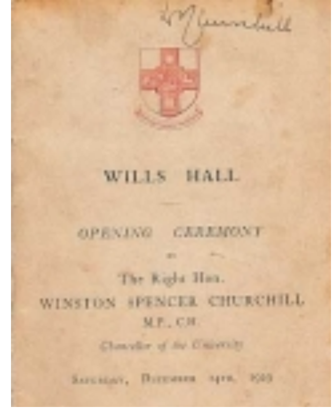
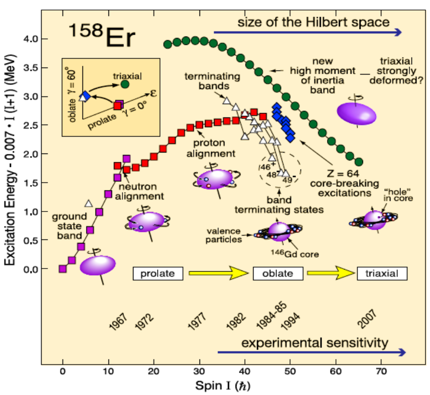
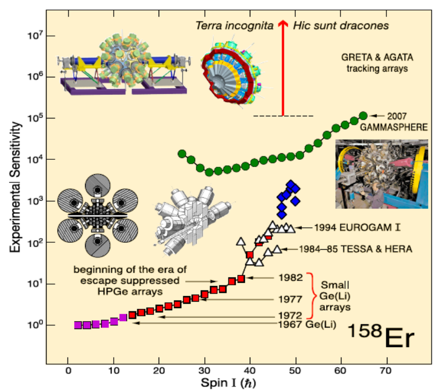
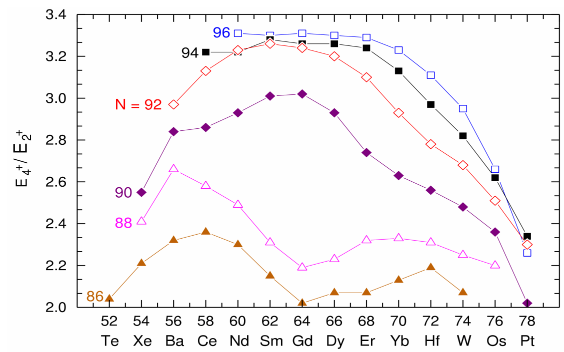
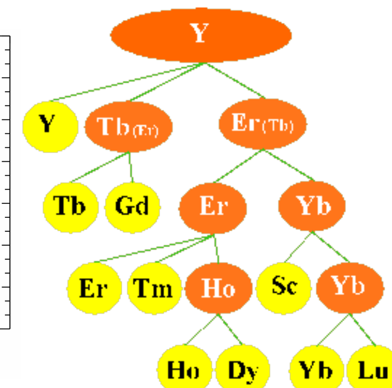
17th UK Nuclear Physics Postgraduate Summer School
University of Bristol
27th August and 6th September 2013





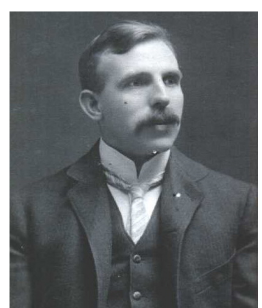


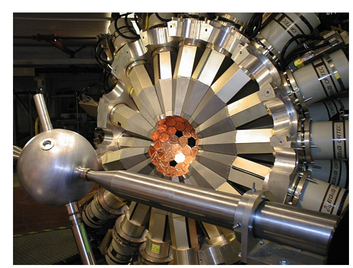


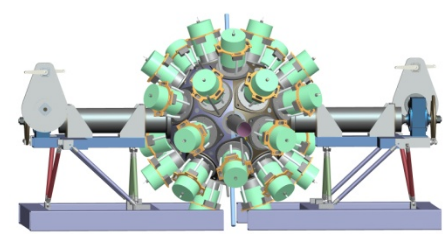


Episode 3: Gamma-Ray Spectroscopy through the Decades: The Textbook Example of 158Er, Band Termination and Beyond!

Mark A. Riley - Florida State University

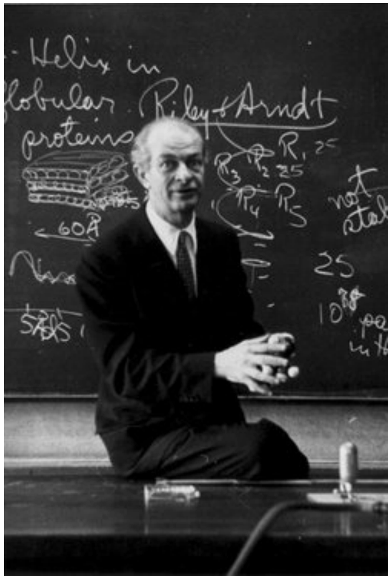




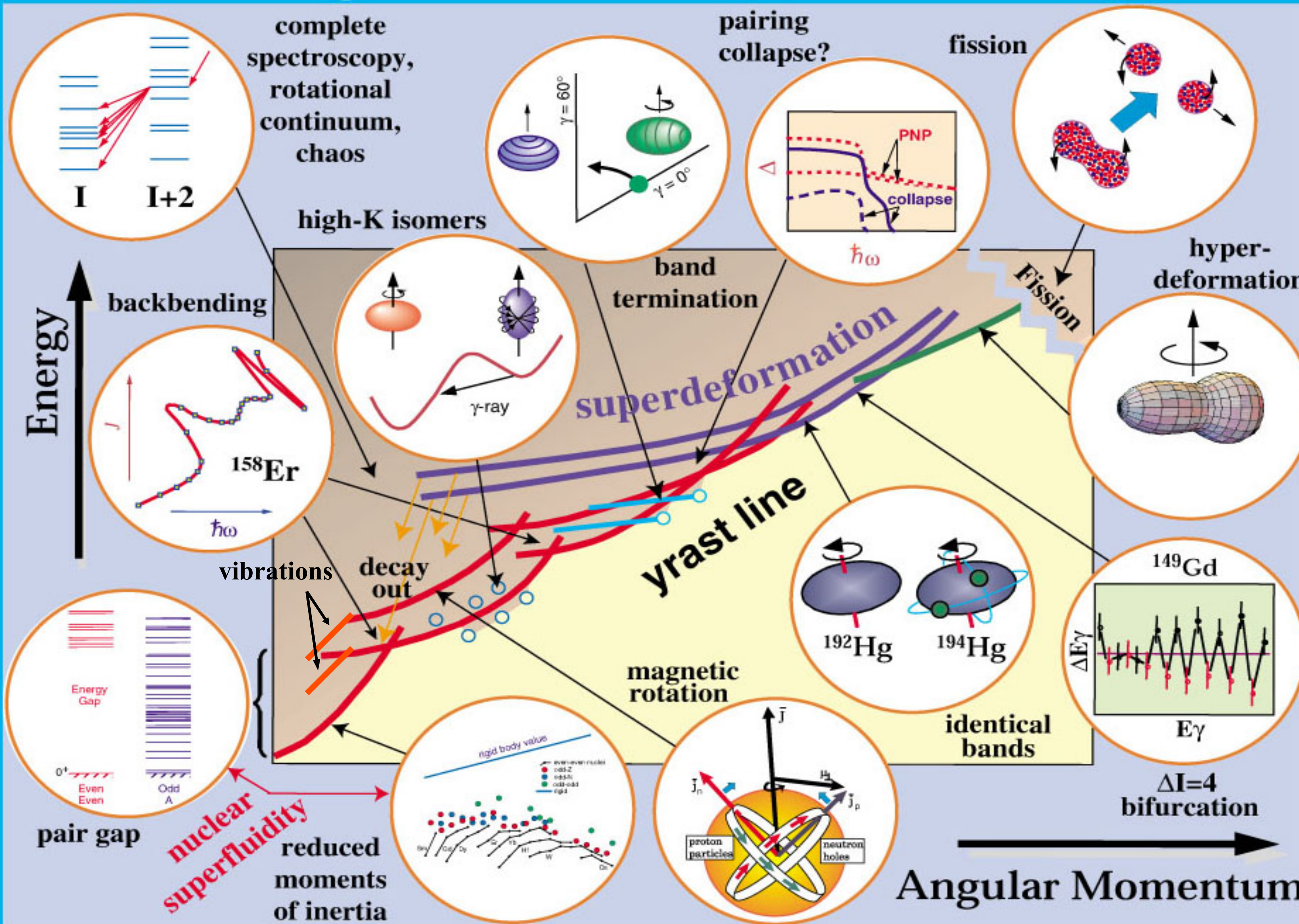


Linus Pauling (1901 – 1994): (He is one of only two people to have been awarded a Nobel Prize in two different fields (the Chemistry and Peace prizes), the other being Marie Curie (the Chemistry and Physics prizes))

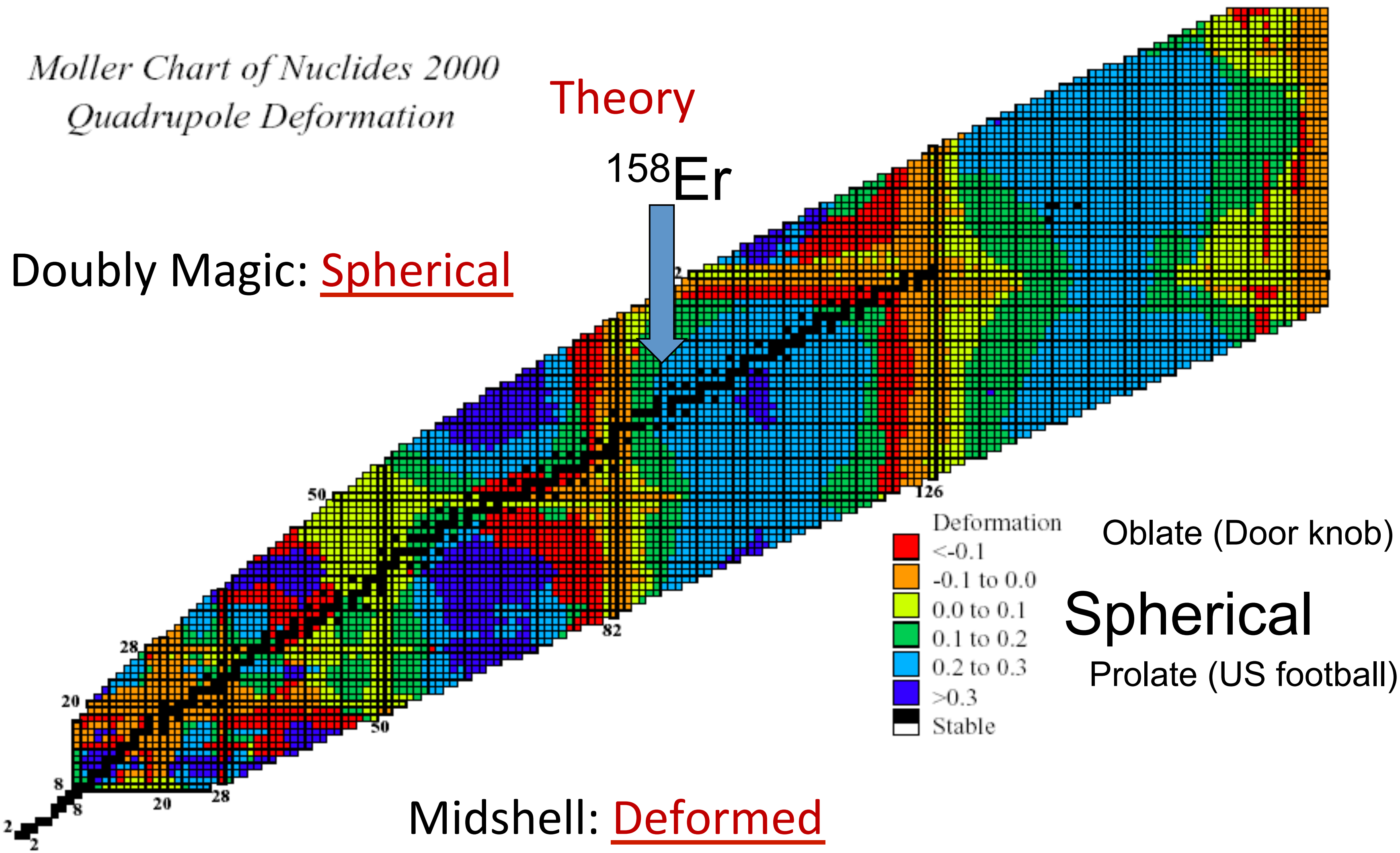
"I like everything about the world. I like the mesons and the hadrons, and the electrons and the protons and the neutrons; and the atoms, the molecules, the self-replicating molecules; the microorganisms, the plants and animals; the minerals; the zunyite and cuprite; the oceans and mountains, and the forests; the stars and the nebulae and the blacks holes, the Big Bang 18 billion years ago. I like it all!"



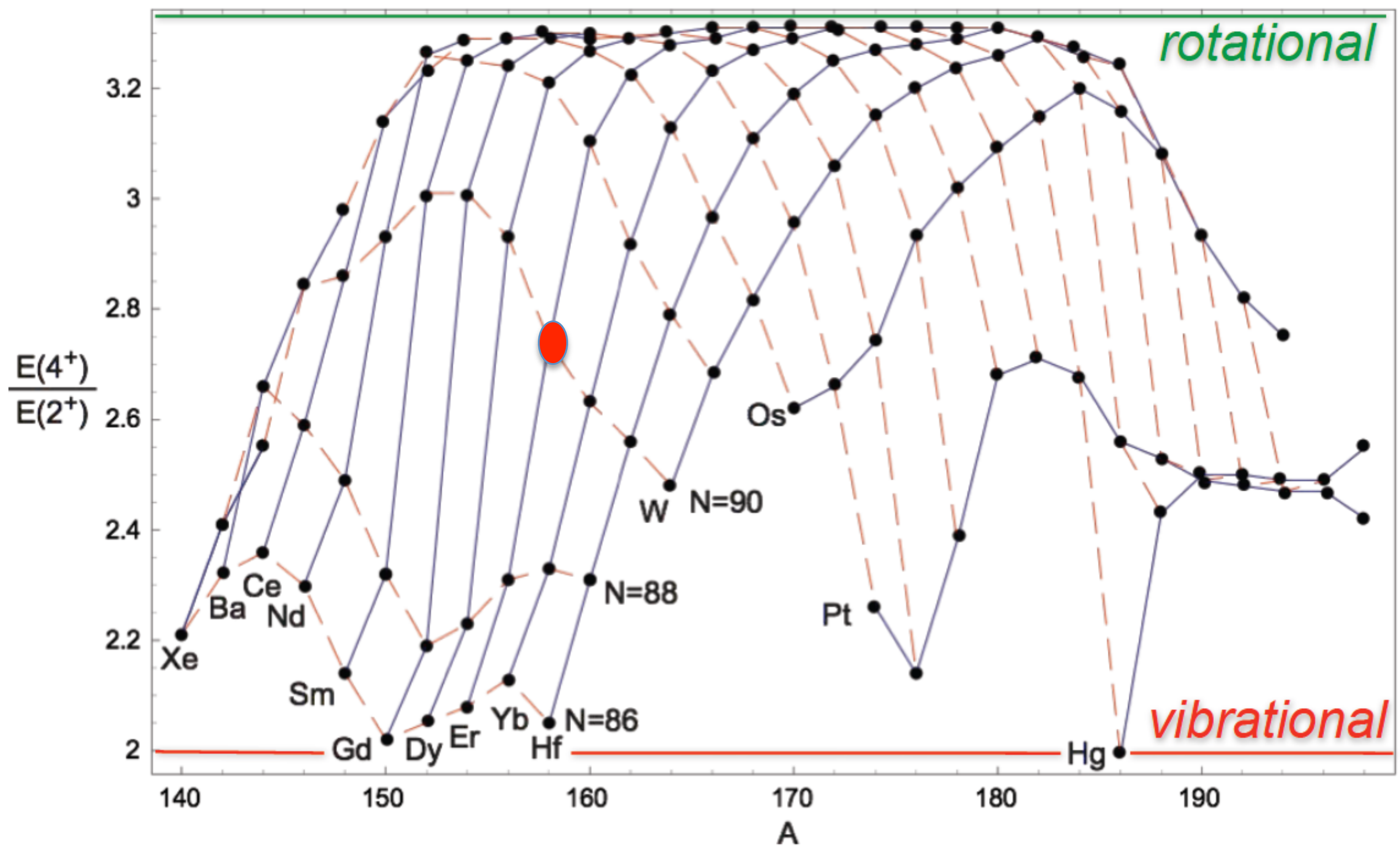
The Angular Momentum World of the Nucleus



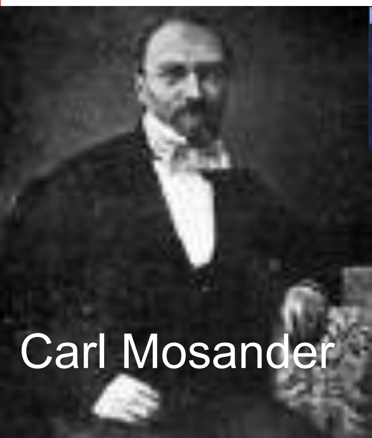
Deformation Systematics

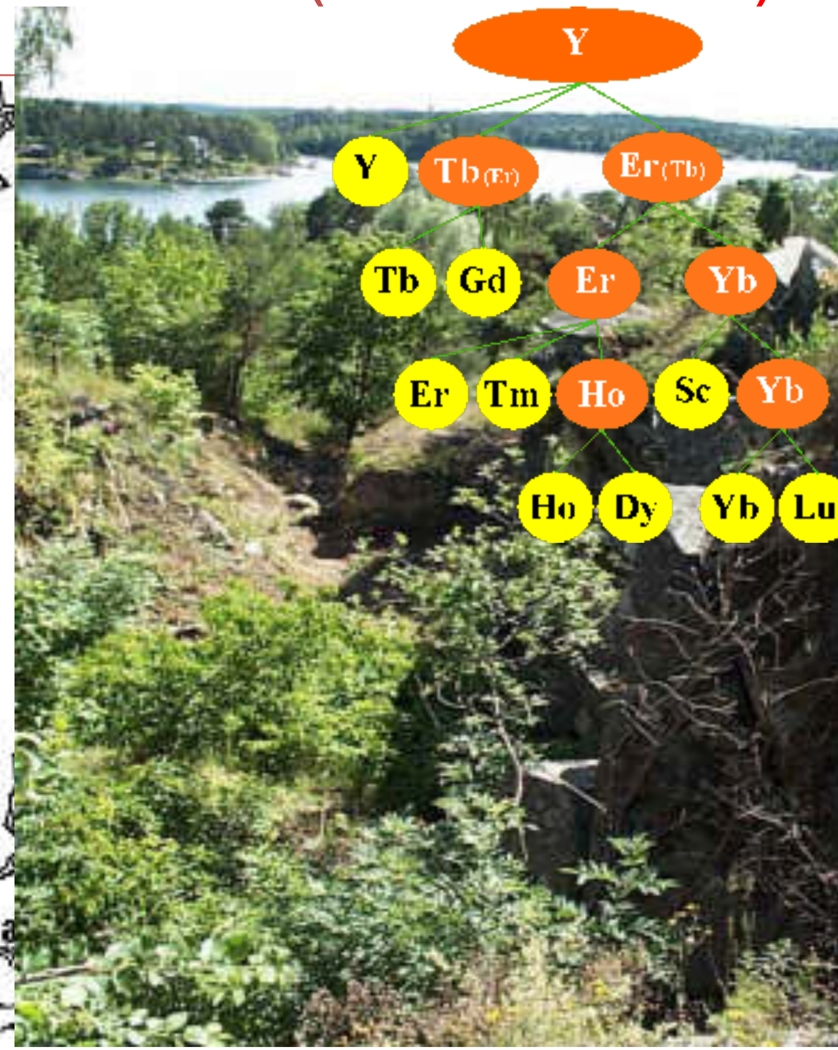


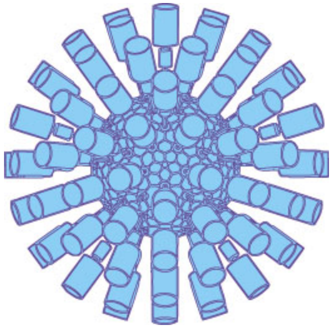
The *N=90* nuclei are transitional in nature, and located at one of the most rapid shape changes on the nuclear mass surface.



1842: The discovery of Erbium (+ other many elements) in Ytterby, a village north of Stockholm (in Ytteria ore)







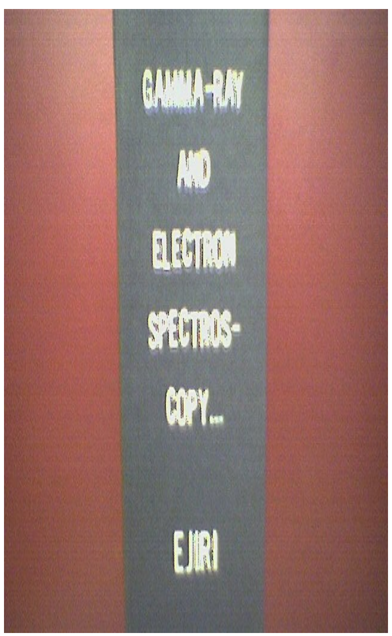
Outline of Talk

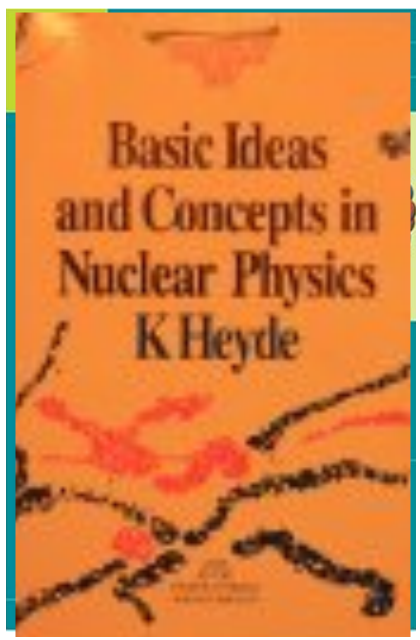
- **An example of a classic textbook nucleus, ^{158}Er**
- **Dramatic Shape Changes and Finite Particle Number Effects in Nuclei, Band Termination and What Lies Beyond: The Continuing Story of ^{158}Er.**
- **A Beautiful Example of the Evolution of Gamma-Ray Spectroscopy through the Decades.**

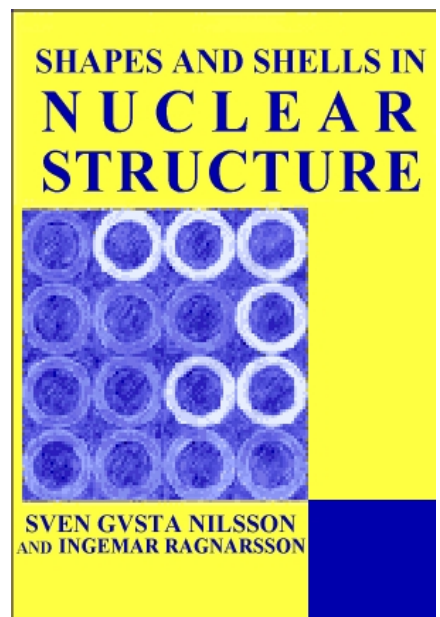
Probably the most famous Erbium isotope is A=158

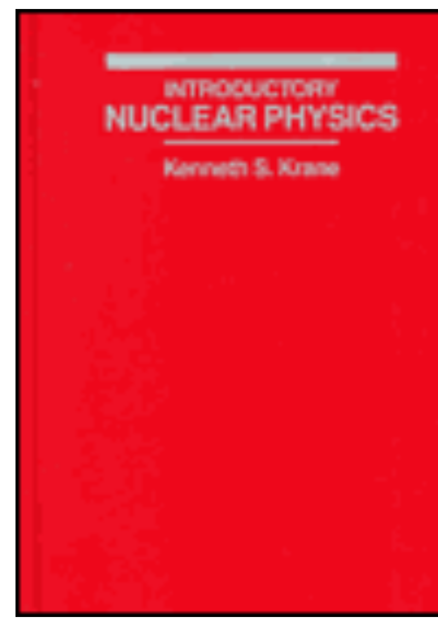
^{158}Er: famous for multiple backbends, band termination (BT) effects and dramatic prolate to oblate shape change above spin 40.

Has become a textbook example in nuclear physics!









Springer Tracts in Modern Physics 242

S.C. Pancholi

Exotic Nuclear Excitations

Springer

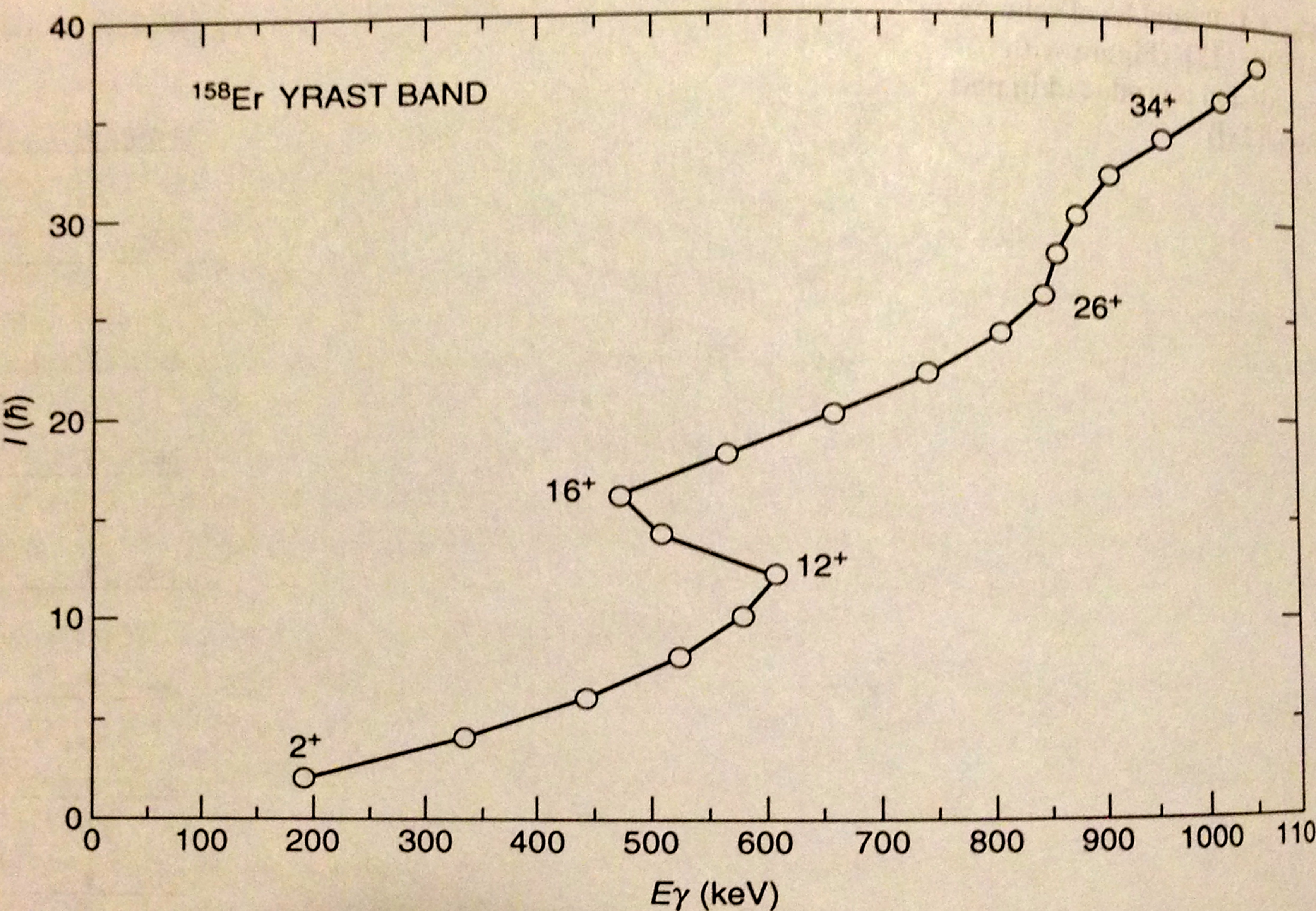


Fig. 1.2 Plot of spin vs. $E\gamma$, for the Yrast rotational band in the even–even ^{158}Er nucleus. (Data from [13])

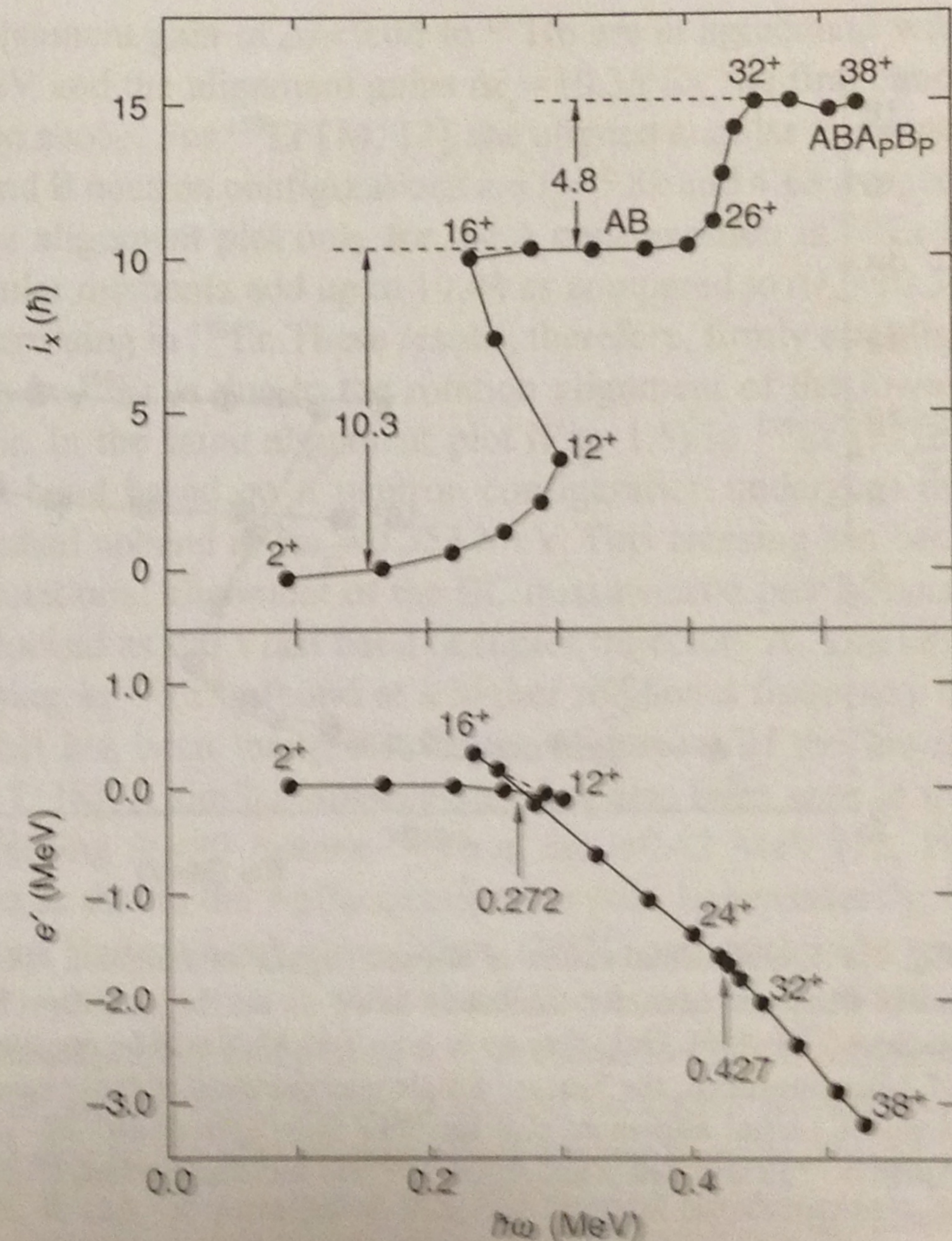


Fig. 1.3 Plots of quasiparticle energies, e', and aligned angular momenta, i_x, versus rotational frequency, $\hbar\omega$, for the Yrast band in ^{158}Er, using $\mathcal{J}_0 = 18.5\ \text{MeV}^{-1}\hbar^2$ and $\mathcal{J}_1 = 85.0\ \text{MeV}^{-3}\hbar^4$ in the parameterization of the ground state band. The bandcrossing frequencies, $\hbar\omega_c$, for the alignments are marked (↑) in the *bottom panel* and the aligned angular momentum gains, Δi_x mentioned in the *upper panel* [15]. (Figure in part reproduced with permission from [15])

Cranked Shell Model Quasi-particle diagram or Spagetti plot!

