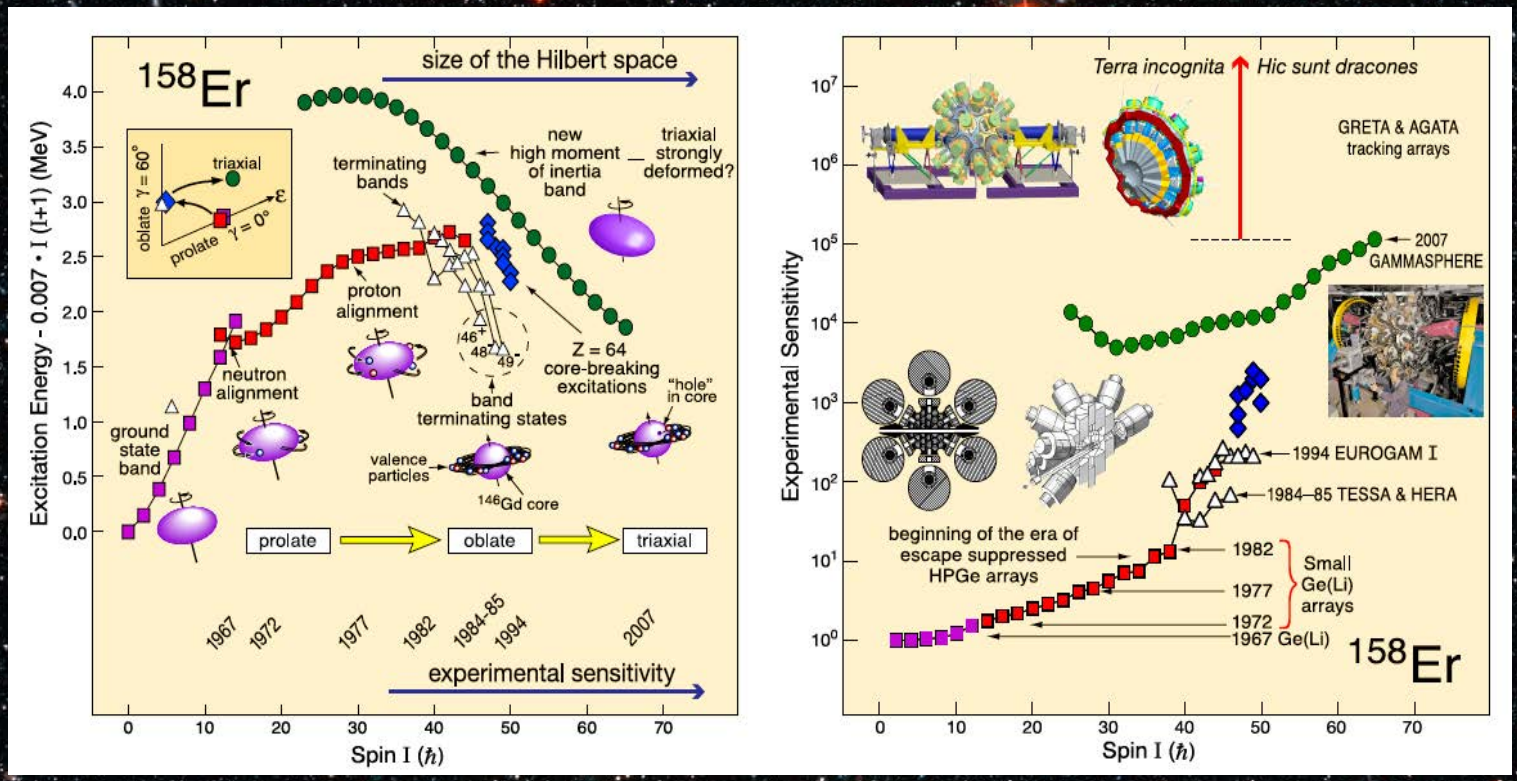
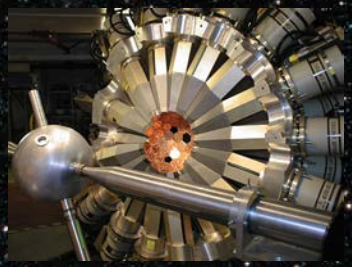
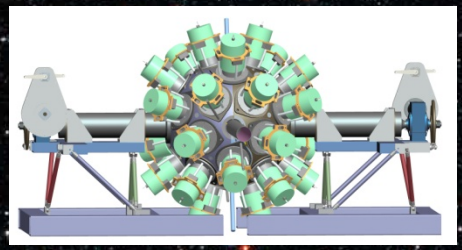


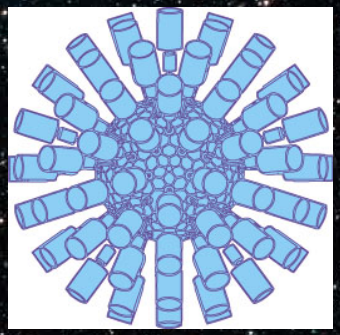
Spin 60 and beyond: Exotic behavior at the limits of angular momentum.

Mark A. Riley - Florida State University (+ LOTS OF FRIENDS!)





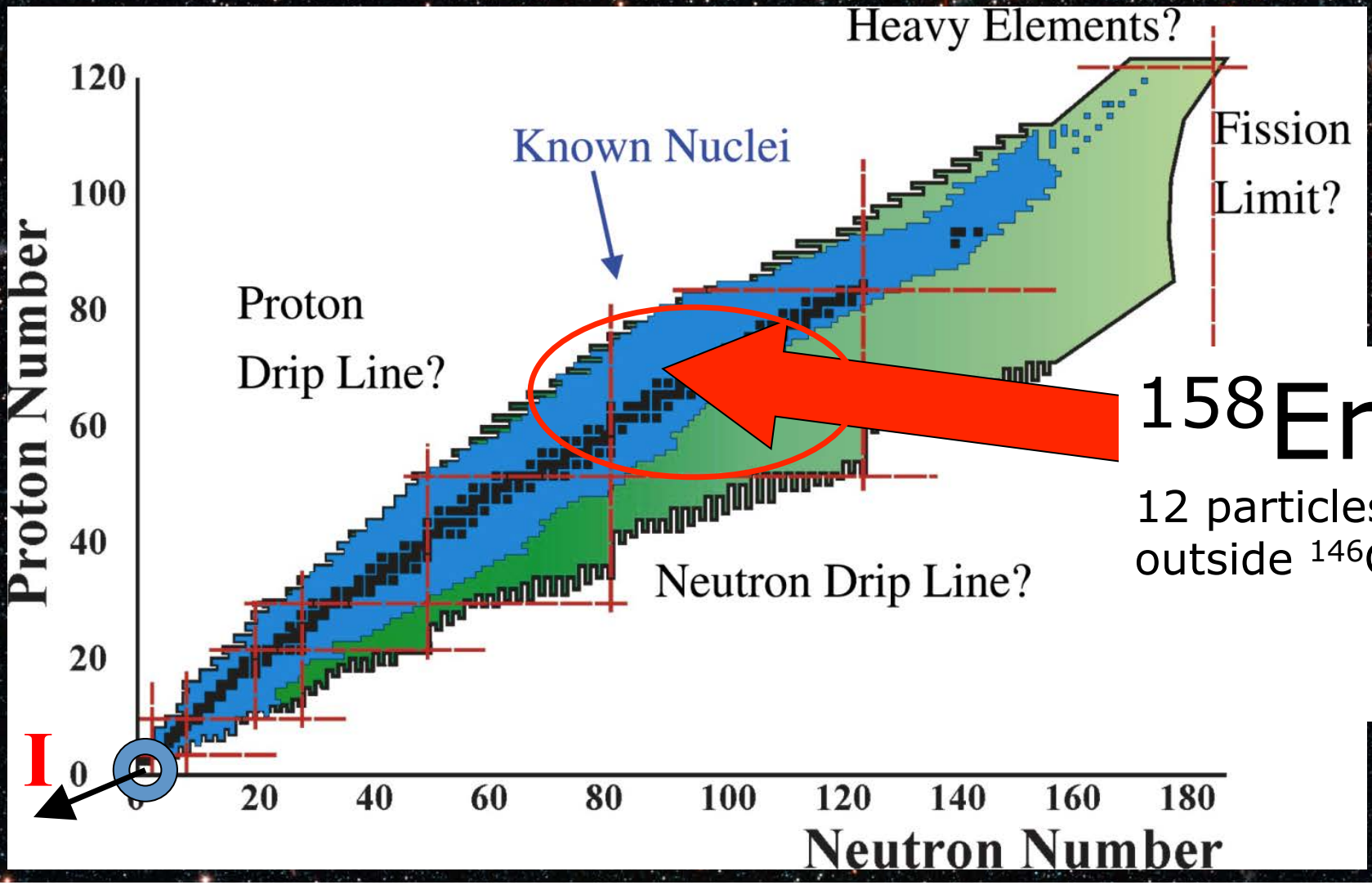
Last night at the reception:
Peter with a few of his students..



Outline of Talk

- The example of ^{158}Er through 4 decades!
- Good for students to know some history.
- Charting out the competing shapes and modes of excitation in its evolution as a function of spin and energy.
- Many people in the room have participated in this great adventure!
- New era of spectroscopy at ultra-high spin (>60) and ultra-low intensities (10^{-4} – 10^{-5} level)
- Results on neighbouring N=90 nuclei and plans for the future.

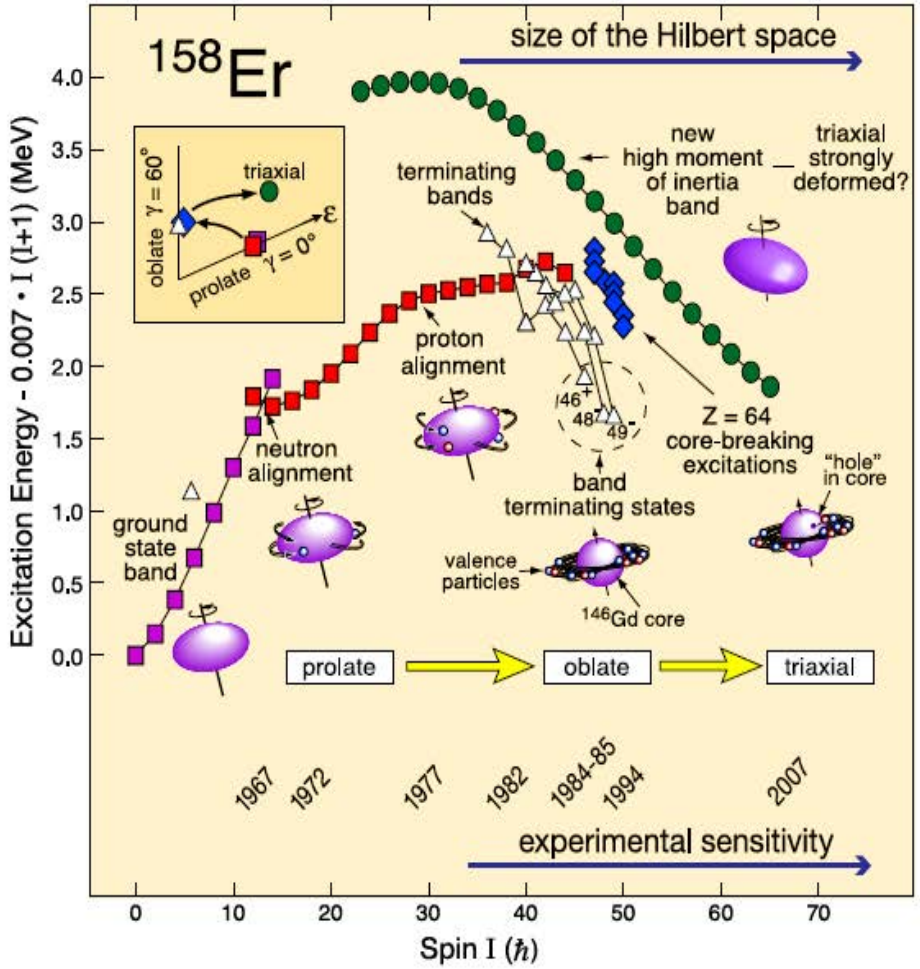
Where are the limits and what happens on the way?

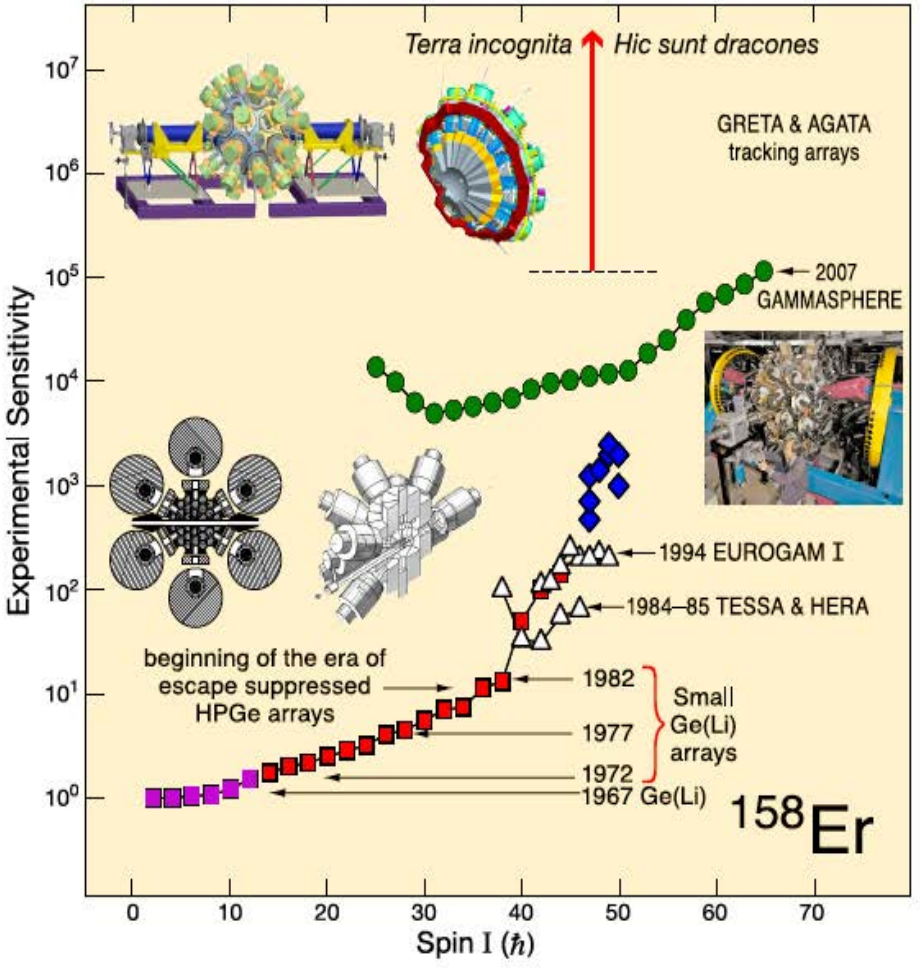


Increasing Angular Momentum and Excitation Energy: A wonderful way to investigate nuclear structure, especially to see what the critically important intruder orbitals are doing.

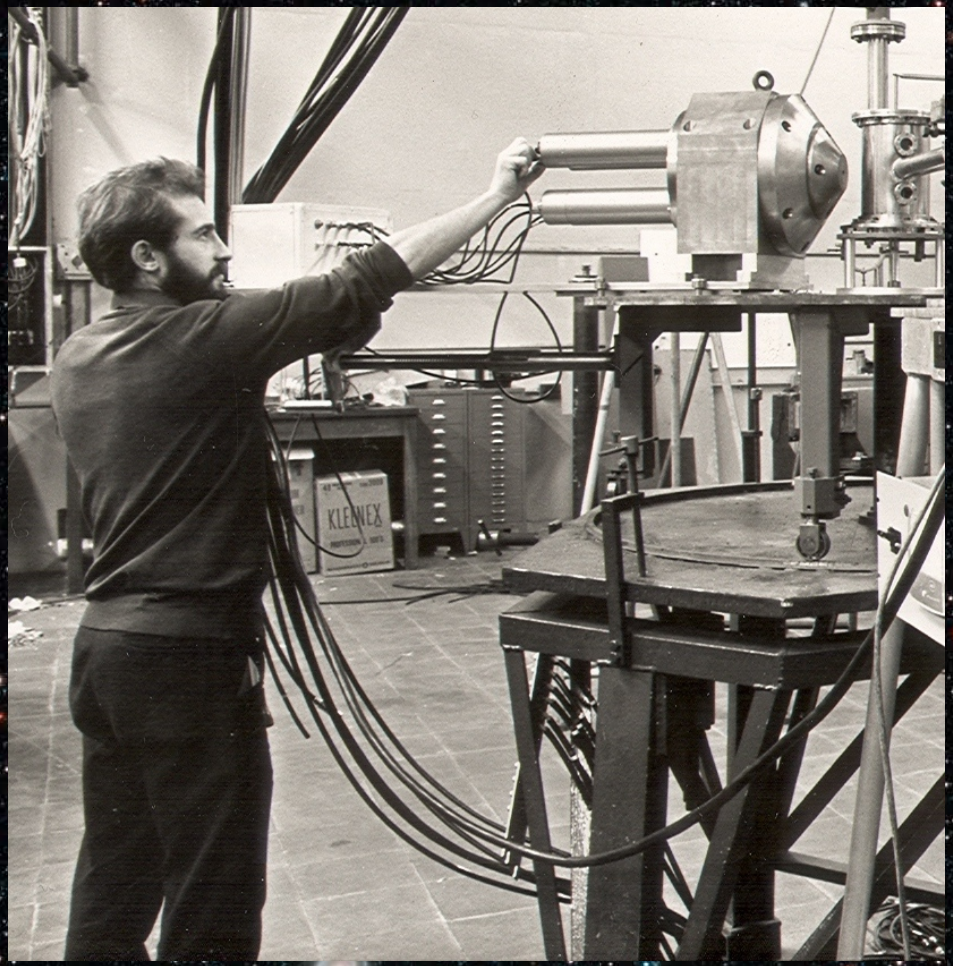
Evolution of Gamma-Ray Spectroscopy

New Detector Systems ⟷ New Physics





Landmark Moment!
JFSS introduces the Escape Suppressed Spectrometer to Liverpool and the UK



A NEW ERA BEGINS!

~1980-1982 TESSA

Escape suppressed array at NBI 5 ESS's

Non-yrast bands to spins in mid 20's

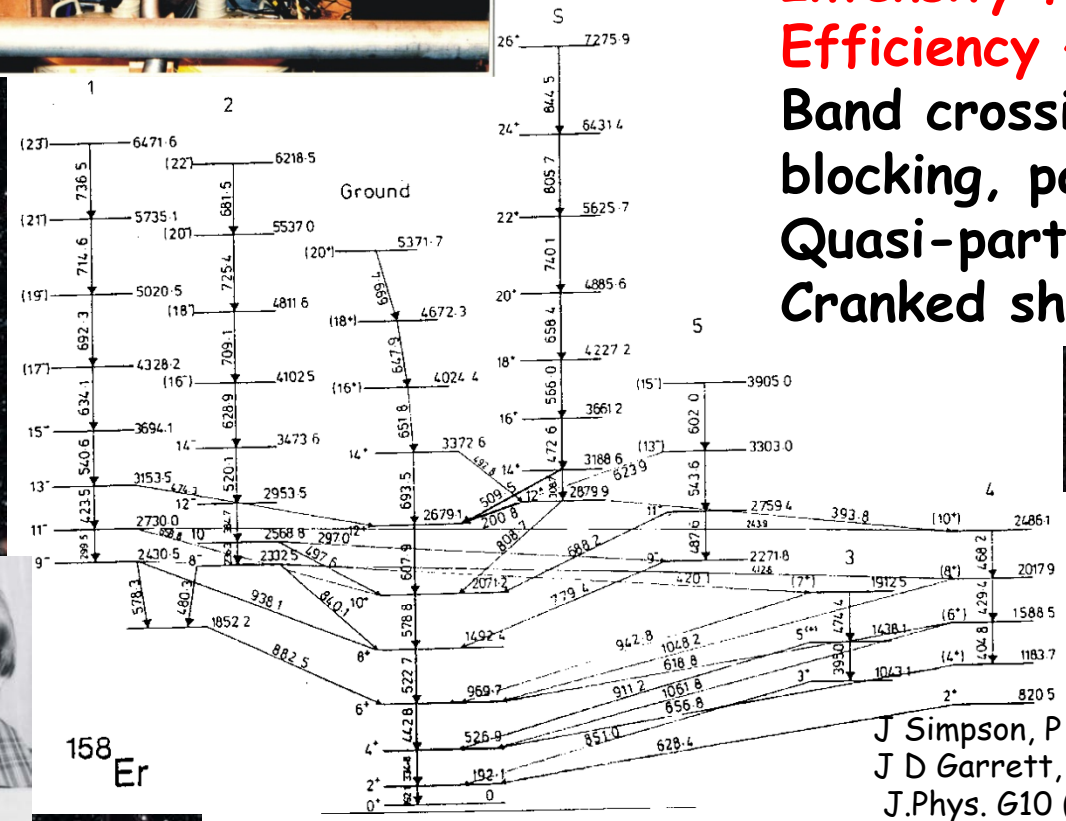
Intensity few %

Efficiency ~0.2%

Band crossing systematics, blocking, pairing reduction

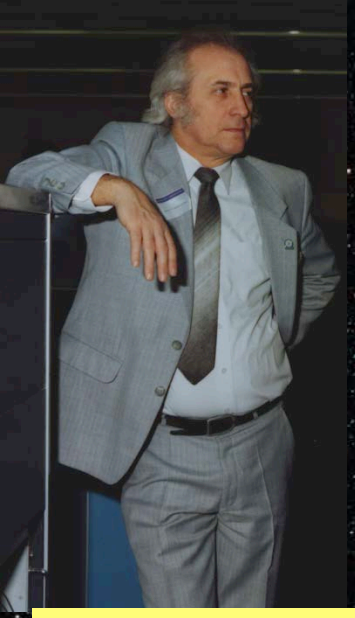
Quasi-particle configurations

Cranked shell model



John was Peter's "first" student!

