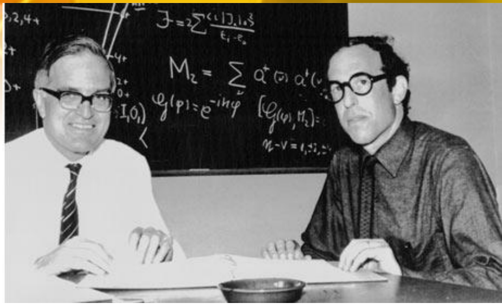
Low lying collective phenomena in N ~ 90 nuclei

University of Zululand
Siyabonga Majola

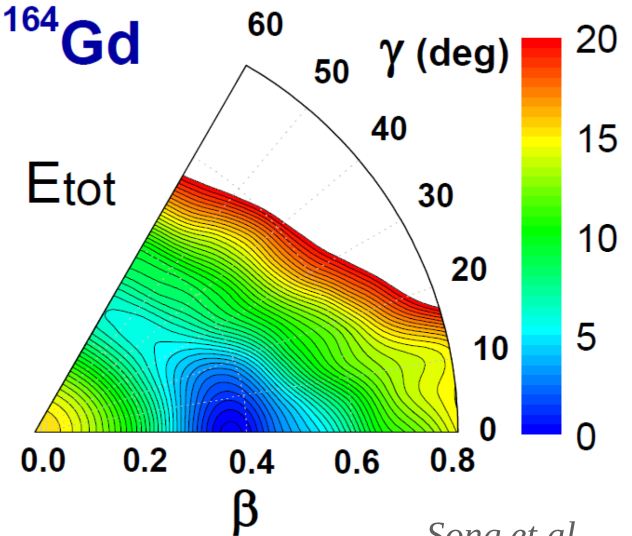
UniZulu 2019

Background and motivation
- Bohr Approach

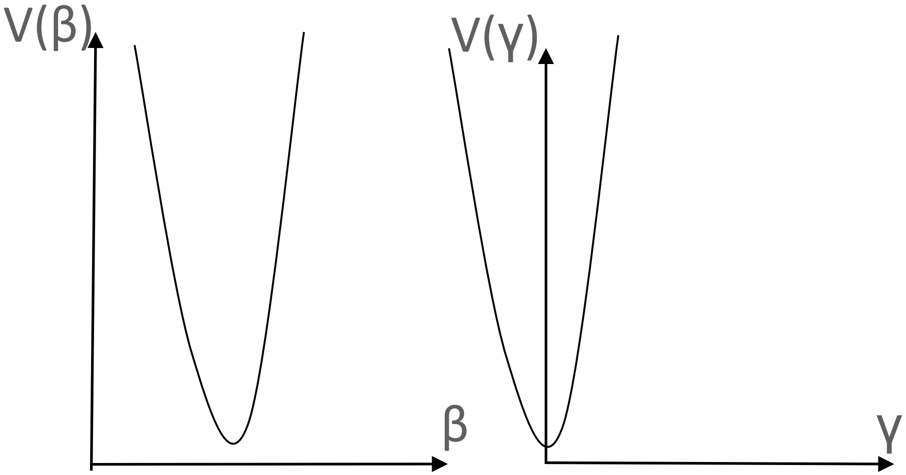
$$H = T_{vib} + T_{rot} + V(\beta,\gamma)$$



$$H = -\frac{\hbar^2}{2}\left[\frac{1}{B^2}\frac{\partial^2}{\partial\beta^2} + \frac{1}{B_\gamma}\frac{1}{\gamma}\frac{\partial}{\partial\gamma}\left(\gamma\frac{\partial}{\partial\gamma}\right)\right] + \frac{\hbar^2}{2\mathfrak{I}}\left(I(I+1)-K^2\right) + \frac{K^2\hbar^2}{2\mathfrak{I}_{z'}} + \frac{1}{2}C_\beta(\beta_2-\beta_0)^2 + \frac{1}{2}C_\gamma\gamma^2$$

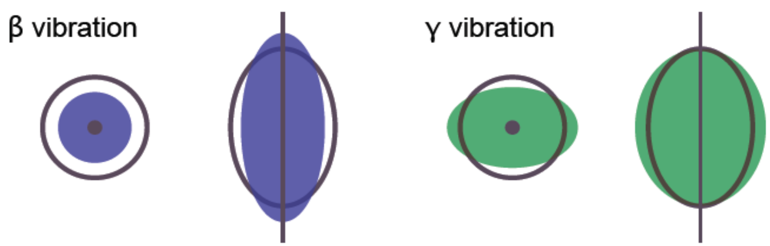


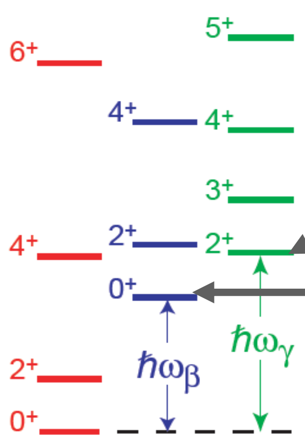
Song et al



Background and motivation
- Early success of the Bohr Approach

Early success of the Bohr in the Rare earth Region





First excited 2^+ state — K=2+

First excited 0^+ state — K=0+

Background and motivation
- 0+ bands do not ALL have the characteristics predicted for β-bands

Characterization of the β vibration and 0_2^+ states in deformed nuclei

P E Garrett

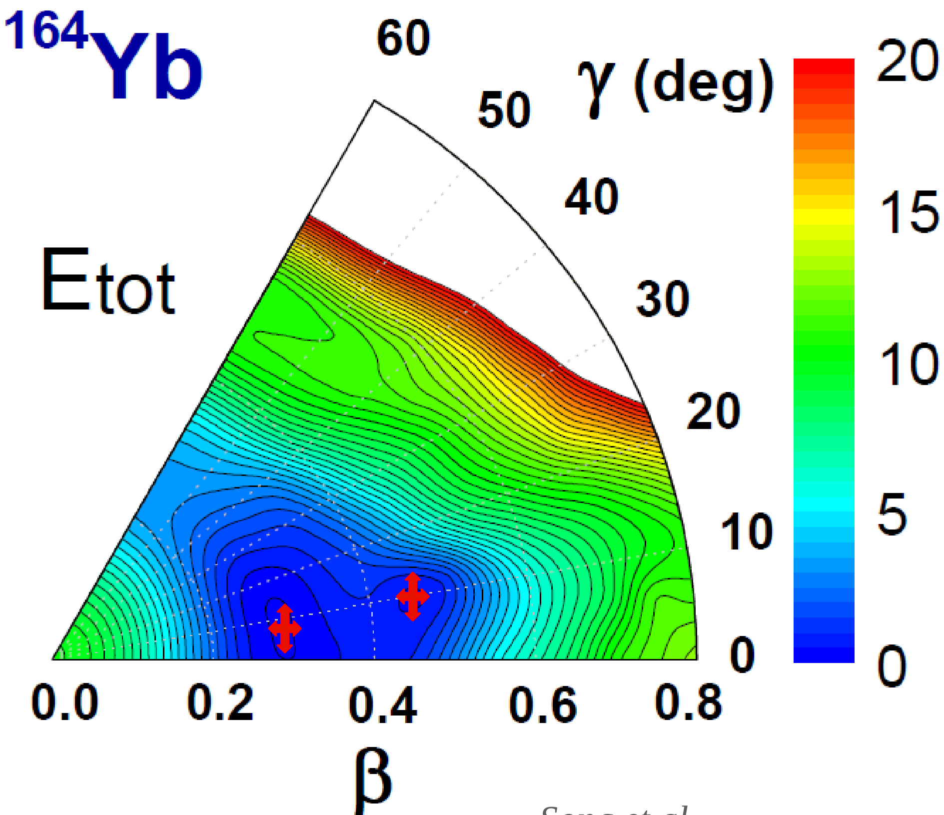
Lawrence Livermore National Laboratory, Livermore, CA 94551, USA

Received 26 October 2000, in final form 7 November 2000

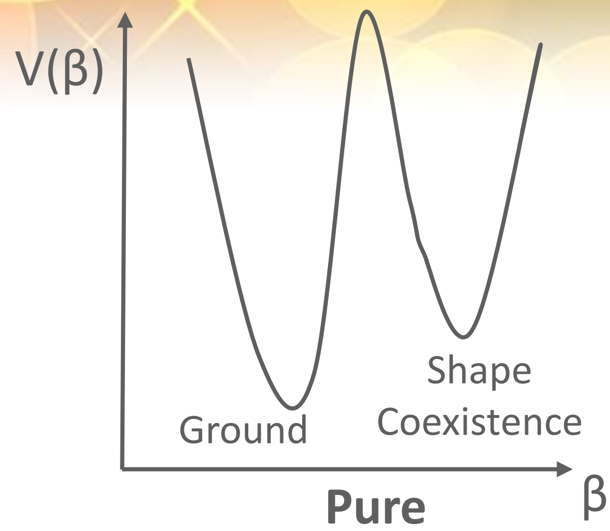
Abstract

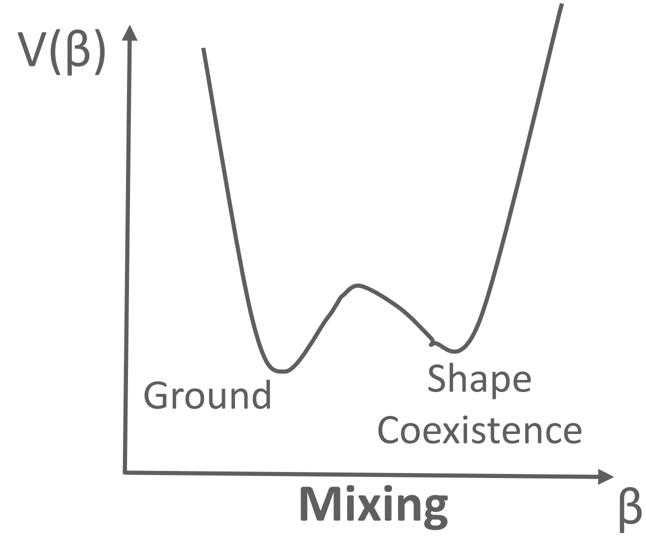
A summary of the experimental properties of the first excited 0^+ states in deformed rare-earth nuclei is presented. By appealing to the original definition of a β vibration laid down in the Bohr–Mottelson picture, it is re-emphasized that most of the 0_2^+ states are not β vibrations. A consideration of all available data, especially that from transfer reactions, and of microscopic calculations of 0^+ states underscores the need to consider the role of pairing in the description, and labelling, of these states.

Background and motivation
- Shape Coexistence



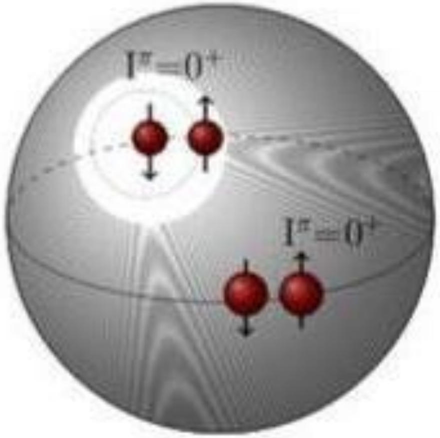
Song et al





Background and motivation
- Pairing

- Further confusion caused by pairing in the N=90, A ≈ 160
  - quadrupole pairing
- Give rise to 0^+ ground states in even-even



Monopole term

$$\Delta = \overbrace{G_0 \sum_{\upsilon'} U_{\upsilon'} V_{\upsilon'}}^{\text{Monopole term}}$$

Background and motivation
- Pairing

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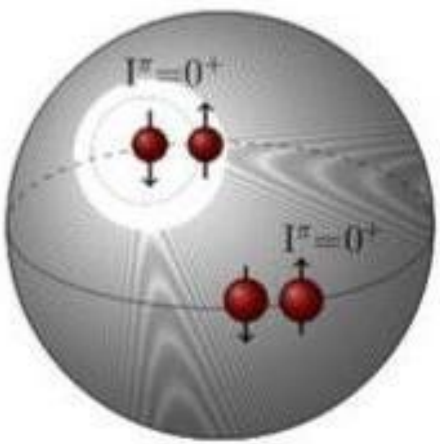
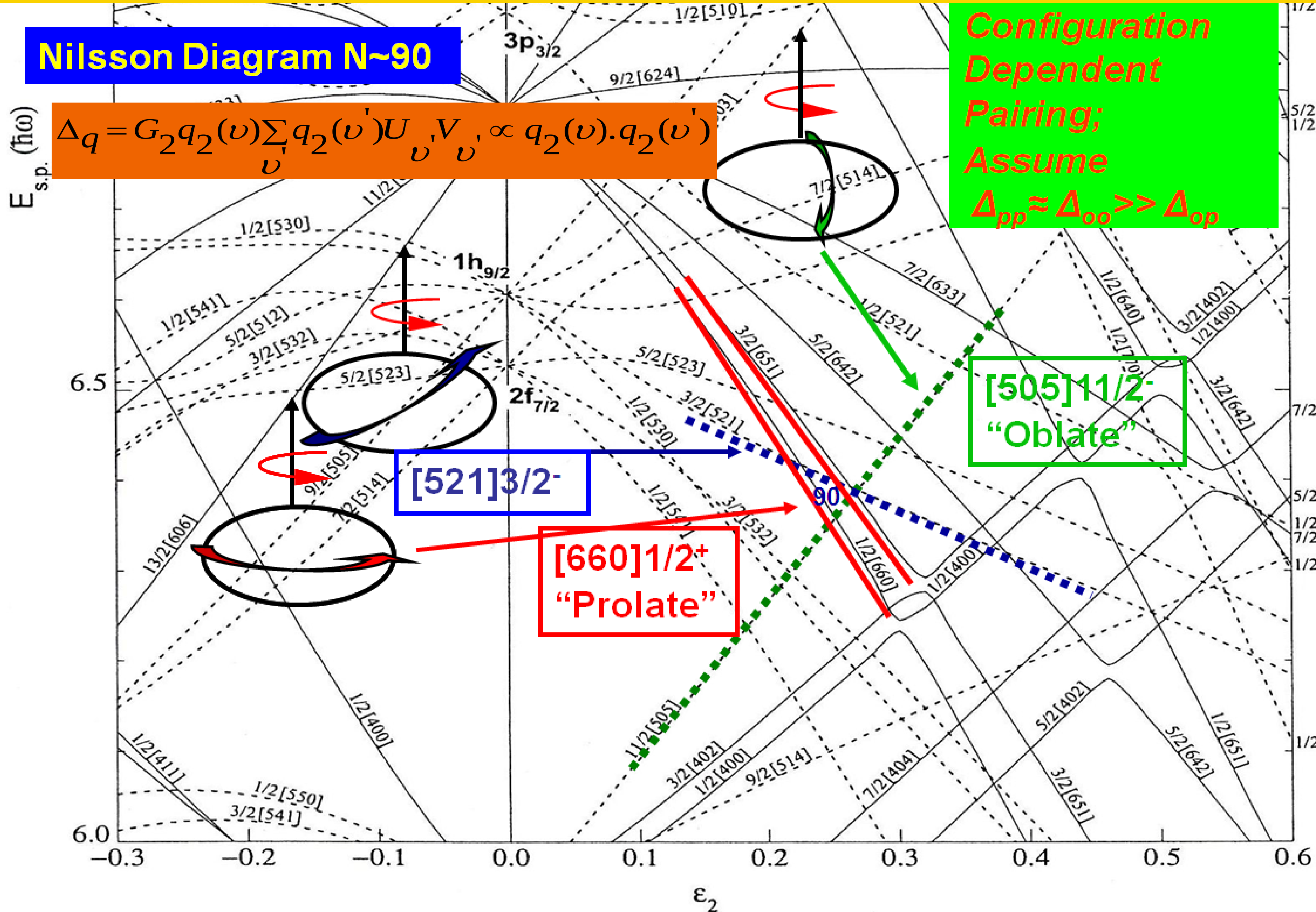


$$\Delta = \overbrace{G_0 \sum_{\upsilon'} U_{\upsilon'} V_{\upsilon'}}^{\text{Monopole term}} + \overbrace{G_2 q_2(\upsilon) \sum_{\upsilon'} q_2(\upsilon') U_{\upsilon'} V_{\upsilon'}}^{\text{Quadrupole term}}$$

Background and motivation

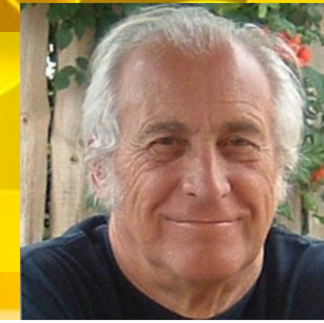


Background and motivation

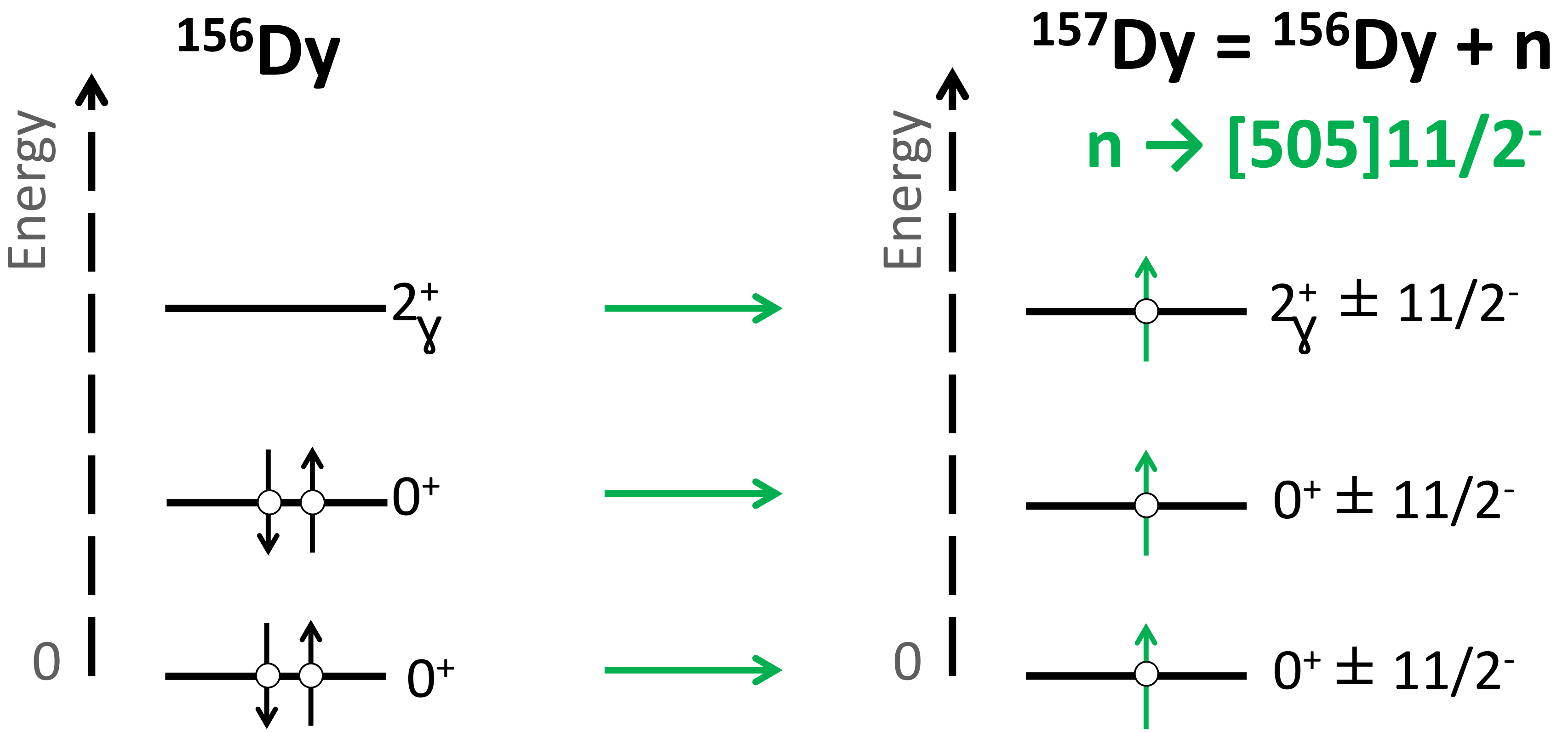
- Three modes of excitation, which could lead to a formation of a first-excited $K^{\pi} = 0^{+}$ bands.

