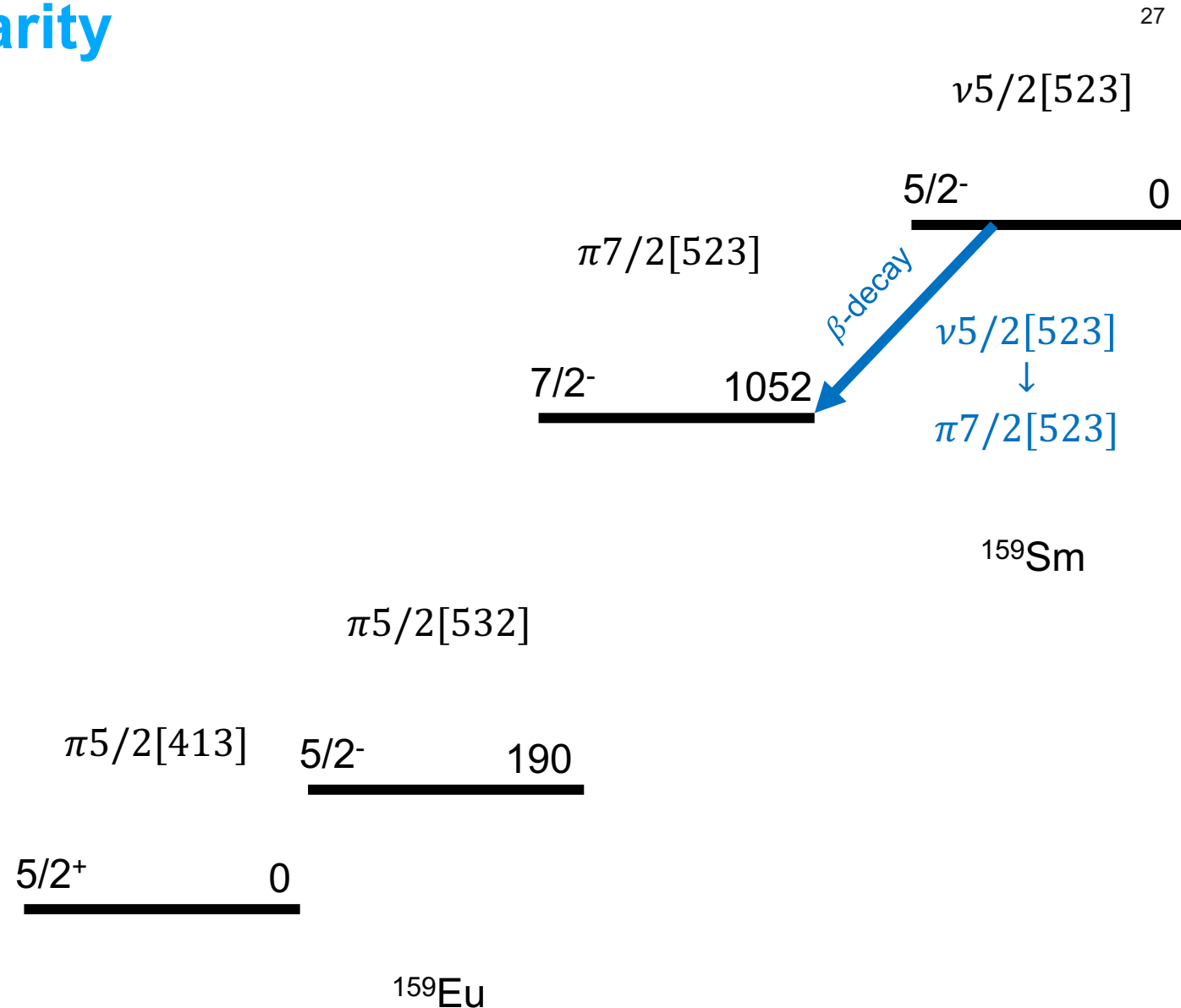


Two Quasiproton Configuration of 1999 keV State

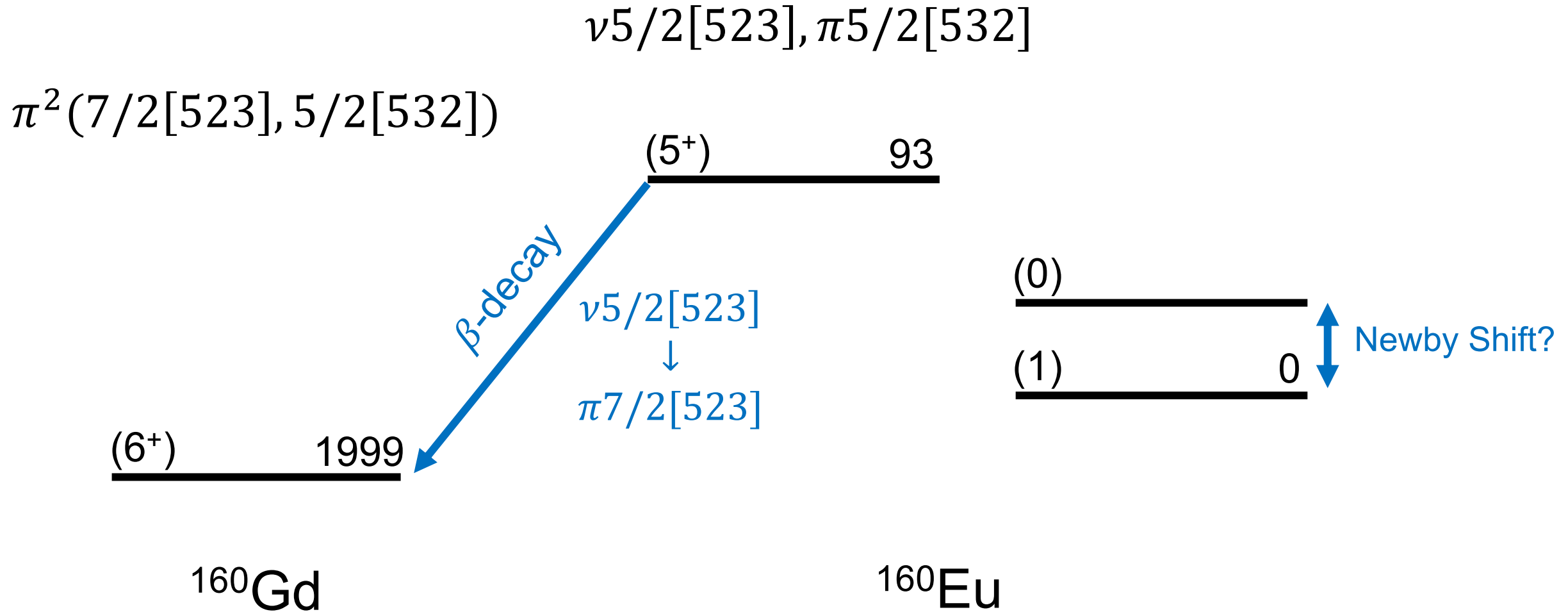


^{160}Eu Parent has Positive Parity

- What is Nilsson configuration?
- Look nearby to $^{159}\text{Sm}/^{159}\text{Eu}$