J Simpson, P A Butler, P D Forsyth, J F Sharpey-Schafer, J D Garrett, G B Hagemann, B Herskind and L P Ekstrom, J.Phys. G10 (1984) 383



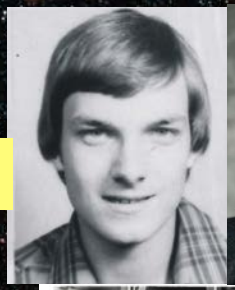
Er-158 experiment at Daresbury Lab in the UK in mid-80's

(Liverpool + NBI)

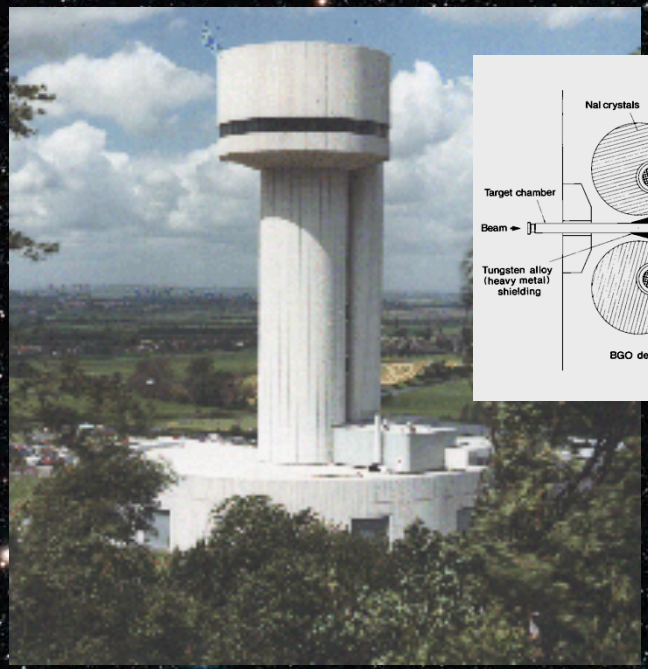
TESSA2

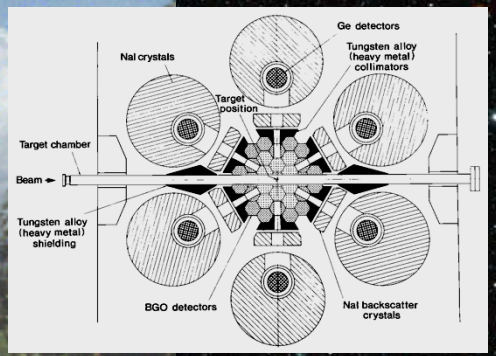
6 ESS + 50 element BGO ball

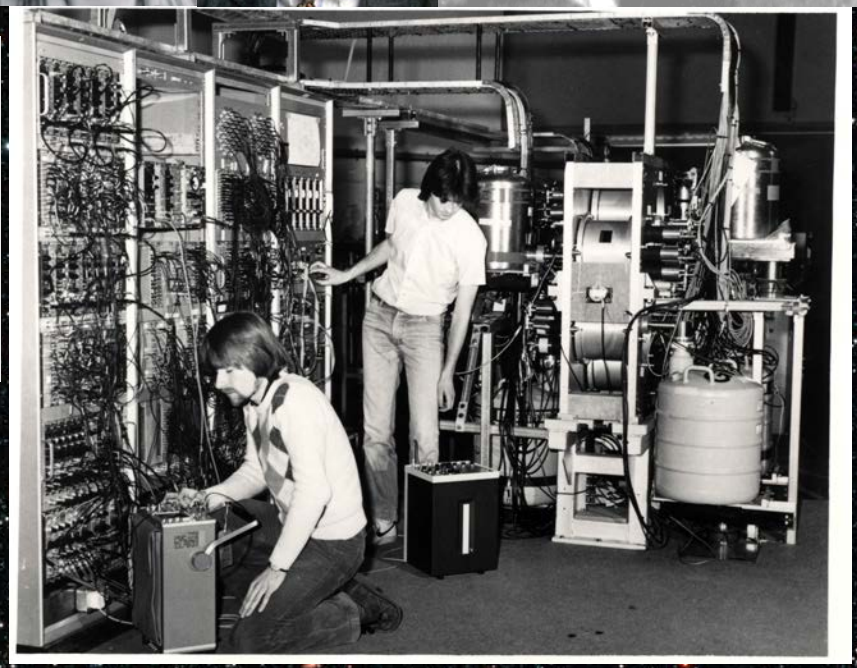
Plus a ^{48}Ca beam!



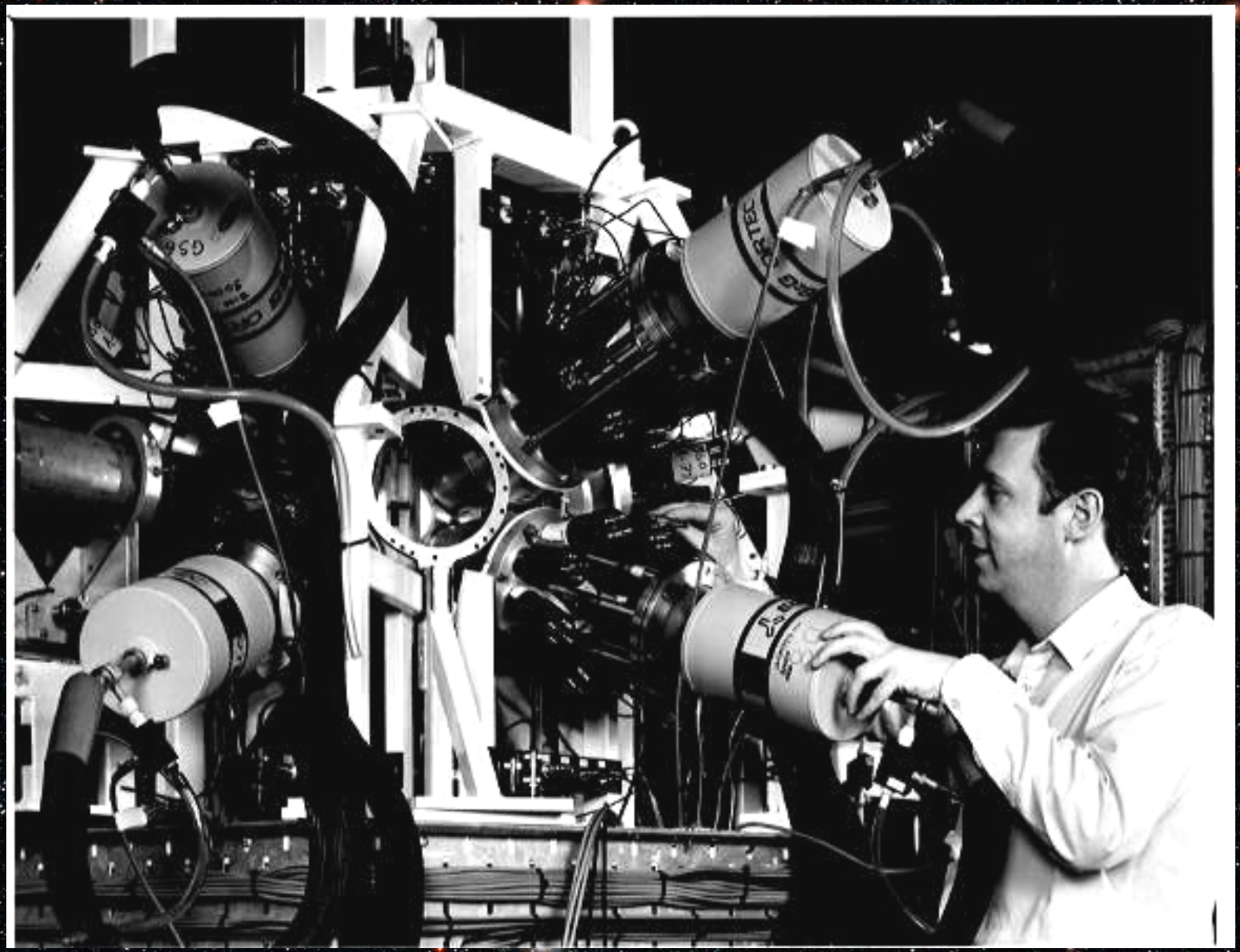
One of my thesis expts.



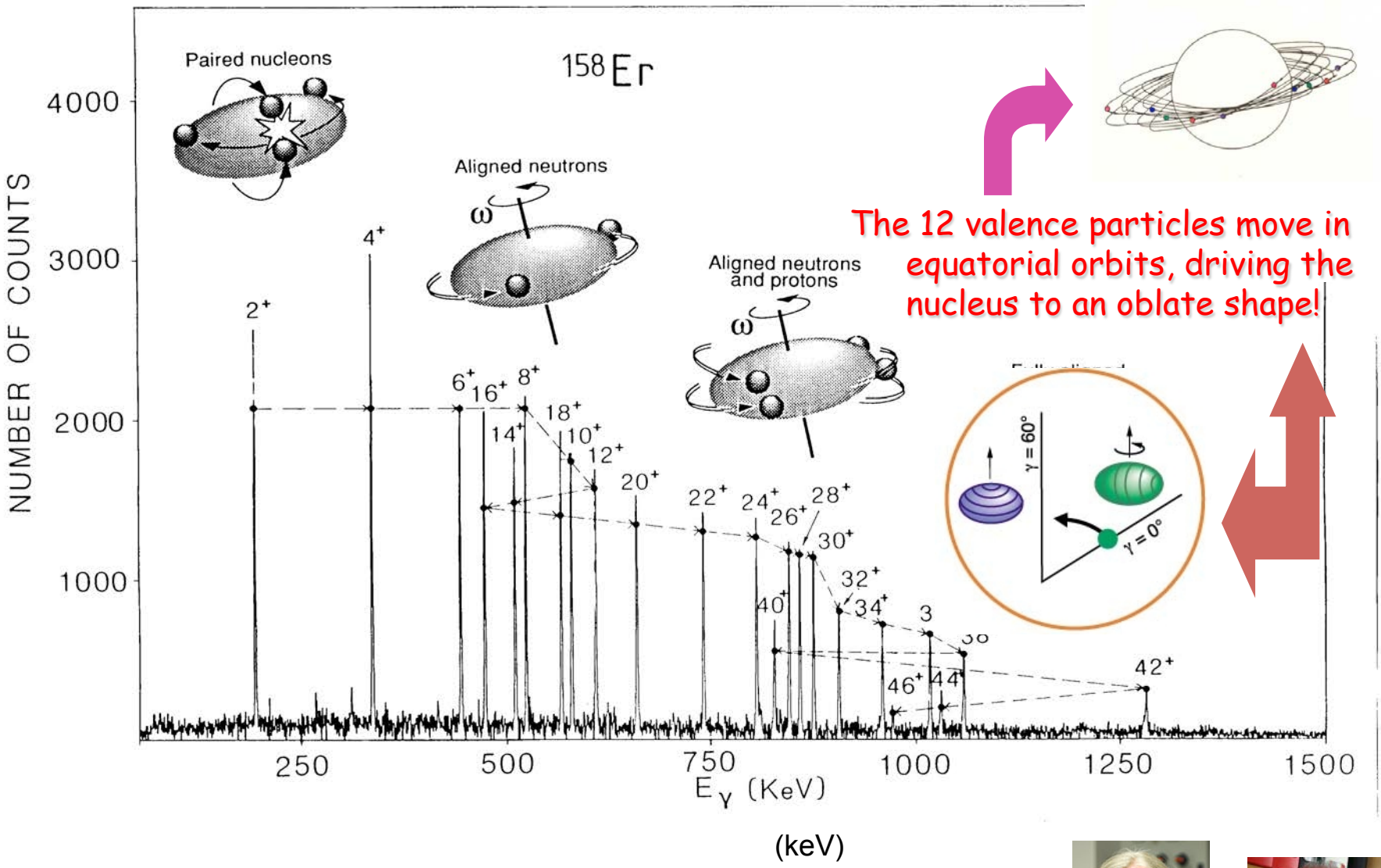




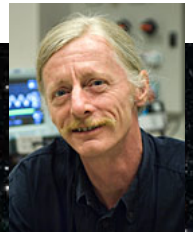
TESSA3: The device that rocked the Universe!



^{158}Er expt at Daresbury – Sharpey-Schafer/Riley/Simpson/Mid-80's

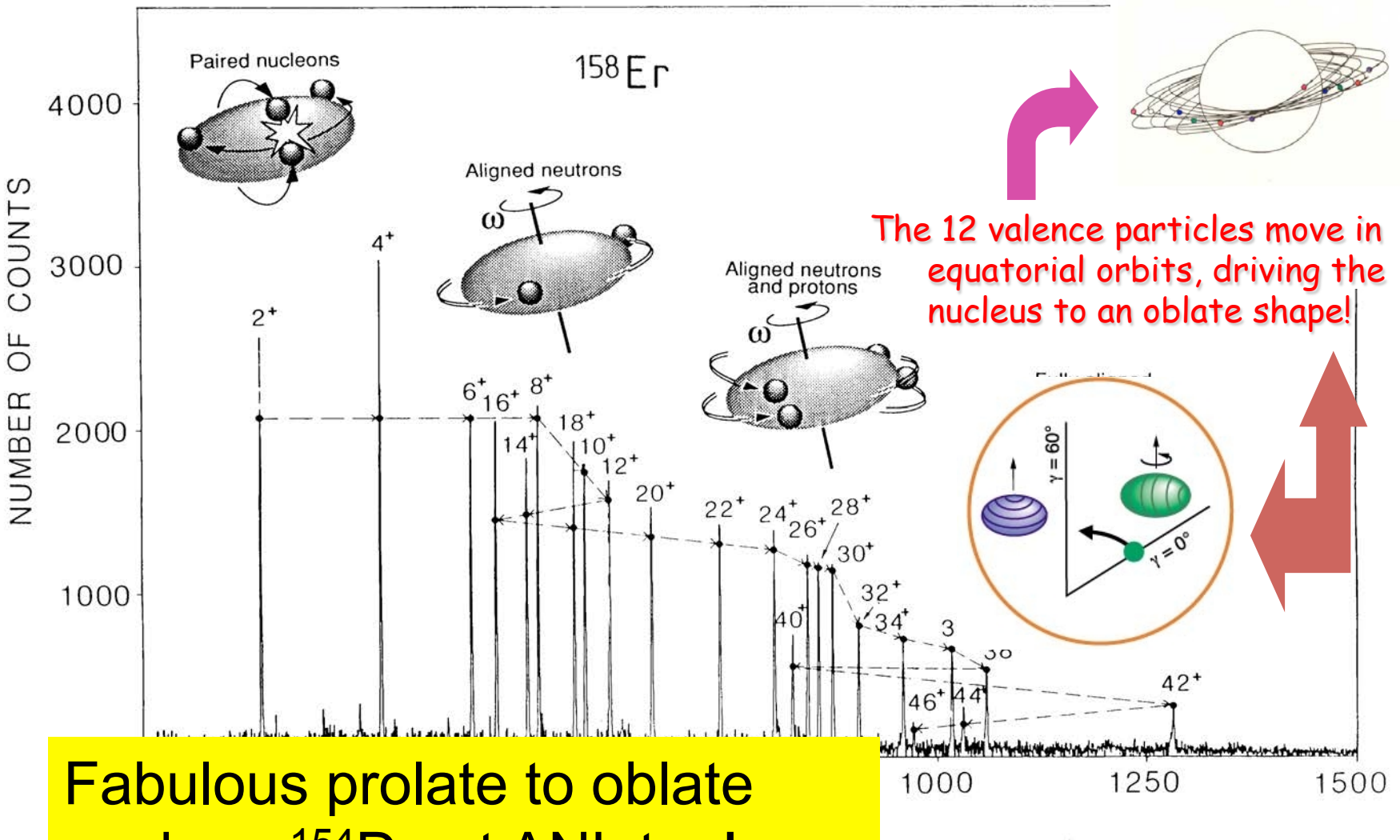


The 12 valence particles move in equatorial orbits, driving the nucleus to an oblate shape!



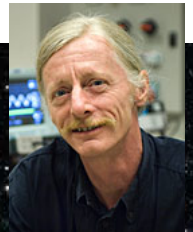
Simpson et al., Phys. Rev. Lett. (1984) – prolate-oblate shape change
LBL group, P.O.Tjom et al., PRL 55 (1985) 2405 – beautiful lifetime measurements
T.Bengtsson and I.Ragnarsson, Physica Scripta T5 (1983) 165
Ragnarsson, Xing, Bengtsson and Riley, Phys. Scripta 34 (1986) 651

^{158}Er expt at Daresbury – Sharpey-Schafer/Riley/Simpson/Mid-80's



The 12 valence particles move in equatorial orbits, driving the nucleus to an oblate shape!

Fabulous prolate to oblate work on ^{154}Dy at ANL too!



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T.Bengtsson and I.Ragnarsson, Physica Scripta T5 (1983) 165
Ragnarsson, Xing, Bengtsson and Riley, Phys. Scripta 34 (1986) 651

^{158}Er expt at Daresbury – Sharpey-Schafer/Riley/Simpson/Mid-80's

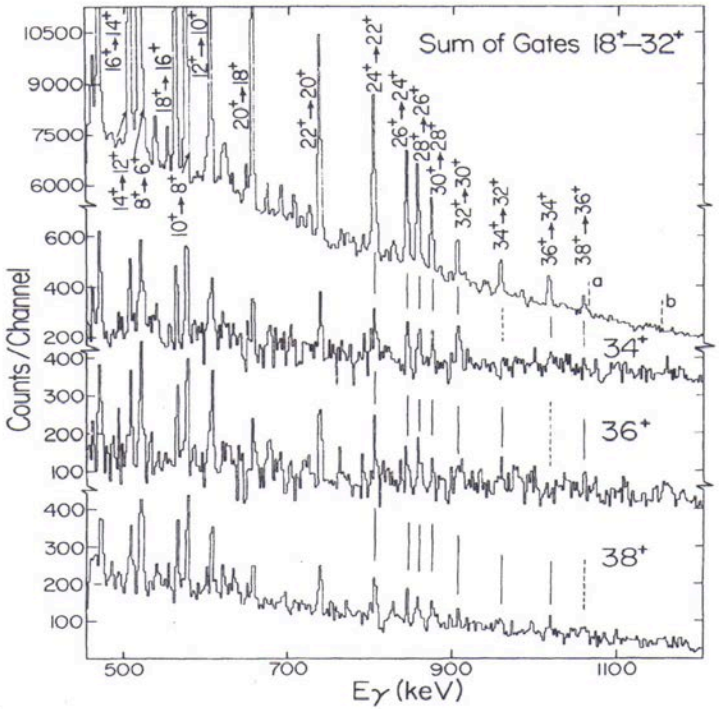
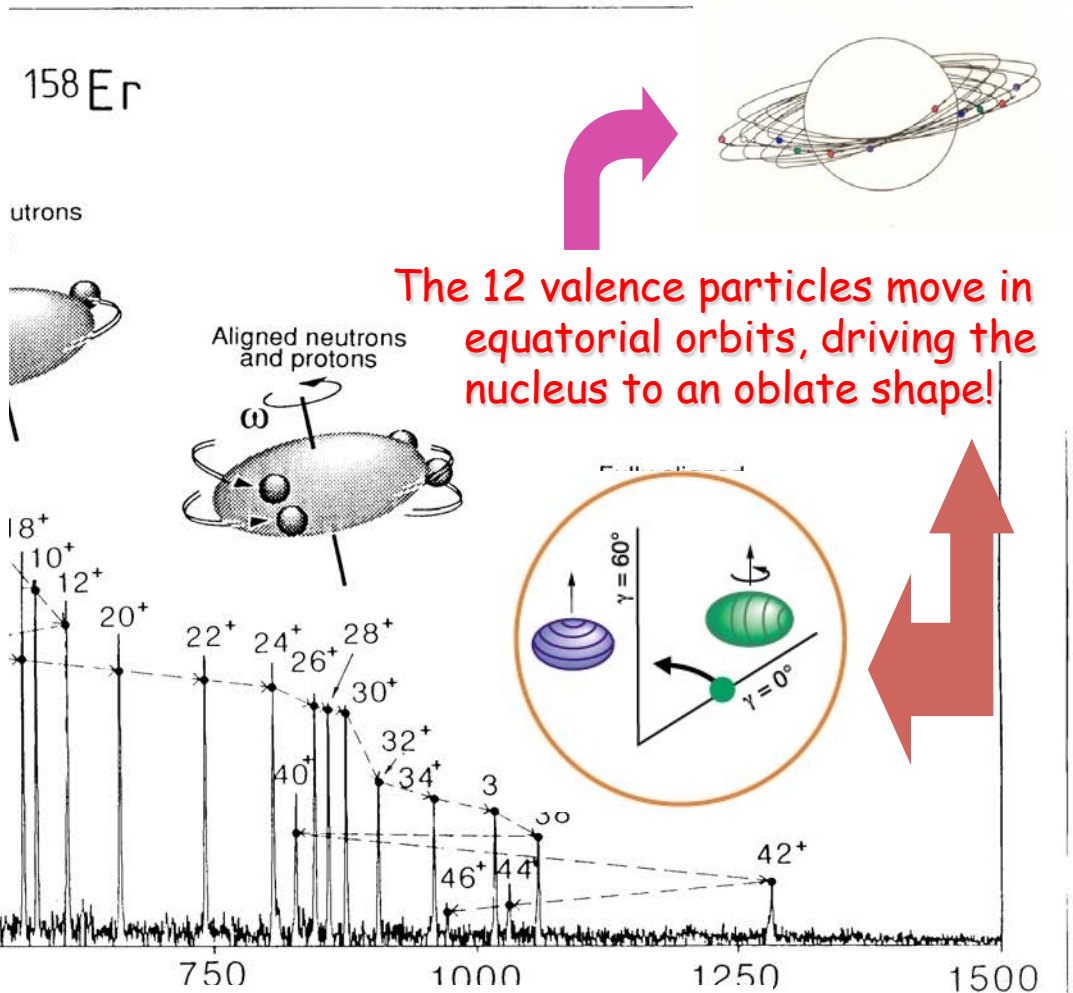


FIG. 1. Coincident γ-ray spectra from the reaction ^{122}Sn(^{40}Ar, $4n$)^{158}Er obtained with indicated gates.