- Are the first excited zero plus states **β, shape co-existence or Quadrupole pairing** bands (**Second vacuum bands**)??

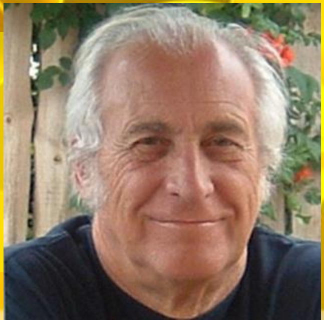
Background and motivation
- Quadrupole pairing Hypothesis test



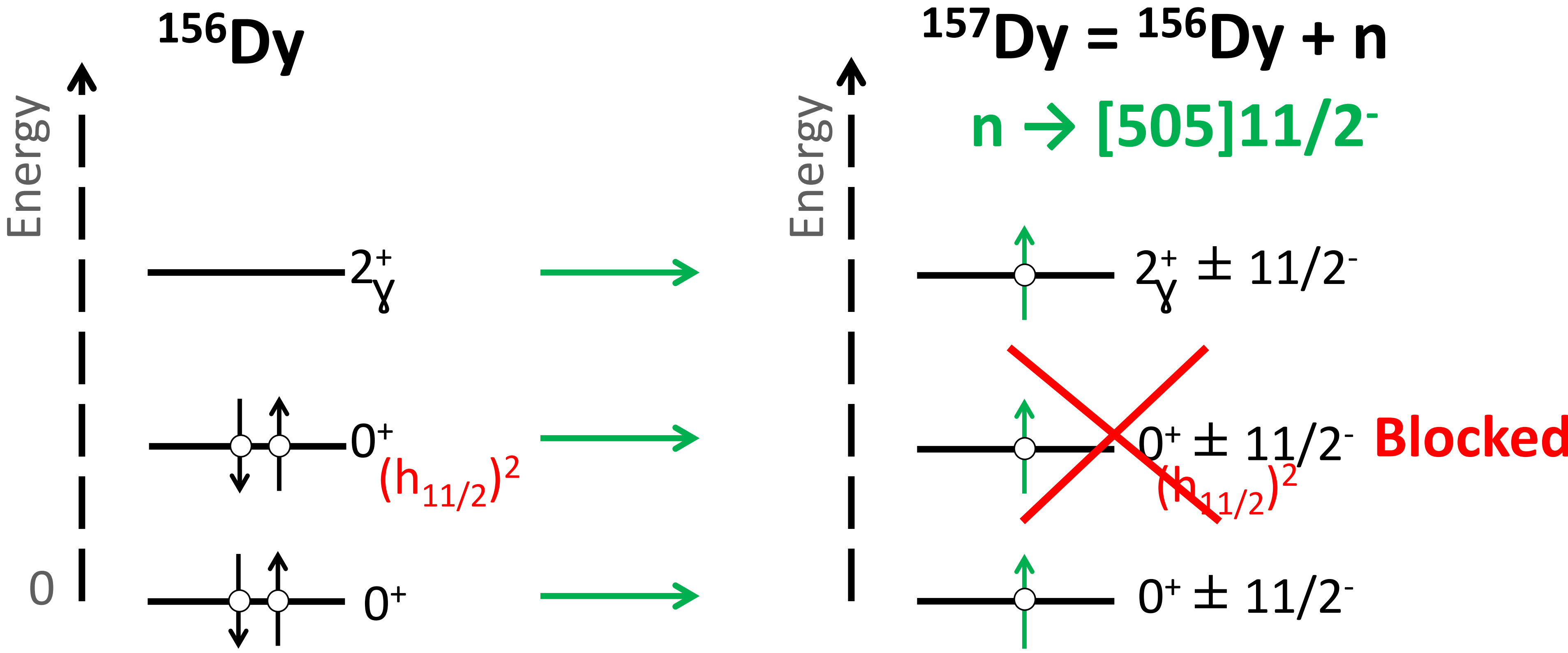
- To get a deeper insight, this study looks at the spectroscopy of ^{156}Dy and ^{157}Dy. The main objective is to observe the coupling of the $h_{11/2}[505]11/2^-$ neutron orbital in ^{157}Dy, to the first-excited $K^{\pi} = 0^+$ and $K^{\pi} = 2^+$ rotational bands of ^{156}Dy.



Hypothesis test

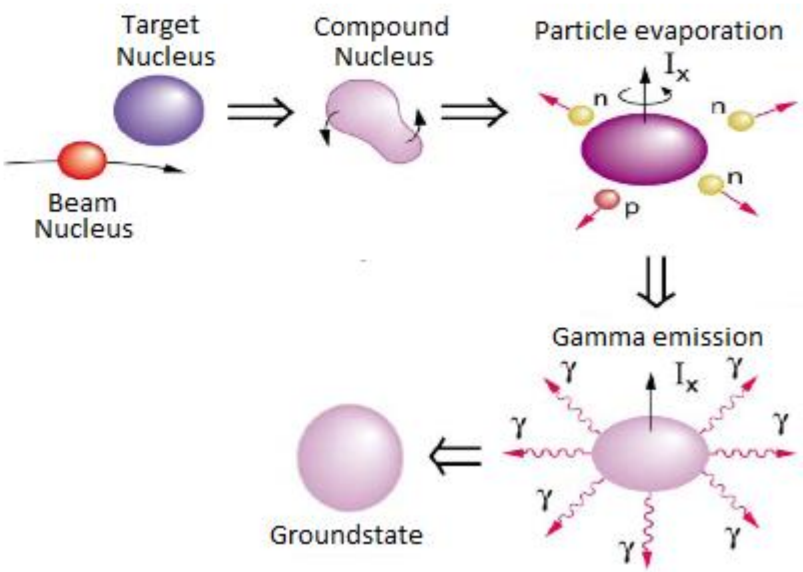


- if the first-excited $K^{\pi} = 0^{+}$ state band is comprised of essentially an $h_{11/2}$ pair of neutrons as called for by the quadrupole pairing hypothesis, then the band formed by the coupling of the $h_{11/2}$ neutron orbital to the first-excited $K^{\pi} = 0^{+}$ state will be absent or Pauli-blocked in ^{157}Dy, thus providing a yes or no test of the hypothesis.



Experimental Details

- $^{155}Gd(\alpha,2n)^{157}Dy$; 25 MeV ~(2-3 days)



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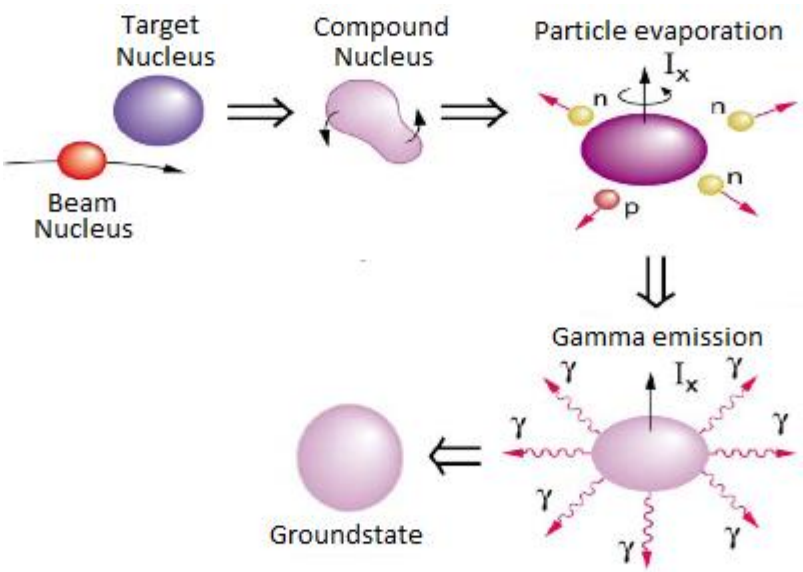
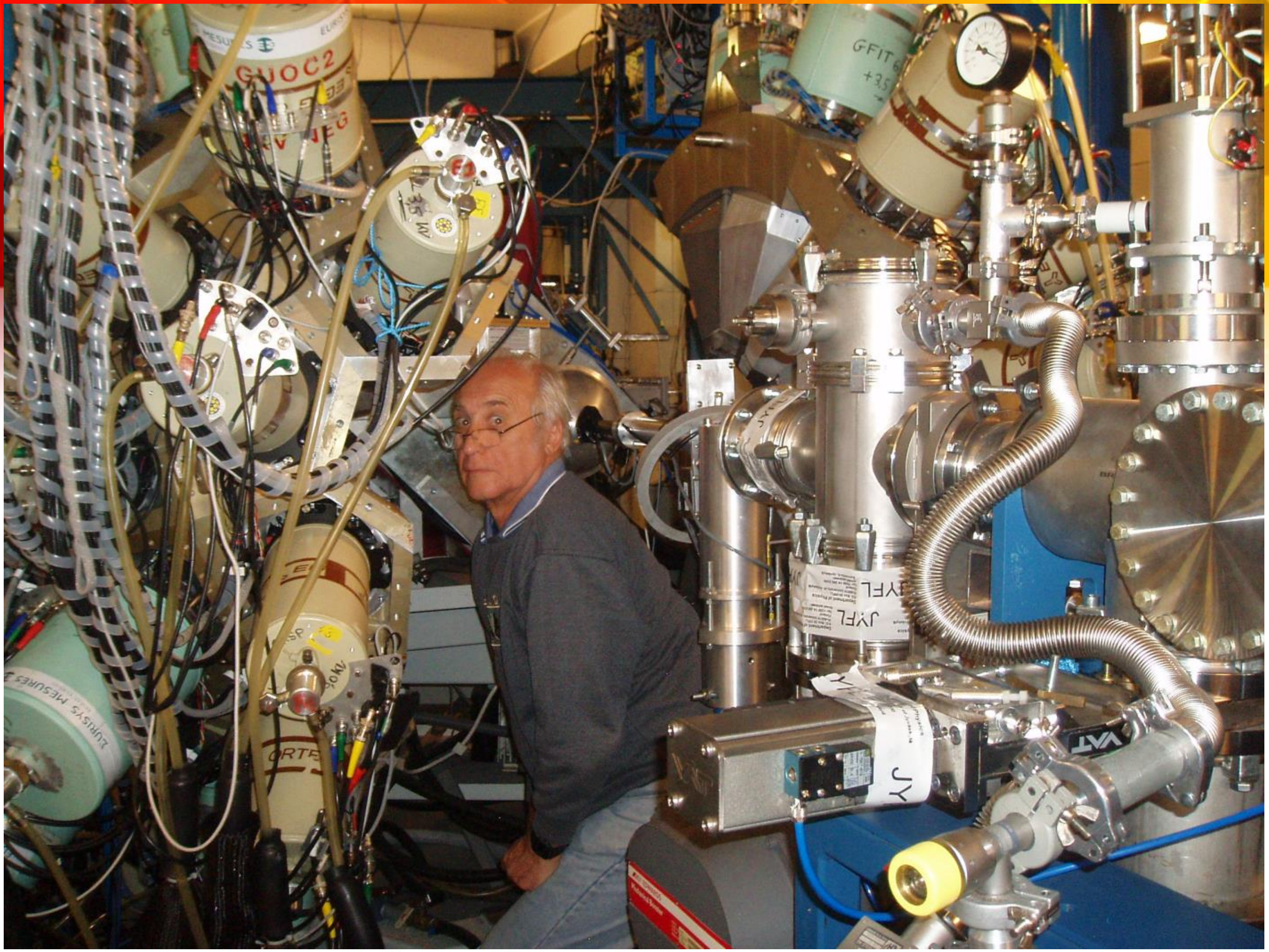


JUROGAM II ARRAY

Collaborators

Department of Physics
University of Jyväskylä, Finland


JYFL

Previous in-beam works

Hayakawa et al, Eur, Phys. J. A 15, 299-302 (2002)

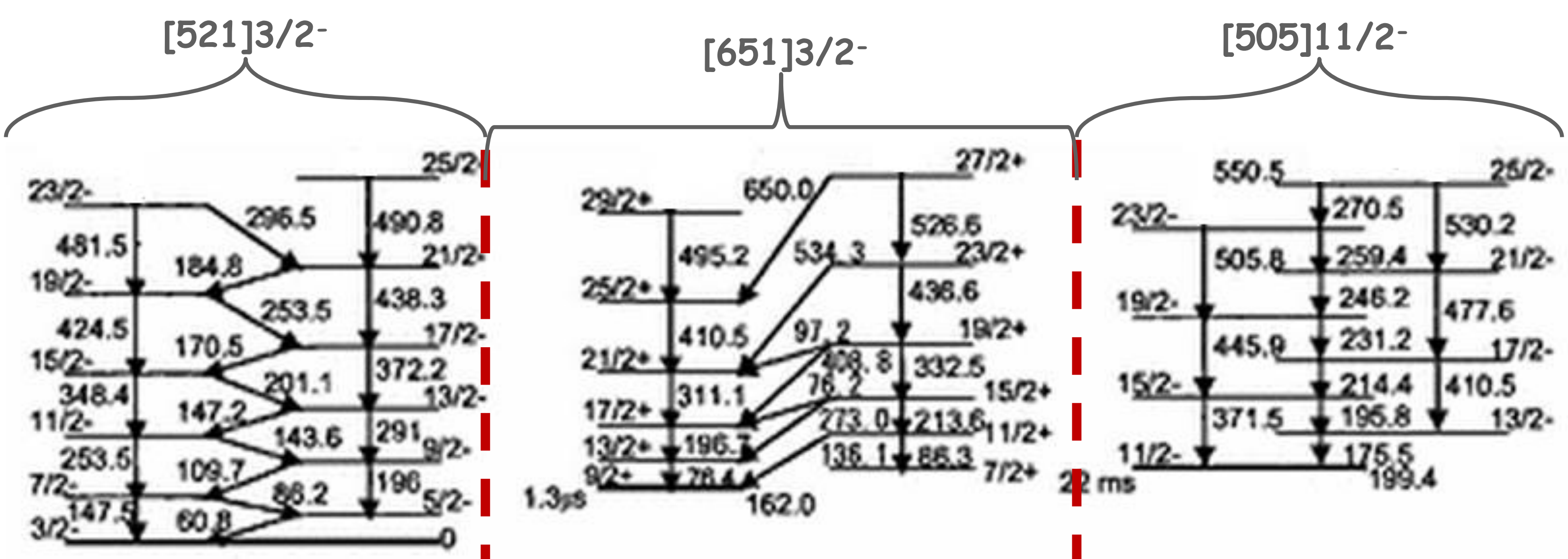
Eur. Phys. J. A 15, 299–302 (2002)
DOI 10.1140/epja/i2002-10082-0

THE EUROPEAN PHYSICAL JOURNAL A

Short Note

Rotational alignment of the $h_{11/2}$ band in ^{157}Dy

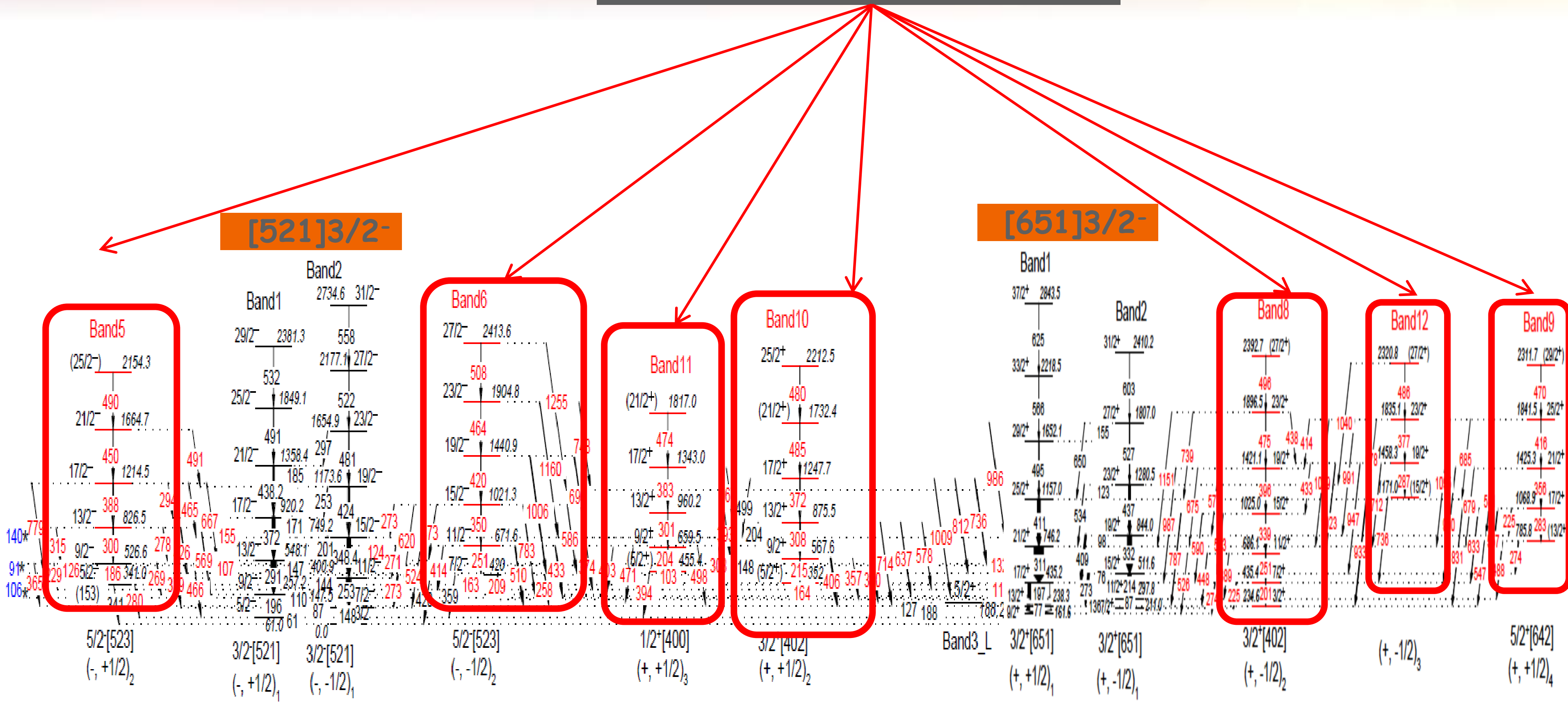
T. Hayakawa[1,a], Y. Toh[1], M. Oshima[1], M. Matsuda[1], Y. Hatsukawa[1], J. Katakura[1], H. Iimura[1], T. Shizuma[1], S. Mitarai[2], M. Sugawara[3], H. Kusakari[4], and Y.H. Zhang[5]