Bengtsson,
Frauendorf,
May,
At. Data and
Nuc. Data
Tables
Vol 35,
15-122, 1986

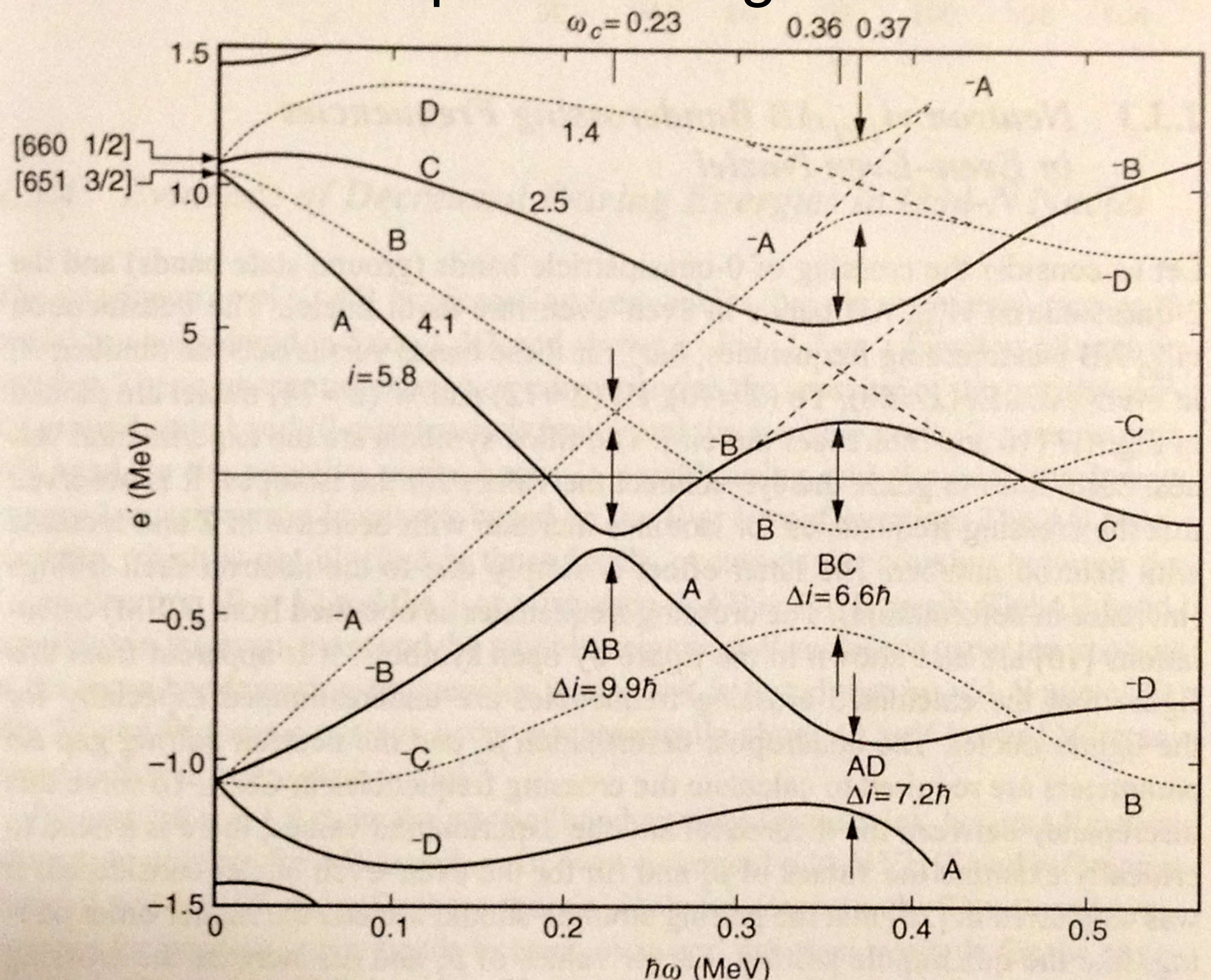


Fig. 1.6 Neutron quasiparticle energies, e', from CSM calculations, in the rotating frame as a function of rotational frequency, $\hbar\omega$ for a few selected trajectories (marked in the figure as *A*, *B*,...), in ^{160}Yb [19]. See text for details. (Figure reproduced with permission from [19])

Proc. Natl. Acad. Sci. USA
Vol. 79, pp. 7073–7075, November 1982
Physics

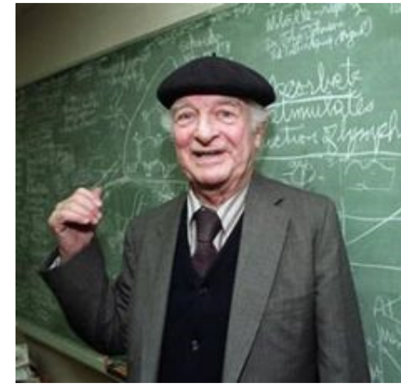
Rules governing the composition of revolving clusters in quasiband and prolate-deformation states of atomic nuclei

(nuclear sizes/$_{36}$Kr/$_{38}$Sr/$_{40}$Zr/$_{42}$Mo/$^{158}_{68}$Er/actinon nuclei)

LINUS PAULING

Linus Pauling Institute of Science and Medicine, 440 Page Mill Road, Palo Alto, California 94306

Contributed by Linus Pauling, August 23, 1982



ABSTRACT A set of rules, involving the magic and semimagic values of neutron and proton numbers and the proton/neutron ratio, is formulated for the composition of the revolving clusters producing the values of the moment of inertia given by the differences in energy of the adjacent levels in quasibands and bands of nuclei. The cluster compositions assigned with use of these rules to isotopes of Kr, Sr, Zr, Mo, and the actinon nuclei and to successive levels of the ground-state band of ^{158}Er lead to reasonable values of the radius of revolution (the distance from the center of the nonrevolving sphere to the center of the cluster). These values correspond to a spheron diameter of about 3.20 fm.

Linus Pauling (1901-1994): (Two Nobel Prizes)

Second Discontinuity in the Yrast Levels of ^{158}Er†

I. Y. Lee, M. M. Aleonard,* M. A. Deleplanque,‡ Y. El-Masri,§ J. O. Newton,‖ R. S. Simon,¶
R. M. Diamond, and F. S. Stephens
Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 13 April 1977)

Discrete yrast transitions from states with spins up to 30$\hbar$ have been observed in ^{158}Er from ^{40}Ar-induced compound-nucleus reactions. A second discontinuity in the level sequence occurs around $I = 28\hbar$. Possible causes and implications of this effect are discussed.

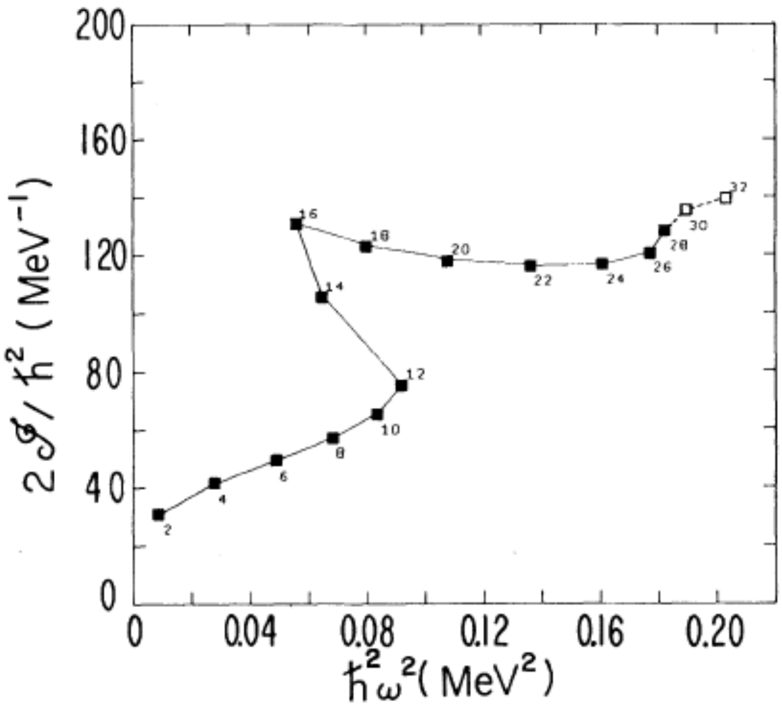
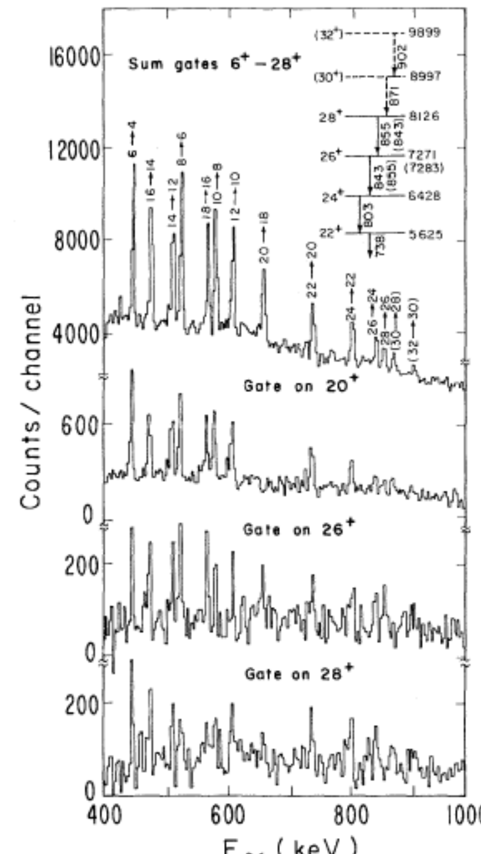


FIG. 2. Plot of the moment of inertia vs the square of the angular velocity for ^{158}Er.

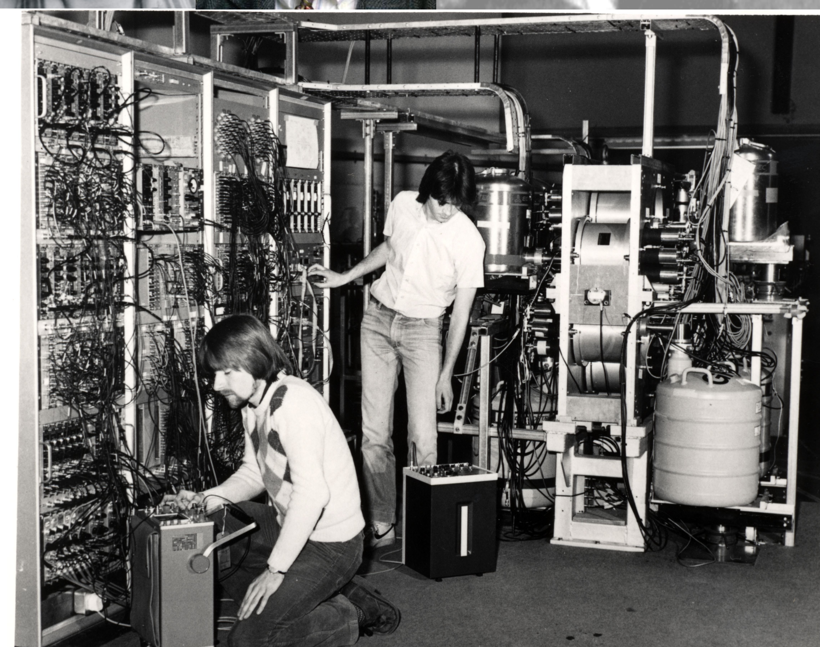


Er-158 experiment at Daresbury proposed by John Sharpey-Schafer

1983 (Liverpool + NBI)
TESSA2
6 ESS + 50 element BGO ball
Plus a ^{48}Ca beam!

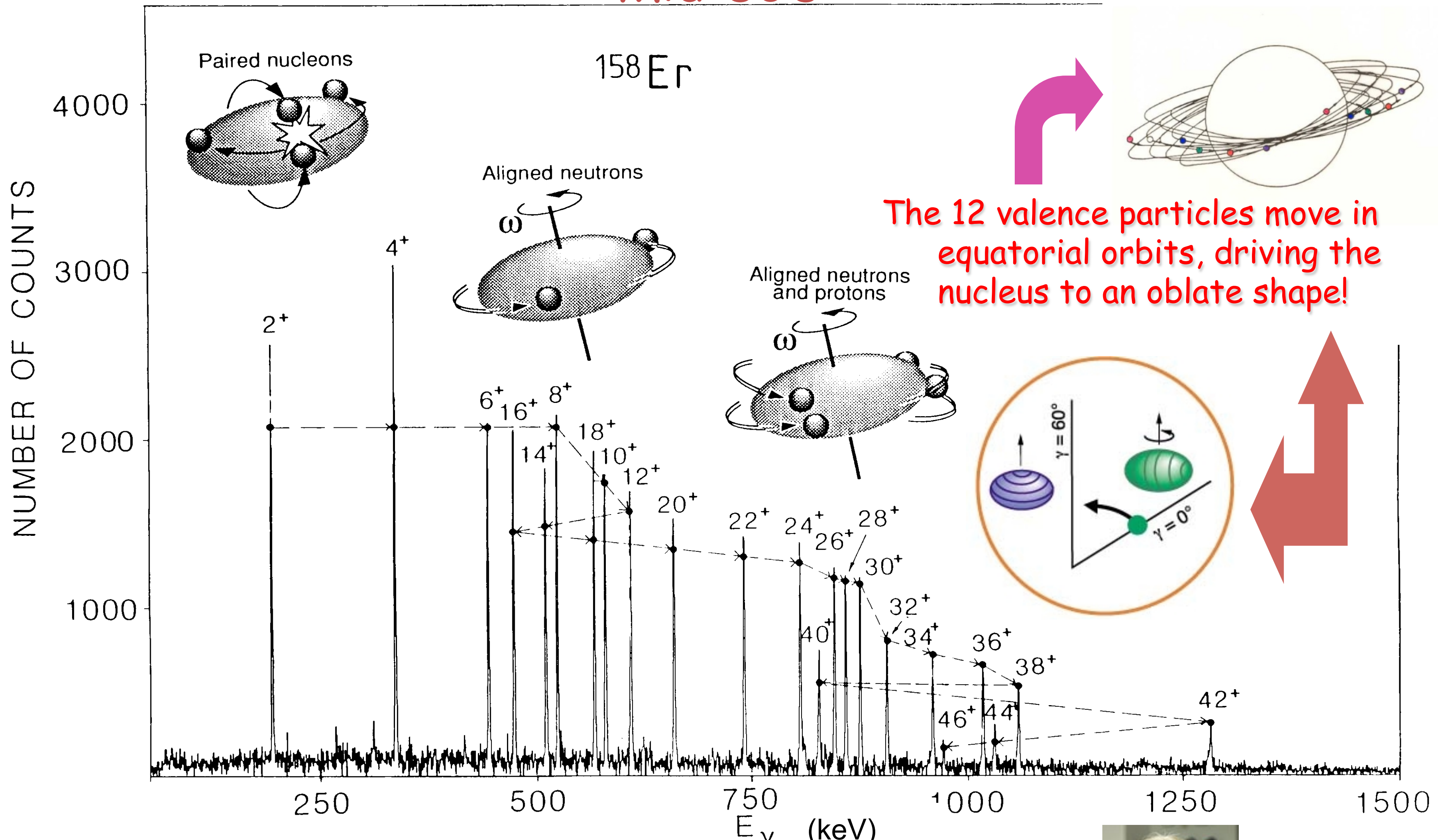
One of my thesis expts.

John Simpson also looked at Er-158 earlier at NBI using TESSA0 for his thesis.



John Simpson and I (and Eddie) only visit ^{158}Er once or twice every decade …. We do look at other nuclei too!!!

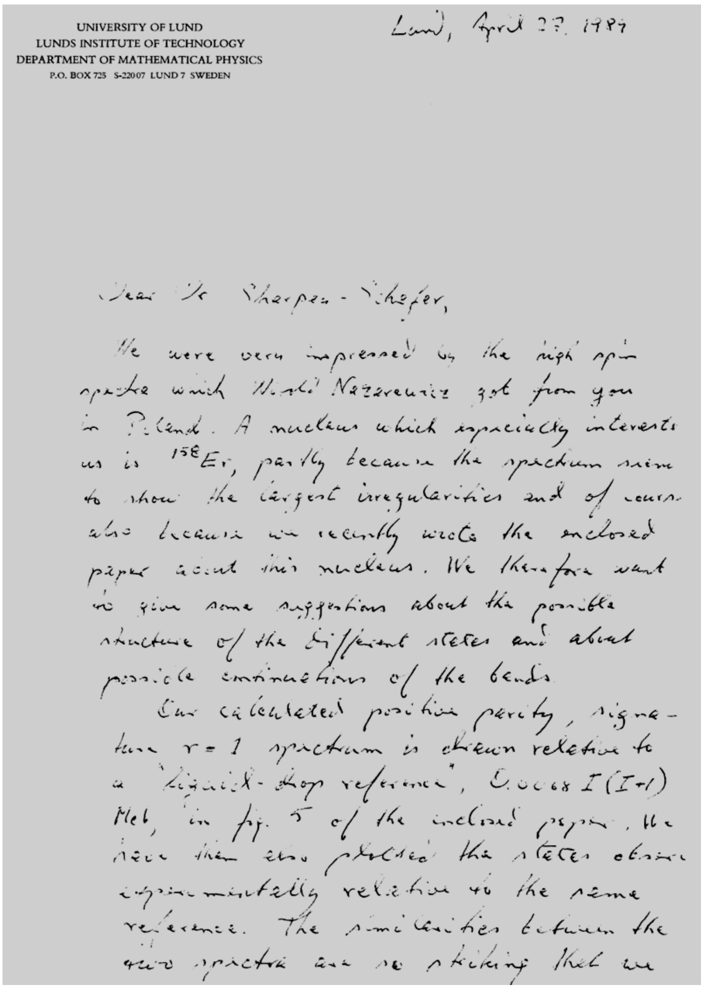
^{158}Er expt at Daresbury - Sharpey-Schafer/Riley/Simpson/ Mid-80's



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

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



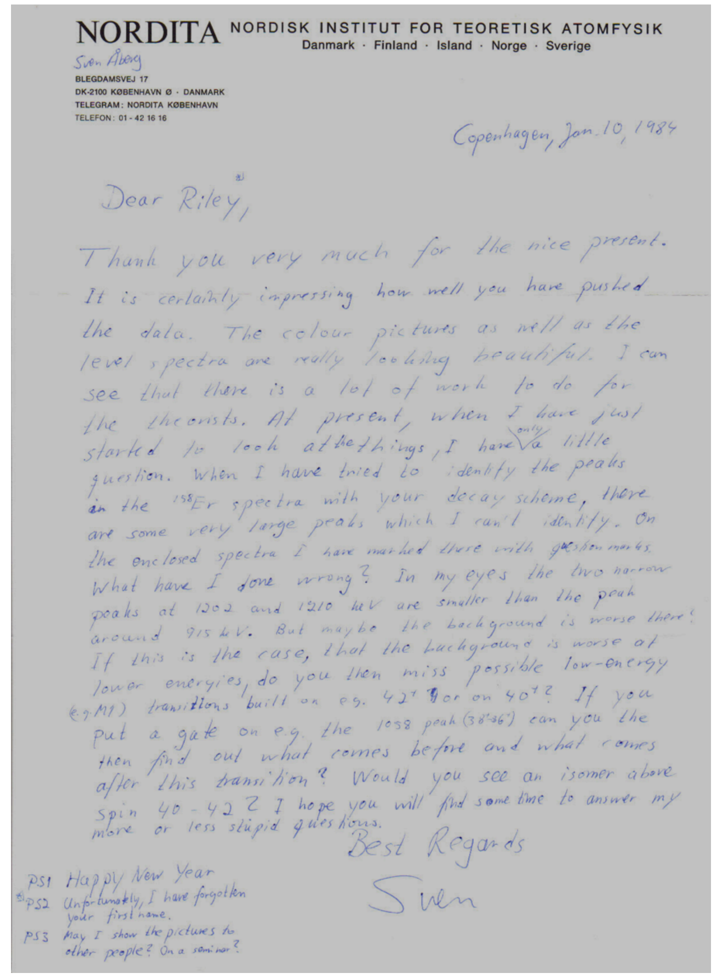
UNIVERSITY OF LUND
LUNDS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF MATHEMATICAL PHYSICS
P.O. BOX 725 S-22007 LUND 7 SWEDEN

Lund, April 27, 1984

Dear Dr Sharpey-Schafer,

We were very impressed by the high spin spectra which Witold Nazarewicz got from you in Poland. A nucleus which especially interests us is ^{158}Er, partly because the spectrum seems 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 drawn relative to a "liquid-drop reference", 0.0068 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,*

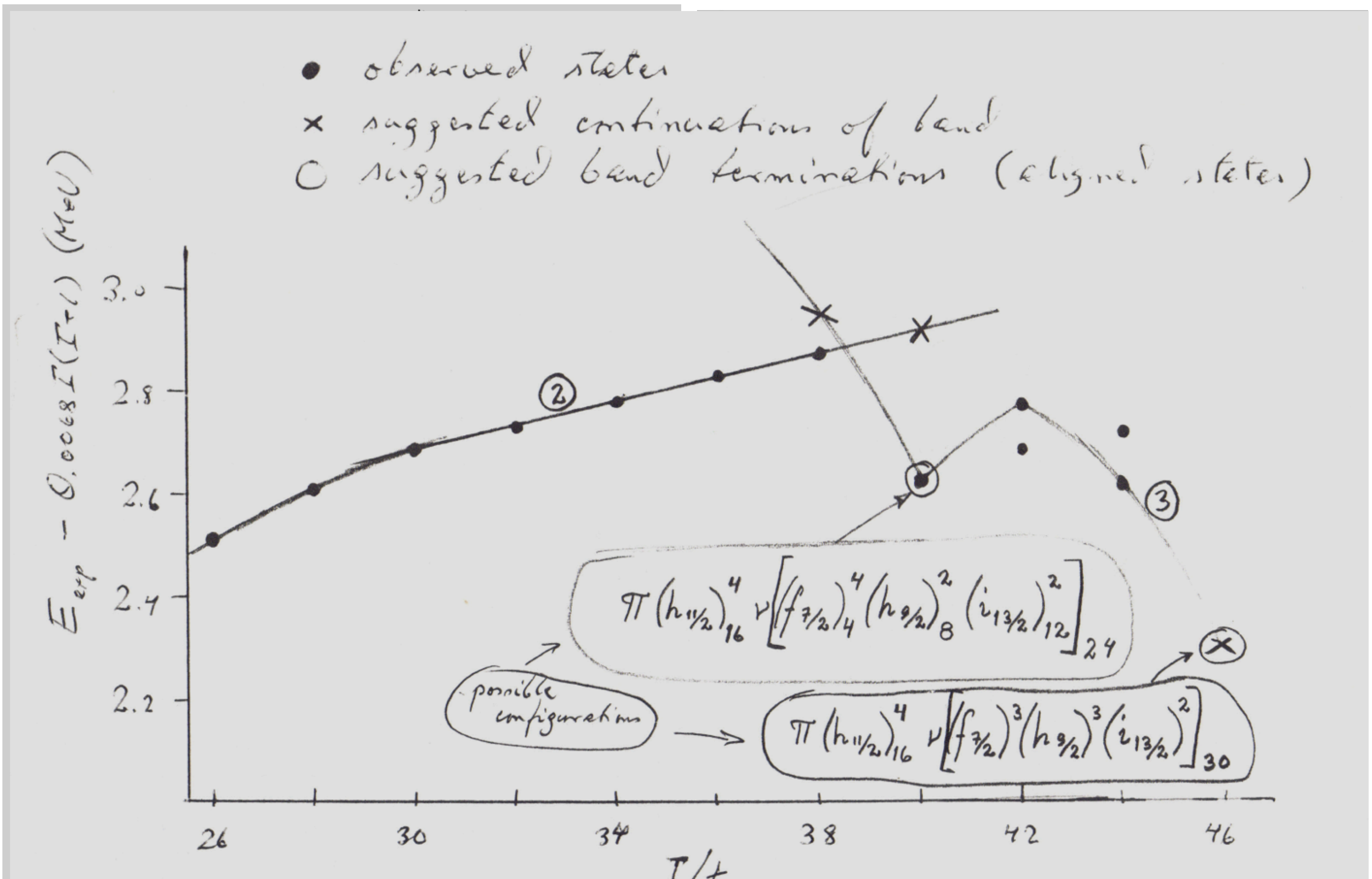
Thank you very much for the nice present. It is certainly impressing how well you have pushed the data. The colour pictures as well as the level spectra are really looking beautiful. I can see that there is a lot of work to do for the theorists. At present, when I have just started to look at the things, 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 (e.g. M1) transitions built on e.g. 42^+ or on 40^+? If you put a gate on e.g. the 1058 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?

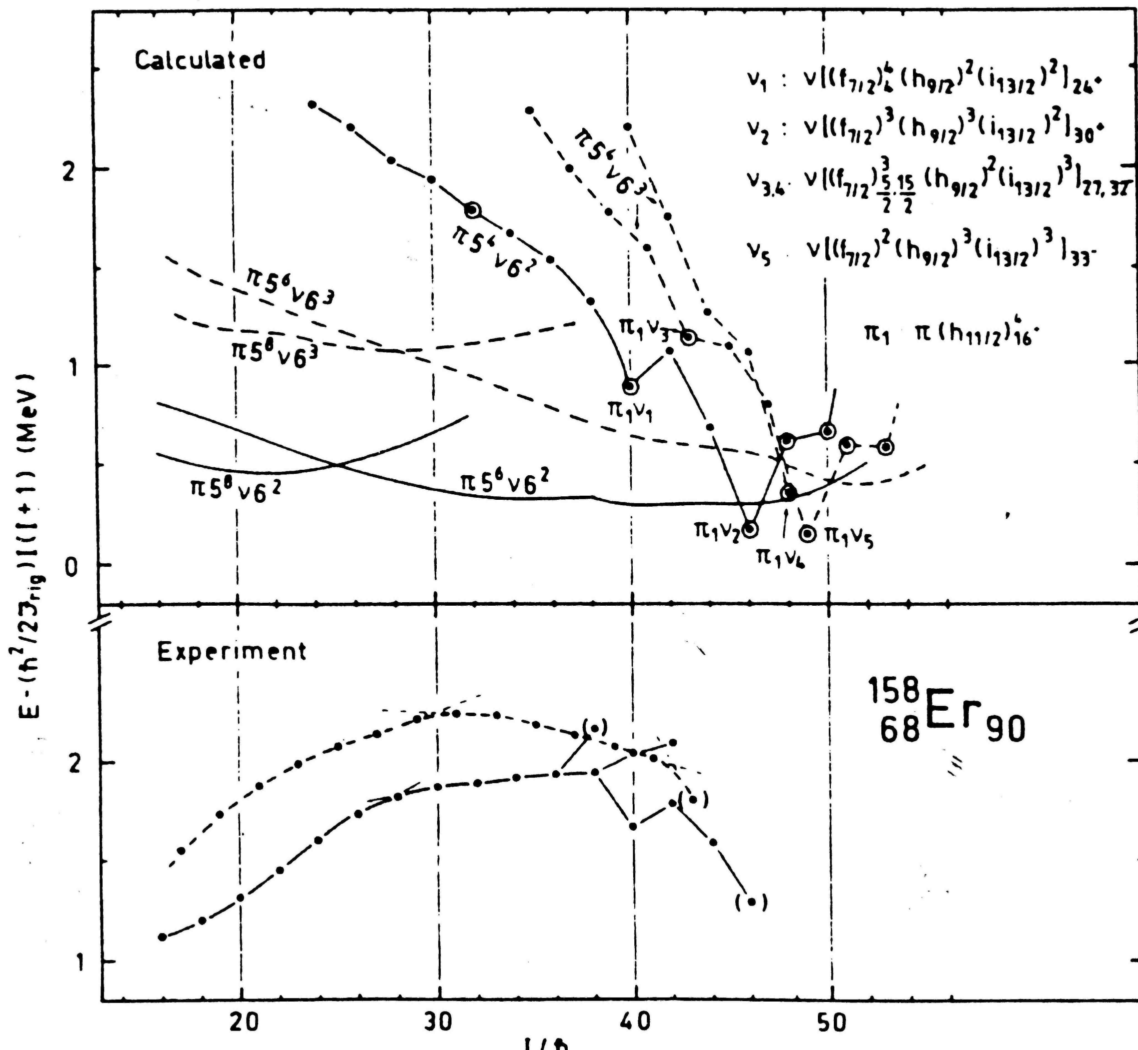
1984 - Liverpool to Lund/Copenhagen letters to/from Sven & Ingemar on ^{158}Er!