The 12 valence particles move in equatorial orbits, driving the nucleus to an oblate shape!

VOLUME 48, NUMBER 8 PHYSICAL REVIEW LETTERS 22 FEBRUARY 1982

Third Discontinuity in the Yrast Levels of ^{158}Er

J. Burde,[a] E. L. Dines,[b] S. Shih,[c] R. M. Diamond, J. E. Draper,[b] K. H. Lindenberger,[d] C. Schück,[e] and F. S. Stephens

Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

(Received 7 December 1981)

Discrete yrast transitions from states with spins up to $I=38$ have been observed in ^{158}Er via the reaction ^{122}Sn(^{40}Ar, $4n\gamma$). In addition to the pronounced backbend at $I=14$ and the

1984 - Liverpool to Lund/Copenhagen letters to/from Sven & Ingemar on ^{158}Er!

UNIVERSITY OF LUND
LUNDS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF MATHEMATICAL PHYSICS
P.O. BOX 725 S-22007 LUND 7 SWEDEN

Lund, April 27, 1987

Dear Dr Sharpey-Schafer,

We were very impressed by the high spin spectra which Wiesław Nazarewicz got from you in Poland. A nucleus which especially interests us is ^{158}Er, partly because the spectrum seem to show the largest irregularities and of course also because we recently wrote the enclosed paper about this nucleus. We therefore want to give some suggestions about the possible structure of the different states and about possible continuations of the bands.

Our calculated positive parity, signature r = 1 spectrum is shown relative to a "liquid-drop reference", $\mathcal{E}_{LDM} = \frac{\hbar^2}{2\mathcal{I}}I(I+1)$ MeV, in fig. 5 of the enclosed paper. We have then also plotted the states observed experimentally relative to the same reference. The similarities between the two spectra are so striking that we

NORDITA NORDISK INSTITUT FOR TEORETISK ATOMFYSIK
Danmark · Finland · Island · Norge · Sverige

Sven Åberg
BLEGDAMSVEJ 17
DK-2100 KØBENHAVN Ø · DANMARK
TELEGRAM: NORDITA KØBENHAVN
TELEFON: 01 - 42 16 16

Copenhagen, Jan. 10, 1984

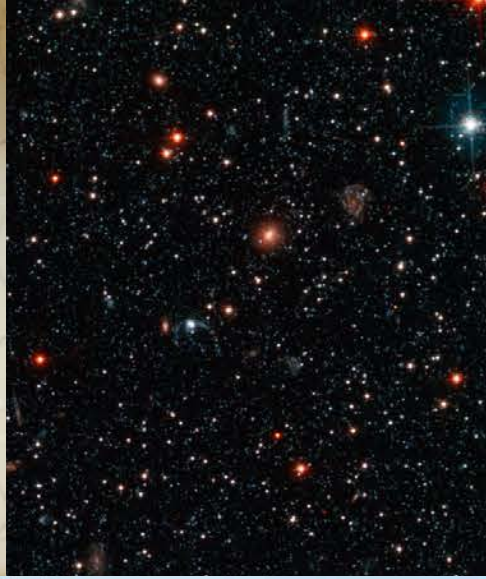
Dear Riley,

Thank you very much for the nice present. It is certainly impressing how well you have pushed the data. The colour pictures as well as the level spectra are really looking beautiful. I can see that there is a lot of work to do for the theorists. At present, when I have just started to look at the things, I have only a little question. When I have tried to identify the peaks in the ^{158}Er spectra with your decay scheme, there are some very large peaks which I can't identify. On the enclosed spectra I have marked these with question marks. What have I done wrong? In my eyes the two narrow peaks at 1202 and 1210 keV are smaller than the peak around 915 keV. But maybe the background is worse there? If this is the case, that the background is worse at lower energies, do you then miss possible low-energy (E2,M1) transitions built on e.g. 42$^+$ or on 40$^+$2 If you put a gate on e.g. the 1038 peak (38→36) can you the then find out what comes before and what comes after this transition? Would you see an isomer above spin 40 - 42 ? I hope you will find some time to answer my more or less stupid questions.

Best Regards

Sven

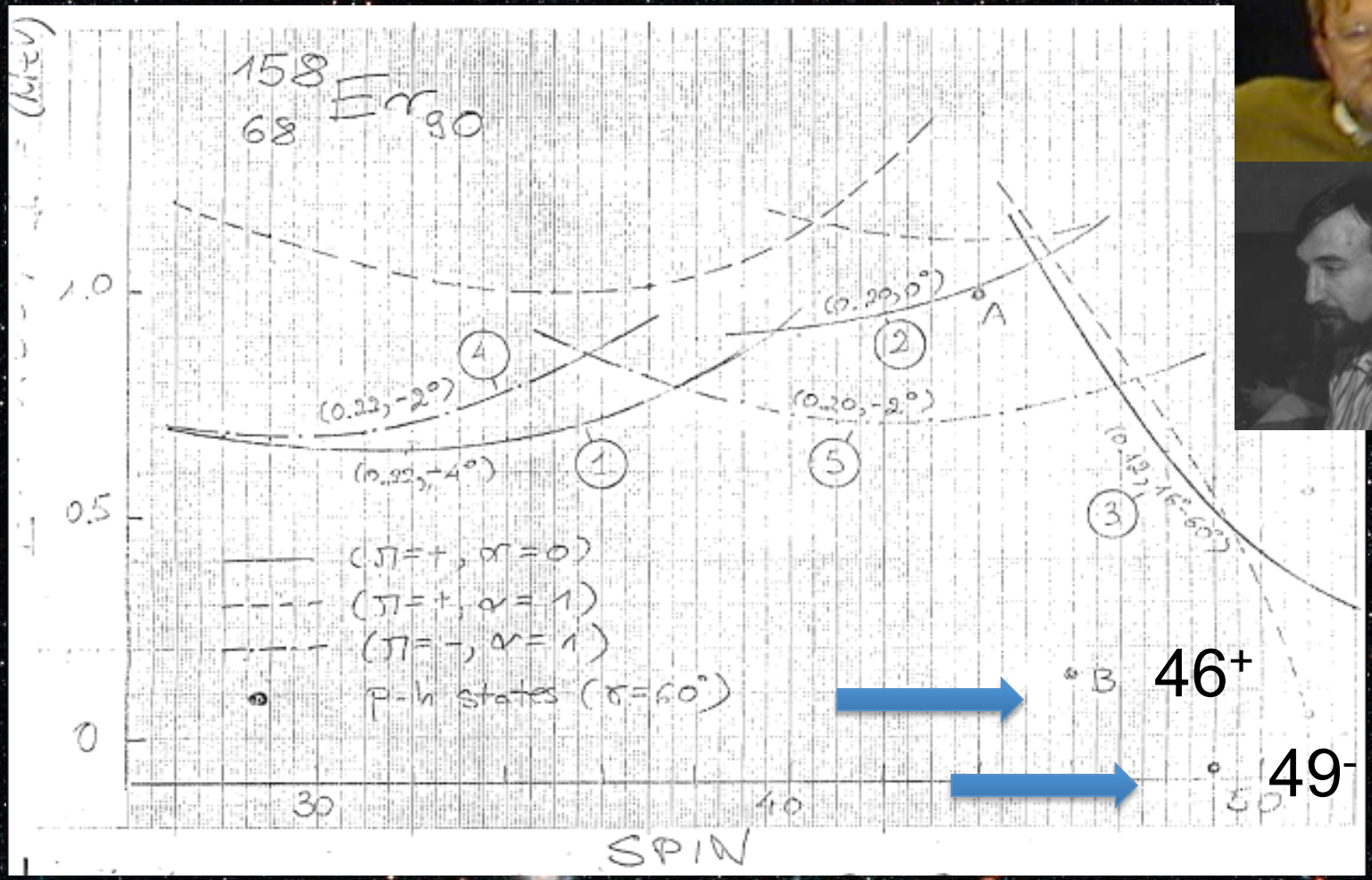
PS1 Happy New Year
PS2 Unfortunately, I have forgotten your first name.
PS3 May I show the pictures to other people? On a seminar?



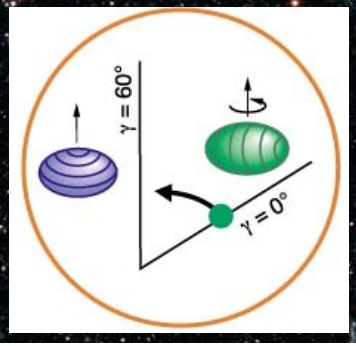
Sweden 2012

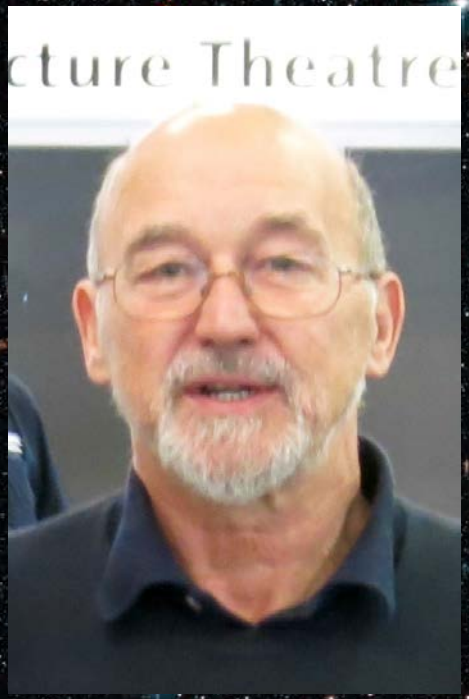
1985: Witek and Jerzy fabulous calculations on ^{158}Er too!

Original hand drawings for the famous 1985 article
Phys. Rev. C31 (1985) 298

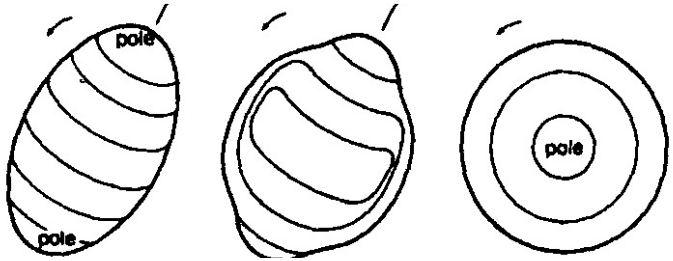


Lund 1985
Serious Stuff!

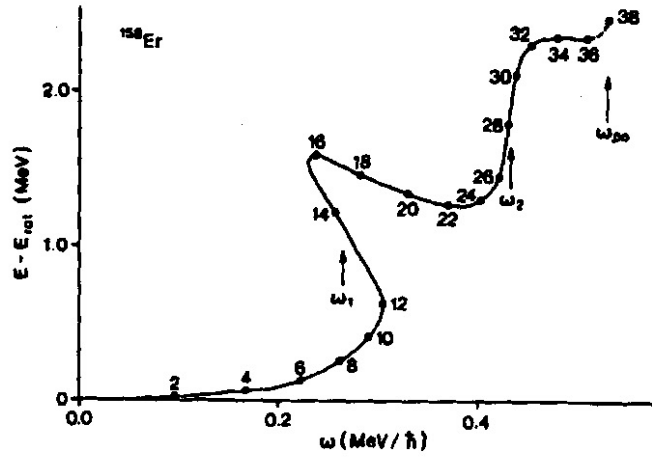




LOW INTERMED HIGH spin



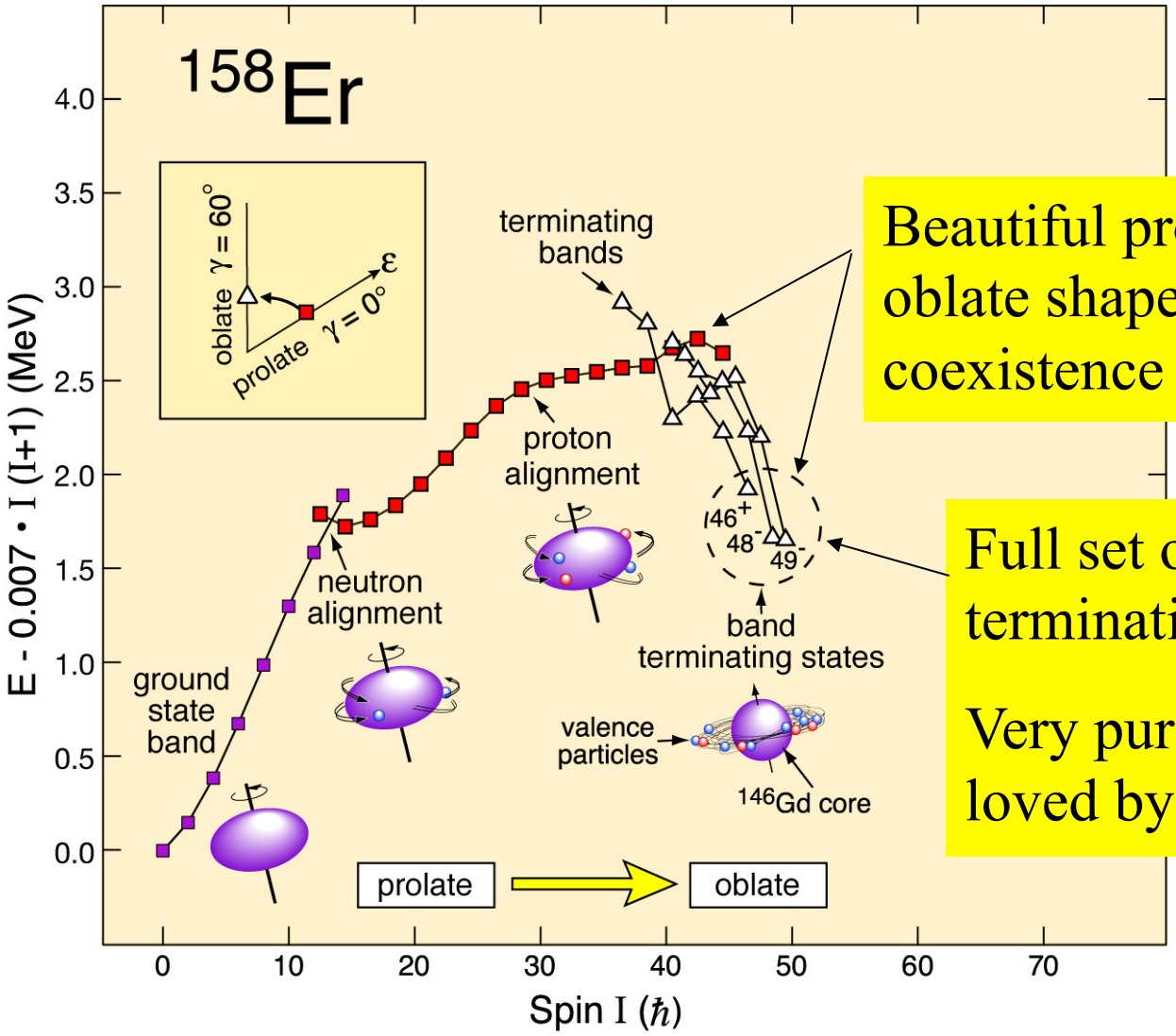
PROLATE TRIAXIAL OBLATE



N. Rowley, fabulous Nature article in 1985

Along the Yrast Line ^{158}Er – circa mid 90's

^{158}Er again at Daresbury but now with EUROGAM (37 ESS)



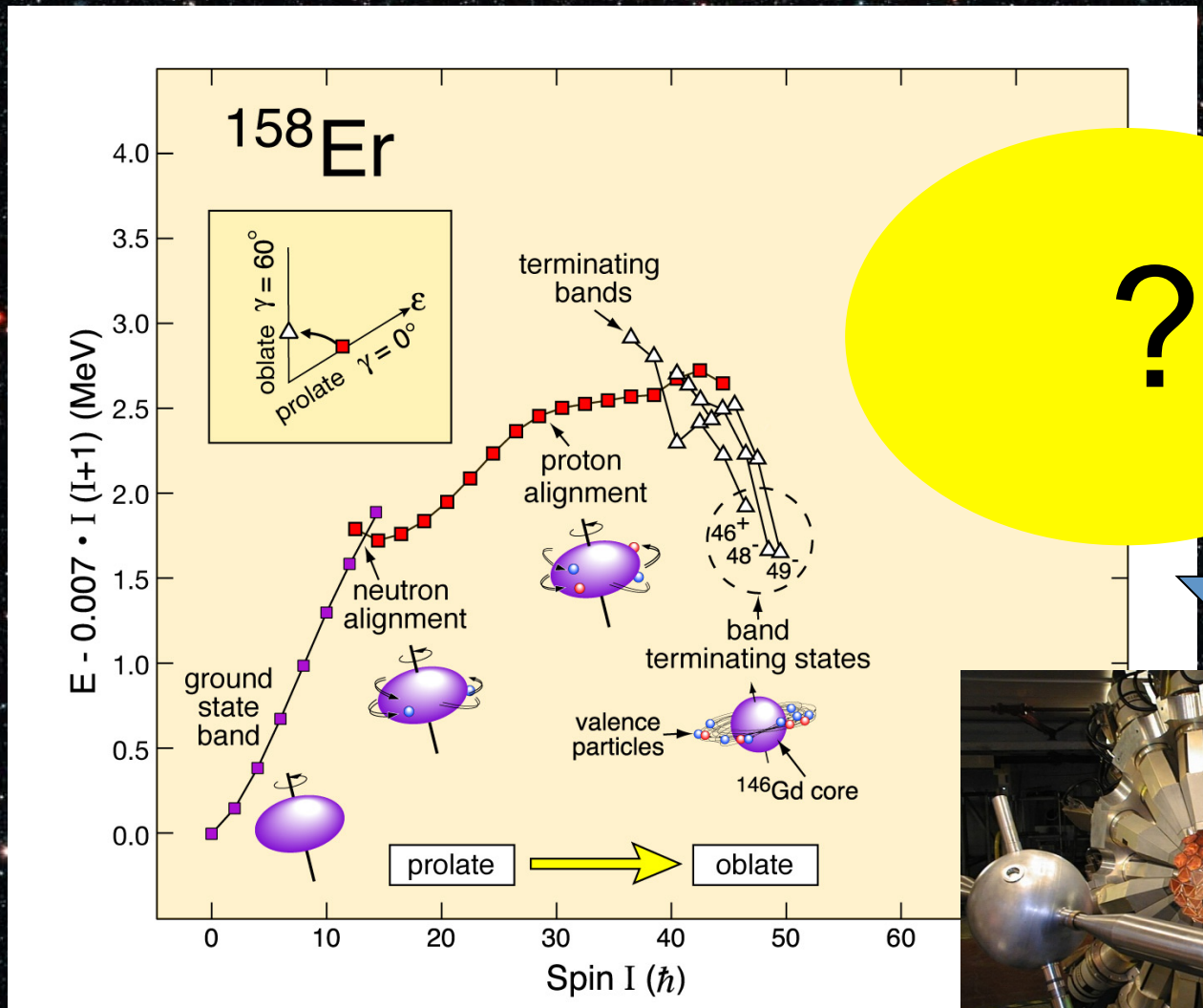
Beautiful prolate – oblate shape coexistence

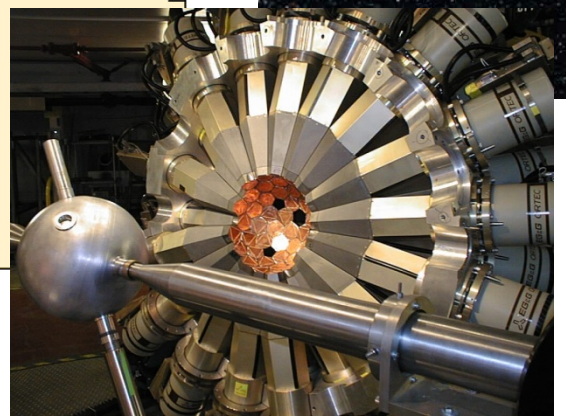
Full set of favored terminations!