Results & Discussion

- New additions in ^{157}Dy

11 New Bands

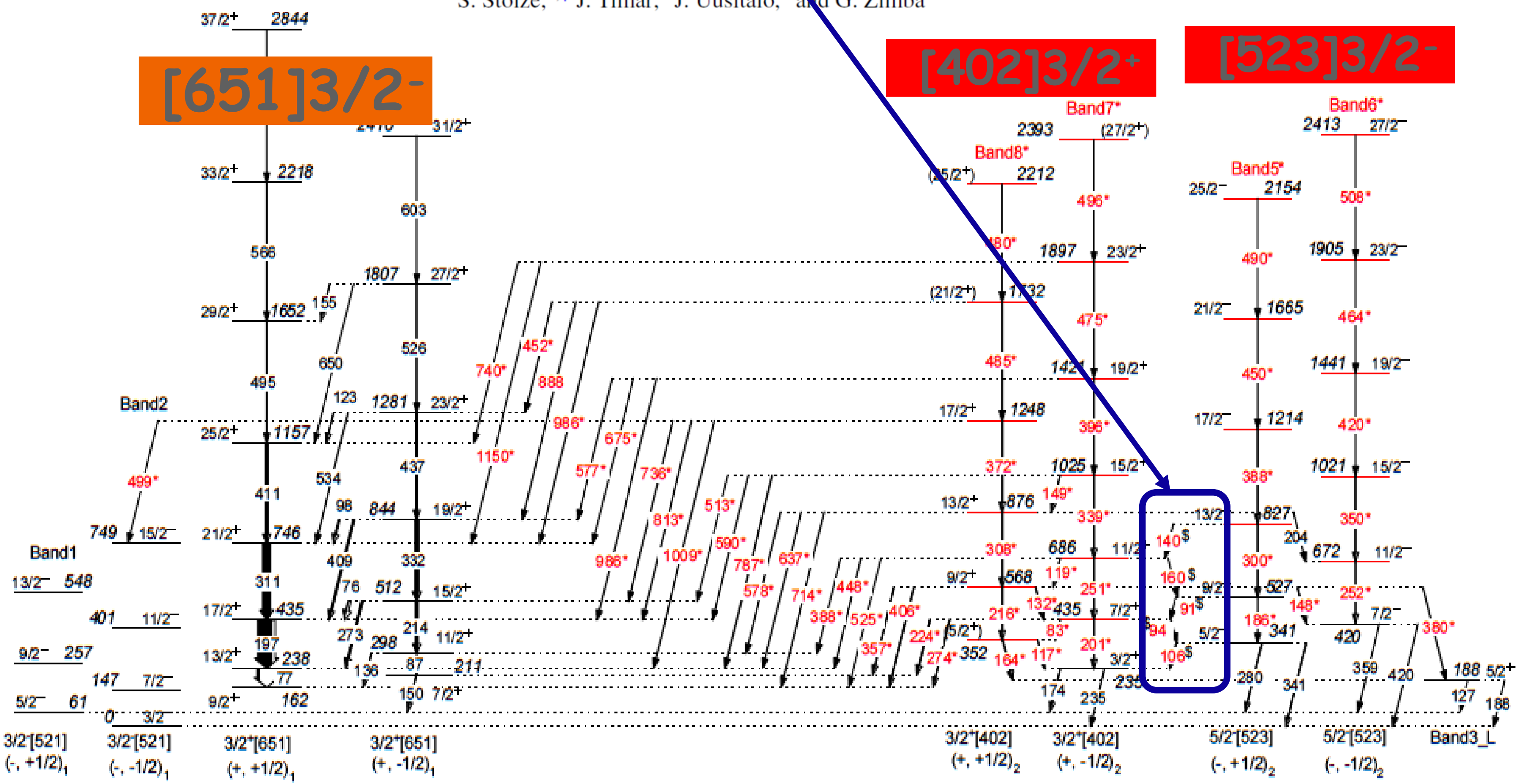


Results: New additions in ^{157}Dy

PHYSICAL REVIEW C **00**, 004300 (2019)

Spectroscopy of low-spin states in ^{157}Dy: Search for evidence of enhanced octupole correlations

S. N. T. Majola,[1,2,3,*] R. A. Bark,[3] L. Bianco,[12] T. D. Bucher,[3] S. P. Bvumbi,[2] D. M. Cullen,[4,7] P. E. Garrett,[12] P. T. Greenlees,[4] D. Hartley,[8] J. Hirvonen,[4] U. Jakobsson,[4] P. M. Jones,[3] R. Julin,[4] S. Juutinen,[4] S. Ketelhut,[4] B. V. Kheswa,[2,3] A. Korichi,[13] E. A. Lawrie,[3,5] P. L. Masiteng,[2] B. Maqabuka,[3] L. Mdletshe,[1,3] A. Minkova,[14] J. Ndayishimye,[3] P. Nieminen,[4] R. Newman,[3] B. M. Nyakó,[9] S. S. Ntshangase,[1] P. Peura,[4] P. Rahkila,[4] L. L. Riedinger,[10] M. Riley,[6] D. Roux,[11] P. Ruotsalainen,[4] J. Saren,[4] J. F. Sharpey-Schafer,[5] C. Scholey,[4] O. Shirinda,[3] A. Sithole,[1,5] J. Sorri,[4,†] S. Stolze,[4,‡] J. Timár,[9] J. Uusitalo,[4] and G. Zimba[2]



Results: New additions in ^{157}Dy

Eur. Phys. J. A (2011) 47: 6
DOI 10.1140/epja/i2011-11006-7

THE EUROPEAN PHYSICAL JOURNAL A

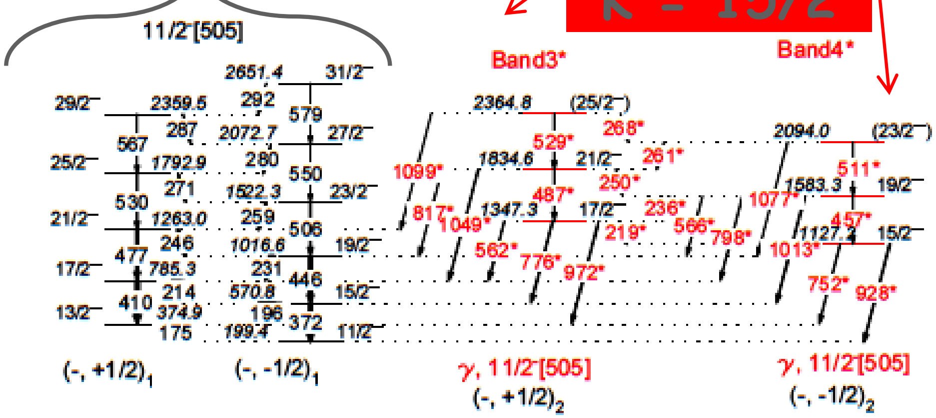
Letter

Blocking of coupling to the 0_2^+ excitation in ^{154}Gd by the [505]11/2$^-$ neutron in ^{155}Gd

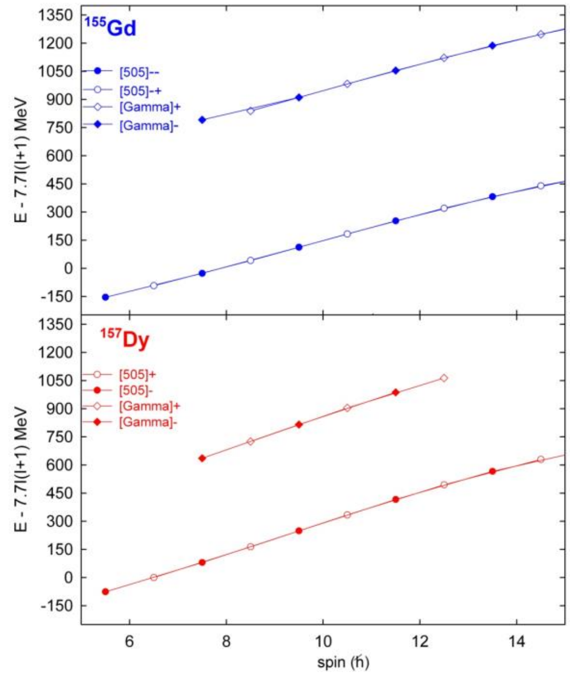
New Bands

[505]11/2$^-$

K = 15/2$^-$

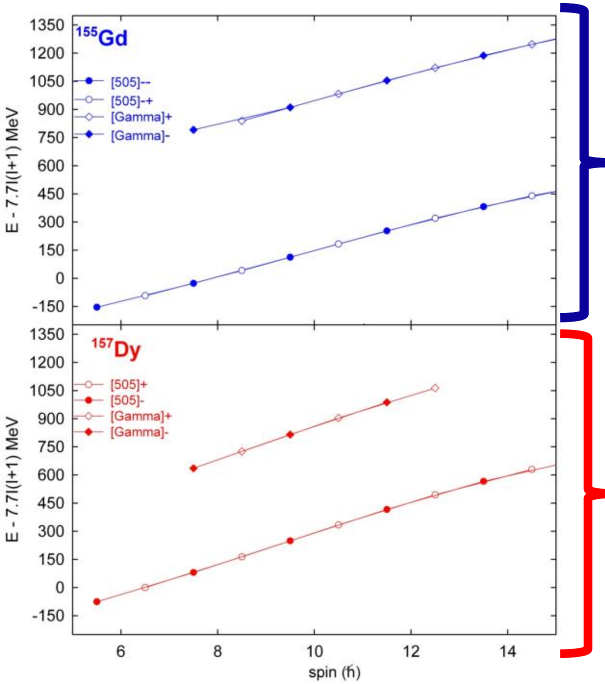


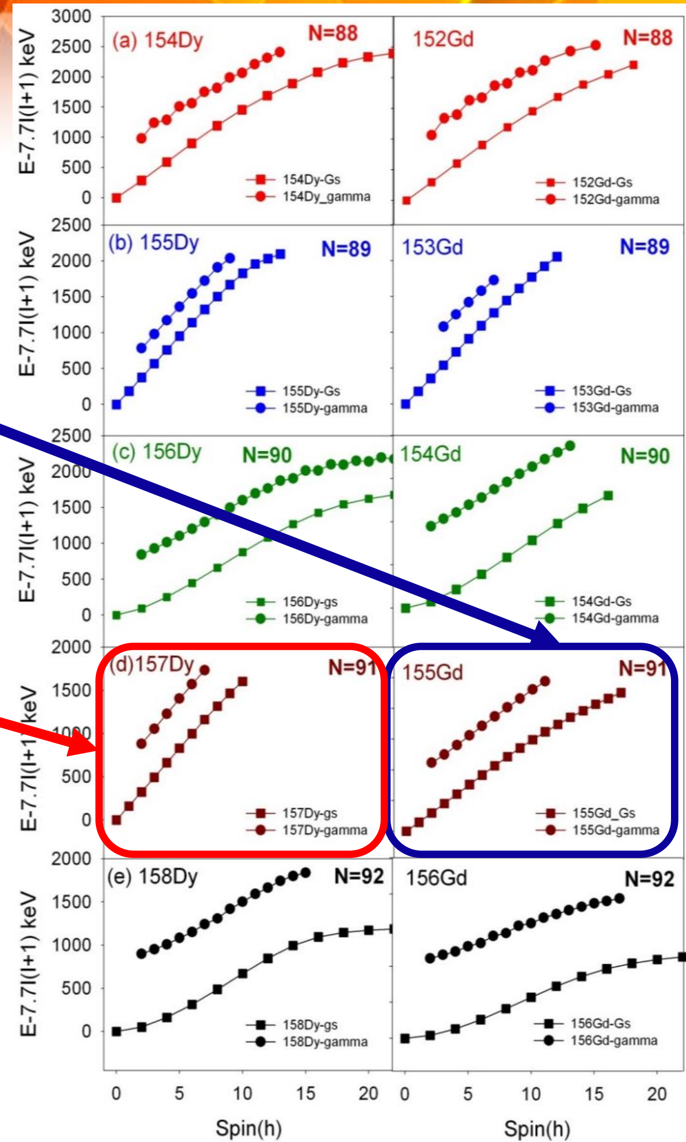
J. Sharpey-Schafer et al, Eur Phys G



Results: New additions in ^{157}Dy

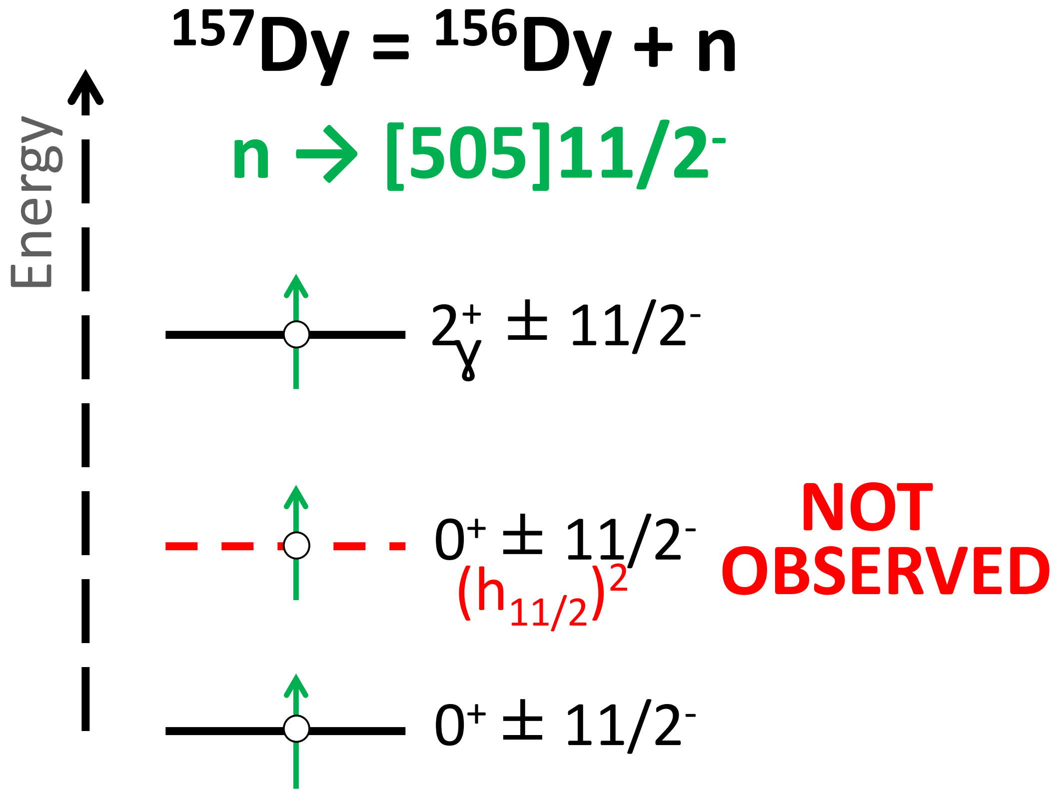
J. Sharpey-Schafer et al, Eur Phys G





Conclusion

- First γ-bands in the odd-even Dy isotope has been observed
- The Tracking of [505]11/2 by its own γ-bands demonstrates the nature of γ-bands
- No sign of β-band



End of part 1

Part 2

Systematics of β and γ bands in even-even N ≈ 90 nuclei

Background and motivation

-Studied by iThemba LABS

This study ranges from Sm to Yb isotopes, with neutron numbers from N = 88- 92

Z	152Yb	153Yb	154Yb	155Yb	156Yb	157Yb	158Yb	159Yb	160Yb	161Yb	162Yb	163Yb	164Yb	165Yb	166Yb	167Yb	168Yb
	151Tm	152Tm	153Tm	154Tm	155Tm	156Tm	157Tm	158Tm	159Tm	160Tm	161Tm	162Tm	163Tm	164Tm	165Tm	166Tm	167Tm
68	150Er	151Er	152Er	153Er	154Er	155Er	156Er	157Er	158Er	159Er	160Er	161Er	162Er	163Er	164Er	165Er	166Er
	149Ho	150Ho	151Ho	152Ho	153Ho	154Ho	155Ho	156Ho	157Ho	158Ho	159Ho	160Ho	161Ho	162Ho	163Ho	164Ho	165Ho
66	148Dy	149Dy	150Dy	151Dy	152Dy	153Dy	154Dy	155Dy	156Dy	157Dy	158Dy	159Dy	160Dy	161Dy	162Dy	163Dy	164Dy
	147Tb	148Tb	149Tb	150Tb	151Tb	152Tb	153Tb	154Tb	155Tb	156Tb	157Tb	158Tb	159Tb	160Tb	161Tb	162Tb	163Tb
64	146Gd	147Gd	148Gd	149Gd	150Gd	151Gd	152Gd	153Gd	154Gd	155Gd	156Gd	157Gd	158Gd	159Gd	160Gd	161Gd	162Gd
	145Eu	146Eu	147Eu	148Eu	149Eu	150Eu	151Eu	152Eu	153Eu	154Eu	155Eu	156Eu	157Eu	158Eu	159Eu	160Eu	161Eu
62	144Sm	145Sm	146Sm	147Sm	148Sm	149Sm	150Sm	151Sm	152Sm	153Sm	154Sm	155Sm	156Sm	157Sm	158Sm	159Sm	160Sm
	82		84		86		88		90		92		94		96		N

15 experiments performed to study 12 nuclei

Nucleus (N)	Reaction(s)	Beam energy (MeV)	Target thickness	Statistics events	Spectrometer(s)
^{150}Sm (88)	136Xe(^{18}O,4n), 148Nd(α,2n)	75, 25	~ 5 mg/cm2 5 mg/cm2	0.5 × 10^9 γγ 2 × 10^{10} γγγ	Afrodite, Jurogam II
$_{152}$Gd (88)	^{152}Sm (α,4n)	45	5mg/cm^2	0.5 × 10^9 γγ	Afrodite
$_{154}$Dy (88)	^{155}Gd(α,4n)	37.5	3.2 mg/cm^2	0.4 × 10^9 γγ	Afrodite
^{156}Er (88)	^{147}Sm(^{12}C,3n)	65	6 mg/cm^2	1.4 × 10^9 γγ	Afrodite
^{158}Yb (88)	^{144}Sm(^{18}O,4n)	78	3 mg/cm^2	2.0 × 10^9 γγ	Afrodite
^{154}Gd (90)	^{152}Sm(α,2n)	25	4 mg/cm^2	0.5 × 10^9 γγ	Afrodite
^{156}Dy (90)	^{155}Gd(α,3n), ^{148}Nd(^{12}C,4n)	25, 65	0.98 mg/cm2 1.53 mg/cm^2	1.4x10^9 γγ, 2.0 × 10^9 γγγ	Jurogam II, Gammasphere
^{158}Er (90)	^{150}Sm(12C,4n)	65	1 mg/cm^2	4.2 × 10^8 γγ	Afrodite
^{160}Yb (90)	^{147}Sm(16O,3n)	73	4 mg/cm^2	2.0 × 10^9 γγ	Afrodite
^{158}Dy (92)	^{156}Gd(α,2n), ^{155}Gd(α,n)	27, 25	11 mg/cm^2, 0.98 mg/cm^2	1.1 × 10^9 γγ, 1.4x10^9 γγ	Afrodite, Jurogam II
^{160}Er (92)	^{152}Sm(12C,4n)	64	5 mg/cm^2	2.7 × 10^9 γγ	Afrodite

$^{148}Nd(^{12}C,4n)^{156}Dy$, Gammasphere

Siyabonga Majola, Darryl Hartley, Lee Riedinger

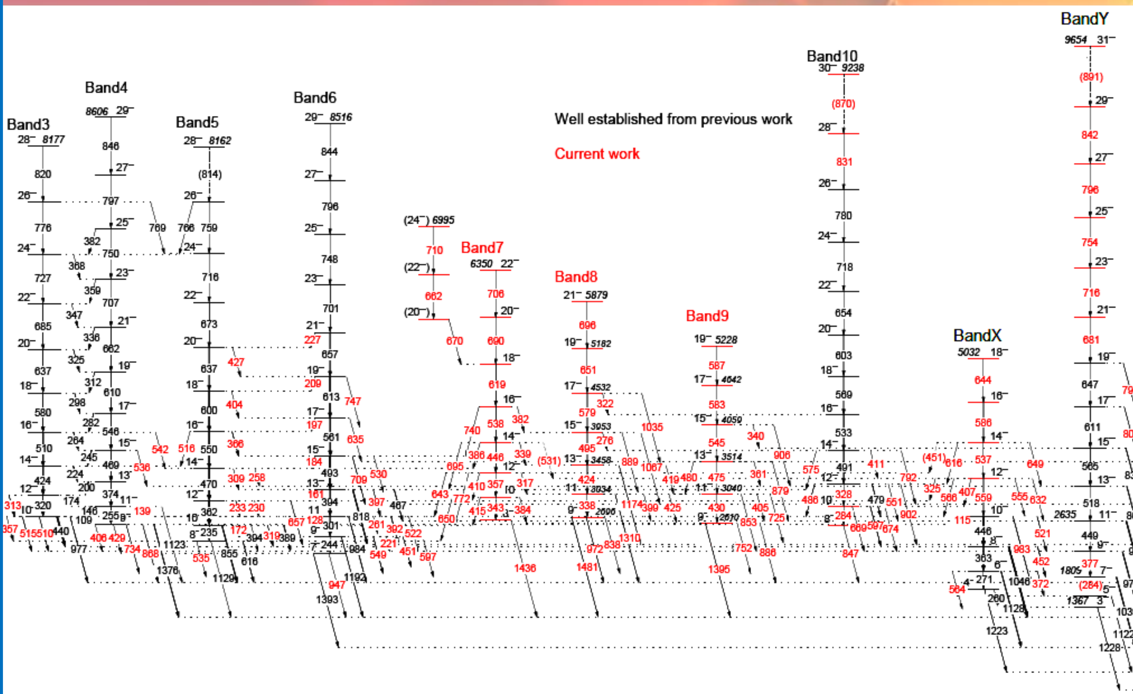


Figure 4.6: Partial level scheme of the negative parity bands deduced on this work for the nucleus of interest. Levels and transitions colored in red repre[…] new findings from this work. On the other hand, everything colored in black indicate findings from previous studies.