Answer: How to interpret exptal data with regard to calcs

"Rigid Rotor" plot for 158Er: Theory (83) and Expt (85)

T.Bengtsson and I.Ragnarsson Physica Scripta T5 (1983) 165

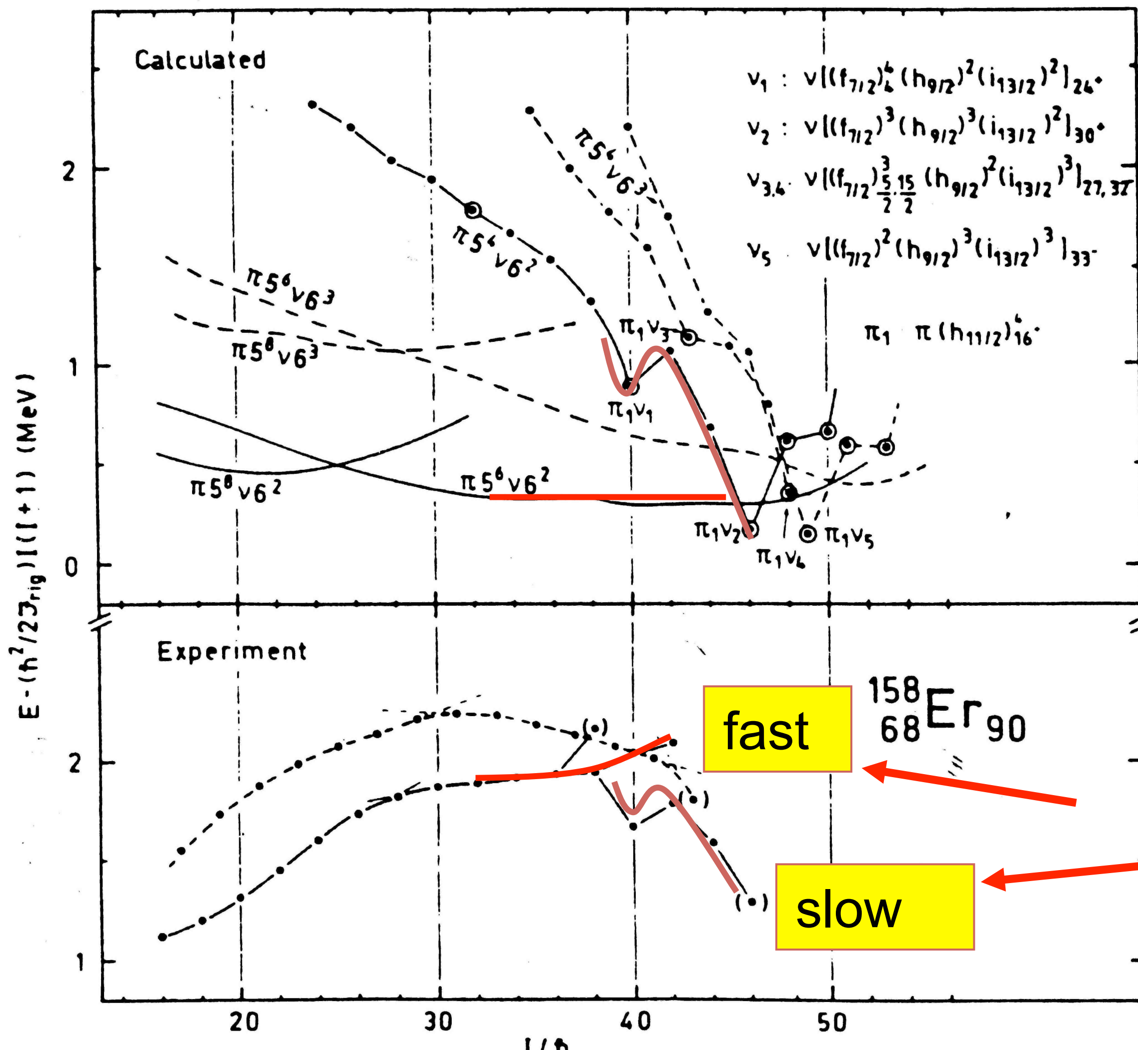


Expt now includes beautiful input from LBL group

Simpson et al., Phys. Rev. Lett. 53 (1984) 648 and Tjom et al., Phys.Rev.Lett. 55 (1985) 2405

"Rigid Rotor" plot for 158Er: Theory (83) and Expt (85)

T.Bengtsson and I.Ragnarsson Physica Scripta T5 (1983) 165



The story gets even better!

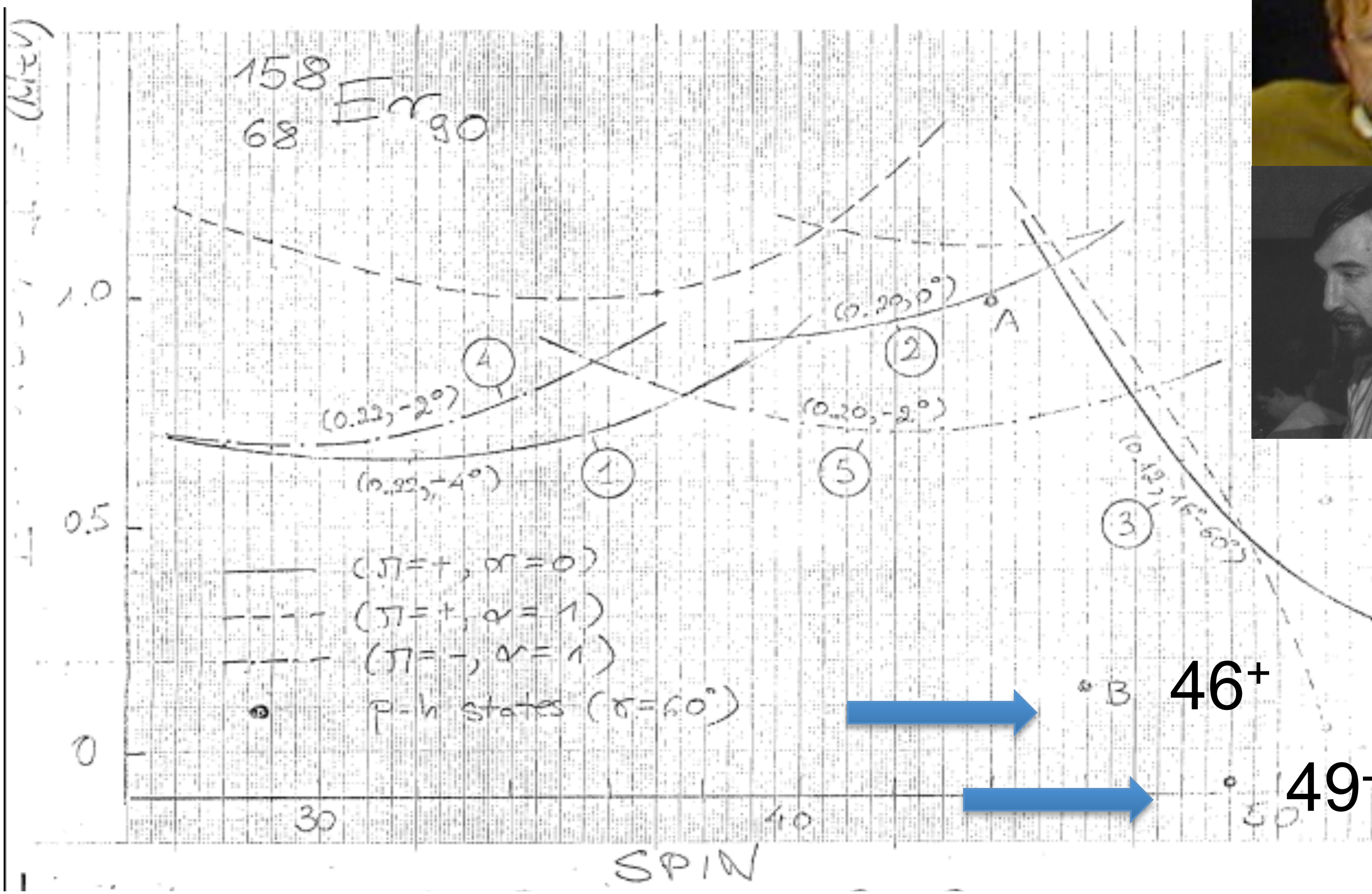
Expt now includes beautiful input from LBL group

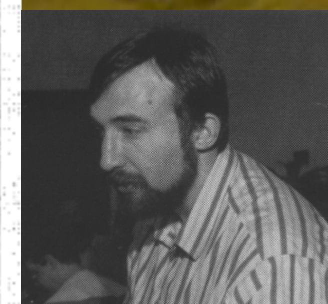
Simpson et al., Phys. Rev. Lett. 53 (1984) 648 and Tjom et al., Phys.Rev.Lett. 55 (1985) 2405

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

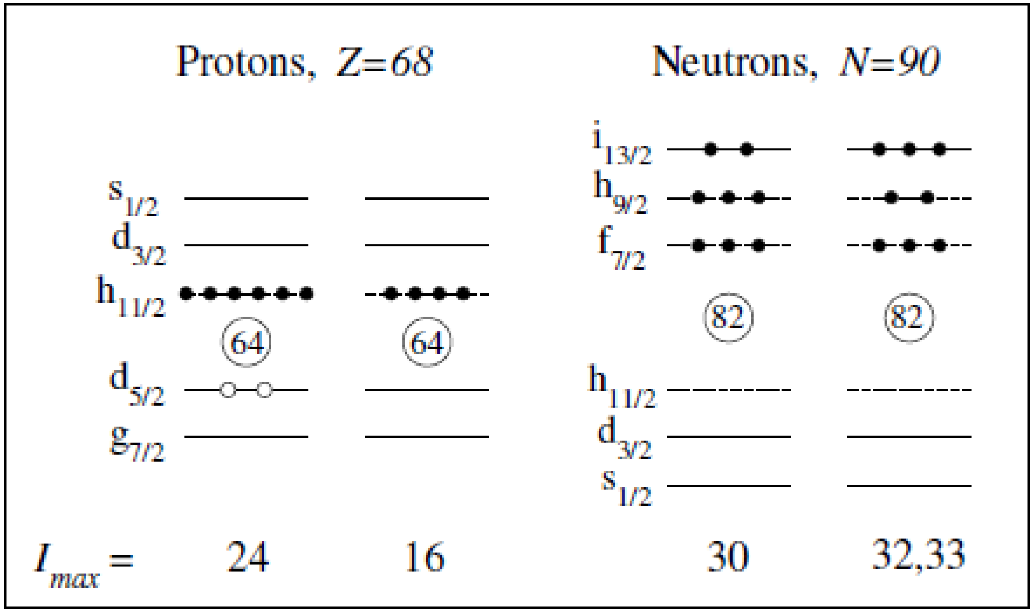
Original hand drawings for the famous 1985 article

Phys. Rev. C31 (1985) 298



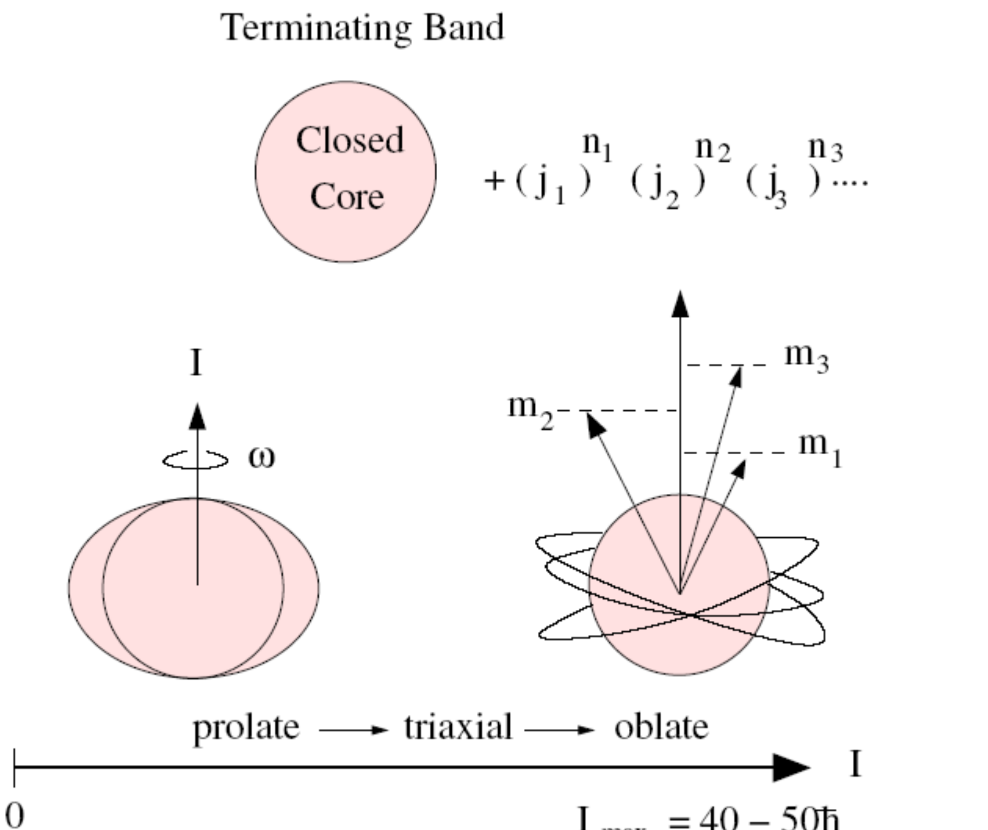


^{158}Er: Filled orbitals relative to ^{146}Gd core.



Band Termination in Heavy Nuclei

- Band termination occurs when the valence nucleons are fully aligned with the axis of rotation.
- In these erbium nuclei a prolate to oblate shape change occurs.
- This was the first time this effect had been seen in such a heavy nucleus.



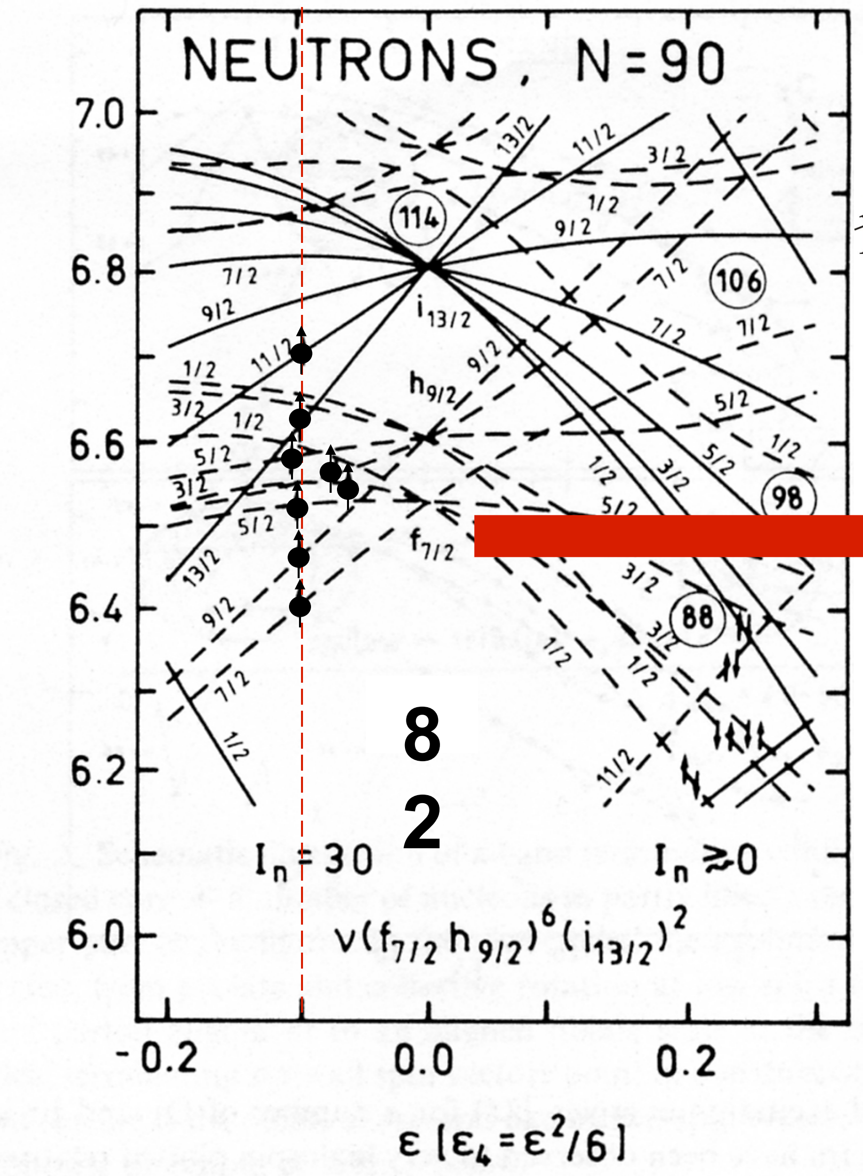
$I_{max} = 40 - 50\hbar$

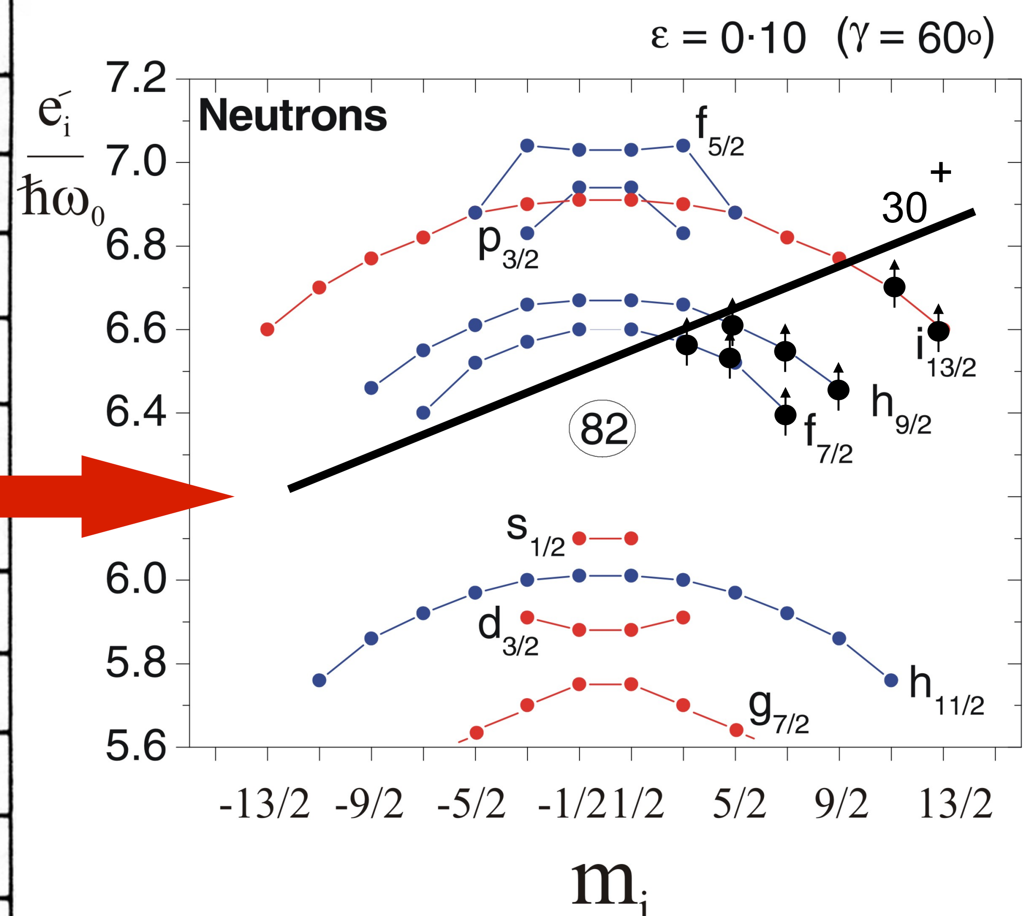
$I = m_1 + m_2 + m_3 + \cdots$

T.Bengtsson and I.Ragnarsson Physica Scripta T5 (1983) 165

Ragnarsson, Xing, Bengtsson and Riley, Phys. Scripta. 34 (1986) 651

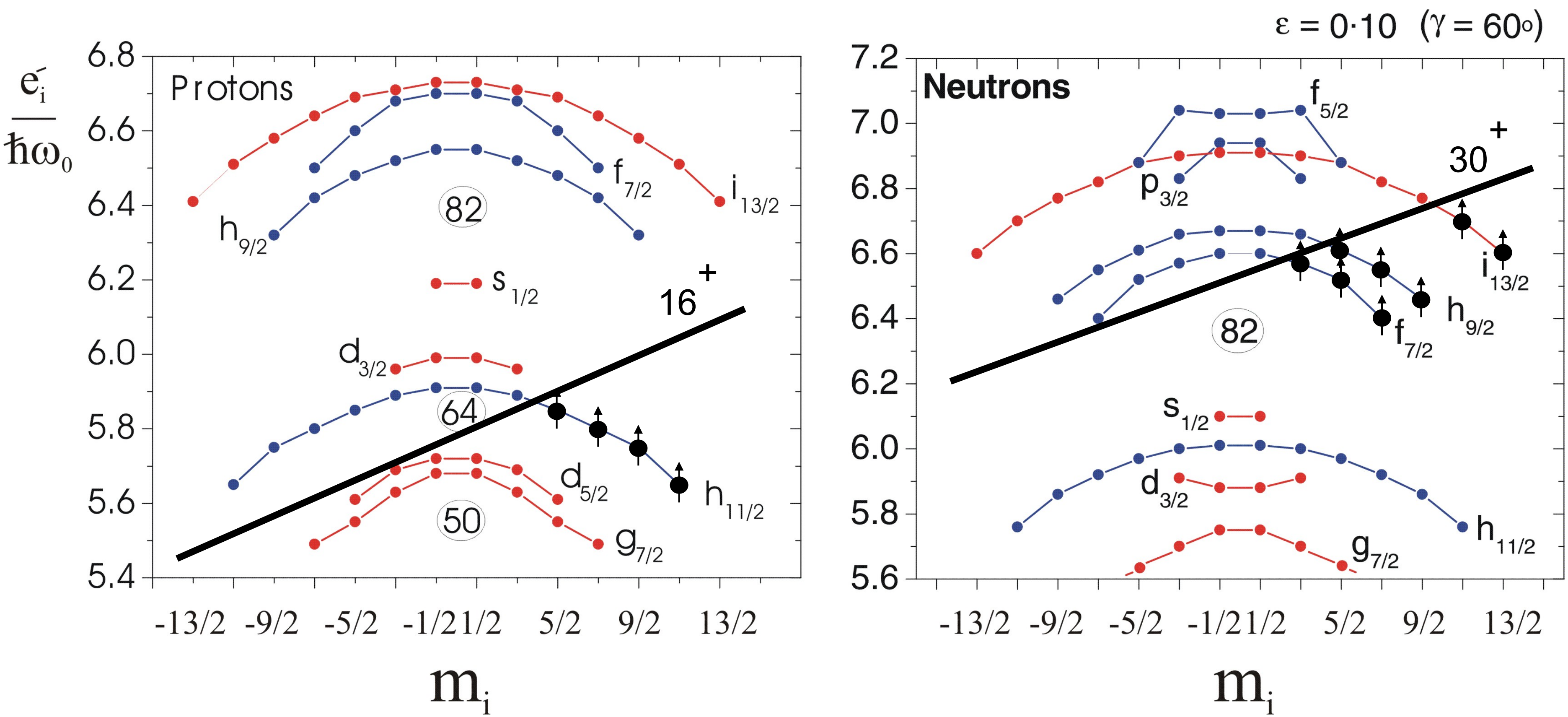
Favored BT States and the Tilted Fermi Surface Method in ^{158}Er (8 valence neutrons above N=82)





$\nu[(h_{9/2}, f_{7/2})^6 (i_{13/2})^2]_{30+}$

Favored BT States and the Tilted Fermi Surface Method. Why 46^+ in ^{158}Er?



$\pi[(h_{11/2})^4]_{16+}$ $\otimes$ $\nu[(h_{9/2}, f_{7/2})^6 (i_{13/2})^2]_{30+}$

Band Termination in ^{158}Er

- At termination ^{158}Er can be thought of as an inert ^{146}Gd core plus 4 protons and 8 neutrons which generate a total spin 46ħ

- The configuration of the 12 valence particles is:

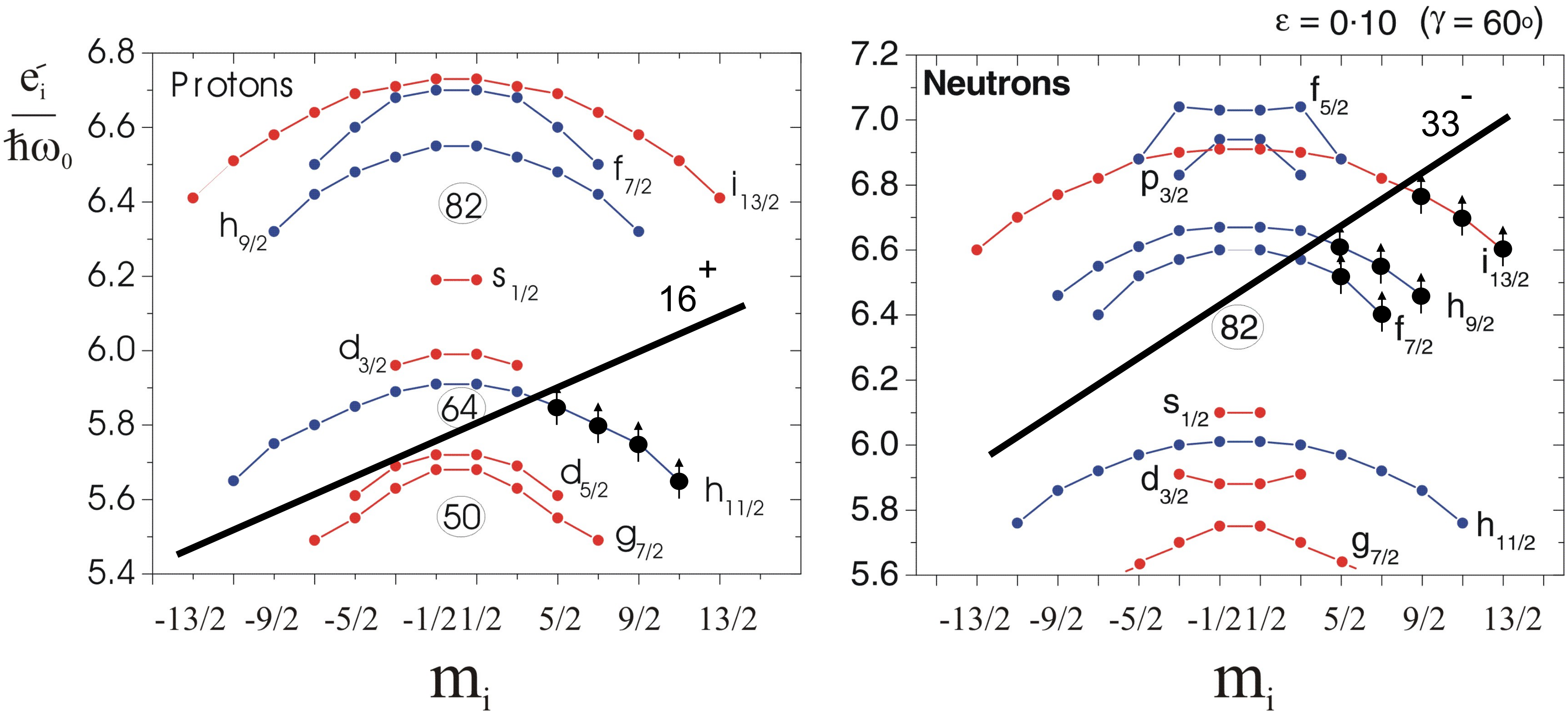
$$\pi(h_{11/2})^4 \otimes \nu(i_{13/2})^2 (h_{9/2})^3 (f_{7/2})^3$$

- The terminating spin value of 46 is generated as:

$$(11/2+9/2+7/2+5/2) + (13/2+11/2) + (9/2+7/2+5/2) + (7/2+5/2+3/2)$$

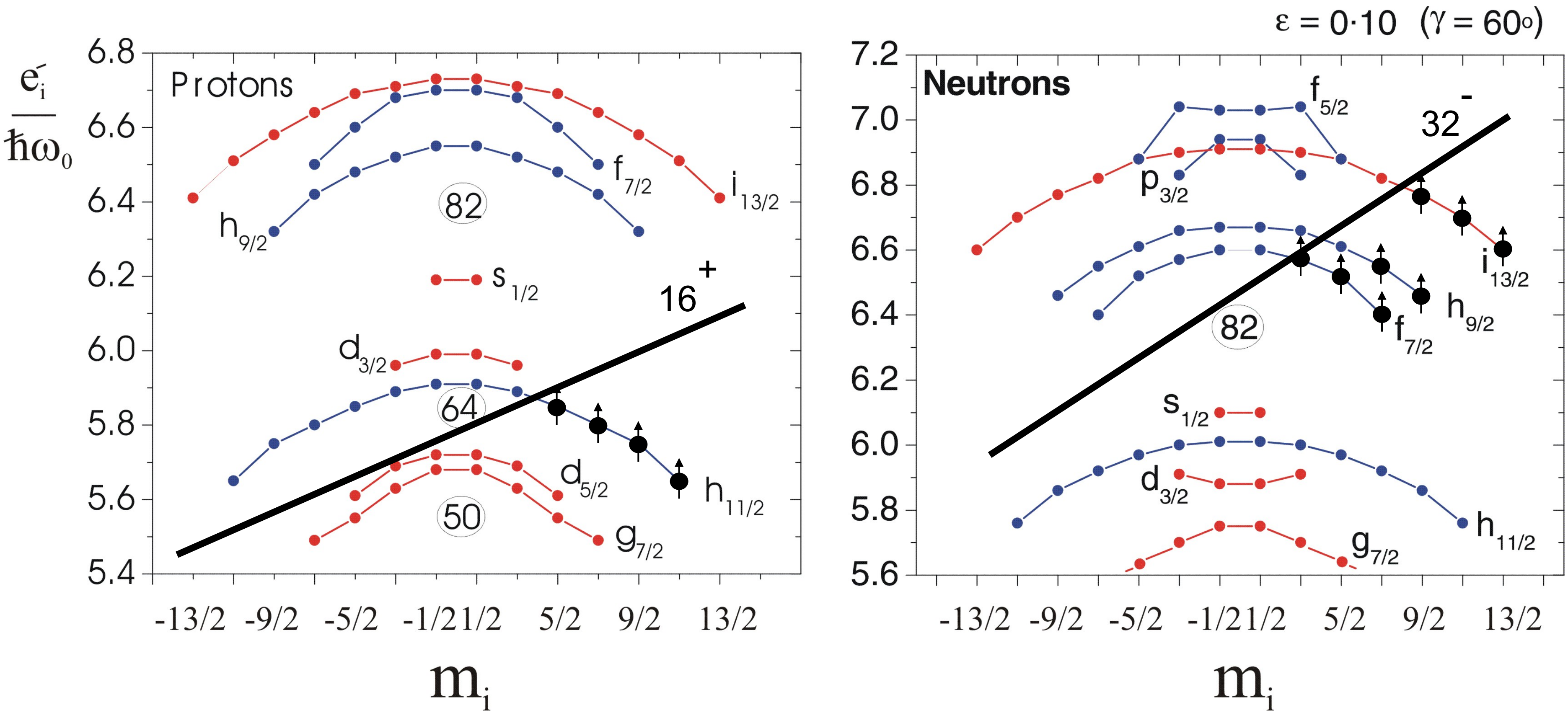
- Parity: $(-1)^4 (+1)^2 (-1)^3 (-1)^3 = +1$

Favored BT States and the Tilted Fermi Surface Method. Predicted Negative parity states. e.g. 49^- (-,1)



$\pi[(h_{11/2})^4]_{16+}$ $\otimes$ $\nu[(h_{9/2}, f_{7/2})^5 (i_{13/2})^3]_{33-}$

Favored BT States and the Tilted Fermi Surface Method. Predicted Negative parity states. e.g. 48^- (-,1)



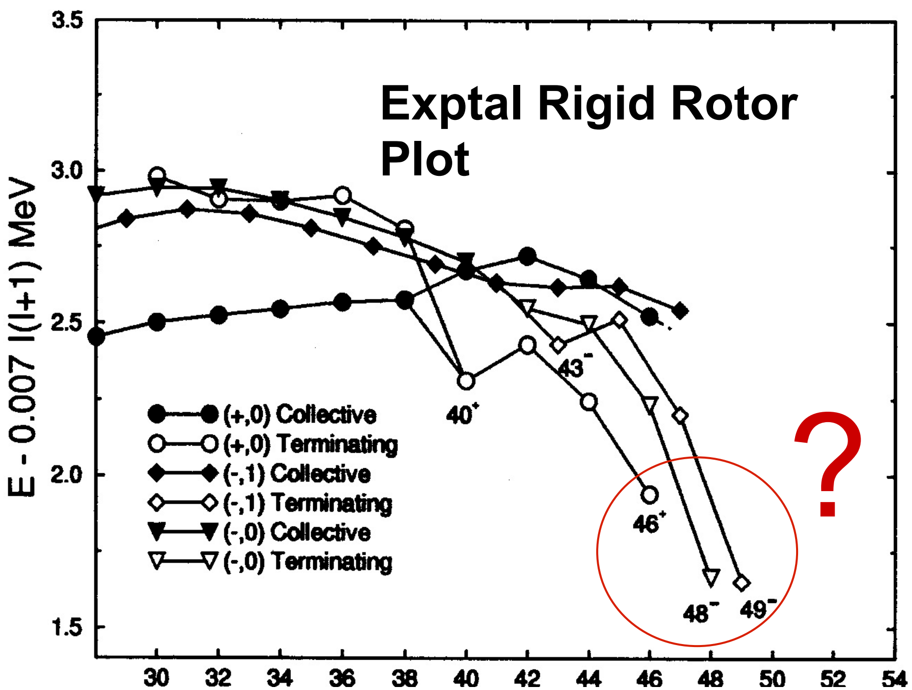
$\pi[(h_{11/2})^4]_{16+}$ $\otimes$ $\nu[(h_{9/2}, f_{7/2})^5 (i_{13/2})^3]_{32-}$