Very pure states – loved by theorists

Simpson, Riley, JFSS et al., Phys. Lett. B327 (1994) 187

In 00's…WHAT LIES ABOVE BAND TERMINATION? … Gammasphere at LBL!

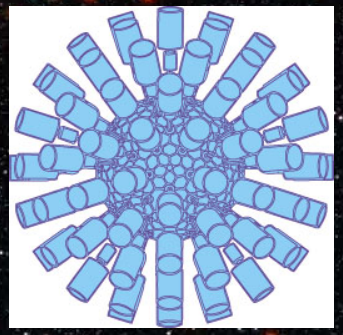


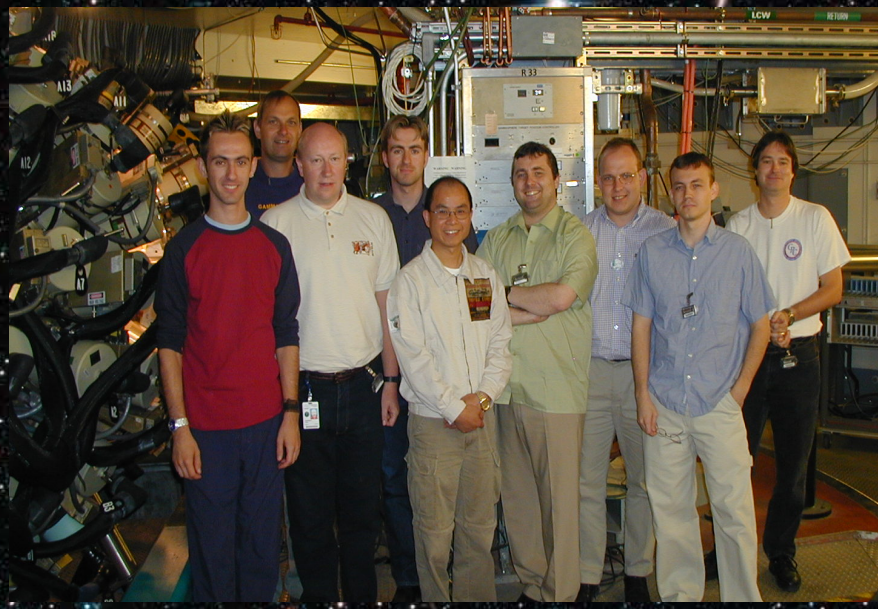


In the 00's: GS = 97 ESS's!
BEYOND BAND TERMINATION in ^{157,158}Er!

- ^{114}Cd(^{48}Ca,4,5n) @ 215MeV
- GS Triggered on clean fold 7+
- Famous phone call to JFSS!
- FSU + Daresbury + Liverpool + LBNL + Lund
- ^{158}Er has taken time to crack
- But we had wonderful early success with ^{157}Er:

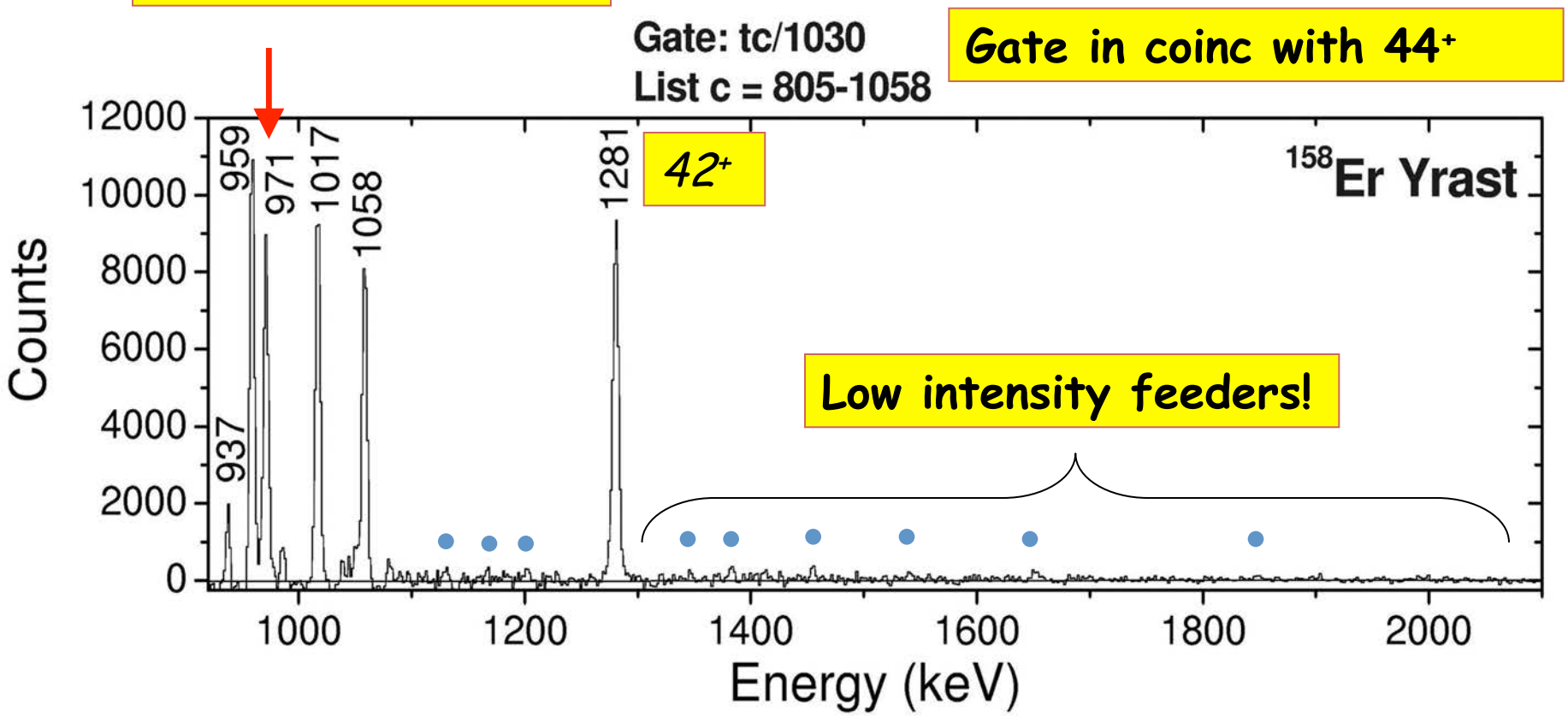
A.O. Evans et al.,
PRL 92, 252502 (2004)



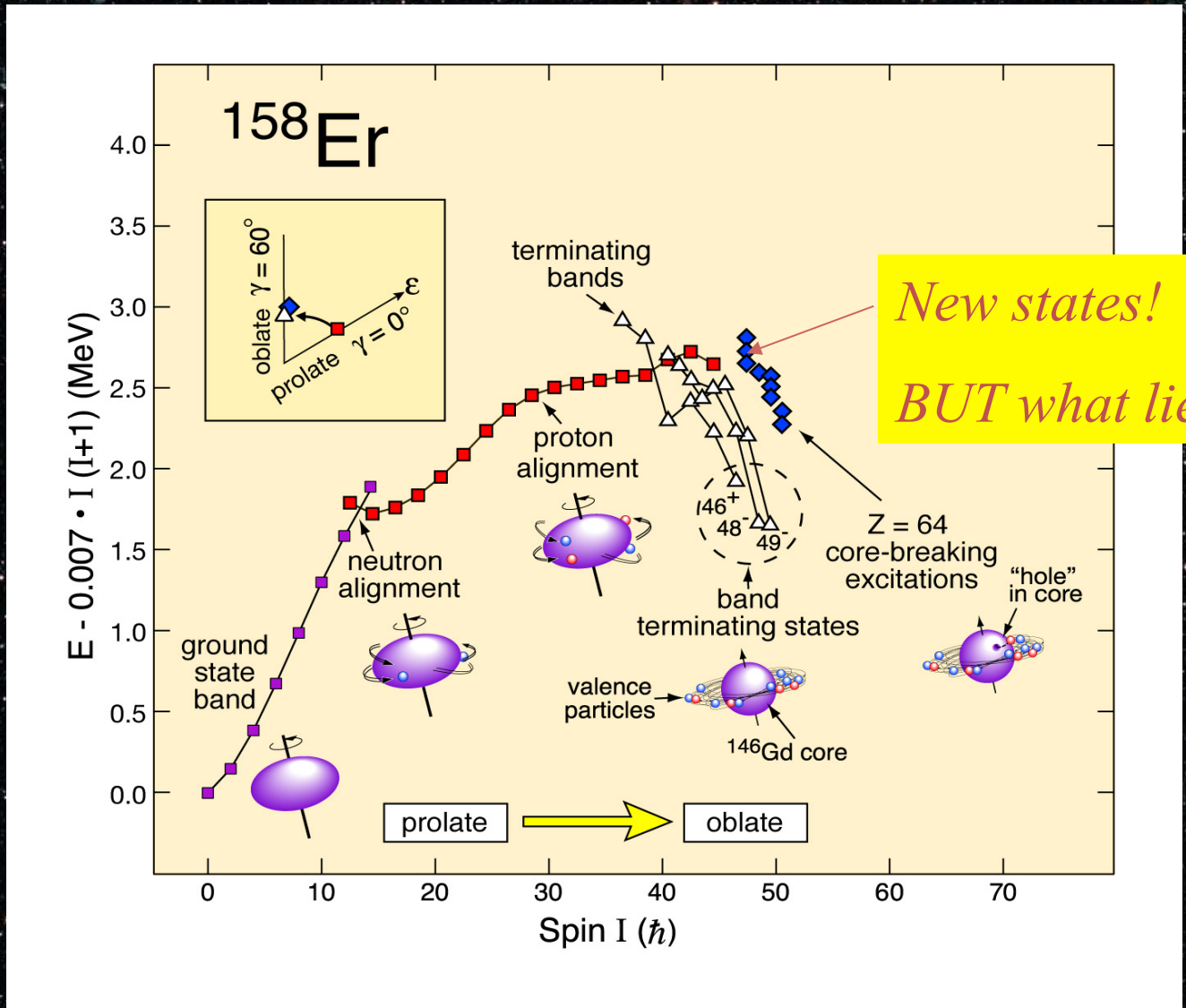


What about ^{158}Er above 46^+?
It had taken us 20 years!
No wonder we could not see it before!

46^+ = 1% of $2^+ \rightarrow 0^+$



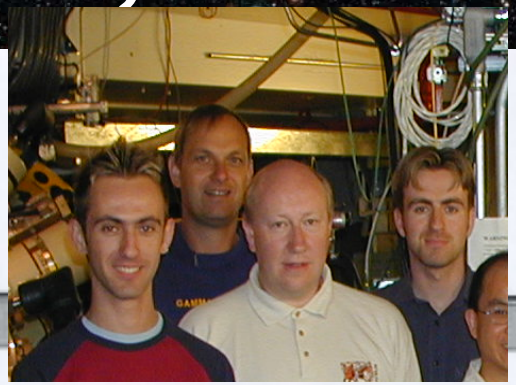
Along the Yrast Line of ^{158}Er, 2005



Always keep hunting for the needle(s) in the haystack

Thanks to Winston …we kept searching and searching and searching!

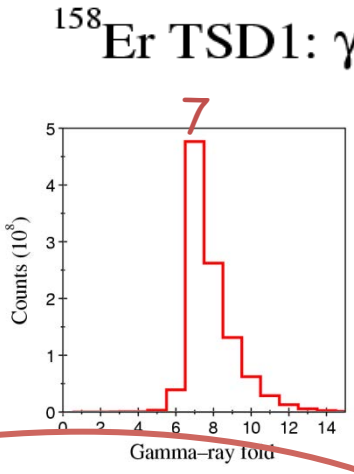
Finally… a breakthrough email from the UK from Aled, Eddie, John and Paul! (very weak signal ~few 10^{-4})



The Return of Collectivity beyond Band Termination in ^{157,158}Er

Band 1 in ^{158}Er – Peter Twin, high fold analysis

~100 times weaker than SD band in ^{152}Dy !



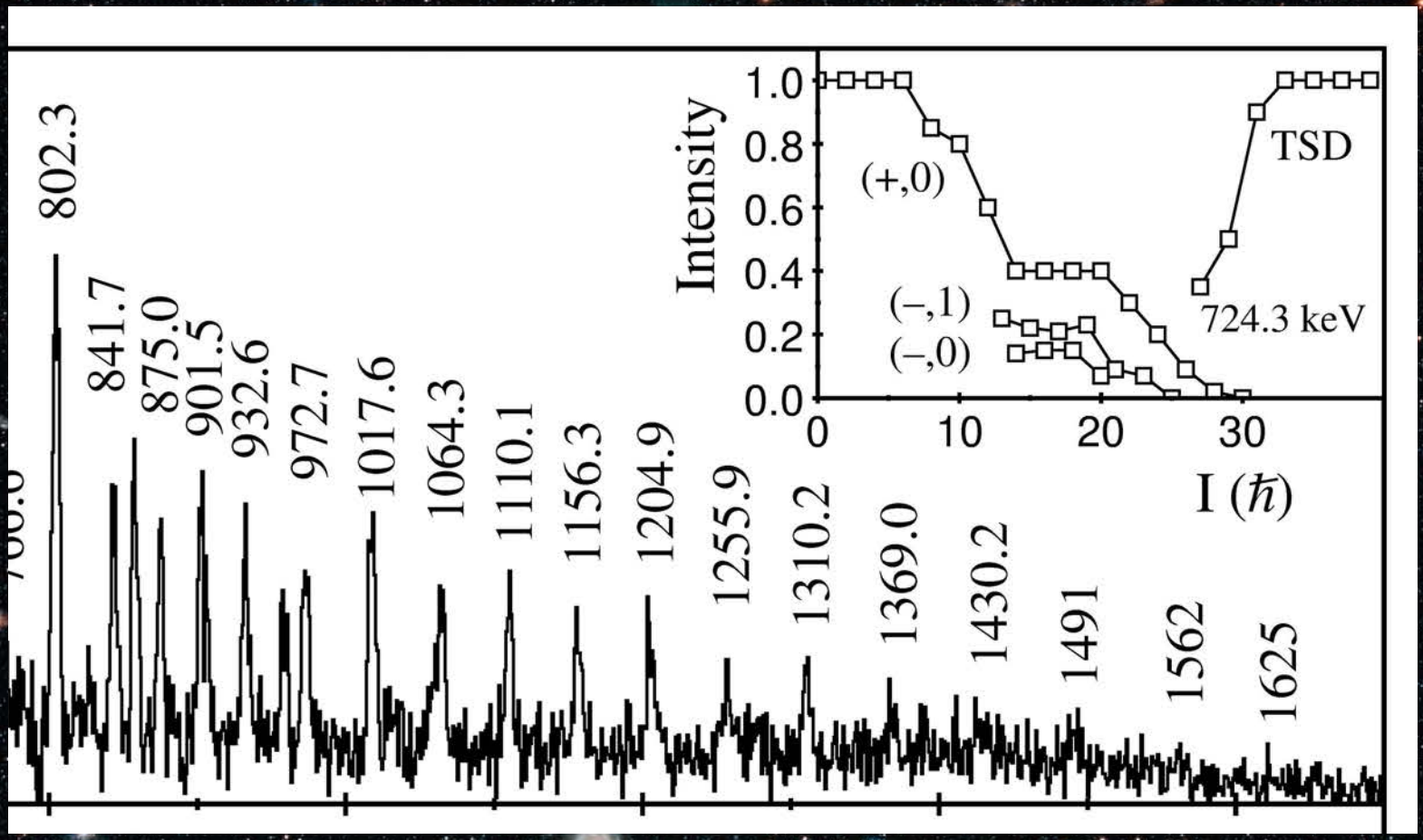
Counts

E_γ (MeV)

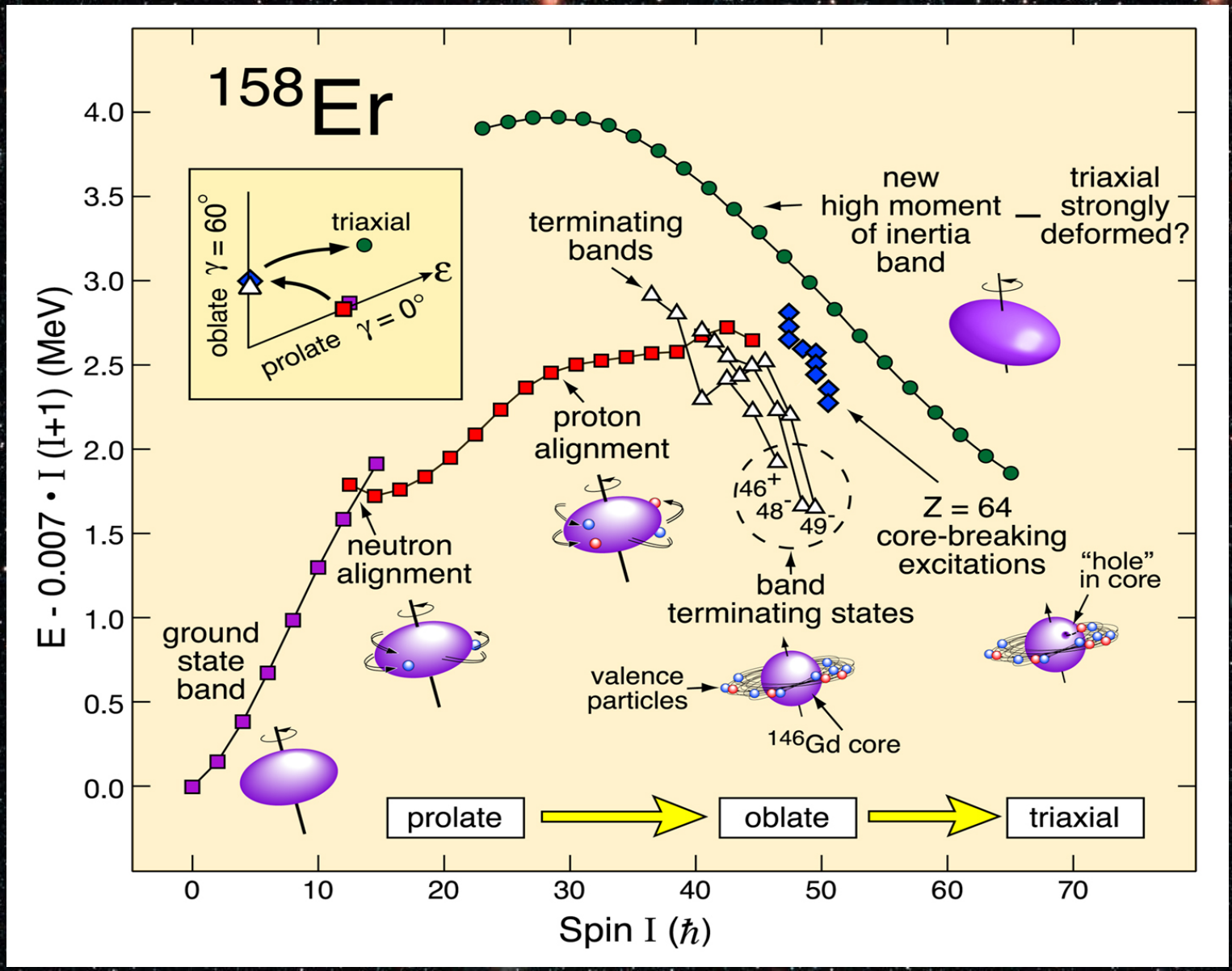
Spin range 25 - 65ħ

Where to place the bands in spin? Decay out is fragmented to several near yrast bands…… hint hint

Band 1 in ^{158}Er… spin range = 25-65!