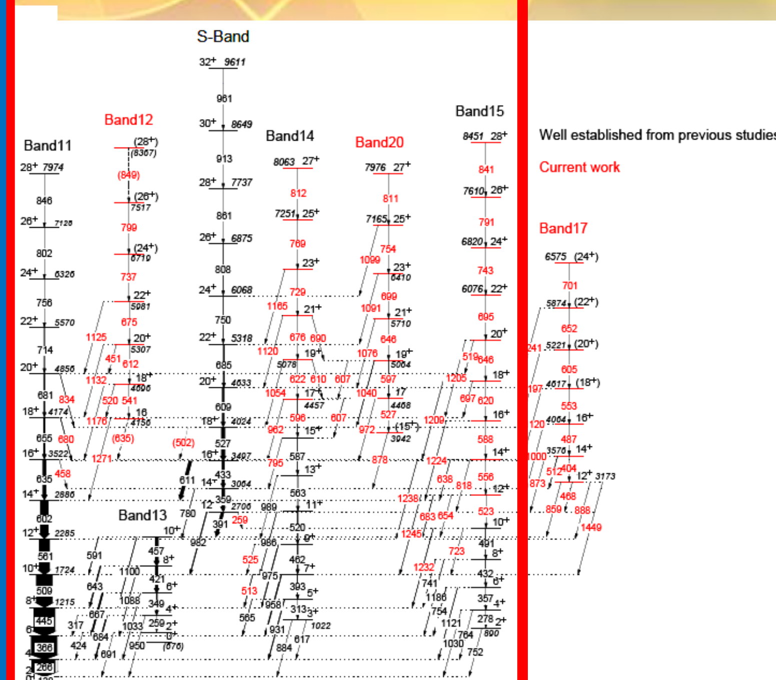
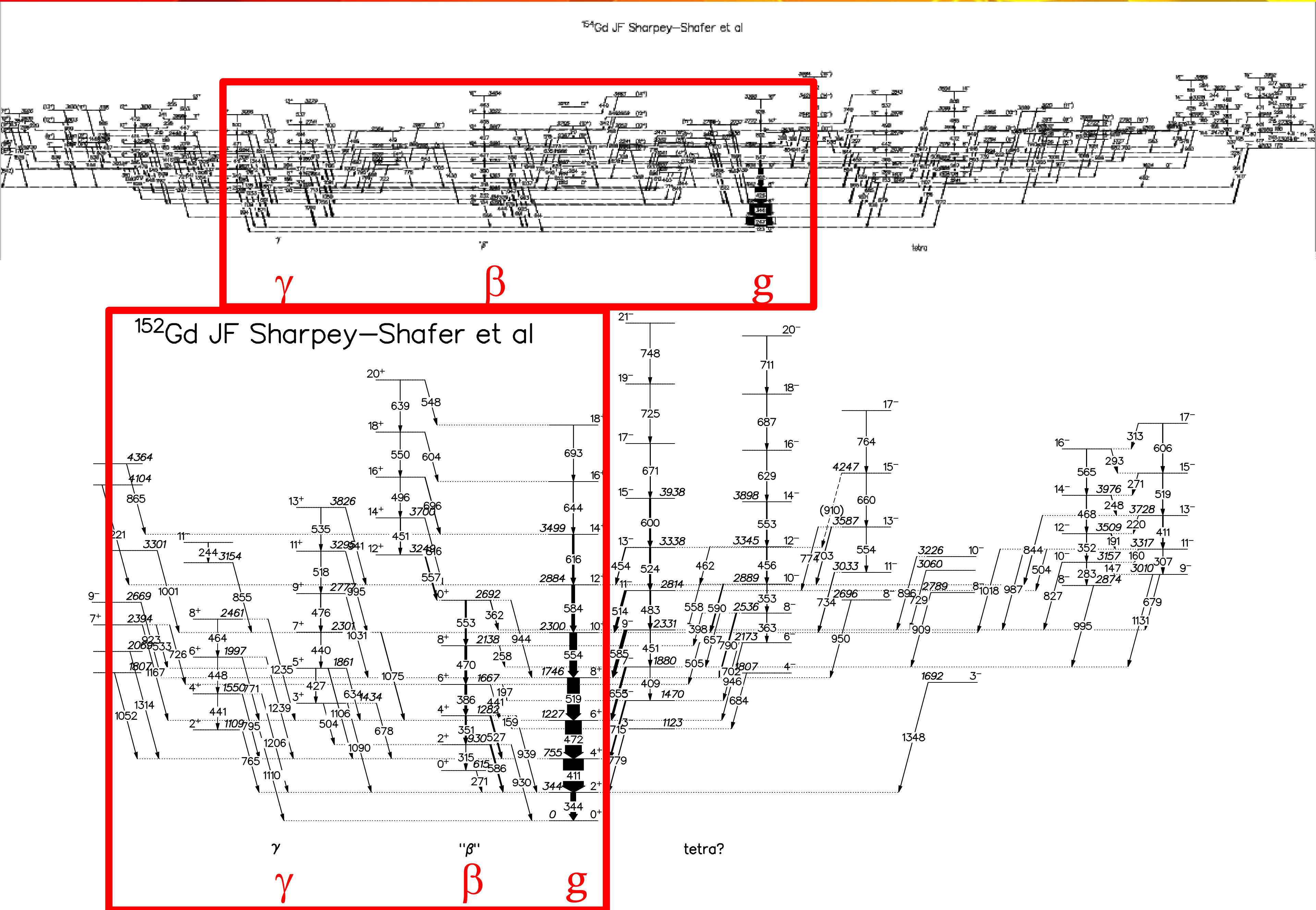


Figure 4.7: Partial level scheme of all the positive parity bands deduced on this prese[…] study for the nucleus of interest. Everything colored in red represents new findings from this work. On the other hand, all previously published levels and transitions are in black.

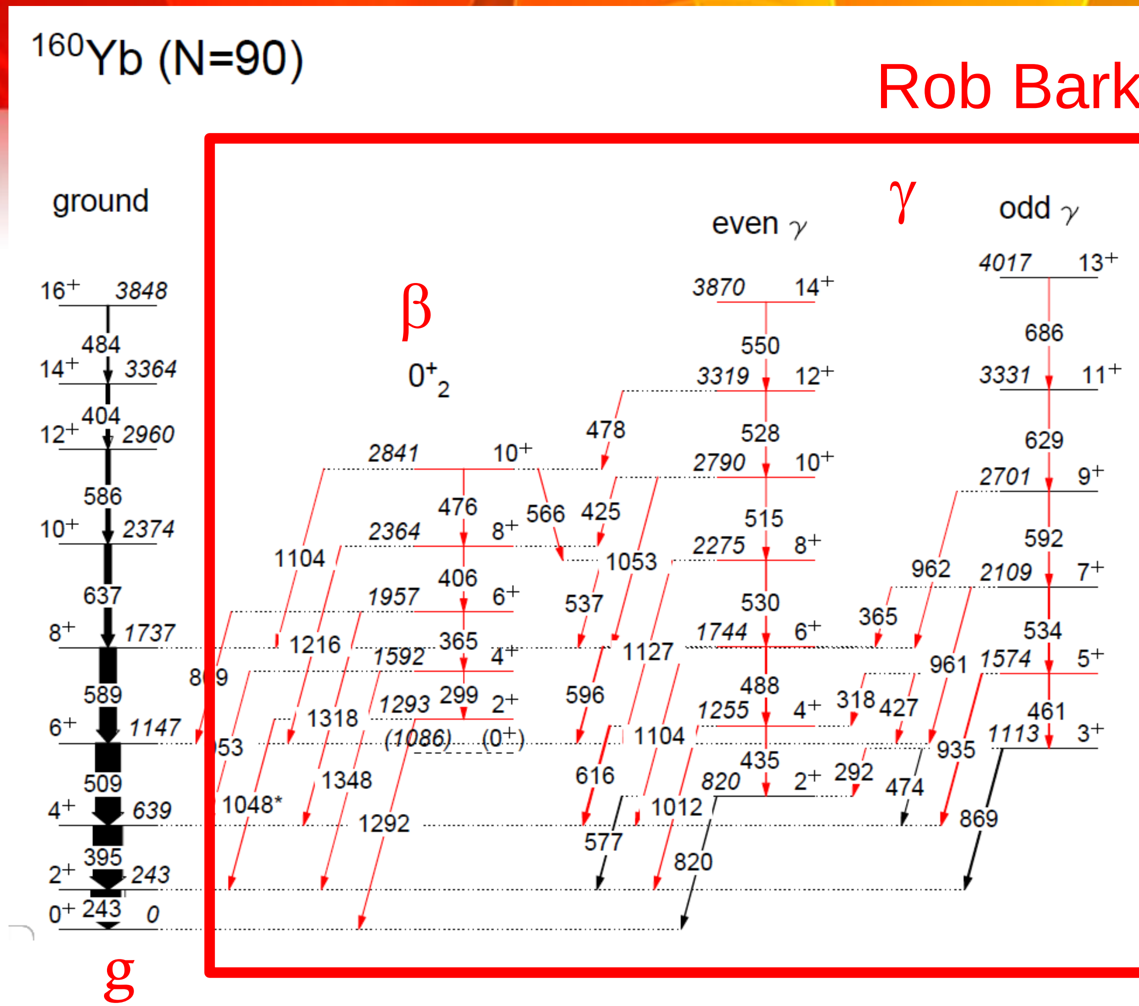
S. Majola, D. Hartley, L. Riedinger, et al PRC 91 034330 (2015)

D. Hartley, L. Riedinger, S. Majola, et al PRC 95 014321 (2017)

^{152}Sm(α,2n)^{154}Gd



$^{147}Sm(^{16}O,3n)^{160}Yb$, AFRODITE



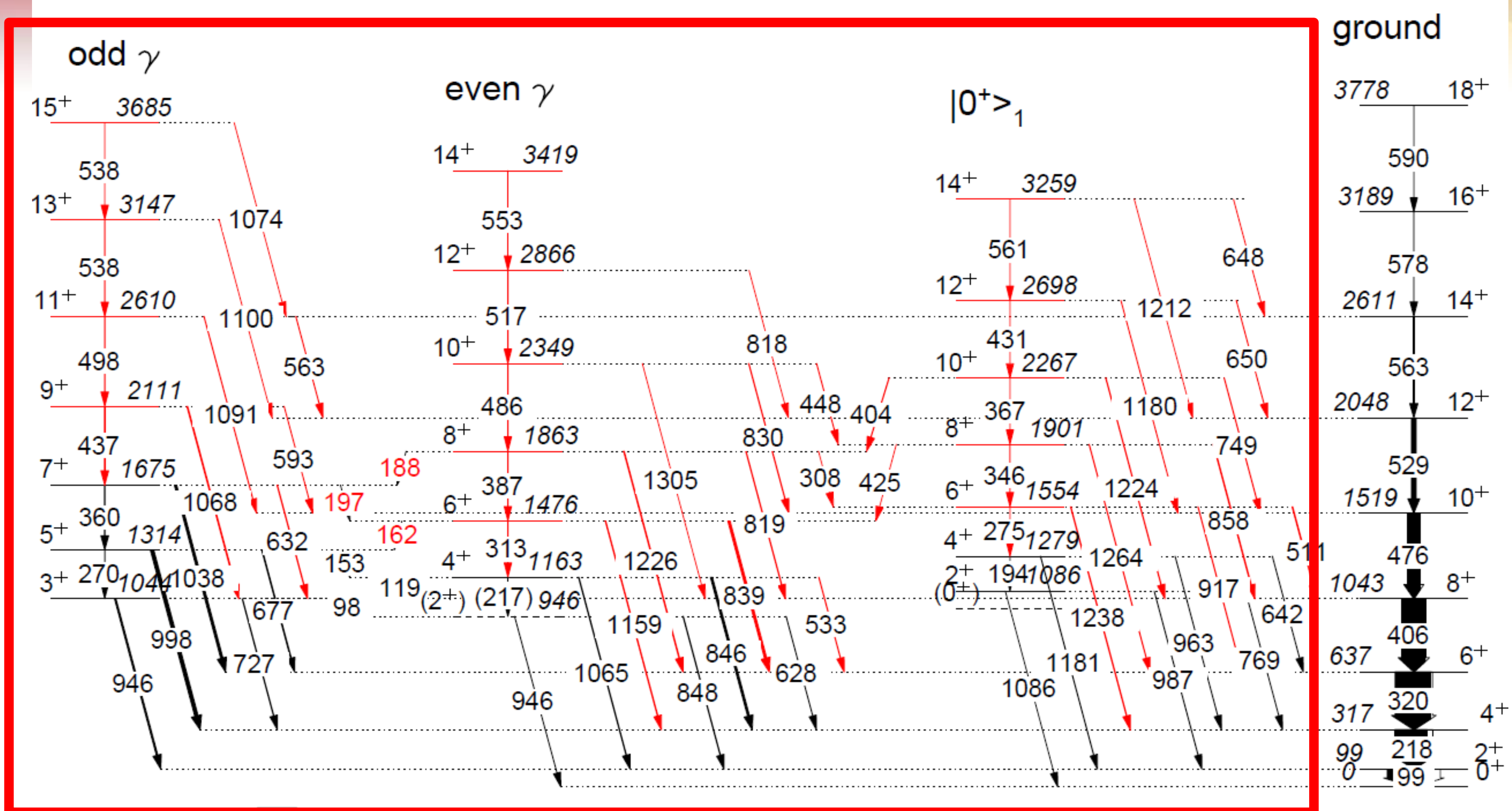
S. Majola et al Phys. Rev. C (2019)

R. A. Bark, J. F. Sharpey-Schafer, et al., Phys. Rev. Lett. 104, 022501 (2010).

^{156}Gd(α,2n) ^{158}Dy, AFRODITE

^{158}Dy (N=92)

Maciek Stankiewicz



S. Majola, et al., PRC, to be published

Beta & Gamma Bands identified to ~12h for the first time in many cases

Also:

^{156}Er JM Rees et al, PRC83, 044314(11)
ES Paul et al, PRC79 044324(09)
^{160}Er K Dushing et al. PRC73 014317(06)
J Ollier et al, PRC, 064322 (09)
^{158}Dy T Hayakwaw PRC 68, 067303(03)
^{152}Sm P Garrett et al PRL 103, 062501(09)

Relativistic Mean Field “Density Functionals” Coupled to the:

Bohr Hamiltonian

Zhipan Li
Jie Meng
Chunyan Song
Jiangjing Yao
Shuangquan Zhang
Zhi Shi
Bangyan Song

Important point:

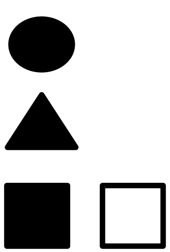
All parameters fixed. Nothing fitted to positive-parity bands

Up Next:
Calculated quantities compared with observables

Beta & Gamma Bands identified to ~12h for the first time in many cases

The determination of a comprehensive set of level energies and branching ratios between bands allows their electromagnetic properties to be compared to nuclear models. To come to an understanding of the properties of these bands, the data obtained in this work are explained using a relativistic mean-field combined with the Bohr Hamiltonian.

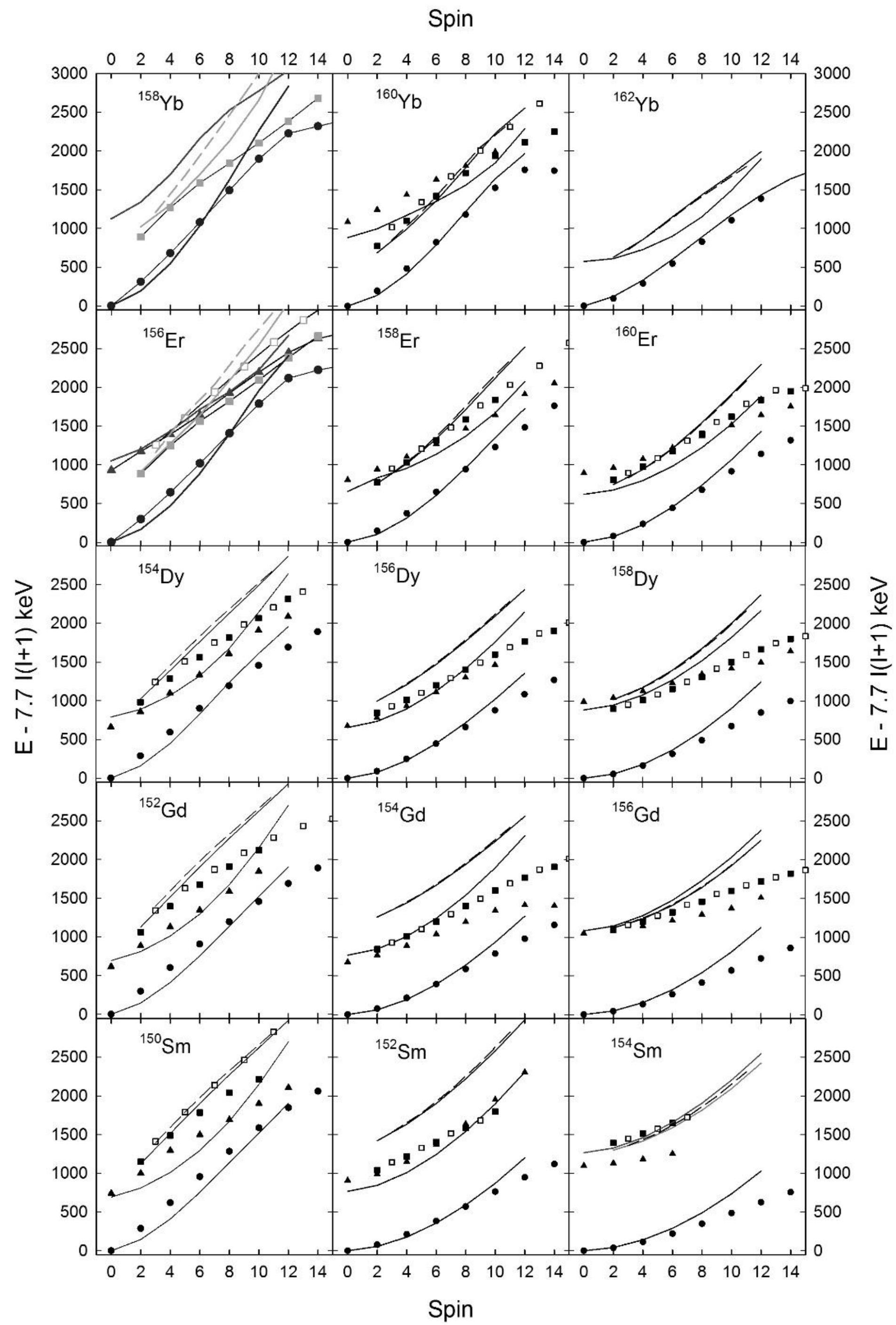
Calculated Energies (lines) compared to experiment (points)