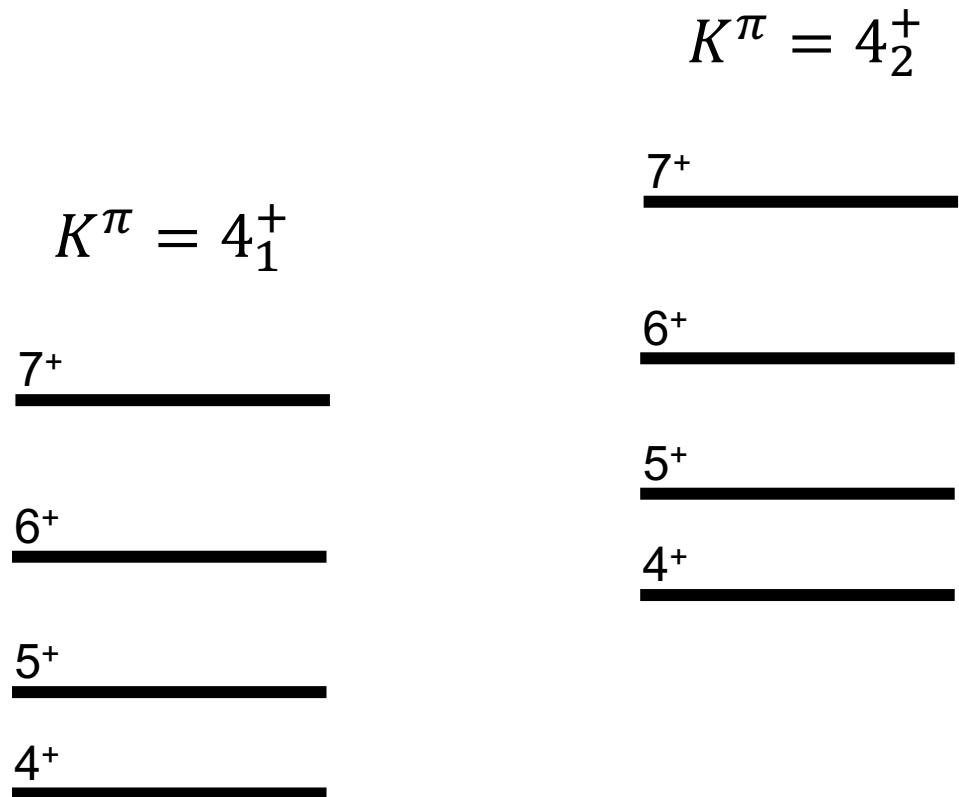


^{160}Eu Ground/isomeric States are Reversed

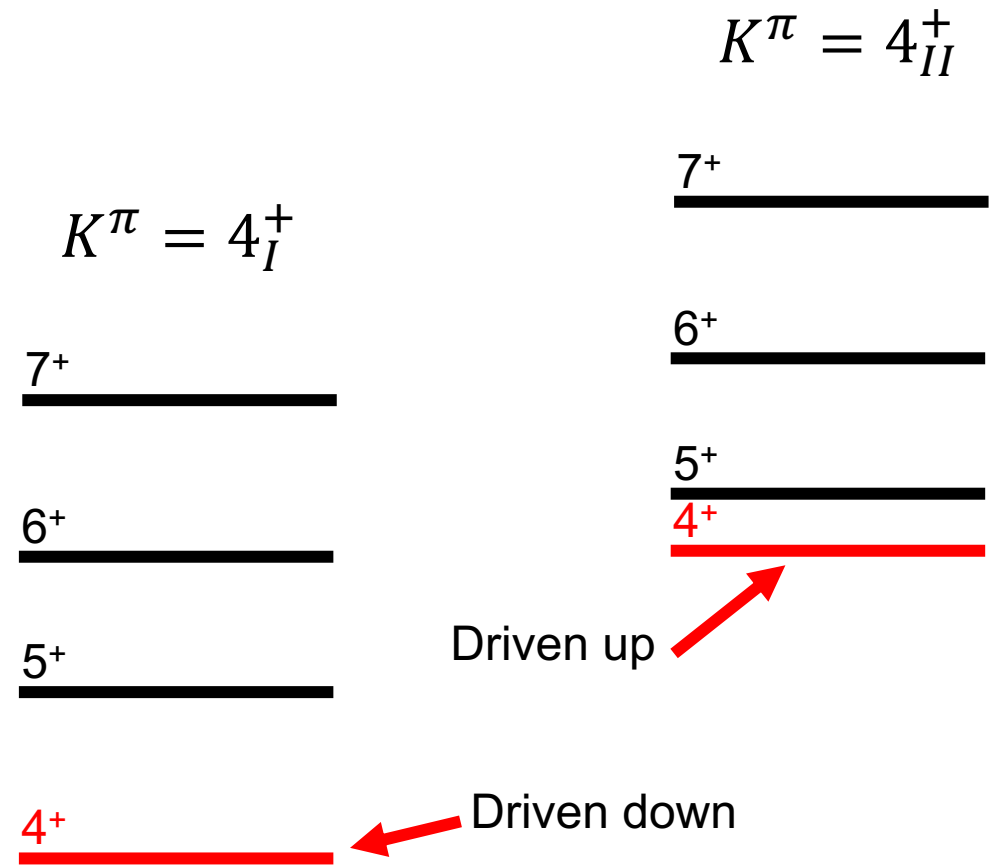


Expected Structure with Band-head mixing

Unmixed

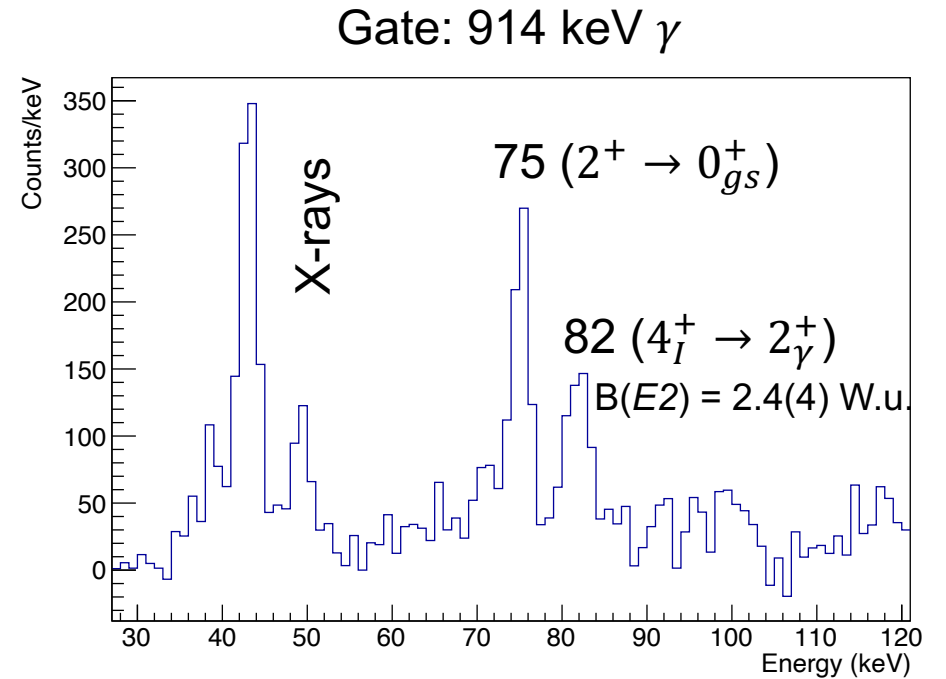


Mixed band-heads



Transitions Into γ -band Consistent with Hexadecapole Interpretation

- Expected to produce strong transitions into γ -band due to small double- γ component in the configuration



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