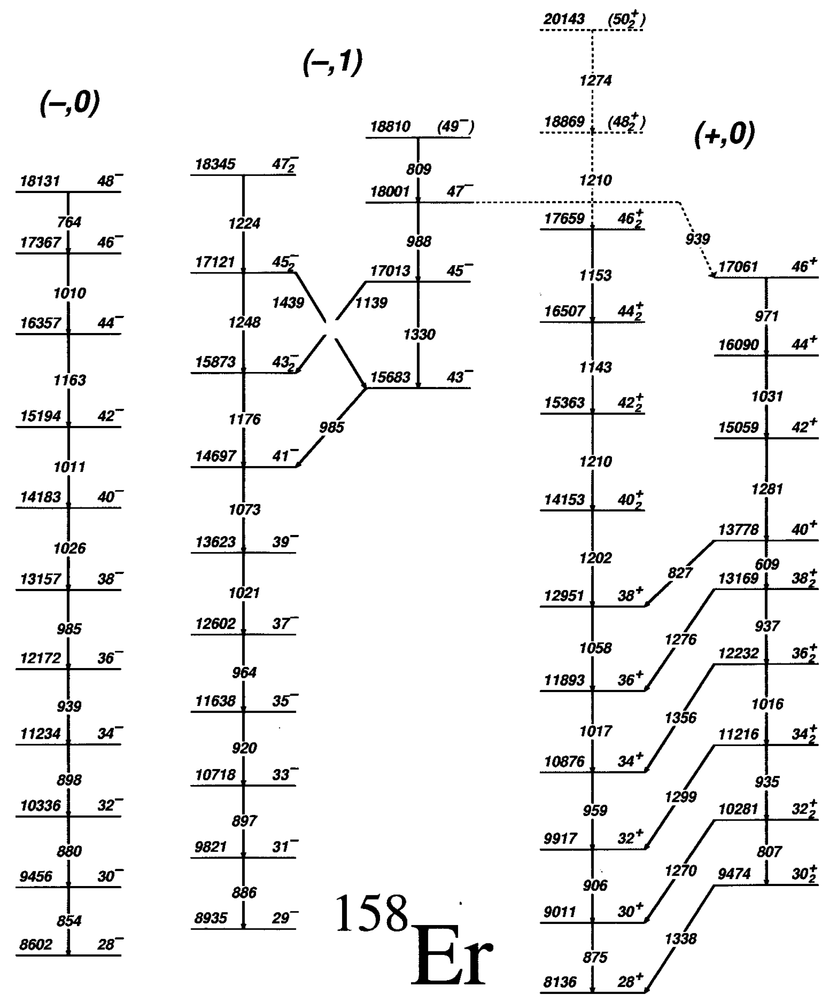
10 years later (1994)
- ^{158}Er again at Daresbury but now with EUROGAM 1

Terminating states in the side bands too

Now see BT states at 46 $^{+}$, 48^{-} and 49^{-} and single particle states at 40^{+} and 43^{-}

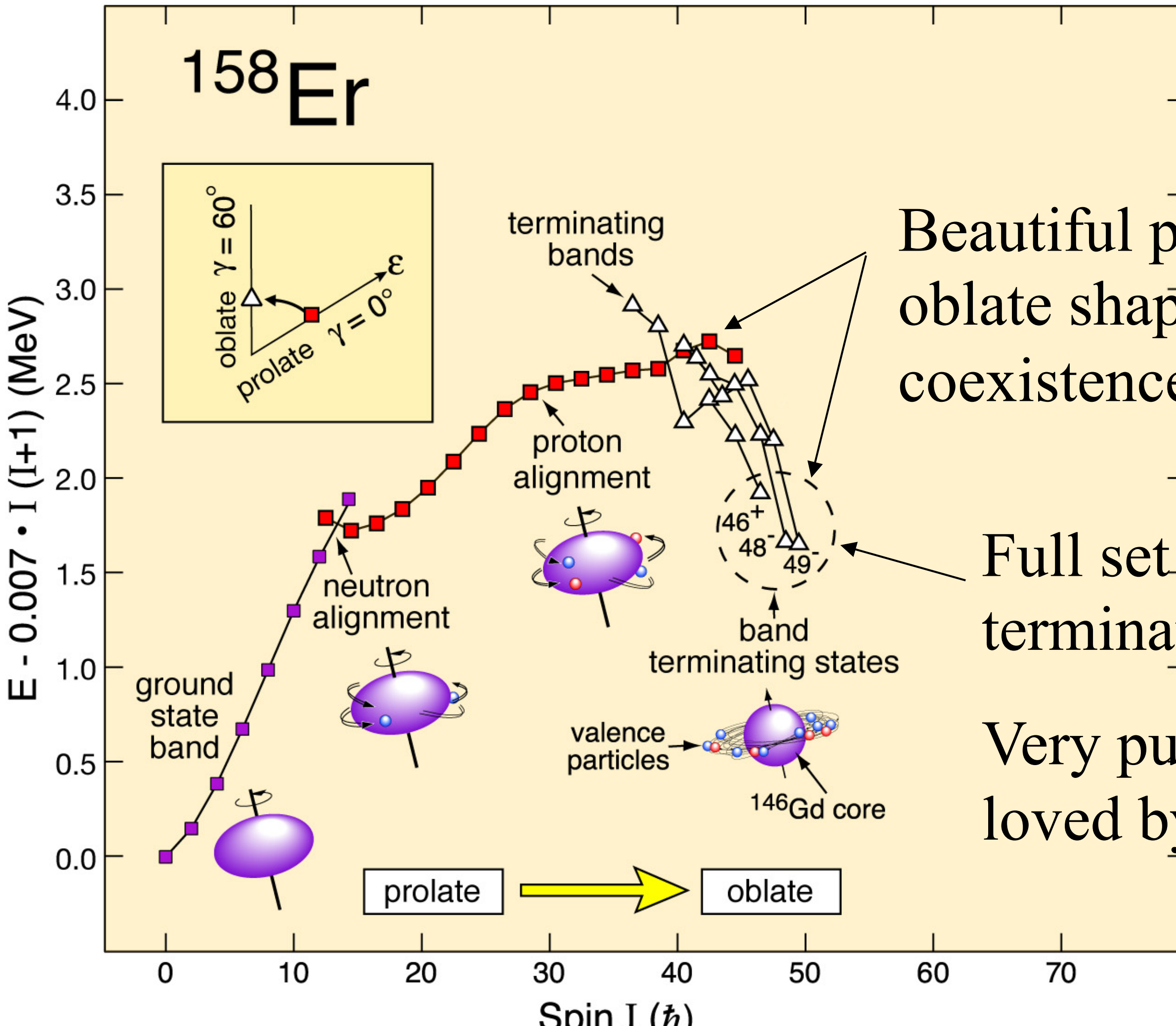
Special BT states were used to help set theoretical parameters.





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

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



Beautiful prolate – oblate shape coexistence

Full set of favored terminations!

Very pure states – loved by theorists

Simpson, Riley, JFSS et al., Phys. Lett. B 327, 187 (1994)

Using the purity of BT states to good effect!

PHYSICAL REVIEW C **71**, 024305 (2005)

Probing the nuclear energy functional at band termination

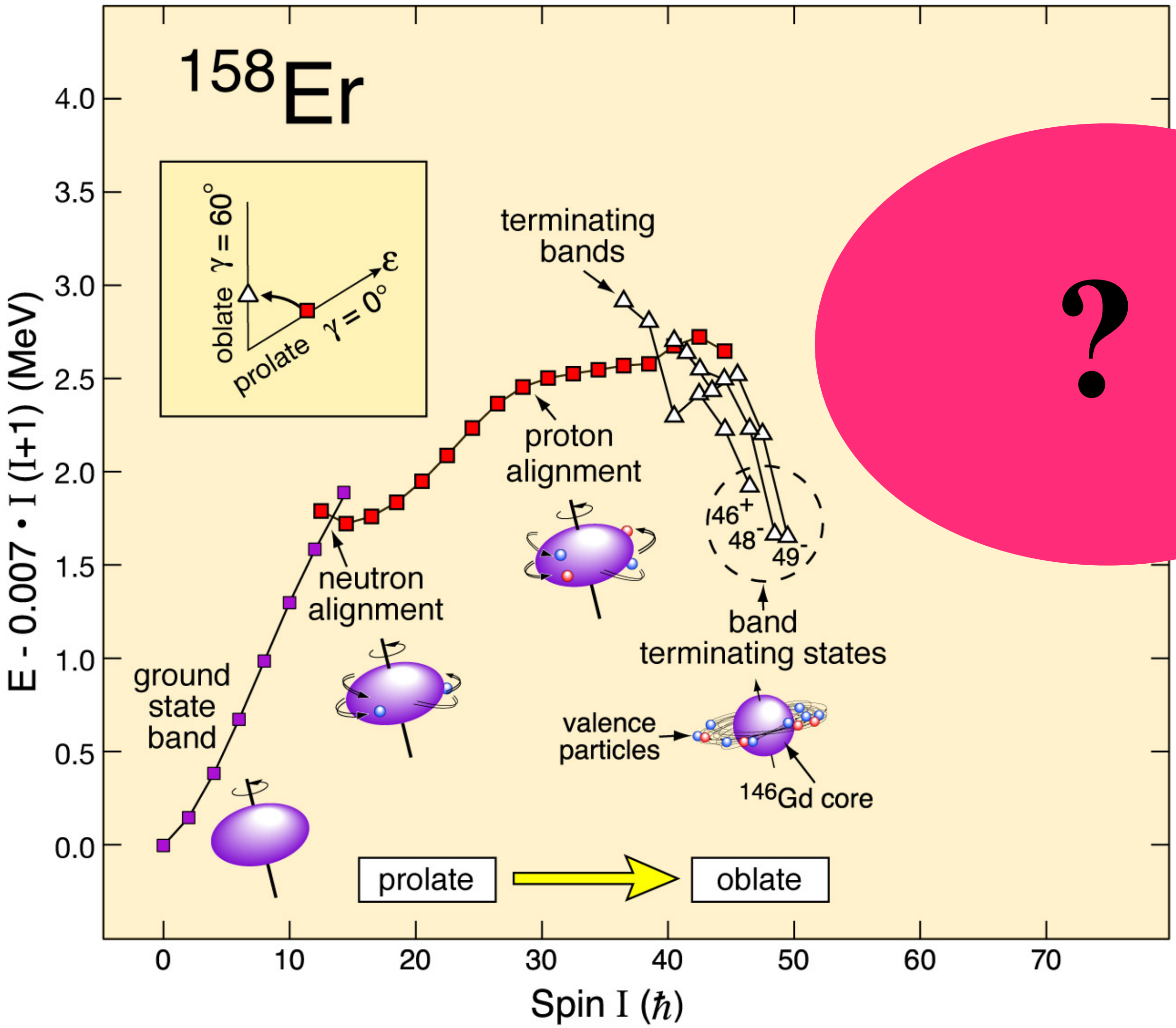
Honorata Zduńczuk,[1,*] Wojciech Satuła,[1,2,†] and Ramon A. Wyss[2,‡]
[1]*Institute of Theoretical Physics, University of Warsaw, ul. Hoża 69, PL-00 681 Warsaw, Poland*
[2]*KTH (Royal Institute of Technology), AlbaNova University Center, SE-106 91 Stockholm, Sweden*
(Received 29 June 2004; revised manuscript received 22 November 2004; published 9 February 2005)

A systematic study of terminating states in the $A \sim 50$ mass region using the self-consistent Skyrme-Hartree-Fock model is presented. The objective of this study is to demonstrate that the terminating states, due to their intrinsic simplicity, offer unique and so far unexplored opportunities to study different aspects of the effective *NN* interaction or nuclear local energy density functional. In particular, we show that the agreement of the calculations to the data depends on the spin fields and the spin-orbit term which, in turn, allows us to constrain the appropriate Landau parameters and the strength of the spin-orbit potential. The present study reveals that the structure and energy of terminating states can be used as a tool to differentiate among the many Skyrme force parametrizations.

DOI: 10.1103/PhysRevC.71.024305 PACS number(s): 21.30.Fe, 21.60.Jz

For a superb review on Band Termination States see, Afanasjev, Fossan, Lane and Ragnarsson, Phys. Rep. 322 (1999) 1

BUT WHAT LIES ABOVE BAND TERMINATION?

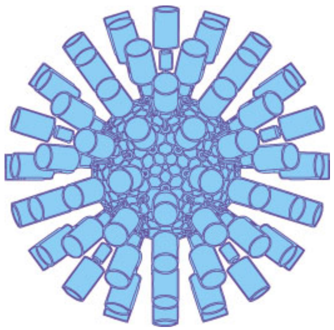


?

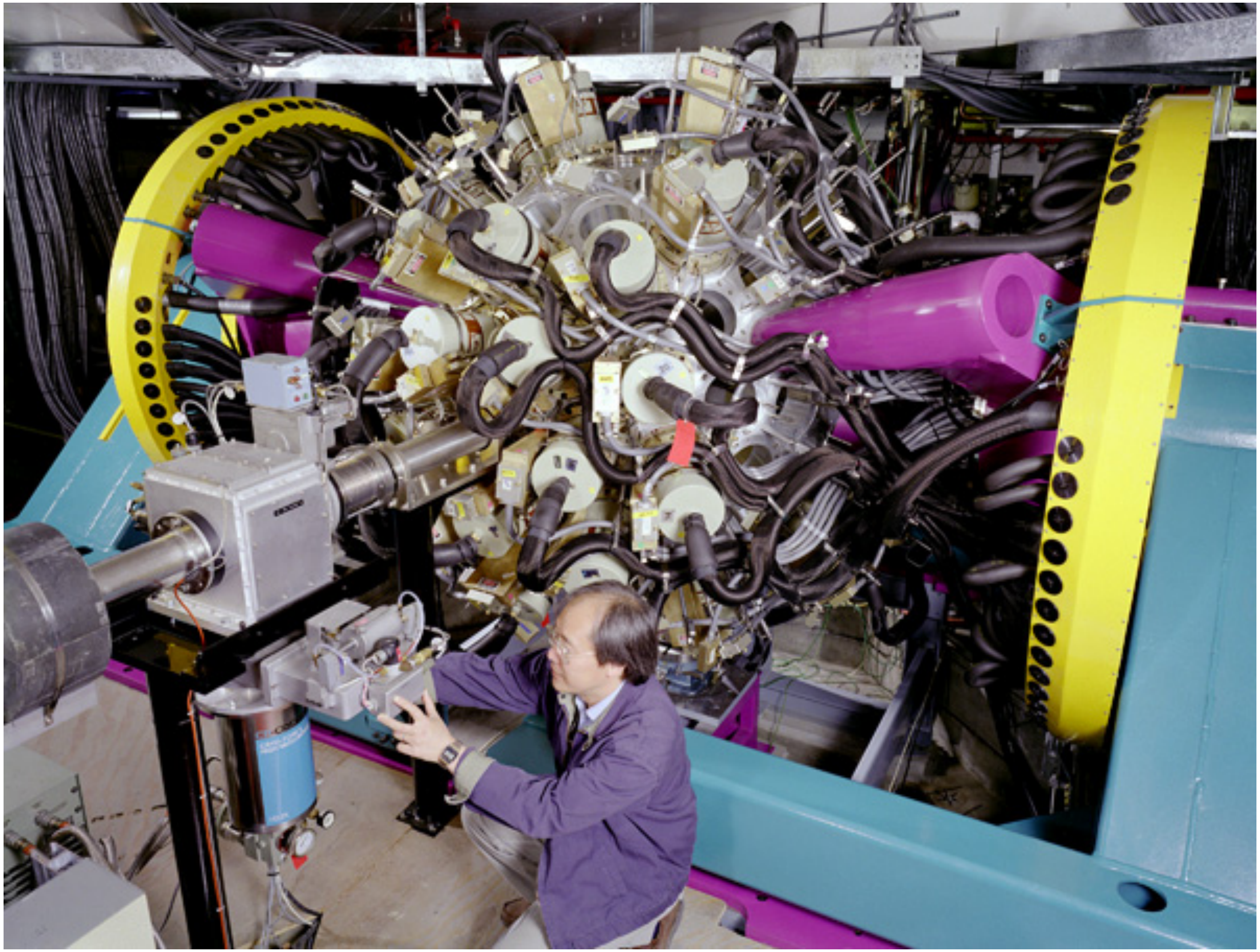
Another 10 years later (2004)! BEYOND BAND TERMINATION in $^{157,158}Er$!

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

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



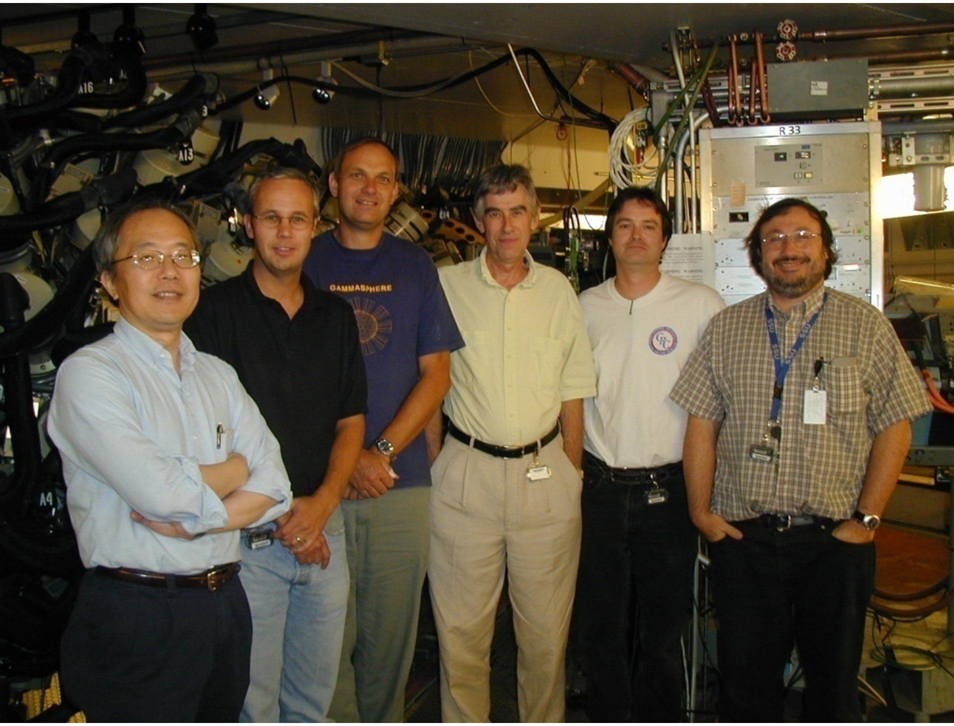
The GAMMASPHERE Spectrometer at Berkeley National Laboratory



Universal Pictures presents The Hulk, directed by Ang Lee, opening June 20, 2003.

Credit: ILM/Universal

Collaborators on mid-00's ^{158}Er GS expt

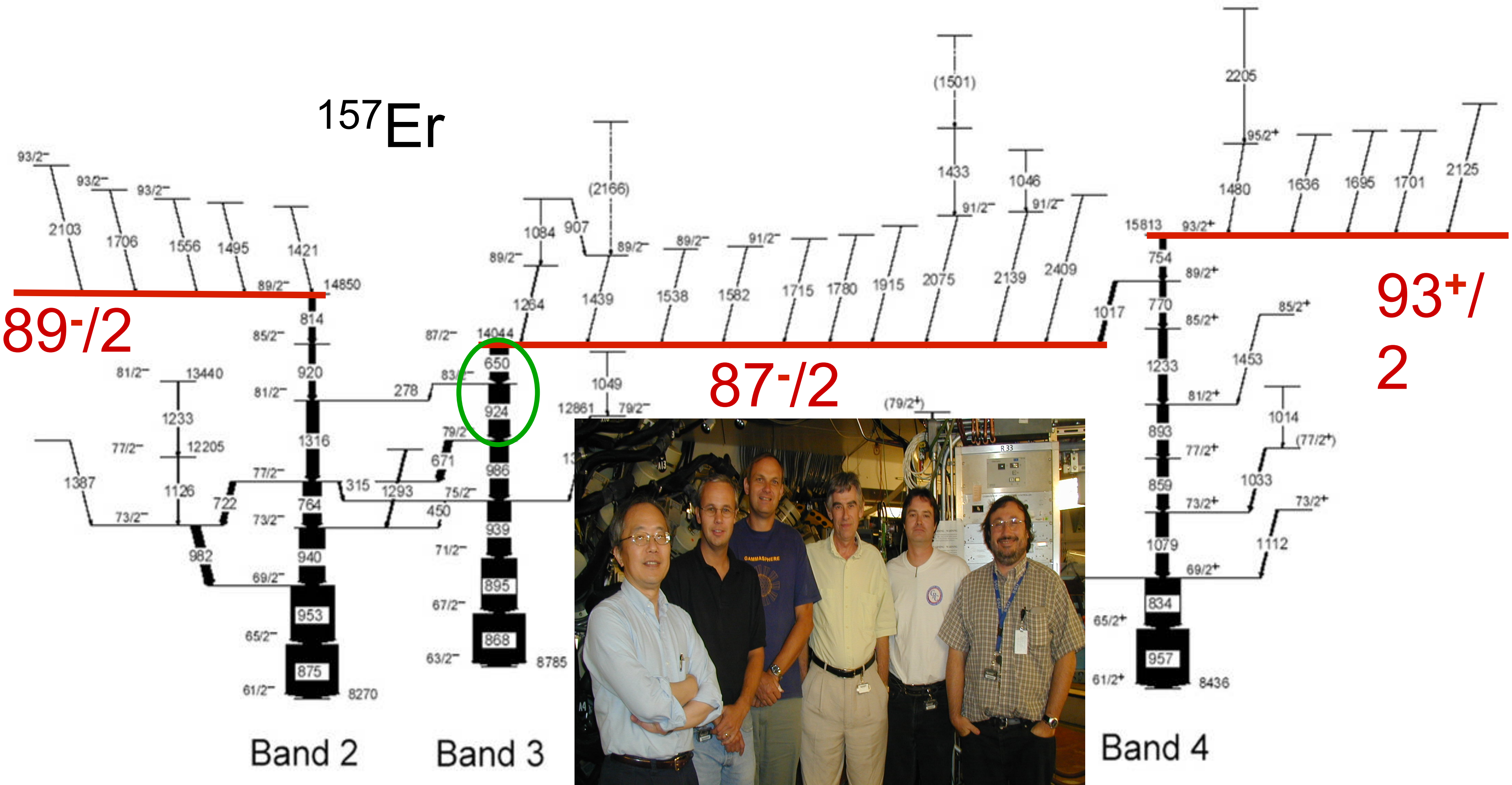



University of Liverpool **A. Evans**, E.S. Paul, P.J. Nolan, P.T.W Choy
Daresbury Laboratory J. Simpson, D.E. Appelbe, D.T. Joss
Florida State University **A. Pipidis**, M.A. Riley, D.B. Campbell
LBNL P.Fallon, D.Ward, A.O.Macchiavelli, R.M.Clark, M.Cromaz, A.Görgen, I.Y. Lee
Lund Institute of Technology I. Ragnarsson, F. Saric

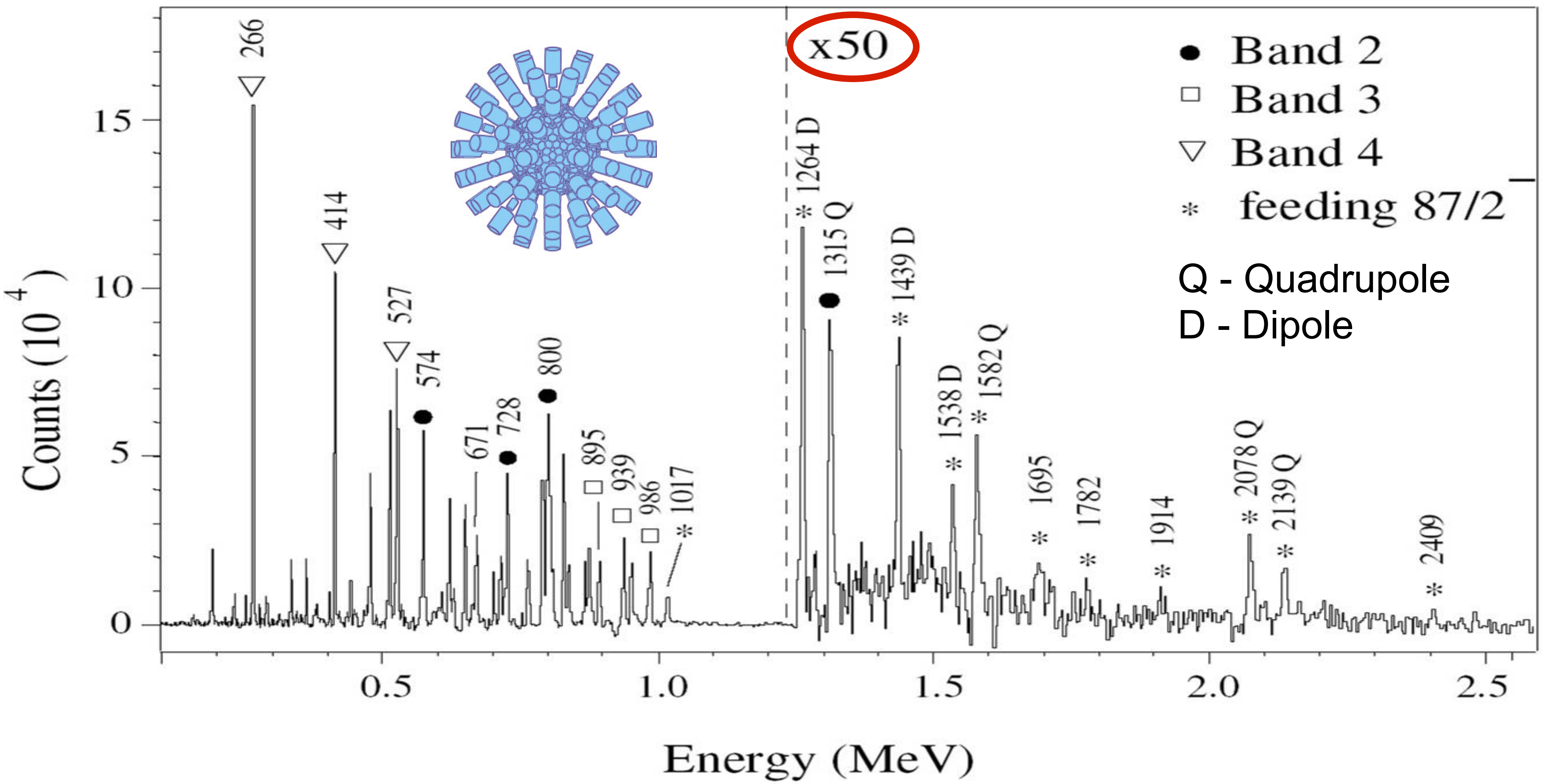
What feeds the special terminating states in ^{157}Er?

Multitude of high energy dipole and quadrupole feeding transitions!

- Feeding intensity to each band ~30% wrt the decay from the BT state (100%) with each transition <10%. Thus massive intensity drop after BT.