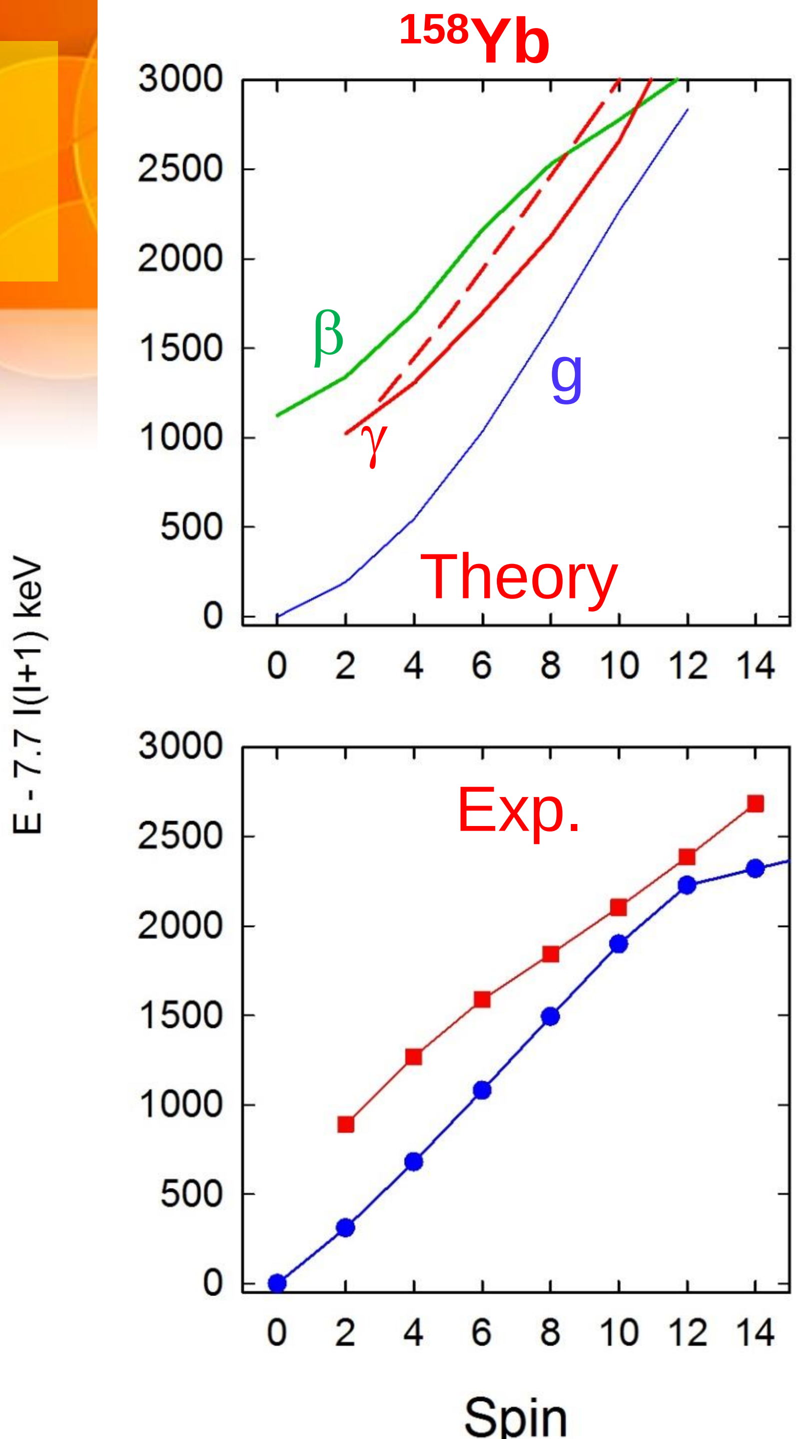
ground band

β band

γ band



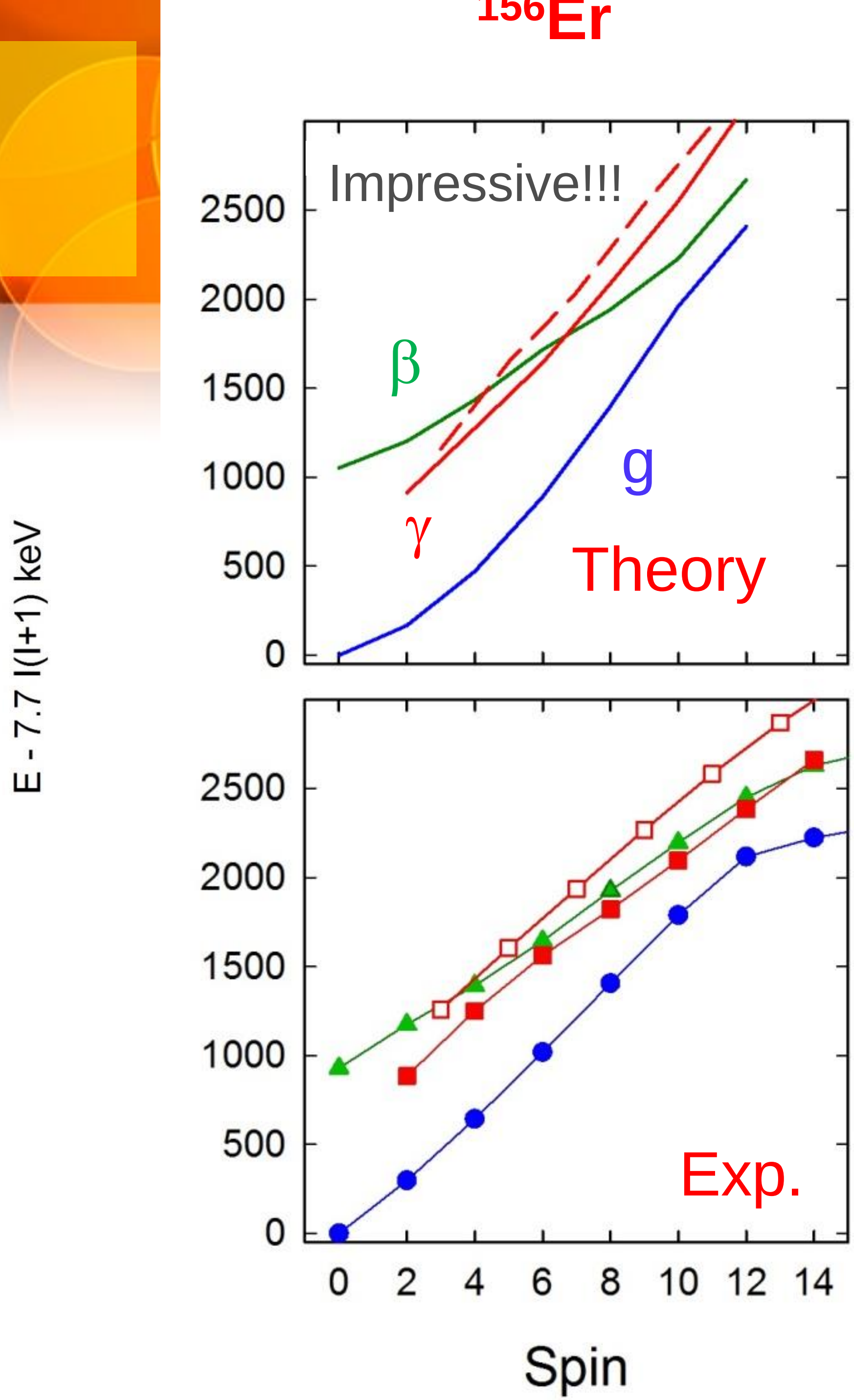
N = 88



158Yb
β
γ
g
Theory
Exp.
E - 7.7 I(I+1) keV
Spin
3000
2500
2000
1500
1000
500
0
0 2 4 6 8 10 12 14

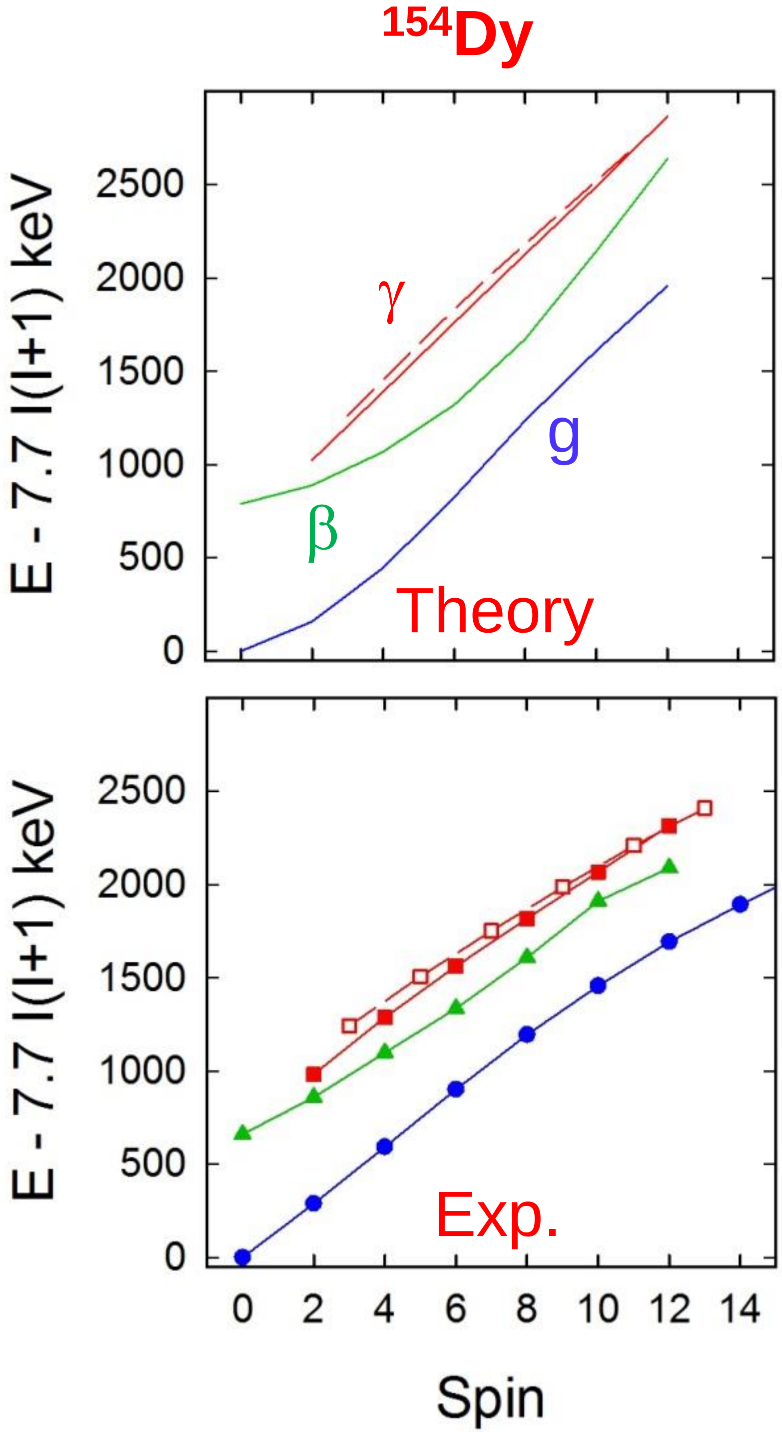
N = 88

- predicts different moments of inertia for β and γ bands



N = 88

- Predicts the order very well
- Predicts signature splitting very well
- Ground parallel to γ bands



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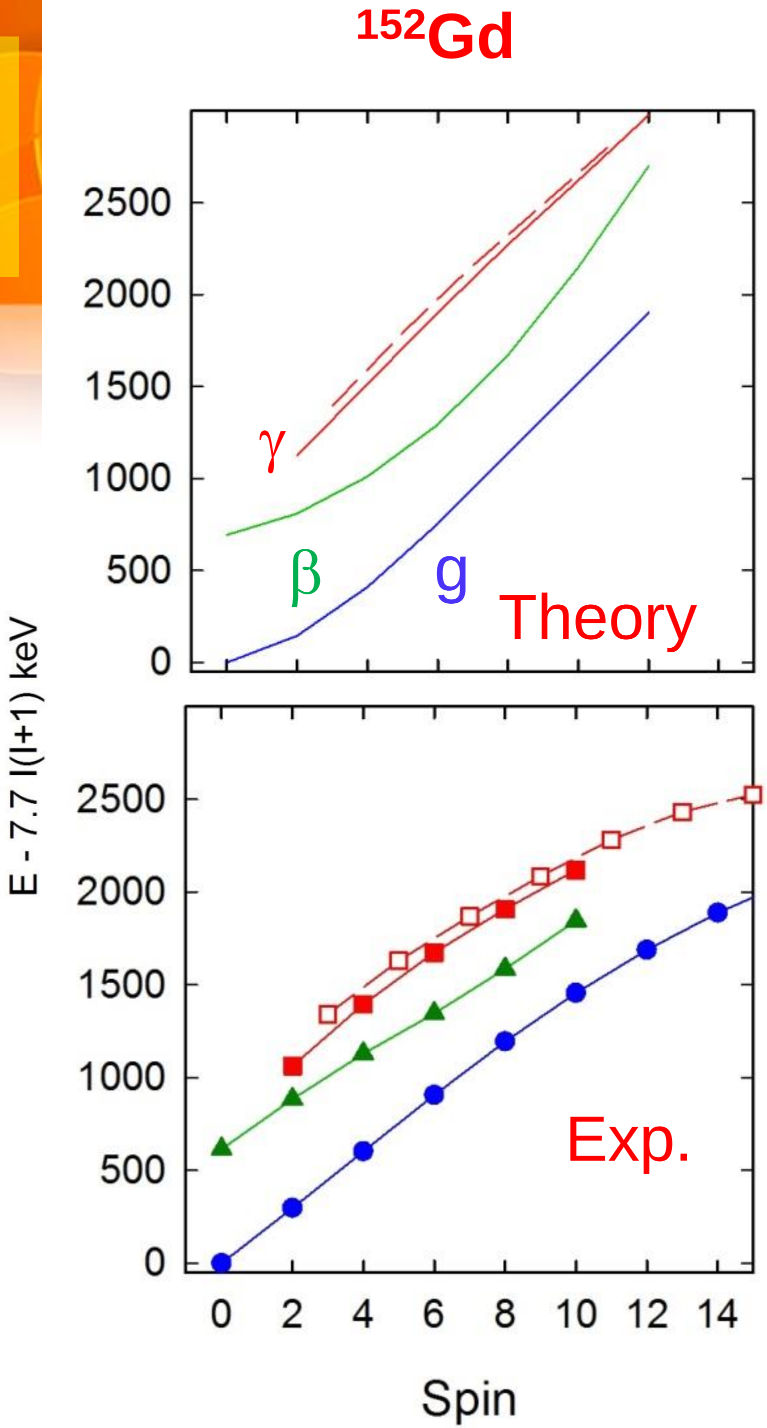
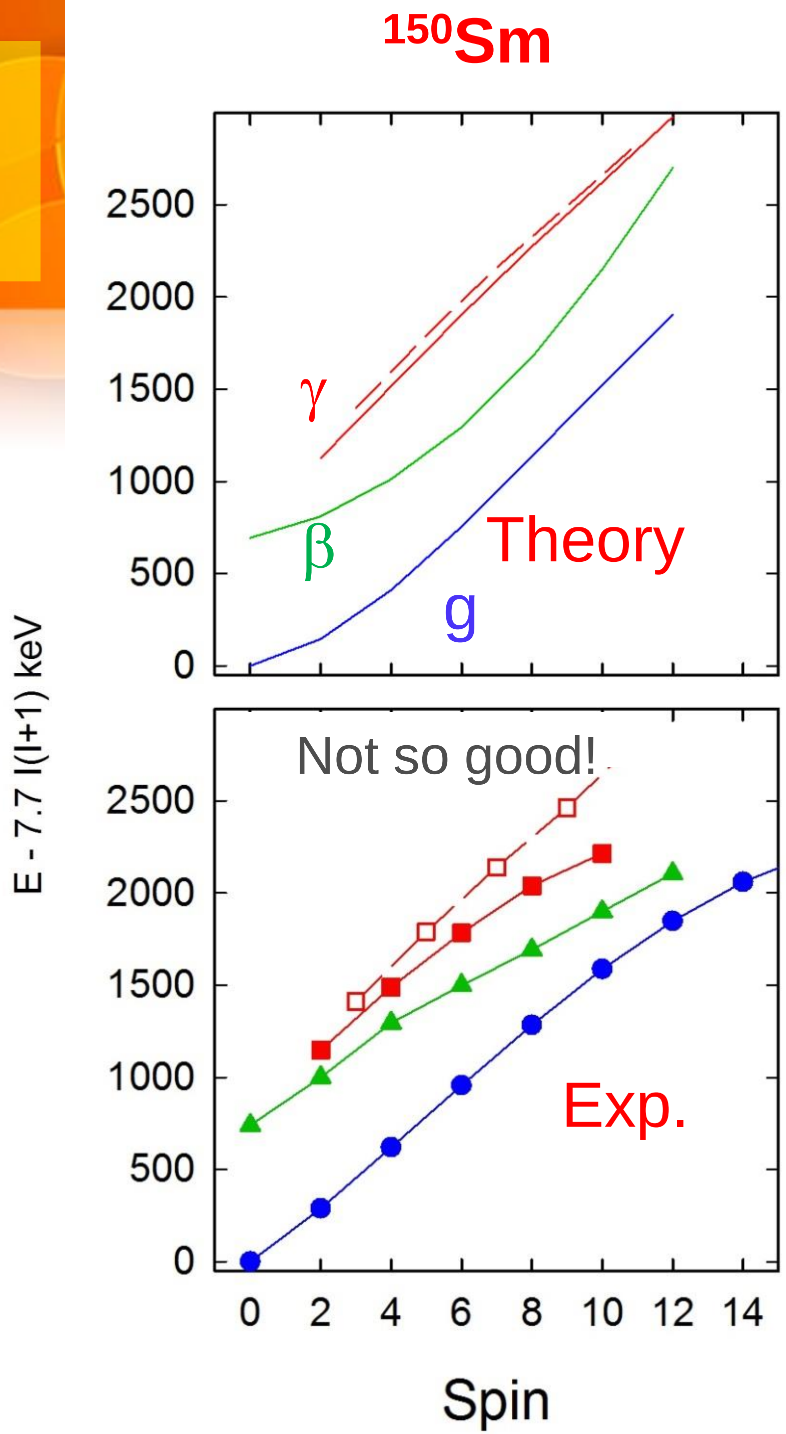