Along the Yrast Line ^{158}Er



PRL 98, 012501 (2007) PHYSICAL REVIEW LETTERS week ending 5 JANUARY 2007

Return of Collective Rotation in ^{157}Er and ^{158}Er at Ultrahigh Spin

E. S. Paul,[1] P. J. Twin,[1] A. O. Evans,[1] A. Pipidis,[2] M. A. Riley,[2] J. Simpson,[3] D. E. Appelbe,[3] D. B. Campbell,[2,*] P. T. W. Choy,[1] R. M. Clark,[4] M. Cromaz,[4] P. Fallon,[4] A. Görgen,[4,†] D. T. Joss,[3,‡] I. Y. Lee,[4] A. O. Macchiavelli,[4] P. J. Nolan,[1] D. Ward,[4] and I. Ragnarsson[5]

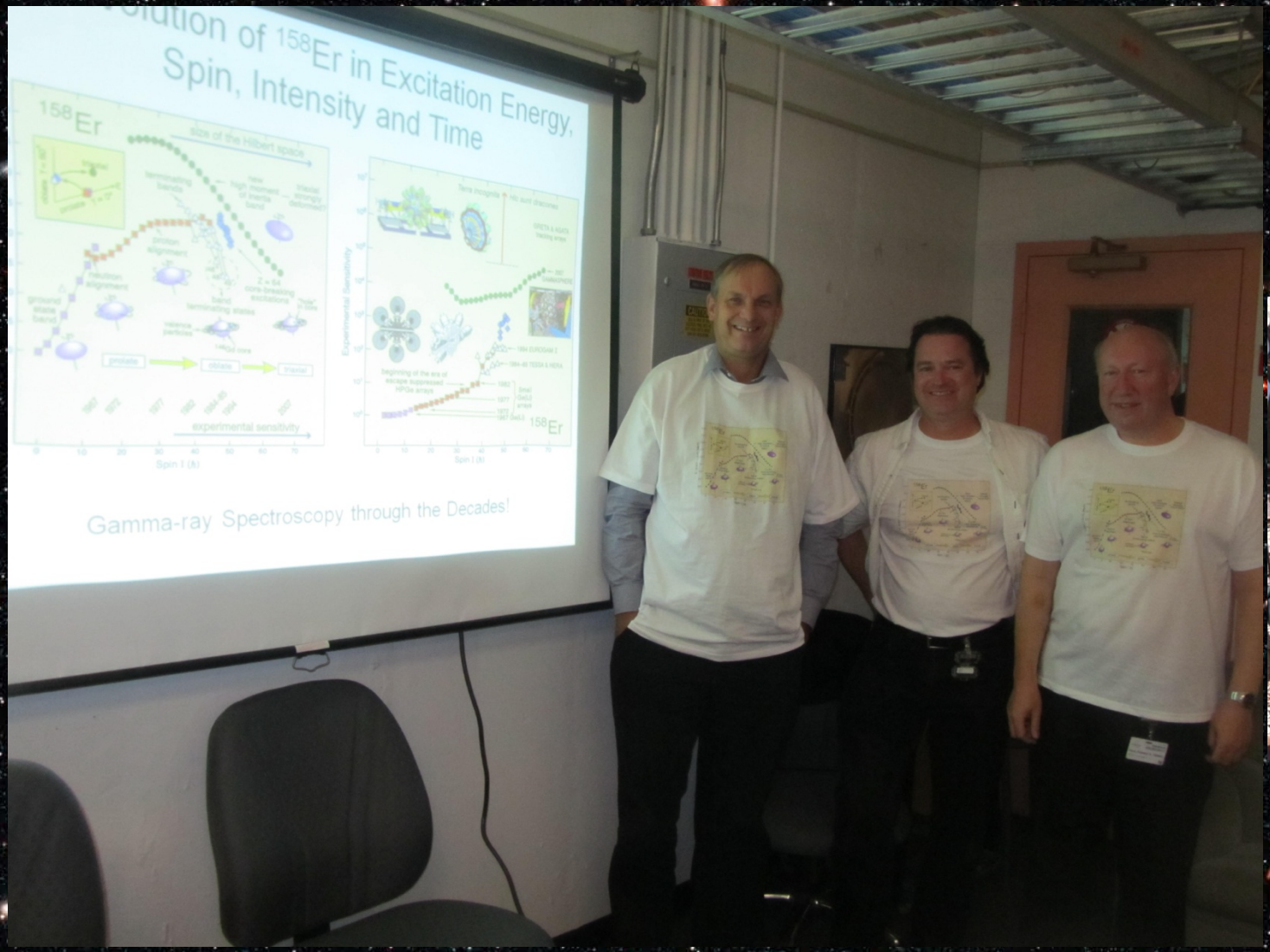
[1]*Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[2]*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*
[3]*CCLRC Daresbury Laboratory, Daresbury, Warrington WA4 4AD, United Kingdom*
[4]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[5]*Department of Mathematical Physics, Lund Institute of Technology, P.O. Box 118, S-22100 Lund, Sweden*

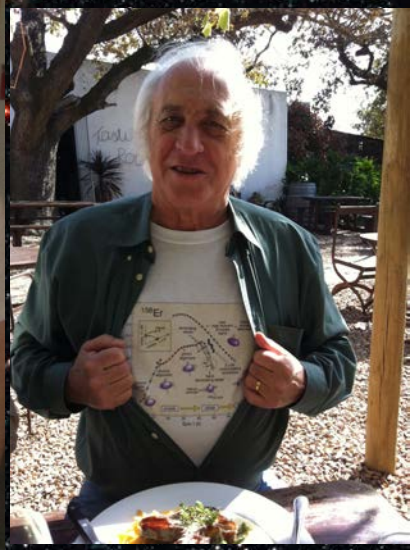
(Received 5 September 2006; published 5 January 2007)

A new frontier of discrete-line γ-ray spectroscopy at ultrahigh spin has been opened in the rare-earth nuclei ^{157,158}Er. Four rotational structures, displaying high moments of inertia, have been identified, which extend up to spin $\sim 65\hbar$ and bypass the band-terminating states in these nuclei which occur at $\sim 45\hbar$. Cranked Nilsson-Strutinsky calculations suggest that these structures arise from well-deformed triaxial configurations that lie in a valley of favored shell energy which also includes the triaxial strongly deformed bands in $^{161-167}$Lu.

Selected as the first ever "Editors Suggestion" in nuclear physics

The Erbium family!

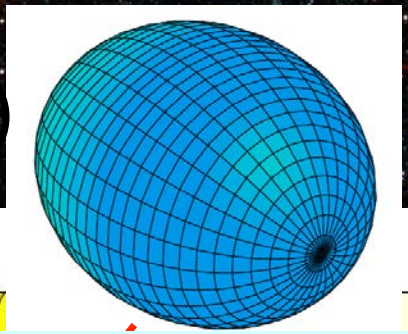




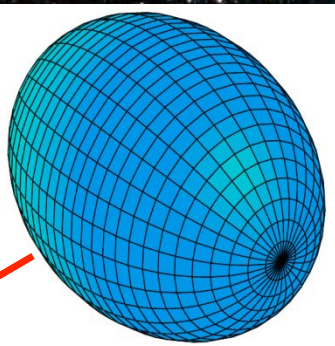

LET IT BE
ERBIUM
PORSCHE


IMAGINE
06-14
158 ERB

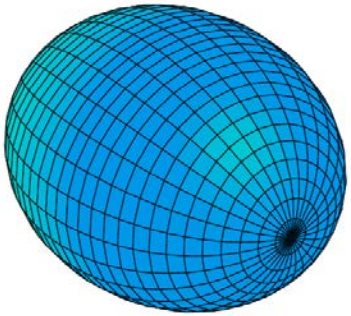
TRIAXIAL (positive-gamma TSD)



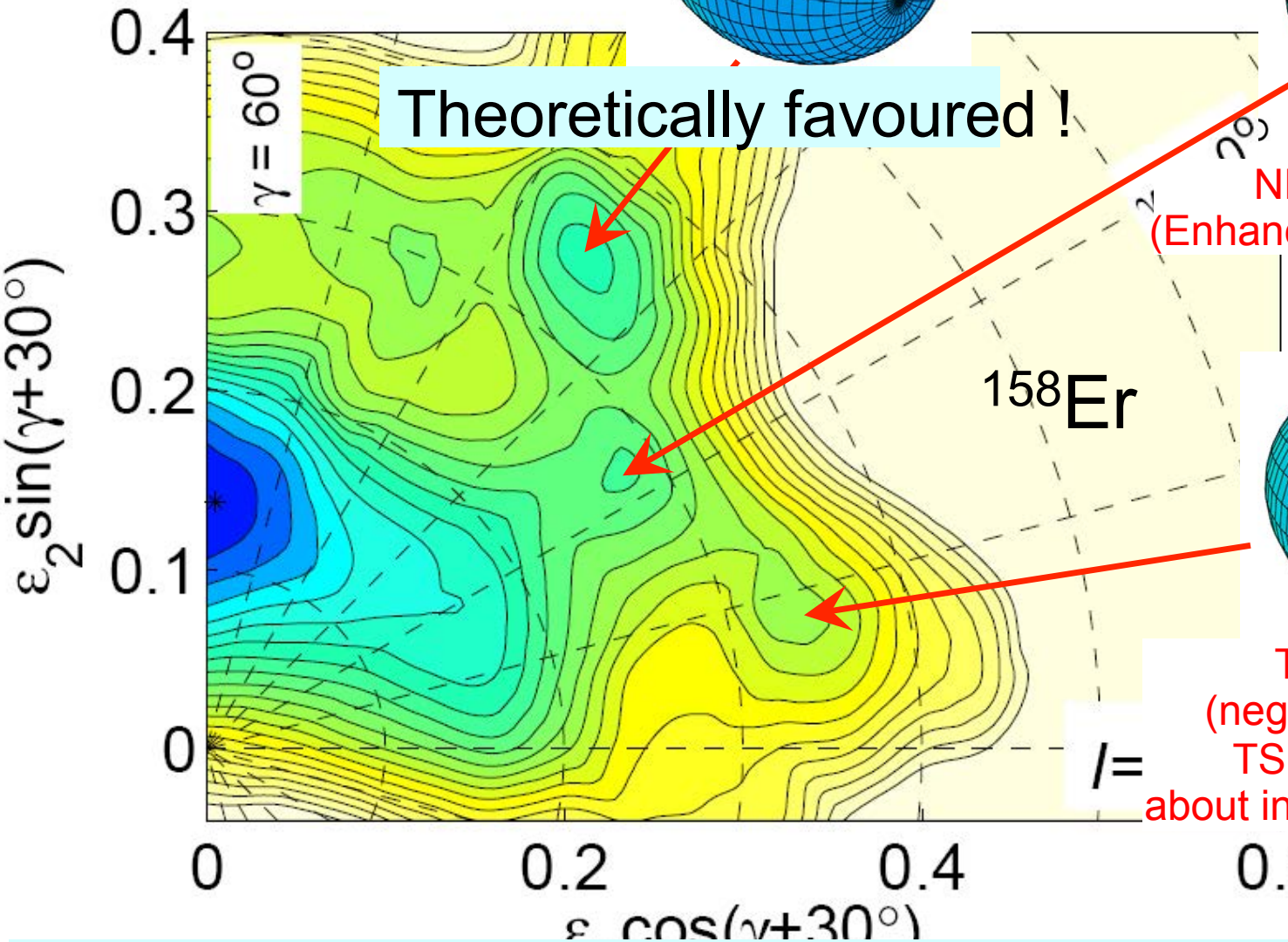
Theoretically favoured !



NEAR-AXIAL (Enhanced Deformation)

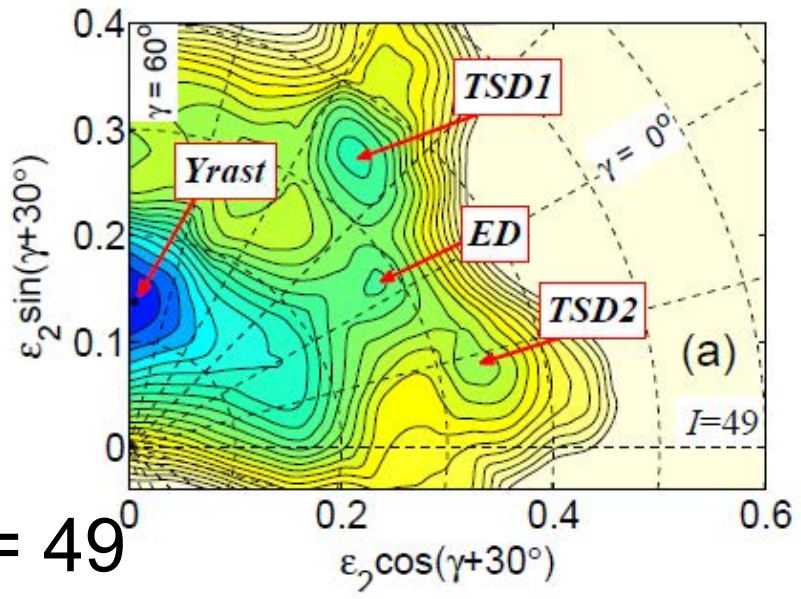


TRIAXIAL (negative-gamma TSD – rotation about intermediate axis)

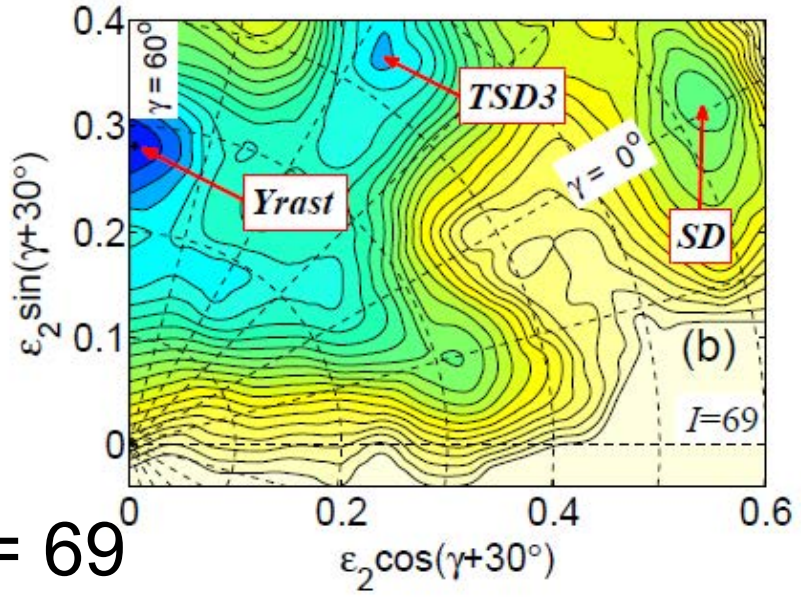


CNS (principal axis cranking) calculations by I. Ragnarsson

What Shape Are the Bands?



I = 49



I = 69

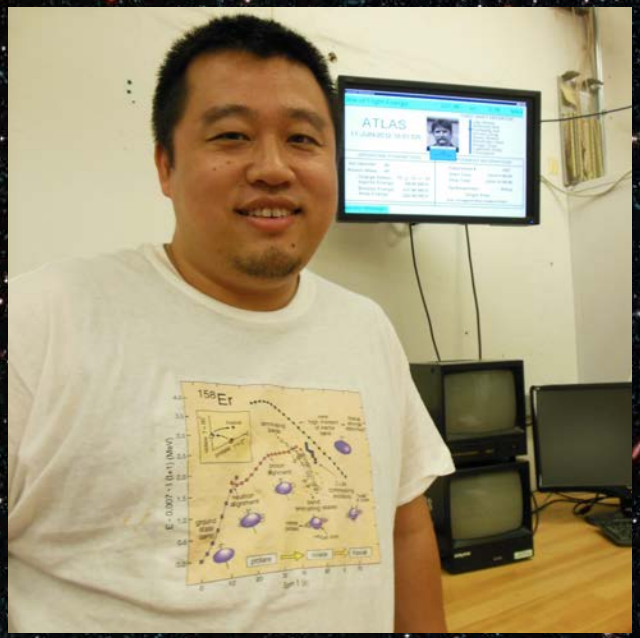
- A variety of possible shapes are predicted, both axially symmetric (ED, SD) and triaxial (TSD1, TSD2, TSD3)
- The TSD1 minimum, with a positive gamma deformation (+20°) was originally assigned to the new bands.

- Quadrupole moment measurements needed?
- NO NEED – we know what they are from theory!
- bands too weak?
- Gammasphere at ANL
- 2 weeks beam time

Cranked Nilsson Strutinsky calcs: Ingemar Ragnarsson

For more than a month we could not see the signal in the thick target data!! … the weak signal was now spread over many angles with unknown Doppler shifts!

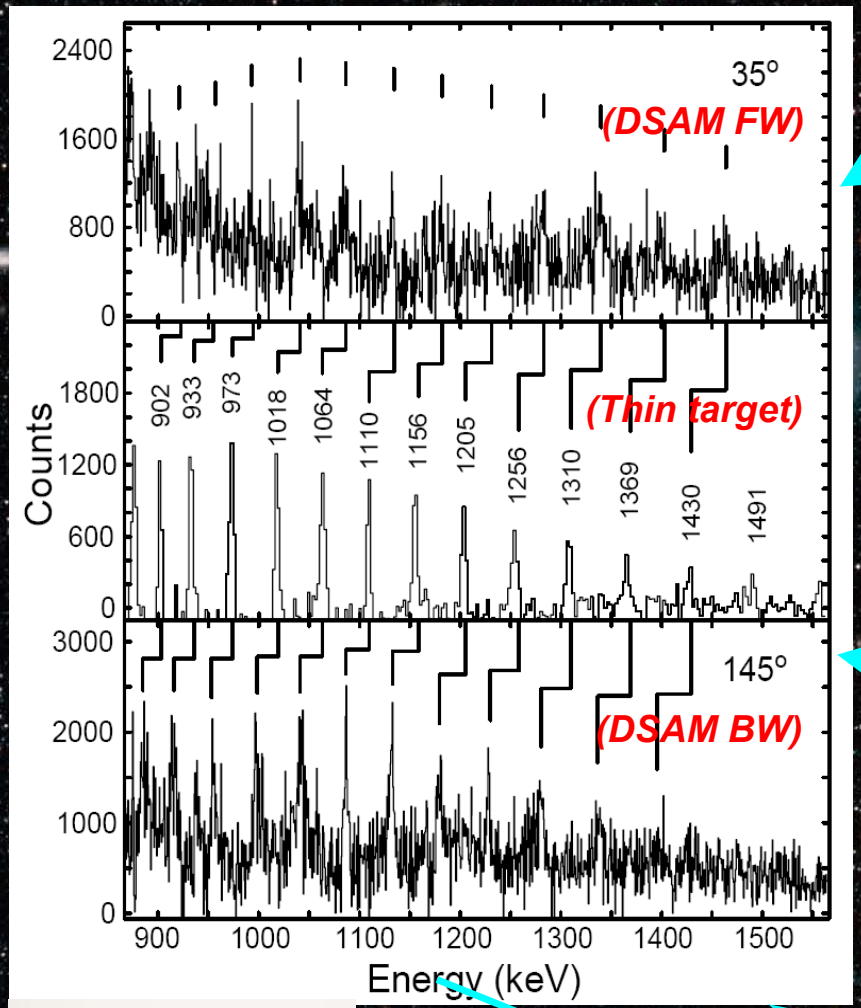
But Xiaofeng kept at it ….. Refining everything looking for those beautiful needles in the haystack!