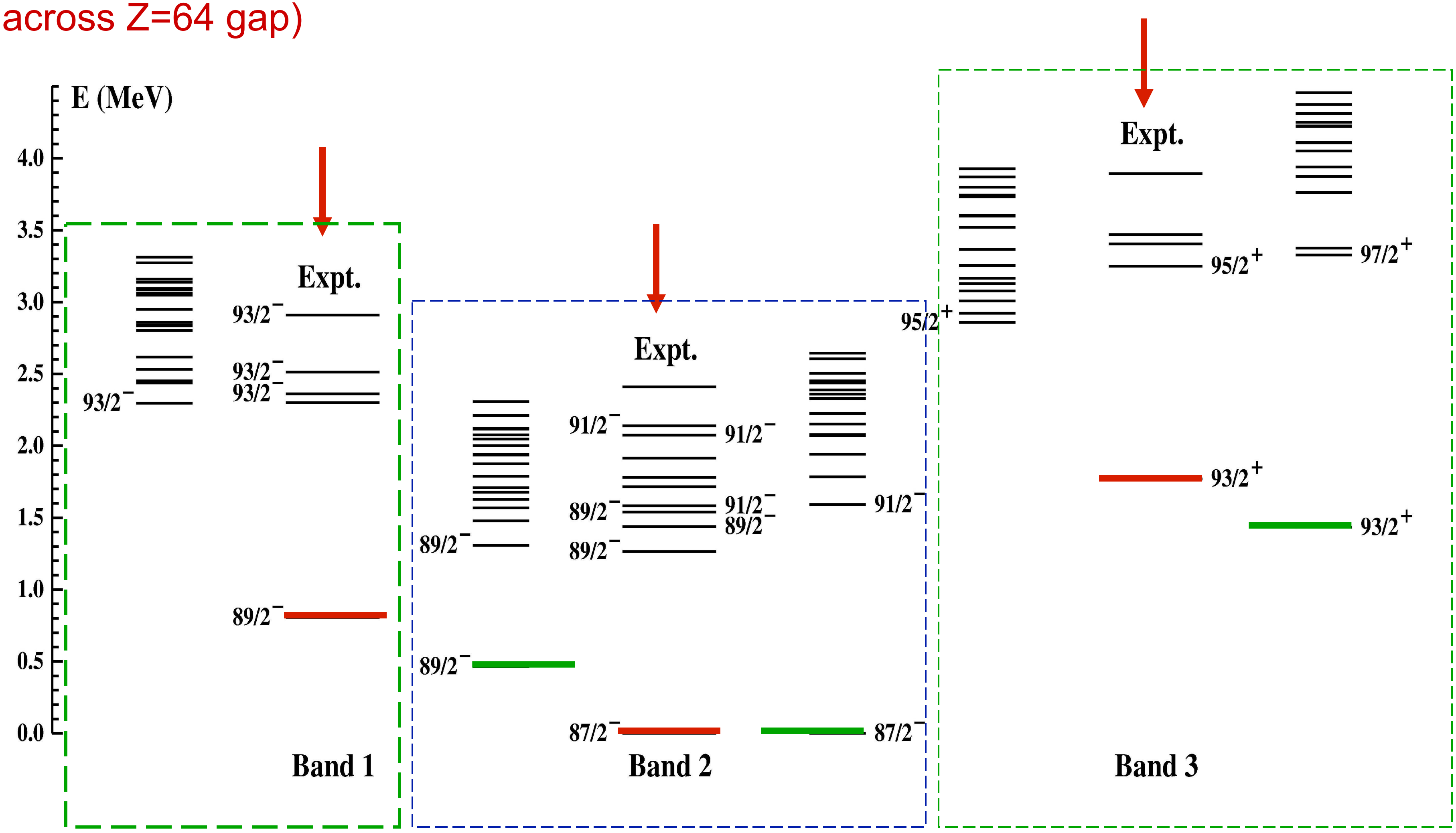


Spectrum of γ-rays in coincidence with 650 and 920keV transitions at top of Band 3



BEYOND BAND TERMINATION in ^{157}Er: Experiment and Theory

New set of cranked Nilsson-Strutinsky calculations by Ragnarsson + Saric (normalized at 87/2^{-} state) for possible states above BT. (Mainly excitations across Z=64 gap)



High-Spin Structure beyond Band Termination in ^{157}Er

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

[1]*Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[2]*CCLRC Daresbury Laboratory, Daresbury, Warrington WA4 4AD, United Kingdom*
[3]*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*
[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*

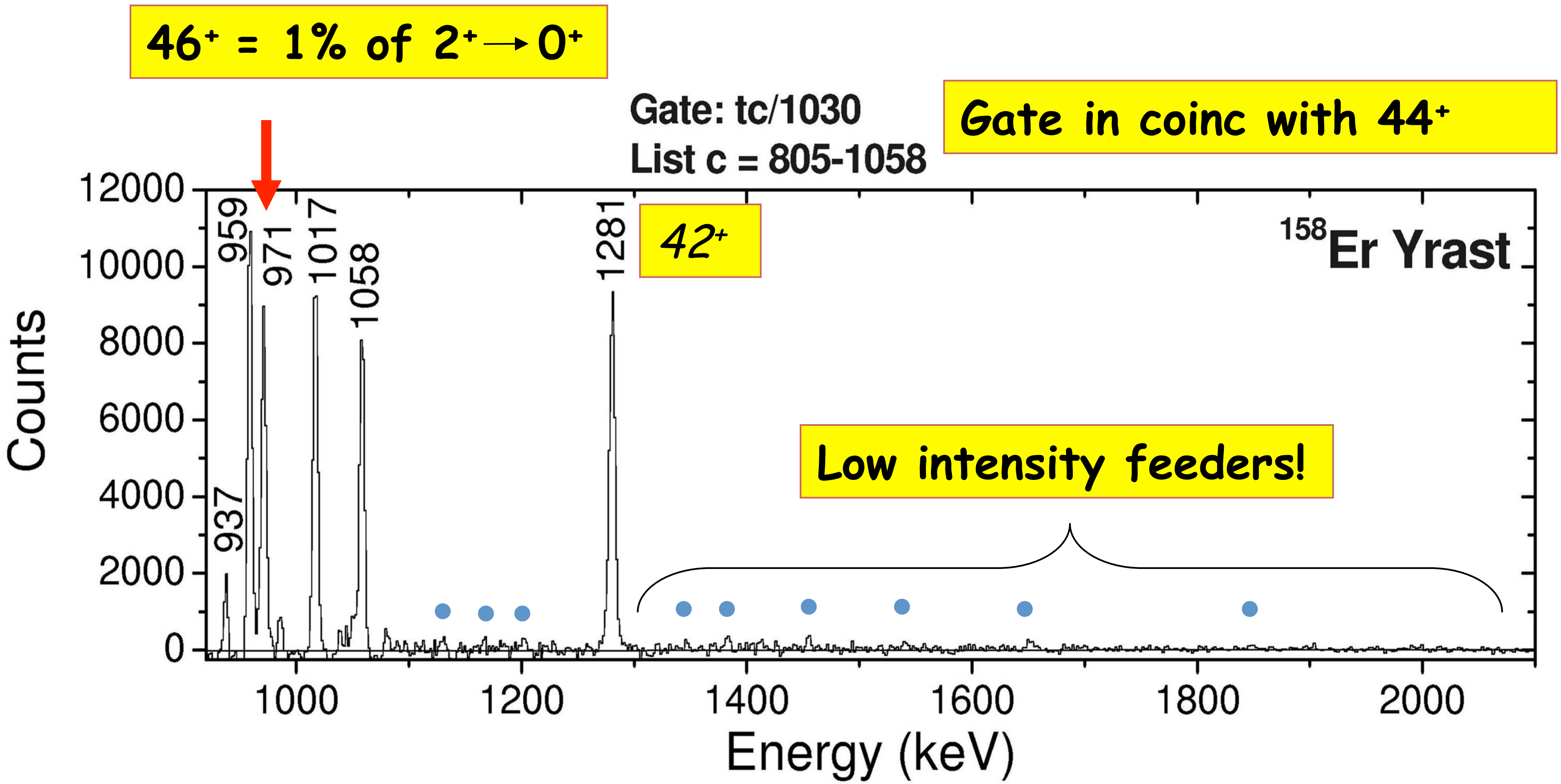
(Received 24 October 2003; published 25 June 2004)

The angular-momentum induced transition from a deformed state of collective rotation to a noncollective configuration has been studied. In ^{157}Er this transition manifests itself as favored band termination near $I = 45\hbar$. The feeding of these band terminating states has been investigated for the first time using the Gammasphere spectrometer. Many weakly populated states lying at high excitation energy that decay into these special states have been discovered. Cranked Nilsson-Strutinsky calculations suggest that these states arise from weakly collective "core-breaking" configurations.

DOI: 10.1103/PhysRevLett.92.252502 PACS numbers: 27.70.+q, 21.10.Re, 23.20.En, 23.20.Lv

What about ^{158}Er above 46$^+$?

No wonder we could not see it before!

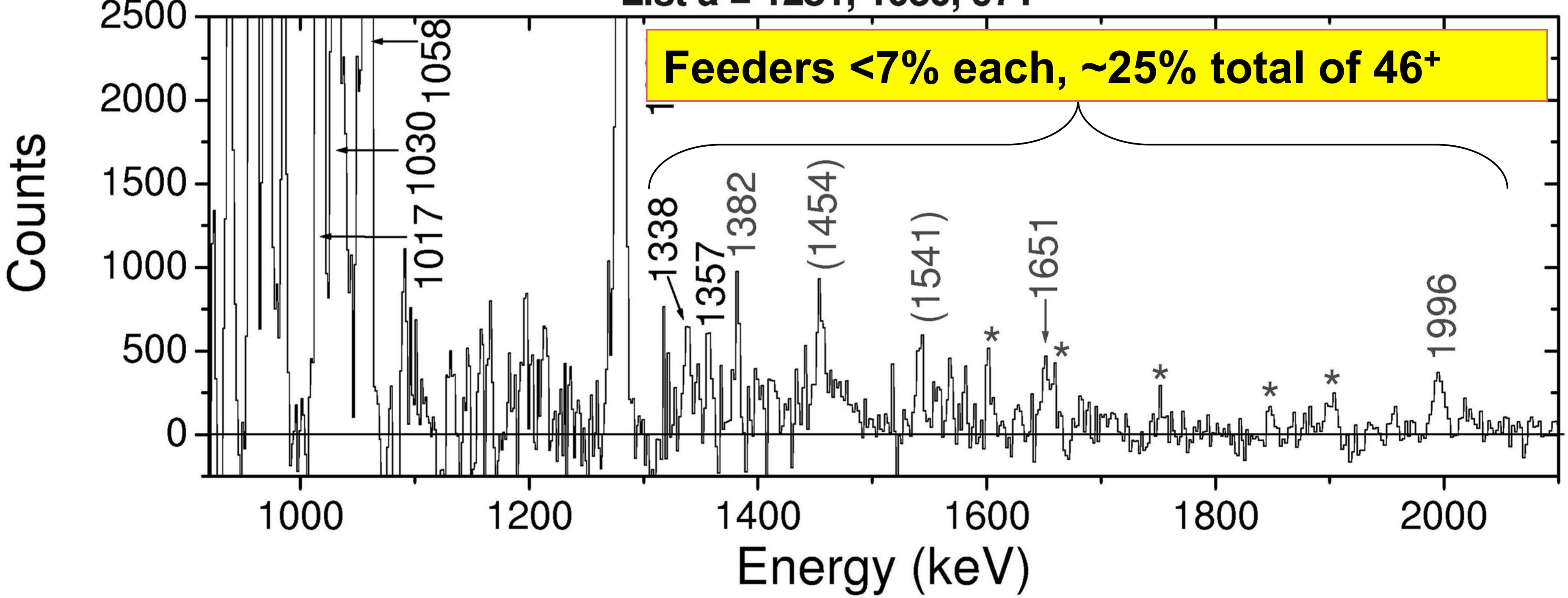


What about ^{158}Er above 46^+?

46^+ = 100%

Clean gate list in coinc with $46,44,42^+$

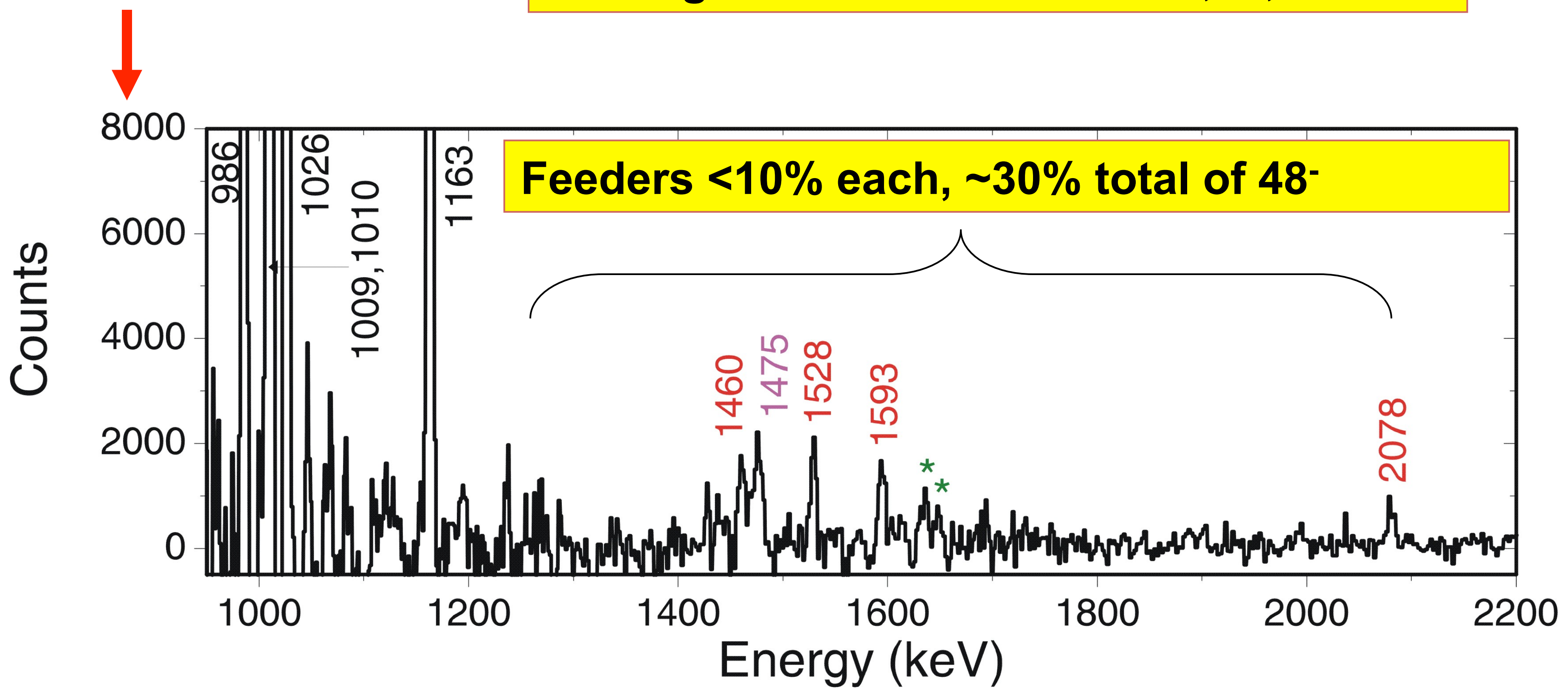
Gate: tz/a
List z = 472, 566, 658, 740, 845, 1058
List a = 1281, 1030, 971



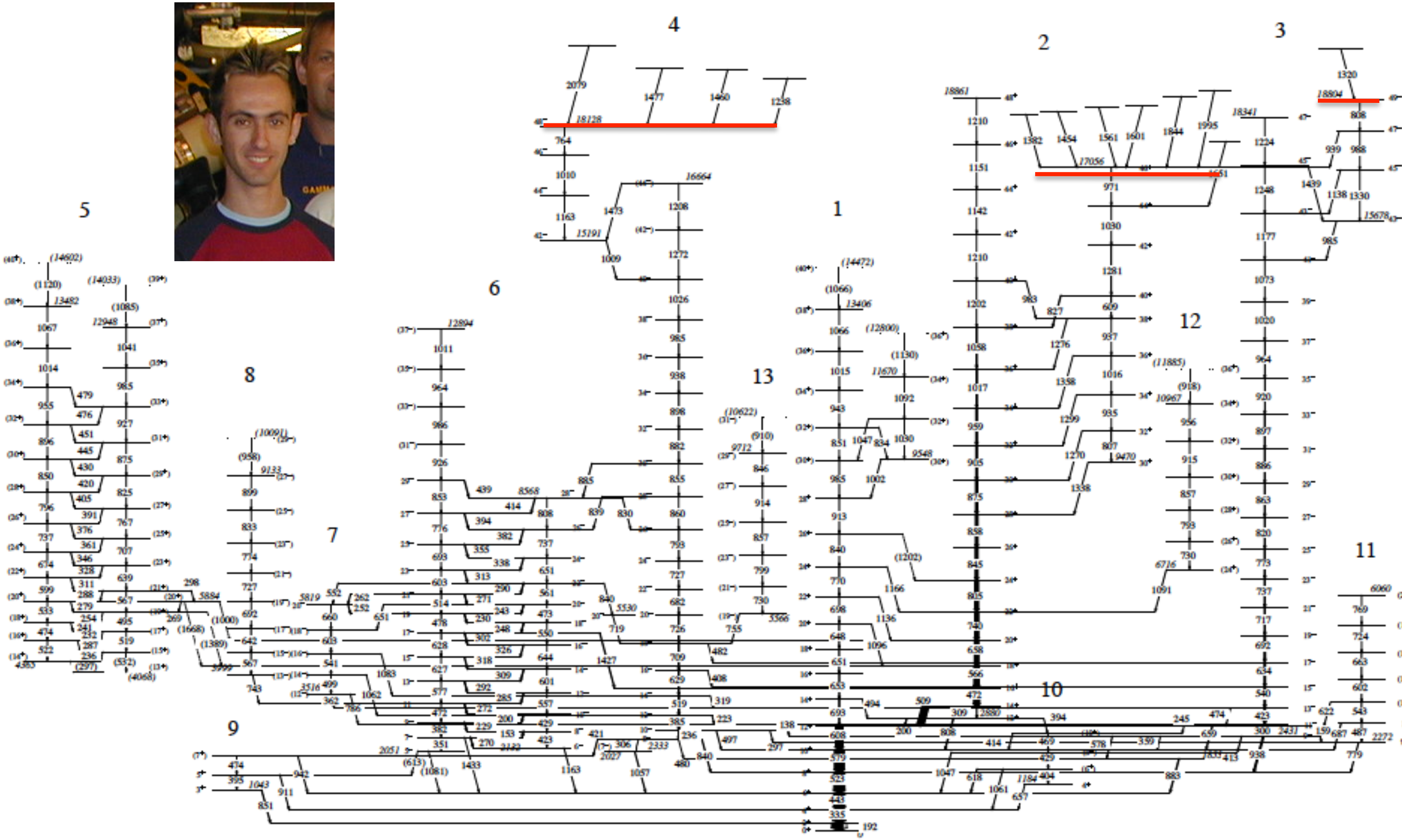
^{158}Er above 48$^-$? Similar story

48$^-$ = 100%

Clean gate list in coinc with 48,46,44$^-$

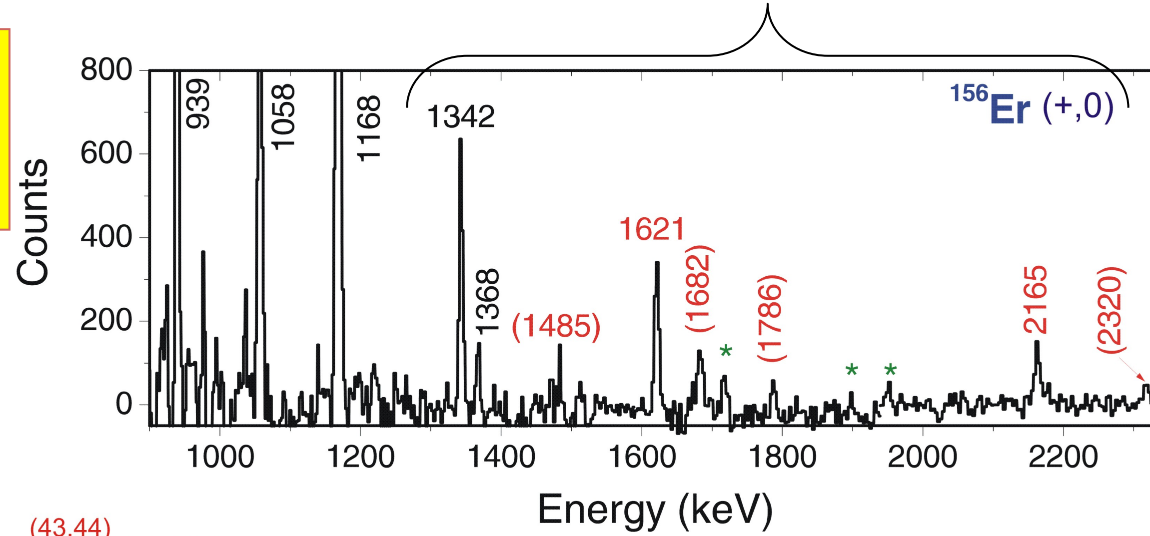


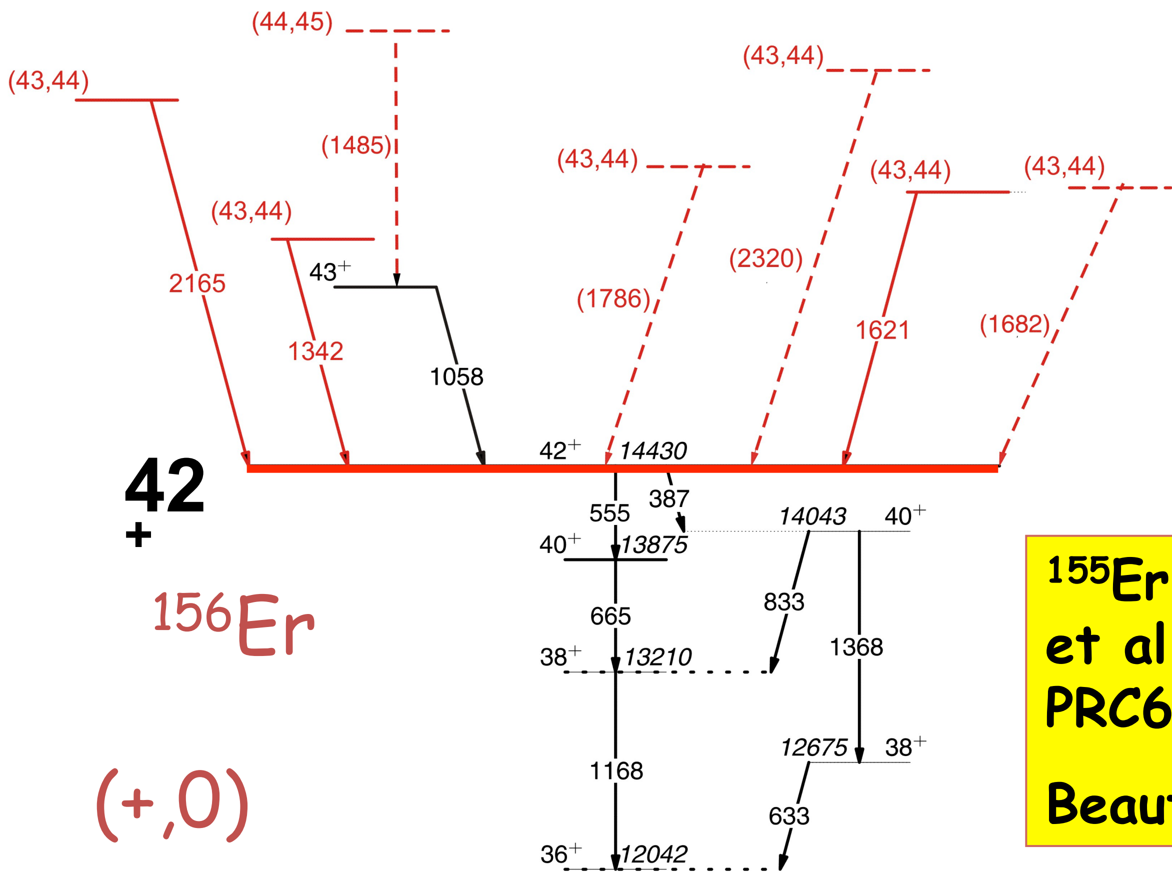
^{158}Er "Normal" deformed level scheme, A. Pipidis, FSU PhD Thesis



What about ^{156}Er above BT at 42^{+}?

Similar picture.

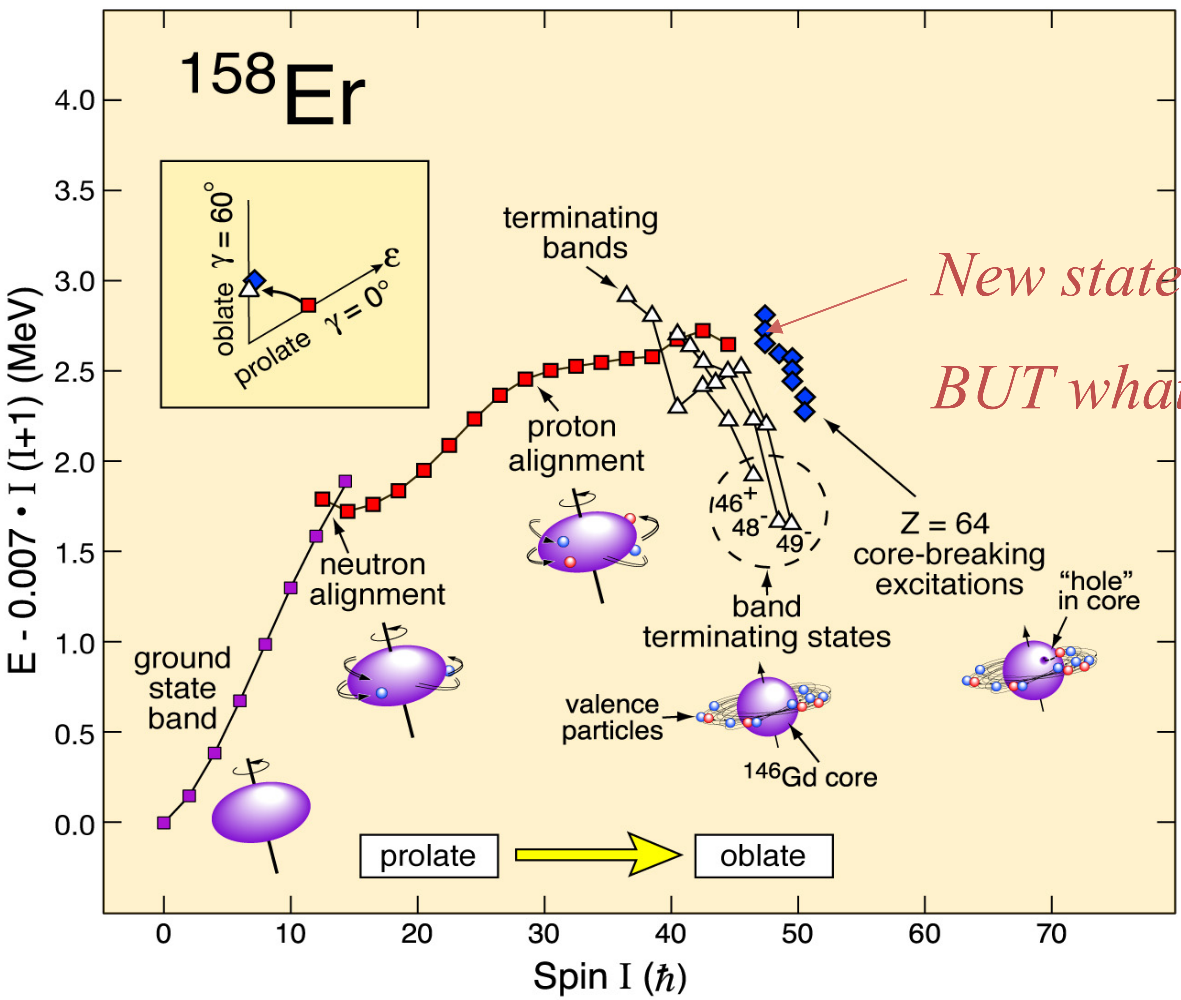




^{155}Er similar pattern too! Nica et al., Euroball. PRC64(2001)034313

Beautiful Er systematics.

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



New states!

BUT what lies above?

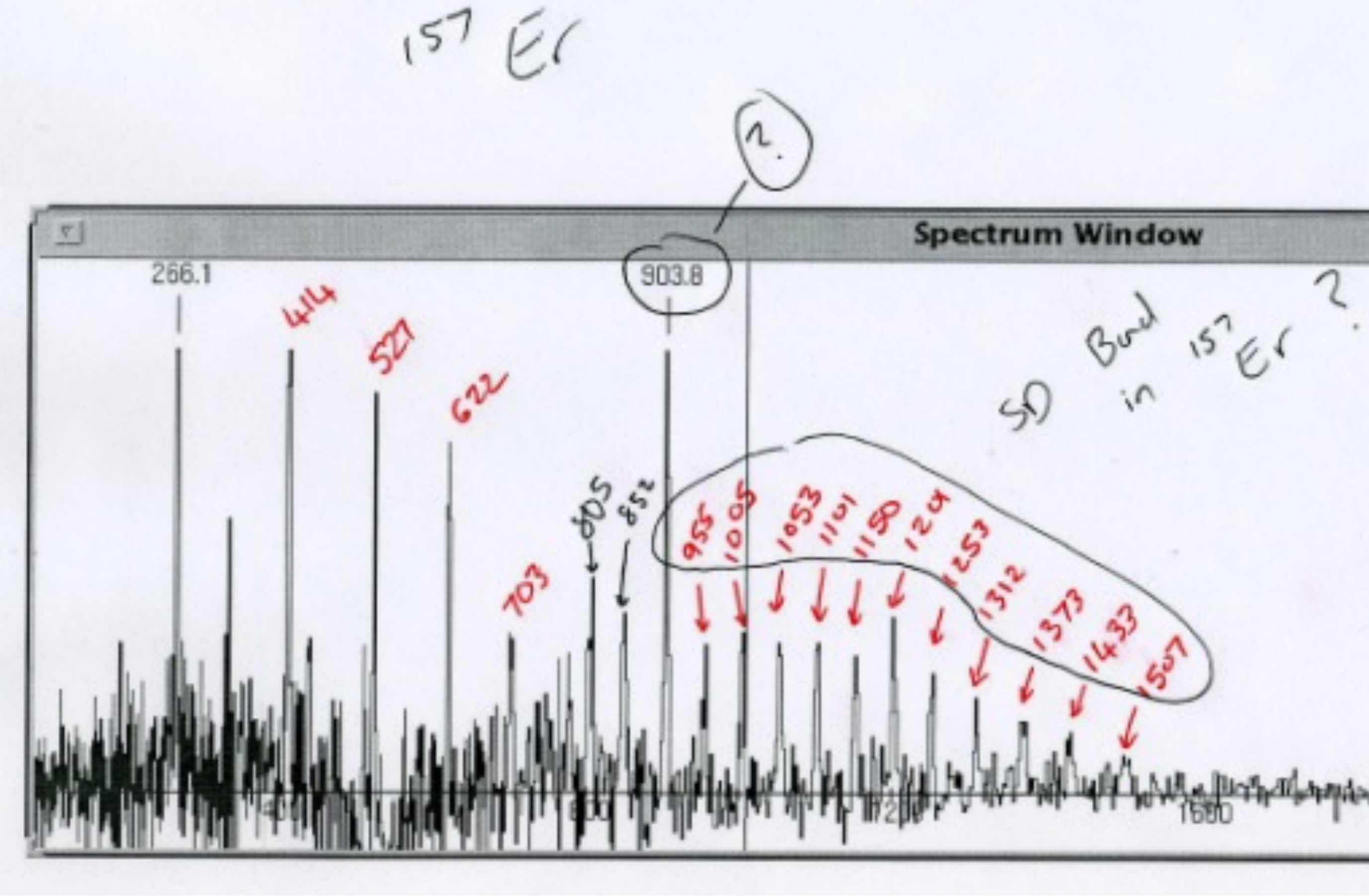
A brief story before we go over to the new stuff!

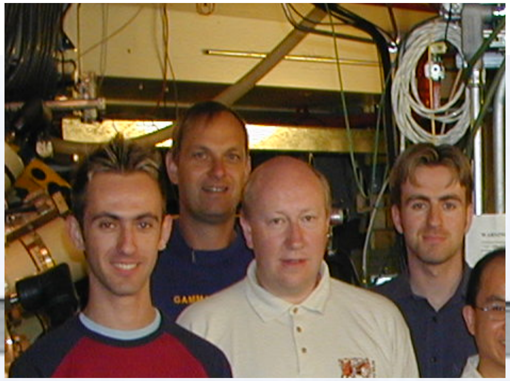
- A year after the first PRL "Beyond Band Termination" was published....
- Eddie Paul, Aled Evans and I were sat having a beer at a conference.
- I said to Eddie/Aled there MUST BE more high spin info in our recent GS expts on $^{157,158}Er$.
- **If they promised to dig the data back out and look some more I would buy the beers for the rest of the day!!**
- They go back to L'pool and the N~90 Erbium story moves to the next chapter ......
- Moral: NEVER GIVE UP! Also buying BEER for your brilliant collaborators is IMPORTANT!

Winston was right!