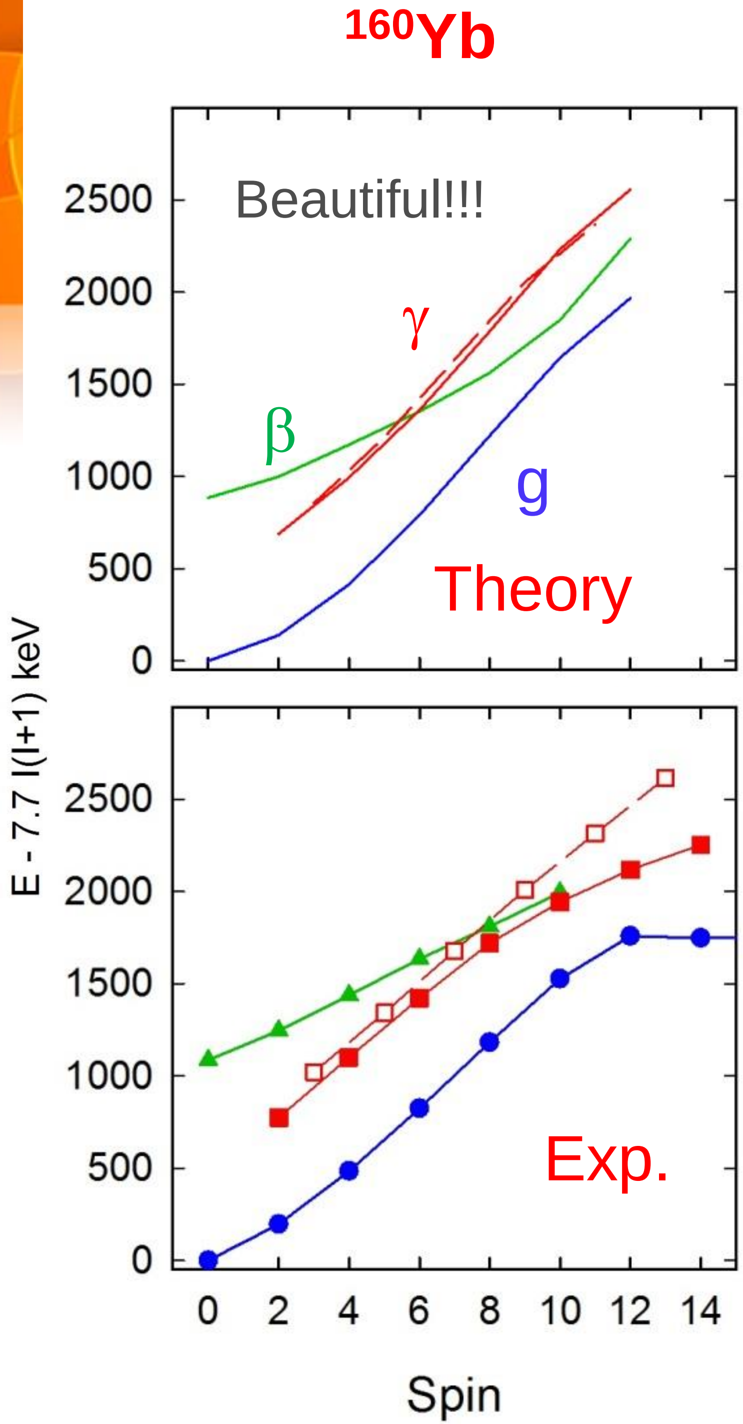
N = 88

- N= 88 covered extremely well by the theory



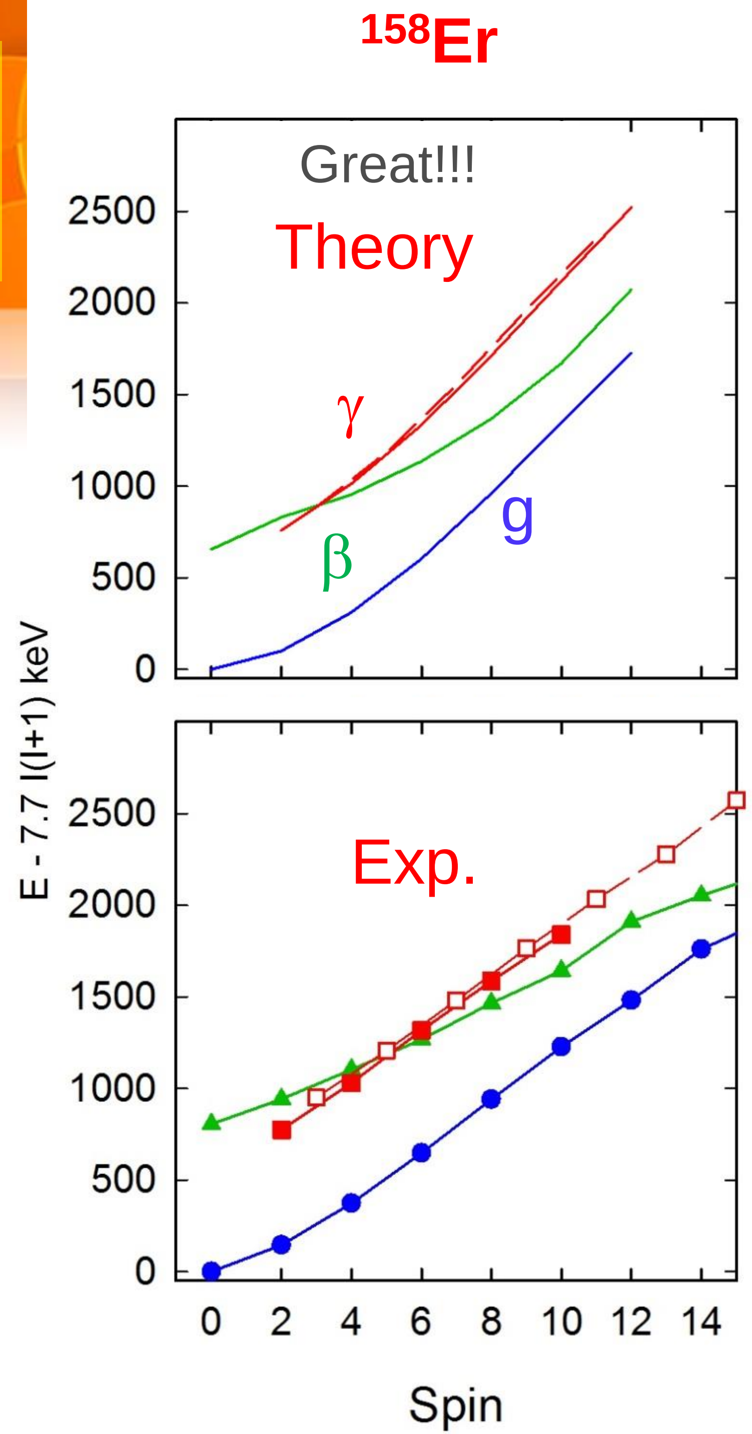
N = 90

- predicts different moments of inertia for β and γ bands
- Predicts the order very well
- Ground parallel to γ bands



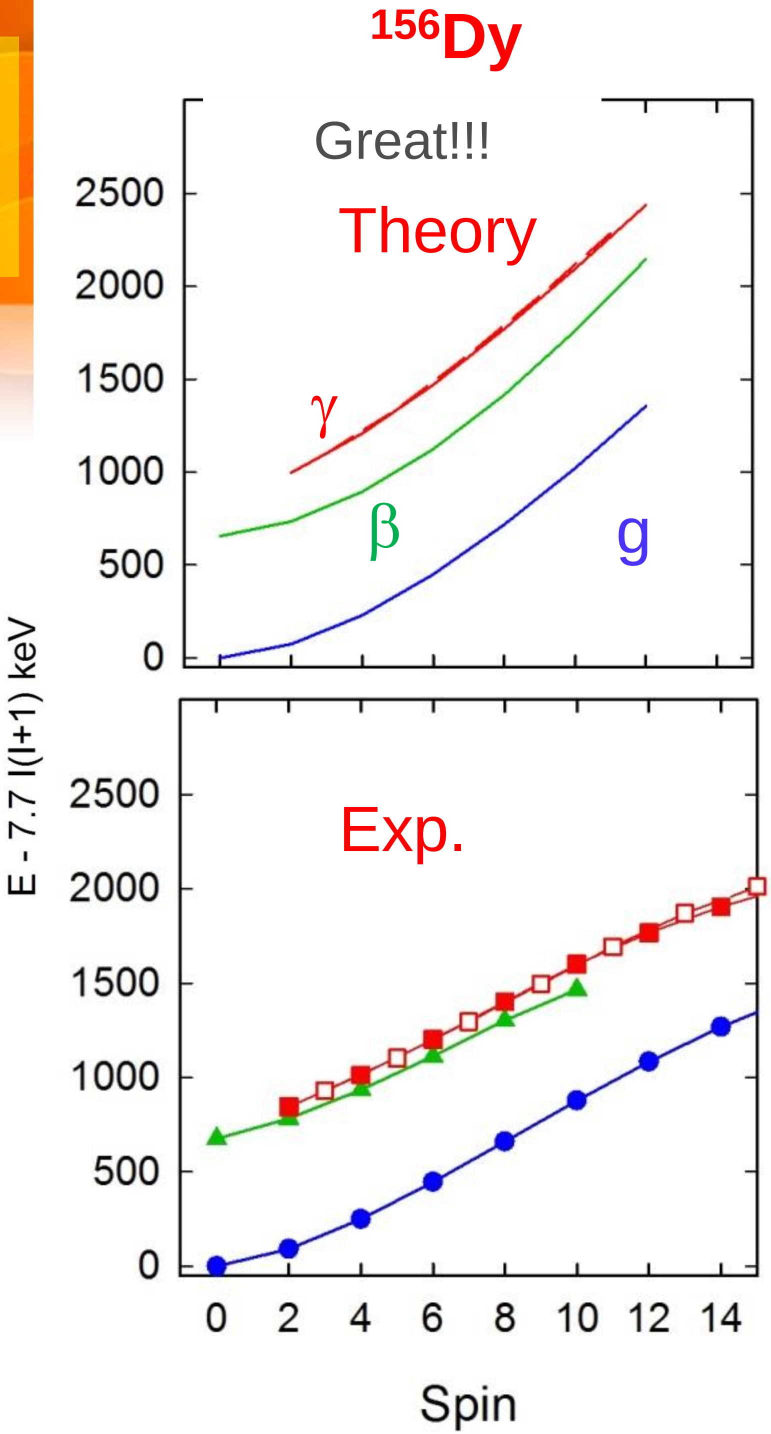
N = 90

- Same story here

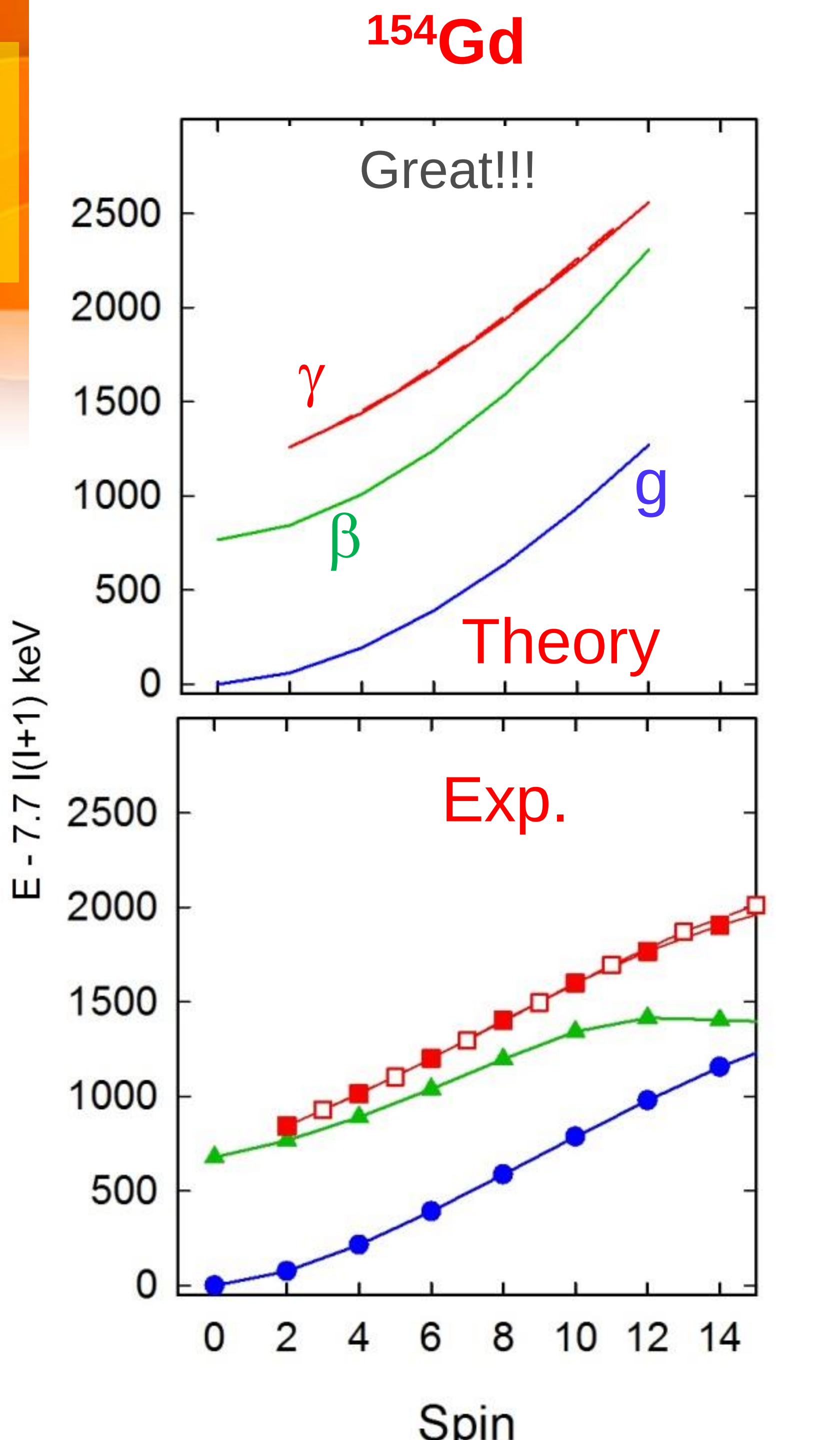


N = 90

- predicts similar moments of inertia for β and γ bands
- Predicts the order very well
- Again! ground parallel to γ bands



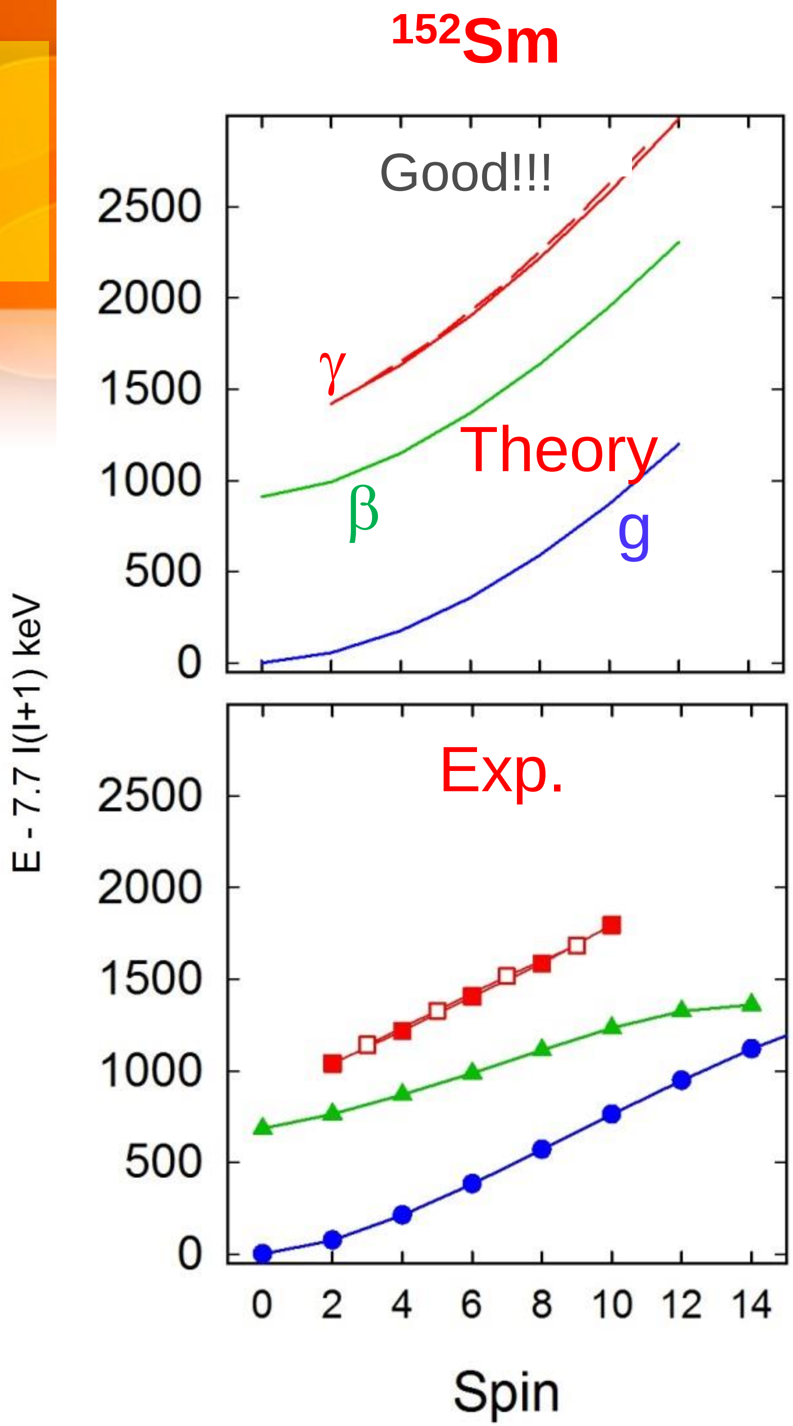
N = 90



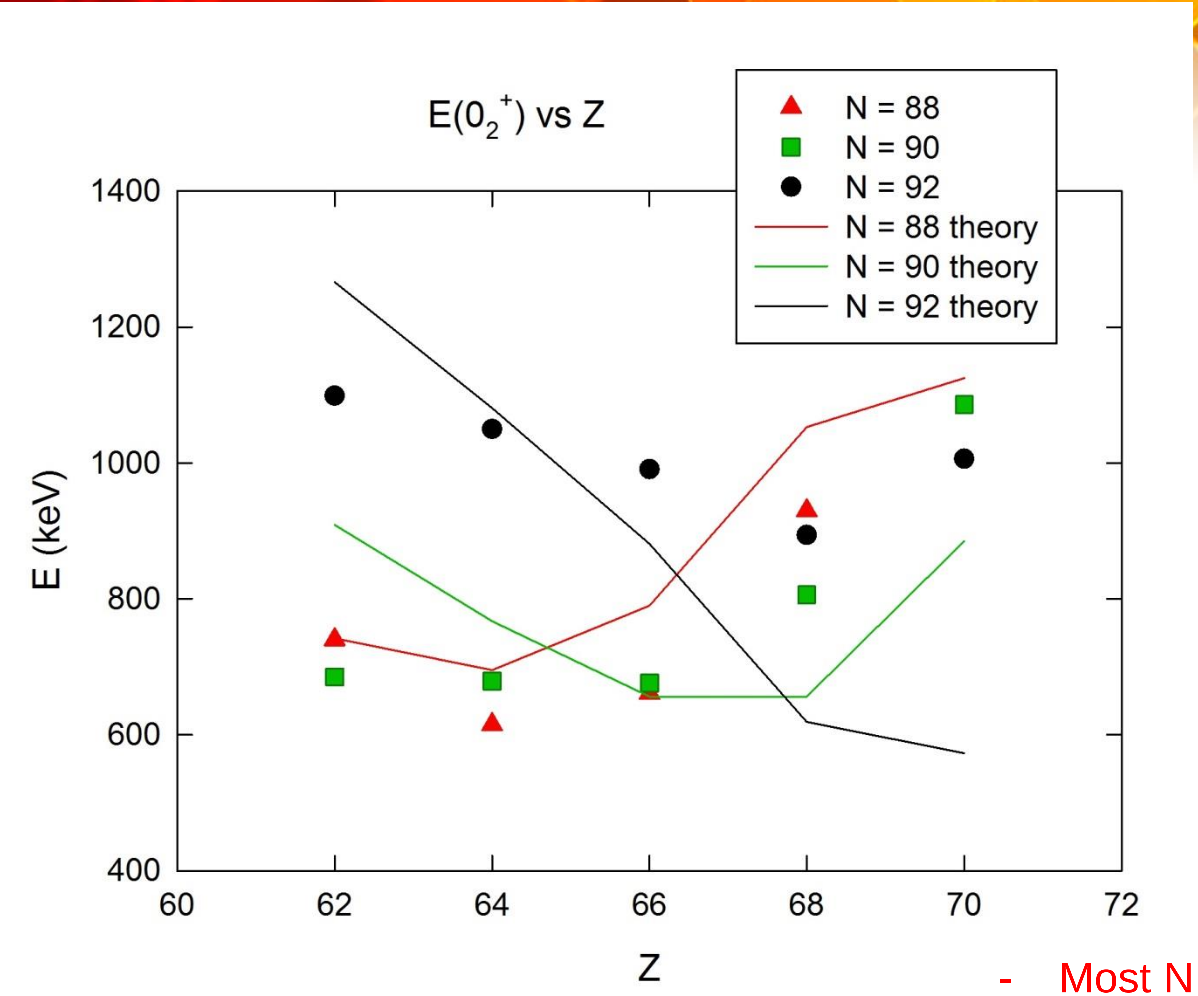
154Gd
Great!!!
γ
β
g
Theory
Exp.
E - 7.7 I(I+1) keV
Spin
2500
2000
1500
1000
500
0
0
2
4
6
8
10
12
14