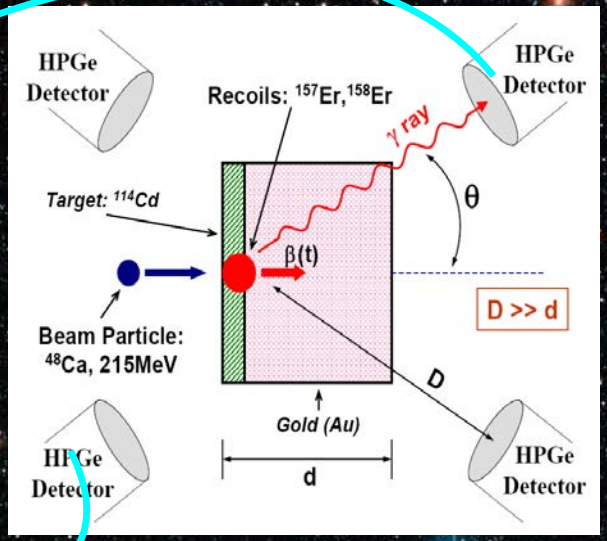


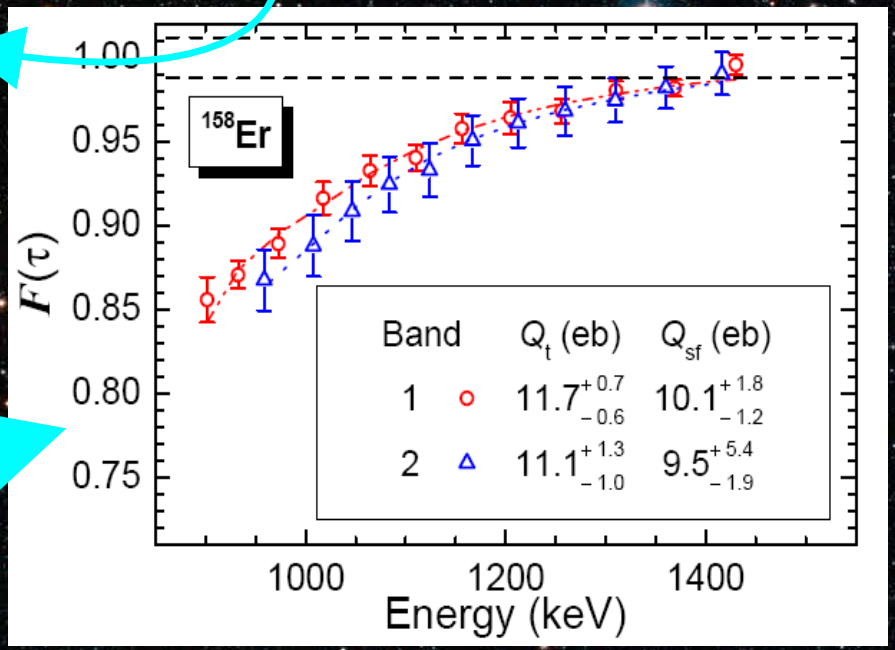

KEEP
CALM
AND
CARRY
ON

Evolution & Measurement

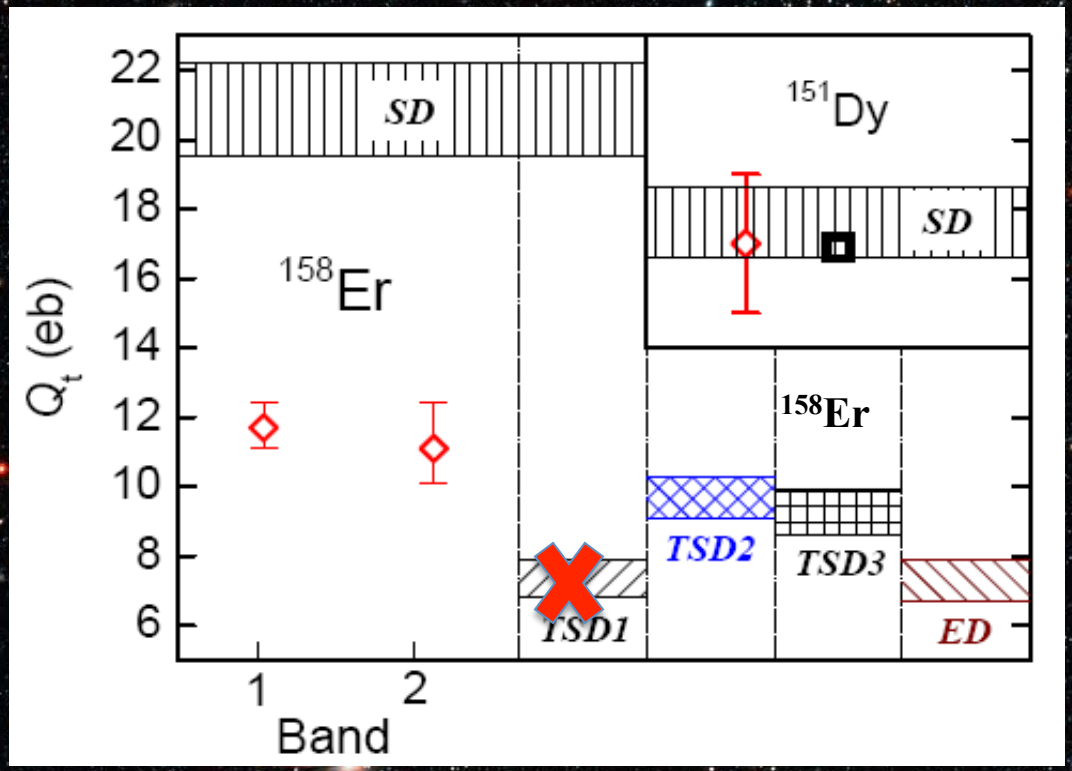
(Paul *et al.*, Phys. Rev. Lett. **98**, 012501, 2007)
(Wang *et al.*, Phys. Lett. B **702**, 127, 2011)







SURPRISING Result!!

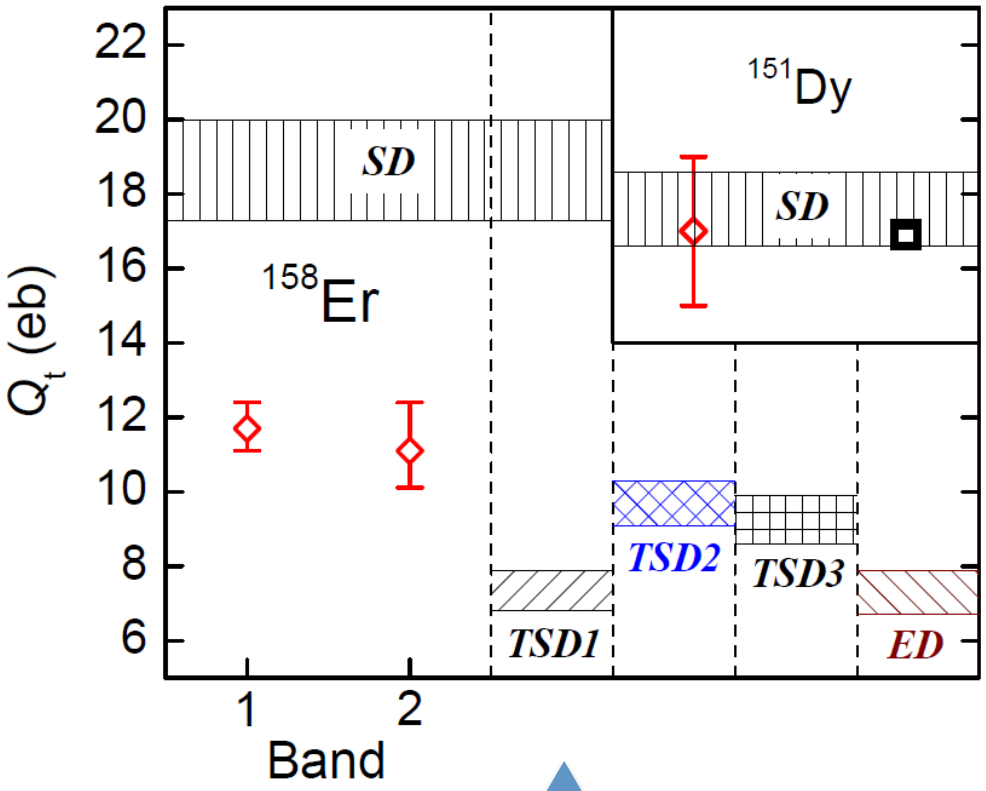


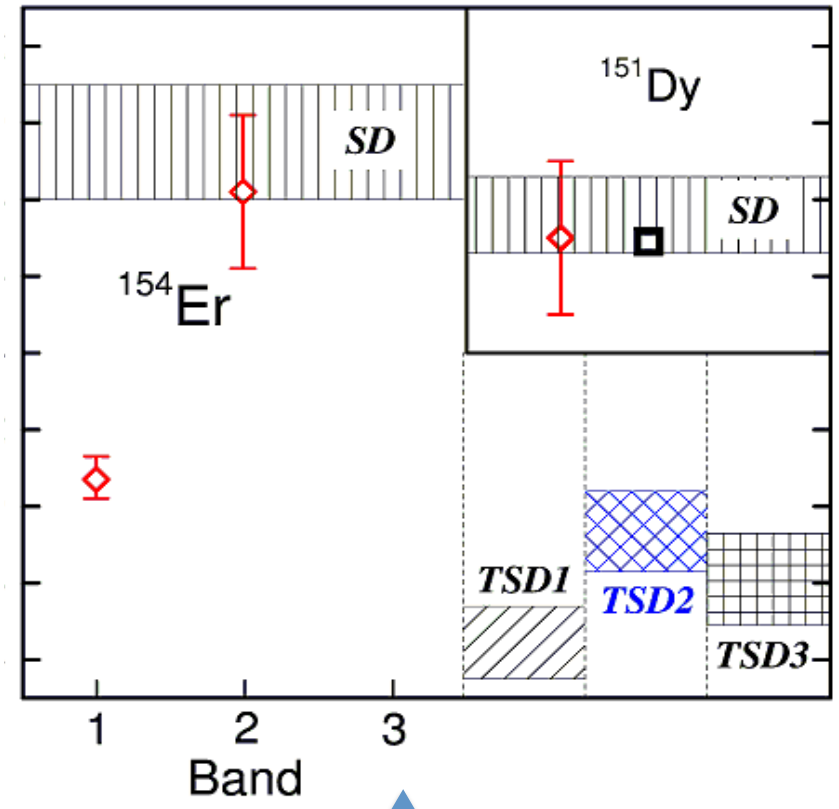
(Wang *et al.*, Phys. Lett. B 702, 127, 2011)

Values in ^{158}Er too large for TSD1!

- *"The CNS calculations do not account for the Q_t data satisfactorily.*
- *What do other theoretical approaches predict?*

Unexpected results in ^{158}Er! … 'Calibrate' Q_t Values with ^{154}Er expt





Wang *et al.*,
Phys. Lett. B 702, 127, 2011

Revill et al,
Phys. Rev. C 88,
031304(R) (2013)

The unexpected results in our ^{158}Er work motivated further theoretical studies.

PRL 108, 092501 (2012) PHYSICAL REVIEW LETTERS week ending 2 MARCH 2012

Self-Consistent Tilted-Axis-Cranking Study of Triaxial Strongly Deformed Bands in ^{158}Er at Ultrahigh Spin

Yue Shi,[1,2,3,4] J. Dobaczewski,[5,4] S. Frauendorf,[6] W. Nazarewicz,[2,3,5] J. C. Pei,[7,2,3] F. R. Xu,[1] and N. Nikolov[2]

[1]*State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*
[2]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[3]*Physics Division, Oak Ridge National Laboratory, Post Office Box 2008, Oak Ridge, Tennessee 37831, USA*
[4]*Department of Physics, PO Box 35 (YFL), FI-40014 University of Jyväskylä, Finland*
[5]*Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, ul. Hoża 69, PL-00681 Warsaw, Poland*
[6]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[7]*Joint Institute for Heavy-Ion Research, Oak Ridge, Tennessee 37831, USA*

(Received 4 December 2011; published 28 February 2012)

The new tilted axis cranking (TAC) calculations reproduced measured $\mathbf{Q_t}$ +J^2, but, the relevant TSD minimum is not yrast until very high spin **~ 70h.**

PHYSICAL REVIEW C 86, 014309 (2012)

Interpretation of the large-deformation high-spin bands in select $A = 158$–168 nuclei

A. Kardan,[1,2] I. Ragnarsson,[1] H. Miri-Hakimabad,[2] and L. Rafat-Motevali[2]
[1]*Division of Mathematical Physics, LTH, Lund University, P.O. Box 118, S-22100 Lund, Sweden*
[2]*Physics Department, Faculty of Science, Ferdowsi University of Mashhad, P.O. Box 91775-1436, Mashhad, Iran*
(Received 27 August 2011; revised manuscript received 27 May 2012; published 5 July 2012)

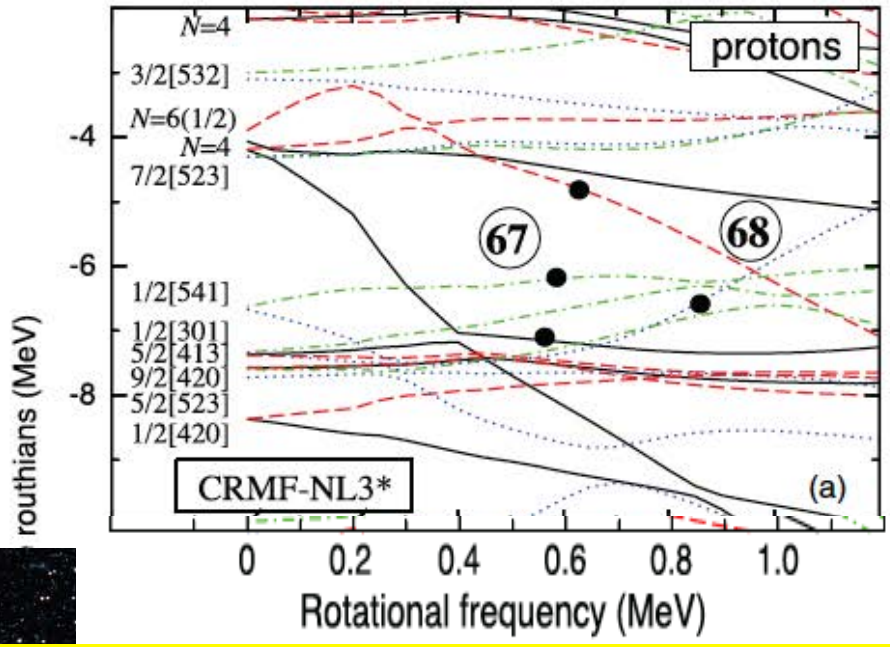
OTHER NEW THEORY PAPERS!

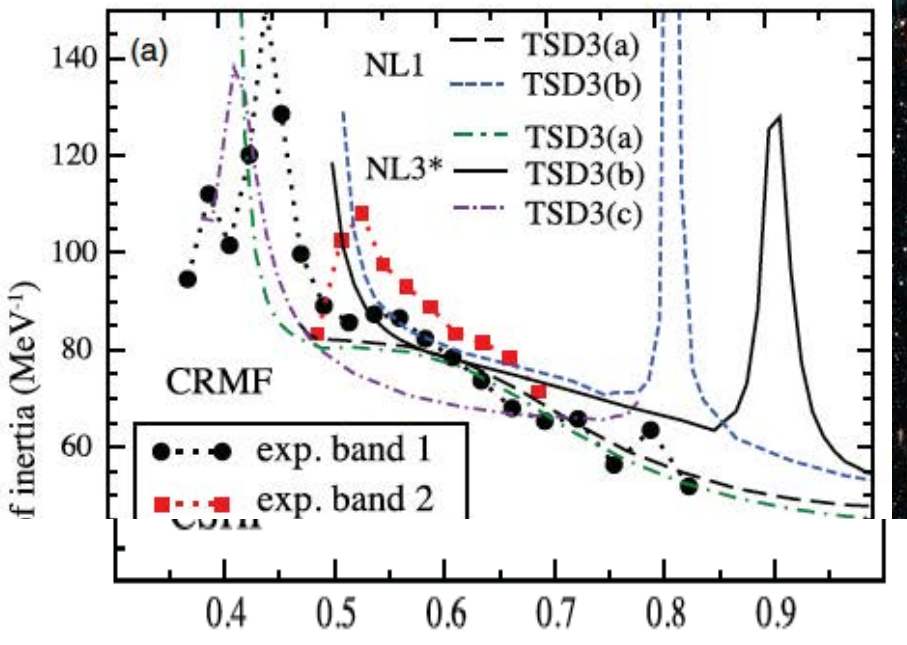
RAPID COMMUNICATIONS

PHYSICAL REVIEW C 86, 031304(R) (2012)

Description of ^{158}Er at ultrahigh spin in nuclear density functional theory

A. V. Afanasjev,[1,2] Yue Shi,[3] and W. Nazarewicz[4,5,6]
[1]*Department of Physics and Astronomy, Mississippi State University, Starkville, Mississippi 39762, USA*
[2]*Joint Institute for Heavy-Ion Research, Oak Ridge, Tennessee 37831, USA*
[3]*State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing 100871, China*
[4]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[5]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[6]*Institute of Theoretical Physics, University of Warsaw, ul. Hoża 69, PL-00-681 Warsaw, Poland*
(Received 22 August 2012; published 17 September 2012)

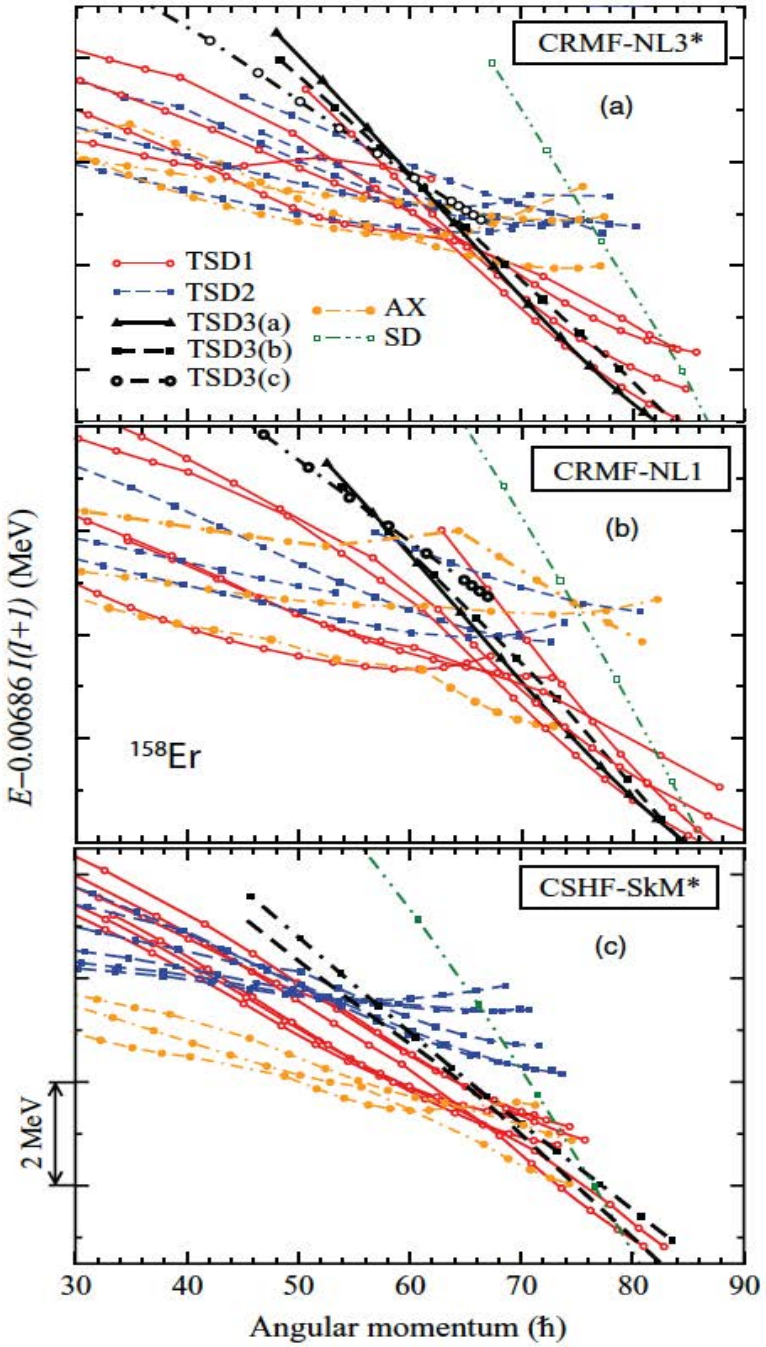




Afanasjev, Shi, Nazarewicz, PRC 86, 031304 (R) (2012)

MOST DETAILED HI-SPIN CALCULATIONS EVER!

If the theoretical spin assignments of Fig. 4 turned out to be correct, the experimental band 1 in ^{158}Er would be the the highest spin structure ever observed. The current study stresses the need for more precise measurements of Q_t and reliable estimates of spins in these bands.