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

Many months later: breakthrough email from the UK



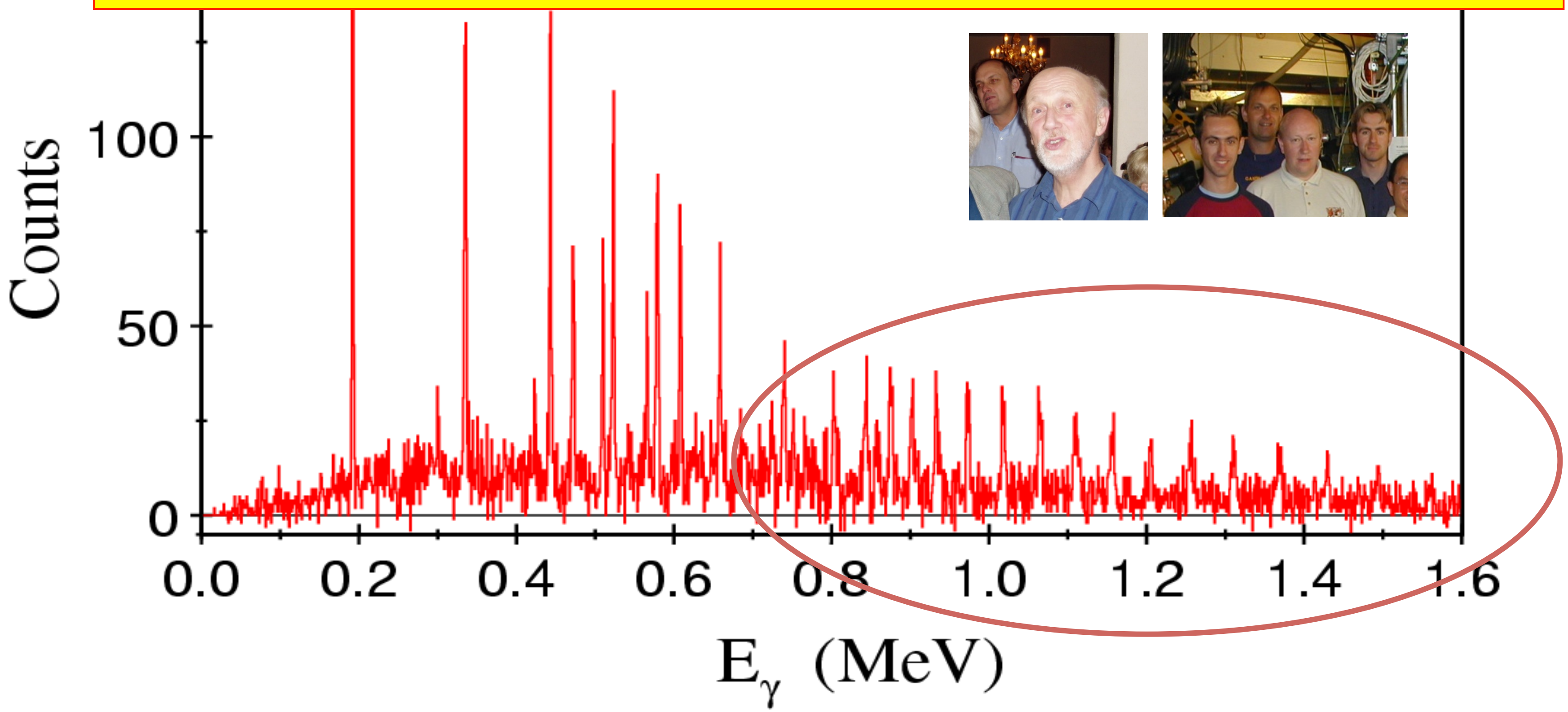


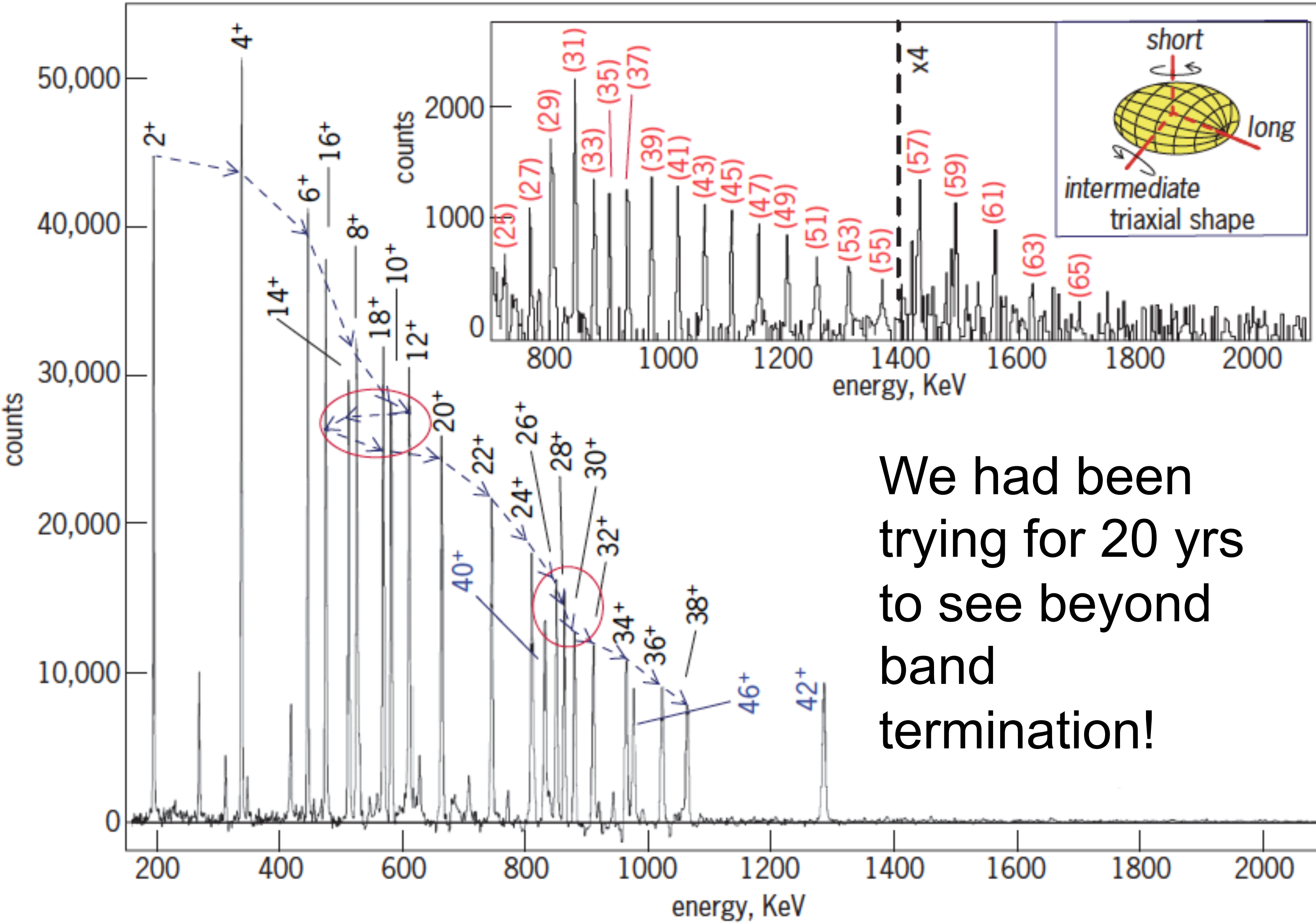
A little later… more from the UK.

Band 1 in ^{158}Er discovered……WOW!

~50-100 times weaker than Superdeformed band in ^{152}Dy!

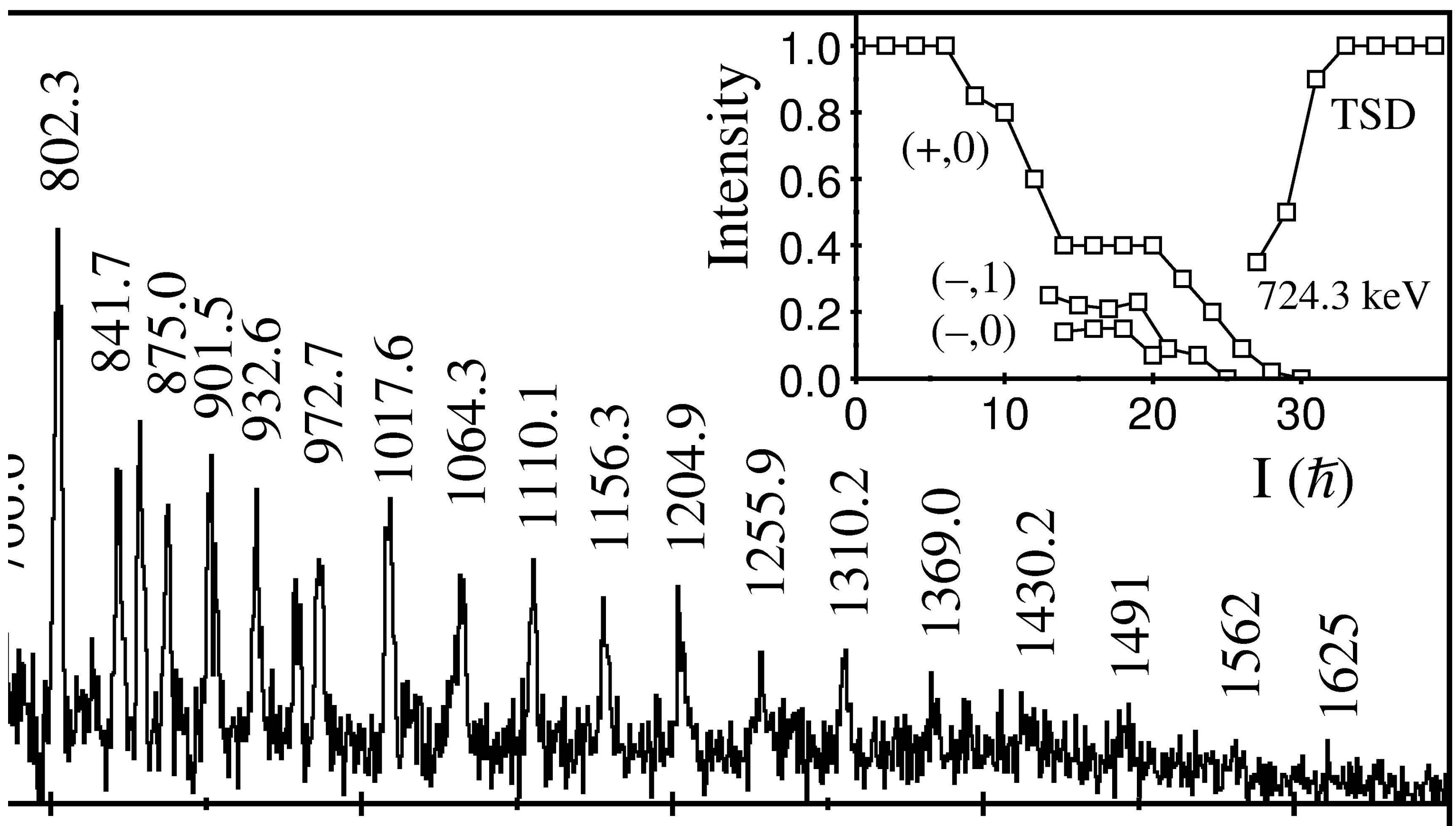
The Return of Collectivity beyond Band Termination in ^{157,158}Er



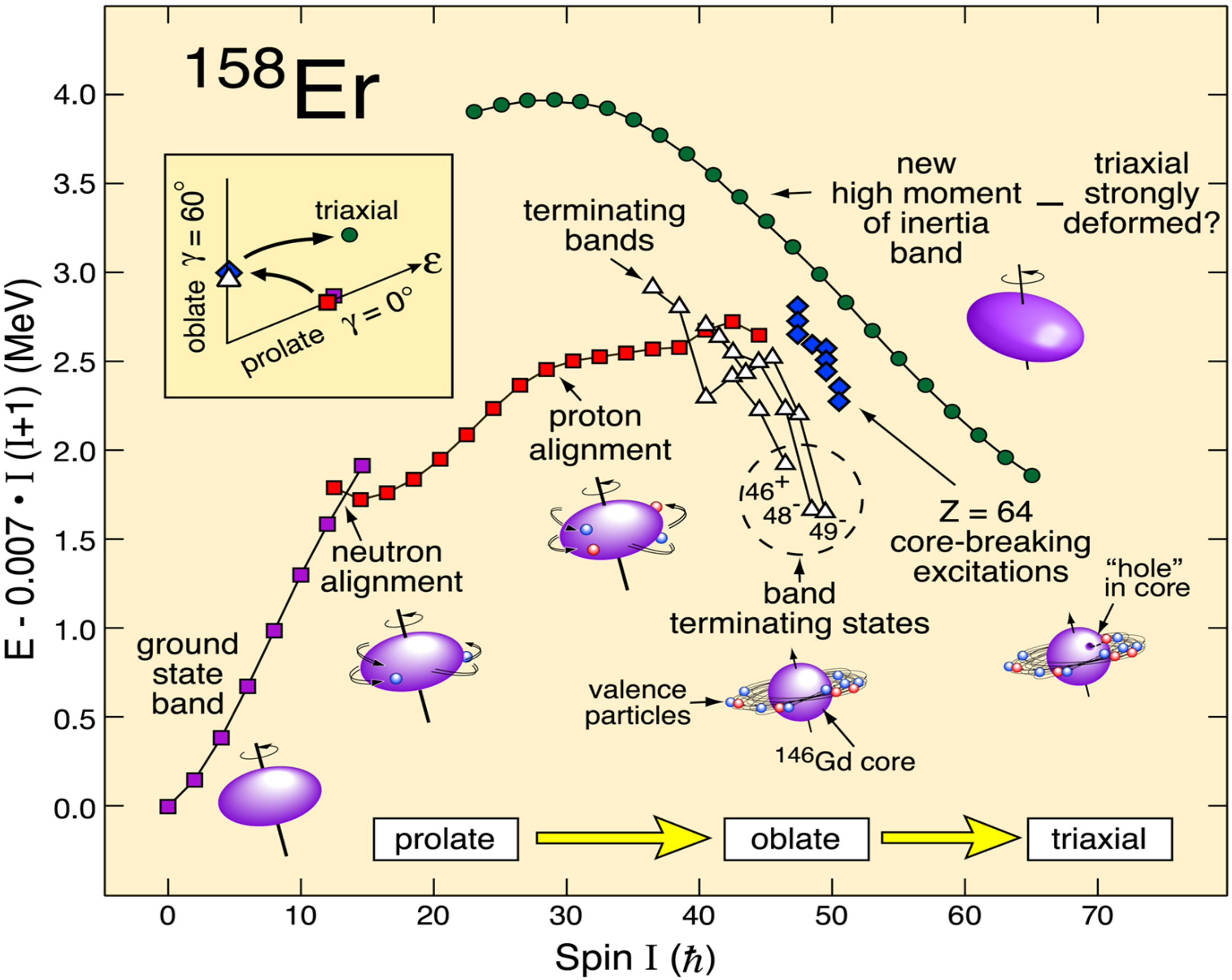


We had been trying for 20 yrs to see beyond band termination!

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

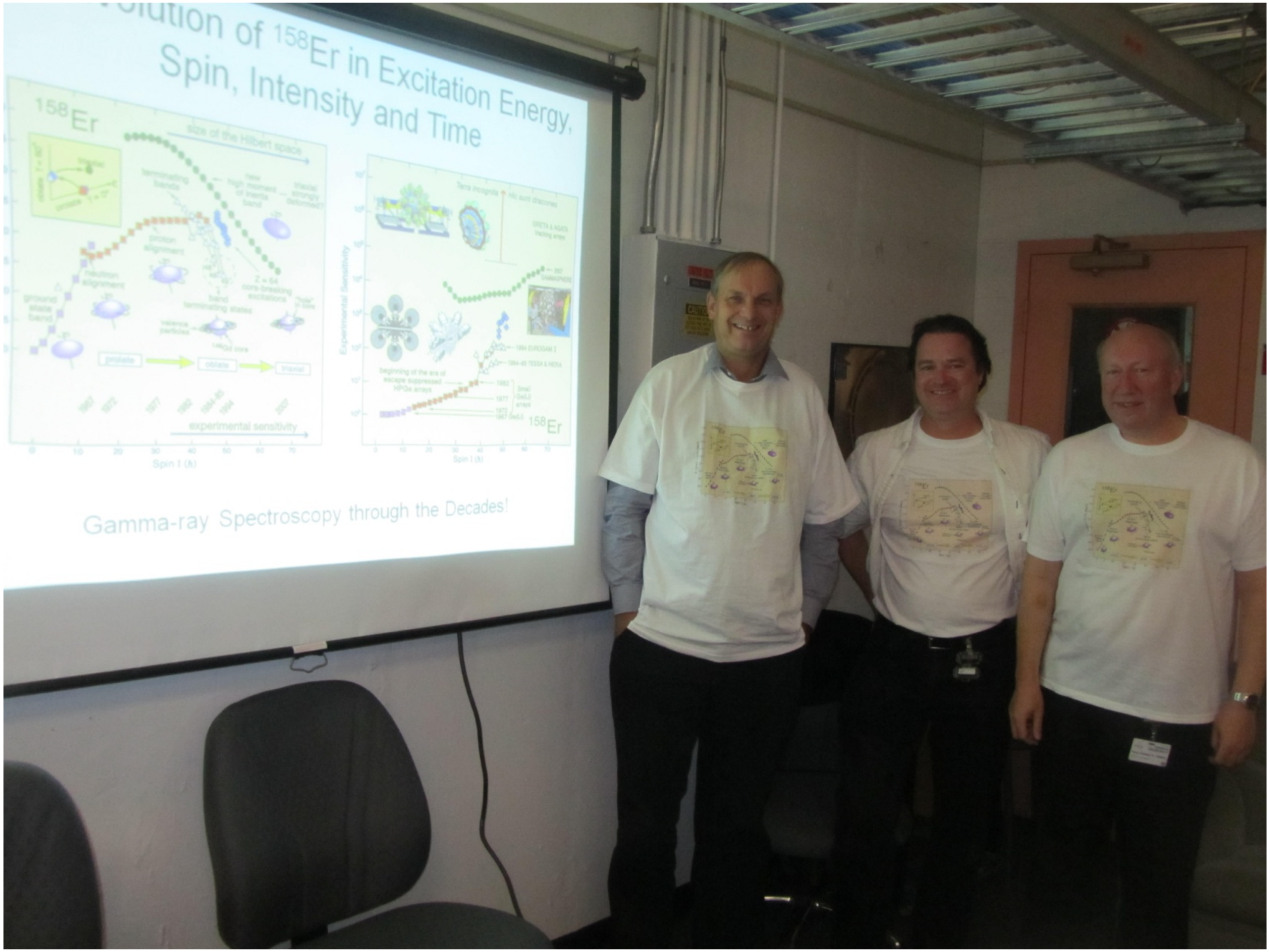
E. S. Paul,[1] P. J. Twin,[1] A. O. Evans,[1] A. Pipidis,[2] M. A. Riley,[2] J. Simpson,[3] D. E. Appelbe,[3] D. B. Campbell,[2,*] P. T. W. Choy,[1] R. M. Clark,[4] M. Cromaz,[4] P. Fallon,[4] A. Görgen,[4,†] D. T. Joss,[3,‡] I. Y. Lee,[4] A. O. Macchiavelli,[4] P. J. Nolan,[1] D. Ward,[4] and I. Ragnarsson[5]

[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 ph

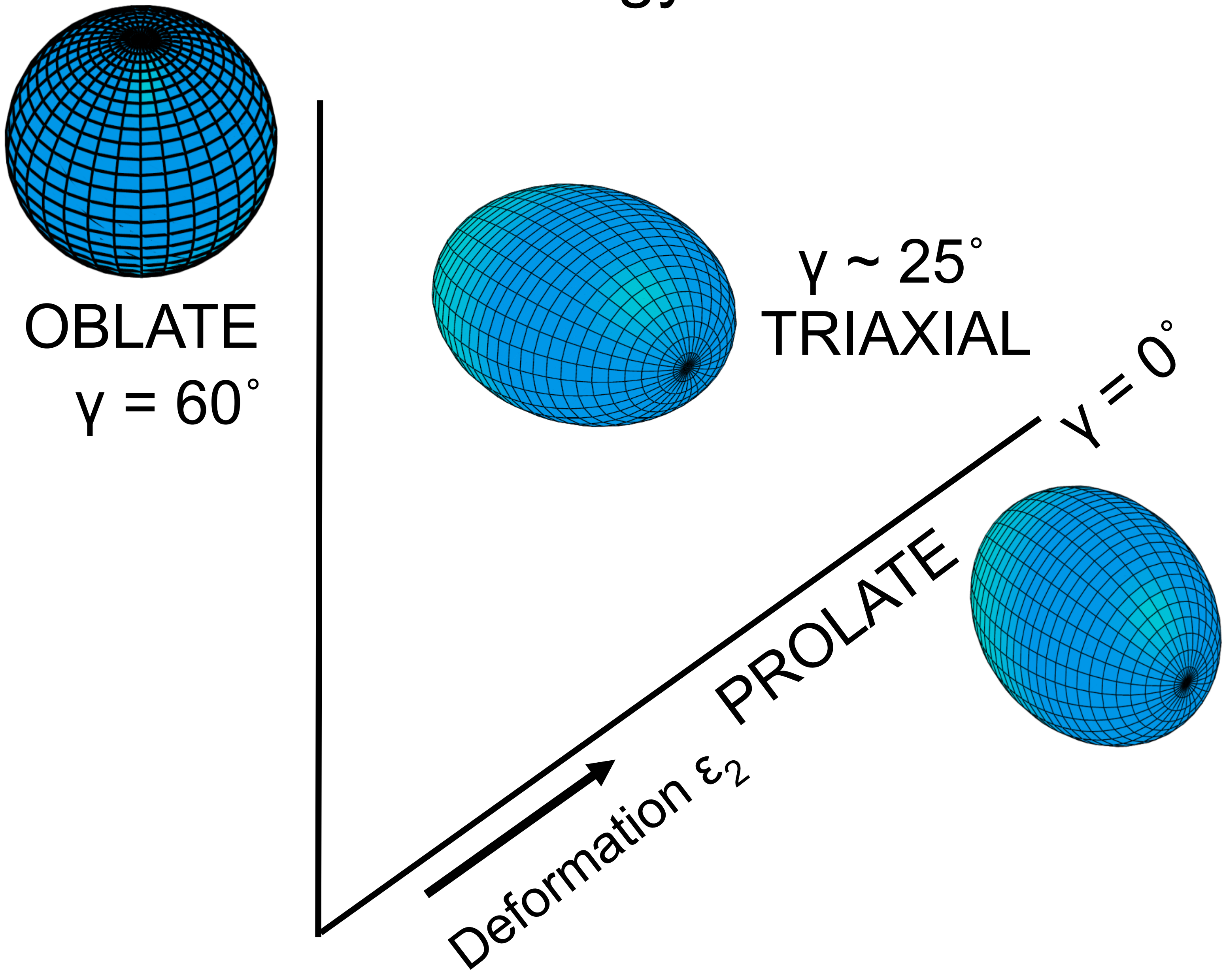
The Erbium family!

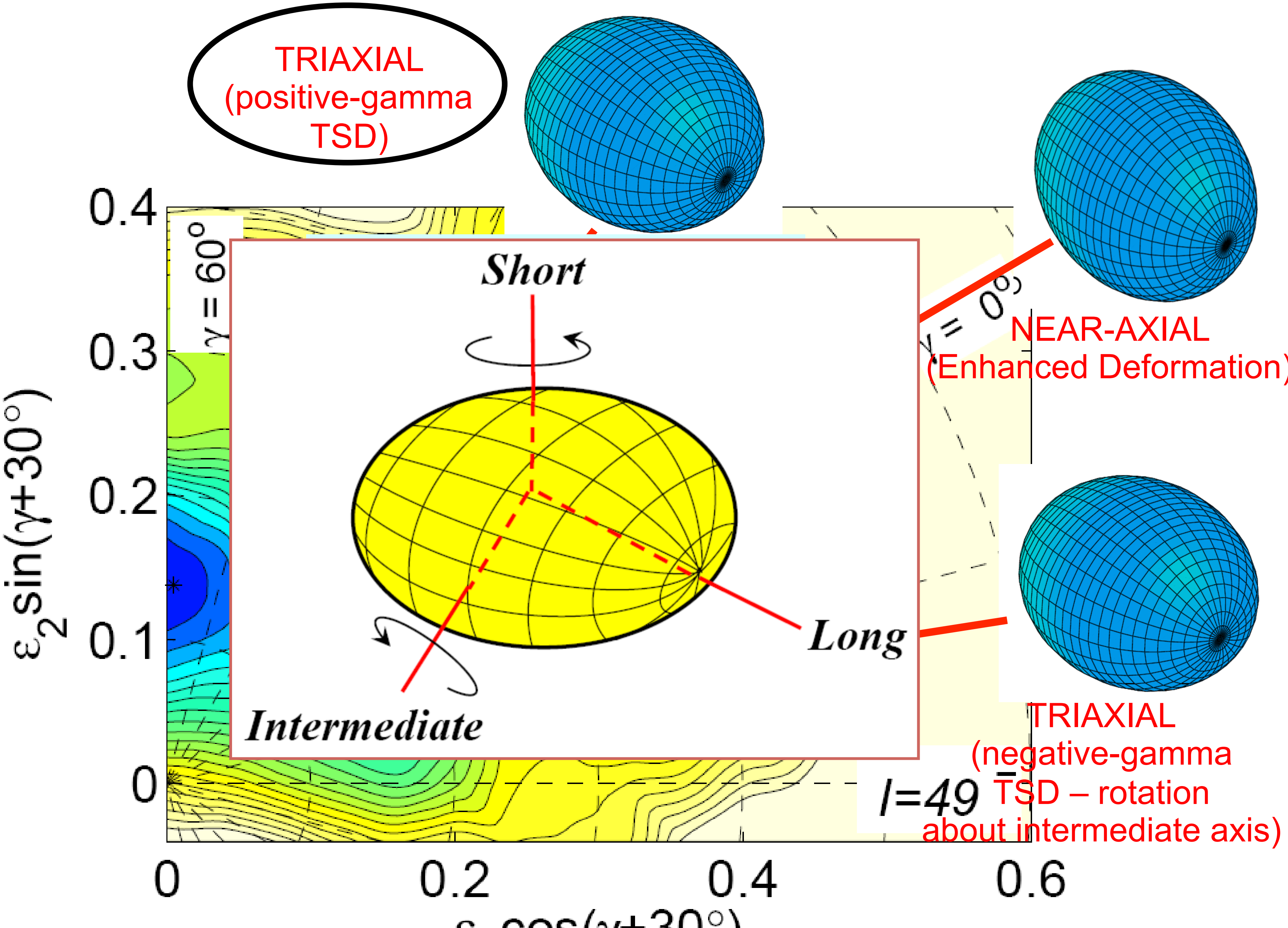



LET IT BE
ERBIUM
PORSCHE


IMAGINE
06-14
158 ERB
PORSCHE

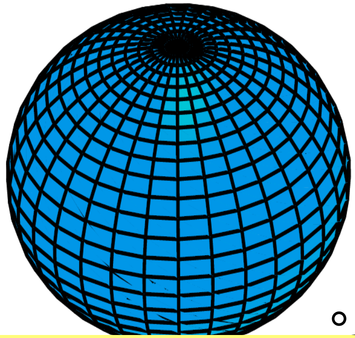
Pot. Energy Surfaces

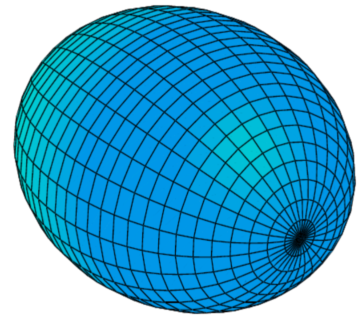




CNS (principal axis cranking) calculations by I. Ragnarsson

PES Lund Convention



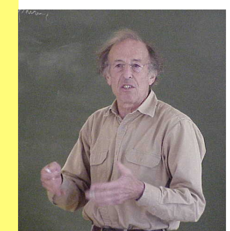


$\gamma \sim 25^{\circ}$

Robust triaxial shapes have been sought after for decades!

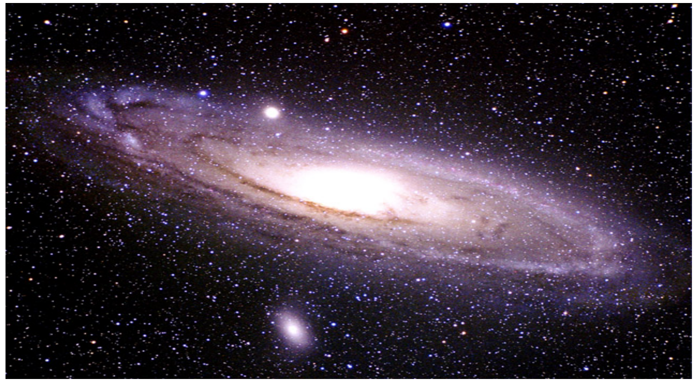
“The study of rotational motion in nuclei with asymmetric shapes is potentially a field of broad scope.” Bohr and Mottelson Vol. 2 pg. 176,

It is only in this last decade that triaxial strongly deformed shapes have been observed. (eg. wobbling modes in Lu nuclei and now the ultra-high spin Er results.)



ROLATE

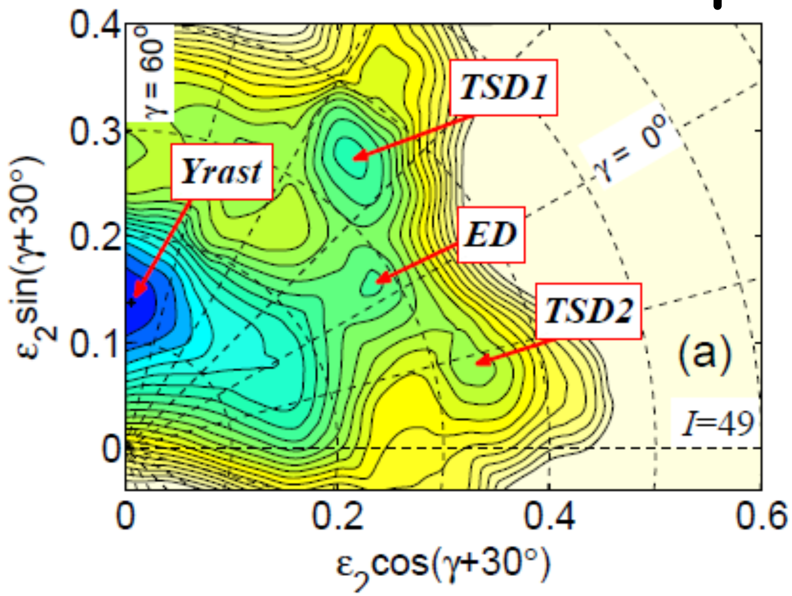
Orbital Dynamics of Triaxial Nuclei

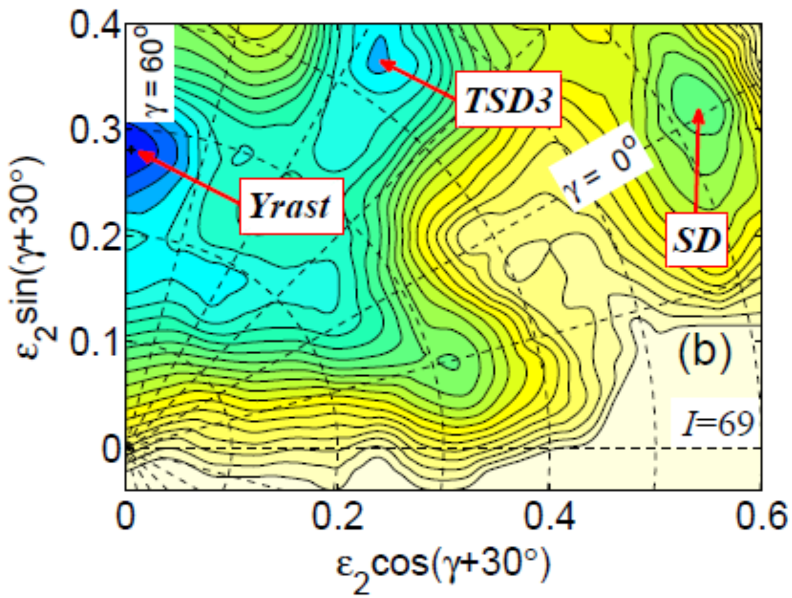


- **Triaxial Black-Hole Galactic Nuclei:** M. Y. Poon & D. Merritt
- Department of Physics and Astronomy, Rutgers University, New Brunswick, NJ 08855
- Astrophysical Journal, Vol. 549, Number 1, Part 1, Page 192

- We construct models of triaxial galactic nuclei containing central black holes using the method of orbital superposition, …. We consider three triaxial shapes : almost prolate, almost oblate and maximally triaxial. …… low angular momentum orbits. …..We attempt to evaluate black hole capture rates in triaxial nuclei.

What Shape Are the Bands?