N = 90

- N= 90 covered extremely well by the theory

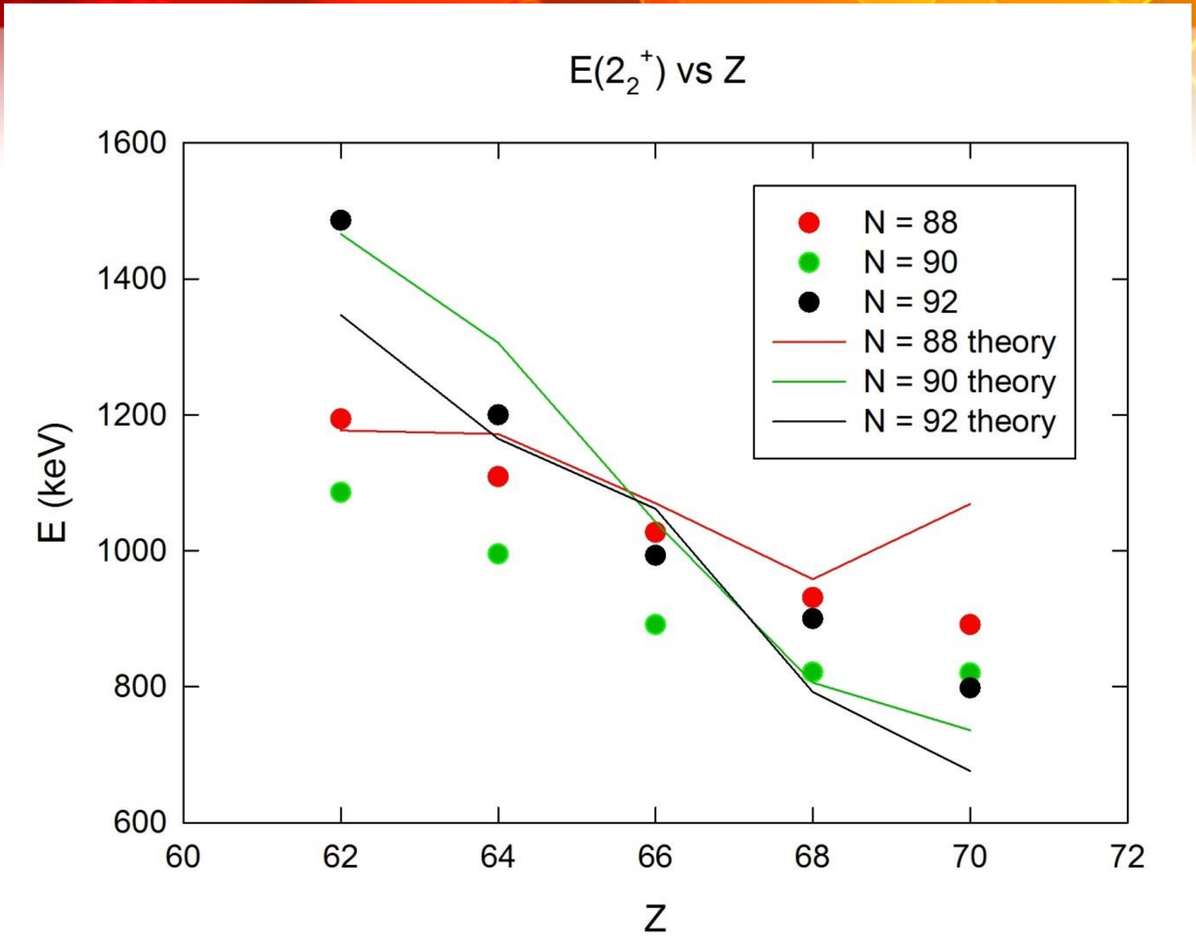


Bandhead energies: 0_2^+ states



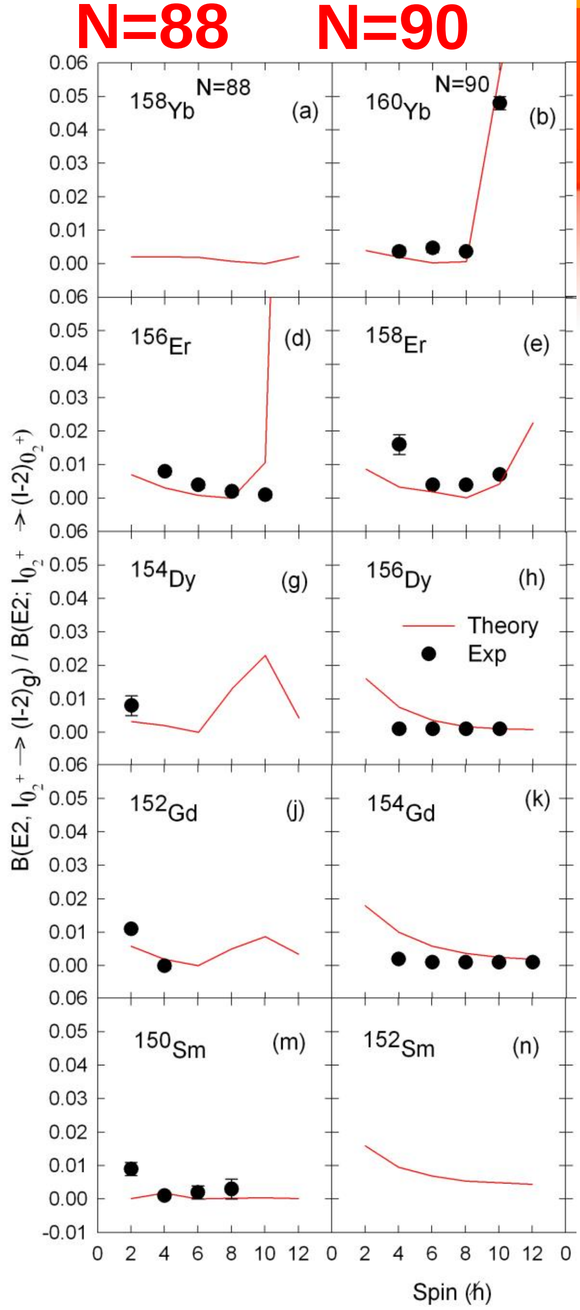
- Most N = 92 underestimated

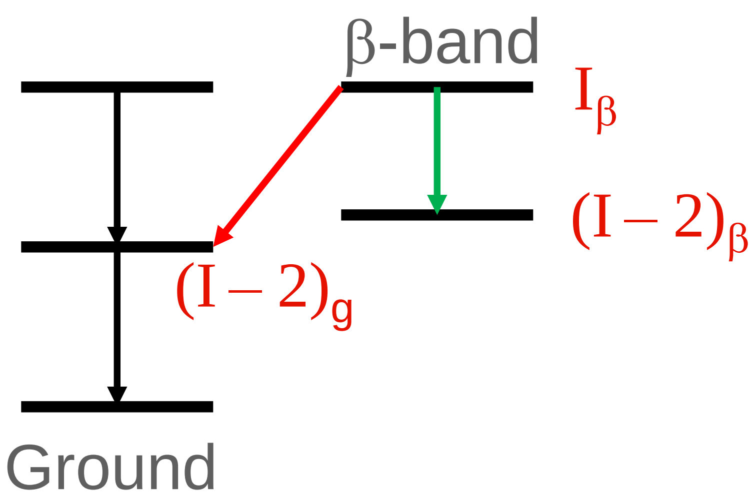
Bandhead energies: 2_2^+ states



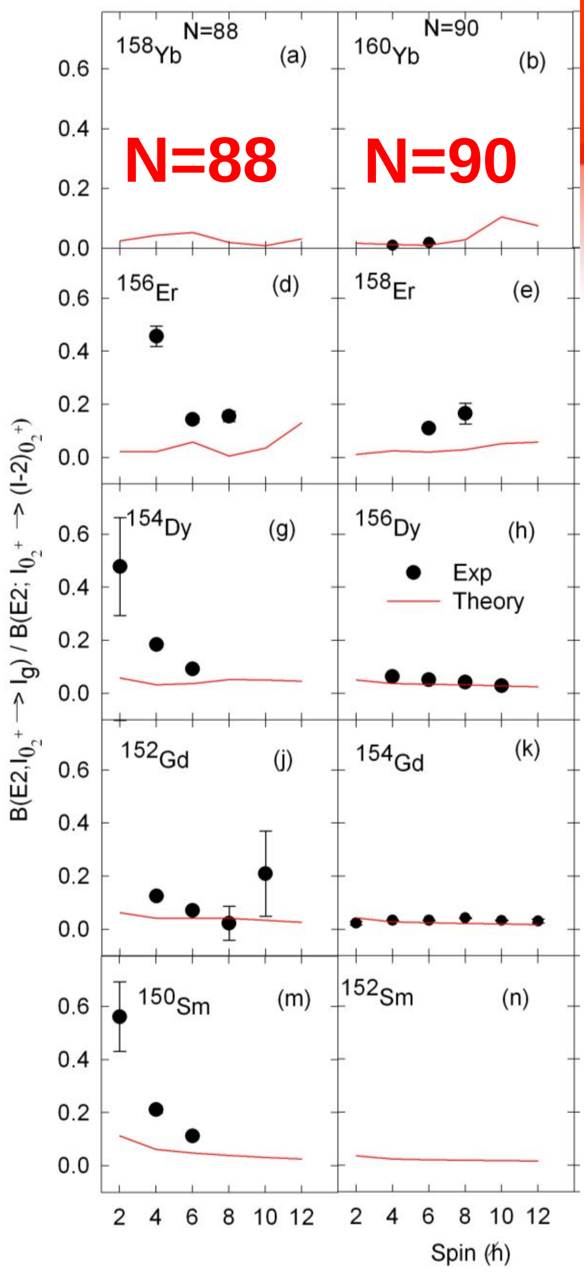
- Trends are generally good

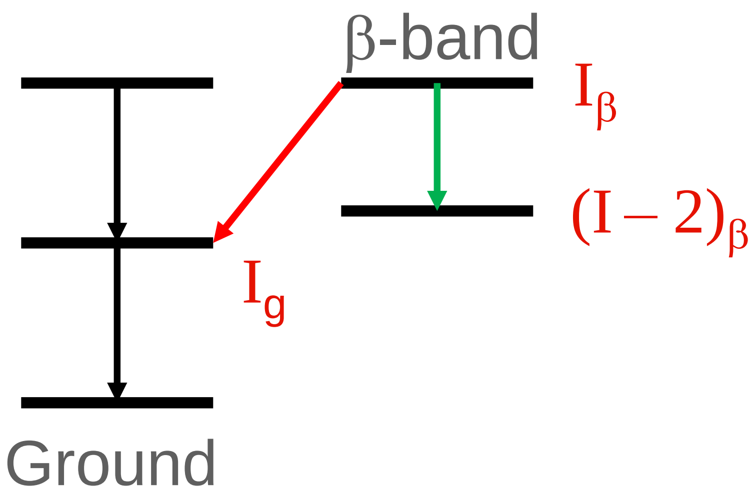
Branching Ratios β-band



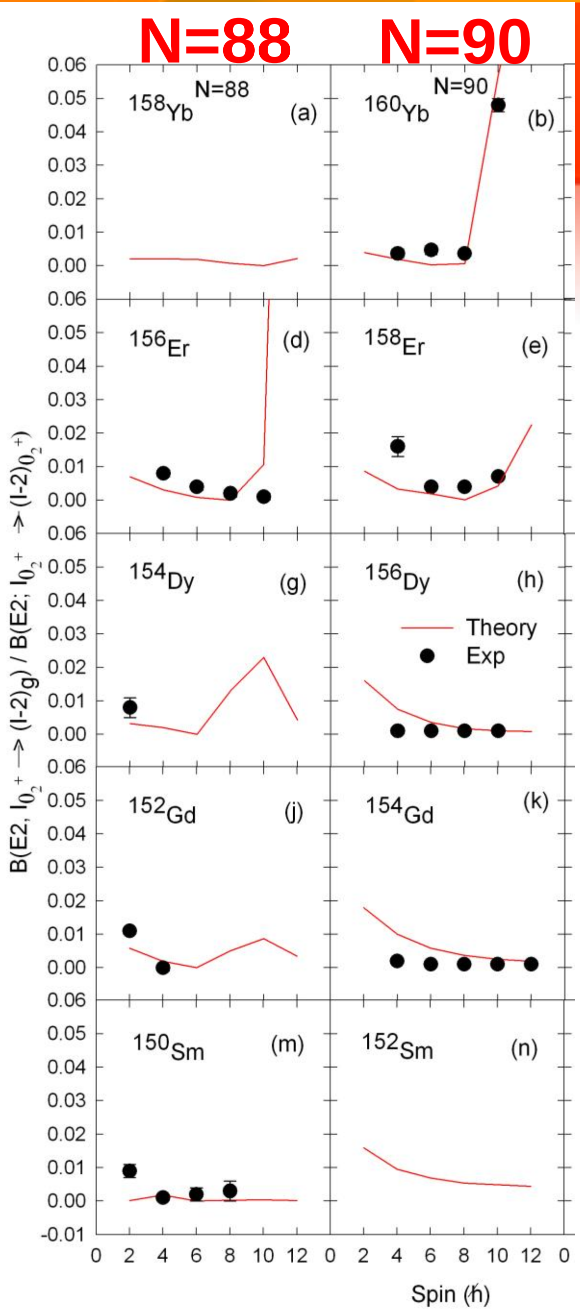


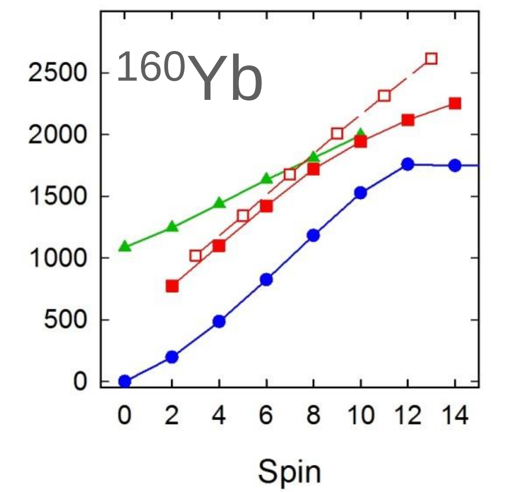
Branching Ratios β-band

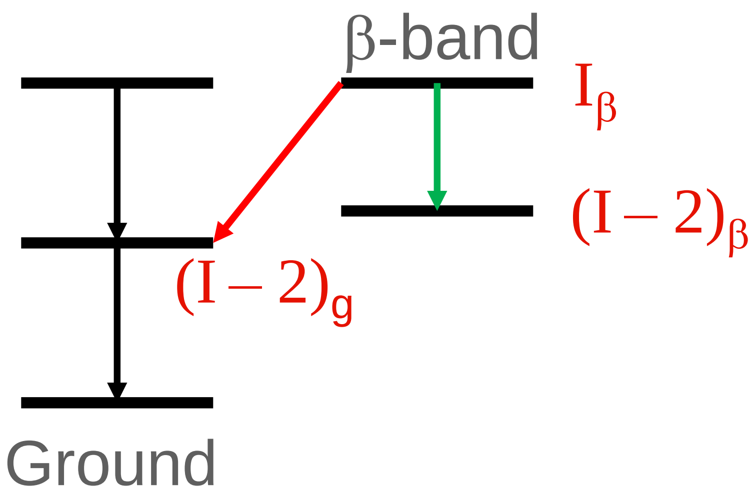




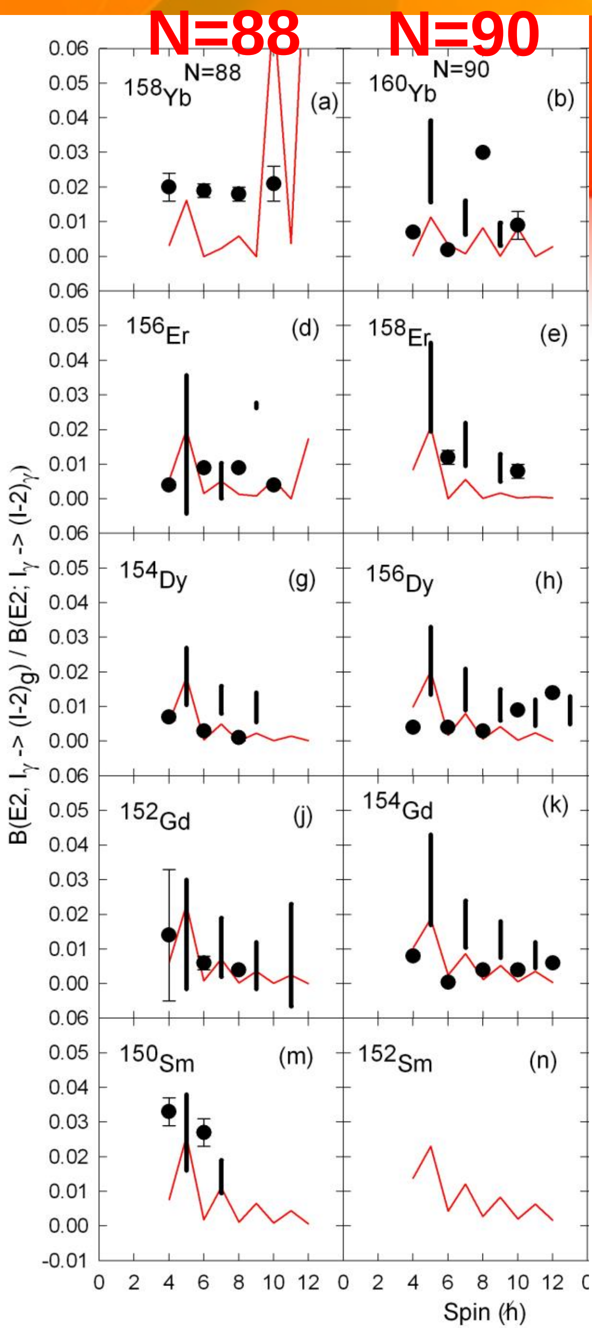
Branching Ratios β-band

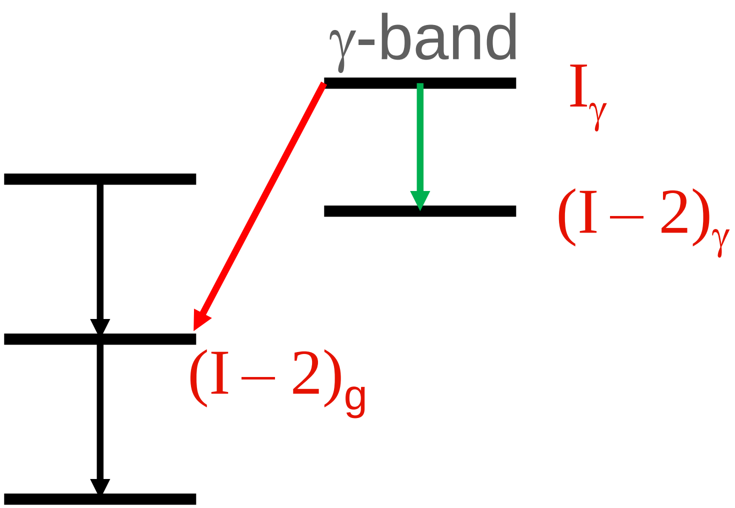




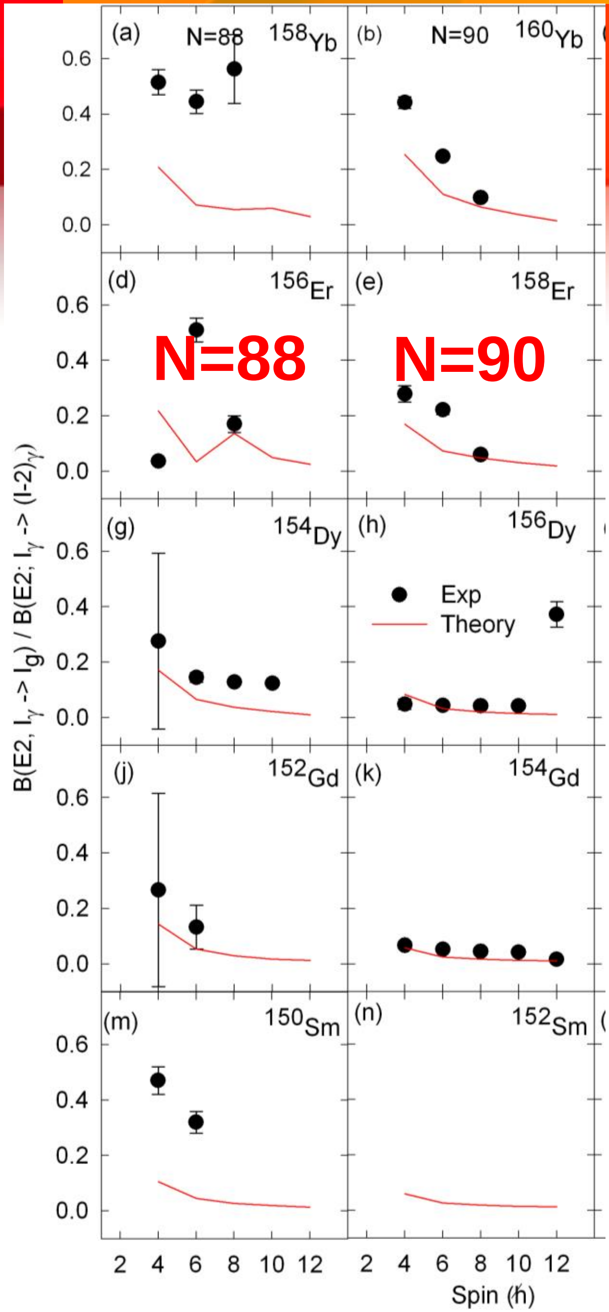


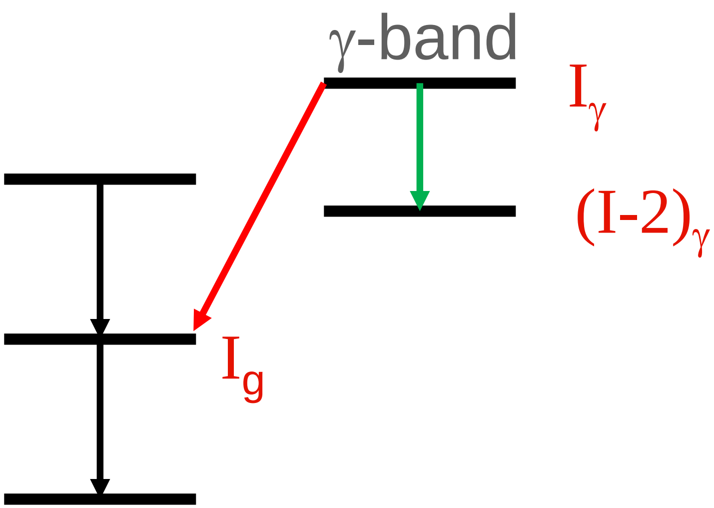
Branching Ratios γ -band



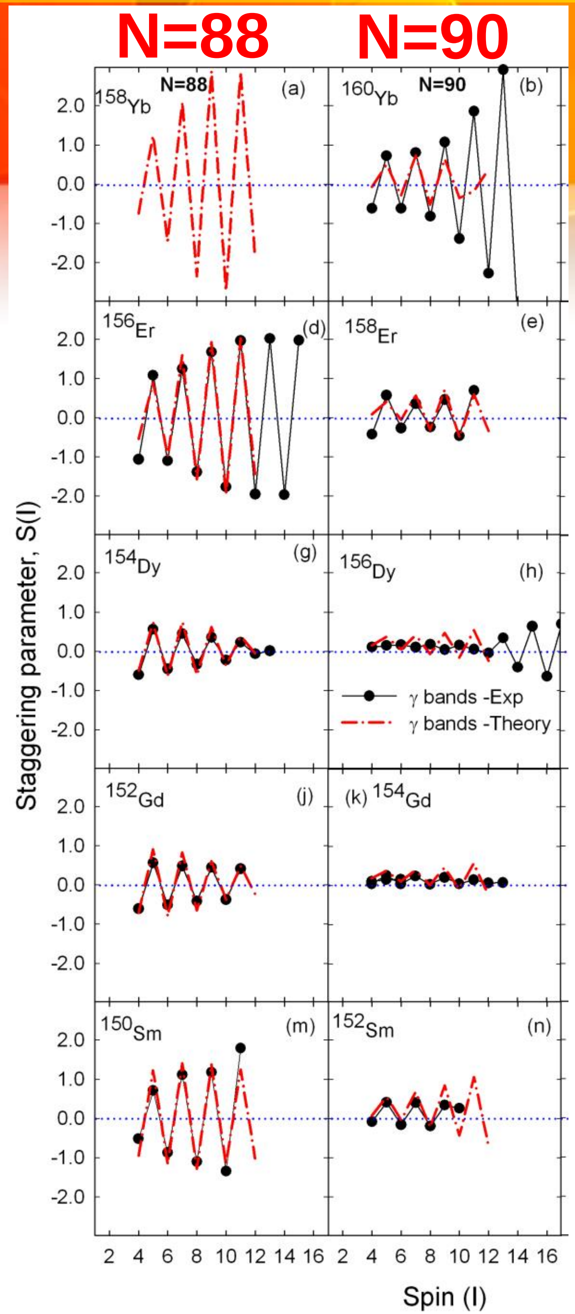


Branching Ratios γ -band



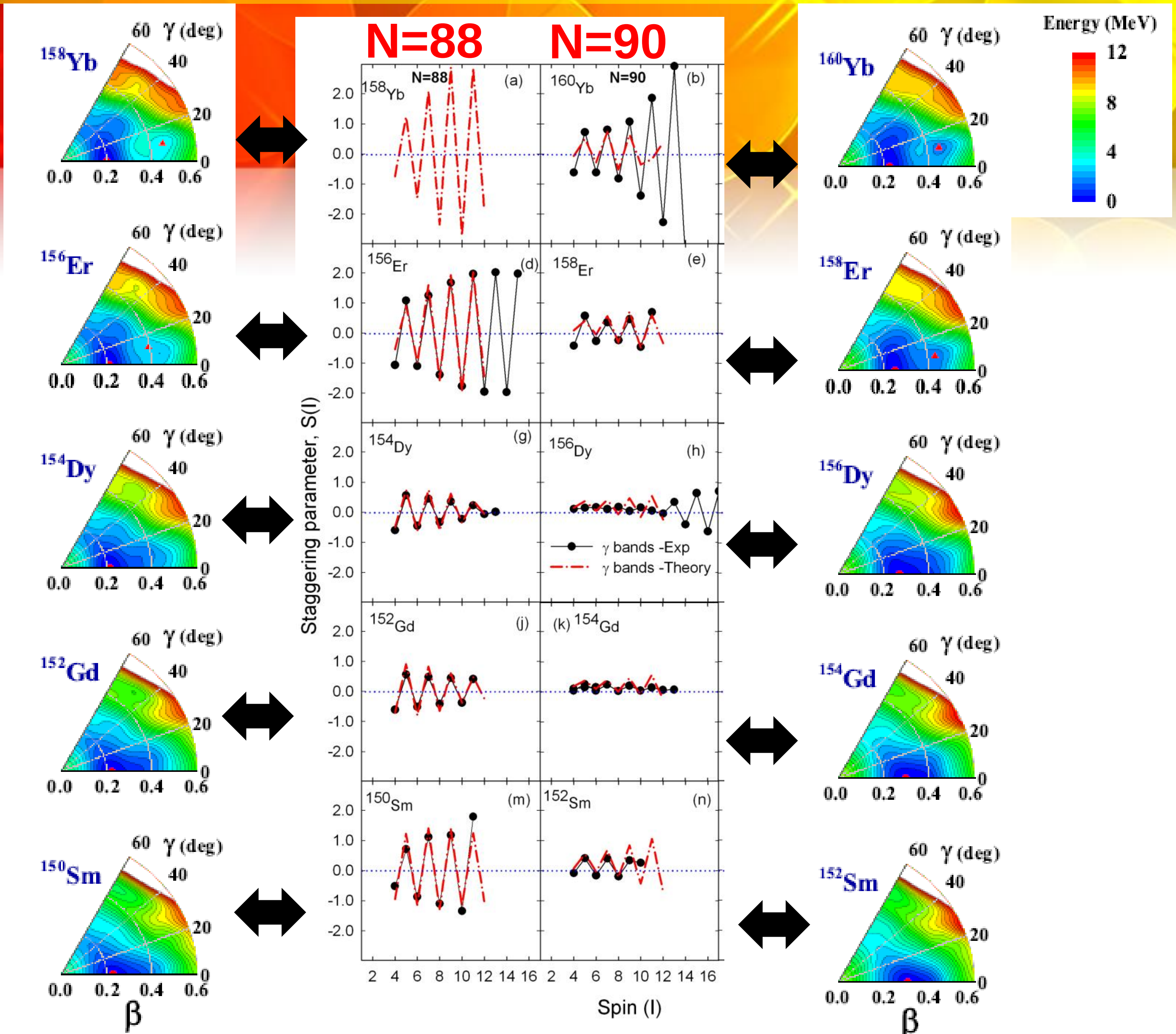


Staggering



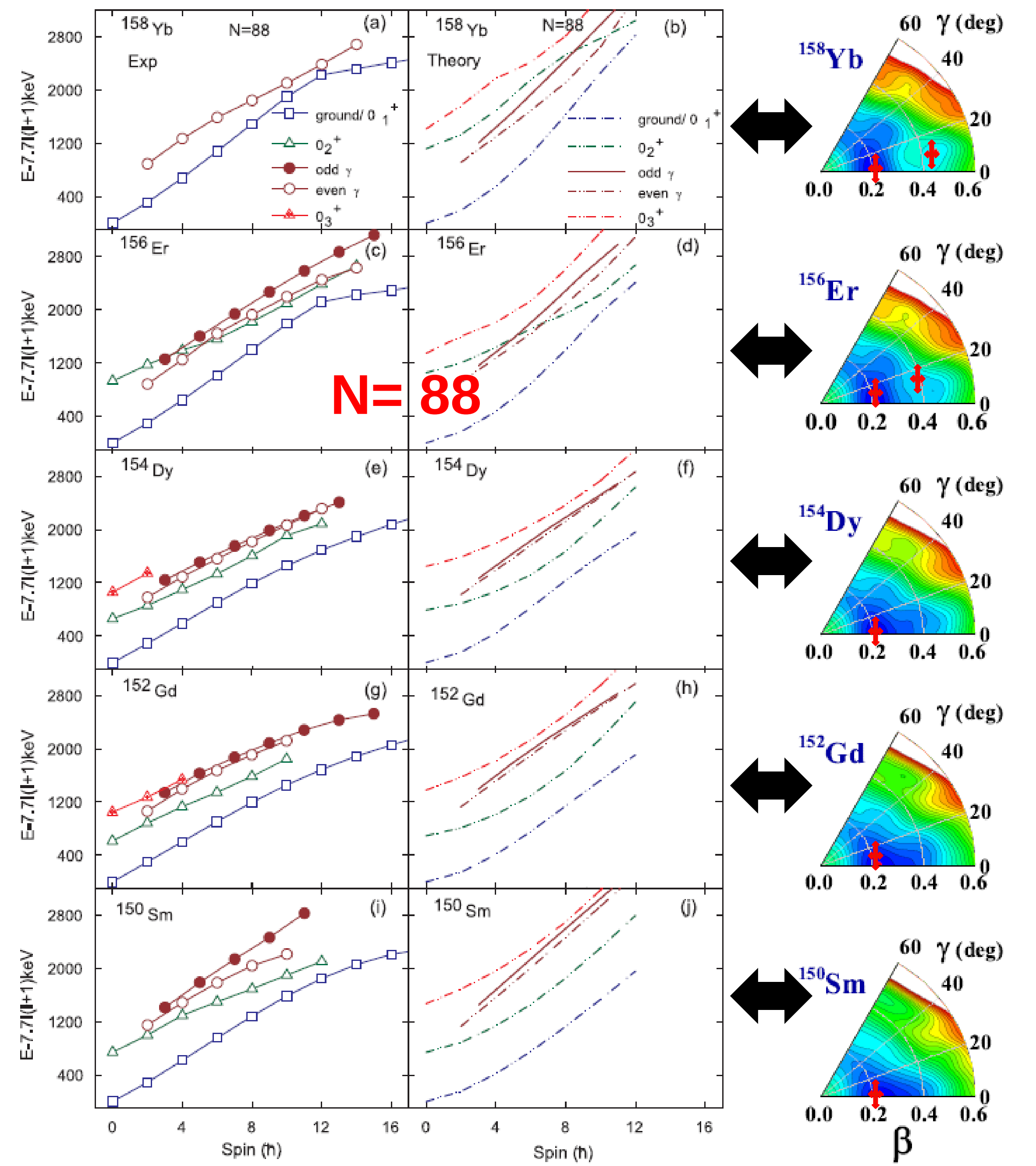
N=88
N=90
158Yb
N=88
(a)
160Yb
N=90
(b)
156Er
(d)
158Er
(e)
154Dy
(g)
156Dy
(h)
γ bands -Exp
γ bands -Theory
152Gd
(j)
(k) 154Gd
150Sm
(m)
152Sm
(n)
2.0
1.0
0.0
-1.0
-2.0
Staggering parameter, S(I)
2 4 6 8 10 12 14 16 2 4 6 8 10 12 14 16
Spin (I)

Staggering

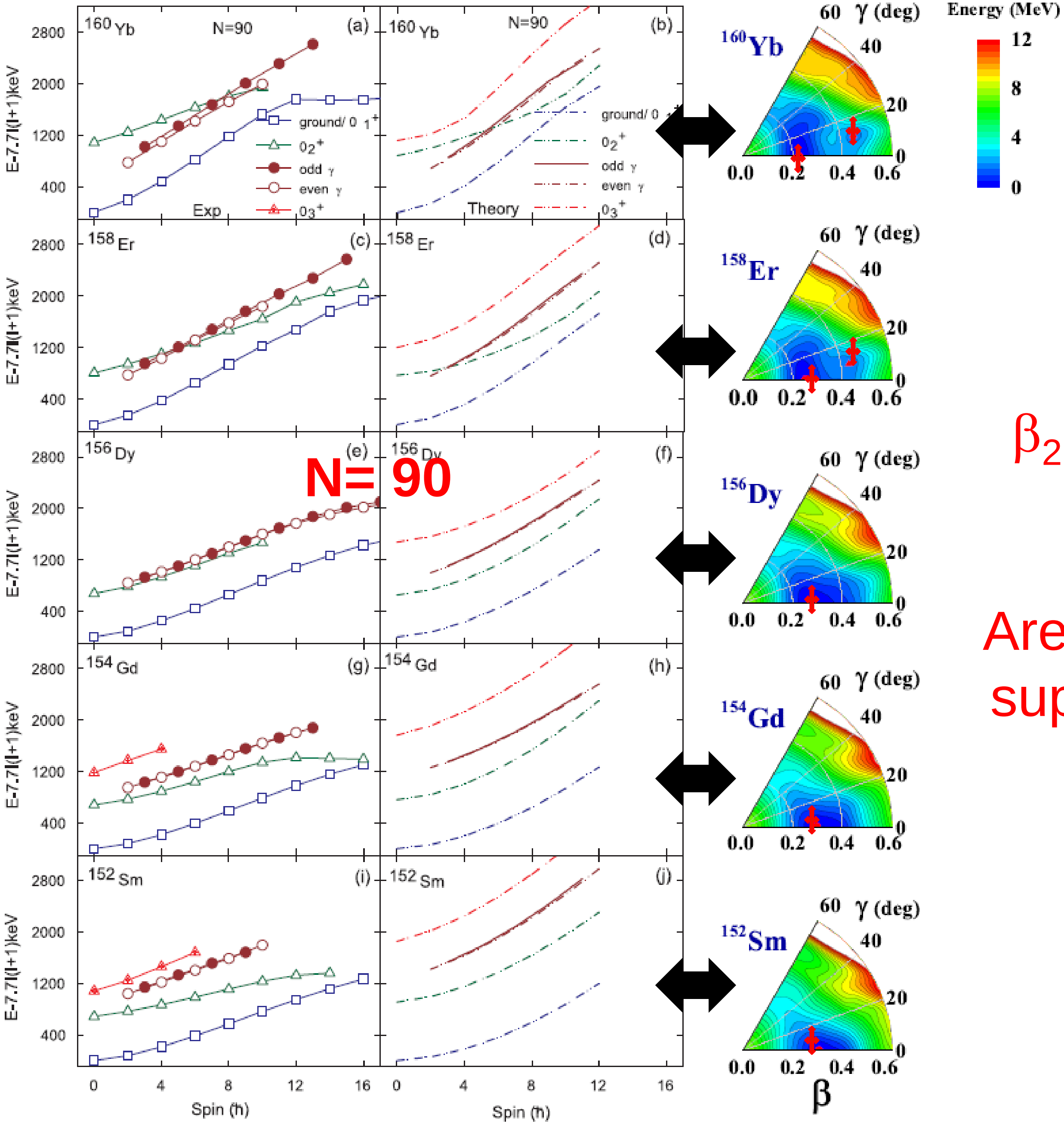


N=88
N=90
158Yb
156Er
154Dy
152Gd
150Sm
160Yb
158Er
156Dy
154Gd
152Sm
γ (deg)
β
Energy (MeV)
Staggering parameter, S(I)
Spin (I)
γ bands -Exp
γ bands -Theory

Second minima in Er, Yb isotopes (N=88)



Second minima in Er, Yb isotopes (N=90)



$\beta_2 \sim 0.45$ and $\gamma \sim 10°$ in Er, Yb isotopes

Are $|0_2^+\rangle$ states, Triaxially super deformed bands??

Conclusion

In order to produce a complete and definitive microscopic picture of the so-called β and γ bands, we have carried out an extensive systematic study of even-even nuclei in the 160 mass region.

Conclusion

Based on this data:

"From Sm to Dy, the $|0_2^+>$ " are well described as "β-bands"

Maybe not "harmonic vibrations" but are essentially well described as solutions of the Bohr Hamiltonian with a realistic potential

Conclusion

Second minima for Er and Yb isotopes is located at $\sim\beta_2 \sim 0.45$ and $\gamma \sim 10°$.