Afanasjev, Shi, Nazarewicz, PRC 86, 031304 (R) (2012)

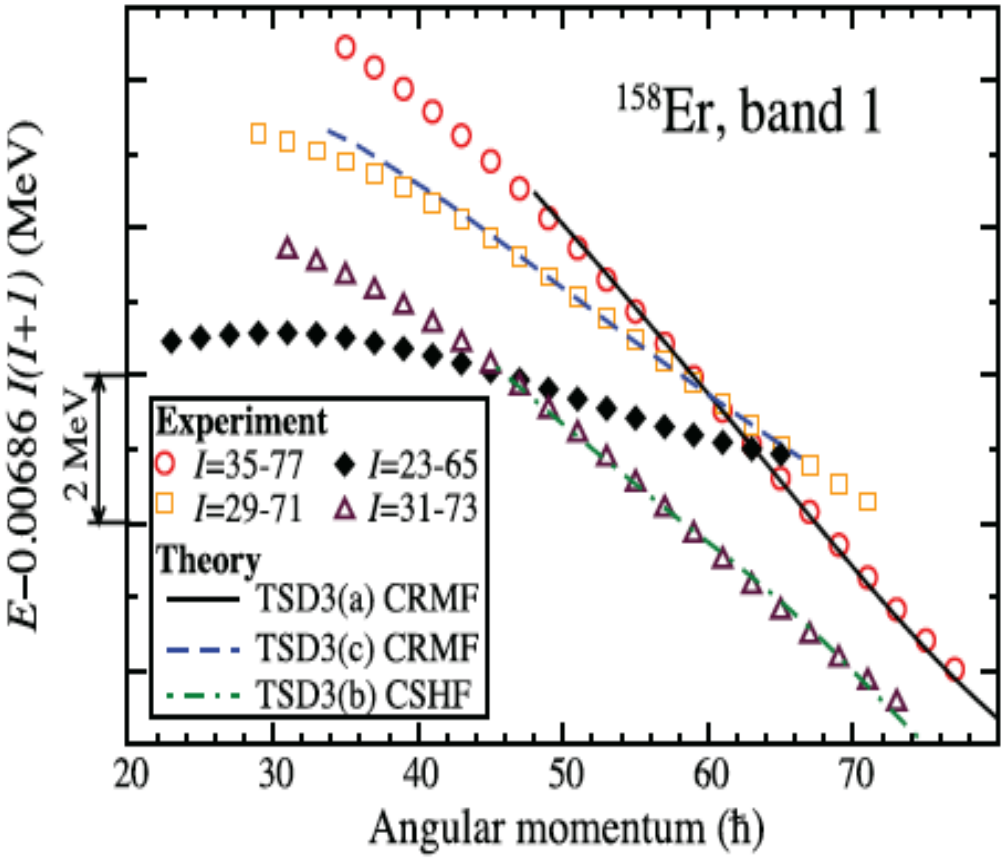
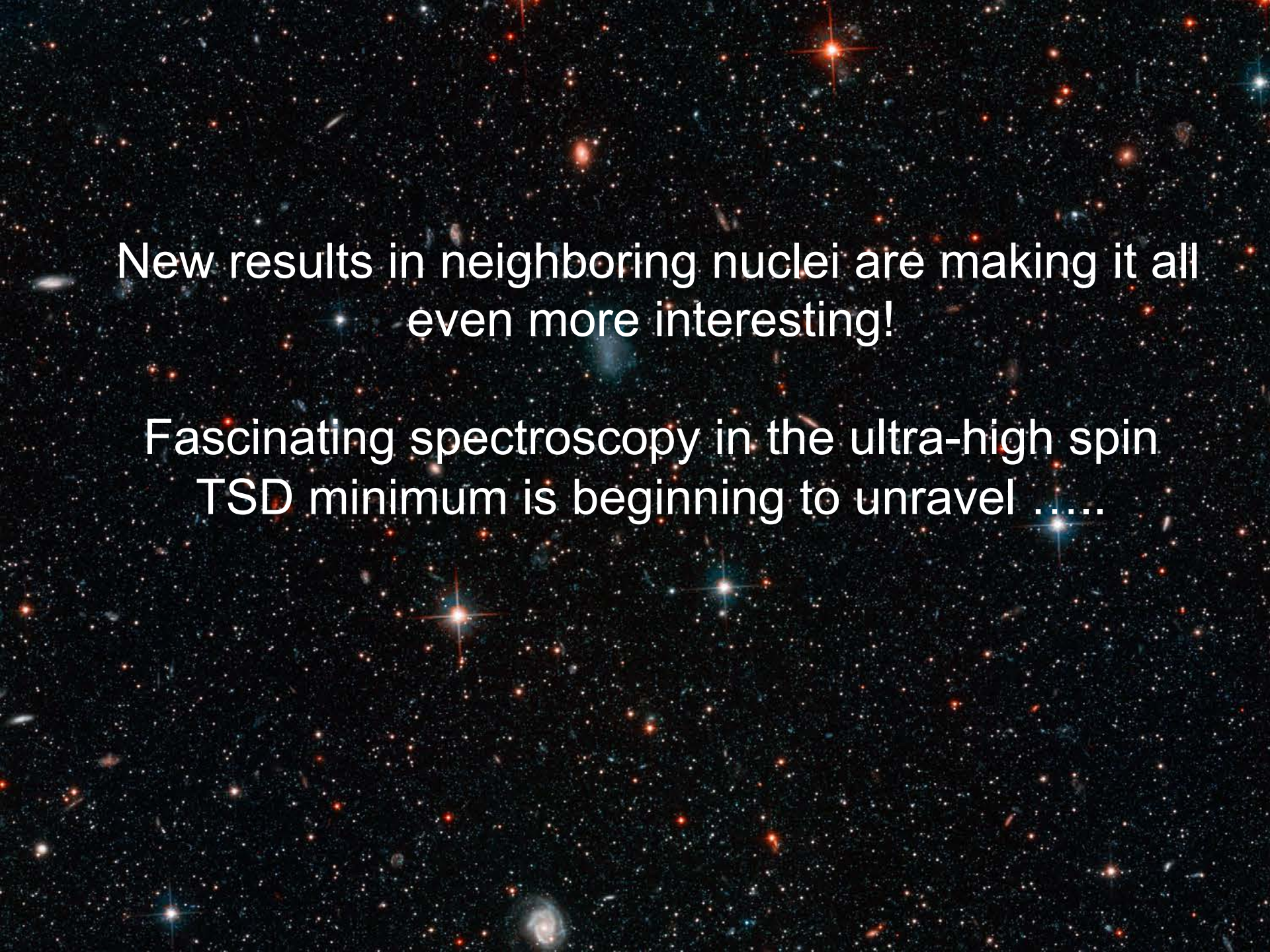
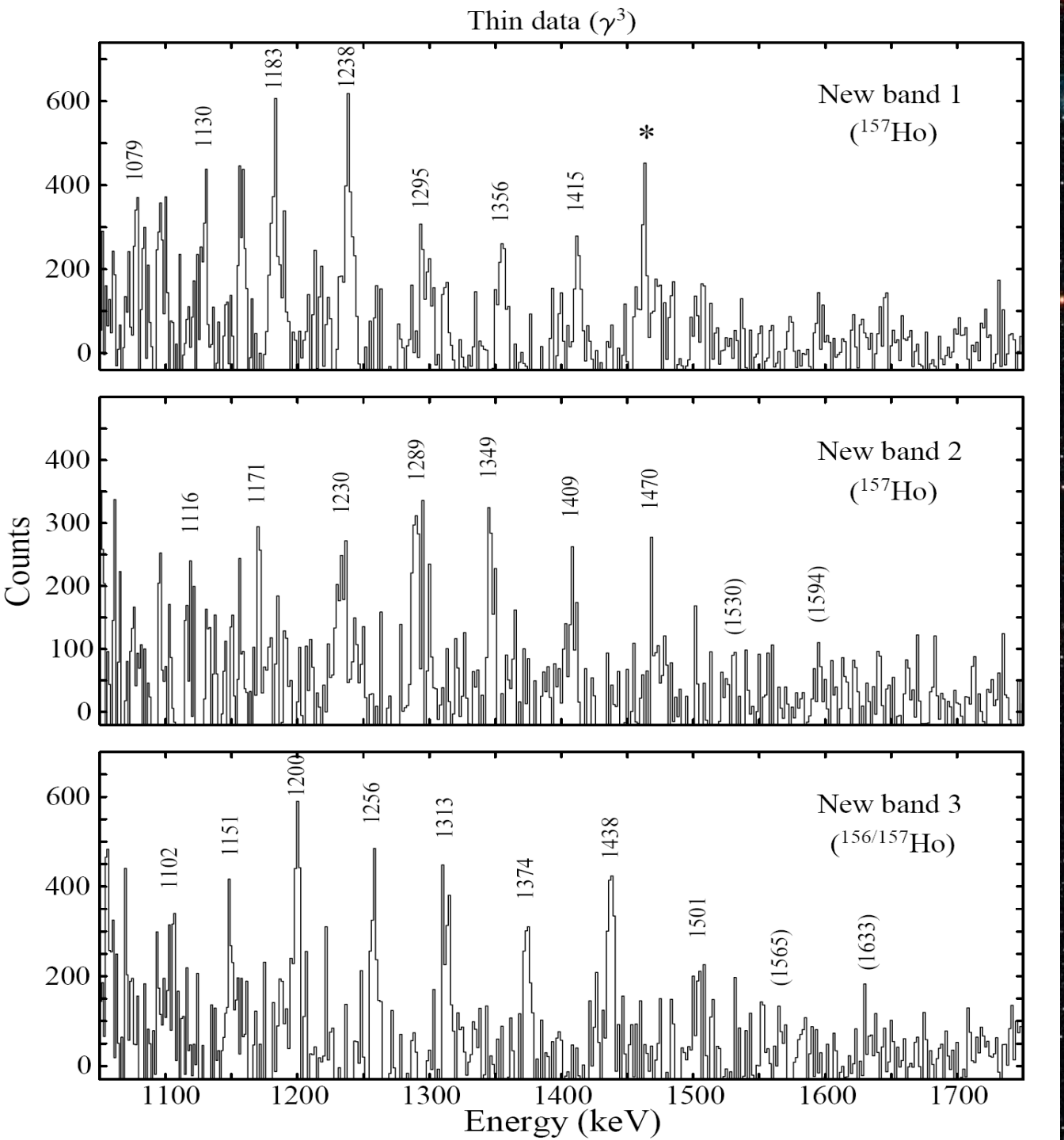


FIG. 4. (Color online) Similar to Fig. 1 but for experimental band 1 assuming different spin assignments (symbols) and for calculated configurations TSD3(a) and TSD3(c) in CRMF-NL3* and TSD3(b) in CSHF-SkM* (lines). The energy of the lowest experimental state is selected arbitrarily to minimize the deviation from calculated configurations.

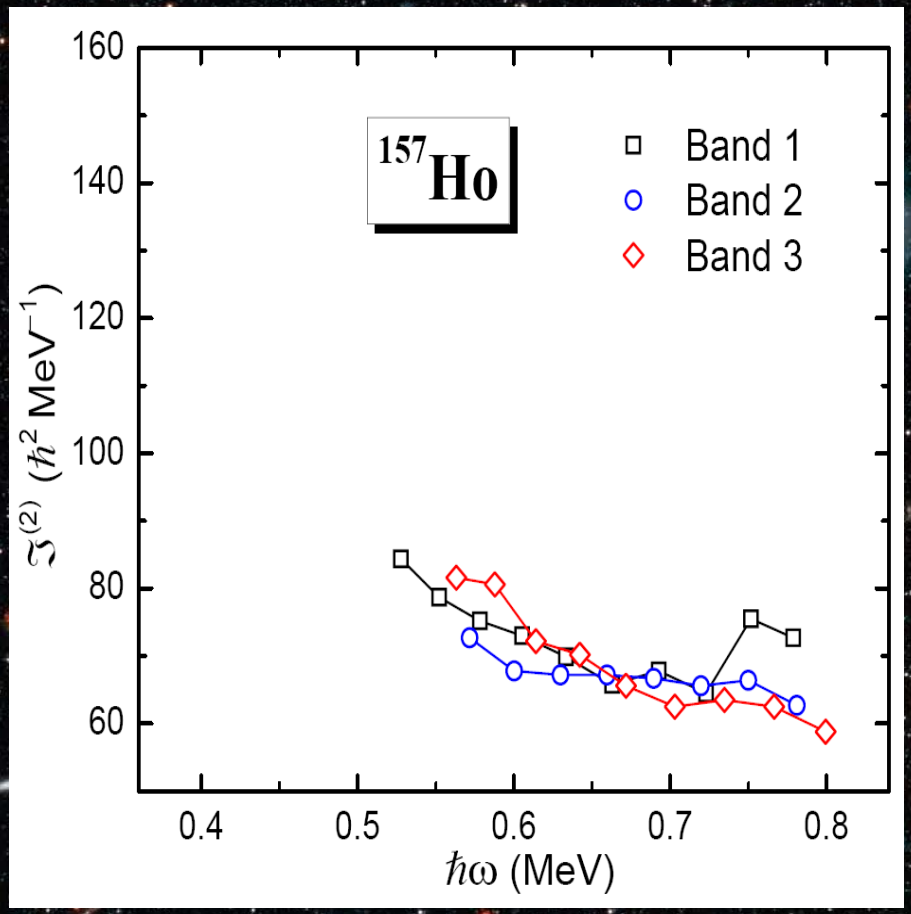

New results in neighboring nuclei are making it all even more interesting!
Fascinating spectroscopy in the ultra-high spin TSD minimum is beginning to unravel …..

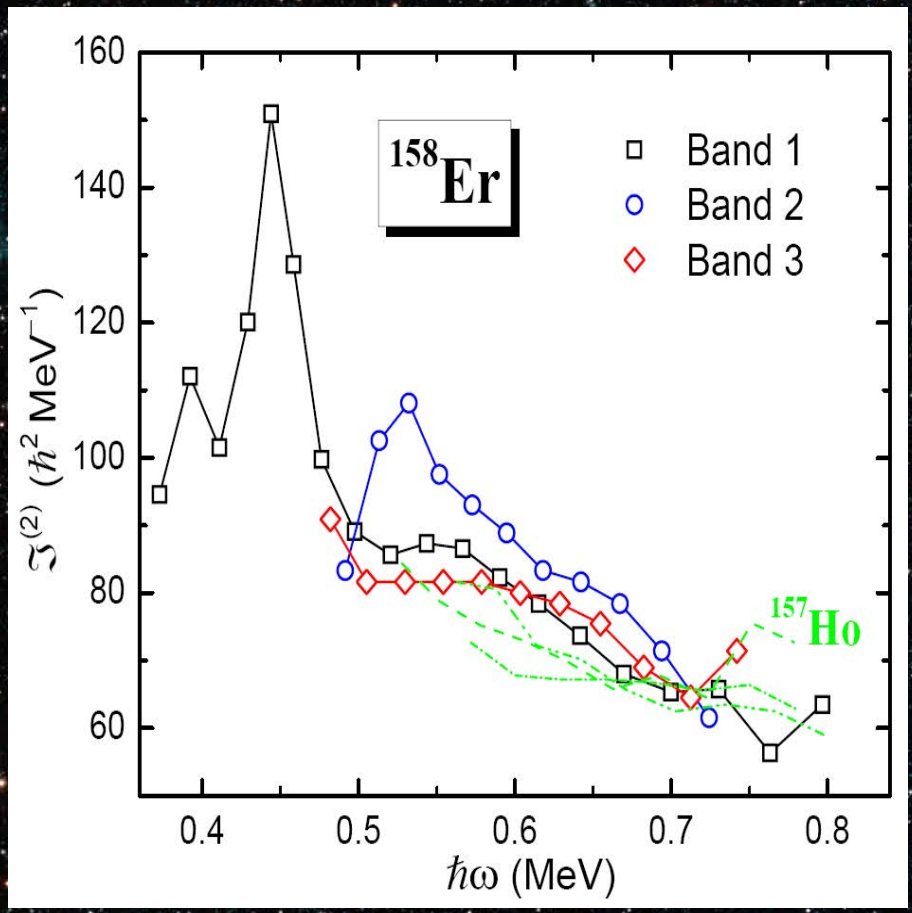
Spectra for new SD/TSD candidate bands in $^{156/157}$Ho

Wang et al, to be published



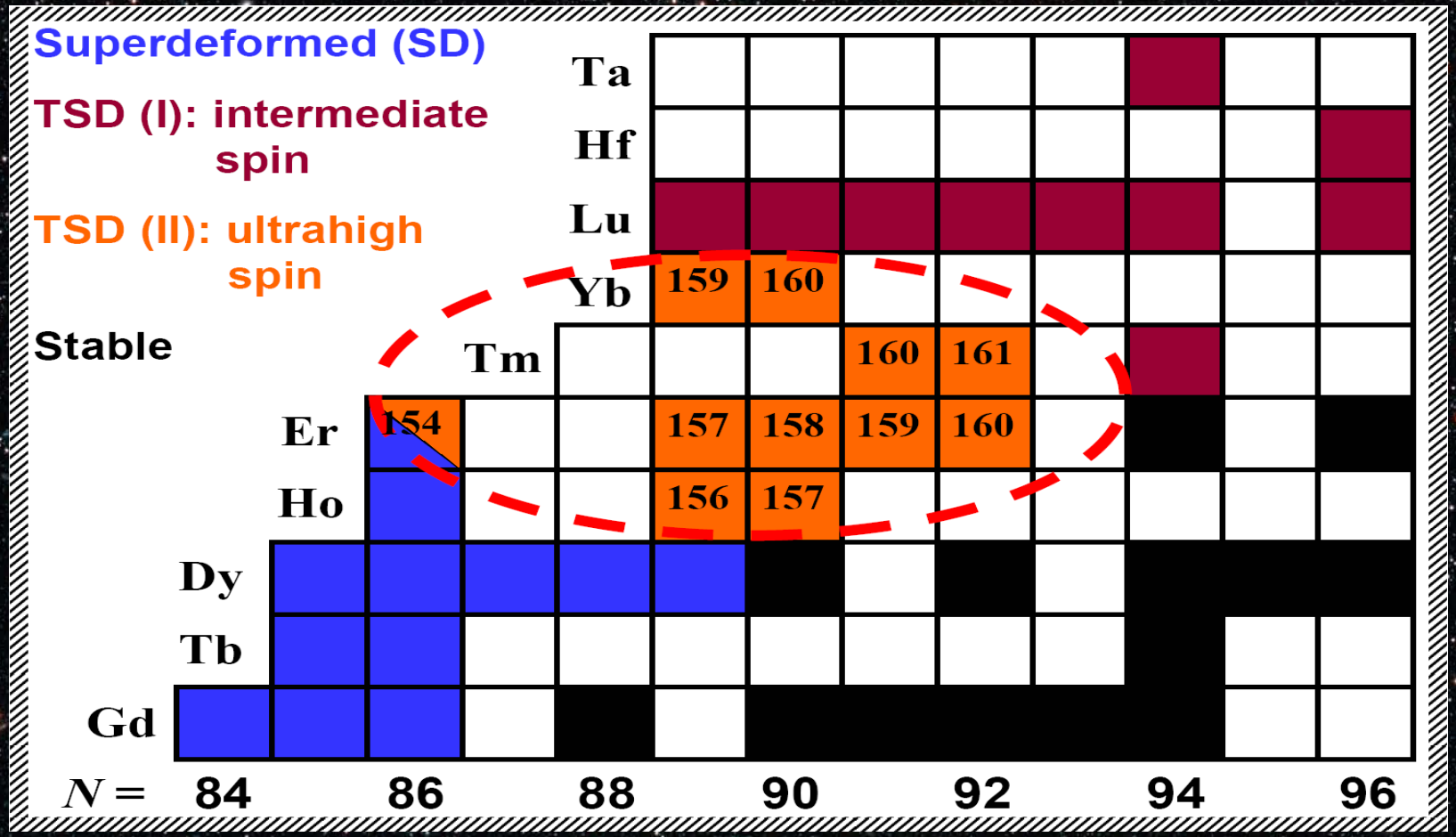
Moment of inertia J(2) of TSD bands: ^{157}Ho vs. ^{158}Er





Bridging the Dy-Gd SD and Lu-Ta TSD regions:

A new class of strongly deformed structures at ultrahigh spin which are proving to be rather interesting

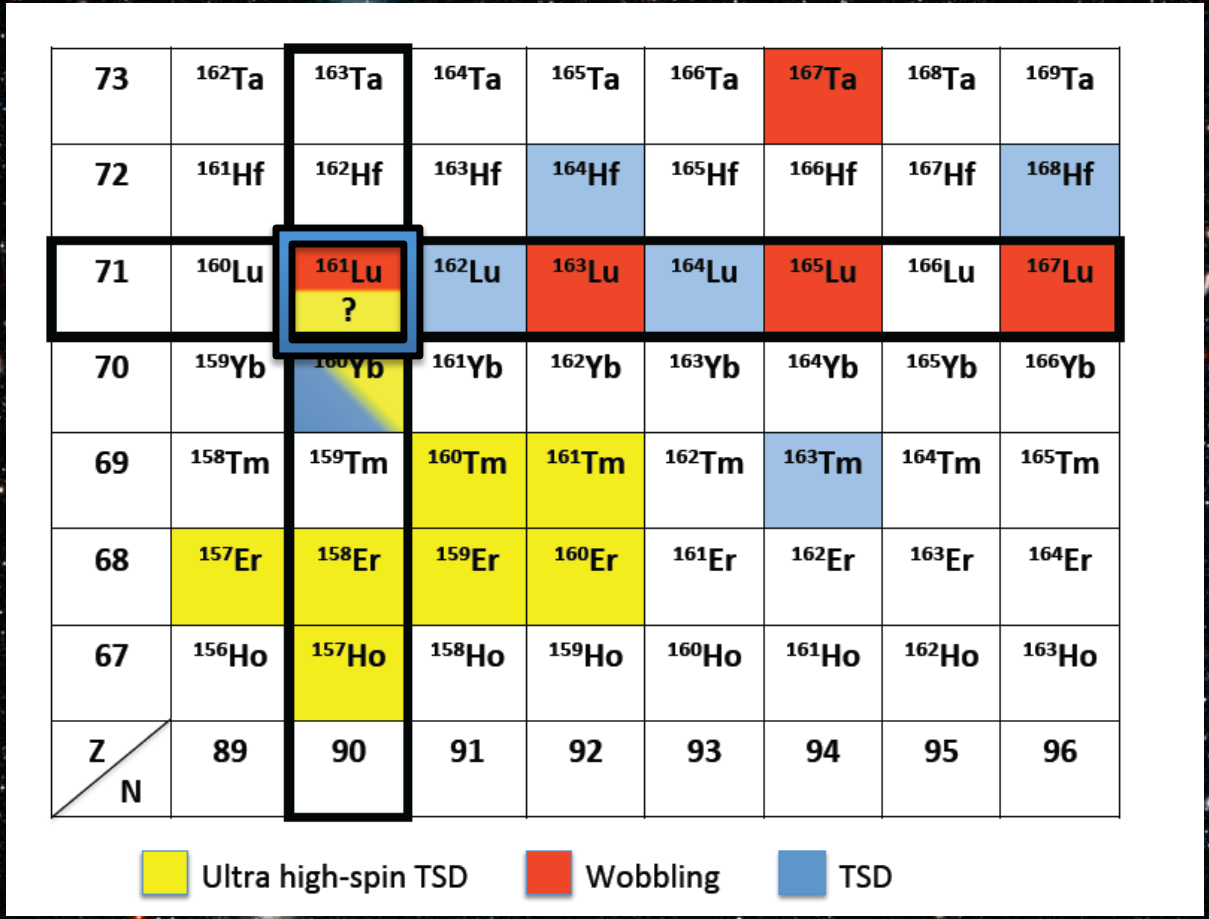


High-spin Study of ^{161}Lu: The Crossroads Between Lower Spin TSD Wobbling and Ultrahigh-Spin TSD Bands?