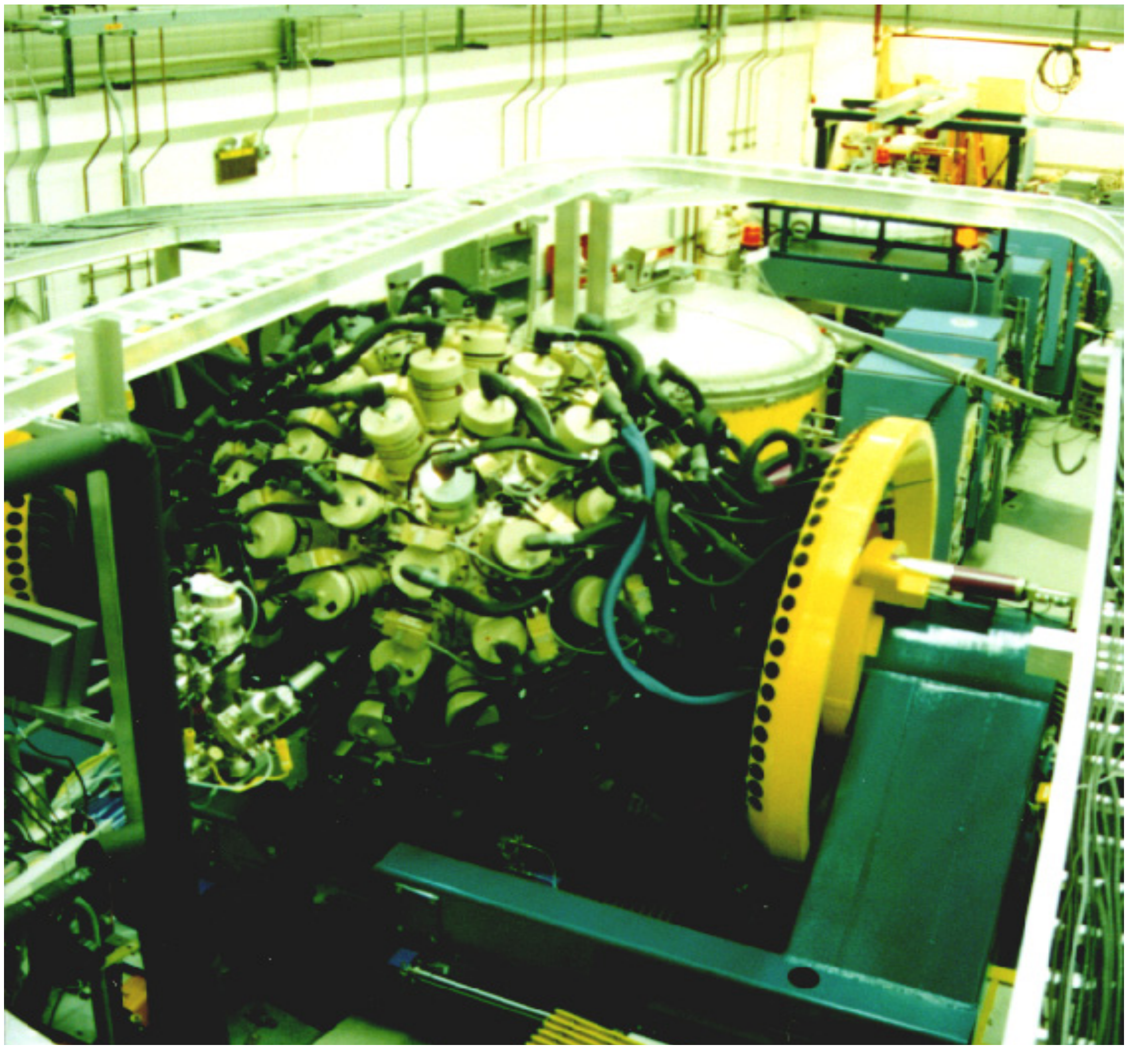


- A variety of possible shapes are predicted, both axially symmetric (ED, SD) and triaxial (TSD1, TSD2, TSD3)
- The TSD1 minimum, with a positive gamma deformation (+20°) was originally assigned to the new bands.

- Quadrupole moment measurements needed?
- NO NEED – we know what they are from theory!
- CANNOT DO IT – bands too weak!

Cranked Nilsson Strutinsky calcs: Ingemar Ragnarsson

GAMMASPHERE at Argonne National Laboratory: ~2 weeks of beamtime!



[Every serious physicist has the ATLAS beam list and Gammasphere on his wall]

Janssens

Argonne NATIONAL LABORATORY

ATLAS

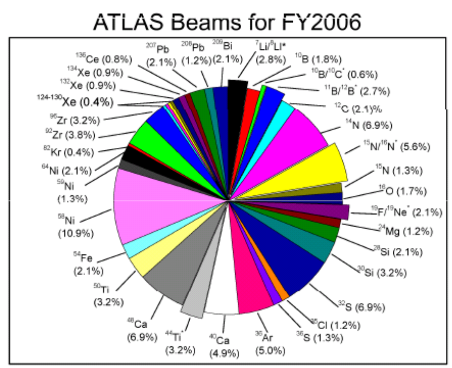
Argonne Tandem Linear Accelerator System

The prime national facility for nuclear structure research

The ATLAS facility is a leading facility for nuclear structure research in the United States. It provides a wide range of beams for nuclear reaction and structure research to a large community of users from the US and abroad. The full range of all stable ions can be produced in ECR ion sources, accelerated in the world's first superconducting linear accelerator for ions to energies of 7-17 MeV per nucleon and delivered to one of several target stations. About 20% of the beam-time is used to generate secondary radioactive beams. These beams are used mostly to study nuclear reactions of astrophysical interest and for nuclear structure investigations.

User community

ATLAS provides beams and experimental instruments for a large community of nuclear scientists. In 2006, there were 436 active users, including 75 graduate students. Typically, research at ATLAS results in 10 Ph.D. theses and 60 publications in peer reviewed scientific journals every year. Beam time is allocated based on the recommendations of a Program Advisory Committee which meets twice a year.



* Radioactive Beams comprised 17% of running time

Distribution of ATLAS beams in FY2006

Research programs

The ATLAS research programs focus on the key questions that are central to our understanding of baryonic matter and on the description of the astrophysical processes that generate energy and produce elements in the stars. These areas of research have been endorsed in several major reviews of the science. Specific issues being addressed are 1) the quantum structure of nuclei, 2) nuclear shapes, 3) exotic decay modes, 4) masses of exotic nuclei, 5) fundamental interactions, 6) nuclear reactions of astrophysical importance, 7) properties of the heaviest nuclei and 8) accelerator mass spectrometry.

GAMMASPHERE is one of the forefront instruments available for experiments at ATLAS. It consists of 110 Compton-suppressed Ge detectors used to detect gamma rays emitted from compound nuclei formed by fusion of accelerated heavy ions and target nuclei.

Future developments

Since its inception in 1985, the ATLAS facility has continually been upgraded in order to be at the forefront of nuclear research. At present, the Californium Rare Ion Breeder Upgrade, CARIBU, is being built. This facility will provide for the acceleration of neutron-rich fission fragments from a one Curie ^{252}Cf source to study neutron-rich nuclei, particularly those of relevance for the astrophysical rapid neutron capture process responsible for the production of a large fraction of the heavy elements in the Universe. A novel superconducting solenoid spectrometer, HELIOS, which is ideal for the study of the structure of these neutron-rich species, is under construction and an energy upgrade of ATLAS is also under way. In order to fully explore neutron-rich nuclei, a current frontier in nuclear physics research, a major new facility for beams of radioactive ions is in the planning stages.

Contact

Robert V. F. Janssens, Scientific Director, Janssens@anl.gov

December 2006

UChicago Argonne LLC

Office of Science U.S. DEPARTMENT OF ENERGY

Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC

Janssens

Quadrupole Moment Measurements in ^{158}Er. Our team!





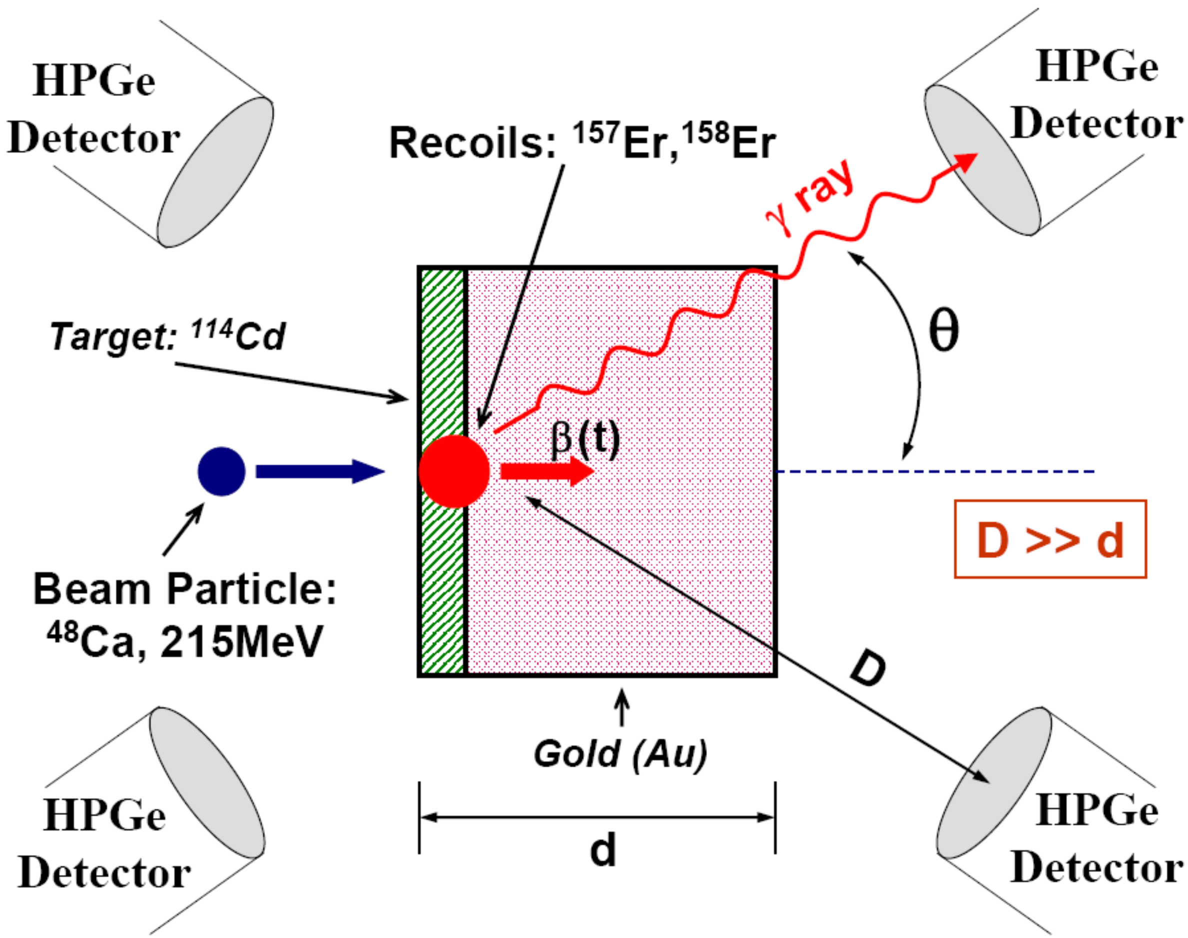

North America,
FSU: X. Wang, M. A. Riley, C. Teal; ANL: M. P. Carpenter, C. J. Chiara, R. V. F. Janssens, F. G. Kondev, T. Lauritsen, S. Zhu;
USNA: D. J. Hartley; UTK: L. L. Riedinger;
ND: A. D. Ayangeakaa, U. Garg, J. Matta; LBNL: P. Fallon, M. K. Petri

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

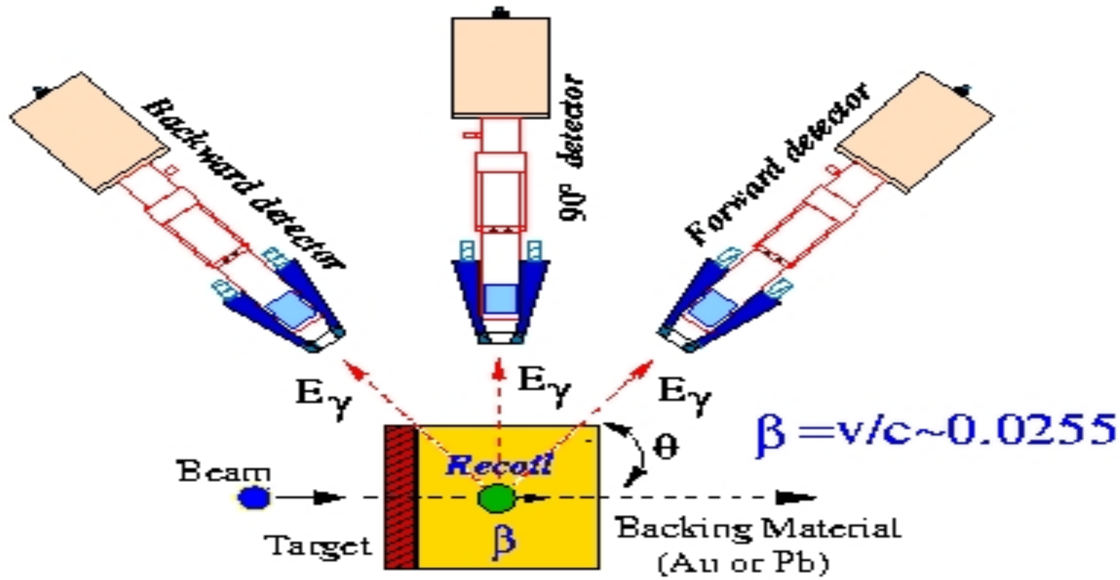
South Africa, iThemba: J. F. Sharpey-Schafer

Experiment and Data analysis

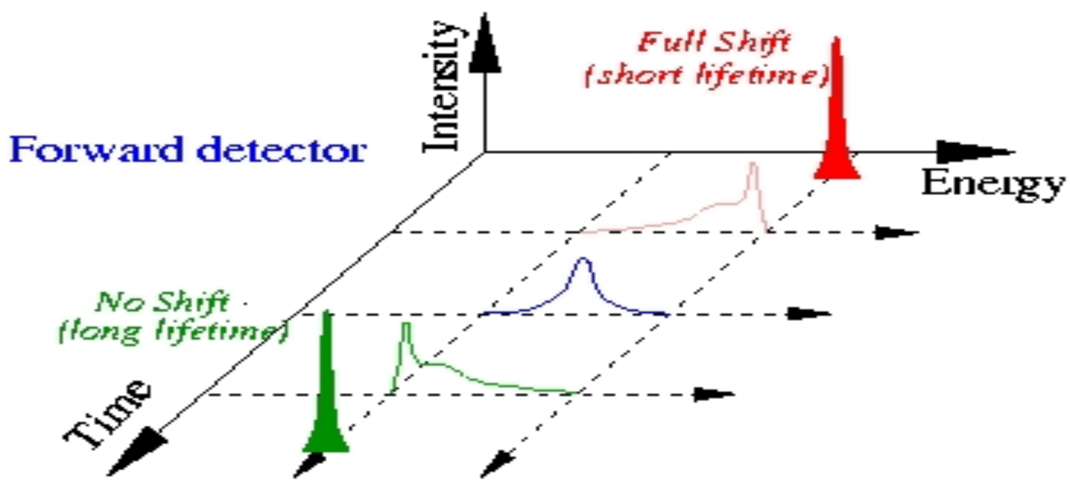
- A DSAM lifetime measurement was carried out with a 215-MeV ^{48}Ca beam and a thick ^{114}Cd target (1 mg/cm^2 ^{114}Cd backed by a 13 mg/cm^2 layer of Au) at the ATLAS facility at ANL.



Doppler-Shift Attenuation Method (DSAM)

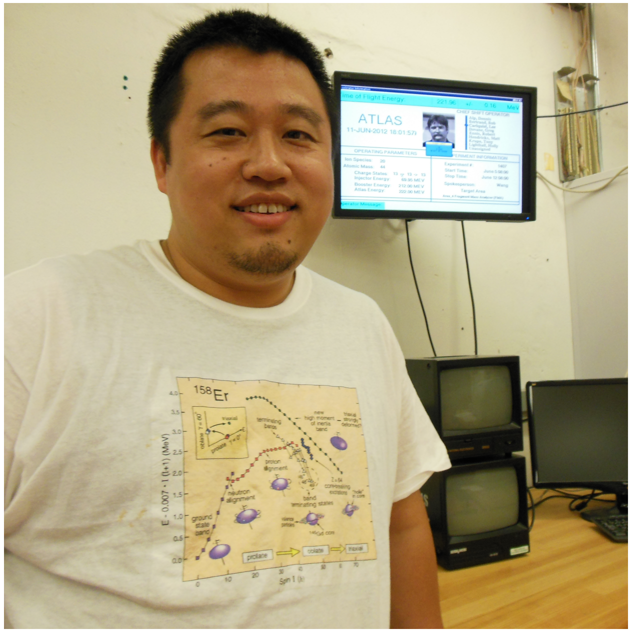


$$E_\gamma(\theta) = E_0\,(1 + F(\tau)\,\beta\cos\theta\,)$$



For more than a month we could not see the bands in the thick target data!!

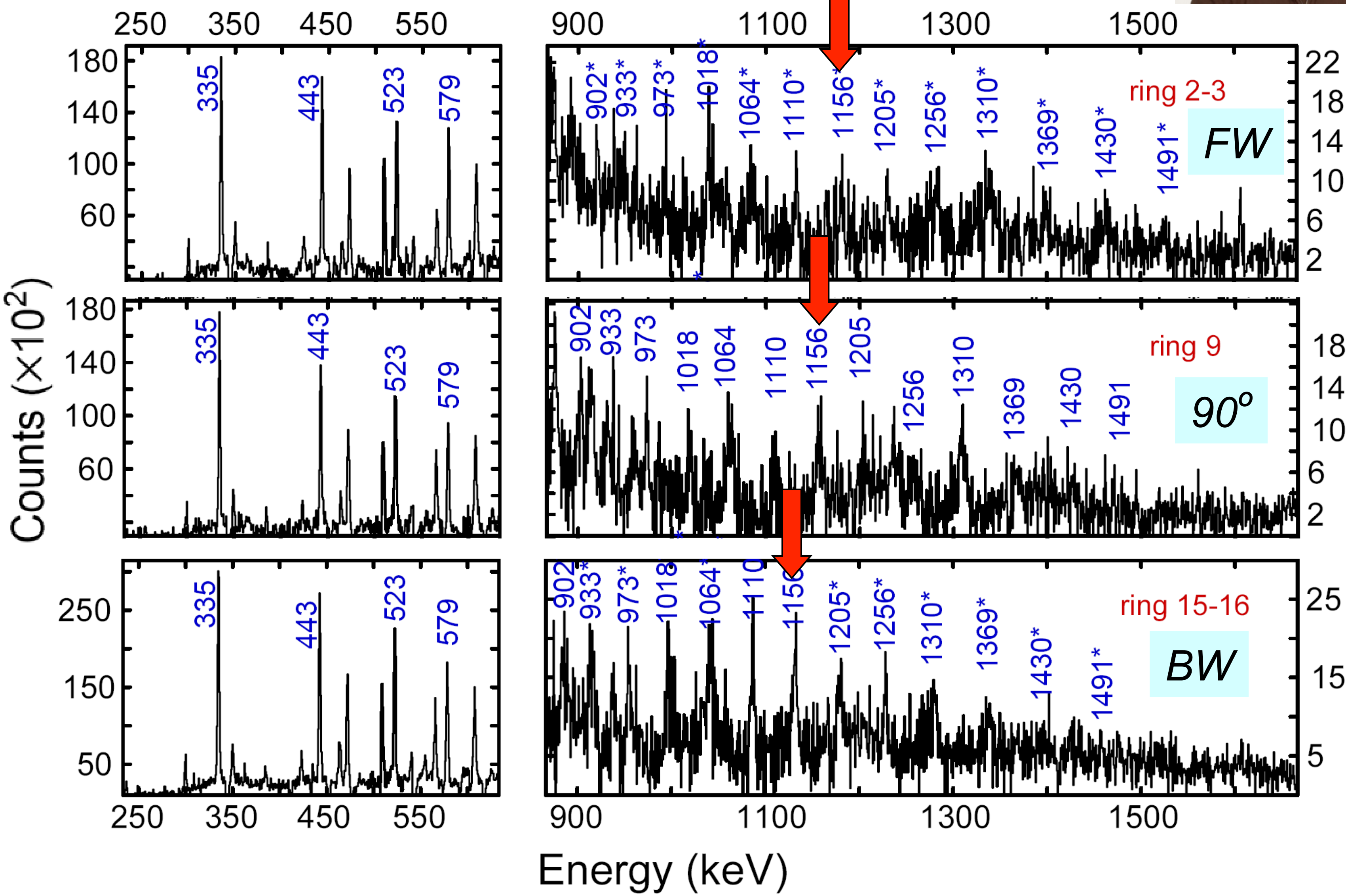
But Xiaofeng kept at it ….. Refining everything looking for those beautiful needles!



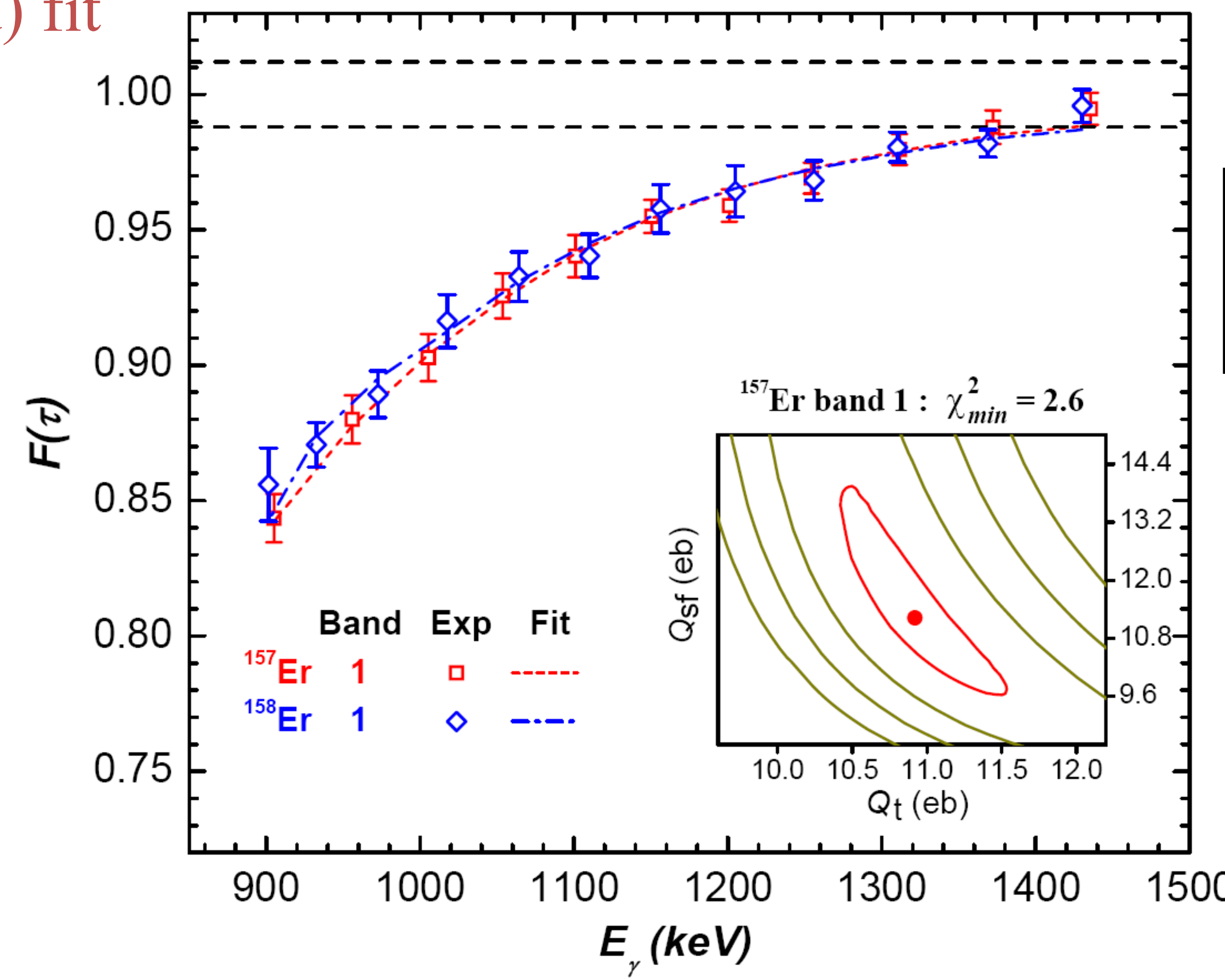

KEEP
CALM
AND
CARRY
ON

DSAM spectra at different angles

^{158}Er band 1 (γ^3)



F(tau) fit



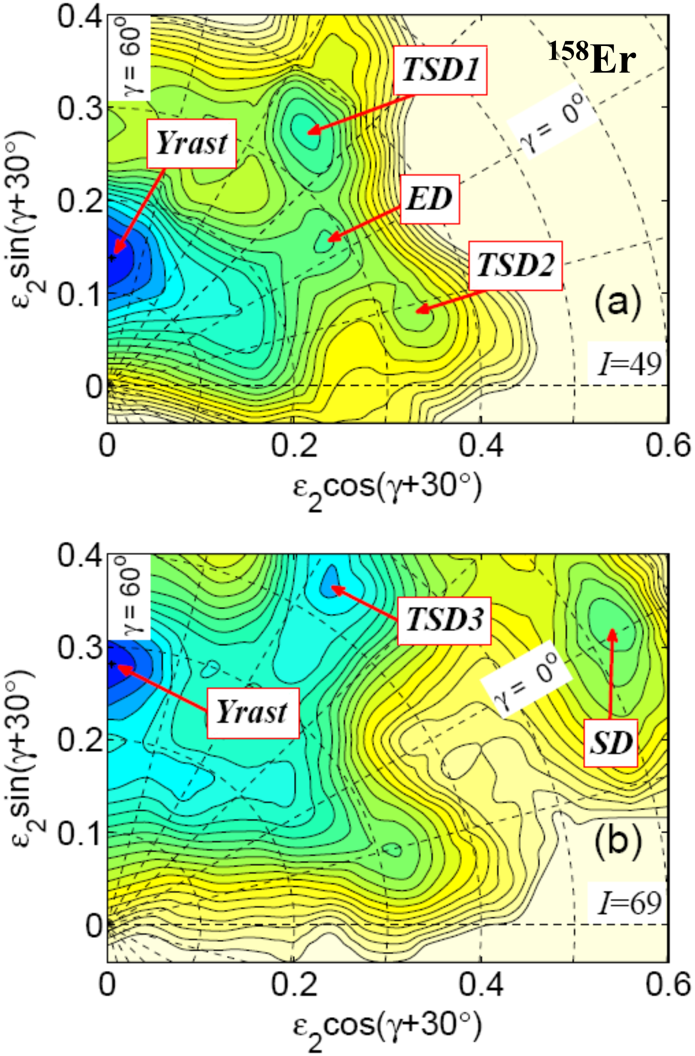
Spin range covered: 33 – 57

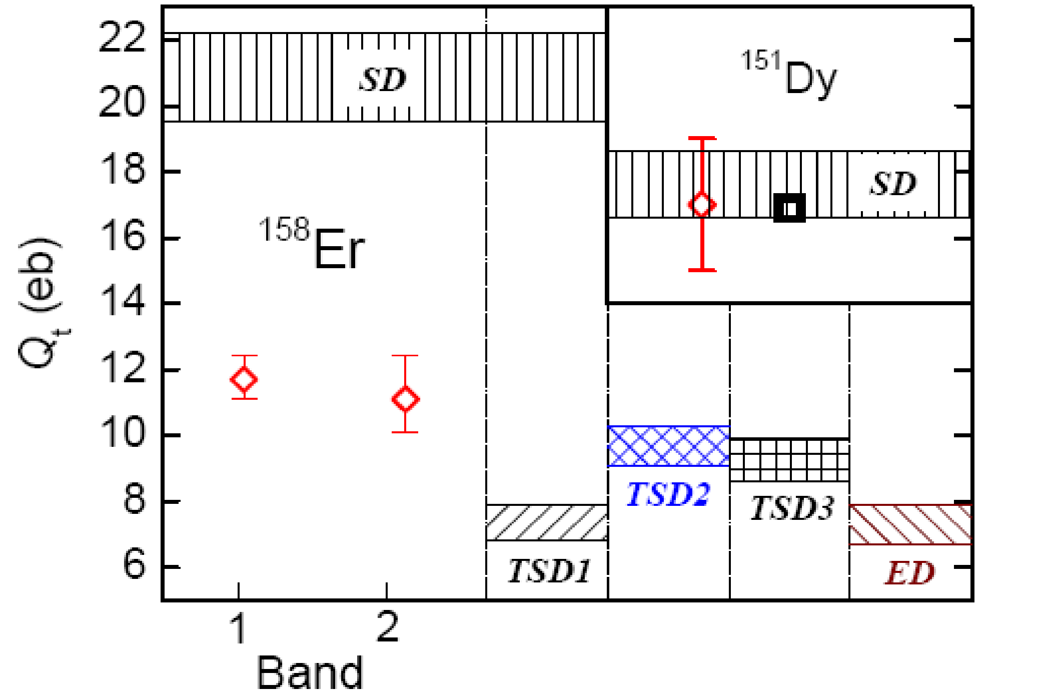
$$F(\tau) = \frac{\overline{E_\gamma} - E_{\gamma 0}}{E_{\gamma 0} * \beta_0 * \cos(\theta)}$$

The fit of extracted F(tau) numbers was performed using the code package "MLIFETIME" (by E. F. Moore, ANL) combined with "SRIM".