This may imply that the 0_2^+ bands in Er and Yb isotopes are Triaxially super deformed bands

Conclusion

Energy staggering and PES plots show that the almost all the N=88 isotones from Sm to Yb are γ soft.

EXPERIMENTALISTS

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Moment of Inertia: Inglis-Belyaev formula

$$\mathcal{I}_k = \sum_{i,j} \frac{(u_i v_j - v_i u_j)^2}{E_i + E_j} |\langle i | \hat{J}_k | j \rangle|^2 \quad k = 1, 2, 3,$$

Mass Parameters calculated in Cranking approximation

$$B_{\mu\nu}(q_0, q_2) = \frac{\hbar^2}{2} [\mathcal{M}_{(1)}^{-1} \mathcal{M}_{(3)} \mathcal{M}_{(1)}^{-1}]_{\mu\nu}$$

$$\mathcal{M}_{(n),\mu\nu}(q_0, q_2) = \sum_{i,j} \frac{\langle i | \hat{Q}_{2\mu} | j \rangle \langle j | \hat{Q}_{2\nu} | i \rangle}{(E_i + E_j)^n} (u_i v_j + v_i u_j)^2$$

Improved by using Thouless-Valatin moments-of-inertia

Z.P. Li. et al PRC 86, 034334 (2012)

Re-cast Bohr Hamiltonian

$$\hat{H} = \hat{T}_{\text{vib}} + \hat{T}_{\text{rot}} + V_{\text{coll}}$$

$$\hat{T}_{\text{vib}} = -\frac{\hbar^2}{2\sqrt{wr}}\left\{\frac{1}{\beta^4}\left[\frac{\partial}{\partial\beta}\sqrt{\frac{r}{w}}\beta^4 B_{\gamma\gamma}\frac{\partial}{\partial\beta}\right.\right.$$

$$\left. - \frac{\partial}{\partial\beta}\sqrt{\frac{r}{w}}\beta^3 B_{\beta\gamma}\frac{\partial}{\partial\gamma}\right] + \frac{1}{\beta\sin 3\gamma}\left[-\frac{\partial}{\partial\gamma}\right.$$

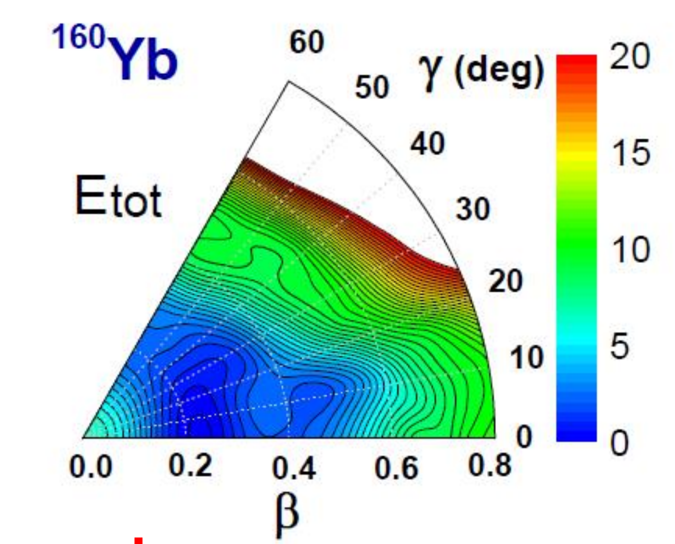
$$\left.\left.\times\sqrt{\frac{r}{w}}\sin 3\gamma B_{\beta\gamma}\frac{\partial}{\partial\beta} + \frac{1}{\beta}\frac{\partial}{\partial\gamma}\sqrt{\frac{r}{w}}\sin 3\gamma B_{\beta\beta}\frac{\partial}{\partial\gamma}\right]\right\}$$

$$\hat{T}_{\text{rot}} = \frac{1}{2}\sum_{k=1}^{3}\frac{\hat{J}_k^2}{\mathcal{I}_k}$$

Need to determine I's, B's

T. Niksic et al PRC 79, 034303 (2009)
Z.P. Li et al., PRC 79, 054301 (2009)

V_{coll} from Relativistic Mean Field



Parameters of PC-F1 functional And pairing strengths adjusted to ground observables of spherical nuclei (binding energies, pairing gaps, charge radii etc)

T. Niksic et al PRC 79, 034303 (2009)
Z.P. Li et al., PRC 79, 054301 (2009)