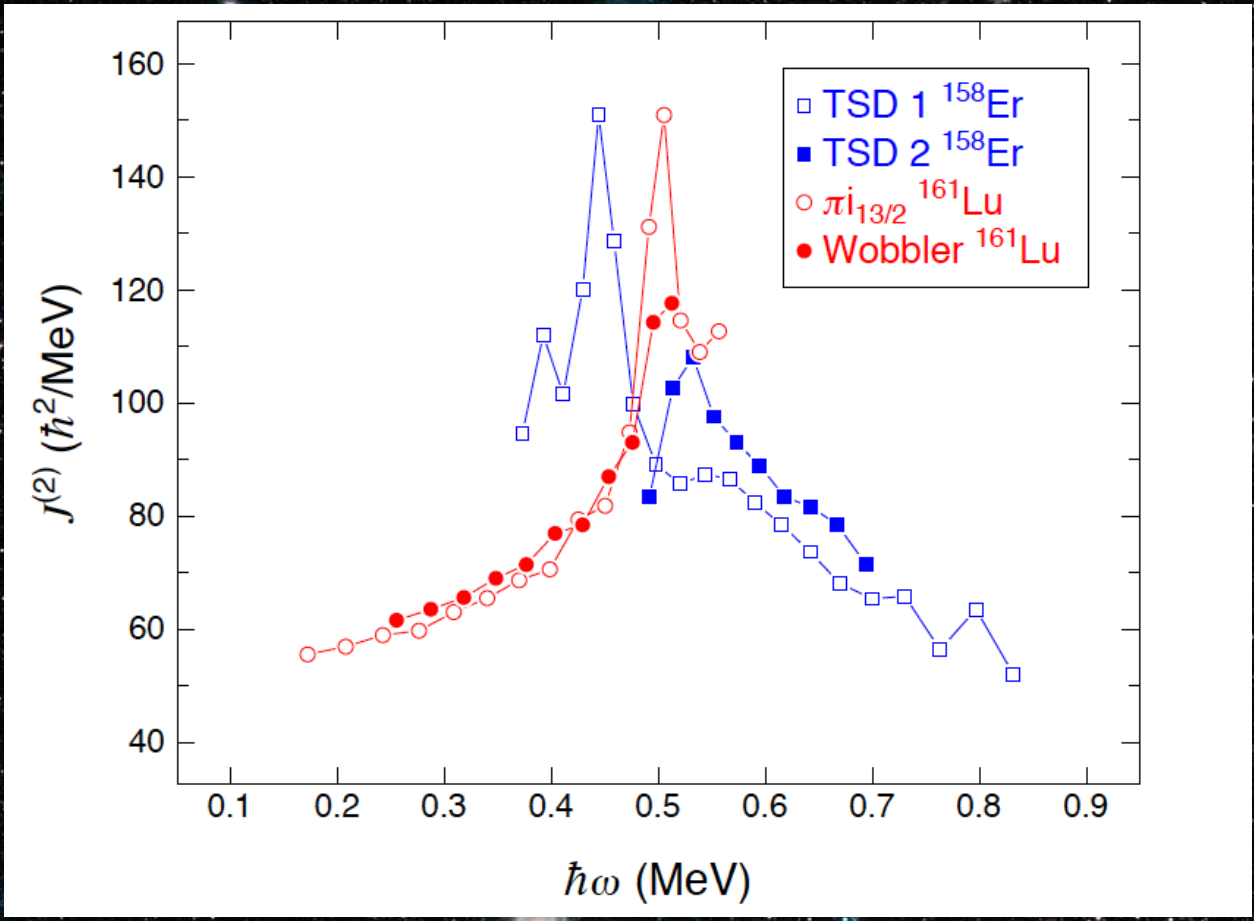
D.J. Hartley,[1] M.A. Riley,[2] J. Simpson,[3] E. S. Paul,[4] R. V. F. Janssens,[5] L.L. Riedinger,[6] A. D. Ayangeakaa,[5] J. Baron,[2] M. Benner,[1] A. Boston,[4], H. Boston,[4] M.P. Carpenter, [5] C.J. Chiara,[5,7] U. Garg,[8] S. Hallgren,[1] J. Harker,5, 7 F.G. Kondev,[9] T. Lauritsen,[5] W.C. Ma,[10] P. Mason,[3] J. Matta,[8] S. Miller,[2] P. Nolan,[4] J.R. Vanhoy[1], K. Villafana,[2] X. Wang,[11] J. Wright,[4] and S. Zhu[5]

Next step:

Approved expt at ATLAS with DGS

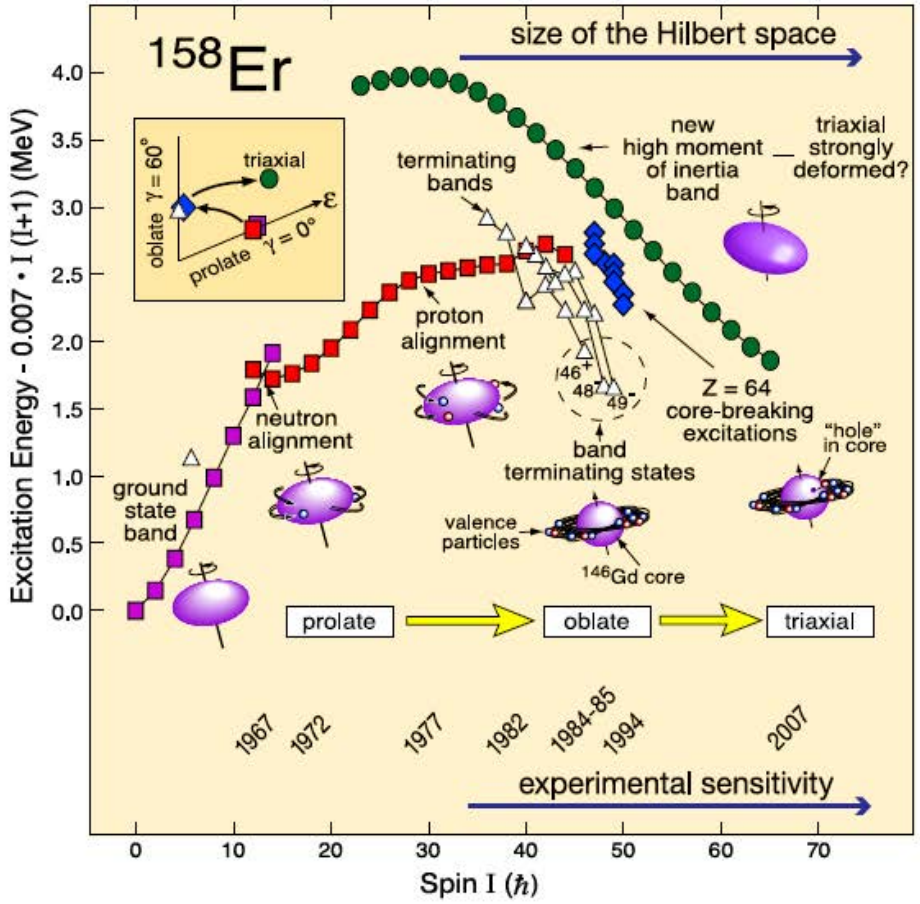


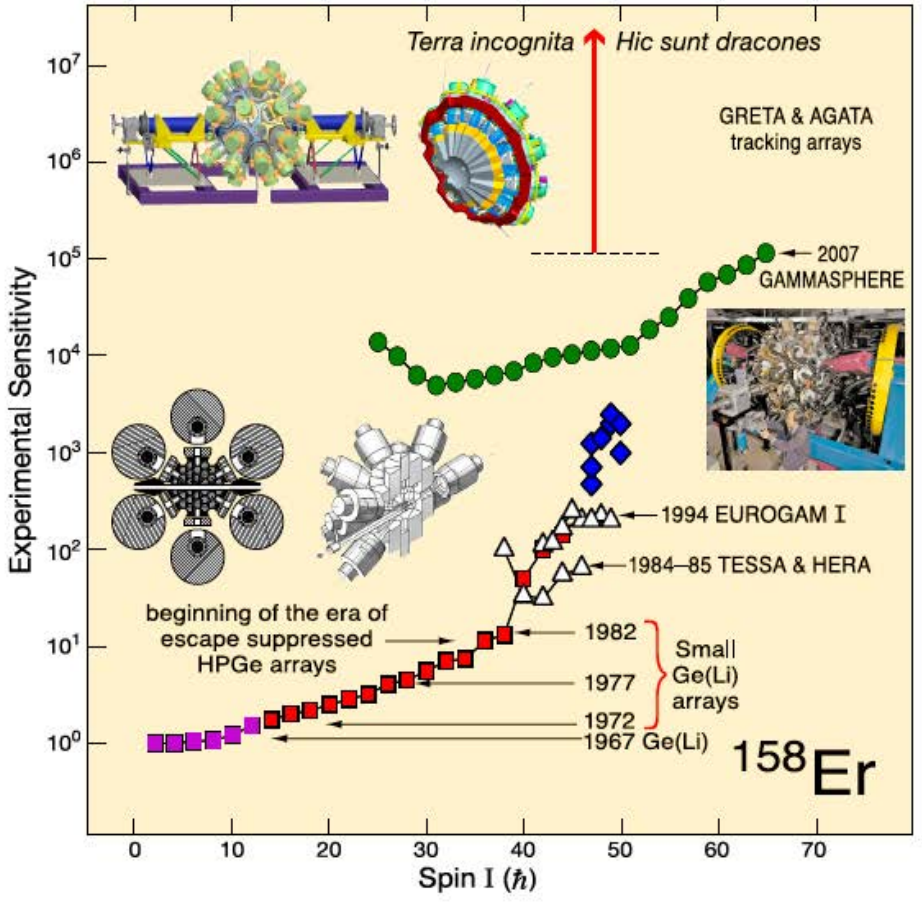
- Ultra-high spin TSD in ^{158}Er compared to lower spin TSD in ^{161}Lu.
- Can we discover ultra-high spin bands in Lu that decay into the low-spin TSD minimum and hence obtain their highly sought after spin and energy values?
- ANL PAC gave us beamtime to go look with DGS this fall! ☺



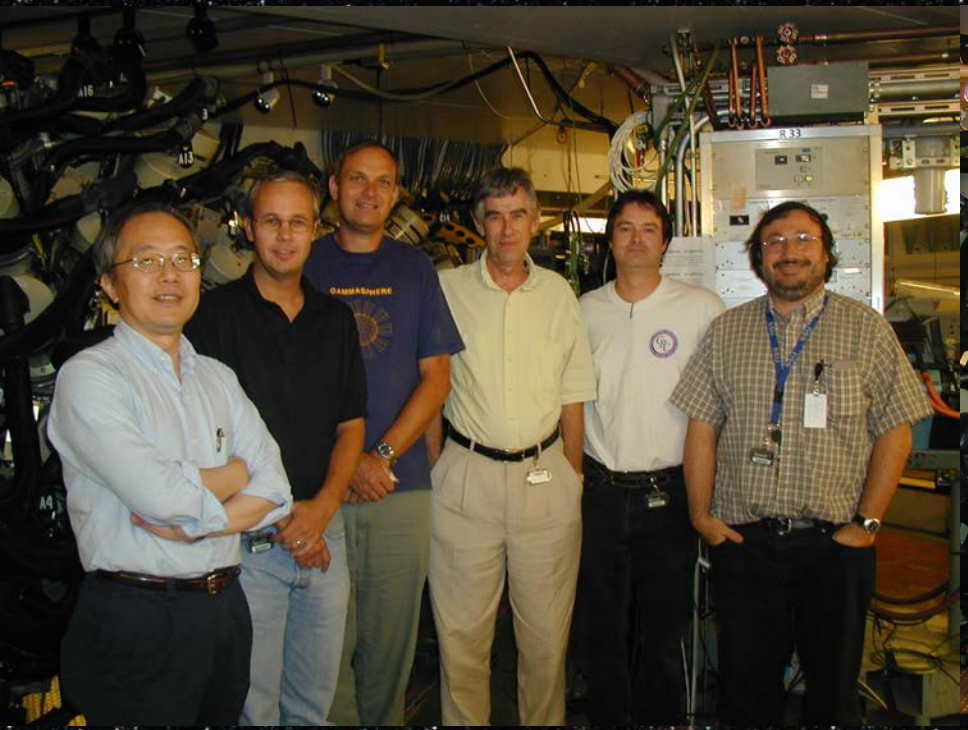
Evolution of Gamma-Ray Spectroscopy

- New Detector Systems = New Physics
- Let the Quest Continue!





Collaborators on ^{157,158}Er GS expt – mid 00's



University of Liverpool **A. Evans**, E.S. Paul, P.J. Nolan, P.T.W Choy

Daresbury Laboratory J. Simpson, D.E. Appelbe, D.T. Joss

Florida State University **A. Pipidis**, M.A. Riley, D.B. Campbell

LBNL P.Fallon, D.Ward, A.O.Macchiavelli, R.M.Clark, M.Cromaz, A.Görgen, I.Y. Lee

Lund Institute of Technology I. Ragnarsson, F. Saric

We phoned JFSS from the control room so he was with us too!

ATLAS EXPTS: MORE ACKNOWLEDGEMENTS





North America

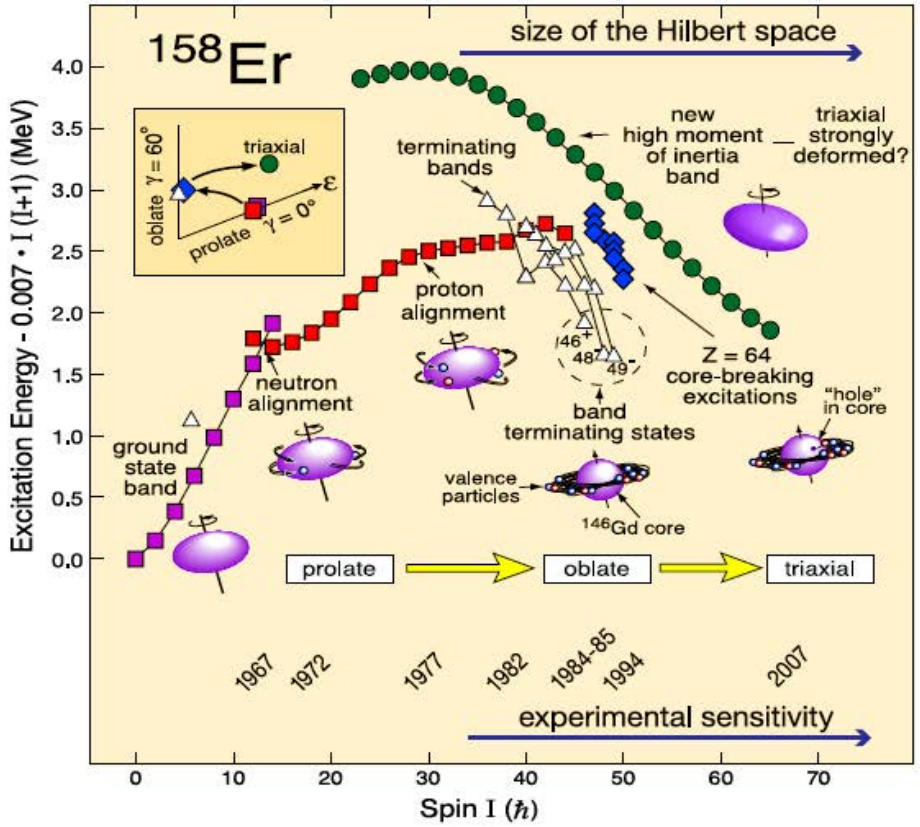
FSU: X. Wang, M. A. Riley, S. M. Miller, J. S. Baron;
ANL: M. P. Carpenter, C. J. Chiara, R. V. F. Janssens, F. G. Kondev, T. Lauritsen, S. Zhu; ***USNA***: D. J. Hartley; ***UTK***: L. L. Riedinger;
ND: U. Garg, J. Matta, A. D. Ayangeakaa; ***ORNL***: D. C. Radford;
ARL: J. J. Carroll, J. Gaison; ***LBNL***: P. Fallon, M. K. Petri

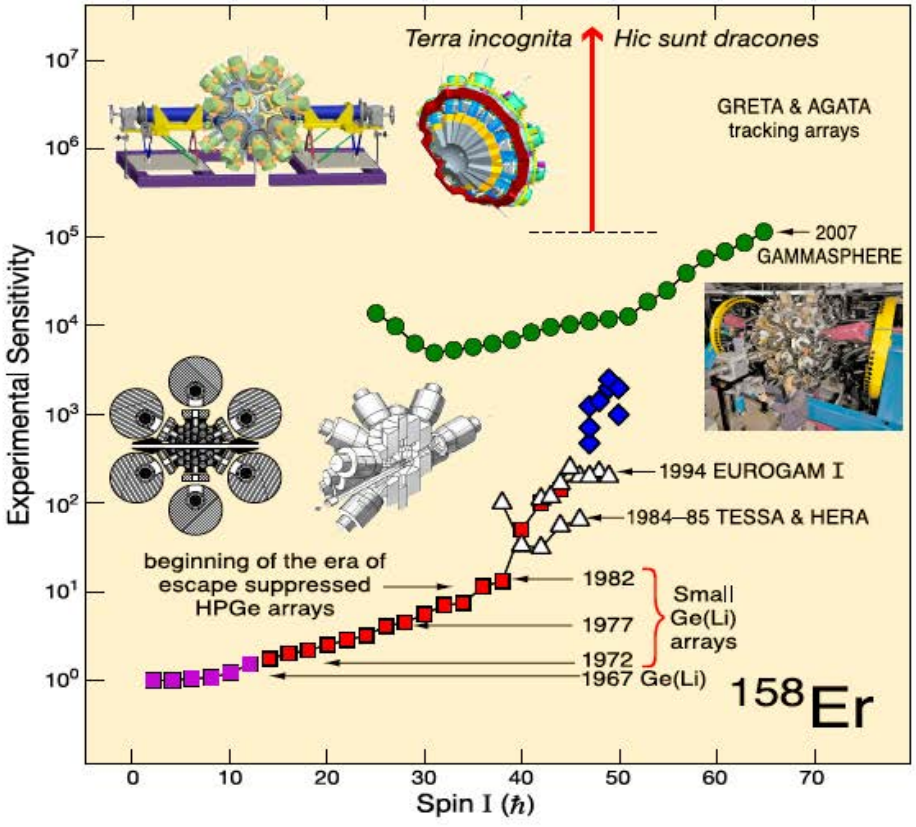
Europe

Liverpool: E. S. Paul, A. J. Boston, H. C. Boston, P. Hampson, D. Judson, P. J. Nolan, J. Rees, J. Revill, S. V. Rigby, C. Unsworth;
Daresbury: J. Simpson, J. Ollier;
Lund: I. Ragnarsson

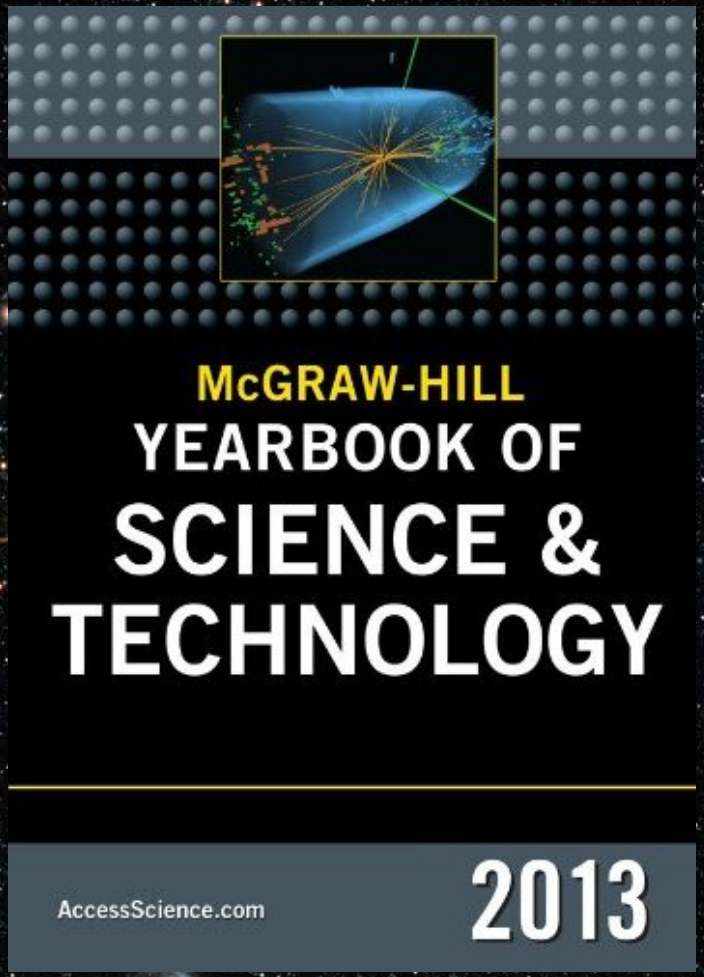
Evolution of Gamma-Ray Spectroscopy and ^{158}Er

(NRC/Nat. Acad. Sci. Decadal Report June 2012, p 49
Nuclear Physics: The Heart of Matter)





“The Fascinating Nuclear Structure World of Erbium-158”
Wang, Riley, Simpson and Paul



THANK YOU Liverpool!
THANK YOU Peter! ☺