Result & Perspective

CNS calculations



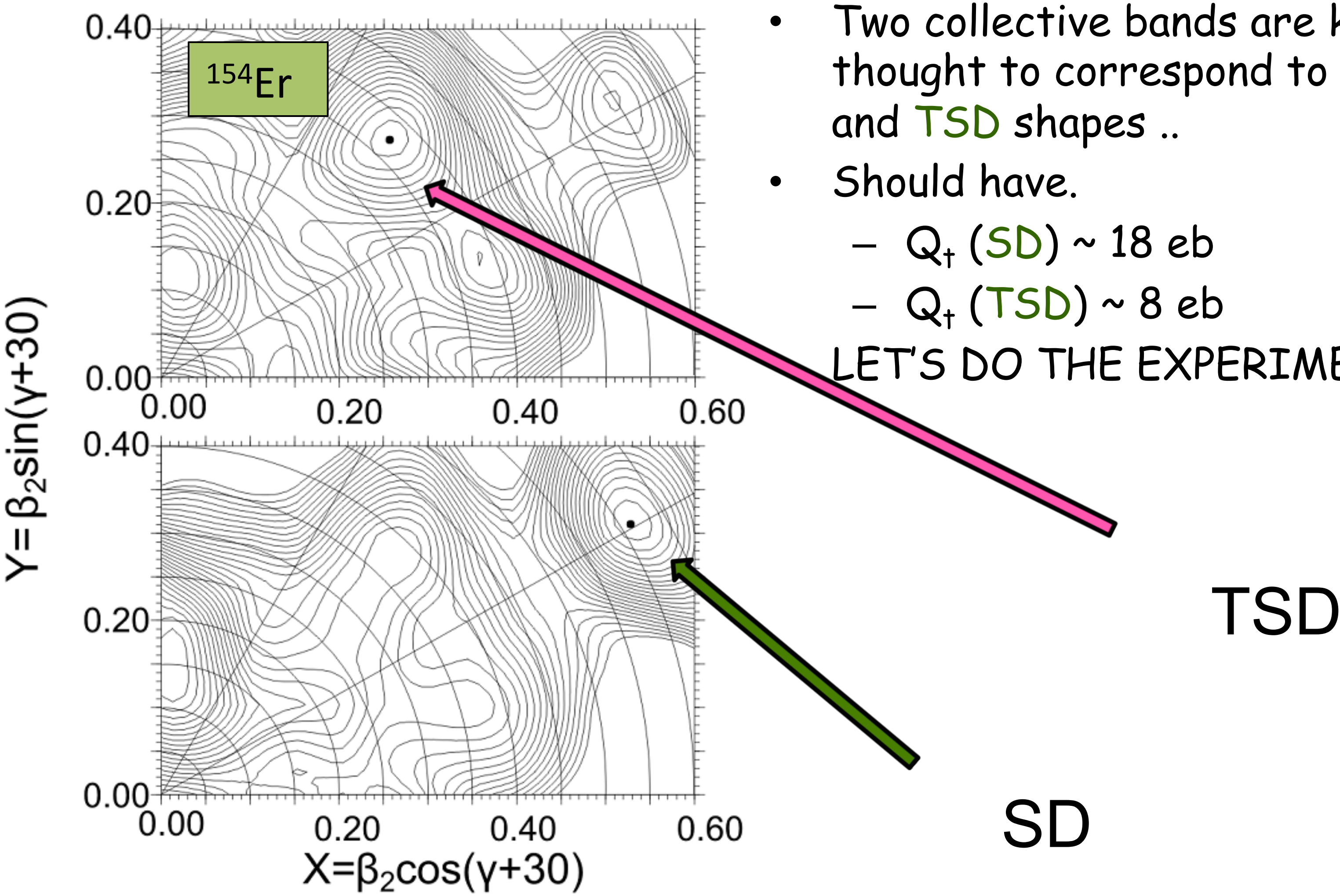


(Wang *et al.*, Phys. Lett. B 702, 127, 2011)

Values in ^{158}Er too large for TSD1!
Hence ^{154}Er expt
^{151}Dy SD values and more…

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

Coexisting "SD" and "TSD" Bands in ^{154}Er

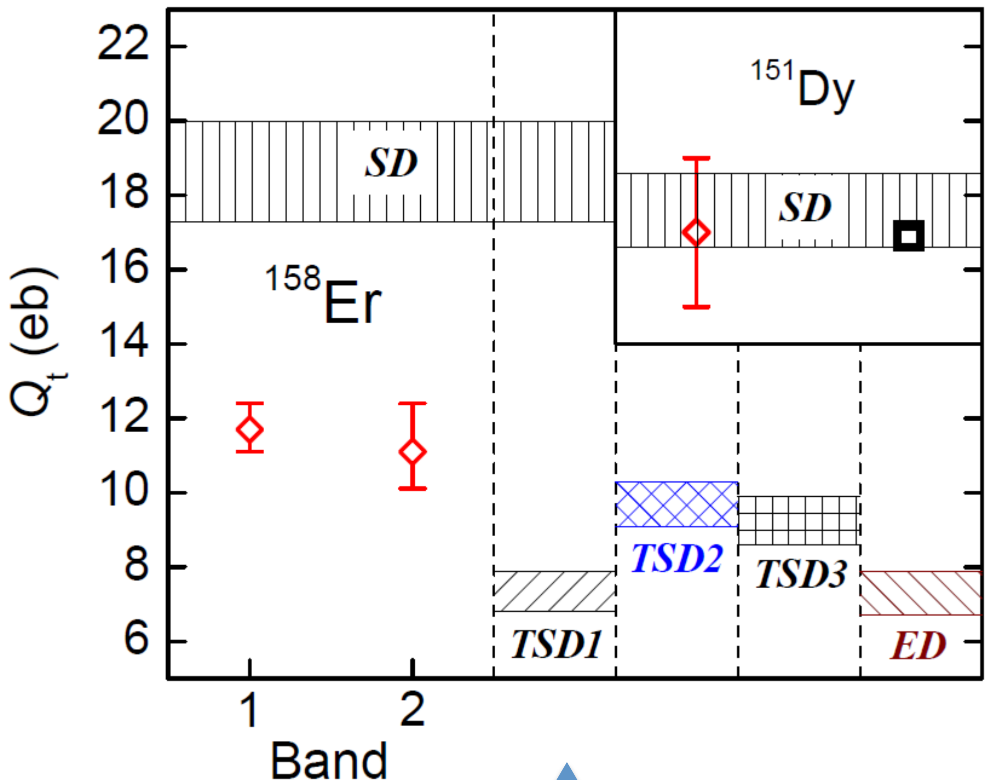


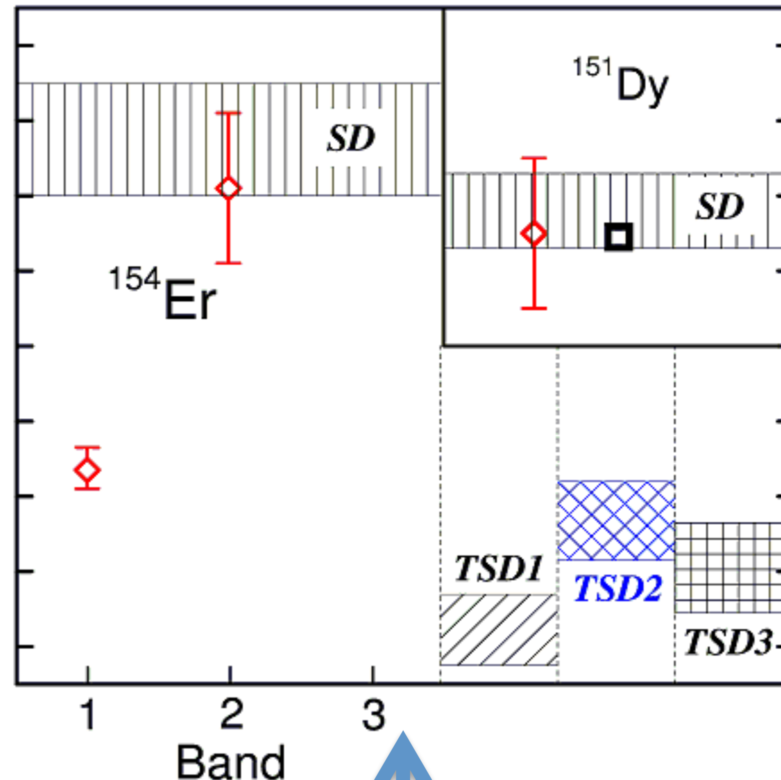
- Two collective bands are known in ^{154}Er, thought to correspond to both axial SD and TSD shapes ..
- Should have.
  - Q_t (SD) ~ 18 eb
  - Q_t (TSD) ~ 8 eb

LET'S DO THE EXPERIMENT!

K. Lagergren, B. Cederwall et al.,
PRL 87, 022502 (2001)

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



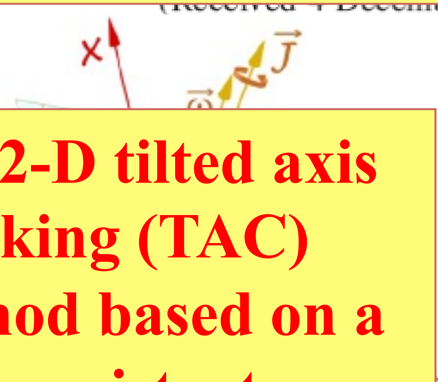


Wang *et al.*, Phys. Lett. B 702, 127, 2011

Revill et al, PRC in press

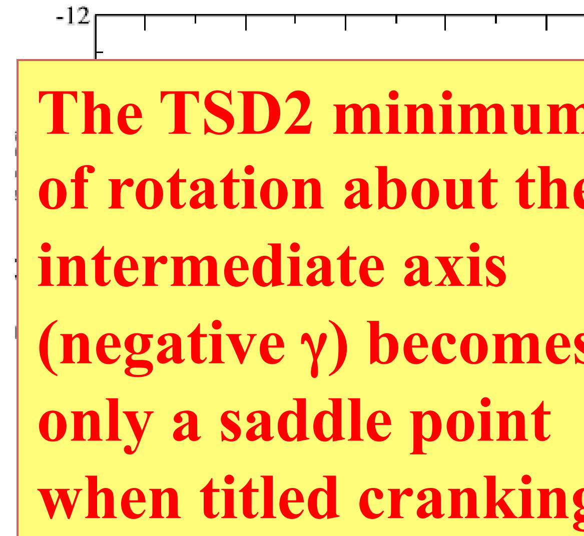
The unexpected result in our ^{158}Er work has

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



The 2-D tilted axis cranking (TAC) method based on a self-consistent Skyrme-Hartree-Fock (SHF) model.

FIG. 1 (c… SD shape. The angles θ (between the x axis and the rotational axis) and α (between $\boldsymbol{\omega}$ and $\boldsymbol{J}$) are defined in the x-y plane. The short, medium, and long axes are denoted by x, y, and z, respectively; that is, the plotted shape corresponds to $\gamma > 0$.



The TSD2 minimum of rotation about the intermediate axis (negative γ) becomes only a saddle point when titled cranking is considered.

FIG. 2 (c… by means o… a function of γ for rotation about the x axis (solid line) compared to those calculated at $\gamma = 15°$ and $22°$ as functions of θ (dashed lines). In the latter case, the Routhians are drawn by uniformly scaling the range of $0° \le \theta \le 90°$ into the corresponding ranges of γ.

PHYSICAL REVIEW C 86, 014309 (2012)

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

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(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

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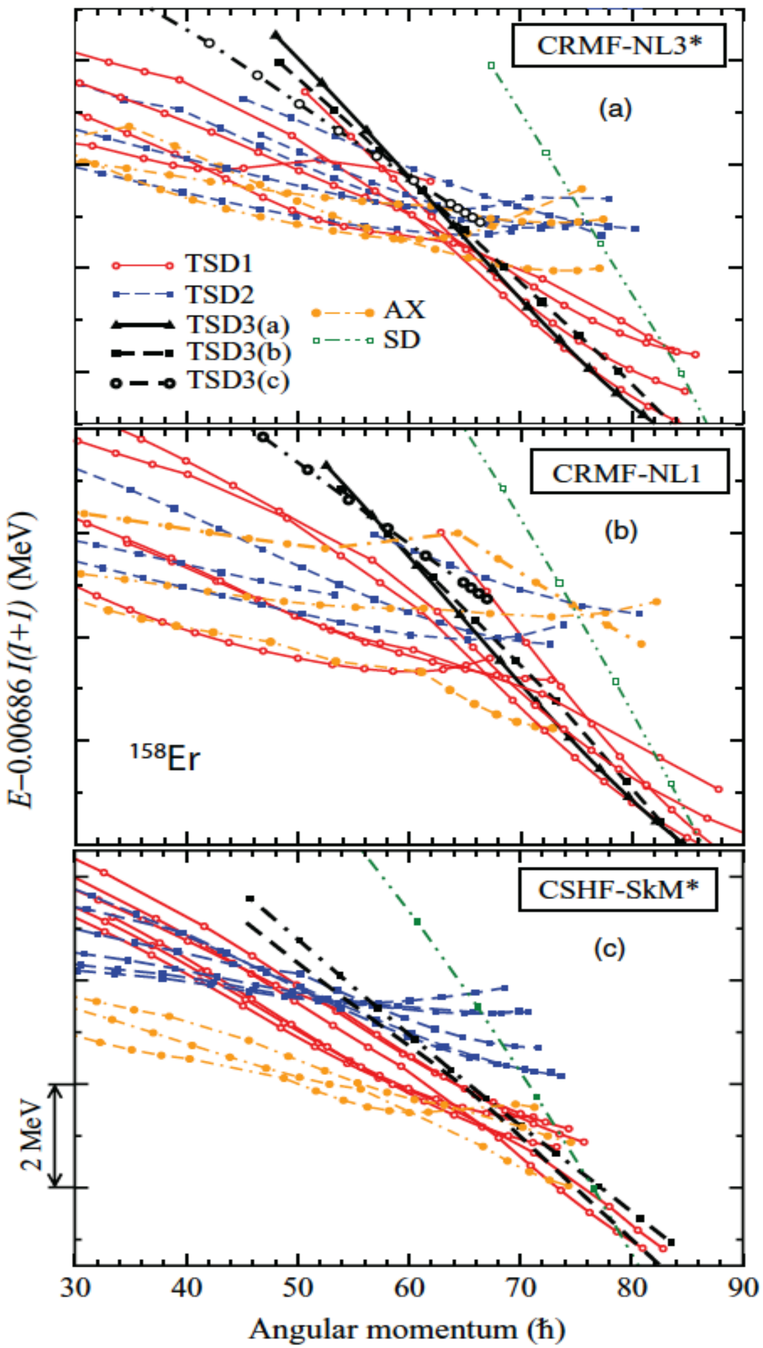
(Received 22 August 2012; published 17 September 2012)



A. V. AFANASJEV, YUE SHI, AND W. NAZAREWICZ

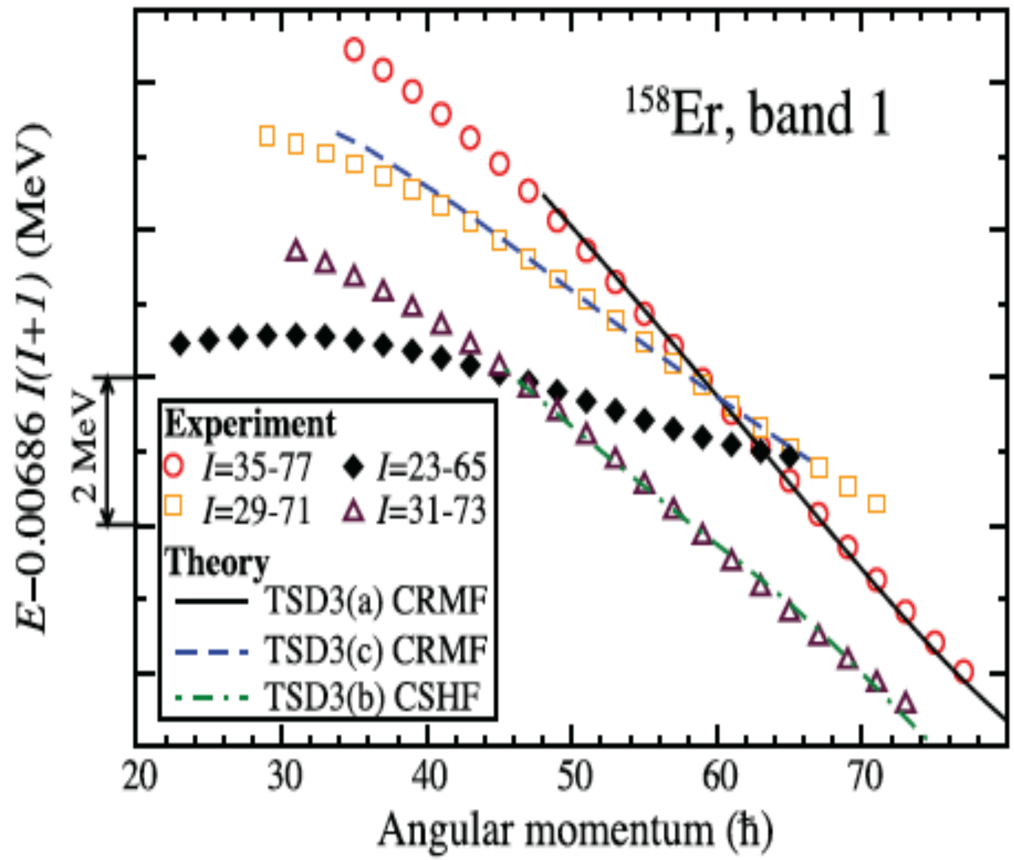
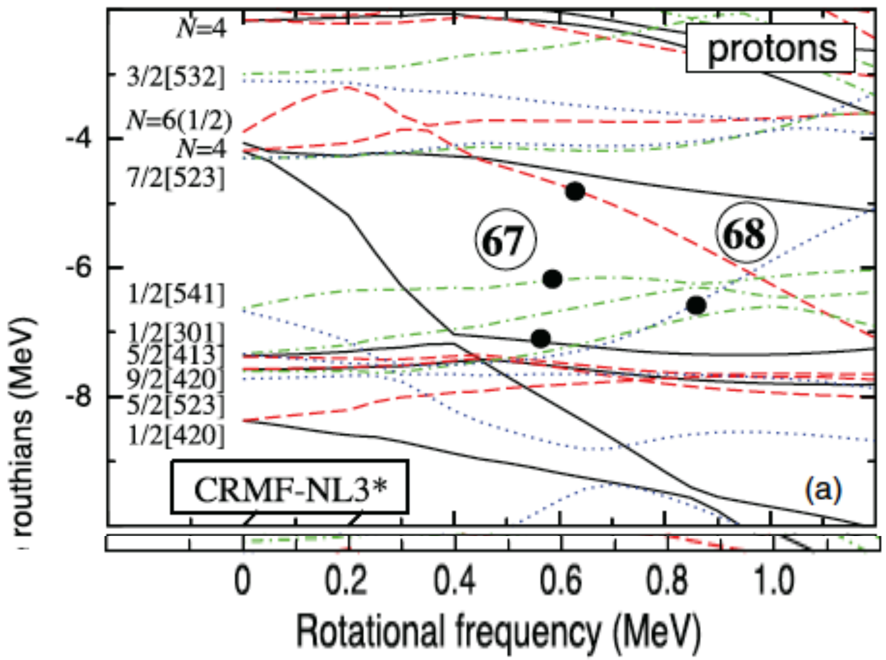
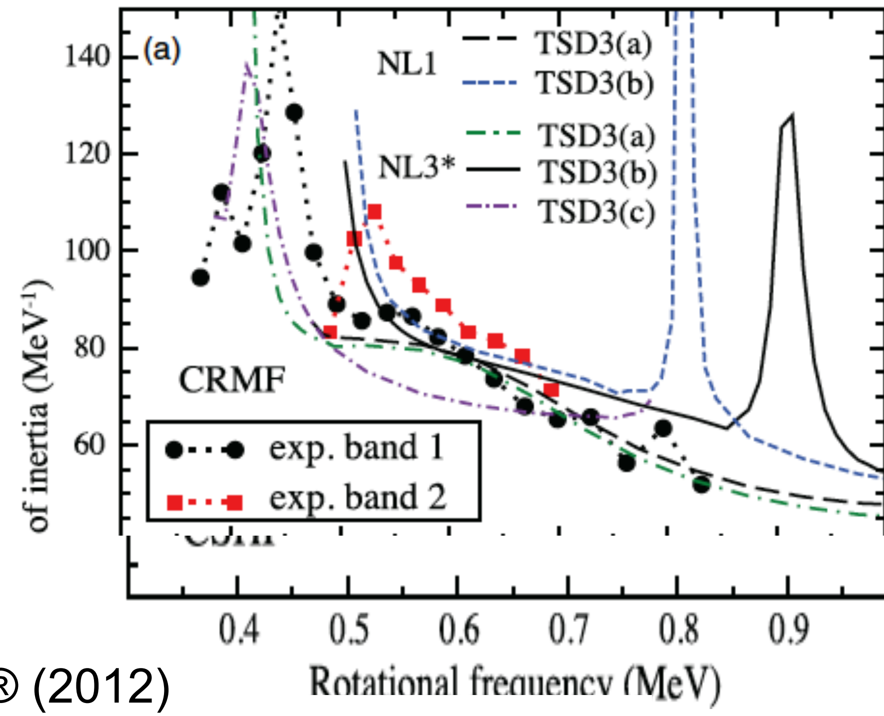


FIG. 4. (Color online) Similar to Fig. 1 but for experimental band 1 assuming different spin assignments (symbols) and for calculated configurations TSD3(a) and TSD3(c) in CRMF-NL3* and TSD3(b) in CSHF-SkM* (lines). The energy of the lowest experimental state is selected arbitrarily to minimize the deviation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





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

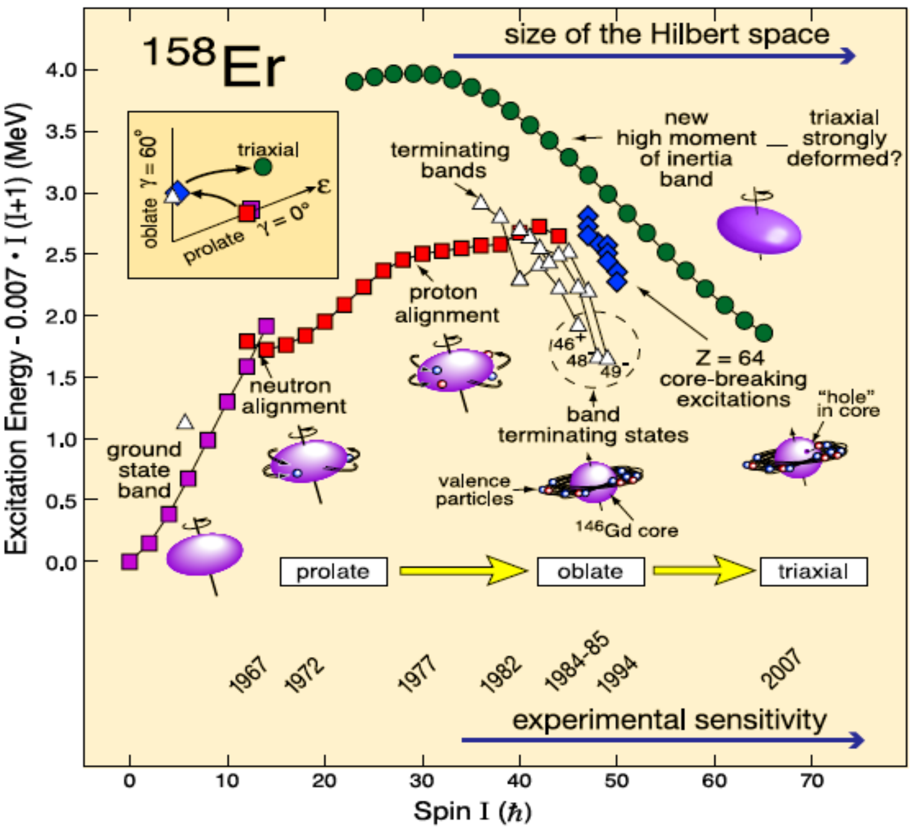
If the theoretical spin assignments of Fig. 4 turned out to be correct, the experimental band 1 in ^{158}Er would be the the highest spin structure ever observed. The current study stresses the need for more precise measurements of Q_t and reliable estimates of spins in these bands.

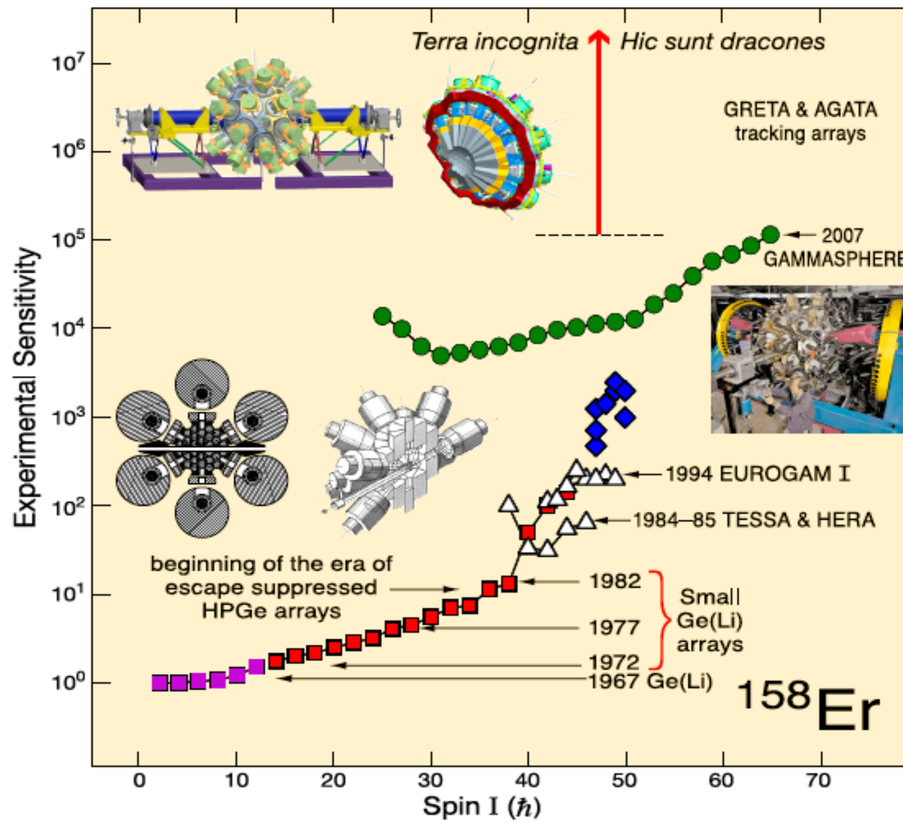
I agree! Digital GS will help

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

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

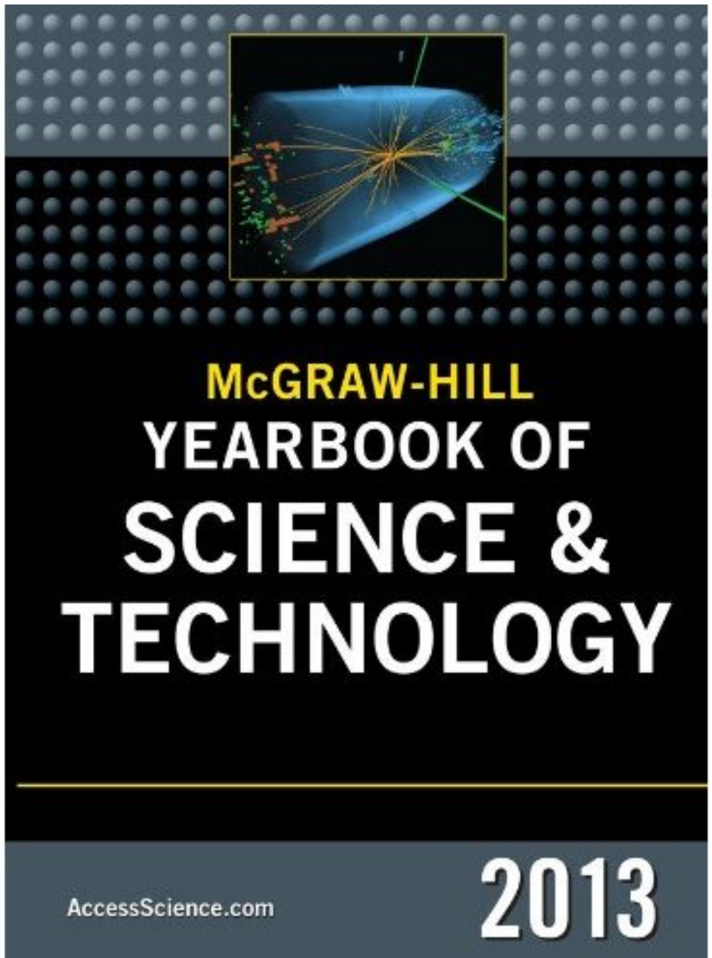
- New Detector Systems = New Physics





"The Fascinating Nuclear Structure World of Erbium-158"

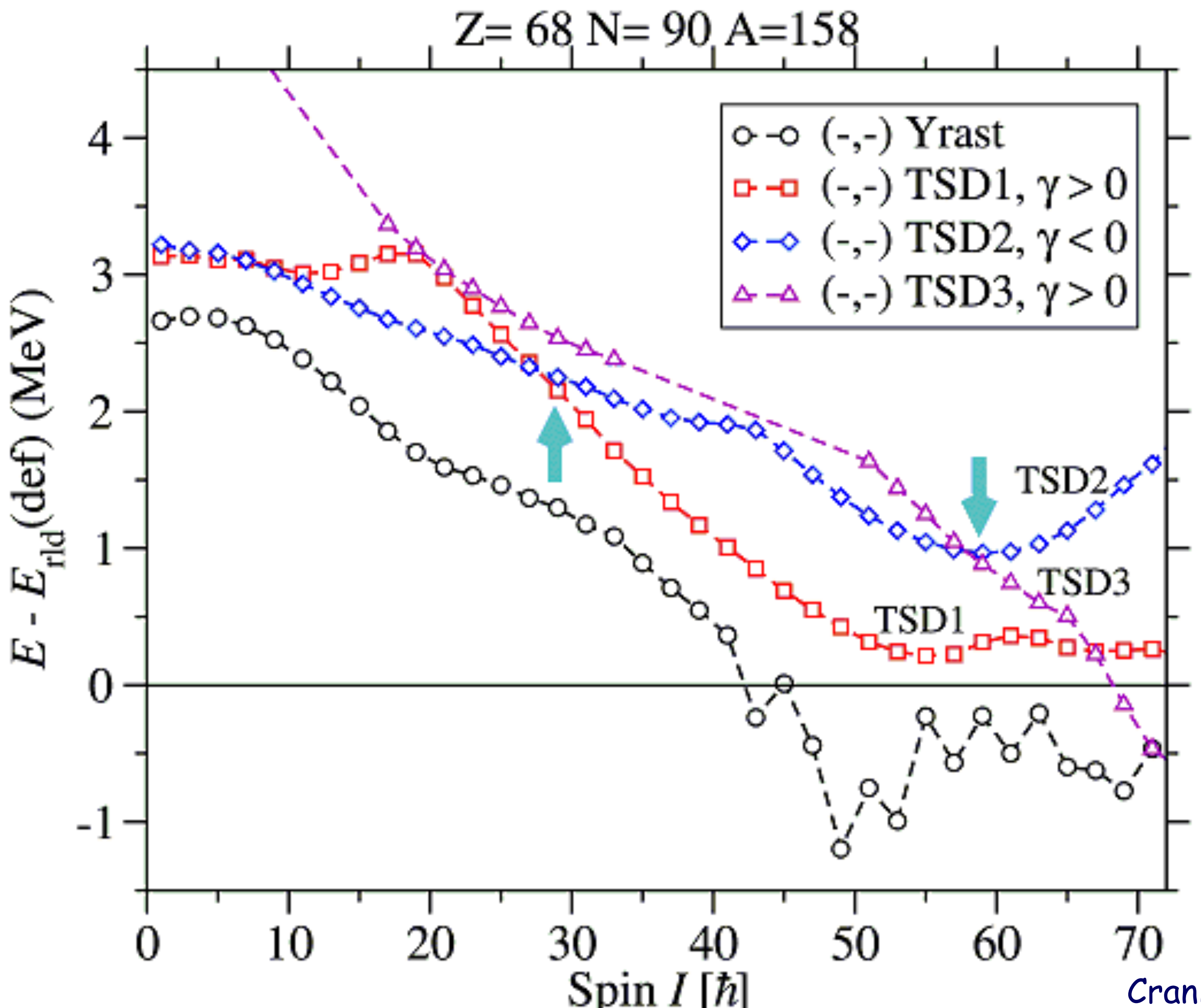
Wang, Riley, Simpson and Paul



- … What will the next decade bring????

End Episode 3:

Relative Energies of the Bands



TSD1 lowest between 30ħ and 65ħ

but...

TSD3 lowest above 65ħ

Cranked Nilsson Strutinsky calcs: Ingemar Ragnarsson

PHYSICAL REVIEW C 69, 054304 (2004)

Phase transitions versus shape coexistence

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(Received 13 November 2003; published 12 May 2004)

The concept of deformed shapes and the appearance of different shapes in a given nucleus was introduced in nuclear physics as early as 1937 by the work of Bohr and Kalckar [1]. In those early days, little did one expect how fruitful these ideas would turn out to be. The discovery of the first

understanding of shape coexistence. Soon after, it was realized that the atomic nucleus, on its way to fission, had to undergo a number of shape changes in which a specific shape could be trapped as an isomeric state in a secondary potential minimum, called fission isomers [3]. Shape coexistence, in-

phases could be linked to the occupation of very specific up- and/or downsloping orbitals, coined "intruder orbitals," which allowed for a simple understanding of the phenomenon of shape coexistence [4,5]. The method put forward in

particle excitations corresponding to oblate shapes [6]. This research field has exploded in recent years due to the highly increased technical capabilities in detecting gamma radiation emitted during the slowing down of the rapid rotation (Gammasphere, Euroball, …).